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VARIABILIDAD CLIMÁTICA DE GRAN ESCALA Y SUS EFECTOS ECOLÓGICOS EN EL PACÍFICO MEXICANO

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"VARIABILIDAD CLIMÁTICA DE GRAN ESCALA Y SUS EFECTOS ECOLÓGICOS EN EL PACÍFICO MEXICANO"

Presentada por el alumno:

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RESUMEN: En el presente estudio se caracterizó la variabilidad ambiental de gran escala (interanual y multidecadal) y sus efectos ecológicos sobre las poblaciones naturales en aguas del Pacífico mexicano y regiones oceánicas adyacentes. A partir de los resultados se identifican tres escalas de variación en el Pacífico mexicano: la escala interanual relacionada con la variabilidad del El Niño/a Oscilación del Sur (ENSO) y la escala cuasidecadal y la multidecadal, asociadas a modos de variación climática del Pacífico Norte. A escala interanual se ha observado que los cambios en la ocurrencia de la ballena de Bryde (*Balaenoptera edeni*) en la Bahía de La Paz están influenciados por la variabilidad del ENSO y probablemente estén mediados por la disponibilidad de sus presas. A escalas cuasidecadales se observa que los vientos tehuanos son una fuente de variabilidad climática extratropical en el Pacífico Oriental Tropical; esta señal de baja frecuencia en los tehuanos puede ser modelada por la variación extratropical del sistema de alta presión del Pacífico Noreste, siendo su teleconexión el movimiento hacia el sur de los frentes fríos que bajan por Norteamérica desde el Pacífico Noreste. A escala multidecadal se distinguen con claridad la alternancia de periodos de enfriamiento y calentamiento en la Corriente de California durante los últimos 110 años. Estos cambios en la temperatura superficial del mar son indicativos de cambios en la circulación oceánica y atmosférica, que en última instancia, afectan los mecanismos de enriquecimiento de las aguas superficiales en toda la cuenca del Pacífico Norte. Esta señal de baja frecuencia representa la variación del régimen. Las respuestas biológicas documentadas relacionadas con esta escala de variación incluyen: 1) la expansión y contracción de poblaciones de la sardina de California (*Sardinops sagax caerulea*) y el calamar gigante (*Dosidicus gigas*), 2) cambios en la distribución en delfines comunes (*Delphinus sp.*), y 3) cambios en los patrones de migración de la ballena azul (*Balaenoptera musculus*); asimismo la evidencia sugiere cambios de largo plazo en la distribución de ballena gris (*Eschrichtius robustus*), ballena de aleta (*Balaenoptera physalus*), delfín de costados blancos (*Lagenorhynchus obliquidens*) y cachalotes (*Physeter macrocephalus*) que podrían estar relacionados con este tipo de variación multidecadal.

ABSTRACT: In the present study large-scale environmental variability (interannual and multidecadal) and their ecological effects on marine populations in the Mexican Pacific and adjacent oceanic regions were characterized. From the results, three scales of variability were identifying in the Mexican Pacific: the interannual scale, associated with the El Niño/a southern oscillation (ENSO); and the quasidecadal and multidecadal scales associated with North Pacific climate variability. At the interannual scale, it was observed that the occurrences of Bryde's whales at La Paz Bay are driven by the ENSO variability and are probably mediated by their prey availability. At quasidecadal scales, the Tehuantepec gap winds are a source of extratropical climate variability in the Eastern Tropical Pacific. This low frequency signal in the Tehuantepec gap winds could be driven by the extratropical variability of the high-pressure system located in the Northeast Pacific, and the teleconnection is given by the southward movement of cold-surges that flow from the Northeast Pacific over North America. At multidecadal scale, the alternating of cooling and warming periods over the past 110 years in the California Current was clearly distinguished. These changes in sea surface temperature are indicative of changes in the ocean-atmosphere circulation, which ultimately affect the mechanisms of surface waters enrichment across the North Pacific basin and this low frequency signal represents the regime variability. The documented biological responses related to this scale of variation include: 1) the expansion and contraction of the California sardine and the giant squid populations, 2) changes in the distribution of common dolphins, and 3) changes in migration patterns of blue whales; further evidence suggests long-term changes in the distribution of gray whale, fin whale, Pacific white-sided dolphin and sperm whales that could be associated with this type of multidecadal variation.

1. Introducción

Como consecuencia de las tendencias político-sociales derivadas de la preocupación por el cambio climático y a la necesidad de un manejo sustentable de los recursos, en las últimas décadas ha tomado cada vez mayor importancia el estudio de la variabilidad climática y sus efectos sobre los recursos naturales. Las observaciones regulares y confiables del clima comenzaron hace 150 años, cuando se dio inicio a una constante y organizada observación global de los sistemas oceánicos y de la atmósfera (Klyashtorin, 2001). Sin embargo, el estudio de la variabilidad climática toma fuerza a finales de los años 80, gracias al desarrollo de una mayor capacidad de cómputo que permitió el uso de una amplia gama de variables ambientales obtenidas con satélites y boyas, y técnicas sofisticadas de análisis (Venegas, 2001).

Además de la periodicidad estacional (invierno-verano), existen ciclos naturales con tendencias bien definidas en el ambiente como: 1) la interanual, relacionada con los eventos del El Niño-La Niña (Wang & Fiedler, 2006); 2) la decadal con periodos de entre 10 y 20 años (Mantua *et al.,* 1997); y 3) la multidecadal con ciclos mayores de 50 años, descritos como variaciones del régimen (Lluch-Belda *et al.,* 1989). En ese sentido, se han documentado cambios en la distribución y abundancia de poblaciones naturales como respuesta a los cambios en el ambiente físico, como la temperatura, cambios en la productividad de los ecosistemas marinos o por una combinación de ambos.

En respuesta a la necesidad de contar con información de calidad para la toma de decisiones en el manejo de los recursos marinos, se están realizando análisis de nuevas bases de datos que se han ido constituyendo en los últimos años, que integran un mayor número de variables de utilidad para comprender mejor la variabilidad climática a diferentes escalas y sus efectos en los ecosistemas explotados por el hombre. El objetivo del presente trabajo de tesis es caracterizar la variabilidad ambiental de gran escala (interanual y multidecadal) y sus efectos ecológicos sobre las poblaciones naturales en aguas del Pacífico mexicano, a través del análisis retrospectivo de la variación climática y oceanográfica en el Pacífico Oriental tropical, Corriente de California y Golfo de California.

2. Antecedentes

Variabilidad interanual: El fenómeno de El Niño Oscilación del Sur (ENSO por sus siglas en inglés), es una fluctuación interanual en el Pacífico tropical-subtropical que afecta globalmente al sistema océano-atmosfera, y se manifiesta en las costas americanas como un calentamiento (El Niño) o enfriamiento (La Niña) anormal de sus aguas. Presenta una periodicidad no regular de entre dos y siete años en variables físicas (Fiedler, 2002), y de cinco años en variables biológicas de la costa del Pacífico nororiental (Lluch-Belda *et al*., 2005). Es la escala de variabilidad dominante en el Pacífico Oriental Tropical (Fiedler & Talley, 2006). Se ha observado que los cambios en la temperatura, estratificación y productividad del mar asociados con el fenómeno de El Niño afectan la supervivencia, reproducción y distribución de las poblaciones de organismos marinos, incluyendo a los depredadores tope vía la disponibilidad y abundancia de sus presas (Fiedler, 2002; Balance *et al*., 2006). En aguas de la Corriente de California, la termoclina y la nutriclina se profundizan significativamente durante la fase Niño de esta oscilación, provocando la caída de la productividad primaria en los sistemas de surgencias estacionales, con un aumento en la temperatura superficial del mar, modificando la riqueza biológica y la distribución latitudinal de la fauna marina (Benson *et al.,* 2002; Lluch-Belda *et al*., 2005).

En aguas del Golfo de California el ENSO es la señal interanual más importante y se asocia a cambios en la precipitación, temperatura superficial del mar y nivel medio del mar (Lluch-Cota *et al*., 2007). Durante las condiciones de El Niño, la productividad primaria cae en el sureste del Golfo, mientras que al norte, incluyendo la región de las grandes islas, y en toda la costa oeste del mismo los efectos del ENSO son poco evidentes (Lluch-Cota, 2000; Kahru *et al.,* 2004; Herrera-Cervantes *et al*., 2010), observándose un aumento de depredadores tope en las inmediaciones de las grandes islas (parte central del Golfo) debido a una mayor disponibilidad de presas (Tershy *et al.,* 1991), por lo que la zona ha sido considerado un refugio de fauna pelágica durante las condiciones adversas de El Niño (Lluch-Belda *et al*., 2003)

Varaibilidad multidecadal (decadal y del régimen): Entre los primeros estudios sobre variabilidad multidecadal en el Pacífico, Namias (1972) describió cambios en la temperatura superficial del mar antes y después de El Niño de 1957-58, atribuyéndolo a la transición entre dos regímenes climáticos, mismos que tuvieron impactos en la abundancia y disponibilidad de recursos pesqueros como el camarón (Lluch-Belda, 1974) y sardina (Lluch-Belda *et al.,* 1986; Huato-Soberanis *et al.,* 1987). Posteriormente numerosos autores han observado en el Pacífico nororiental señales de variabilidad ambiental a diferentes escalas, como la oscilación decadal-bidecadal (10-30 años) y de muy baja frecuencia (50-90 años) (Ware, 1995; Wooster & Hollowed, 1995; Mantua *et al.,* 1997)

La variabilidad multidecadal en aguas del Pacífico está representada principalmente por la oscilación decadal del Pacífico (PDO por sus siglas en inglés), presentándose como un ciclo interno en el sistema océano-atmosférico, que comprende la alternancia de una fase cálida y otra fría cada diez a treinta años sobre latitudes medias y altas (Mantua *et al*., 1997). Se ha detectado que la intensidad de las condiciones del ENSO podrían estar mediadas por la fase del PDO; durante las condiciones cálidas del PDO, los efectos de El Niño son potenciados a lo largo de la costa de México, Estados Unidos y Canadá (ej. El Niño 1997: Mestas-Núñez & Miller, 2006).

Los cambios abruptos entre fases multidecadales son conocidas como cambios de régimen (Overland *et al*., 2008). El cambio de régimen mejor documentado en el Pacífico Norte fue el ocurrido a medidos de la década de los 1970s, con una fuerte señal en variables físicas y biológicas, incluyendo productividad primaria (Ebbesmeyer *et al.*, 1991; Roemmich & McGowan, 1995), biomasa y distribución de las poblaciones de sardinas y anchovetas (Kawasaki, 1983; Lluch-Belda *et al.*, 1989) y de otras especies de peces (Beamish & Bouillon, 1993; Mantua *et al*., 1997; Holbrook *et al*., 1997). Estos cambios impactan las redes tróficas marinas y en última instancia afectan la distribución y la supervivencia de grandes pelágicos como aves y mamíferos marinos (Trites & Larkin, 1996; Veit *et al*., 1997; Trites *et al*., 2007).

La variación multidecadal y efectos ecológicos en aguas del Pacífico Oriental Tropical ha sido menos documentada que para el Pacífico Norte (Mestas-Nuñez & Miller, 2006). Se ha observado que la amplitud y frecuencia de los fenómenos del ENSO presentan variaciones a escalas decadales (Gu & Philander, 1995,1997; Wang & Wang, 1996); al igual que su intensidad que parece estar relacionada con las condiciones prevalentes del PDO (Bernal *et al.,* 2001; Mestas-Nuñez & Miller, 2006). A su vez, se ha observado que el cambio de régimen de mediados de los 1970 coincide con un cambio en el sistema océano-atmósfera sobre el Pacífico Oriental Tropical, incluyendo el aumento en la temperatura superficial del mar y un debilitamiento en el régimen de vientos (Graham, 1994; Clarke & Lebedev, 1996), con consecuencias ecológicas sobre la productividad biológica de la región (Urban *et al.,* 2000; McPhaden & Zhang, 2002). También se ha observado la prevalencia (por dos o tres años) de periodos cálidos o fríos asociados al ENSO, relacionados con el cambio de régimen que comenzó en 1989 (Fiedler, 2002). En aguas del Golfo de California aún no está claro hasta qué punto la variación de baja frecuencia (ej. PDO o escalas del régimen) afecta su hidrografía (Lluch-Cota *et al.,* 2007). Sin embargo, la similitud de las relaciones observadas entre la costa peninsular del Pacífico y la del Golfo con la variabilidad decadal del Pacífico Norte (PDO), sugiere que la variabilidad climática de baja frecuencia se ve forzada latitudinalmente por la atmosfera, debido a que el aislamiento oceánico entre ambas costa aumenta de sur a norte (Lluch-Belda *et al*., 2009).

3. Justificación

La caracterización de las variaciones climáticas en la región del Pacífico mexicano es insuficiente, a pesar de su importancia como forzante de la disponibilidad de los recursos marinos. En esta tesis se propone que la comprensión de estas variaciones y su regularidad podría permitir el desarrollo de pronósticos de largo plazo (Lluch-Belda *et al*., 2002), lo que potenciaría nuestras capacidades de manejo de los recursos marinos.

4. Hipótesis

La variabilidad climática en el Pacífico mexicano es detectable y tiene impactos demostrables en poblaciones naturales.

5. Objetivos

Caracterizar la variabilidad ambiental de gran escala y sus efectos sobre las poblaciones naturales en el Pacífico mexicano

5.1. Objetivos Particulares:

Caracterizar la variabilidad ambiental del Pacífico mexicano por bandas de frecuencia.

Identificar los mecanismos físicos que se relacionan con estas variaciones

Relacionar los modos de variabilidad con los cambios en la distribución y abundancia de poblaciones naturales.

Generar hipótesis de los mecanismos de transferencia de las tales variaciones.

6. Metodología

6.1 Área de estudio

El Océano Pacífico frente a las costas de México incluye la región norte del Pacífico Oriental Tropical, la parte sur de la Corriente de California y el Golfo de California. Aquí confluyen tres sistemas de corrientes oceánicas superficiales y numerosos procesos oceanográficos de importancia biológica como: 1) surgencias estacionales que se dan en la costa occidental de la Península de Baja California, Golfo de California y Golfo de Tehuantepec, 2) remolinos de mesoescala asociados a la Corriente de California y aquellos que se originan por la acción de los vientos Tehuanos en el Golfo de Tehuantepec, y 3) frentes térmicos que se dan principalmente en la frontera entre las aguas cálidas del Pacífico Oriental Tropical y las aguas frías de la Corriente de California frente a la costa peninsular (Fig. 1).

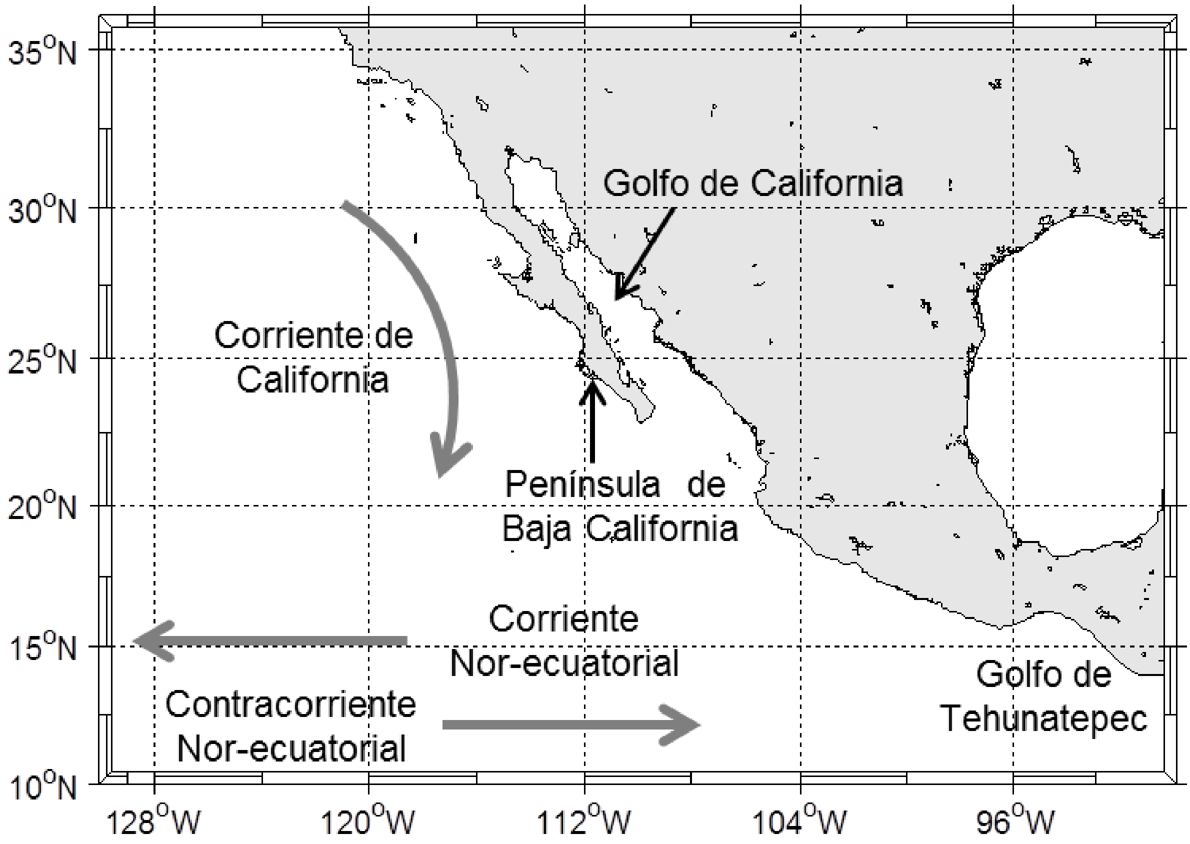


Figura 1: Área de estudio; corrientes oceánicas superficiales (flechas grises).

6.2 Fuentes de información

Para la caracterización del marco ambiental se utilizaron datos mensuales de variables físicas y biológicas detalladas en la Tabla 1. Todas las variables cubren una extensión temporal mínima de 20 años y máxima de 110 años. La resolución espacial es variable, pero para el caso particular de las componentes zonal y meridional del viento, se calculó el promedio mensual y se redujo la resolución espacial calculando el promedio en cuadrantes de 2x2 grados, para un mejor manejo de los datos.

Tabla 1: Fuentes de información de variables físicas: Temperatura Superficial del mar (TSM) y vientos; y variables biológicas: concentración superficial de clorofila (Chl) utilizadas en el estudio; la resolución espacial está en grados, excepto los datos de Chl que están en kilómetros.

Variables	Resolución temporal	Resolución espacial	Extensión (años)	URL
TSM (ERSST)	mensual	2x2	1900-2010 (110 años)	http://lwf.ncdc.noaa.gov/ersst/
TSM (NOAA_OI_SST_V2)	mensual	1x1	1988-2007 (20 años)	http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html
Vientos (zonales y meridionales)	diaria	0.25x0.25	1988-2007 (20 años)	http://podaac.jpl.nasa.gov/DATA_CATALOG/ccmpinfo.html
Chl (Aqua-Modis)	mensual	9x9	1988-2007 (20 años)	http://oceancolor.gsfc.nasa.gov/cgi/l3

También se utilizaron índices climáticos (Tabla 2) de diferentes patrones de variabilidad climática, de diversas fuentes, integradas en la página de internet del CICIMAR-IPN (Centro Interdisciplinario de Ciencias Marinas del Instituto Politécnico Nacional, www.cicimar.ipn.mx/oacis/Indices_Climaticos.php).

Tabla 2: Índices climáticos seleccionados para el presente estudio; el acrónimo del índice corresponde a su nombre en inglés

Índice	Descripción	Referencia
SOI	Variabilidad atmosférica relacionada al ENSO en el Pacífico Sur-ecuatorial	Trenberth, 1984
MEI	Variabilidad oceánica y atmosférica relacionada al ENSO en el Pacífico Ecuatorial	Wolter ,1987; Wolter & Timlin, 1993
NOI	Variabilidad atmosférica extratropical relacionada al ENSO en el Pacífico Nororiental	Schwing *et al.*, 2002
PDO	Primer modo de variación oceánica sobre el Pacífico Norte	Mantua *et al*, 1997
NPGO	Segundo modo de variación oceánica sobre el Pacífico Norte	Di Lorenzo *et al*., 2008
NAO	Primer modo de variación atmosférica sobre el Hemisferio Norte (Atlántico)	Barnston & Livezey 1987
PNA	Segundo modo de variación atmosférica sobre el Hemisferio Norte (Pacífico y Norteamérica)	Barnston & Livezey 1987
ATI	Primer modo de variación de la temperatura superficial del mar en el Atlántico tropical	Deser & Timlin, 1997

Para el análisis e interpretación de los cambios en las poblaciones naturales se utilizaron los registros de presencia-ausencia de cetáceos en el suroeste del Golfo de California, así como evidencia de cambios en poblaciones naturales reportados en publicaciones científicas y reportes técnicos de organismos especializados. Los registros de presencia-ausencia de cetáceos en el suroeste del Golfo de California fueron realizados por personal del Programa de Investigación de Mamíferos Marinos de la Universidad Autónoma de Baja California Sur. Todos los datos se recolectaron desde embarcaciones medianas (eslora ≤ 50 pies) que se utilizaron como plataformas de investigación bajo condiciones inferiores o iguales a 3 en la escala de Beaufort (las condiciones por arriba de este valor reducen significativamente la capacidad de detectar cetáceos). Se siguió un método consistente de búsqueda, en el cual la embarcación se condujo en línea recta, a velocidad crucero (11 nudos), siguiendo un recorrido predeterminado y tratando de cubrir la mayor parte del área en un lapso de tres días en promedio. Durante cada viaje de muestreo, tres observadores (uno al frente y uno a cada lado de la embarcación) buscaron cetáceos durante los recorridos. El bote se detuvo cada 30 min para hacer una revisión de las aguas vecinas barriendo los 360º circundantes al mismo con binoculares (7×50), al mismo tiempo que se hacía cambio de guardia. Al avistarse un cetáceo, se registraron la fecha, la hora, la especie, la localización, el número de animales, el comportamiento y su asociación con otras especies (aves, peces, mamíferos marinos y tortugas). Estos datos se utilizaron para calcular la abundancia relativa mensual de cetáceos (numero de animales por hora de esfuerzo) como un indicador de la ocurrencia de estas especies en el área de estudio. Para ello, se calculó el número total de animales avistados y el número efectivo de horas trabajas por mes muestreado.

6.3 Métodos

Las series de tiempo de las variables ambientales pueden representarse por la siguiente ecuación:

$$S(t) = A_0 \cos(\varphi_o) + A_1 \cos(\omega t - \varphi_1) + A_2 \cos(2\omega t - \varphi_2) + R(t) \qquad (1)$$

Donde: A es la amplitud, ω es la frecuencia, φ es la fase y t representa el tiempo; por otro lado, el primer término de la ecuación ($A_{(0)}$) representa la media, los dos siguientes términos (A_1 Cos $(\omega\ t - \varphi_1) + A_2$ Cos $(2\ \omega\ t - \varphi_2)$) la variabilidad estacional y el último ($R_{(t)}$) los residuales, que contendrían la variabilidad temporal de mayor escala como la interanual y la decadal. Para el análisis de la información. La variabilidad estacional se calculó con mínimos cuadrados (Ripa, 2002), para posteriormente extraerse junto con la media a todas las series temporales de las variables consideradas (Tabla 1). De esta forma nos quedamos con los residuales o anomalías, que es la parte de la variación temporal que nos interesa. En algunos casos se extrajo la tendencia lineal a las anomalías, debido a que es un modo de variación que forma parte de un ciclo de mayor periodo que la extensión misma de los datos, de tal manera que no se puede resolver, es decir, no se le puede dar un sentido físico (existencia de una relación y una vinculación entre dos fenómenos o estados físicos).

Para el filtrado de señales climáticas en las series temporales se utilizaron funciones empíricas ortogonales (FEOs) y FEOs rotadas (Venegas, 2001). Las FEOs y su variante rotada (rotación varimax) son métodos de análisis exploratorios utilizados en estudios de variabilidad climática y permiten descomponer las señales en un conjunto reducido de funciones que explican la mayor variabilidad posible. Una característica de estos métodos es su capacidad de representar los datos distribuidos espacialmente de forma compacta, de tal manera que los procesos físicos detrás de los datos o sus efectos, pueden ser mejor visualizados e interpretados por el investigador (Venegas, 2001). Las FEOs (ecuación 2) descomponen la variabilidad de los residuos o anomalías *R(t)* de todos los cuadrantes en un número de funciones ortogonales $F_n(x,y)\, f_n(t)$; donde cada una representa un modo de variación independiente (Björnsson & Venegas, 1997; Wikle & Cressie, 1999; Venegas, 2001).

$$R(t) = \sum_{n=1}^{n=N} F_n(x,y)\, f_n(t) \qquad (2)$$

Donde $F_n(x,y)$ es el patrón espacial o autovector y $f_n(t)$ la serie temporal de dichos modos. Finalmente se calculó la varianza local explicada (ecuación 3) por cada modo de variación para toda el área de estudio

$$EV = \frac{var(F_n(x,y)\, f_n(t))}{var(S(x,y,t))} \qquad (3)$$

Donde $var(S(x,y,t))$ es la varianza local de la serie de anomalías (S) en un cuadrante determinado y $var(F_n(x,y)\, f_n(t))$ es la contribución de dicho modo de variación a la varianza en cada cuadrante.

Estos análisis se realizaron tanto para las anomalías de temperatura superficial del mar como para las de componentes del viento. Para el caso particular de los vientos, se realizó una FEO conjunto, previa estandarización de las series utilizadas. Este tipo de variante de las FEOs se utiliza cuando se usa más de una variable para el análisis, como con los vientos que se utilizan dos (la componente meridional y la zonal), por esa razón su patrón espacial (autovectores) está formado por un campo vectorial.

Por otra parte se realizó un suavizado con promedios móviles de 13 meses a las series temporales de las anomalías de las variables ambientales (Tabla 1), de los modos de variación obtenidos de los análisis FEOs y de los índices climáticos (Tabla 2), como una forma de filtrar la señal de mesoescala y resaltar las condiciones prevalentes de gran escala (interanual y decadal). En algunos casos se calculó la climatología (promedio de cada mes a lo largo de todo el año) de algunas variables ambientales y de la ocurrencia estacional de cetáceos. A su vez se calculó la climatología por periodos interanuales dependiendo de los valores de las anomalías de la temperatura superficial del mar (ATSM), teniendo periodos interanuales fríos (ATSM ≤ –0.5 ºC), cálidos (ATSM ≥ 0.5 ºC) y neutros (–0.5 ºC < ATSM < 0.5 ºC) y se graficaron para observar posibles cambios en la escala estacional durante cada condición interanual. Por último se realizaron correlaciones de Spearman y Pearson de las series temporales suavizadas para evaluar estadísticamente las relaciones observadas e identificar posibles conexiones y forzamientos.

7. Resultados

Se identificaron tres escalas de variación en el Pacífico mexicano: 1) la escala interanual relacionada con la variabilidad del ENSO; 2) la escala cuasidecadal relacionada con el segundo modo de variación del Pacífico Norte (NPGO); y 3) la escala multidecadal relacionada con el primer modo de variación del Pacífico Norte (PDO). La diferenciación entre estas escalas permite asociar la variabilidad a patrones y procesos físicos propios de cada escala, aunque se reconoce que no son realmente independientes. Dada la complejidad de las interacciones entre las escalas de variación y sus efectos en poblaciones naturales, se decidió abordar un caso de estudio para cada escala (interanual, decadal y multidecadal) como ejercicio demostrativo, mismo que son la base de trabajos científicos publicados (ver anexos) o sometidos.

7.1 Escala interanual

Se analizaron los registros de presencia y ausencia de la ballena de Bryde (*Balaenoptera edeni*) en la Bahía de La Paz, Baja California Sur, México (Fig. 2) entre 1988 y 2006. Todos los datos se tomaron siguiendo un método consistente de búsqueda, con un recorrido predeterminado (Fig. 2b), Para los análisis descriptivos y estadísticos, se consideraron los datos de aquellos meses que presentaron al menos dos viajes de muestreo (88 en total; Tabla 3). Adicionalmente se trabajó con los datos de: 1) promedios mensuales de la temperatura superficial del mar (NOAA_OI_SST_V2, Tabla1) y sus anomalías para la Bahía de La Paz, como un indicador de la variación estacional e interanual a escala local; 2) promedios mensuales de la concentración superficial de clorofila (Chl, Tabla1) para la Bahía de La Paz, como un indicador de los patrones estacionales e interanuales de la productividad primaria en la Bahía; 3) valores mensuales del Índice de la Oscilación del Norte (NOI, Tabla 2), como un indicador de la variabilidad interanual relacionada con el ENSO en el Pacífico Noreste; y 4) valores mensuales del Índice de la Oscilación Decadal del Pacífico Norte (PDO, Tabla 2), como un indicador de la variabilidad decadal del Pacífico Norte.

Tabla 3: Estadísticos básicos para el número de viajes, horas de esfuerzo efectivo y número de ballenas registrados por mes.

	Promedio	Mínimo	Máximo	Desviación estándar
Viajes	3.5	2	5	0.9
Esfuerzo	29.9	11.8	68.3	9
Ballenas	2.5	0	17	3.5

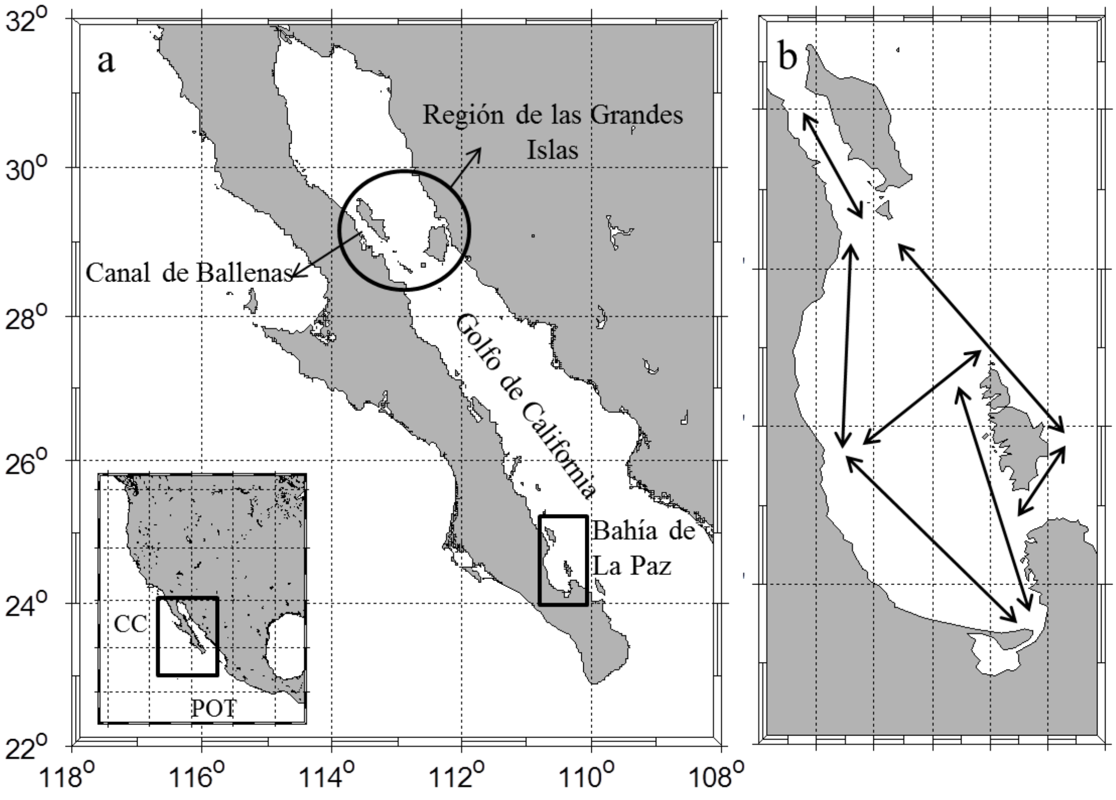


Figura 2: a) Localización regional del área de estudio, Corriente de California (CC), Pacífico Oriental Tropical (POT); b) Bahía de La Paz y rutas predeterminadas de muestreo (flechas negras).

Los datos de temperatura superficial del mar (TSM) mostraron un patrón estacional bien definido en la Bahía de La Paz. (Fig. 3a): una estación templada (TSM < 24.20 ºC) durante el invierno y la primavera boreal (diciembre a mayo) y una estación cálida (TSM > 24.20 ºC) durante el verano y el otoño boreal (junio a noviembre). A escala interanual, la serie de anomalías de la temperatura superficial del mar sigue muy de cerca el comportamiento del ENSO representado por el NOI (Pearson $R = -0.8$, $P < 0.05$), con anomalías negativas durante las condiciones de La Niña y anomalías positivas durante condiciones de El Niño (Fig. 4a). Las concentraciones de clorofila en la superficie del mar (Fig. 3b) mostraron valores mayores durante la primera parte del año, y se acentuaron al inicio de la estación cálida (junio) durante condiciones interanuales neutrales, así como hacia la mitad de la estación templada (febrero) durante condiciones interanuales frías. Las concentraciones más bajas de clorofila se presentaron hacia el final de la estación cálida durante condiciones interanuales frías y neutrales, y a lo largo de todo el año durante condiciones interanuales cálidas (Fig. 3b).

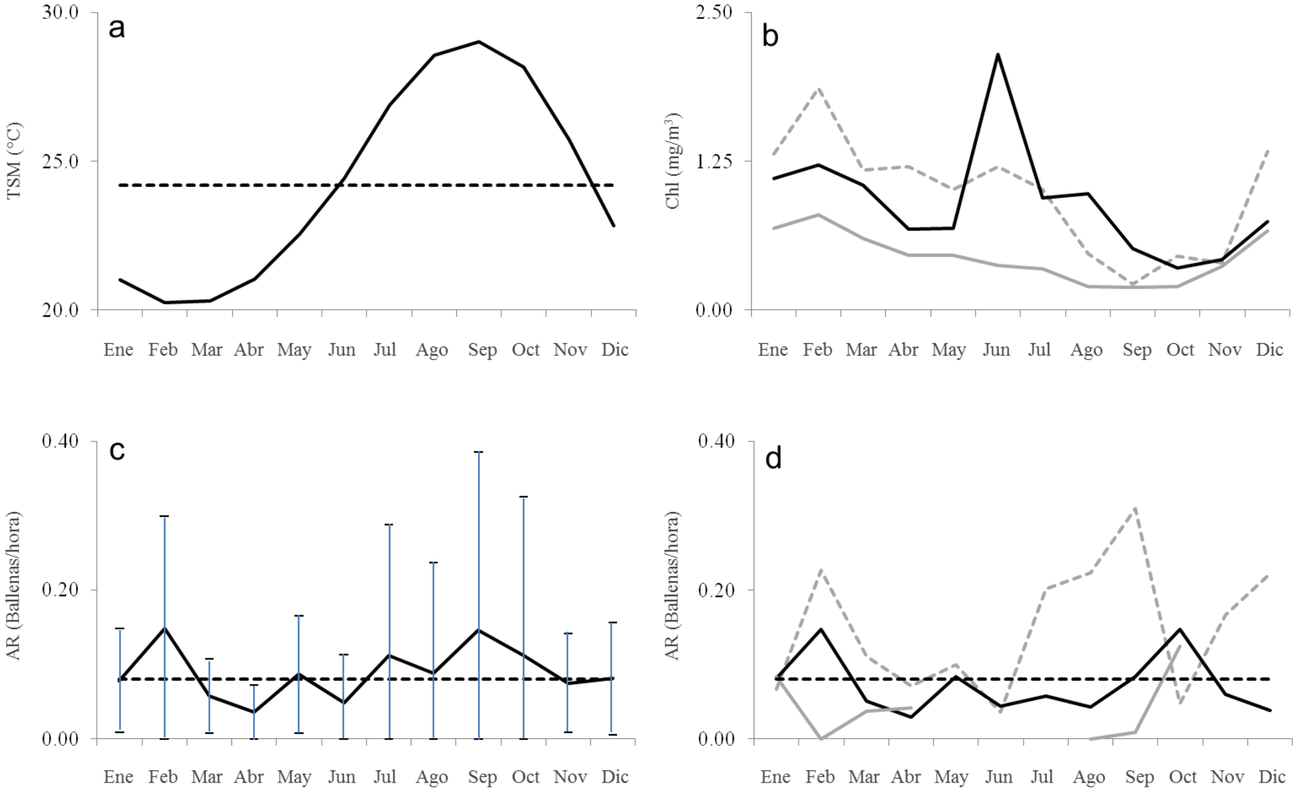


Figura 3: Climatología para la Bahía de La Paz de: a) temperatura superficial del mar (TSM, línea sólida) y su promedio anual (línea discontinua); b) concentración mensual de clorofila superficial durante condiciones interanuales frías (línea gris discontinua), cálidas (línea gris sólida) y neutrales (línea negra sólida); c) Promedio mensual y desviación estándar de la abundancia relativa (AR) de la ballena de Bryde (línea negra sólida) y su promedio global (línea negra discontinua); d) Promedio mensual de la AR de la ballena de Bryde durante condiciones interanuales frías (línea gris discontinua), cálidas (línea gris sólida) y neutrales (línea negra sólida), y promedio global (línea negra discontinua).

La ocurrencia anual de la ballena de Bryde no mostró ningún patrón estacional (Fig. 3c), y no se registraron diferencias estadísticas entre estaciones (prueba de Mann-Whitney*: Z = –0.89, P = 0.37, n1 = 45, n2 = 43*), tanto durante condiciones interanuales frías como cálidas y neutrales (Fig. 3d); sin embargo, los valores más elevados de abundancia relativa se registraron durante condiciones frías de La Niña y los valores más bajos durante condiciones cálidas de El Niño (Fig. 3d).

El promedio global de la abundancia relativa mensual de esta especie fue de 0.09 ballenas por hora de esfuerzo con variaciones de entre 0 y 0.67 ballenas por hora de observación (Tabla 4; Fig. 4b). Se evidenció una relación entre la ocurrencia de las ballenas de Bryde y las anomalías de la temperatura superficial del mar asociada al ENSO: se registraron consistentemente un gran número de animales durante condiciones frías de La Niña. La correlación de Spearman entre la abundancia relativa y las distintas medidas de variabilidad ambiental confirmó esta observación, mostrando que su ocurrencia se relacionó únicamente con las anomalías de la temperatura superficial del mar ($R = -0.25$, $P < 0.05$, $n = 88$) y con NOI ($R = 0.25$, $n = 88$). El promedio de la abundancia relativa de la ballena de Bryde fue un orden de magnitud superior durante condiciones frías (La Niña) que durante condiciones cálidas (El Niño) y neutras (tabla 4). Esta relación también se observa en la ocurrencia anual de la ballena de Bryde (Fig. 3d): con menos animales, respecto al promedio global, durante condiciones El Niño, y más animales durante condiciones La Niña.

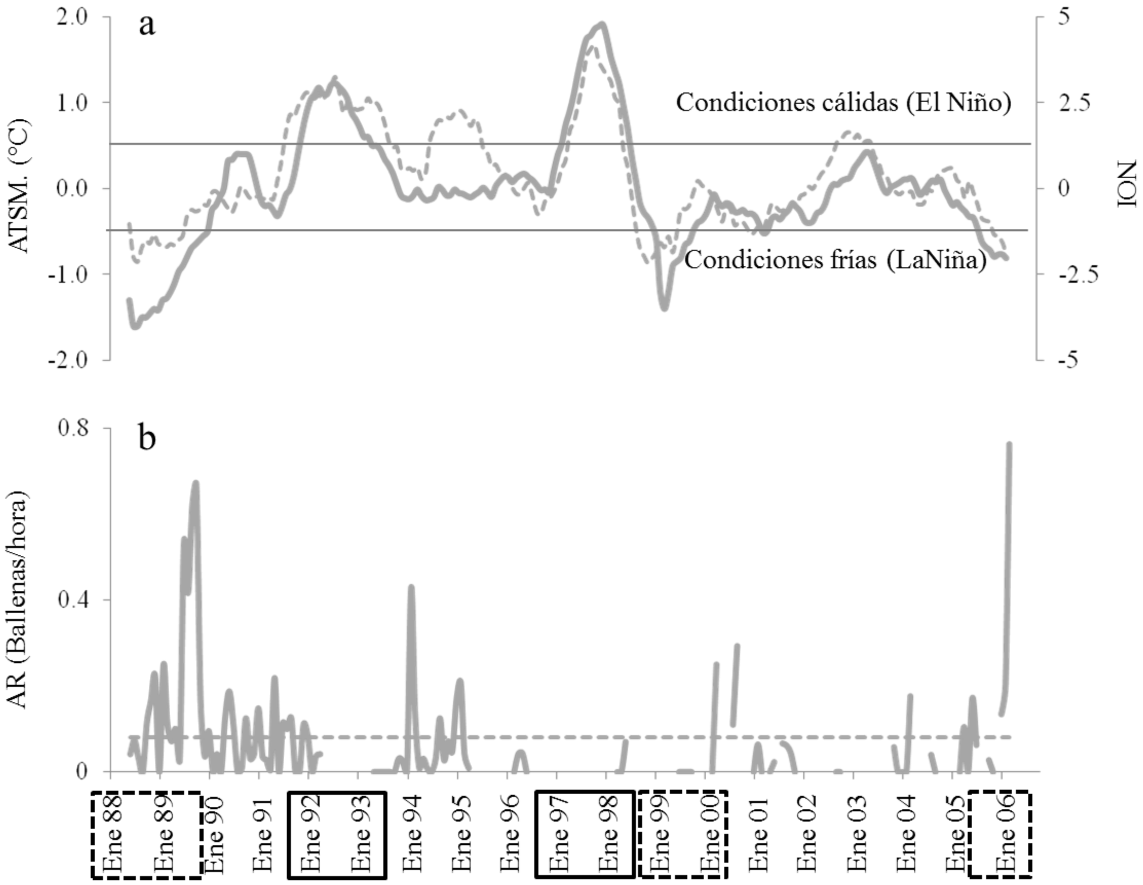


Figura 4: a) Anomalía de la temperatura superficial del mar (ATSM) en la Bahía de La Paz (línea gris sólida) e Índice de la Oscilación del Norte (NOI, línea gris punteada); este último fue multiplicado por –1 con propósitos comparativos; b) abundancia relativa (AR) mensual de la ballena de Bryde (línea gris sólida) y su promedio global (línea gris discontinua); los recuadros discontinuos representan condiciones Niña) y sólidos condiciones Niño.

Tabla 4: Estadísticos básicos para la abundancia relativa mensual de la ballena de Bryde en condiciones frías, cálidas, neutras y globales.

Meses	n	Promedio	Mínimo	Máximo	Desviación estándar
Fríos	21	0.15	0	0.62	0.18
Cálidos	9	0.06	0	0.13	0.05
Neutrales	58	0.07	0	0.67	0.11
Todos	88	0.09	0	0.67	0.13

7.2 Escala decadal

Para esta escala de variación, se analizaron anomalías sin tendencia lineal del viento zonal y meridional (Tabla 2) dentro del área limitada por latitudes 5-60°N y la longitudes 140-60°O (Fig. 5); y de temperatura superficial del mar (NOAA_OI_SST_V2; Tabla 2) entre los 5-21°N de latitud y 120-80°O de longitud (Fig. 5). Como representación de la variabilidad de los vientos Tehuanos, se seleccionó la serie de anomalías de la componente meridional del viento de un cuadrante específico en el Golfo de Tehuantepec (serie a la que ahora en adelante llamaremos tehuanos). Se escogió únicamente la componente meridional del viento porque la orientación del paso montañoso fuerza el flujo meridional de los mismos. Los vientos tehuanos sin tendencia lineal presentaron una fuerte correlación con la oscilación del giro del Pacífico norte o NPGO por sus siglas en inglés (Tabla 5) y al graficar ambas series se puede observar una variación cuasidecadal (Fig. 6a), mientras que de no extraerse la tendencia lineal en los tehuanos, la mayor correlación se da con el índice del Atlántico tropical (ATI) seguido por el NPGO (Tabla 5), y al graficar la serie de los tehuanos con el ATI se puede ver claramente que ambas series comparten una tendencia lineal (Fig. 6b).

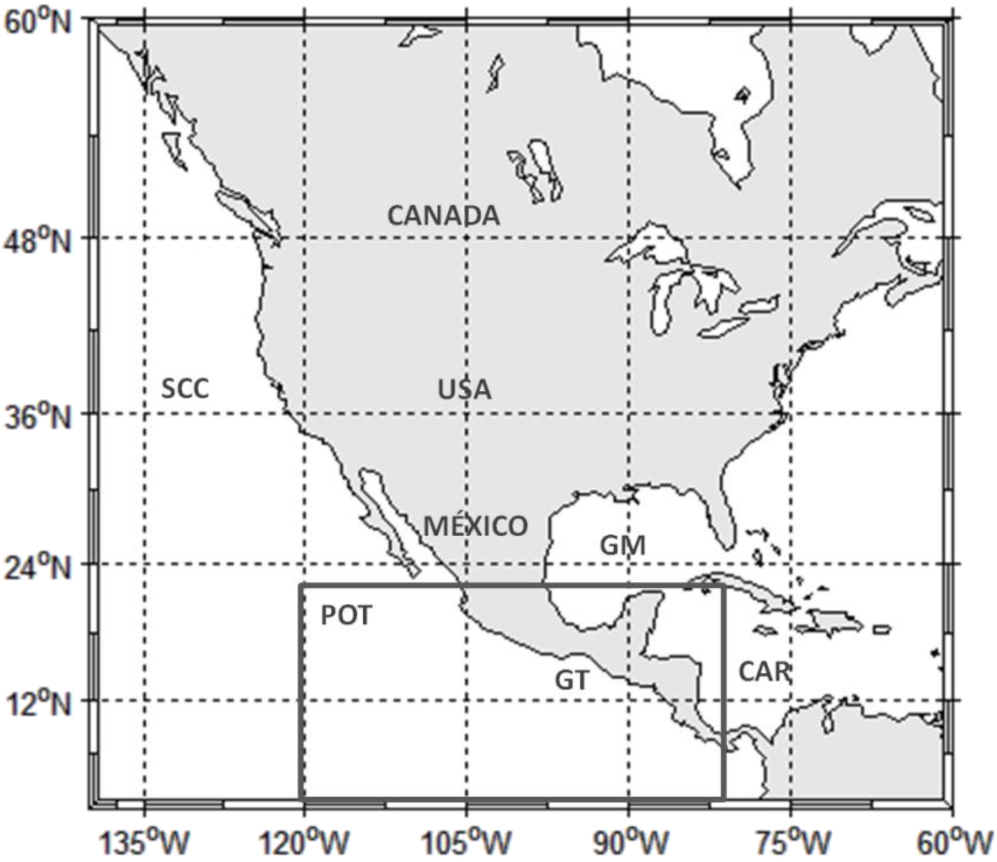


Figura 5: Área de estudio de las anomalías de vientos; Golfo de Tehuantepec (GT), Pacífico Oriental Tropical (POT), Golfo de México (GM), Sistema de La Corriente de California (SCC), Caribe (CAR); recuadro chico: área de estudio de la anomalías de temperatura superficial del mar en el POT.

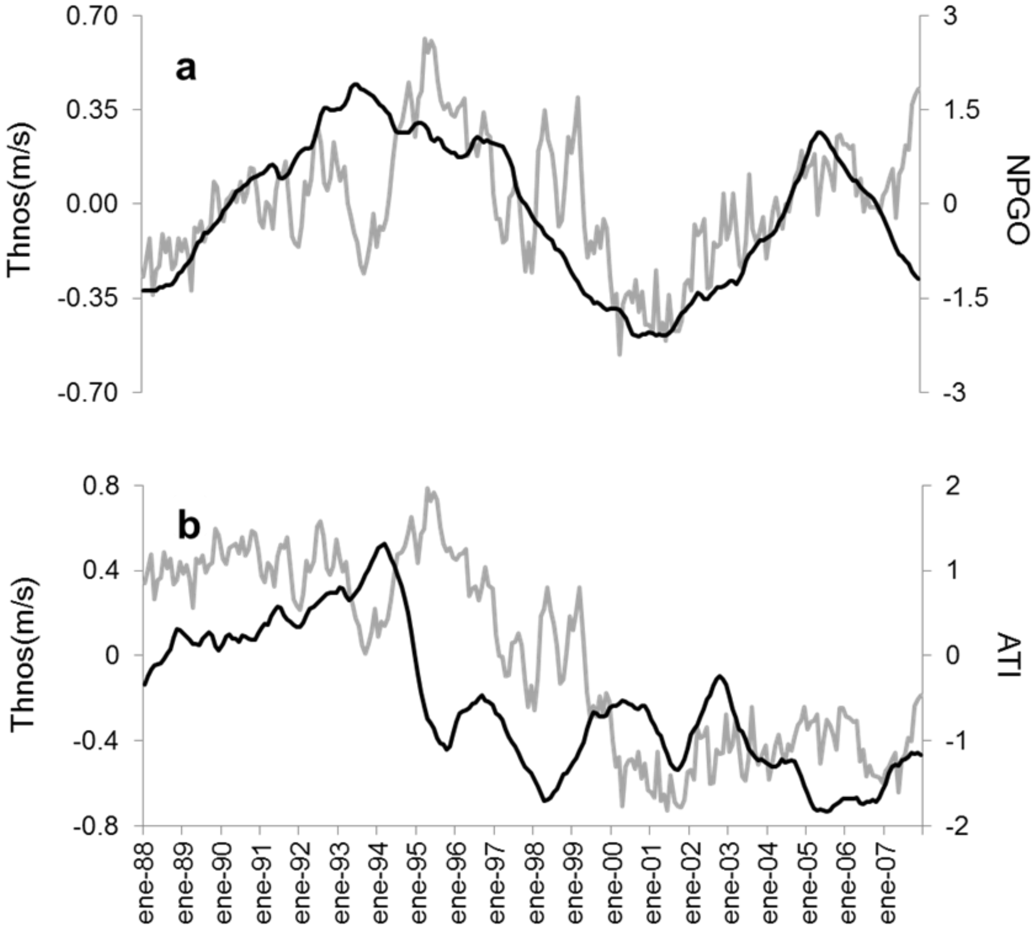


Figura 6: Series suavizadas (13 meses) de las anomalías de los tehuanos (Thnos, línea gris): a) sin tendencia y el índice NPGO (líneas negra) y b) Tehuanos con tendencia lineal y el índice ATI (línea negra); ambos índices climáticos fueron multiplicados por -1 con fines comparativos.

Tabla 5: Coeficiente de correlación de Pearson de las series suavizadas 13 meses de los tehuanos (Thnos) con (c/t) y sin tendencia (s/t) lineal; del 2do y 5to modo de variación de las anomalías de vientos obtenidos del FEO; y de los dos primeros modos de las anomalías de la temperatura superficial del mar (TSM) en el Pacífico Oriental Tropical con índices climáticos; NC: correlación no significativa

	Anomalías de vientos				Anomalías de TSM	
	Thnos c/t	Thnos s/t	2do FEO	5to FEO	1er FEO rot. TSM	2do FEO rot. TSM
MEI	NC	NC	0.7	0.2	0.9	0.4
PDO	NC	NC	0.6	NC	0.6	-0.3
NPGO	-0.5	-0.6	-0.3	-0.4	-0.5	0.6
ATI	-0.6	NC	NC	NC	NC	0.3
NAO	0.3	NC	-0.3	-0.2	-0.2	NC
PNA	-0.2	NC	NC	-0.2	NC	0.2

Para el análisis y caracterización de los patrones regionales y globales en las anomalías de vientos y temperatura superficial del mar se realizó un análisis de FEO y su variante rotada. A continuación, solo se presentan los resultados con un sentido físico y que son relevantes a la hora de interpretar y discutir la variabilidad en bajas frecuencias observada en los vientos tehuanos. A escala regional el segundo modo de variación de las anomalías de los vientos captura la variabilidad del ENSO, evidenciado por una fuerte correlación con el índice MEI (Tabla 5, Fig. 7). Este modo muestra un patrón espacial que representa la variabilidad de las anomalías en los vientos asociada al ENSO sobre áreas tropicales y latitudes medias (Fig. 8). Por otra parte, el quinto modo captura la variabilidad a escala regional del NPGO relacionada con la variabilidad de baja frecuencia observada en los vientos tehuanos, no solo por su correlación con el mismo índice (Tabla 5), sino también por presentar el mismo patrón cuasidecadal presente en los tehuanos (Fig. 9) y su dominio espacial en los vientos meridionales incluye la Corriente de California, el Golfo de México, el Istmo y el Golfo de Tehuantepec (Fig. 10).

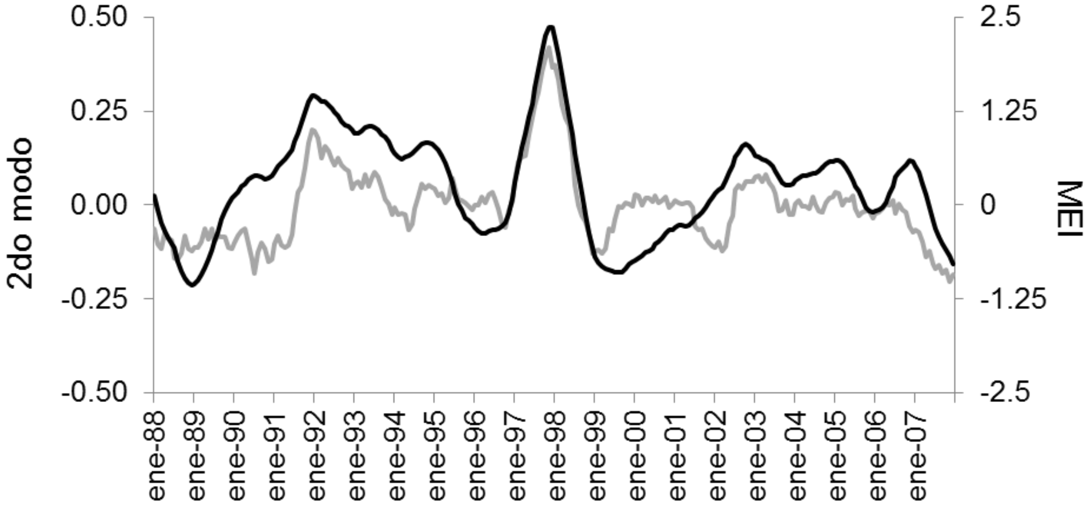


Figura 7: Series suavizadas (13 meses) del segundo modo de variación de las anomalías de vientos (línea gris) obtenido del FEO e índice del MEI (línea negra)

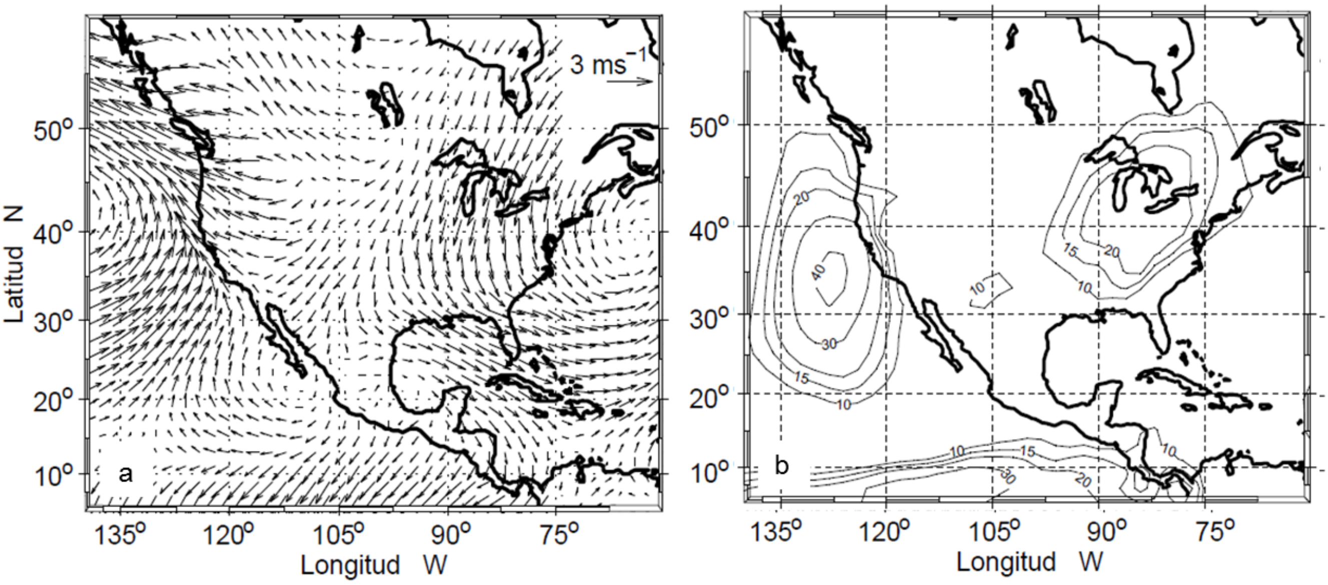


Figura 8: a) Patrón espacial del segundo modo de variación (FEO) de las anomalías de la componente zonal y meridional del viento; b) porcentaje de la varianza local de las anomalías de los vientos meridionales explicada por el segundo modo.

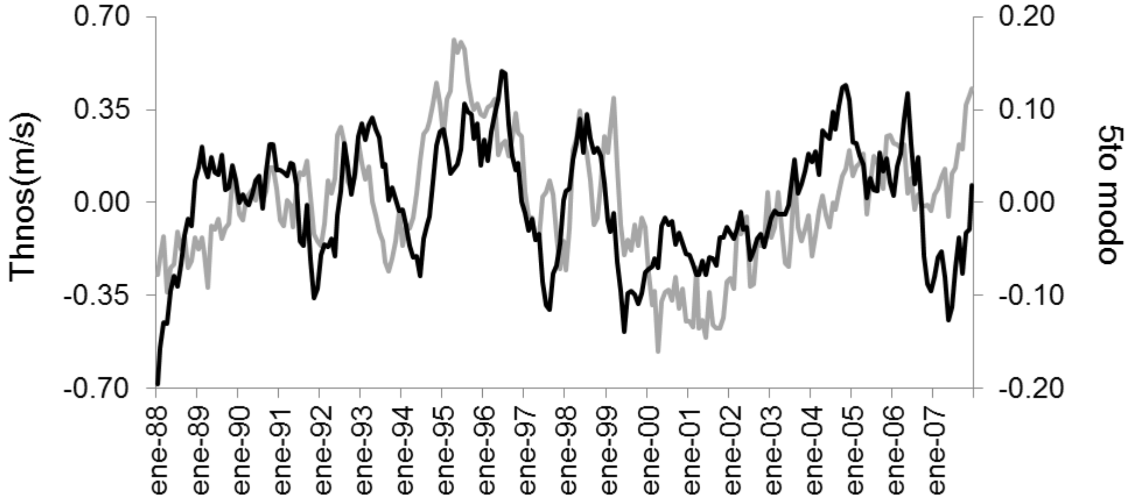


Figura 9: Series suavizadas (13 meses) de las anomalías de los tehuanos (Thnos, línea gris) y del quinto modo de variación de las anomalías de vientos (línea negra) obtenido del FEO.

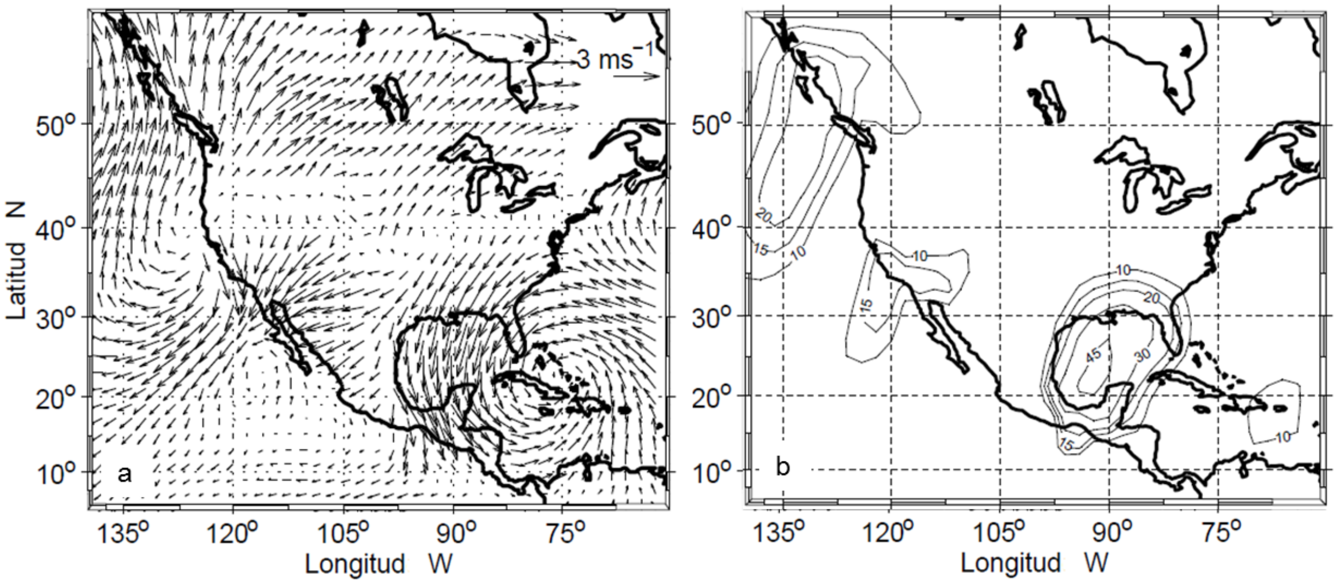


Figura 10: a) Patrón espacial del quinto modo de variación (FEO) de las anomalías de la componente zonal y meridional del viento; b) porcentaje de la varianza local de las anomalías de la componente meridional explicada por el quinto modo.

Del análisis de las FEO sobre las anomalías de temperatura en el Pacífico Oriental Tropical (Fig. 5), se escogieron los resultados de los dos primeros modos del análisis de FEO rotado, porque ambos representan la señal tropical del ENSO y la extratropical observada con anterioridad en los Tehuanos, y llegan a explicar cerca del 66% de la varianza total de las anomalías de la temperatura superficial del mar en la región norte del Pacífico Oriental Tropical. El primer modo contiene una gran parte de la varianza global y muestra una fuerte correlación con la variabilidad climática del ENSO representada por el MEI (Fig. 11a, Tabla 5). Por otro lado, el segundo modo muestra una fuerte correlación con el segundo modo de variabilidad climática del Pacífico Norte, representada por el NPGO (Fig. 11b, Tabla 5), además de que presenta el mismo patrón cuasidecadal observado en los tehuanos (Fig.11c). Al graficar el patrón espacial de ambos modos, destaca un corredor oceánico longitudinal al suroeste del Golfo de Tehuantepec (Fig. 12), donde se puede observar que el primer modo pierde representatividad y el segundo modo la gana llegando a explicar más del 40% de la varianza local de las anomalías de temperatura superficial en su área núcleo entre las latitudes 12-15°N y las longitudes 98-116°O.

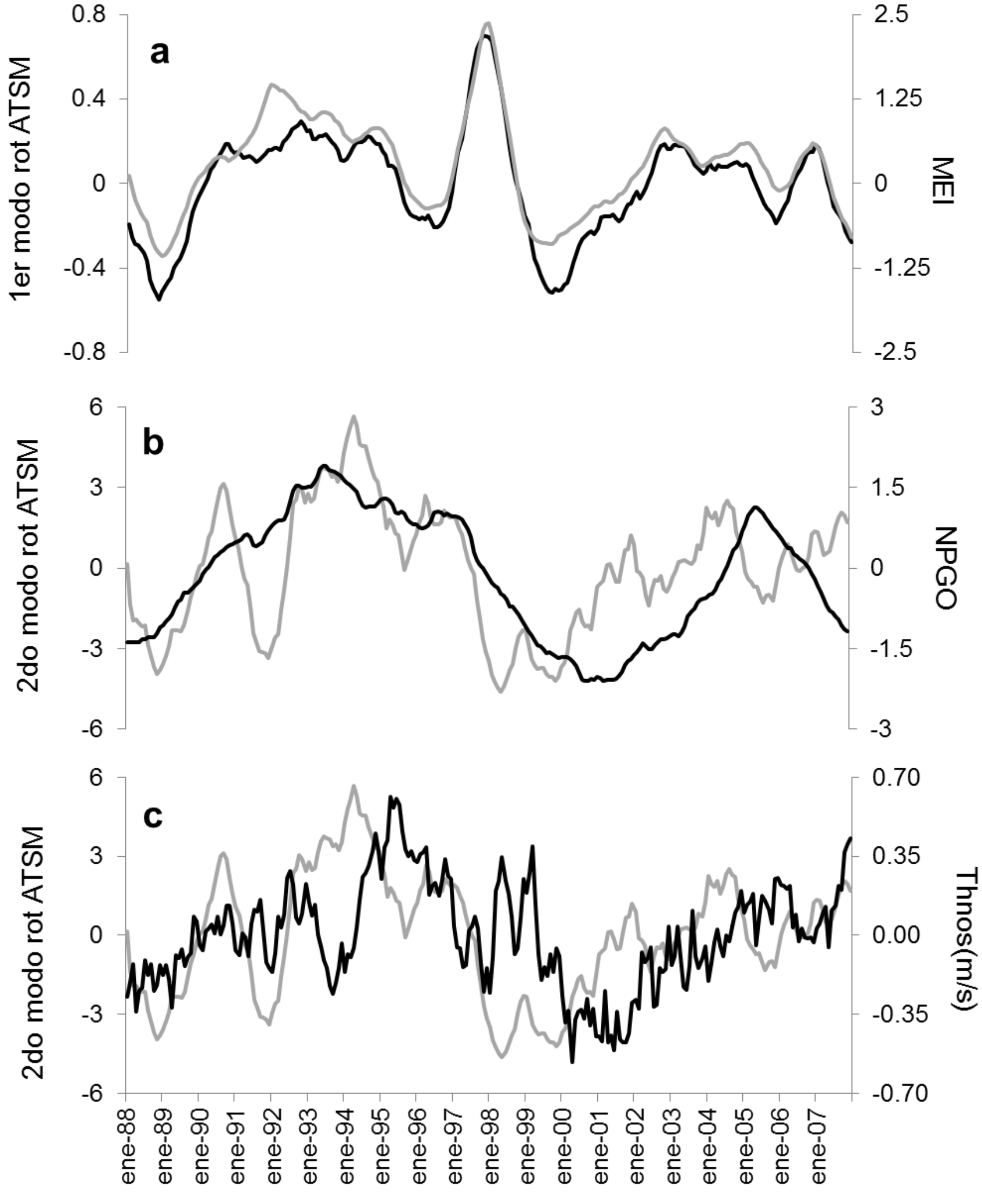


Figura 11: Series suavizadas (13 meses) de: a) primer modo de variación del FEO rotado de las anomalías de la temperatura superficial del mar (ATSM; línea gris) e índice del MEI (línea negra); b) segundo modo de variación del FEO rotado (línea gris) e índice del NPGO (línea negra); c) segundo modo rotado (línea gris) y las anomalías de los tehuanos (Thnos, línea negra); el segundo modo y el NPGO fueron multiplicados por -1 con fines comparativos.

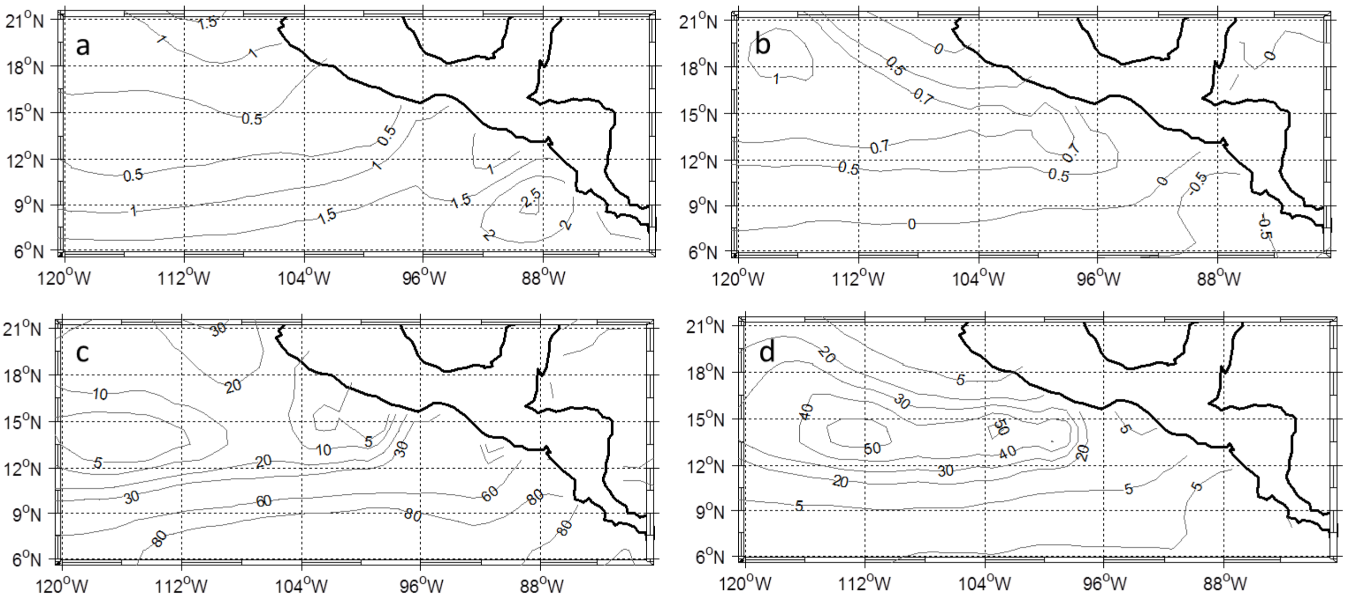


Figura 12: Patrón espacial del primer (a) y segundo (b) modo de variación (FEO rotado) de las anomalías de la temperatura superficial del mar; porcentaje de la varianza local de las anomalías de temperatura superficial explicada por el primer (c) y segundo (d) modo de variación.

7.3 Escala multidecadal o del Régimen

El primer modo de variación en la porción sur de la Corriente de California explica aproximadamente el 50% de la variación total en toda el área de estudio. En su serie temporal (Fig. 13) se aprecian ciclos de frecuencia media (interanual) y baja (multidecadal). La elevada correlación con el índice de la oscilación del norte (NOI, Tabla 2, $R= -0.7, p<0.05$), sugiere que la variabilidad interanual de este modo es producto del forzamiento extratropical del ENSO, mientras que la señal de baja frecuencia representa la variación del régimen, asociada con el PDO ($R= 0.6, p<0.05$). Esta escala de variación presentó en los últimos 110 años tres tendencias de enfriamiento: uno desde 1900 hasta finales de la década de 1910, otra de 1940 a mediados de la década de 1970 y el observado en los últimos 10 años; y dos tendencias de calentamientos, uno desde finales de la década de 1910 hasta principios de la década de 1940 y otro de mediados de la década de 1970 hasta finales del siglo pasado (Fig. 13). Su patrón especial muestra una distribución típica de un modo global, donde la temperatura aumenta o disminuye en toda el área al mismo tiempo acorde al signo de su serie temporal (Fig. 13); aunque no lo hace de forma uniforme, sintiéndose con mayor intensidad en la región costera, especialmente al oeste de la Península de Baja California. Con respecto a la varianza local, explica más del 60% en toda la región de la Corriente de California (Fig. 14), mientras que al sur de la Península se puede observar que la varianza local explicada es menor, llegando a explicar menos del 50%. Si se amplía el área de estudio a todo el Pacífico Norte, podemos ver que el patrón encontrado en la Corriente de California forma parte de un patrón de variabilidad climática de mayor escala, con un dipolo como patrón espacial: donde la parte central del Pacífico y las costas japonesas se enfrían, mientras que la costa americana y especialmente la Corriente de California se calienta; y en el sentido opuesto, cuando la parte central del Pacífico se calienta la Corriente de California se enfría (Fig. 15).

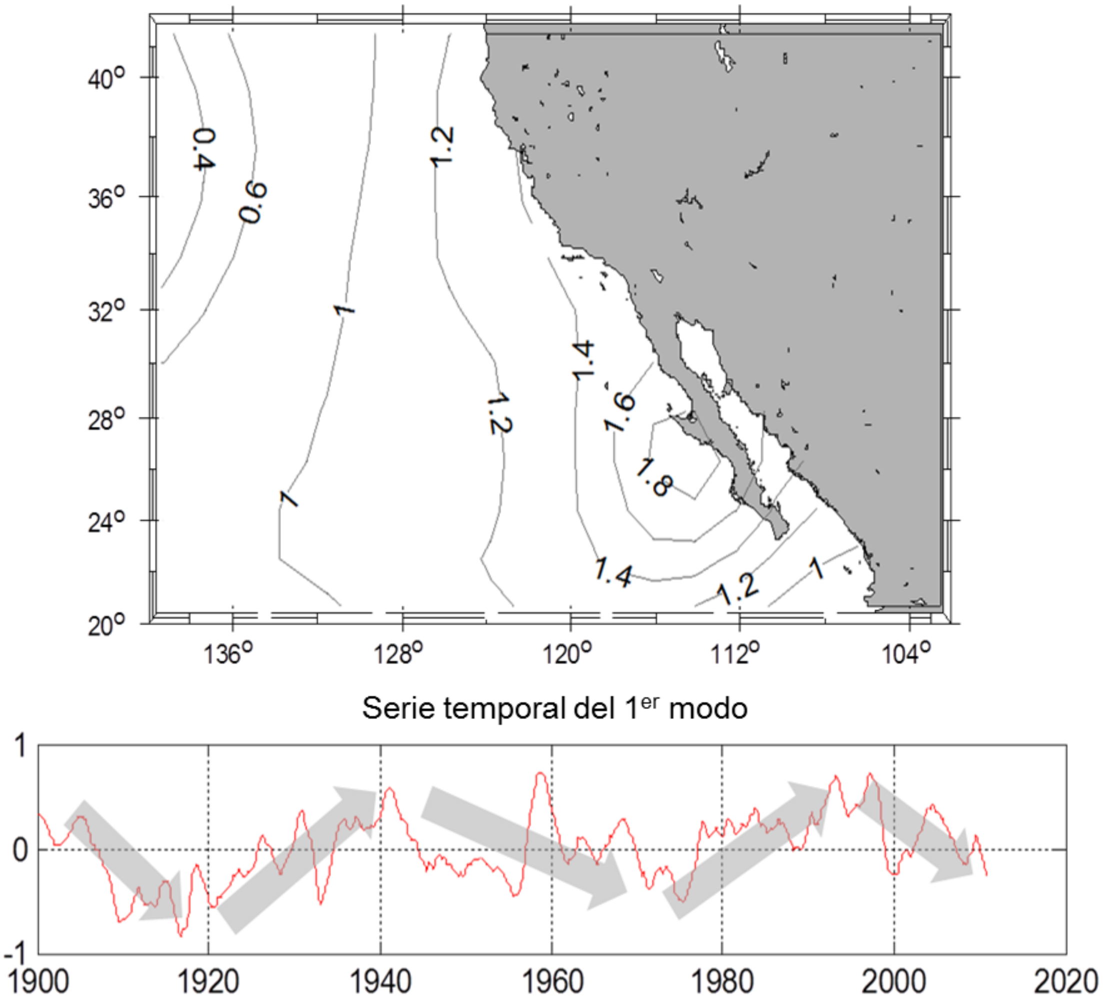


Figura 13: Patrón espacial y temporal del primer modo de variación (FEO) de las anomalías de la temperatura superficial del mar en la porción sur de la Corriente de California; las flechas grises representan la variación multidecadal del régimen.

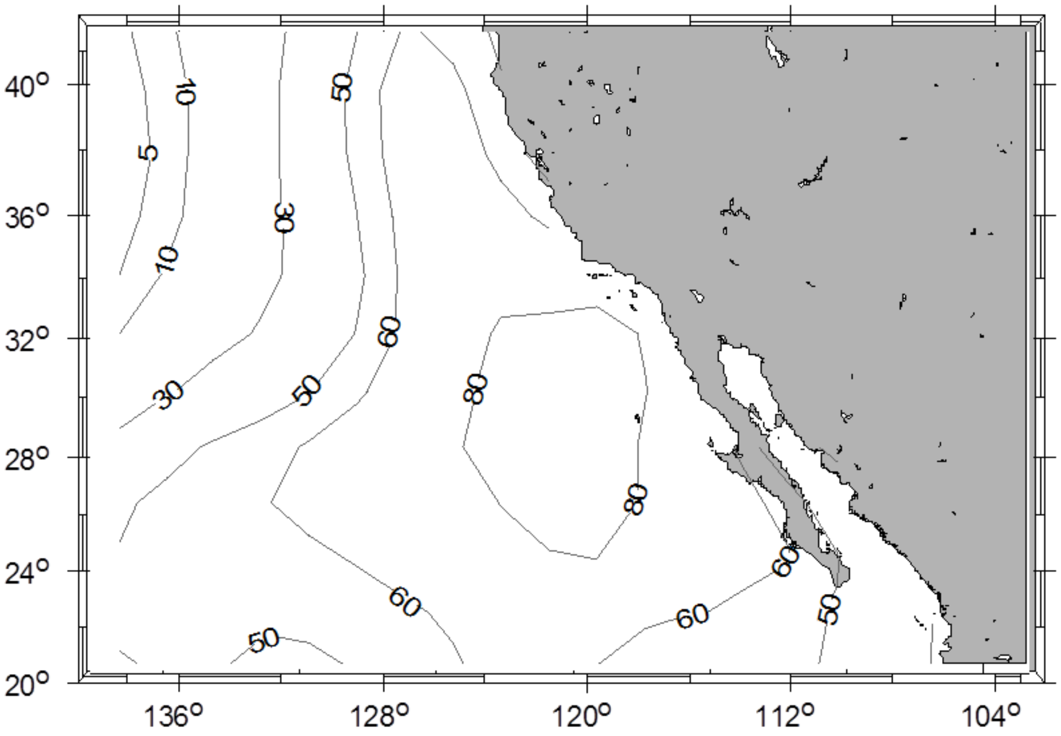
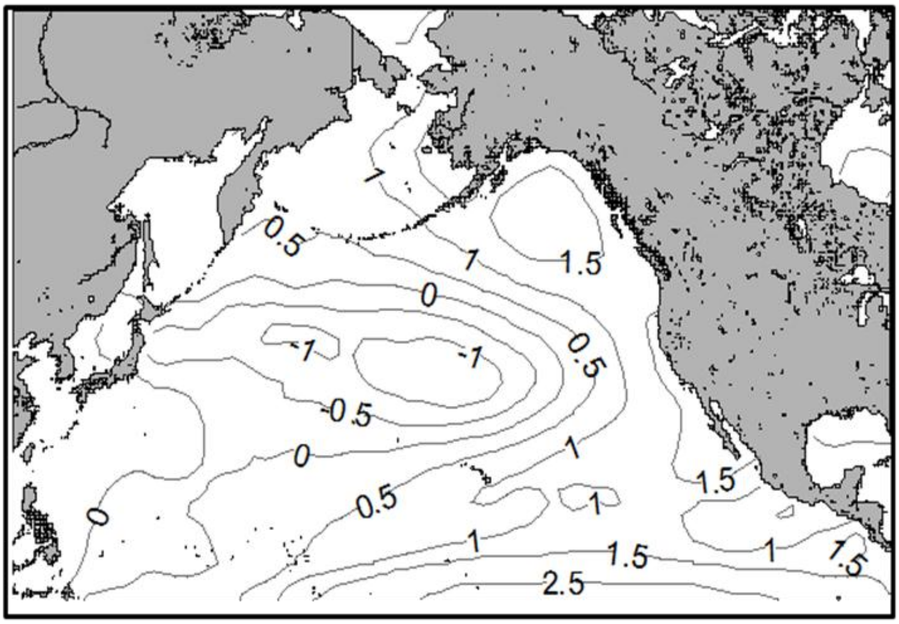


Figura 14: Varianza local explicada por el primer modo de variación de las anomalías de la temperatura superficial del mar en la porción sur de la Corriente de California.



Serie temporal del 1er modo

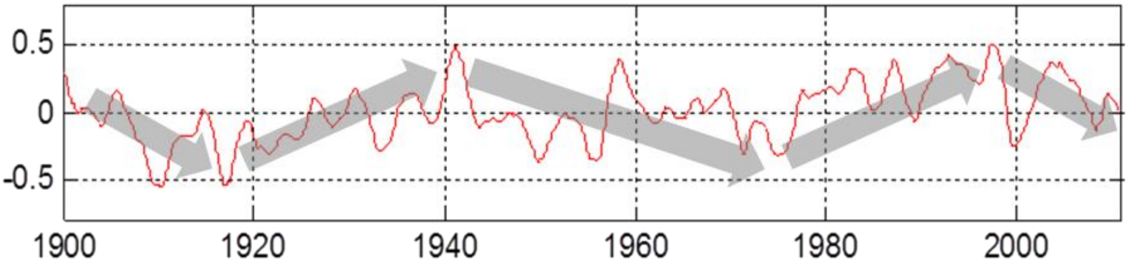


Figura 15: Patrón espacial y temporal del primer modo de variación (FEO) de las anomalías de la temperatura superficial del mar en el Pacífico Norte; las flechas grises representan la variación multidecadal del régimen.

En cuanto a las respuestas biológicas de largo plazo, podemos ver que en el ambiente pelágico de la Corriente de California la respuesta más común son los cambios en la distribución de las especies (Tabla 6), donde en algunos casos como sardinas y calamares, estos cambios son cíclicos y están bien documentados, en otros casos se han observados aparentemente cambios cíclicos pero aun falta comprobar dicha hipótesis como con el delfín común y la ballena azul, y un tercer grupo de especies que no presentan indicios de una variación cíclica en sus poblaciones, pero no se descarta que ello suceda. Estos cambios se pueden agrupar en 4 tipos: 1) la expansión y contracción del rango de distribución, 2) la redistribución de las poblaciones dentro de su propio rango de distribución, 3) el desplazamiento latitudinal de todo su rango de distribución, y 4) el cambio en los patrones espaciales de migración. Estos cambios pueden ser forzados de forma directa (tolerancia a ciertas condiciones físicas del ambiente como la temperatura) o indirecta (cambios en la disponibilidad de presas).

Tabla 6: Especies que presentaron tendencias de largo plazo en sus poblaciones.

Especie	Respuesta	Forzamiento	Fuente
Sardina de California (*Sardinops sagax caeruleus*)	Expansión y contracción de sus poblaciones	Extensión hábitat apropiado para desove y reclutamiento	Kawasaki, 1983; Lluch-Belda *et al.*, 1989
Calamar gigante (*Dosidicus gigas*)	Expansión y contracción de sus poblaciones	Extensión hábitat apropiado para desove y reclutamiento	Cosgrove, 2005; Zeidberg & Robinson, 2007; Rodhouse, 2008
Delfín común (*Delphinus sp*)	Redistribución en su propio rango	Disponibilidad de presas	Danil *et al.,* 2010
Delfín de costados blancos (*Lagenorhynchus obliquidens*)	Cambio latitudinal de su rango de distribución	Tolerancia a cierto rango de temperatura	Salvadeo et al., 2010
Cachalote (*Physeter macrocephalus*)	Redistribución en su propio rango	Disponibilidad de presas	Jaquet *et al.,* 2003; Barlow & Forney, 2007
Ballena gris (*Eschrictius robustus*)	Cambio latitudinal de su rango de distribución	Tolerancia a cierto rango de temperatura	Salvadeo *et al.,* 2011
Ballena de aleta (*Balaenoptera physalus*)	Redistribución en su propio rango	Disponibilidad de presas	Moore & Barlow, 2011
Ballena azul (*Balaenoptera musculus*)	Cambio espacial en patrón migratorio	Disponibilidad de presas	Calambokidis *et al.,*2009

8. Discusión

8.1 Escala interanual: La ballena de Bryde (*Balaenoptera edeni*) en el suroeste del Golfo de California: su relación con la variabilidad del ENSO y la disponibilidad de presas

A lo largo del año, se observan dos estaciones bien marcadas en el Golfo de California: un periodo templado y muy productivo durante el invierno y la primavera boreal, y un periodo cálido y menos productivo durante el verano y el otoño boreal (Álvarez-Borrego & Schwartzlose, 1979; Soto-Mardones *et al*., 1999; Lluch-Cota *et al*., 2007). Durante la estación templada prevalecen vientos del nor-noroeste que promueven la formación de surgencias en la costa este del golfo, fertilizando todo del golfo, mientras que durante la estación cálida predominan los vientos del sur-sureste y se generan surgencias débiles a lo largo de la costa peninsular (Soto-Mardones *et al*., 1999, Lluch-Cota *et al*., 2007). Sin embargo, se presenta un descenso marcado en la productividad primaria en la mayoría de las localidades del golfo durante la estación cálida debido a la intrusión de aguas oligotróficas provenientes del Pacífico Norte subtropical y a la estratificación de sus aguas como consecuencia de la intensa radiación solar y los débiles vientos (Jiménez-Illescas *et al*., 1997; Obeso-Nieblas, 2003). En contraste con el resto del golfo, la productividad primaria en la región de las grandes islas (Fig. 2) permanece elevada a lo largo de todo el año debido a una fuerte mezcla de las aguas por corrientes de mareas (Lluch-Cota *et al*., 2007). En la Bahía de La Paz la temperatura superficial del mar siguió el mismo patrón estacional descrito para el resto del Golfo (Fig. 3a), pero el patrón no es tan claro para el caso de la productividad primaria (Fig. 3b): durante la estación templada se observan concentraciones de clorofila elevadas relacionadas con procesos de enriquecimiento del mismo golfo, pero el pico más prominente de clorofila se presenta al inicio de la estación cálida, especialmente durante los años neutrales (Fig. 3b). Esta elevada productividad se debe a la hidrografía propia de la Bahía de La Paz, que la hace un área importante de agregación de cetáceos, cuando las áreas circundantes son más oligotróficas (Pardo, 2009).

En general, los patrones de ocurrencia y movimientos de mamíferos marinos están bien definidos y se relacionan con la variabilidad estacional que determina la disponibilidad de sus presas (e.g., Lusseau *et al*., 2004, Keiper *et al*., 2005, Mercuri, 2007). Sin embargo, las ballenas de Bryde no presentaron un patrón estacional bien definido en la Bahía de La Paz durante el periodo de estudio (Fig. 3c; prueba de Mann-Whitney: $Z = –0.89, p = 0.37, n_1 = 45, n_2 = 42$). Estas ballenas parecen estar presentes todo el año, siendo más abundantes al inicio de la estación templada y la mayor parte de la estación cálida, especialmente durante periodos interanuales fríos (Fig. 3d).

Esta falta de estacionalidad puede deberse a la propia ecología de la especie, pues la ballena de Bryde no efectúa migraciones entre latitudes altas y bajas. En general, se sabe poco acerca de sus movimientos migratorios (Kato, 2002; Reeves *et al*., 2002). Estas ballenas no parecen formar agregaciones reproductivas y se cree que su ciclo de reproducción es ligeramente distinto al del resto de los miembros de la familia Balaenopteridae, en el sentido de que no tienen una estación de reproducción y crianza (Leatherwood *et al*., 1988). No obstante, se han observado patrones estacionales de la presencia de esta especie en algunas regiones, incluyendo el Golfo de California, que sugieren movimientos estacionales (Rice, 1974; Cummings, 1985; Tershy *et al*., 1990, 1993; Zerbini *et al*., 1997; Kato, 2002). En el Canal de Ballenas (Fig. 2), Tershy *et al.* (1990, 1993) registraron un mayor número de ballenas de Bryde durante la estación cálida que durante la estación templada. Estos autores proponen que durante la estación templada las ballenas de Bryde se desplazan a otras áreas del golfo, probablemente hacia el sur. Esta migración hipotética coincide con el desplazamiento estacional de los cardúmenes de sardina dentro del mismo golfo. En particular, durante la estación cálida las sardinas restringen su distribución a aguas con surgencias permanentes en la región de las grandes islas, mientras que durante la estación templada la expansión de las aguas productivas permite a los cardúmenes de sardina ocupar todo el golfo (Lluch-Belda et al. 1986; Hammann *et al.,* 1998; Bakun *et al*., 2009).

La falta de un patrón estacional en la Bahía de La Paz (suroeste del golfo) que se observa en los resultados de este estudio también fue observada en un estudio previo (Flores-Ramírez *et al*., 1997). Esto puede deberse a la presencia de dos poblaciones de esta especie en el sur del golfo que visitan la Bahía de La Paz en distintos momentos del año, como lo sugieren Urbán y Flores-Ramírez (1996). Esta idea ha sido sustentada por resultados preliminares de un estudio genético efectuado por Dizon *et al*., (1995), que indica la posible presencia de una población interna del Golfo y una población externa distribuida en el Pacífico Oriental Tropical (Fig. 2). Rice (1974) propuso que la población la ballena de Bryde del Pacífico Oriental Tropical es migratoria: pasa el invierno en aguas ecuatoriales y se desplaza al Pacífico Norte en el verano. Así, las ballenas observadas en la Bahía de La Paz durante la estación cálida podrían pertenecer principalmente a esta población, la cual probablemente aprovecha las fracciones de las poblaciones de sardinas en la costa oeste de Baja California que se mueven hacia el sur de la península y Golfo (Félix-Uraga *et al*., 2005). Por otro lado, las ballenas observadas durante la estación templada pueden corresponder, según los movimientos estacionales propuestos por Tershy *et al.* (1990, 1993), principalmente a la población del golfo, la cual sigue los movimientos de la población de sardinas del golfo.

A escala interanual, el ENSO es considerado la influencia más importante sobre la variabilidad climática dentro del Golfo de California, afectando a la temperatura superficial del mar y la productividad primaria (Bernal *et al*., 2001; Lluch-Cota *et al*., 2007). En ese sentido, las anomalías de la temperatura superficial del mar para la Bahía de la Paz siguen muy de cerca la fenomenología del ENSO en el Pacífico Noreste, representada por el índice NOI (*Pearson* $R = -0.8$, $P < 0.05$), con anomalías negativas durante las condiciones de La Niña y positivas durante condiciones de El Niño (Fig. 4a). Como en el resto del Golfo, en la Bahía de La Paz la productividad primaria se incrementa durante las condiciones frías de La Niña, mientras que durante las condiciones cálidas de El Niño disminuye (Fig. 3b).

En aguas del Golfo de California se ha observado que la abundancia de sardinas varía debido a grandes fluctuaciones en su reclutamiento relacionadas con la variabilidad interanual del ENSO. Durante los eventos de El Niño, el reclutamiento de la sardina del Pacífico es afectado por la intrusión de aguas cálidas que reducen el hábitat de desove, mientras que durante los eventos de La Niña sucede lo contrario (Lluch-Belda *et al*., 1986; Hammann *et al*., 1998; Bakun *et al*., 2010). En relación a esta variación en el clima, la ocurrencia de la ballena de Bryde mostró una relación significativa con el fenómeno del ENSO, indicada por su correlación con los valores de las anomalías de la temperatura superficial del mar ($R = -0.25$, $p < 0.05$, $n = 88$) y NOI ($R = 0.25$, $p < 0.05$, $n = 88$), resultando en promedio una abundancia relativa un orden de magnitud superior durante condiciones frías (La Niña) que durante condiciones cálidas (El Niño) y neutras (Tabla 4). Esta relación también se evidencia claramente en la figura 3d, en la que se observa que hay menos ballenas respecto a la media global a lo largo del año durante condiciones de El Niño, mientras que se observaron con mayor frecuencia respecto a la media global durante condiciones de La Niña.

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Estos resultados muestran que, independientemente de la estación del año, se registró un mayor número de ballenas de manera consistente durante las condiciones frías de La Niña, cuando la población de sardina se distribuye más al sur dentro del Golfo de California. En contraste, se registraron menos ballenas durante condiciones de El Niño y neutrales (Tabla 4; Fig. 3d & 4b). En el último estudio con ballenas de Bryde en Bahía de La Paz, Urbán & Flores-Ramírez (1996) notaron un pico de abundancia durante condiciones frías de La Niña en 1989, seguido por un decremento en la abundancia durante los años siguientes (1990–1991), pero no pudieron confirmar la relación entre la abundancia de la especie y el fenómeno de ENSO debido a una serie de datos limitada (tres años). Los cambios en la abundancia y distribución de las poblaciones de cetáceos relativos a la variabilidad climática se deben, en su mayor parte, a los efectos sobre la abundancia y disponibilidad de sus presas (e.g., Manzanilla, 1989; Shane, 1995; Keiper *et al*., 2005; Ballance *et al*., 2006; Learmonth *et al*., 2006). Las grandes ballenas requieren grandes y densos parches de presas, por lo que su distribución, abundancia y movimientos están influenciados por la dinámica de sus presas (Learmonth *et al*., 2006). Además, como depredadores activos, las grandes ballenas son capaces de desplazarse en respuesta a cambios en el clima; por ejemplo, se observaron numerosas ballenas desplazarse hasta el Mar de Bering para alimentarse durante El Niño de 1997–1998 (Tynan, 1999). Para el caso particular de la ballena de Bryde, se ha observado una mayor presencia durante condiciones de El Niño en las Islas Maldivas (Océano Índico), que podría estar relacionada con una mayor disponibilidad de presas, en este caso anchovetas (Anderson, 2005). En aguas del golfo, Tershy *et al.,* (1991) observaron una mayor presencia de cetáceos ictiófagos (incluyendo ballenas de Bryde) en el Canal de Ballenas durante El Niño de 1982–1983, y sugirieron que esta área con alta productividad y abundancia de presas sirve como refugio durante periodos adversos. Nuestras observaciones son consistentes con lo propuesto por Tershy *et al*., (1991), al registrarse menos ballenas de Bryde en la Bahía de La Paz durante condiciones de El Niño, cuando la distribución de sardina se contrae al norte del Golfo. Mientras que durante las condiciones de La Niña se observaron, consistentemente, grandes números de ballenas de Bryde, coincidiendo con la expansión hacia el sur de la población de sardinas al interior del golfo (Lluch-Belda *et al*., 1986; Hammann *et al.,* 1998).

8.2 Escala decadal: Los vientos tehuanos como fuente de variabilidad decadal y extratropical en el Pacífico Oriental Tropical

El Golfo de Tehuantepec (Fig. 5) posee un régimen de vientos que lo distingue del resto del el Pacífico Oriental Tropical, conocidos como “nortes” o “tehuanos”; soplan mayormente durante los meses fríos del año (octubre-mayo) y son el resultado de la combinación del movimiento hacia el sur de masas de aire frio (frentes fríos) sobre Norteamérica y la presencia de un paso de baja altitud en el macizo montañoso próximo al Golfo de Tehuantepec (Clarke, 1988; Schultz et al., 1997; Romero-Centeno et al., 2003; Amador et al., 2006). Estos vientos transfieren rápidamente energía de la atmósfera al océano produciendo surgencias costeras y remolinos de mesoescala conocidos como “eddies” (Kessler, 2006). Estos remolinos atrapan, retienen y transportan nutrientes, materia orgánica y fitoplancton desde la costa hacia el interior del Pacífico Oriental Tropical; permaneciendo en el mar por meses, desplazándose miles de kilómetros hacia el oeste desde sus áreas de origen próximas a las costas mexicanas (Willett, 1996; Müller-Karger & Fuentes-Yaco, 2000; González-Silvera et al., 2004; Palacios & Bograd, 2005; Willett et al., 2006).

Esta particularidad del Golfo de Tehuantepec queda de manifiesto en nuestros resultados por la falta de relación de los tehuanos con el índice del MEI (Tabla 5), señal dominante en la variabilidad climática del Pacífico Oriental Tropical (Fig. 7, 8, 11a, 12a, c). Mientras que sí presentaron una fuerte correlación con la oscilación del giro del Pacífico norte o NPGO por sus siglas en inglés (Fig. 6a; Tabla 5). En ambas series se puede observar una sincronización en baja frecuencia, con una oscilación cuasidecadal, comúnmente observada en el Pacífico Norte. En ese sentido, luego de la variabilidad de baja frecuencia del PDO, el NPGO representa el segundo modo de variación climática en el Pacífico Norte. También conocido como patrón de Victoria, su variabilidad es forzada por la interacción entre el sistema de alta presión del Pacífico Noreste y el sistema de baja presión de las Aleutianas y refleja principalmente los cambios en los vientos sobre la Corriente de California (Di Lorenzo et al., 2008). Teniendo en cuenta lo anterior se plantea la hipótesis de que la teleconexión entre los vientos tehuanos y el segundo modo de variación climática del Pacífico Norte está determinada por la variabilidad del sistema de alta presión del Pacífico Noreste, ya que este sistema tiene una relación directa con los frentes fríos que descienden por el continente norteamericano y que son responsables de la formación del mecanismo físico que fuerza a los vientos tehuanos. En ese sentido, existen dos tipos de frentes fríos: 1) los “nortes”, producto del desplazamiento hacia el sur de masas de aire frío que se originan en la tundra canadiense, los cuales se caracterizan por un fuerte descenso de las temperaturas en toda la región y son responsables de tehuanos intensos; y 2) los “oestes”, producto del desplazamiento hacia el sur de masas de aire frío que se desprenden del sistema de alta presión del Pacífico Norte, cruzan las montañas rocallosas y descienden hacia el sur; estos son menos severos y fuerzan tehuanos menos intensos (Mecikalski & Tilley, 1992; Schultz et al., 1998).

Con relación a los patrones regionales de las anomalías de los vientos obtenidos con el análisis de FEOs, el quinto modo de variación es el patrón espacial que mejor se ajusta a la hipótesis de teleconexión planteada con anterioridad, debido a que presenta el mismo patrón cuasidecadal observado en los tehuanos (Fig. 9) y su dominio espacial representa un modo de variación meridional de los vientos que involucra regiones de la Corriente de California, el Golfo de México y al Istmo y Golfo de Tehuantepec (Fig. 10); además, respalda a dicha hipótesis el hecho de que explique un gran porcentaje de las anomalías en los vientos meridionales sobre el Golfo de México (Fig. 10b), donde los ‘nortes” (vientos meridionales) son el rasgo distintivo de la entrada de frentes fríos al Golfo de México (Mendoza *et al.,* 2007), pieza clave del mecanismo físico que fuerza a los Tehuanos (Liang *et al.,* 2009).

La contraparte oceánica de los tehuanos está representada por el segundo modo de variación de las anomalías de la temperatura superficial del mar en el Pacífico Oriental Tropical, obtenidos al rotar nuevamente los ejes de variación de los FEOs. Se considera que este modo de variación captura principalmente la variabilidad de baja frecuencia asociada con estos vientos, porque al igual que los tehuanos presentó una fuerte correlación con el NPGO (Fig. 11b, Tabla 5) además de presentar el mismo patrón cuasidecadal de baja frecuencia observado en los tehuanos (Fig.11c). Al graficar el patrón espacial del primer y segundo modo de variación de las anomalías de la temperatura superficial del mar, llama la atención un corredor oceánico longitudinal al suroeste del Golfo de Tehuantepec presente en ambos modos (Fig. 12), que coincide con la región geográfica donde se localiza un fenómeno oceánico que en la literatura se conoce como “Cuenco de Tehuantepec” (Willett et al., 2006). Este fenómeno oceánico tiene un ciclo anual de gran amplitud, al igual que el Domo de Costa Rica, pero en comparación está muy poco descrito en la literatura. Casi ausente durante los meses de cálidos del año (junio-noviembre), se desarrolla como un evento aislado durante los meses fríos (diciembre-mayo) y se caracteriza por tener la isoterma de 20ºC diez metros más profunda que en las áreas oceánicas circundantes (Kessler, 2006). Willett et al. (2006) sugieren que este corredor oceánico es por donde circulan los remolinos de mesoescala que se originan por acción de los tehuanos, por lo que se plantea la hipótesis de que en dicho corredor está concentrada la variabilidad oceánica transferida por estos vientos.

En relación con la variabilidad climática presente en la cuenca del Atlántico y su posible influencia en la variabilidad de los tehuanos, Karnauskas et al. (2008) identifican una señal de baja frecuencia, entre 1988 y 2004, forzada por la variación en la temperatura superficial del mar en la región tropical del Atlántico, representada por el índice ATI (Tabla 2). En el presente estudio y con el mismo periodo de tiempo examinado, este índice climático del Atlántico tropical no se correlacionó con los tehuanos (Tabla 5). Sin embargo, de no removerse la tendencia lineal en las anomalías de los vientos, el ATI es el que presenta la mayor correlación (Tabla 5), por lo que durante este periodo 1988-2007 la relación entre los tehuanos y la variabilidad climática en el Atlántico Tropical estaría dada por una tendencia lineal, relación que se puede observar en la figura 6b. En ese sentido podemos decir que la tendencia lineal es un modo de variación que forma parte de un ciclo de mayor periodo que la extensión misma de los datos, siendo un modo de variación que no se puede resolver, y por esa la razón se extrae de los datos para el análisis. Considerando nuestros resultados y los de trabajos previos, no se rechaza un posible forzamiento del Atlántico Tropical sobre los tehuanos, pero se sugiere que dicha relación podría estar asociada con escalas mayores a los 20 años. Futuros trabajos, con series más largas, podrán determinar cómo influye el Atlántico Tropical en el forzamiento de los tehuanos.

8.3 Escala multidecadal: Movimientos de macro-fauna relacionados con la variación del régimen en la Corriente de California

En los últimos 110 años se distinguen con claridad en la porción sur de la Corriente de California tres procesos de enfriamiento y dos de calentamiento (Fig. 13). Estos cambios en la temperatura superficial del mar son indicativos de procesos oceánicos complejos que en última instancia, afectan los mecanismos de enriquecimiento de las aguas superficiales en toda la cuenca del Pacífico Norte. Esta señal de baja frecuencia representa la variación del régimen, presente en el primer modo de variación oceánica del Pacífico Norte (Fig. 15), con un patrón espacial conformado por un dipolo similar al presentado por la Oscilación Decadal del Pacífico (PDO, Tabla 2), mismo índice con el cual presenta una fuerte correlación (*PDO*, $R = 0.6$, $p < 0.05$).

En la porción sur de la corriente, este modo de variación del Pacífico Norte se presenta con un dominio espacial global, donde la temperatura aumenta o disminuye en toda el área al mismo tiempo acorde al signo de su serie temporal (Fig. 13). Sin embargo, no lo hace de manera uniforme, sintiéndose con mayor intensidad en la región costera de la Península de Baja California (Fig. 13); esta es un área dinámica en términos oceanográficos debido a la presencia de surgencias estacionales, giros y sistemas oceánicos frontales. Con respecto a la varianza local explicada, esta es mayor al 60% en toda la región de la corriente, mientras que al sur de la Península disminuye, llegando a explicar menos del 50% (Fig. 14). Esto es debido a una mayor influencia de la variabilidad climática del Pacífico Tropical, dominada por los eventos de enfriamiento y calentamiento interanuales asociados al ENSO (Lluch-Belda *et al*., 2009).

Las respuestas biológicas documentadas relacionadas con esta escala de variación incluyen: 1) la expansión y contracción de poblaciones de la sardina de California (Sardinops sagax caerulea) y el calamar gigante (Dosidicus gigas), 2) cambios en la distribución en delfines comunes (Delphinus sp.), y 3) cambios en los patrones de migración de la ballena azul (Balaenoptera musculus); asimismo la evidencia sugiere cambios de largo plazo en la distribución de ballena gris (Eschrichtius robustus) ballena de aleta (Balaenoptera physalus), delfín de costados blancos (Lagenorhynchus obliquidens) y cachalotes (Physeter macrocephalus) que podrían estar relacionados con este tipo de variación multidecadal. A continuación se discuten cada una de los casos mencionados anteriormente.

La sardina de California es el vertebrado más abundante en la Corriente de California, siendo un componente clave del ecosistema pelágico por ser la presa principal de numerosos depredadores como peces, calamares, aves y mamíferos marinos (Bakun *et al*., 2010). Esta especie tiene dos centros poblacionales de distribución, uno en la costa oeste de la Península de Baja California y otro dentro del Golfo de California. A partir de estos centros, los cardúmenes de sardinas se expanden y contraen en las aguas circundantes dependiendo de las condiciones ambientales. Esta especie presenta marcadas fluctuaciones interanuales en su abundancia debido a fuertes cambios en su reclutamiento, relacionados principalmente con la variabilidad ambiental del ENSO y sus efectos en sus áreas de desove (Lluch-Belda *et al*., 1986; Hammann *et al*., 1998). Además de estas fluctuaciones interanuales, sardinas y anchovetas presentan expansiones y contracciones de sus poblaciones en un ciclo aproximado de 60 años conocidas como variación del régimen (Fig. 16; Kawasaki, 1983; Lluch-Belda *et al.*, 1989). Estos ciclos pueden observarse con claridad en los desembarcos comerciales de sardina en el estado de California (Fig. 18) y en el registro fósil en los últimos 2000 años (Baumgartner *et al*., 1992). En ese sentido, Chavez *et al.* (2003) proponen dos escenarios ambientales distintivos: una fase cálida o régimen de sardinas y una fase fría o régimen de anchovetas. Nuestros resultados no difieren de los suyos, aunque sí existe una diferencia sustancial al interpretarlos: ellos interpretan al ambiente como estático (fase fría o cálida), mientras que en la presente tesis se plantea un ambiente dinámico con tendencias de calentamiento (1920-1940 & 1975-2000) y enfriamiento (1900-1920, 1940-1975 & 2000 hasta la actualidad), donde las poblaciones de sardinas se expanden hacia el norte durante un calentamiento (Fig. 16) registrándose abundantes capturas en aguas californianas (Fig. 17) y se contraen frente a la costa Peninsular durante un enfriamiento (Fig. 16) con un desplome de las capturas en aguas californianas (Fig. 17).

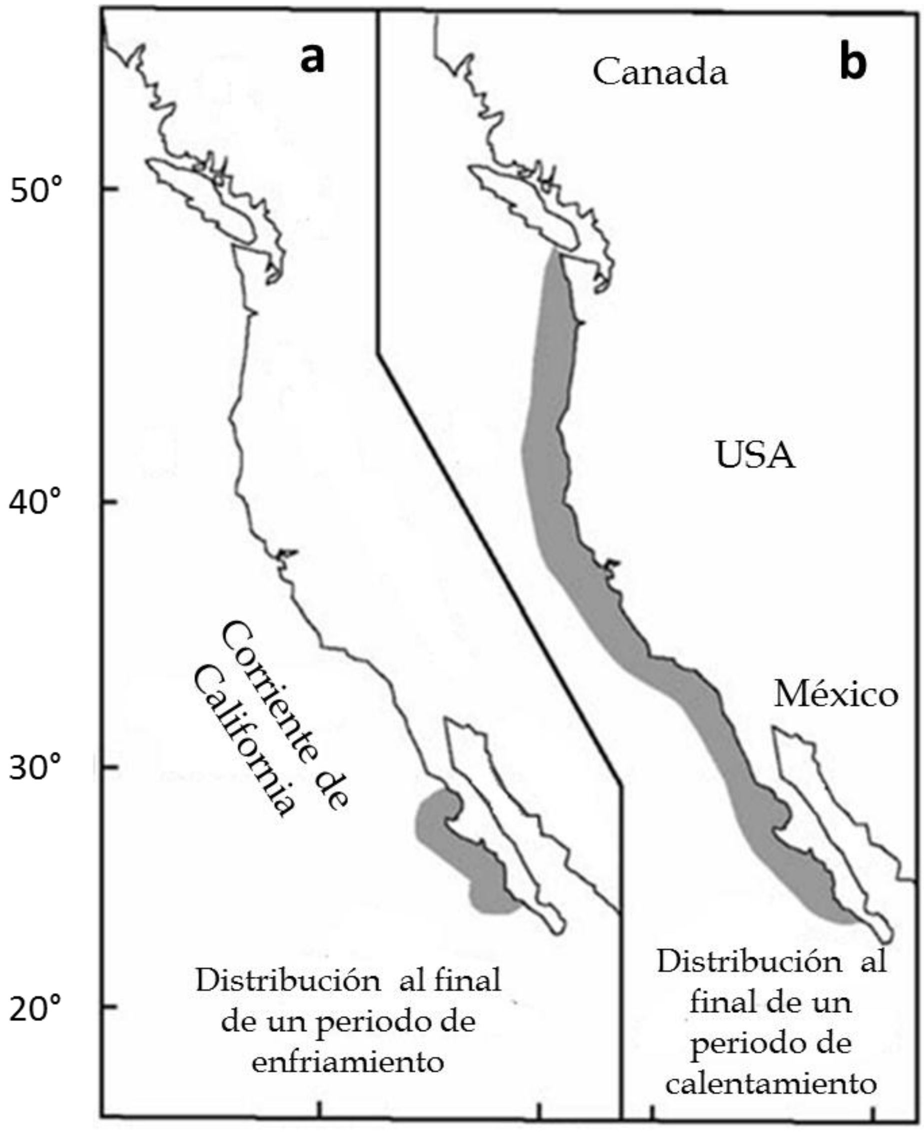

Figura 16: a) Contracción y b) expansión de las poblaciones de sardina de California en la Corriente de Califronia (Bakun *et al.,* 2010).

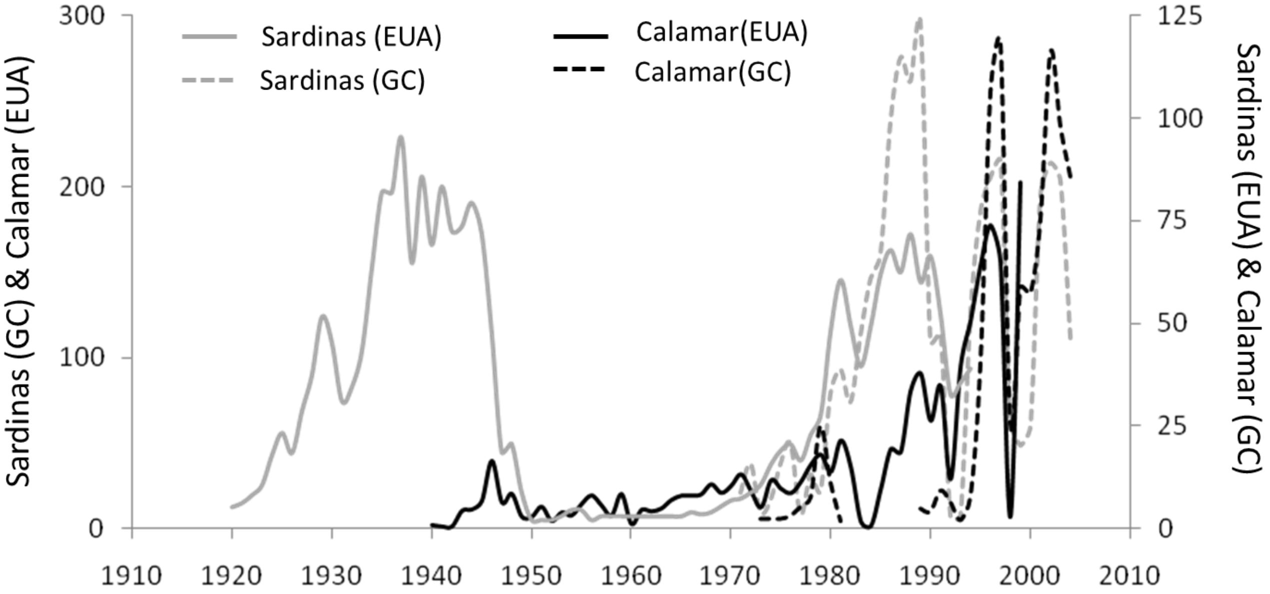

Figura 17: Capturas de sardina de California frente a las costas de California (EUA, miles de toneladas) y del Golfo de California (GC, miles de toneladas); Capturas de calamar gigante frente a las costas de California (EUA, millones de libras) y en el Golfo de California (GC, miles de toneladas); fuentes: FAO (1997), SAGARPA y pagina web de la NOA (http://www.pfeg.noaa.gov/research/climatemarine/cmffish/cmffishery.html).

El calamar gigante es una especie endémica del Pacífico Oriental Tropical; siendo uno de los mayores omastréfidos, alcanzando tallas en estado adulto de 2.5 m con un peso aproximado de 50 kg. Es un predador importante de la tramas tróficas marinas, alimentándose de sardinas, anchovetas, mictófidos, crustáceos y calamares de tallas chicas (Markaida & Sosa-Nishizaki, 2003; Armendáriz-Villegas, 2005; Field *et al.*, 2007), además de que transfiere la energía de estos niveles hacia los grandes predadores como atunes, picudos, tiburones y mamíferos marinos (Galván-Magaña *et al*., 2006; Field *et al*., 2007). En términos pesqueros, el calamar gigante sostiene una de las mayores pesquerías de calamar en el mundo, operando en aguas oceánicas frente a las costas de Perú, Chile, Centroamérica y en el Golfo de California (Morales-Bojórquez *et al*., 2001; Waluda & Rodhouse, 2006). Publicaciones científicas recientes, anécdotas y datos de desembarcos de pesqueros (Fig. 17), dan cuenta de una expansión en el rango de distribución del calamar gigante en las Corrientes de California y de Humbolt, en las pasadas décadas (Fig. 18;

Cosgrove, 2005; Chong *et al*., 2005; Wing, 2006; Zeidberg & Robinson, 2007). Esta expansión en su distribución ha generado diversas hipótesis relacionadas con la variabilidad climática y la reducción de los predadores tope que los consumen o que compiten con estos por los niveles tróficos inferiores (Zeidberg & Robinson, 2007; Waters *et al*., 2008). Sin embargo, la coincidencia de la reciente expansión hacia los polos en ambos hemisferios, y los informes de una mayor abundancia y presencia en las costas de América del Norte y del Sur en la década de 1930 (Rodhouse, 2008), justo al final del periodo de calentamiento de 1920-1940, sugiere un mecanismo de forzamiento físico, que podría estar relacionado con las tendencias a largo plazo de calentamiento y la expansión hacia los polos de su hábitat primario: la capa de mínimo oxigeno (Bazzino, 2008).

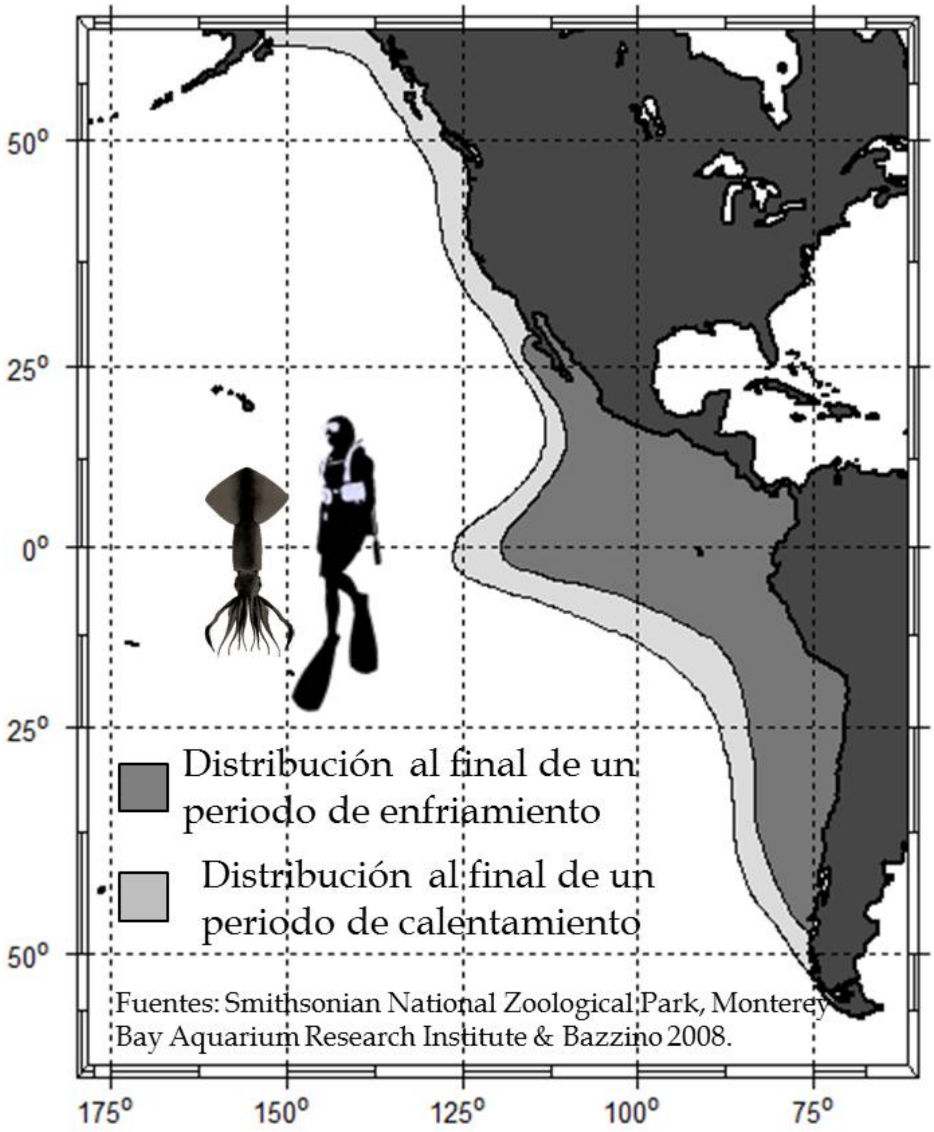

Figura 18: Expansión y contracción de las poblaciones de calamar gigante.

El cachalote es el mayor de los odontocetos o ballenas dentadas. Con una distribución cosmopolita, los grupos de hembras y juveniles se distribuyen en aguas tropicales y templadas, mientras que los machos solitarios se distribuyen en aguas polares y bajan a latitudes menores únicamente para reproducirse. Generalmente se los encuentra en aguas profundas, alimentándose principalmente de calamares epi y mesopelágicos (Whitehead, 2003). En aguas de la Corriente de California Barlow & Forney (2007) han observado que sus abundancias son temporalmente variables y las estimaciones más recientes (2001-2005) son marcadamente más altas que las estimaciones para el periodo 1991-1996. A su vez, Jaquet *et al*. (2003) observan en aguas del

Golfo de California que muy pocos avistamientos fueron reportados durante la década de 1980 y a partir del año 1992 estos han ido incrementando. Actualmente estas ballenas están presentes todo el año en aguas del Golfo de California y la gran proporción de hembras maduras y crías de un año sugiere que el Golfo es una región importante para alimentación y reproducción de cachalotes (Jaquet *et al*., 2003). Como se sabe que los cachalotes se alimentan principalmente de calamar gigante en aguas del Pacífico Oriental, un aumento en su presencia tanto en el golfo como en la Corriente de California, podría estar relacionado con la expansión del calamar gigante en estas áreas (Jaquet *et al*., 2003; Barlow & Forney, 2007). Al mismo tiempo, se ha observado una disminución en la abundancia de cachalotes en las Islas Galápagos desde principios de 1990 (Whitehead *et al*. 1997) y se han detectado animales de Galápagos en el interior del Golfo de California (Jaquet *et al*. 2003), lo que sugiere un desplazamiento hacia el norte de sus poblaciones.

El delfín común *(Delphinus sp.*) es un delfín cosmopolita de tamaño medio (de 2 a 2.5m), que se distribuye en aguas oceánicas y costeras de regiones tropicales y templadas (Reeves *et al.,* 2002). En aguas de la Corriente de California es el cetáceo más comúnmente observado y el más abundante (Barlow & Forney, 2007). Las manadas de estos animales depredan generalmente sobre cardúmenes de pelágicos menores como sardinas, anchovetas y calamares de tallas chicas (Reeves *et al*., 2002; Salvadeo, 2009). Danil *et al.* (2010) han observado una señal decadal en la frecuencia de varamientos de esta especie en las playas de San Diego, al sur de California, con una mayor incidencia durante periodos de enfriamiento (Fig.19). A partir de estos resultados los autores plantean dos hipótesis: 1) los varamientos reflejan un cambio en su distribución, con una mayor presencia de estos animales cerca de la costa durante la fase fría del régimen; y 2) los varamientos reflejan un cambio en la salud de sus poblaciones consecuencia de un cambio en la dieta (sardina-anchoveta) debido a los cambios de régimen. Los mismos autores se inclinan más por la segunda hipótesis, debido a que se ha documentado que un cambio en las biotoxinas aportadas por las presa desempeña un papel importante en la mortalidad de estos delfines, y las anchovetas son el principal vector de la toxicidad del ácido domoico en el delfín común (Berman & Fahy, 2003). En este caso, no se descarta ninguna de las dos hipótesis, aunque creemos que los varamientos reflejan más un cambio en la distribución costa-océano: con una distribución oceánica (costera) durante los periodos de calentamiento (enfriamiento), cuando la sardina (anchoveta) es más abundante y los cardúmenes se distribuyen en aguas oceánicas (costeras) (Schwartzlose *et al*., 1999; Checkley *et al*., 2009, MacCall, 2009).

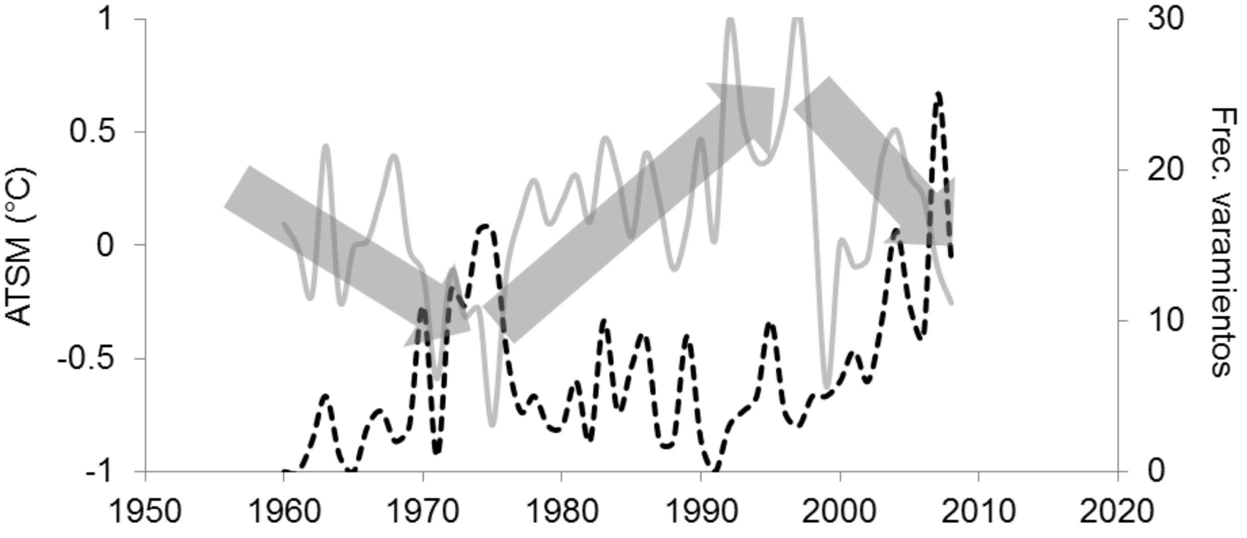

Figura 19: Patrón temporal del primer modo de variación de las anomalías de la temperatura superficial del mar (ATSM) en la porción sur de la Corriente de California (línea gris sólida) y frecuencia de varamientos por año de delfines comunes al sur de California (línea negra punteada) obtenida de Danil et al. (2010); las flechas representan la variación multidecadal del régimen.

El Delfín de costados blancos del Pacífico es un delfín oceánico de tamaño medio (de 2 a 2.5m), que se distribuye en aguas templadas del Pacífico Norte, alimentándose de sardinas, anchovetas, mictófidos y calamares de tallas chicas. Esta especie es frecuentemente observada en aguas de la Corriente de California y una de las más abundantes junto con el delfín común (Leatherwood *et al*., 1984; Stacey & Baird, 1990; Keiper *et al.,* 2005). El límite sur-oriental de su distribución es el Golfo de California, reportado como un visitante estacional del suroeste del golfo en los meses fríos del año (Aurioles *et a*l., 1989). En las últimas tres décadas, Salvadeo *et al.* (2010) han documentado una disminución en la presencia de esta especie de delfines en el límite sur de su distribución. Teniendo en cuenta que el ambiente térmico es fisiológicamente importante para los animales, especialmente para las crías, hembras preñadas y juveniles, los autores enumeran tres evidencias consistentes con un desplazamiento hacia los polos en su rango de distribución: 1) su presencia se ha reducido en aproximadamente un orden de magnitud por década desde la década de 1980 en el suroeste del golfo (Tabla 7); 2) la contracción mensual de su presencia hacia los meses más fríos del año en el suroeste del golfo (Fig. 20); y 3) su presencia ha incrementado en las costas canadienses en las últimas décadas (Morton, 2000). En este último caso los autores discuten una aparente ciclicidad de baja frecuencia en su presencia asociado a los cambios de régimen en pelágicos menores. Teniendo en cuenta lo anterior y más allá de si estos cambios son debido a la temperatura o a las presas, la evidencia apunta a que esta especie podría presentar un cambio cíclico en su rango de distribución, distribuyéndose más al sur al final de un periodo de enfriamiento y más al norte hacia el final de un periodo de calentamiento (Fig. 21).

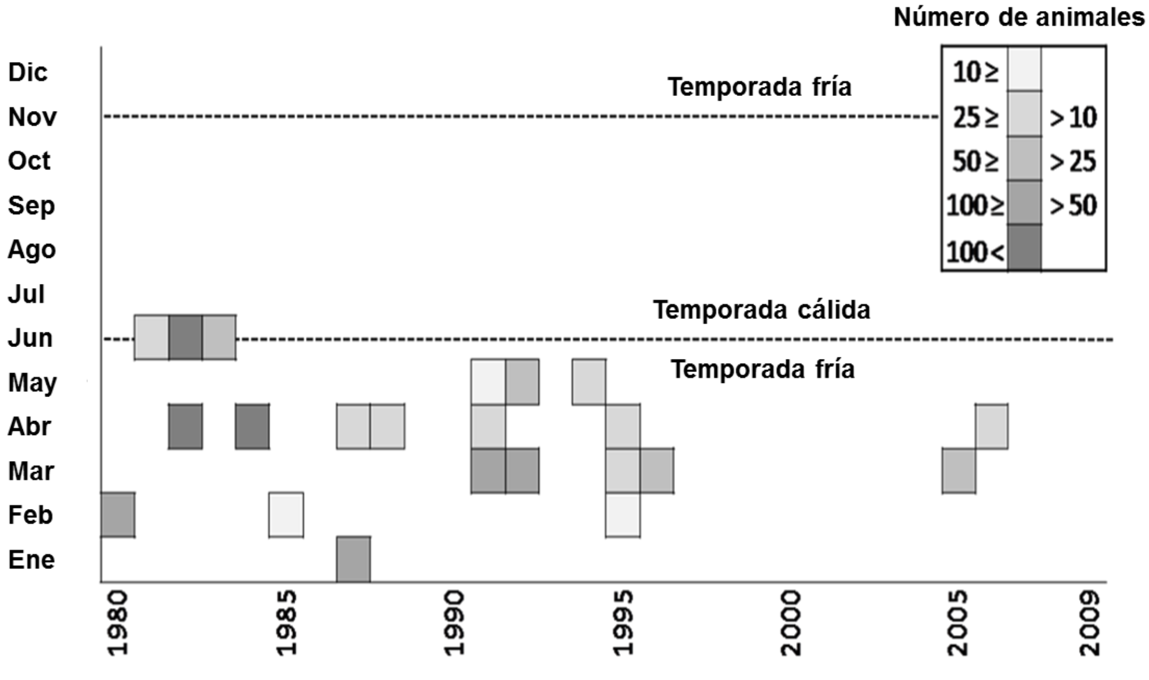

Figura 20: Número de delfines de costados blancos observados por mes en el Suroeste del Golfo de California (Salvadeo *et al.,* 2010).

Tabla 7: Datos históricos por década del delfín del costados blancos del Pacífico: Esfuerzo total de horas navegadas (Esf.); número de avistamientos totales (No Av); números de animales observados (No An); promedio (Pro), mínimo (Min), máximo (Max) y desviación estándar (DE) del tamaño de grupo; número de avistamientos (Av) y animales (An) por hora de navegación (Salvadeo *et al*., 2010).

Periodo	Esf.	No Av.	No An.	Pro..	Mín.	Máx.	DE.	Av./hr	An./hr
1980s	252	10	647	65	2	200	67	0.04	2.6
1990s	1659	16	316	20	1	45	12	0.01	0.2
2000s	1986	2	50	25	20	30	7	0.001	0.03

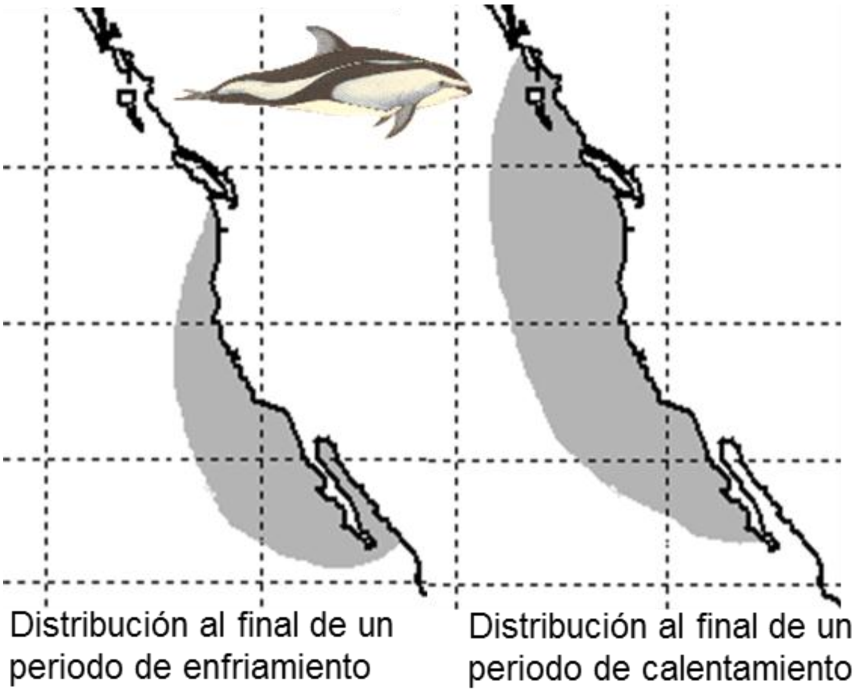

Figura 21: Distribución hipotética del delfín de costados blancos del Pacífico al final de un periodo de enfriamiento y uno de calentamiento.

La ballena azul es el animal más grande conocido que haya existido, pudiendo alcanzar los 30 metros de longitud y unas 180 toneladas de peso. Perteneciente al suborden de los Misticetos (ballenas barbadas), la ballena azul es una especie filtradora que se alimenta exclusivamente de krill (orden Euphausiacea) y en algunas ocasiones de langostilla (*Pleuroncodes planipes*). Con una distribución cosmopolita, su presencia y movimientos migratorios están ligados fuertemente a la productividad oceánica (Reeves *et al*., 2002). Previo a la expansión de la industria ballenera, esta especie se distribuía ampliamente desde Pacífico Oriental Tropical hasta las aguas de Alaska, mientras que en la actualidad se distribuye en la porción sur de su antiguo rango, con un circuito migratorio que incluye las aguas frente a las costas de California y de la Península de Baja California, el Golfo de California y el Domo de Costa Rica (Calambokidis & Barlow, 2004, Calambokidis *et al.,* 2009). A partir de datos históricos de capturas, avistamientos y estudios de fotoidentificación estos últimos autores plantean un cambio cíclico en el patrón de migración de estas ballenas relacionado con los cambios de régimen y mediados por la disponibilidad de sus presas; con un mayor uso de áreas norteñas (British Columbia y Alaska) y una menor presencia en aguas californianas durante condiciones de enfriamiento, mientras que durante condiciones de calentamiento se observa una mayor presencia en aguas californianas y su casi ausencia en el norte (Fig. 22).

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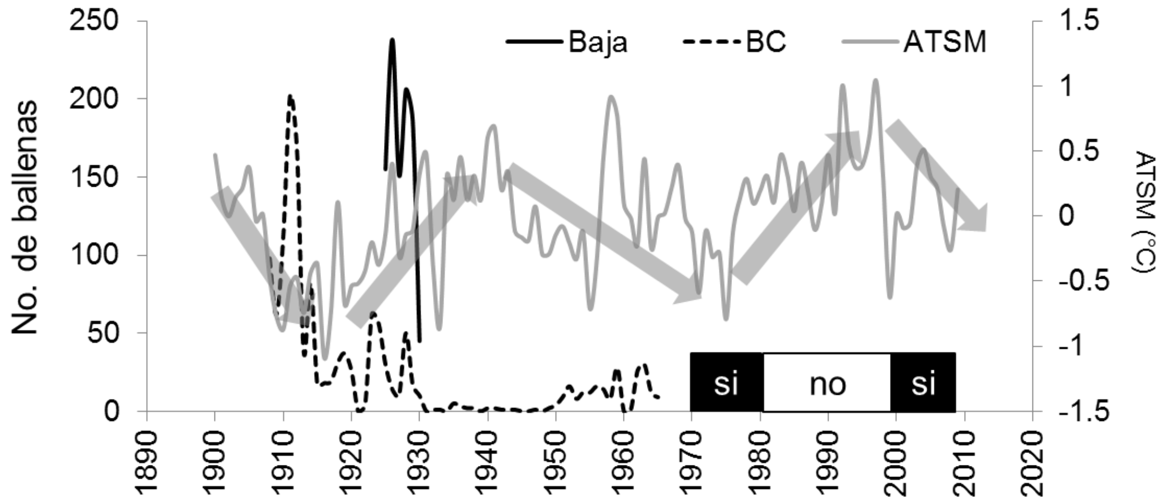

Figura 22: Número de ballenas azules cazadas por año en British Columbia (BC) y Baja California (Baja) obtenido de Calambokidis *et al.* (2009); los recuadros muestran la presencia temporal de la especie en el área de British Columbia y Alaska documentada en reportes técnicos y publicaciones científicas citados por Calambokidis *et al*. (2009); patrón temporal del primer modo de variación de las anomalías de la temperatura superficial del mar (ATSM) en el Pacífico Norte, las flechas representan la variación multidecadal del régimen.

La ballena de aleta es el segundo misticeto en tamaño luego de la ballena azul, pudiendo alcanzar los 27 metros de longitud. Con una distribución cosmopolita, esta especie está presente en todos los océanos del mundo, pudiéndosele observar en aguas subpolares y templadas y en menor medida en los trópicos. La ballena de aleta es una especie filtradora que se alimenta de kril, pelágicos menores y calamares de tallas pequeñas (Reeves *et al*., 2002). En aguas de la Corriente de California, Moore & Barlow (2011) observan un incremento en los números poblacionales de estas ballenas desde mediados de la década de los 90 (Fig. 23); los mismos autores plantean que dicho incremento no se sostiene bajo la lógica de un crecimiento poblacional in situ, sino más bien por un cambio en su distribución con el ingreso de nuevos animales al área de la Corriente de California durante dicho periodo. También se ha documentado un aumento en la presencia de esta especie en cruceros en torno a las islas Aleutianas (ej. Barreta & Hunt, 1994; Zervini *et al.,* 2006), pasando de estar completamente ausentes en los registros a mediados de los 70 (al final de un periodo de enfriamiento), a estar presentes para finales de los 80 y con una población en aumento hacia principios del presente siglo (al final de un periodo de calentamiento). A la luz de las evidencia y como lo señalan Moore & Barlow (2011), esta tendencia a largo plazo podría ser un efecto de las variación del régimen, mediados por la disponibilidad de presas en la Corriente de California y en otras regiones del Pacífico Norte.

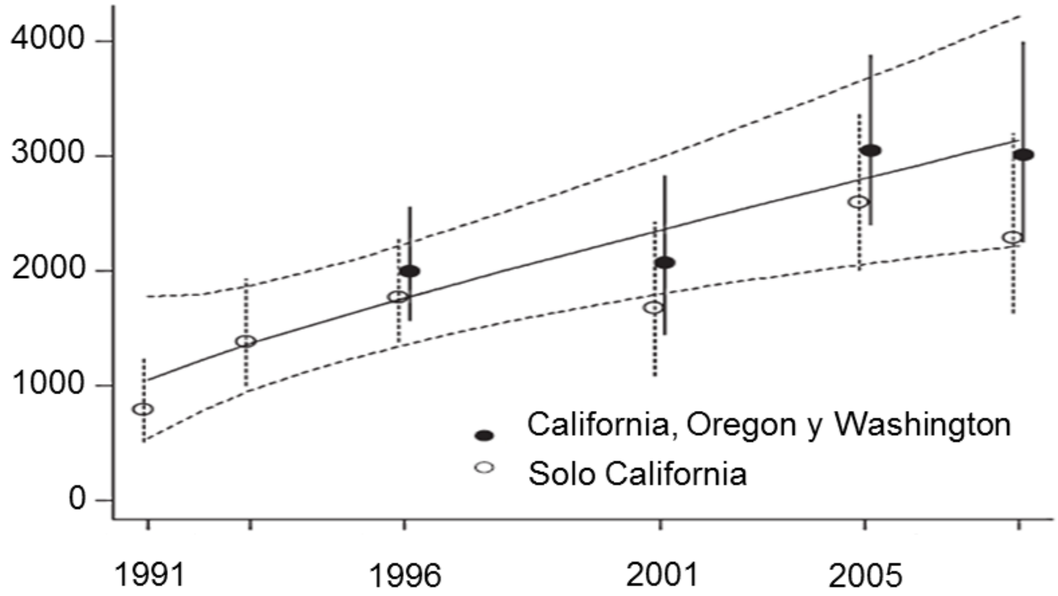

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Figure 23: Estimación de la abundancia (número de animales) y tendencia poblacional (con intervalos de credibilidad del 90%) para la ballena de aleta en aguas de la Corriente de California (Moore & Barlow, 2011).

La ballena gris es un misticeto de tamaño medio que puede alcanzar los 14 m de longitud y pesar cerca de 45 toneladas. Cada invierno boreal la ballena gris migra hacia sus áreas de reproducción y crianza en lagunas costeras de la Península de Baja California, para volver con la primavera a sus áreas de alimentación en los mares de Bering y Chukchi, donde se alimentan principalmente de fauna bentónica (Rice & Wolman, 1971). Luego de ver diezmadas sus poblaciones por la industria ballenera, la población de ballena gris del Pacífico Oriental parece haberse recuperado y llegado a la capacidad de carga del ambiente, con un tamaño de población que fluctúa entre los

20.000 y 22.000 animales (Rugh *et al*., 2008). Teniendo en cuenta que el ambiente térmico es fisiológicamente importante para los animales y especialmente para las crías, Salvadeo *et al.* (2011) plantean una serie de evidencias que suponen un desplazamiento hacia el norte del rango de distribución de madres con cría durante el último periodo de calentamiento. Lamentablemente no contamos con evidencia para suponer un cambio cíclico de su distribución debido a la falta de información, pero no se descarta que esto ocurra; presentandouna distribución más sureña al final de un periodo de enfriamiento y más norteña hacia el final de un periodo de calentamiento (Fig. 24).

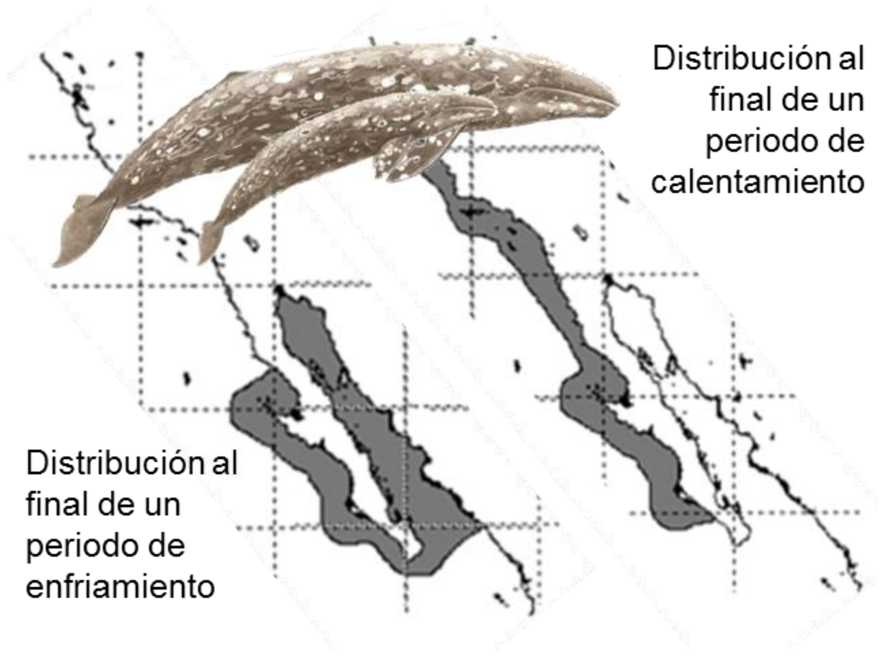

Figura 24: Distribución hipotética de madres con cría de ballena gris durante la época de reproducción y crianza (diciembre-abril) al final de un periodo de enfriamiento y calentamiento.

En resumen, podemos decir que para el caso de sardinas y calamares, la expansión y contracción en su rango de distribución parecen estar relacionada con la extensión del hábitat adecuado para la reproducción y el reclutamiento de sus poblaciones; mientras que para el caso del cachalote, el delfín común y las grandes ballenas barbadas (azul y de aleta), los cambios en la distribución de sus poblaciones parecen estar relacionados con los cambios en la abundancia y disponibilidad de sus principales presas. Por último, en el caso de la ballena gris y el delfín de costados blancos del Pacífico los cambios en su distribución parecen ser forzados por la importancia del ambiente térmico para los animales, en especial para el grupo poblacional más vulnerable como crías y juveniles por su tamaño corporal que les dificulta la retención de calor y un mayor gasto energético en la termorregulación corporal (Yeates & Houser, 2008).

Al parecer, los cambios en la distribución de macrofauna pelágica aquí expuestos incluyen a todos los nichos tróficos superiores como: 1) los consumidores secundarios (ej. pelágicos menores, calamares de tallas chicas y grandes ballenas barbadas) que se alimentan principalmente de organismos del fito y zooplancton, 2) los consumidores terciarios (ej. ballenas barbadas menos la azul, calamares de tallas grandes y delfines) que se alimentan de pelágicos menores como sardinas, anchovetas, calamares de tallas chicas y mictófidos, y 3) grandes predadores (ej. cachalotes) que están al final de las tramas tróficas oceánicas. Para el caso de sardinas, calamares, ballena azul y delfín común la evidencia sugiere que dichos cambios son cíclicos; mientras que para el cachalote, la ballena de aleta, la ballena gris y el delfín de costados blancos no hay evidencia de una ciclicidad como tal, pero no se descarta que esto suceda.

Por último, el primer modo de variación de las anomalías de la temperatura superficial del mar en la Corriente de California muestra una tendencia de enfriamiento en los últimos 10 años (Fig. 13). Si la ciclicidad observada se repite, deberíamos esperar en la próxima década la contracción y disminución de las poblaciones de sardinas y calamares en aguas de la Corriente de California, seguida de una redistribución de los cachalotes hacia aguas del Pacífico Oriental Tropical y la Corriente de Humbolt; para el caso particular del delfín de costados blancos y la ballena gris se esperaría el regreso de ambas especies como visitantes estacionales del Golfo de California, mientras que el delfín común continuará siendo muy abundante frente a las costas de California y la ballena azul seguiría utilizando las aguas oceánicas frente a British Columbia y Alaska.

9. Conclusiones

Se identificaron tres escalas de variación en el Pacífico mexicano: 1) la escala interanual relacionada con la variabilidad del ENSO en el Pacífico Ecuatorial, 2) la escala cuasidecadal relacionada con el segundo modo de variación del Pacífico Norte (NPGO), y 3) la escala multidecadal del régimen relacionada con el primer modo de variación del Pacífico Norte (PDO). La diferenciación entre estas escalas permite asociar la variabilidad a patrones y procesos físicos propios de cada escala, aunque se reconoce que no son realmente independientes.

A escala interanual se ha observado que los cambios en la ocurrencia de la ballena de Bryde (*Balaenoptera edeni*) en la Bahía de La Paz están influenciados por la variabilidad del ENSO y probablemente estén mediados por la disponibilidad de sus presas.

A escalas decadales se observa que los vientos tehuanos son una fuente de variabilidad climática extratropical en el Pacífico Oriental Tropical; esta señal de baja frecuencia en los tehuanos puede ser modelada por la variación extratropical del sistema de alta presión del Pacífico Noreste, siendo su teleconexión el movimiento hacia el sur de los frentes fríos que bajan por Norteamérica desde el Pacífico noreste.

A escala multidecadal se distinguen la alternancia de periodos de enfriamiento y calentamiento durante los últimos 110 años en la Corriente de California. Esta alternancia es indicativa de cambios en la circulación oceánica y atmosférica, que en última instancia afectan los mecanismos de enriquecimiento de las aguas superficiales en toda la cuenca del Pacífico Norte. Las respuestas biológicas documentadas relacionadas con esta escala de variación son la expansión y contracción de poblaciones de sardinas y calamares y el cambio en los patrones de distribución en ballenas azules y delfines comunes. Asimismo la evidencia sugiere cambios de largo plazo en la distribución de ballena gris, ballena de aleta, delfín de costados blancos y cachalotes que podrían estar relacionados con este tipo de variación multidecadal.

10. Referencias

Álvarez-Borrego S. & R. A Schwartzlose. 1979. Water masses of the Gulf of California. Ciencias Marinas 6: 43–63.

Amador J. A., Alfaro E. J., Lizano O. G. & V. O. Magaña. 2006. Atmospheric forcing of the eastern tropical Pacific: A review. Progress in Oceanography 69: 101–142.

Anderson 2005. Observations of cetaceans in the Maldives, 1990-2002. Journal of Cetacean research and management 7(2):119–135.

Armendáriz-Villegas, J. 2005. Hábitos alimenticios del Calamar Gigante (Dosidicus gigas; Orbigny, 1835), en el Centro del Golfo de California durante los años 2002 y 2003. Tesis de licenciatura, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., México.

Aurioles D. G., Gallo-Reynoso J. P., Muñoz E. L. & J. V. Ejido. 1989. El delfín de costados blancos (Lagenorhynchus obliquidens, Gill 1865) (Cetacea: Delphinidae) residente estacional en el suroeste del Golfo de California, México. Anales del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología 60:459–472.

Bakun A., Babcock E. A., Lluch-Cota S. E., Santora C. & C. J. Salvadeo. 2009. Issues of ecosystem-based management of forage fisheries in ‘‘open’’ non-stationary ecosystems: the example of the sardine fishery in the Gulf of California. Reviews in Fish Biology and Fisheries 20(1): 9-29.

Ballance L. T., Pitman R. L. & P. C. Fiedler. 2006. Oceanographic influences on seabirds and cetaceans of the eastern tropical Pacific: A review. Progress in Oceanography 69: 360–390.

Barnston A. G., & R. E. Livezey. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Review 115: 1083-1126.

Barlow, J. & K. A. Forney. 2007. Abundance and density of cetaceans in the California Current ecosystem. Fishery Bulletin 105: 509–526.

Barreta L. & J. L. Hunt. 1994. Changes in the Numbers of Cetaceans near the Pribilof Islands, Bering Sea, between 1975–78 and 1987–89. Artic 47(4): 321–326.

Baumgartner, T. R., Soutar A. & V. Ferreira-Bartrina. 1992. Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. CalCOFI. Rep. 33:24–40.

Bazzino, G. 2008. Estructura poblacional, movimientos horizontales y migraciones verticales del calamar gigante en el Golfo de California y en el Océano Pacífico frente a la Península de Baja California. Tesis de doctorado, Centro de Investigaciones Biológicas del Noroeste, La Paz, B.C.S., México. 126 pp.

Beamish, R. J. & D. R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences 50: 1002–1016.

Benson S. R., Croll D. A., Marinovic B. B., Chavez F. P. & J. T. Harvey. 2002. Changes in the cetacean assemblage of a coastal upwelling ecosystem during El Niño 1997–98 and La Niña 1999. Progress in Oceanography 54 : 279–291.

Berman, M. S. and K. Fahy. 2003. Domoic acid and dolphins; a deadly combination. Presentado en la 15th Biennial Conference on the Biology of Marine Mammals, 14–19 Diciember 2003, Greensboro, NC.

Bernal, G., Ripa, P. & J. C. Reguera. 2001. Oceanographic and climatic variability in the lower Gulf of California: links with the tropics and North Pacific. Ciencias Marinas 27(4): 595–617.

Björnsson H. & S. A. Venegas. 1997. A manual for EOF and SVD analyses of climate data. McGill University, CCGCR Report No. 97-1, Montréal, Québec, 52pp.

Calambokidis, J., & J. Barlow. 2004. Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods. Marine Mammal Science 20:63–85.

Chavez F. P., Ryan J., Lluch-Cota S. E. & C. M. Niquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299:217–221.

Checkley M. D., Ayon P., Baumgartner T. R., Bernal M., Coetzee J. C., Emment R., Guevara-C. R., Hutchings L., Ibaibarriaga L. Nakata H., Oozeki Y., Planque B., Schweigert J., Stratoudakis Y. & C. D. van der Lingen. 2009.

Habitats. En: Checkley D M., Alheit J., Oozeki Y. & C. Roy (ed). Climate Change and Small Pelagic Fish. Cambridge University Press.

Chong, J., Oyarzun, C., Galleguillos, R., Tarifeño, E., Sepúlveda R. & C. Ibáñez 2005. Fishery biology parameters of jumbo squid, *Dosidicus gigas* (Orbigny, 1835) (Cephalopoda: Ommastrephidae), in Central Chile coast (29°S-40°S) during 1993-1994. Gayana 69(2):319-328

Clarke, A. J. 1988. Inertial wind path and sea surface temperature patterns near the Gulf of Tehuantepec and Gulf of Papagayo. Journal of Geophysical Research 93: 15 491–15

Clarke A. J. & A. Lebede. 1996 Long-term changes in the equatorial Pacific trade winds. Journal of Climate 9: 1020-1029.

Cosgrove, J. A. 2005. The first specimens of Humboldt squid in British Columbia. PICES Press 13(2):30–31.

Danil K., Chivers S. J., Henshaw M. D., Thieleking J. I., Daniels R. & J. A. St. Leger. 2010. Cetacean strandings in San Diego County, California, USA: 1851–2008. Journal of Cetacean Research and Management 11(2): 163–184

Di Lorenzo E., Schneider N., Cobb K. M., Chhak, K, Franks P. J. S., Miller A. J., McWilliams J. C., Bograd S. J., Arango H., Curchister E., Powell T. M. & P. Rivere 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change, Geophysical Research Letter 35: L08607, doi:10.1029/2007GL032838

Dizon A. E., Lux C. A., Leduc R. G., Henshaw M. & R. L. Brownwell. 1995. An interim phylogenetic analysis of sei and Bryde's whale mitochondrial DNA control region sequences. Paper SC/47/ NP23 presented to the International Whaling Commission Scientific Committee (unpublished), 12 pp.

Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H. & K. T. Redmond. 1991. 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. Seventh annual Pacific climate workshop (PACLIM), Asilomar, California, USA, April 1990.

FAO. 1997. Review of the state of world fishery resources: marine fisheries. FAO Fisheries Circular 920, FIRM/C920, Rome, Italy.

Félix-Uraga R., Quiñónez-Velázquez C., Kevin T., Hill K.T., Gómez-Muñoz V.M., Melo-Barrera F.N. & W. García-Franco. 2005. Pacific Sardine (*Sardinops sagax*) stock discrimination off the west coast of Baja California and southern California using otolith morphometry. CalCOFI Rep. 46: 113–121.

Fiedler, P. C. 2002. Environmental change in the eastern tropical Pacific Ocean: review of ENSO and decadal. Marine Ecology Progress Series. 244: 265–283.

Fiedler, P. C. & L. D. Talley. 2006. Hydrography of the eastern tropical Pacific: A review. Progress in Oceanography 69: 143–180.

Field, J. C., Baltz, K., Phillips, A. J. & W. A. Walker. 2007. Range expansion and trophic interactions of the jumbo squid, *Dosidicus gigas*, in the California Current. CalCOFI Reports 48:131-146.

Flores-Ramírez S., Urbán R. J., Delgado-González O. & J. Vargas-Salinas. 1997. Avistamientos de rorcual tropical, *Balaenoptera edeni* (Cetacea: Balaenopteridae) y temperatura del agua, en Baja California Sur, México. Revista Biología Tropical 45: 1209–1214.

Galván-Magaña, F., Olson, R. J., Bocanegra-Castillo, N. & V G. Alatorre-Ramirez. 2006. Cephalopod prey of the apex predator guild in the epipelagic eastern Pacific Ocean In: The role of squid in open ocean ecosystems, Olson, R. J. & Young, J. W. (Eds.), pp. 45-48, GLOBEC international project, Honolulu, Hawaii, USA.

Gardner, S. C. & S. Chávez-Rosales. 2000. Changes in the relative abundance and distribution of gray whales (*Eschrichtius robustus*) in Magdalena Bay, Mexico during an El Niño event. Marine Mammal Science 16:728–738.

Gendron D. 1993. Índice de avistamiento y distribución del género Balaeneptera en el Golfo de California, México, durante febrero, marzo y abril de 1988. Revista de Investigaciones Científicas Universidad Autónoma de Baja California Sur (Serie Ciencias Marinas), No. Especial SOMMEMA 1: 21–29.

Gonzalez-Silvera, A., Santamaría-del-Angel, E., Millan-Nuñez, R. & H. Manzo-Monroy. 2004. Satellite observations of mesoscale eddies in the Gulfs of

Tehuantepec and Papagayo (Eastern Tropical Pacific). Deep-Sea Research II 51: 587-600.

Graham N. E. 1994 Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: Observations and model results. Climate Dynamics 10: 135-162.

Gu, D., & S.G.H. Philander, 1995: Secular changes of annual and interannual variability in the tropics during the past century. Journal of Climate 8: 864-876.

Gu D. & S.G.H Philander. 1997 Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. Science 275: 805-807

Hammann M. G., Nevárez-Martínez M. O. & Y. Green-Ruíz. 1998. Spawning habitat of the Pacific sardine (Sardinops sagax) in the Gulf of California: Egg and larval distribution 1956–1957 and 1971–1991. CalCOFI Rep. 39: 169–179.

Herrera-Cervantes H., Lluch-Cota S., Lluch-Cota D., Gutiérrez de Velazco San Román & D. Lluch-Belda. 2010. Enso influence on satellite-derived Chlorophyll trends in the Gulf of California. Atmósfera 23(3): 253-262.

Holbrook, S., Schmitt, R. & J. Stephens. 1997. Changes In An Assemblage of Temperate Reef Fishes Associated With A Climate Shift. Ecological Applications 7: 1299-1310.

Huato-Soberanis, L. & D. Lluch-Belda. 1987. Mesoscale cycles in the series of environmental indices related to the sardine fishery in the Gulf of California. CalCOFI Rep. 28: 128-134.

Jaquet, N., Gendron, D. & A. Coakes. 2003. Sperm whales in the Gulf of California: residency, movements, behavior, and the possible influence of variation in food supply. Marine Mammals Science 19(3):545-562.

Jiménez-Illescas R., Obeso-Nieblas M. & Salas de León. 1997. Oceanografía física de la Bahía de La Paz. In: Urbán-Ramírez. J. & M. Ramírez-Rodríguez (eds.), La Bahía de La Paz, Investigación y Conservación. UABCS-CICIMAR-SCRIPPS, México, pp. 31–41.

Kahru, M., Marinone, S.G., Lluch-Cota, S.E., Pare´s-Sierra, A. & G. Mitchell. 2004. Ocean color variability in the Gulf of California: scales from the El Niño–La Niña cycle to tides. Deep Sea Research II 51: 139–146.

Kawasaki, T. 1983. Why do some pelagic fishes have wide fluctuations in their numbers? - biological basis of fluctuation from the viewpoint of evolutionary ecology., p. 1065-1080. In G.D. Sharp and J. Csirke (eds.), Reports of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources. FAO Fish. Rep. 291 (2, 3): 1224 p.

Karnauskas, K. B., Busalacchi, A. J. & R Murtugudde. 2008. Low-frequency variability and remote forcing of gap winds over the East Pacific warm pool. Journal of Climate 21: 4901-4918.

Kato H. 2002. Bryde's whales *Balaenoptera edeni* and *B. brydei*. In: Perrin W. F., Würsig B. & J. G. M. Thewissen (eds.), Encyclopedia of Marine Mammals. Academic Press, San Diego, pp 171–177.

Keiper C. A., Ainley D. G., Allen S. G. & J. T. Harvey. 2005. Marine mammal occurrence and ocean climate off central California, 1986 to 1994 and 1997 to 1999. Mar. Ecol. Prog. Ser. 289: 285–306.

Kessler, W. S. 2006. The circulation of the eastern tropical Pacific: A review. Progress in Oceanography 69: 181–217.

Klyashtorin, L. B. 2001. Climate Change and Long-Term Fluctuations of Commercial Catches -The Possibility of Forecasting. FAO Fisheries Technical Paper-T410. 86 pp.

Learmonth J. A., Santos M. B., Pierce G. J., Crick H. Q. P. & R. A. Robinson. 2006. Potential effects of climate change on marine mammals. Oceanography and Marine Biology: An Annual Review 44: 431–464.

Leatherwood, S., Reeves, R. R., Bowles, A. E., Stewart, B. S. & K. R. Goodrich.1984. Distribution, seasonal movements and abundance of Pacific white-sided dolphins in the eastern North Pacific. Science Report Whales Research Institute 35:129–157

Leatherwood S., Reeves R. R., Perrin W. F. & W. E. Evans. 1988. Ballenas, delfines y marsopas del Pacífico nororiental y de las aguas árticas adyacentes: Una guía para su identificación. Comisión Interamericana del Atún Tropical (IATTC), Informe Especial No. 8, La Jolla, California, 245 pp.

Liang, J., McWilliams, J. C. & N. Gruber. 2009. High-frequency response of the ocean to mountain gap winds in the northeastern tropical Pacific. Journal of Geophysical Research 114: C12005

Lusseau D., Williams R. & B. Wilson. 2004. Parallel influence of climate on the behaviour of Pacific killer whales and Atlantic bottlenose dolphins. Ecology Letters 7: 1068–1076.

Lluch-Belda, D. 1974. La Pesquería de Camarón de Alta Mar en el Noroeste: Un análisis Biológico-Pesquero. Inst. Nal. de Pesca SC/9.

Lluch-Belda, D. Magallón F. J. & R. A. Schwartzlose. 1986. Large fluctuations in the sardine fishery in the Gulf of California: Possible causes. CalCOFI Rep. 27: 136-140.

Lluch-Belda, D., Crawford, R.J.M., Kawasaki, T., MacCall, A.D., Parrish, R.H.,. Schwartzlose R.A & P.E. Smith. 1989. World-wide fluctuations of sardine and anchovy stocks: The regime problem. South African Journal of Marine Science 8: 195-205.

Lluch-Belda, D., Lluch-Cota, D.B. & S.E. Lluch-Cota. 2002. Is interannual change predictable at the California Current System? Oceanography of the Eastern Pacific II : 74-85.

Lluch-Belda, D., Lluch-Cota, D. & S. Lluch-Cota. 2003. Baja California’s Biological Transition Zones: Refuges for the California Sardine. Journal of Oceanography 59: 503 -513.

Lluch-Belda, D., Lluch-Cota, D.B. & S.E. Lluch-Cota. 2005. Changes in marine faunal distributions and ENSO events in the California Current. Fisheries Oceanography. 14 (6): 458–467.

Lluch-Belda, D., Del Monte-Luna P., & S. Lluch-Cota. 2009. 20TH century variability in Gulf of California SST. CalCOFI Rep.50: 147-154.

Lluch-Cota, S.E., 2000. Propuesta de bases para un sistema de informacio´n ambiental para la pesquería de sardina del Golfo de California. Tesis doctorado, Centro de Investigaciones Biológicas del Noroeste, La Paz, México.

Lluch-Cota, S., Aragón-Noriega, E. A., Arreguín-Sánchez, F., Aurioles-Gamboa, D., Bautista-Romero, J., Brusca, R. C., Cervantes-Duarte, R., Cortés-Altamirano, R., Del-Monte-Luna, P., Esquivel-Herrera, A., Fernández, G., Hendrickx , M. E., Hernández-Vázquez, S., Herrera-Cervantes, H., Kahru, M., Lavín, M., Lluch-Belda, D., Lluch-Cota, D. B. López-Martínez, J., Marinone, S.G., Nevárez-Martínez, M. O., Ortega-García, S., Palacios-Castro, E., Parés-Sierra, E., Ponce-Díaz, G., Ramírez-Rodríguez, M., Salinas-Zavala, C. A.,. Schwartzlose, R. A. & A. P. Sierra-Beltrán. 2007. The Gulf of California: Review of ecosystem status and sustainability challenges. Progress in Oceanography 73: 1–26.

Namias, J., 1972. Large-scale and long-term fluctuations in some atmospheric and oceanic variables. In: Dyrssen, D., Jagner, D. (Eds.), Proceedings of the 20th Nobel Symposium, Gothenburg, Sweden. Almqvist and Wiksell, Stockholm, pp. 27–48.

MacCall A. D. 2009. Mechanisms of low-frequency fluctuations in sardine and anchovy populations. En: Checkley D M., Alheit J., Oozeki Y. & C. Roy (ed). Climate Change and Small Pelagic Fish. Cambridge University Press.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. & Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78(6): 1069–1079.

Manzanilla S. R.1989. The 1982–1983 El Niño event recorded in dentinal growth layers in teeth of Peruvian dusky dolphins (Lagenorhynchus obscurus). Canadian Journal of Zoology 67: 2120–2125.

Markaida U, Sosa-Nishizaki O (2003) Food and feeding habits of jumbo squid Dosidicus gigas (Cephalopoda: Ommastrephidae) from the Gulf of California, Mexico. Journal of the Marine Biological Association of the United Kingdom Vol.83, pp. 507–522.

McPhaden M. S. & D. Zhang. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. Nature 415: 603-608.

Mecikalski, J. R. & J. S. Tilley. 1992. Cold surges along the front range of the Rocky mountains: Development of a classification scheme. Meteorology and Atmospheric Physics 48: 249-271.

Mendoza, B., García-Acosta, V., Velasco, V., Jáuregui , E. & R. Díaz-Sandoval. 2007. Frequency and duration of historical droughts from the 16th to the 19th centuries in the Mexican Maya lands, Yucatan Peninsula Climate Change 83:151–168.

Mercuri M. 2007. Varamiento de mamíferos marinos en isla Magdalena, BCS, México, y su relación con factores físicos y biológicos. Tesis de Maestría, CICIMAR-IPN, La Paz, BCS, México,107 pp

Mestas-Nuñez A. M. & A. J. Miller. 2006. Interdecadal variability and climate change in the eastern tropical Pacific: A review. Progress in Oceanography 69: 267-284.

Moore J.E. & J. Barlow. 2011. Bayesian state-space model of fin whale abundance trends from a 1991–2008 time series of line-transect surveys in the California Current. Journal of Applied Ecology 48:1195–1205.

Moore, S. E. & H. P. Huntington. 2008. Arctic marine mammals and climate change: impacts and resilience. Ecological Applications 18:157–165.

Morales-Bojórquez, E., Cisneros-Mata, M. A., Nevarez-Martínez, M. O. & A. Hernández-Herrera. 2001. Review of stock assessment and fishery biology of *Dosidicus gigas* in the Gulf of California, Mexico. Fisheries Research 54: 83-94.

Morton, A. 2000. Occurrence, photo-identification and prey of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in the Broughton Archipelago, Canada 1984–1998. Marine Mammals Science 16:80-93.

Müller-Karger, F.E. & C. Fuentes-Yaco. 2000. Characteristics of wind-generated rings in the eastern tropical Pacific Ocean. Journal of Geophysical Research 105: 1271–1284.

Obeso-Nieblas M. 2003. Variabilidad espaciotemporal de las condiciones oceanográficas de la Bahía de La Paz, BCS, México. Tesis de Doctorado, CICIMAR-IPN, La Paz, BCS, México, 337 pp.

Overland, J., Rodionov, S., Minobe, S. & , N. Bond. 2008. North Pacific regime shifts: Definitions, issues and recent transitions. Progress In Oceanography Vol.77 (2-3): 92-102.

Palacios D. M. & S. J. Bograd. 2005. A census of Tehuantepec and Papagayo eddies in the northeastern tropical Pacific. Geophysical Research Letter 32: 1-4.

Pardo M. A. 2009. Condiciones fisicoquímicas y biológicas que modulan la abundancia de cetáceos sobre Cuenca Alfonzo, Golfo de California. Tesis de maestría, CICIMAR-IPN, La Paz, BCS, Mexico,101 pp.

Reeves R. R., Stewart B., Clapham P. J. & J. A. Powell. 2002. Guide to Marine Mammals of the World. Knopf, New York, 527 pp.

Rice D. W. 1974. Whales and whale research in the eastern North Pacific. In: Schevill WE (ed.), The Whale Problem: A Status Report. Harvard Press, Cambridge, Massachusetts, pp.170–195.

Ripa, P. 2002. Least squares data fitting. Ciencias Marinas 28:79-105.

Roemmich, D. & J. McGowan. 1995. Climate warming and the decline of zooplankton in the California Current. Science 267:1324-1326.

Rodhouse P. G. 2008. Large-scale range expansion and variability in ommastrephid squid populations: a review of environmental links. CalCOFI Reports 49:83-89.

Romero-Centeno, R., Zavala-Hidalgo, J., Gallegos, A., & J. O'Brien. 2003, Isthmus of Tehuantepec Wind Climatology and ENSO Signal. Journal of Climate 16: 2628-2639.

Salvadeo C. J., Gómez-Gallardo U., Lluch-Belda D. & J. Urbán. 2009. The odontocete community and its environment in the southwestern Gulf of California. Latin American Journal of Aquatic Mammals 7(1-2): 23-32.

Salvadeo C. J., Lluch-Belda, D., Gómez-Gallardo, A., Urbán-Ramírez, J. and C. D. MacLeod. 2010. Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific. Endangered Species Research 11:13-19.

Salvadeo C. J., Daniel Lluch-Belda, Salvador Lluch-Cota & Milena Mercuri. 2011. Review of Long term macro-fauna movement by multi-decadal warming trends in the Northeastern Pacific. Climate Change-Geophysical Foundations and Ecological Effects, ISBN 978-953-307-419-1

Scheinin, A. P., Kerem, D., MacLeod, C. D., Gazo, M., Chicote C. A. & M. Castellote. 2011. Gray whale (*Eschrichtius robustus*) in the Mediterranean Sea: anomalous event or early sign of climate-driven distribution change? Marine Biodiversity Records 4:e28.

Schultz, D. M., W. E. Bracken, L. F. Bosart, G. J. Hakim, M. A. Bedrick, M. J. Dickinson, & K. R. Tyle. 1997. The 1993 superstorm cold surge: Frontal structure, gap flow, and tropical impact. Monthly Weather Review 125: 5–39.

Schultz, D. M., Bracken W. E. & L. F. Bosart. 1998. Planetary- and synoptic-scale signatures associated with Central American cold surges. Monthly Weather Review 126: 5–27.

Schwartzlose, R. A., J. Alheit, A. Bakun, T.R. Baumgartner, R. Cloete, R.J.M. Crawford, W.J. Fletcher, Y. Green-Ruiz, E. Hagen, T. Kawasaki, D. Lluch-Belda, S.E. Lluch-Cota, A.D. MacCall, Y. Matsuura, M.O. Nevárez-Martínez, R.H. Parrish, C. Roy, R. Serra, K.V. Shust & M.N. War 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. South African Journal of Marine Science 21: 289-347.

Schwing, F. B., Murphree, T. & P. M. Green. 2002. The Northern Oscillation Index (NOI): A New Climate Index for the Northeast Pacific. Progress in Oceanography 53(4): 115-139

Shane SH. 1995. Relationship between pilot whales and Risso's dolphins at Santa Catalina Island, California, USA. Marine Ecology Progress Series 123: 5–11.

Shelden, K. W., Rugh, D. J., & A. Schulman-Janiger. 2004. Gray whales born north of Mexico: indicator of recovery or consequence of regime shift? Ecological Applications 14:1789–1805.

Soto-Mardones L., Marinone S. G. & A. Parés-Sierra. 1999. Time and spatial variability of sea surface temperature in the Gulf of California. Ciencias. Marinas 25: 1–30.

Stacey, P.J. & R.W. Baird. 1990. Status of the white-sided dolphin, *Lagenorhynchus obliquidens*, in Canada. Canadian Field-Naturalist 105:219–232.

Tershy B. R.. 1992. Body size, diet, habitat use, and social behavior of Balaenoptera whales in the Gulf of California. Journal of Mammalogy 73: 477–486.

Tershy B. R., Breese D. & C. S. Strong. 1990. Abundance, seasonal distribution and population composition of Balaonopterid whales in the Canal de Ballenas, Gulf of California, Mexico. International Whale Commission Report (Special Issue) 12: 369–375.

Tershy B. R., Breese D. & S. Alvarez-Borrego. 1991. Increase in cetacean and seabird numbers in the Canal de Ballenas during an El Niño-Southern Oscillation event. Marine Ecology Progress Series 69: 299–302.

Tershy B. R., Urbán-Ramírez J., Breese D., Rojas L. & L. T. Findley. 1993. Are fin whales resident to the Gulf of California? Revista de Investigaciones

Científicas Universidad Autónoma de Baja California Sur (Serie Ciencias Marinas), No. Especial SOMMEMA 1: 69–72.

Trenberth, K. E. 1984. Signal versus Noise in the Southern Oscillation. Monthly Weather Review 112:326-332.

Trites, A. W. & P. A. Larkin. 1996. Changes in the abundance of Steller sea lions (*Eumetopias jubatus*) in Alaska from 1956 to 1992: how many were there? Aquatic Mammals 22: 153-166.

Trites, A. W., Deecke, V. B., Gregr, E. J., Ford, J. K. B. & P. F. Olesiuk. 2007. Killer whales, whaling and sequential megafaunal collapse in the North Pacific: a comparative analysis of dynamics of marine mammals in Alaska and British Columbia following commercial whaling. Marine Mammal Science 23: 751-765.

Tynan C. T. 1999. Redistributions of cetaceans in the southeast Bering Sea relative to anomalous oceanographic conditions during the 1997 El Niño. PICES Science. Report 10: 115–117.

Urbán R. J. & S. Flores-Ramírez . 1996. A note on Bryde’s whales (Balaenoptera edeni) in the Gulf of California, Mexico. . International Whale Commission Report 46: 453–457.

Urbán, R. J., Rojas, L. B., Pérez-Cortéz, H., Gómez-Gallardo, A. U., Swartz, S. Ludwing, S. & L. Brownell. 2003a. A review of gray whales on their wintering grounds in Mexican waters. Journal of Cetacean Research and Management 5:281–295.

Urbán, R. J., Gómez-Gallardo, U. A. & S. Ludwig. 2003b. Abundance and mortality of gray whales at Laguna San Ignacio, Mexico, during the 1997–98 El Niño and the 1998–99 La Niña. Geofisica Internacional 42:439-446.

Urbán, R. J., Gómez-Gallardo U. A., Rojas-Bracho, L. & S. L. Swartz. 2010. Historical changes of gray whales abundance in San Ignacio and Ojo de Liebre breeding lagoons, Mexico. International Whale Comition Scientific Committee Paper, SC/62/BRG36.

Urban, F.E., Cole, J.E. & J.T. Overpeck. 2000. Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. Nature 407: 989-993.

Veit, R. R., Mcgowan, J. A., Ainley, D. G., Wahls, T. R., & P. Pyle. 1997. Apex marine predator declines ninety percent in association with changing oceanic climate. Global Change Biology 3: 23–28.

Velarde E., Ezcurra E., Cisneros-Mata A. & M. F. Lavín. 2004. Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. Ecological Applications 14: 607–615.

Venegas S. A. 2001. Statistical methods for signal detection in climate. Danish Center for Earth System Science Report No. 2. 96 pp.

Waluda, C. M. & P. G. Rodhouse 2006. Remotely sensed mesoscale oceanography of the central Eastern Pacific and recruitment variability in Dosidicus gigas. Marine Ecology Progress Series 310:25–32.

Wang, B. & Y., Wang. 1996. Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. Journal of Climate 9: 1586-1598.

Wang, C. & P. C. Fiedler. 2006. ENSO variability and the eastern tropical Pacific: A review. Progress in Oceanography 69: 239–266.

Ware, D. M. 1995. A century and a half of change in the climate of the NE Pacific. Fisherias Oceanography. 4: 267-277.

Waters, G. M., Olson, R. J., Field, J. C. & T. E. Essington. 2008. Range expansion of the Humboldt squid was not caused by tuna fishing. Proceedings of the National Academy of Sciences 105(3): E5-E5.

Whitehead, H. 2003. Sperm Whales: Social Evolution in the Ocean. University of Chicago Press, Chicago USA

Whitehead, H., Christal, J. & S. Dufault. 1997. Past and distant whaling and the rapid decline of sperm whales off the Galápagos Islands. Conservation Biology 11:1387-1396.

Wikle C. K. & N. Cressie. 1999. A dimension reduced approach to space-time Kalman filtering Biometrika 86:815-829.

Willett, C.S. 1996. A study of anticyclonic eddies in the eastern tropical Pacific Ocean with integrated satellite, in situ, and modelled data. Ph.D. thesis, University of Colorado, Boulder, Colorado.

Willett, C.S., Leben, R.R. & M.F. Lavín. 2006. Eddies and Tropical Instability Waves in the eastern tropical Pacific: A review. Progress in Oceanography 69: 218–238.

Wing, B. L. 2006. Unusual invertebrates and fish observed in the Gulf of Alaska, 2004–2005. PICES Press 14(2):26–28.

Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. Journal of climate and ***Applied*** Meteorology 26: 540-558

Wolter, K., and M. S. Timlin, 1993: Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proc. of the 17th Climate Diagnostics Workshop, Norman, OK, NOAA/NMC/CAC, NSSL, Oklahoma Clim. Survey, CIMMS and the School of Meteor., Univ. of Oklahoma, pp 52-57

Wooster, W. S. & A. B. Hollowed. 1995. Decadal-scale variations in the eastern subarctic Pacific: Winter ocean conditions. Canadian Special Publication of Fisheries and Aquatic Science. 121: 81-85.

Yeates L. C. & D. S. Houser. 2008. Thermal tolerance in bottlenose dolphins (Tursiops truncatus). The Journal of Experimental Biology 211: 3249-3257

Zeidberg L. D. & B. H. Robinson. 2007. Invasive range expansion by the Humboldt squid, *Dosidicus gigas*, in the eastern North Pacific. Proceedings of the National Academy of Sciences 104(31):12948-12950.

Zerbini A. N., Secchi E. R., Siciliano S. & P. C. Simões-Lopes. 1997. A review of the occurrence and distribution of whales of the genus Balaenoptera along the Brazilian coast. International Whale Commission Rep. 47: 407–417.

Zerbini, A.N., Waite, J.M., Laake, J.L. & P.R. Wade. 2006. Abundance, trends and distribution of baleen whales off western Alaska and the central Aleutian Islands. Deep-Sea Research 53: 1772–1790.

11. Anexos

Artículos publicados durante el doctorado en los que participo como autor:

Bakun A, Babcock EA, Lluch-Cota SE, Santora C and **CJ Salvadeo**. 2009. “Issues of ecosystem-based management of forage fisheries in ‘‘open’’ non-stationary ecosystems: the example of the sardine fishery in the Gulf of California”. Rev Fish Biol Fisheries. DOI 10.1007/s11160-009-9118-1

Salvadeo CJ, Lluch-Belda D, Gómez-Gallardo A, Urbán-Ramírez J and CD. MacLeod. 2010. Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific. Endangered Species Research DOI: 10.3354/esr00252

Tripp-Valdez MA, Lluch-Cota SE, Del Monte-Luna P and **CJ Salvadeo**. 2010. The importance of grey literature in fisheries ecology: an example based on the throphic role of small pelagic in the Gulf of California. Oceánides 25(1): 59-73.

Del Monte Luna P., Lluch Cota S., **Salvadeo CJ**., Lluch-Belda D. 2011. Ecosystem-level effects of the small pelagics fishery in the Gulf of California. CICIMAR Oceánides. 26: 51-62

Salvadeo CJ, Flores-Ramírez S, Gómez-Gallardo A, MacLeod CD, Lluch-Belda D, Jaume-Schinkel S and J Urbán-Ramírez. 2011. Bryde’s whale (Balaenoptera edeni) in the southern Gulf of California: relationship with climate and prey availability. Ciencias Marinas 37(2): 215-225.

Salvadeo CJ, Daniel Lluch-Belda, Salvador Lluch-Cota & Milena Mercuri. 2011. Review of Long term macro-fauna movement by multi-decadal warming trends in the Northeastern Pacific. Climate Change-Geophysical Foundations and Ecological Effects, ISBN 978-953-307-419-1.

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REVIEW

Issues of ecosystem-based management of forage fisheries in "open" non-stationary ecosystems: the example of the sardine fishery in the Gulf of California

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Abstract The Gulf of California system presents major challenges to the still developing frameworks for ecosystem-based management (*EBM*). It is very much an *open system* and is intermittently subject to important influxes of migratory visitors, including large pelagic predatory fishes and small pelagic forage fishes. These migrants include the more tropical species from the coastal ecosystems to the south and perhaps subtropical sardines and anchovies from the California Current upwelling system. In addition to the multi-annual ENSO-scale and what may seem to be rather erratic episodes of major population incursions, the Gulf presents nonstationary, transient aspects on a variety of longer time scales. Moreover, the removal of top predators by commercial and sport fisheries has introduced trends that must be affecting the entire ecosystem, and certainly the forage fishes that are their major prey base. In addition to size limits, fishing seasons, area closures and license limitations, the fishery is managed by an ad hoc adaptive management system, in which the fishing season can be shortened or additional areas closed to fishing if pre-season exploratory fishing surveys indicate a shortage of small pelagic fishes on the fishing grounds. Whether this system is likely to be sustainable in the long term is difficult to determine, given the potential for rapid changes in the system because of environmental changes and/or feedbacks within the food web. Thus it appears that innovative management frameworks, among other things utilizing the comparative method, may be required in order to determine defensible tradeoffs between precaution and resource utilization.

Keywords Ecology · Management · Environment · Clupeoid fishes · Radical variability · Transient responses · Stock assessment · ENSO

Introduction

Toward ecosystem-based management (EBM) for forage fisheries

Fisheries management has traditionally used regulations such as catch quotas, effort limitations, gear

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restrictions and time/area closures to control fishing mortality, in the belief that there is some optimal level of fishing mortality that will maximize the long term average yield without jeopardizing the sustainability of the fishery. Management benchmarks such as optimal fishing mortality rates and biomass levels, as well as the current status of the population relative to those benchmarks, are calculated within a stock assessment framework that makes mathematical assumptions of strong density dependence and system stationarity, mainly because these assumptions make the resulting predictive models amenable to parameterization with data that can practicably be obtained. But recently, a continuing sequence of unexpected fishery collapses, in many notable cases involving stocks of small pelagic *forage fishes*, has called the basic reliability of these approaches into question, even as the ever lengthening time series of available data exposes significant fallacies in the fundamental assumptions on which they are built (Freon et al. 2005; MacCall 2009).

The concept of ecosystem based management of fisheries (EBM, also called EAF for ecosystem approach to fishing), which has emerged in the past decade largely as a critique of conventional fisheries science and management, calls for a more nuanced understanding of non-stationarities, spatial patterns and dynamics, ecosystem-level processes and feedbacks, and the potential unintended consequences of fisheries removals. According to Pikitch et al. (2004), EBM of fisheries should (1) avoid degradation of ecosystems; (2) minimize the risk of irreversible change to natural assemblages of species and ecosystem processes; (3) obtain and maintain long-term socioeconomic benefits without compromising the ecosystem; and (4) generate knowledge of ecosystem processes sufficient to understand the likely consequences of human actions.

In addition to the usual imperatives of EBM, such as minimizing habitat damage and bycatch of threatened species, an effective EBM system for forage fish would require an understanding of the potential impact of removals of biomass of the forage fish on other components of the food web, either plankton that may be released from predation, or predators such as piscivorous fish, sea birds and mammals that may be forced to change their distribution or switch prey species and could suffer loss of productivity if their forage fish food source is depleted. The EBM system would also need to incorporate an understanding of the mechanisms controlling rapid, radical variations in abundance, distribution and productivity of forage fish populations, and of the relative complexity of the ecosystem interactions and feedbacks these variations may set in motion.

The extreme variability that characterizes small pelagic fish recruitment implies that traditional fishery management measures such as total allowable catch (TAC) quotas based on estimates of long term average yield from stock assessment may not be effective in preventing episodes of serious overfishing. In some small pelagic fisheries, regime specific harvest rates, allowing the fishery to take a larger fraction of the population in more productive regimes, could potentially be effective (Polovina 2005). However, the character of such “regimes”, as well as their duration, is currently confidently definable only after the fact. Katsukawa and Matsuda (2003) suggested requiring a multispecies small pelagic fishery to target only the species that are more abundant each year, to remove pressure from species undergoing a period of low productivity. This approach is complicated by the tendency for less abundant forage fish species to school together with more abundant species (Bakun and Cury 1999) and thus to be equally vulnerable, in a per unit biomass sense, to the same fishing operations. If they could be effectively employed, such management measures might improve long term average yields from some small pelagic fisheries, but they probably cannot eliminate the risk of stock collapse during times of particularly unfavorable environmental conditions. Thus, an effective EBM system for forage fish should be precautionary and as robust as possible with respect to potential uncertainties.

Complex adaptive systems

Marine ecosystems are prime examples of complex adaptive systems (Levin 1998, 1999). They are dynamically nonlinear (Hsieh et al. 2005) and possibilities for self-enhancing nonlinear feedback loops clearly exist (Bakun and Weeks 2006). Perhaps the most fundamental feedback loop may be what Bakun and Weeks called the “*P2P*” (signifying “prey to predator”) *loop* in which the forage fishes impact their potential predators by eating their eggs and larvae.

They offer the analogy of the potential difficulty of maintaining stability in a terrestrial African veldt ecosystem if antelopes and zebras, were themselves voracious carnivores that relentlessly hunted and consumed young lions, leopards and cheetahs that when they were adults would be preying on them. A clue to the unexpected durability of recent collapses of formerly massive stocks of fishes such as cod, in spite of each female spawning literally millions of eggs, might be the subsequent increases of the small pelagic forage fishes which, while being the favored prey of the cod, are particularly adept at filtering cod eggs from the water column as favored food items (Bakun and Weeks 2006; Hjermann et al. 2004).

But forage fish themselves, for which such a *P2P feedback loop* explanation may not be easy to envision, have been susceptible to similar puzzling durability in their stock collapses. For example, both the massive California and Japanese sardine populations literally disappeared entirely from their ecosystems for two full decades before initiating their more recent rebounds, from which the Japanese stock has already experienced a second abrupt collapse. Meanwhile, the Peruvian anchoveta has been battered repeatedly by massive unrestrained fishing, has exhibited multiple significant declines, but has generally rebounded relatively rapidly. Moreover, the intervening periods of lowered anchoveta abundance tended to be significantly counteracted by increases in other forage fish species, such as sardines and the young age classes of jack mackerel. In contrast, the initial collapse of the formerly enormous Southeast Atlantic sardine population operating in the marine ecosystem off Namibia has never recovered to more than 10% of its former magnitude, nor has it been significantly replaced by comparably abundant populations of alternative forage fish species.

To the extent that nonlinear feedbacks (such as *P2P* and others proposed by Bakun and Weeks 2006) are realized, conventional modeling efforts cannot be expected to encompass the full range of possible outcomes and so must fail to be reliably predictive of the very types of radical consequences that may be most important to avoid. However, the dynamic nonlinearities that clearly exist in marine ecosystems (Hsieh et al. 2005), while preventing precise prediction of outcomes of actions taken, evidently do not normally produce utterly chaotic ecosystem responses. Rather, strong regularities such as apparent ocean basin-scale synchronies and rather consistent patterns of species alternations (Bakun 1996, 2005b; Chavez et al. 2003), suggest the action of important regulating and stabilizing mechanisms. As will be discussed in the sections to follow, these must be quite different from the simple density-dependent *carrying capacity*-type arguments that are reflected in the formulation of the classical fisheries management models, even when fisheries models are augmented with nuances such as environmentally-driven recruitment time series.

The ecological role of forage fishes

In most large marine ecosystems (*LME*s) of the world, the biological communities exhibit a striking "*wasp waist*" configuration of their trophic structures (Rice 1995; Bakun 1996, 2006a; Cury et al. 2000). That is, they typically contain (1) a very large number of species at the lower (e.g., planktonic) trophic levels, (2) a large number of species (e.g., predatory fishes, large coelenterates, seabirds, marine mammals, etc.) that, as adults at least, feed near the apex of the foodweb, and (3) a crucial intermediate trophic level, occupied by small, plankton-feeding pelagic *forage fishes*, that is typically dominated by only one, or at most several, species. In such cases, the trophic energy of the system must flow upward from a highly diverse lower-trophic-level complex of species through a very narrow, constricted "chokepoint" in order to become accessible to the highly diverse upper-trophic-level complex of species that depends on it.

For example, the fish biomass of the world's major temperate eastern ocean boundary upwelling systems, as well as the western boundary of the North Pacific, tends to be dominated by a single species of sardine (of the genera *Sardinops* or *Sardina*) and a single species of anchovy (genus *Engraulis*) that have historically tended to alternate in dominance on multi-annual time scales. In other cases, a single anchovy species (e.g., *Engraulis anchoita* in the Falkand/Malvinas Current of eastern South America), or a single menhaden species (e.g., *Brevoortia tyrannus* in the Gulf Stream region off the eastern U.S.) may prevail. Tropical analogs of these temperate ocean ecosystems tend to be dominated by analogous tropical species such as sardinellas (*Sardinella* spp.), anchoviellas (*Anchoviella* spp.) and thread herrings (*Opisthonema* spp.). Other *wasp waist* examples are herring (*Clupea* *harengus. C. pallasii*), sprat (*Sprattus* spp.), capelin (*Mallotus villosus*) or sandeels (*Ammodytes* spp.) of boreal shelf ecosystems. In the Southern Ocean, Antarctic krill (*Euphausia superba*) may represent an invertebrate analog. During high abundance phases, the dominant *wasp waist* species by itself often constitutes the major portion of the total animal biomass of its entire regional ecosystem.

Accordingly, this massive population of *wasp waist* forage fish performs a crucial role in the overall function of its entire ecosystem. Modeling studies (Rice 1995) have confirmed that variations in its abundance and productivity regulate variability in the overall trophic dynamics of these ecosystems. Typically these populations of small pelagic planktivores experience wide inter-annual variability in reproductive success. Because of their short life spans, this results in extreme variability in their population sizes that has major effects on the trophic levels above, which depend on the *wasp-waist* populations as their major food source, and also on the trophic levels below which are fed upon by the *wasp waist* populations. Thus the major control on the productivity of the entire complex of species in these ecosystems may be neither "bottom up" nor "top down" but rather "both up and down from the middle" (Rice 1995; Bakun 1996; Cury et al. 2000; Arreguín-Sanchez et al. 2002).

Another key aspect is that the *wasp-waist* level is the lowest trophic level that is mobile, in the sense that it can expand, contract, or relocate its area of operation according to its own internal dynamical and behavioral responses, which may or may not be keyed to environmental changes (Bakun 2005a, 2006a). A prime example is the well-documented range contraction of the California sardine population after its initial collapse (Fig. 1). Such movements in geographical distribution have the potential to massively alter patterns of population productivities and trophic flow structures in the areas involved.

Accordingly, the proper management of fishery exploitation of these *wasp-waist* forage fishes may be critical for the preservation of the integrity of the total species complex and of the trophic functioning of the overall regional marine ecosystem. As mentioned earlier, conventional fisheries management has experienced notable failures in recent decades, and there is a resulting widespread consensus for a need for more holistic EBM (Pikitch et al. 2004), particularly since demand for forage-fish-based animal and aquaculture feeds is undergoing an explosive growth phase that is expected to continue into the foreseeable future. However, while the drive for EBM is expected to be the single most important influence on development of future assessment and management policies, no EBM approach has yet been applied to any exploited forage fish population in the world (Barange et al. 2009).

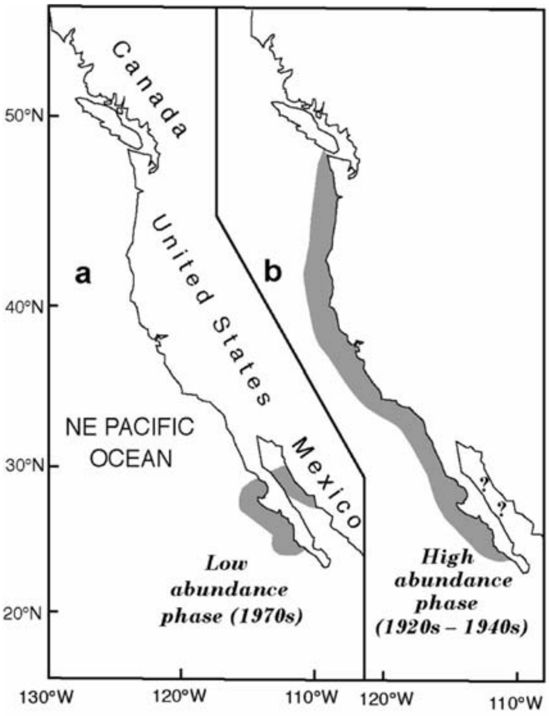

Fig. 1 Changes in distributional extent between high and low abundance phases of sardines (*Sardinops sagax caeruleus*) in the NE Pacific (redrawn from Bakun 2005b)

In this paper, we examine the potential issues involved in terms of a particular regional exploited forage fish population, the sardine (*Sardinops sagax caeruleus*) population of the Gulf of California. This particular ecosystem appears to well represent some key unresolved issues (notably those associated with *nonstationarity* and *system openness*) in EBM of forage fish resources. It also well represents characteristic economic, social and political issues, being an important economic driver for a rapidly developing regional economy. Moreover, the fish stock on which it is based constitutes an important food base for higher trophic level fishes and other charismatic megafauna (García-Rodríguez and Aurioles-Gamboa 2004) that directly underlie additional key economic drivers (eco-tourism, sport fishing, diving, etc.). The Gulf ecosystem itself, for which the sardines and other small pelagics fulfill the *wasp waist* function, currently still represents a priceless remaining “jewel” of the earth’s natural biological heritage, incorporating some of the most pristine natural ecological complexes left on earth, including more than 776 species of macro-invertebrates and 77 species of fish found nowhere else on our planet (Lluch-Cota et al. 2007). Large portions of the total world’s populations of a number of marine bird species breed within the Gulf. There are 36 species of marine mammals occurring here, one (the vaquita *Phocoena sinus*, a critically endangered small porpoise) being found nowhere else. In terms of terrestrial biodiversity, the 922 islands within the Gulf if California host 90 species of endemic plants and animals, including 60 endemic reptile species (Lluch-Cota et al. 2007).

Fig. 2 Bathymetry of the Gulf of California (redrawn from Lluch-Cota et al. 2007)

The Gulf of California

The physical and climatic contexts[1]

The Gulf of California is the eastern Pacific Ocean’s only inland sea. Geologically, it is among the youngest peripheral seas in all the world’s oceans, its mouth having opened as little as 4 million years ago (Oskin and Stock 2003). It is long and narrow, being 1,130 km long and 80–209 km wide and is divided into a series of large deep basins and trenches that deepen to the south (Fig. 2). Maximum depth at the mouth is greater than 3,000 m. The pronounced depth of the southern half of the Gulf, unusual for such a semi-enclosed sea, provides an opportunity for large populations of unexploited small vertically-migrating mesopelagic fishes (e.g., *Benthosema panamense*, *Triphoturus mexicanus* and *Diogenichthys laternatus*), which appear to provide an alternative to small pelagic forage fish for predators such as jumbo squid (*Dosidicus gigas*).

Most of the northern Gulf is less than 200 m deep and experiences large-amplitude tidal effects, the tidal range reaching nearly 7 m near its inner end (Gutiérrez and González 1999). A zone in the vicinity of two large islands, Tiburón and Angel de la Guarda, situated somewhat north of the midpoint of the Gulf is dominated by strong tidal currents and resulting mixing of the water column. One of the great rivers of North America, the Colorado, flows into the Gulf at its upper (northern) end, but that inflow has steadily vanished over the past century as a result of steadily increasing impoundment to supply agricultural irrigation for much of the southwestern USA. The surrounding coastland areas are notably arid, with very little runoff entering from the western (peninsular) side. However, the eastern (continental) side receives significant runoff from continental mountain ranges of the inland interior.

As regards meteorology, winds in the Gulf tend to blow predominantly along its long axis. During the summer they are relatively weak, blowing predominantly from the southeast toward the northwest. However during the winter, winds blow predominantly from the opposite direction, from the head toward the mouth of the Gulf (from northwest to southeast). In the mid-Gulf and southern Gulf zones, the equatorward winds on the eastern side of Gulf continue through April at least (Marinone 2003). This leads to upwelling on the continental side that tends

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[1] Much of the information in this section comes rather directly from the recent multiple-authored review by Lluch-Cota et al. (2007); see references list, below.

to push surface water westward, to then converge and downwell as it approaches the peninsular coast. The southward current (Allen 1973) produced by the upwelling processes occurring at the eastern coast of the Gulf contributes to an anticyclonic (clockwise) circulation south of the big islands, which yields additional upwelling sources around the edges of the eddy (Bakun 2006b), as well as convergence toward the eddy center. Together, these processes yield a configuration called an *ocean triad*, because it comprises an appropriate sequence of *enrichment*, *concentration* and *retention* mechanisms (Bakun 1996, 2006b; Agostini and Bakun 2002) such that the area is a good nursery habitat for forage fish populations. A source of nutrient input (*enrichment*) of comparable importance is the intense tidal mixing that occurs in the vicinity of the big islands (Lluch-Cota et al. 2007). This contributes to the *enrichment* component of the winter *ocean triad* configuration, and in addition, continues to be a vigorous enrichment factor through the year.

Sardine spawning takes place mostly between fall and winter as upwelling extends along the eastern coast of the Gulf (Cisneros-Mata et al. 1995), thereby inserting larvae into the favorable winter–spring triad circulation. One result is the observed accumulation of late larvae and juveniles on the western side of the Gulf during the summer.

The mouth of the Gulf stands directly in the path of polewardly-propagating geophysical waves (Allen 1975) associated with the El Niño episodes that break out intermittently in the equatorial Pacific. During El Niño years, these waves propagate into the Gulf along the continental coast deepening the subsurface thermocline and nutricline and causing a northward flow tendency near the coast. These processes act to suppress the cooling and enrichment effects of the local wind-induced upwelling that occurs during winter in the spawning ground along the eastern coastal boundary of the Gulf. This implied suppression of the productive ocean triad system suggests that sardine reproductive success might tend to decline during annual El Niño episodes, although cooling and enrichment generated by the continuing tidal mixing in the zone near the big islands evidently allows a degree of successful reproduction to continue even under El Niño conditions.

In any case, catches of adult sardines have tended to decline during El Niño years (e.g., 1991/1992 and 1997/1998, Fig. 3). This effect on adults may be due to the action of higher temperatures in diminishing or even suspending the annual southward migration of the sardine within the Gulf, thereby reducing catches in the customary fishing zone of the central Gulf (Lluch-Belda et al. 1986; Huato-Soberanis and Lluch-Belda 1987). This effect on adults could also feed back to poor reproductive success in El Niño years by preventing reproduction in what normally would constitute the most favorable reproductive habitat (Lluch-Cota 2000).

The sardine fishery in the Gulf of California

The Pacific sardine is the dominant species (50–80% of total landings) in a multispecies purse seine fishery that operates from ports in the central and Southern Gulf of California, from November through July (Nevárez-Martínez et al. 1999). Sardines and other small pelagic fishes are also caught in relatively small numbers near the mouth of the Gulf for use as bait by vessels targeting tuna (Rodríguez-Sánchez et al.

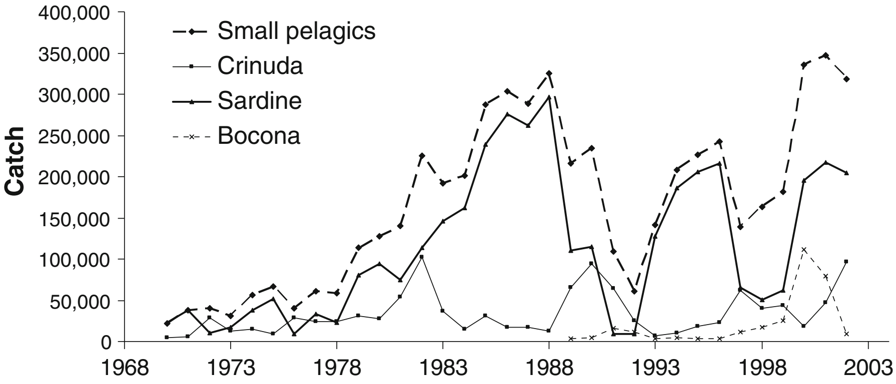

Fig. 3 Annual landings of sardines (tonnes) and other small pelagic fishes in the Gulf of California, redrawn from Lluch-Cota et al. (2007) ["Crinuda": *Opisthonema libertate*, "Bocona": *Cetengraulis mysticetus*]

2003), and there is a developing fishery to supply sardines as feed for tuna farming operations (Dorry et al. 2008). In the directed fishery, about 85% of the total catch is used for reduction to fishmeal, mostly for animal feeds. Sardines are also packed in cans for sale to domestic and foreign markets. During years of poor sardine abundance, its low catches are compensated to some degree by increases of other small pelagic fishes such as the tropical thread herring *Opisthonema libertate* (Lluch-Belda et al. 1989) and, starting in the early 1990s, the tropical anchovy *Cetengraulis mysticetus* (Fig. 3). For this reason, the reduction industry is not as strongly affected by low abundance periods as the canning industry, in which there has historically been a clear preference for sardines (Lluch-Cota et al. 2007).

The fishery for small pelagic fish in the Gulf began in the 1970s, and landings increased to a peak in 1988–1989 of nearly 300,000 tons (Fig. 3), whereupon the fishery collapsed abruptly to less than one-third of that amount the following year. This collapse caused the loss of 3,000 jobs and about half of the fleet and processing plants. (Lluch-Cota et al. 1999). Landings have been highly variable since then, and tropical species of forage fish have become more prevalent in the catch (Fig. 3).

The sardine fishery has been regulated and managed by the federal government of Mexico since 1993 under Norma Oficial Mexicana (NOM) 003-PESC-1993. The NOM recognizes that the abundance of sardine and other small pelagic species fluctuates with environmental conditions but can also be influenced by fishing. The NOM specifies a minimum size limit of 150 mm in length for sardines, regulates fishing gear and fleet capacity, and requires that the fishery be closed in times and areas where the majority of sardines are spawning but does not include total allowable catch (TAC) quotas (NOM 003-PESC-1993). The development of a NOM is a collaborative effort between federal authorities and fishermen organizations and other NGOs, with final approval by Congress (Hernandez and Kempton 2003). The fishery does not yet have a formal fishery management plan, although one is currently being developed as required by the 2007 Ley General De Pesca y Acuacultura Sustentables (Nueva Ley DOF 24-07-2007). Since 1993, the Centro Regional de Investigación Pesquera (CRIP) in Sonora, a branch of the Instituto Nacional de Pesca (INP), has conducted a pre-season exploratory fishing survey in the fishing grounds, in cooperation with the fishing industry, in order to forecast expected catches for the year. If the abundance of fish on the grounds is low, the INP and the industry can agree to more extensive time and area closures.

The small pelagic fishery of the Gulf of California is currently being assessed for potential certification as a sustainable fishery under the Marine Stewardship Council.

EBM for the Gulf of California sardine fishery

The Gulf of California ecosystem has several characteristics that complicate fishery management and that should probably be taken into consideration in efforts to develop an effective system of EBM. The system is open in the sense that it is impacted by wider oceanographic conditions in the surrounding coast, and the movements of animals in response to these conditions. Also, in addition to the fact that the abundance of sardines and other small pelagic fishes varies dramatically at a number of time scales, the Gulf has undergone secular changes over time (non-stationarity) that impact the productivity of sardines. These factors must be taken into account when evaluating the sustainability of the small pelagic fishery. Trophic interactions and the importance of sardines as a source of food for predators should also be incorporated into any EBM system.

System “Openness”

The marine ecosystem within the Gulf is very much an *open system*, having a direct open connection to the wider northeast Pacific Ocean. The mouth of the Gulf itself constitutes the major separation between the Pacific coastal ecosystem extending to the north along the Baja California peninsula, which is strongly affected by coastal upwelling and cool California Current flow, and the coastal ecosystem to the south which reflects a transition to the warmer, more tropical, less upwelling-affected zones to the south. The Gulf ecosystem is intermittently subject to important influxes of migratory visitors, including predators such as tunas, billfishes and jumbo squids, whose incursions may or may not be related to tracking of movements of preferred environmental conditions. There are also major exchanges of small pelagic forage fishes, certainly with the more tropical analog species (*Opisthonema* spp., *Cenengaulis mysticetus*, *Oligoplites* spp.) from the coastal ecosystems to the south, but also perhaps with temperate sardines and anchovies from the California Current upwelling system that extends northward from the Gulf mouth, which the Gulf habitat in many ways mimics. In addition to the multi-annual ENSO-scale and what may otherwise seem to be rather erratic major population incursion episodes, fishing pressure itself could conceivably be involved in inducing migrational episodes via mechanisms such as the one called *school-mix feedback* by Bakun (2005b).

The Pacific sardine fishery in the Gulf of California developed, following the collapse of the Ensenada sardine fishery on the Pacific side of the Baja California Peninsula, to harvest what appears to have been at that time a growing local sardine population within the Gulf itself (Schwartzlose et al. 1999). This was several decades after the initial major collapse of the major northern California Current population of the same species that in the first half of the twentieth century had supported one of the world's great fisheries. By the 1970s, this northern subpopulation of Pacific sardine was entirely unobserved in its previous habitat that had earlier stretched along the open Pacific coastline of North America from the northern part of Baja California all the way to southern Canada (Fig. 1a), and was widely considered to have become permanently extinct (Fig. 1b). Meanwhile, a very much smaller southern California Current subpopulation held on within a lightly exploited refuge on the Pacific side of the southern half of the peninsula of Baja California.

Sardines continued to dominate the catch of small pelagic fishes in the Gulf of California until a major collapse of the fishery occurred in 1990/1991 (Fig. 3). Suddenly, anchovies (*Engraulis mordax*) appeared in abundance, a fish that in the knowledge of the current inhabitants had never before existed there; it is also a fish that in many other temperate coastal ecosystems of the world has exhibited a pattern of intermittently replacing sardines. The first time an anchovy was ever reliably recorded in the Gulf was in 1986 (Hammann and Cisneros-Mata 1989), just as the earlier increasing trend in sardine population abundance had evidently reversed to an abrupt decreasing trend (Nevárez-Martínez et al. 1999). The anchovy population established itself and briefly augmented what remained of the Gulf small pelagic fishery (Lluch-Belda et al. 1992), while sardines nearly disappeared completely from the landings by the 1991/1992 fishing season. But the story did not finish there. In the face of this exploitation, the anchovy population declined quickly, with catches falling to zero in 1996/1997, while the sardine catches increased, supporting a catch of over two hundred thousand tons in 1996/1997 (Fig. 3), the same year that anchovies ultimately entirely disappeared from the catches. Sardine catches increased through 1996/1997, dropped off during the 1997/1998 El Niño (when the adult sardine resource evidently did not collapse but sardine schools were restricted to their usual distribution around the big islands and did not expand south to the customary fishing ground along the eastern coast of the gulf.), stayed low through 2000, and recovered in 2001 and have remained relatively high through the present (Fig. 3, Lluch-Cota et al. 2007).

A subsequent analysis of fish scale deposits in anaerobic sea floor sediments (Holmgren-Urba and Baumgartner 1993) has indicated that this was not the first time anchovies had made an incursion into the Gulf of California, but in fact they had entirely dominated the fish biomass in the Gulf for most of the nineteenth century. Earlier, it had been thought that the Baja California peninsula, extending far south into quite tropical waters, constituted an effective barrier to exchange of temperate sardine and anchovy populations between waters of the Gulf and those of the California Current on the other (Pacific Ocean) side of the peninsula. But recent analysis of catches of these species by the tuna fleet, which uses them as bait, have shown that both species regularly frequent waters well south of the southern extremity of the peninsula (Rodríguez-Sánchez et al. 2003), actually occurring as far south as the Islas Revillagigedo which are some 400 km to the southward of Cabo San Lucas, the southern tip of the Baja Peninsula. In addition, Holmgren-Urba and Baumgartner (1993), in comparing their paleo-sedimentary scale deposit time series for the Gulf to that produced by Soutar and Isaacs (1974) for a California Current site in the Santa Barbara Channel, found indications of migratory shifts between the two systems at multi-decadal periods. Significant amounts of anchovy larvae were again briefly observed in the Gulf during the highly anomalous conditions of the 1997/1998 El Niño, coinciding with near absence of sardine larvae (Sánchez-Velaso et al. 2000).

Jumbo squid may also migrate into the Gulf. These large, extremely mobile, voraciously-feeding invertebrates are the object of a very important fishery in the Gulf. During the extremely intense 1982–1983 El Niño, the jumbo squid virtually disappeared from the Gulf for a number of years well after the El Niño-associated anomalies had retreated and the Gulf had already returned to more "normal" conditions. Later, in 1989 jumbo squid again reappeared in the Gulf, and by 1993 the fishery resumed operations. Catch rapidly increased to 140,000 tons by 1997. Then, in conjunction with another extremely intense El Niño in 1997–1998, the jumbo squid population appears to once again have largely exited the Gulf, with almost no catches being recorded there. Meanwhile, high concentrations of jumbo squid were detected off the west coast of the peninsula (Lluch-Cota et al. 2007), operating in that separated but normally similar coastal upwelling ecosystem, but which, during El Niño conditions, is protected by the barrier of the Gulf entrance from the anomalously high ocean temperatures and poor primary productivity that permeate the interior of the Gulf system.

While some of the above hypothesized migratory movements remain controversial (some experts preferring a scenario of separate populations simply collapsing and rebuilding in place, with apparent synchronies, etc., being coincidence or driven by the same large-scale climatic episodes) they do represent plausible reasons to question the "closed" local system autonomy that is often assumed in the classical models and conventional management methodologies. It is hard to see how the large changes in the catches of anchovies and jumbo squid that have been observed over the last decade could be explained as reflecting population productivity within the Gulf alone. Whether or not sardines themselves migrate into and out of the Gulf of California, the migratory movement of their predators and potentially competing forage fishes could influence the mortality and growth rates of sardines, and their reproductive success. This additional source of variability could bias assessments of stock status and influence the potential sustainability of the fishery.

Nonstationarity

Small pelagic populations are generally variable and subject to periods of low and high abundance, and this is certainly true of Gulf of California sardines. In addition, it appears that the physical–biological system of the Gulf of California may, in a number of respects, conform poorly to the standard assumption of stationarity that provides the rationale for parameterizing conventional models and procedures based on historical time series of data and for establishing rigidly fixed benchmarks and triggers for management actions.

While the relative geological youth of the Gulf of California basin is probably not a significant factor, the nearly total cutoff of Colorado River inflow during the twentieth century is almost certainly relevant, undoubtedly having triggered sequences of transient population responses that are still in the process of unfolding. For example, the evidence for domination of the "*wasp waist*" of the Gulf ecosystem by anchovies during the nineteenth century, and its apparent total absence in the later twentieth century before its brief, rather ethereal reappearance in the 1990s that coincided with the initial sardine collapse, has been discussed in the previous section. Anchovies throughout the world exhibit a generally higher degree of affinity for estuarine-affected habitats than do sardines, perhaps reflective of their much coarser gillraker structures that they employ as food filtering apparatus. While not capable of filtering as small a size of food particles as can sardines, anchovies may be less likely to experience clogging of these structures a result of terrestrial sediment material and other particulate matter characterizing estuarine situations. Note that free flow of water through gill structures is critical also for respiration in these fishes. Thus a question arises as to whether it may have been the cutoff of Colorado River inflow that shifted the advantage at the *wasp waist* of the Gulf ecosystem from anchovies to sardines.

The major physical and biological anomalies affecting the Gulf in association with El Niño events are also certainly initiating transients in the biological/trophic system that play out on a variety of time scales. Moreover, there seems to a relevant longer, not yet totally understood *Pacific regime shift* time scale (~20–60 years), (Chavez et al. 2003; Bakun 2005b) that appears to be more or less linked to variations in the Pacific ocean–atmosphere–climate system that themselves may or may not have cyclic elements (Overland et al. 2009).

Finally, the history of fishing in the region could potentially be causing evolutionary changes in both the small pelagic fishes and their predators. The small pelagic fishery is managed with minimum size limits, so that fishing mortality is higher on large individuals. Harvest, and particularly size selective harvest, has been shown to cause reductions in age and size at maturity and other changes in life history characteristics (Jørgensen et al. 2007). In the lab these heritable changes in growth rates and size at maturity can occur in as little as four generations (Conover and Munch 2002). Such evolutionary changes in life history traits are one possible explanation for the fact that exploited fish populations are often more variable than unexploited ones (Anderson et al. 2008).

Like system openness, non-stationarity can potentially invalidate the stock assessment models used to design fishery management strategies for sardines. In particular, a level of harvest that would be sustainable in one decade may not be sustainable in the next, so that a long term management strategy should be able to adapt to changing conditions.

Stock assessment and status of the sardine population

Unlike many industrial fisheries, management of the small pelagic fishery in the Gulf of California is not based on fisheries reference points calculated through fisheries stock assessment. However, the available stock assessments can be used as a source of information about the productivity of the stock and its ability to sustain fishing pressure, keeping in mind the caveats about system openness, non-stationarity and variability outlined above.

The sardine population has been the subject of several stock assessments in the late 1990s, including a virtual population analysis (VPA) covering the period 1972–1990 (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 1999), which was later updated through 1997 (Nevárez-Martínez 2000), and a statistical catch at age model used for bioeconomic scenario monitoring (de Anda-Montañez and Seijo 1999). Both the highest catch ever recorded (1988/1989) and the subsequent collapse (1991/1992) occurred during this assessed period. The increasing catch between 1983 and 1989 corresponded to an increase in effort with a resulting increase in fishing mortality rate (de Anda-Montañez and Seijo 1999; Nevárez-Martínez 2000). The collapse in 1991/1992 was apparently caused by a combination of several years of low recruitment and severe overfishing (de Anda-Montañez and Seijo 1999). When recruitment started to increase in the late 1990s, apparently because of good environmental conditions, biomass increased with a 1 year time lag (Nevárez-Martínez 2000), as would be expected for a fast growing species like sardines. However, the increase in adult biomass was less than would be expected from the large numbers of juveniles observed in surveys during the late 1990s (Instituto Nacional de la Pesca 2006).

These assessment models appeared to be able to match the observed catch trends fairly well, which is perhaps surprising given that they make the classical stationarity assumptions. Allowance for the fact that environmental factors impact recruitment is included in the models (Nevárez-Martínez 2000; de Anda-Montañez and Seijo 1999), but potential trends in life history characteristics and natural mortality rates are not included. Thus, management benchmarks (e.g., Maximum Sustainable Yield, Instituto Nacional de la Pesca 2006) calculated from these models should be treated with caution.

There is a growing consensus that small pelagic fisheries, because they are short lived, highly dynamic, spatially complex, and influenced by environmental factors and trophic dynamics, cannot be managed based on classical stock assessment techniques. Rather, within-season management measures should be based on direct fishery independent surveys of population abundance and recruitment, such as ichthyoplankton sampling and acoustic methods (Barange et al. 2009). Pre-season experimental fishing surveys of small pelagic catch rates on the fishing grounds are routinely made as part of the management process overseen by the Federal Government of Mexico. Management decisions are made on the basis of these data at quarterly meetings (Instituto Nacional de la Pesca 2006). Size limits, limits on total boat numbers per area, and seasonal areal closures are used as management tools. For example, the western side of the Gulf where juveniles accumulate in the summer season is currently closed to fishing during part of the summer.

In principle, this adaptive management system based on fishery independent surveys is an appropriate method to manage a small pelagic fishery because it allows managers to react quickly to changes in population abundance. However, this system can be expected to work reliably (even in the absence of unexpected shifts in ecosystem configuration) only if time and area closures are sufficiently extensive to constrain or even reduce fishing mortality during periods of low recruitment. If the closures are only used to protect young fish or spawning fish, they may not be sufficient during times of unfavorable oceanographic conditions (de Anda-Martínez and Seijo 1999). The high variability in catches is probably an unavoidable consequence of the dynamic nature of the system (de Anda-Martinez and Seijo 1999). Consequently, economic disruptions such as plants closing and boats entering and leaving the fishery are likely to be a continuing feature of this fishery.

The sustainability of the fishery for sardines will also depend on the dynamics of other small pelagic fish that are caught in the purse seine fishery. Although sardines dominated this fishery in the 1970s and 1980s, thread herring and tropical anchovies have become more important in recent years (Fig. 3). It is unclear whether the increased abundance of these other species in the Gulf releases sardines from fishing pressure or provides an equally beneficial alternative food source for birds and mammals, or whether these species may compete with sardines for food.

Ecosystem role of sardines in the Gulf of California

As a key wasp-waist component of the food web in the Gulf of California, it is expected that changes in the abundance of sardines will influence the abundance of predators such as marine mammals and sea birds, as well as of lower trophic level organisms that either feed upon them or are fed upon by them. Sardines, with their relatively fine gillrakers, are able to feed on phytoplankton as well as zooplankton (van der Lingen 1994). For example, López-Martínez et al. (1999) found 13 genera of phytoplankton and 41 genera of zooplankton in the stomachs of sardines from the central Gulf of California, and that Pacific sardines consumed a wider range of particle sizes than did Northern anchovy or thread herring.

Sardines are an important component of the diet of many commercially and ecologically important fish species in the Gulf of California, including striped marlin (*Tetrapturus audax*, Abitia-Cárdenas 1992), sciaenids, scombrids and carangids (Arreguin-Sanchez et al. 2002). For migratory large pelagic fishes (such as sailfish *Istiophorus platypterus*; Arizmendi-Rodríguez 2004), blue marlin (*Makaira mazara*; Abitia-Cárdenas 1992), and dolphinfish (*Corhyfaena hippurus*; Tripp-Valdez 2005), scalloped hammerhead shark (*Sphyrna lewini* Torres-Rojas et al. 2006), and teutophague cetaceans (Salvadeo 2008), entering the gulf in summer, giant squid is the most important prey. Sardine is a minor component of the diet of the commercially important giant squid, for which mictophids *Benthosema panamense*, *Triphoturus mexicanus* and *Diogenichthys laternatus* represent the major diet component (Markaida and Sosa-Nishizaki 2003; Markaida 2006). Whether sardine abundance influences the abundance of any of these mesopelagic fish species is unknown. It is also possible that decreases in abundance of predators such as tunas and billfishes due to fishing could influence the population dynamics of sardines and other forage fish. For example, yellowfin tuna in the eastern Pacific is currently estimated to be at 36% of its unexploited population (IATTC 2008). The other tunas and the billfishes are less depleted, but the large removals of predator biomass in the region are likely to have impacts throughout the food web.

Sardines and other small pelagic fishes are prey for brown pelicans (*Pelecanus occidentalis*; Jiménez-Castro 1988), blue-footed (*Sula nebouxii*; Castillo-Guerrero 2003) and brown boobies (*S. leucogaster*; Mellink et al. 2001; Suazo-Guillén and Mellink 2004), which have their largest breeding colonies in the Gulf of California, as well as Heermann's gulls (*Larus heermanni*) and elegant terns (*Sterna elegans*), both of which are quasi-endemic with more than 90% of their breeding populations in the Gulf. The diet and breeding success of these birds is dependent on sardine abundance, so much so that Velarde et al. (2004) could predict both catch per unit effort (CPUE) and total catch of sardines in the fisheries of the Central Gulf with models that included the proportion of sardines in the diet of elegant terns and the breeding success of Heerman's gulls at a breeding colony in the same region. Velarde et al. (2004) proposed using these predictions to inform management of the fishery.

For some cetaceans, small pelagic fishes are the major diet component, particularly for the small odontocetes (*Delphinus* sp.), the most abundant cetaceans in the Gulf (Salvadeo 2008), and *Balaenoptera edeni* (Urbán and Flores 1996). Other odontocetes feed mostly on giant squid (pilot *Globicephala macrorhynchus* and sperm *Physeter macrocephalus* whales, Jaquet and Gendron 2002), or zooplankton (blue whale, *Balaenoptera musculus*).

Distributions of many of the species that prey on sardines are quite variable from 1 year to the next. For example, Bryde's whale (*Balaenoptera edeni*), common dolphin (*Delphinus delphis*), blue-footed booby and brown booby were more abundant in the Canal de Ballenas in the Central Gulf of California during the 1983 El Niño than in subsequent years (Tershy et al. 1991), which the authors attributed to the fact the this area has high productivity irrespective of the ENSO cycle and might therefore serve as a refuge from adverse conditions.

Sardines are an important component of California sea lion (*Zalophus californianus*) diets at places and seasons when sardines are abundant, such as near Angel de la Guarda and Isla Tiburon in the summer (García-Rodríguez and Aurioles-Gamboa 2004). There is some evidence of correlation between sardine abundance and sea lion pup counts, implying the possibility of bottom up control of sea lion populations (Lluch-Cota et al. 2007). Because sea lions are dependant on the availability and quality of food that they can find within range of their rookeries, changes in sardine distribution can have a profound effect on their production. The California sea lions in the Gulf of California are genetically distinct from the population off the coast of the USA (Maldonado et al. 1995). The population has declined by 20% over the last 20 years (Szteren et al. 2006) with 8 of the 13 colonies showing a declining trend, including all but one of the colonies in the Central Gulf. On the other hand, a recent population viability assessment (PVA, Gonzalez-Suarez et al. 2006) found that the population was likely to be increasing, although this result depended on the assumptions made about movements between breeding colonies, with greater isolation of breeding colonies increasing vulnerability.

Finally, the small pelagic fishery could directly impact populations of other species through bycatch. Purse seine fisheries for small pelagic fishes tend to have very low levels of bycatch of other fish and invertebrate species (Kelleher 2005). Vessels have been observed discarding some of their catch of sardines when the fish are too small, or the haul is too large to fit in the hold of the vessel, and there is also a small amount of bycatch of giant squid and triggerfish (Balistidae, Instituto Nacional de la Pesca 2006). Although no observer data exist from the Gulf of California fishery, bycatch of fishes is not expected to be significant. No data are available on interactions between the small pelagic fishery and protected species of mammals and sea birds, but there is some concern that California pelicans and common dolphins may be caught (Dorry et al. 2008). The sardine fishery does not overlap with the range of the endangered vaquita (*Phocoena sinus*), which is found only in the Northern Gulf (Rojas-Bracho et al. 2006).

Sustainability in the long term

The previous section discussed the potential for sustainable EBM of sardines in the Gulf of California, given our understanding of the dynamics of the system at present. To develop a management system that is sustainable in the long term it is necessary to evaluate the potential that the ecosystem will change drastically, and perhaps irreversibly, due to climate change or feedbacks within the food web. One basis for forecasting potential outcomes in the Gulf system is to look at what has happened in comparable systems throughout the world.

Comparative eco-dynamics

The proximity of the upwelling system in the Gulf of California to a rather more temperate upwelling system (the California Current system that stretches far northward along the outer Pacific coast) resembles quite similar dual-system configurations situated off the west coasts of South America and southern Africa that feature nearly identical *wasp-waist* species complexes (Bakun 1996).

The Humboldt Current LME contains two quasi-autonomous upwelling systems, a more temperate one located off central and northern Peru that features strong upwelling occurring year round but with peak upwelling intensity during austral winter, and a more seasonal upwelling system extending along the coast of Chile, peaking in intensity during austral spring or summer. The Benguela Current LME of the SW Atlantic is made up of the Northern Benguela upwelling system off Namibia and southern Angola, and the Southern Benguela upwelling system off the nation of South Africa. Upwelling in the northern Benguela system continues throughout the year, peaking in intensity in austral winter, while in the southern Benguela it is much more seasonal, peaking in austral spring and summer. Exchanges of sardine and anchovy stock components between the Peruvian and Chilean systems are obvious during El Niño episodes. Similar exchanges between the two Benguela systems are likely, but have not been so obvious. Strong dynamic similarities of these three "doublet" system configurations extend to include rather precisely congruent patterns of seasonalities of the upwelling processes.

However, beneath the striking patterns of similarity lie enormous differences in fishery productivity and evident system resilience. The Peruvian upwelling system is the undisputed world's champion producer of exploited fish biomass. For example, in the late 1960s, the single country, Peru, exploiting a single fish species, the anchoveta (*Engraulis ringens*), routinely landed more fishery tonnage than the combined total of all the other fished species, both marine and freshwater, landed by all the other countries of North and South America combined. In seeming paradox, the Humboldt system appears to be less productive in terms of primary productivity than the Benguela systems. In fact, a recent study by Carr (2001) indicates that it may be only half as productive as the Benguela system. Nonetheless, the Benguela system produces less than one-twentieth the tonnage of fish routinely harvested from the Humboldt system. Moreover, while the Peruvian system has apparently managed to absorb all the blows that a massive, largely unregulated fishing industry could deliver, massive fishing by mobile fleets in the 1970s produced a collapse of the northern Benguela sardine stock and evidently switched that stock to a low productivity mode from which it has not recovered to this day.

Bakun and Weeks (2008) concluded that this "miracle of Peru" might be understood as a combination of two factors. The first is the advantageous low-latitude situation of Peru that combines strong upwelling-based nutrient enrichment with low wind-induced turbulence generation and relatively extended mean "residence times" within the favorable upwelling-conditioned near-coastal habitat. The second involves the rather novel inference that El Niño events, which are widely considered the to be the bane of the Peruvian marine ecosystem, may in reality be a unique boon in that the cyclic "resetting" of the system by temporarily destructive El Niño perturbations serves to interrupt malignant growth of adverse self-amplifying feedback loops (Bakun and Weeks 2006) within the nonlinear biological dynamics of the ecosystem.

In the contrasting case of the Northern Benguela, Bakun and Weeks (2006) argue that this ecosystem has been shifted to, and durably trapped within, an "adverse" phase, ultimately due to massive overfishing by distant-water fleets in the 1970s, that initiated a sequence of adverse nonlinear feedback loops that finally led to a degraded system that no longer favors reproductive success to the degree that it had formerly. Among the suggested factors were: (1) destruction of migratory linkages that had earlier permitted synergistic use of specialized subregional segments of the regional habitat, (2) associated removal of grazing control, allowing burgeoning planktonic growth, (3) resulting explosive proliferation of rapid-responding, opportunistic zooplanktivores, (4) ultimate infestation of the fish reproductive habitats by the zooplanktivores, with extremely destructive predation on fish eggs and larvae as a consequence.

Being located on the eastern side of the Pacific and therefore similarly directly in the path of ocean-transmitted ENSO effects, the Gulf of California system may be more similar to the Peru system in its intermittent perturbation by El Niño-associated environmental anomalies. Indeed, the Gulf of California sardine fishery appears to have rebounded very quickly from its major collapse episode in its brief history. This might be grounds for a degree of cautious optimism. However, the Gulf of California ecosystem is quite dissimilar to Peru, and also to the northern Benguela, as regards the magnitude of its fishery production. On the other hand, to this date, damaging jellyfish infestations have not appeared to be a major problem in the Gulf of California (although there seems to be a sense that jellyfish may be increasing in abundance even in the face of a growing fishery on them in the Gulf). Thus, a long term EBM strategy for the Gulf should probably involve monitoring for increases in jellyfish or other signs that the system is moving toward a drastic change in configuration, similar to the Benguela example.

Climate change: what might the future hold?

Climate change is likely to influence the Gulf of California and its fisheries through alteration of the upwelling system in the Gulf itself, and through changes in the ENSO (El Niño Southern Oscillation) process. One of the reasons that coastal upwelling tends to be a spring-summer phenomenon in the subtropics, and a more year-round phenomena in more near-equatorial regions such as Peru, is that a strong pressure gradient forms between a thermal low pressure cell that develops over the heated land surface and higher pressure existing over the more slowly warming waters of the ocean. This cross-shore pressure gradient supports an alongshore wind that drives an offshore-directed Ekman transport of the ocean surface layer which in turn, requires upwelling of subsurface waters to balance the surface water export.

Eastern sides of oceans are characterized by much drier atmospheres than western sides. Because the most important greenhouse gas in the earth's atmosphere is water vapor, eastern ocean boundary regions tend naturally to experience a much reduced greenhouse effect. Consequently, nighttime cooling by long wave radiation is rapid and efficient. This tends to relax the thermal low pressure cells that had built up over the coastal landmass during the day. But as atmospheric greenhouse gas content increases, nighttime radiative cooling is suppressed and the average rate of heating over the land is further enhanced relative to that over the ocean, causing intensification of the low pressure cells over the coastal interior. This generates a feedback sequence as the resulting pressure gradient increase is matched by a proportional wind increase, which correspondingly increases the intensity of the upwelling in a nonlinear manner (Trenberth et al. 1990) which, in concert with ocean surface cooling produced by the intensified upwelling, further enhances the land-sea temperature contrast, the associated cross-shore pressure gradient, the upwelling-favorable wind, and so on. Moreover an additional contributing set of feedback mechanisms involves greenhouse-associated effects on the vegetal land cover that may regulate the heating of the coastal landmass (Diffenbaugh et al. 2004). A variety of observational evidence indicates that this projected increase in upwelling intensity, intensified by climate change, may even now be in the process of unfolding in the major upwelling regions of the world (Bakun 1990, 1992; Shannon et al. 1992; Schwing and Mendelssohn 1997; Mendelssohn and Schwing 2002).

One would expect that climate change might act to intensify the low pressure over the Sonora coastlands along the eastern side of the Gulf, at least during the spring and summer heating seasons. This would favor upwelling intensification along the eastern side. But it would also tend to increase the monsoon effect of the thermal heating of the continental landmass to the north, which tends to induce southerly winds in the Gulf. Thus, it is not clear which effect would predominate, although one could guess that the summer monsoon effect would be strongest in the northern Gulf, while the upwelling-intensifying effect might act strongest in the mid- and southern Gulf.

On a much larger, Pacific-basin scale, growing evidence, modeling findings, and resulting scientific consensus (e.g., Vecchi et al. 2006; Vecchi and Soden 2007) predicts, as a result of continued buildup of greenhouse gases in the earth's atmosphere, relaxation of the Pacific trade wind system, which is a key dynamic "player' in the ENSO system that produces the most intense perturbations of conditions in the Gulf of California. Thus, the Pacific equatorial system, due to relaxation of the trade wind circulation, may become in some ways more chronically "El Niño"-like in its underlying mean background state. Accordingly, while long-term mean seasonal conditions may be expected to become more chronically El Niño-like, the El Niño-associated anomalies transmitted to the Gulf of California can be expected to be less intense. These El Niño-like conditions could be more favorable to more tropical species of forage fish, and less favorable to sardines.

How these competing effects might play out in the future is unclear. But it does seem abundantly clear that rapid unidirectional climate change caused by continued increasing releases of greenhouse gases must be considered yet an additional source of uncertainty and potential peril with respect to EBM of the fishery on small pelagic forage fish, as well as other fisheries and various other types of ecosystem values that may be linked to processes occurring at the *wasp waist* of the marine ecosystem in the Gulf of California.

Discussion

In summary, small pelagic forage fish populations are well known for their extremely variable population dynamics. This variability may be a key element in their evolved ability to interrupt incessant growth of predation pressure. Fisheries management has not been effective in controlling the radical fluctuations of exploited populations of forage fish; in fact, harvested populations are generally more variable than unexploited ones (Hsieh et al. 2006; Brander 2005). This variability has economic consequences in that fishery yields tend to be variable and difficult to predict. The natural variability of forage fish populations, and their high productivity and fast growth rates, allow forage fish populations, after they have been depleted, to recover more rapidly than slower growing and more stable fish populations (Hutchings 2001). This implies that the risk of permanently harming a forage fish population (and consequently the surrounding ecosystem) through overfishing are lower than for other kinds of fish. But a worrying counter-example is the case of the Namibian sardine, where over-fishing in the 1970s seems to have durably transformed that ecosystem to a degraded state of reduced fishery productivity that has featured a major shift from dominance by sardines to dominance of the "*wasp waist*" trophic level by jellyfish and pelagic gobies (*Sufflogobius bibarbatus*). Unfortunately, the question of what causes a pelagic marine ecosystem to "cross the line" to such a state of durable degradation is currently unanswered.

Marine ecosystems may operate to more or less degree as complex *adaptive systems*, and under this awkward reality, approaches that are designed to identify the most likely outcome of actions or events may entirely miss the less likely, but highly radical, outcomes that may lurk hidden in the "tails" of the probability distributions; even if such a radical outcome may be less likely in any particular case, it may be potentially so critical that the need to avoid it may predominate in importance over any other issue. Examples of this nature might be calamitous system transitions to widespread anoxia (Weeks et al. 2004; Chan et al. 2007) or durable infestation with medusas or other jelly predators (Daskalov 2002; Dumont and Shiganova 2003; Lynam et al. 2006) that may preclude reproductive success of *wasp waist* forage fish species that are vital to maintenance of a diverse, productively-functioning ecosystem, but in particular, to controlling the mechanisms that may generate such transitions (Bakun and Weeks 2006, 2008; Richardson et al. 2009).

Because no one system is so well understood that the probability of a transition to an unfavorable state can be confidently estimated, it will be necessary to look beyond one's particular local ecosystem in order to begin to discern such a probability distribution of a range of potential outcomes. The great evolutionary biologist, Ernst Mayr, has called the *comparative method* and the better known *experimental method* the "two great methods of science" (Mayr 1982). The comparative method is the method of choice when experimental controls are unavailable. Large marine ecosystems and large, mobile fish populations, are hardly amenable to experimental controls, and so the *comparative method* is the available alternative.

In such a case, it may be considered a high priority to assemble available experience and observations according to a well-founded comparative framework categorized as to ecosystem type and function. This would not only provide a basis for conceiving outcomes that may not have yet occurred in a system of interest, but would serve as a basis for convincing stakeholders of the importance of taking sufficient actions to guard against the worst of these, even if their likelihood may be undemonstrated in their local situation. Of course, the balance between precaution and use is always a value judgment. But it is also true, that politics works, not necessarily on the basis of proven facts, but on the basis of narratives. The extent that marine ecosystems may be preserved may depend significantly on the availability of such precautionary narratives.

The examination of the case of the sardine fishery in the Gulf of California has pointed to a number of potentially important elements of such narratives. System openness and nonstationarities have clearly emerged as important factors in interpreting available information. Effects of possible short-time-scale evolutionary adaptation appear to deserve attention. The details of the physical processes controlling ecosystem function are important. Successful management strategies for other small pelagic fisheries have been based on either the ability to forecast year class strength based on environmental conditions or (more commonly) on same-season estimates of abundance from surveys. These types of approaches, in contrast to classical stock assessment, allow management to adapt to the changing abundance of the target species (Barange et al. 2009).

The current management of the sardine fishery in the Gulf of California does appear already to include several essential EBM elements. For example, design of currently established areal fishery closures is evidently based on understanding of physical ecosystem processes and knowledge of life cycle processes and spatial habitat use by the fish stock. Most importantly, efforts are made to monitor, at least roughly, stock abundance prior to each fishing season. This may be sufficient to identify major problems before the situation may be further degraded by uninformed actions, provided that appropriate management actions are taken based on this information. The fact that the sardine catches continue to rebound in the face of an unrelenting level of fishing offers a plausible argument that this approach may have worked, at least so far. On the other hand, there is evidence, even for highly variable and productive forage fish species, that the lower a population falls during a stock collapse, the longer it will take to recover (Hutchings 2001). Reduced fishing mortality during the recovery phase may not be as effective at speeding recovery (Hutchings 2001), implying that it is better to reduce fishing during stock declines to speed subsequent recovery. Whether the ad hoc adaptive management strategy currently used for Gulf of California sardines reduces mortality sufficiently during periods of low stock productivity or whether management of the small pelagic fishery in the Gulf of California could be improved with more formal science-based harvest control rules cannot be known without an updated assessment that adequately accounts for the temporal and spatial complexity of the system.

The dynamics of the food web in the Gulf of California also merit further research, to determine whether the small pelagic fishery adversely impacts other species. The ecological importance of sardines and other small pelagic fishes as food for breeding populations of birds and mammals and potentially as grazers controlling phytoplankton growth underscore the importance of an ecosystem based approach to management of these fisheries. Considerable data exist on the diets of predators, so that it may be possible to develop a detailed trophic model for the pelagic ecosystem in the Gulf of California. Such an analysis, particularly if it was spatially explicit, would be useful for evaluating the ecosystem impacts of the small pelagic fishery.

Even if the fishery appears to be sustainable in the short term, a more elaborate system of ecosystem observations (to try to keep track of any potential expansion of zones of anoxia or of incipient increases of “jelly predators”) may be warranted, given the potential importance of associated consequences. Effective arguments for the necessary resources to accomplish this may depend on availability of a well-founded, abundantly-exemplified, broadly-based interregional comparative framework, as argued earlier. Accordingly, assembly of such a framework would seem to be a high priority. Broadly-based international collaborative efforts, and willingness to share what might be considered proprietary information, would probably be vital in accomplishing it.

Summary comments and opinions

In summary, it must be said that sustainable management of small pelagic fisheries in situations such as that of the sardine in the Gulf of California remains, at the present state of our science, somewhat of a “wing and a prayer” proposition. It appears probable that such resource populations would vary radically even in the absence of fishing.

In any ecosystem, the natural population increases of top predators must eventually be limited by “carrying capacity”, i.e., limited ultimately by absence of sufficient food. In general terms, coastal upwelling ecosystems are the most productive type of ecosystem existing in the world’s oceans, but they also tend to be the ones characterized by the most radical variability. Thus, when more or less inevitable starvation-related mortality of charismatic top predator fauna (e.g., seabirds, marine mammals, etc.) may occur in an upwelling situation, particularly one like the Gulf of California that is also subject to intense Pacific ENSO variability, it is likely to occur in rather massive, highly visible surges. But, however distressing, such episodes may be a necessary feature of such ecosystems (in much the same way that periodic forest fires have been found to be essential features of healthy forest ecosystems).

That being admitted, it is undeniable that modern industrial fisheries powered by fossil fuels ultimately have the capacity, if unchecked, to utterly devastate the structure and productivity of marine ecosystems, thereby depriving society of economic, cultural, and esthetic goods and services that we have come to accept as part of our natural patrimony. Therefore, we must require that these fisheries be managed as effectively as possible for the common good.

In the case of the Gulf of California sardine fishery, the management framework, based on in season estimation of abundance at the fishing grounds and biologically reasonable closed areas and seasons, seems to be adaptive. However, in the absence of a published fishery management plan and up-to-date stock assessments of the major species, it is difficult to tell whether the actual management measures that are taken every year are sufficient to sustain the resource and achieve the broader objectives of ecosystem based management. Management of this fishery currently employs basic but useful elements that can be implemented without enormously increased expenditures on detailed assessments of variabilities of both exploited and unexploited (e.g., jellyfish, mesopelagic fish, temporary migratory “visitors”, marine mammals and birds etc.) components, i.e., those made by much richer, more technologically-endowed regions. On the other hand, it presently is not well documented as to how management measures (i.e., size and location of aerial closures) are determined. Moreover, production of updated formal stock assessments of major exploited components, etc., could yield an additional useful source of accessory information on the stocks themselves, as well as on ecosystem linkages and apparent consequences. In the Gulf of California case, the existence of alternate trophic pathways through the “*wasp waist*” (forage fish-dominated) “chokepoint” of the ecosystem, as well as the history of resilience of other ecosystems (e.g., Peru) similarly impacted by radical ENSO-related variability, may offer some degree of reassurance.

However, lurking always in the background is our lack of real understanding of the sort of radical shift that (as described in System “Openness”) after an episode of extended heavy overfishing, left the Northern Benguela ecosystem in a durable state of seriously degraded fishery productivity. Avoiding this type of regrettable consequence must certainly be a first goal of management. But unfortunately, we don’t have available a very good “road map” of the way to do it.

Clearly, our science as a whole is in need of improved technological and conceptual tools. Due to old assumptions as to the nature of the problems, it has become the pervasive custom to regionalize fisheries-related research, and thus to fund scientific development only in terms of value to a specific regional situation. This has left fisheries science largely without the resources to effectively address globally-pertinent generic issues that we are coming to recognize as recorded historical time series become longer and experiences, both positive and negative, multiply (other than via the favorable trend toward a growing number of international comparative symposia that at least allow sharing of regional information). Accordingly, we are forced to continue to rely on the old assumptions even as we are led by our experience to question them. This puts us in the uncomfortable position of being without definite answers to serious questions, often leaving the central questions as to appropriate tradeoffs between precaution and utilization to be issues more of conceptual beliefs, philosophy, and ethics, than of hard science.

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References

Abitia-Cárdenas LA (1992) Espectro trófico energético del marlin rayado *Tetrapturus audax* (Philippi, 1887) Y marlin azul *Makaira mazar* (Jordan y Snider, 1901), del area de Cabo San Lucas, B.C.S., México. Tesis de Maestría CICIMAR-IPN, La Paz, B.C.S., México

Agostini VN, Bakun A (2002) “Ocean Triads” in the Mediterranean sea: physical mechanisms potentially structuring reproductive habitat suitability (example application to European anchovy, *Engraulis encrasicolus*). Fish Oceanogr 11:129–142. doi:10.1046/j.1365-2419.2002.00201.x

Allen JS (1973) Upwelling and coastal jets in a continuously stratified ocean. J Phys Oceanogr 3:245–257. doi:10.1175/1520-0485(1973)003<0245:UACJIA>2.0.CO;2

Allen JS (1975) Coastal trapped waves in a stratified ocean. J Phys Oceanogr 5:300–325. doi:10.1175/1520-0485(1975)005<0300:CTWIAS>2.0.CO;2

Anderson CNK, Hsieh CH, Sandin SA, Hewitt R, Hollowed A, Beddington J, May RM, Sugihara G (2008) Why fishing magnifies fluctuations in fish abundance. Nature 452:835–839. doi:10.1038/nature06851

Arizmendi-Rodríguez DI (2004) Hábitos alimenticios del pez vela *Istiophorus platypterus* (Shaw y Nodder, 1791) en el área deMazatlán Sinaloa, México. Tesis de Maestría CICIMAR-IPN, La Paz, B.C.S., México

Arreguín-Sanchez F, Arcos E, Chavez EA (2002) Flows of biomass and structure in an exploited benthic ecosystem in the Gulf of California, Mexico. Ecolog Mod 156:167–183. doi:10.1016/S0304-3800(02)00159-X

Bakun A (1990) Global climate change and intensification of coastal ocean upwelling. Science 247:198–201. doi:10.1126/science.247.4939.198

Bakun A (1992) Global greenhouse effects, multi-decadal wind trends and potential impacts on coastal pelagic fish populations. ICES Mar Sci Symp 195:316–325

Bakun A (1996) Patterns in the Ocean: Ocean Processes and Marine Population Dynamics. University of California Sea Grant, San Diego, California, USA, in cooperation with Centro de Investigaciones Biológicas de Noroeste, La Paz, Baja California Sur, Mexico, 323 pp

Bakun A (2005a) Seeking an expanded suite of management tools: implications of rapidly-evolving adaptive response mechanisms (e.g., "school-mix feedback"). Bull Mar Sci 76:463–483

Bakun A (2005b) Regime shifts, Ch. 25. In: Robinson AR, Brink K (eds) The sea, vol 13. Harvard University Press, Cambridge, pp 971–1026

Bakun A (2006a) Wasp-waist populations and marine ecosystem dynamics: navigating the "predator pit" topographies. Prog Oceanogr 68:271–288

Bakun A (2006b) Fronts and eddies as key structures in the habitat of marine fish larvae: opportunity, adaptive response and competitive advantage. Sci Mar 70(S2):105–122. doi:10.3989/scimar.2006.70s2105

Bakun A, Cury P (1999) The "school trap": a mechanism promoting large-amplitude out-of-phase population oscillations of small pelagic fish species. Ecol Lett 2:349–351. doi:10.1046/j.1461-0248.1999.00099.x

Bakun A, Weeks SJ (2006) Adverse feedback sequences in exploited marine ecosystems: are deliberate interruptive actions warranted? Fish Fish 7:316–333. doi:10.1111/j.1467-2979.2006.00229.x

Bakun A, Weeks SJ (2008) The marine ecosystem off Peru: what are the secrets of its fishery productivity and what might its future hold? Prog Oceanogr 79:290–299. doi:10.1016/j.pocean.2008.10.027

Barange M, Bernal M, Cercole MC, Cubillos L, Cunningham CL, Daskalov GM, de Moor CL, De Oliveira JAA, Dickie-Collas M, Hill K, Gaughan DJ, Jacobson LD, Köester FW, Masse J, Nishida H, Ñiquen M, Oozeki Y, Palomera I, Saccardo SA, Santojanni A, Serra R, Somarakis S, Stratoudakis Y, Uriarte A, van der Lingen CD, Yatsu A (2009) Current trends in the assessment and management of small pelagic fish stocks, Chapter 9. In: Checkley DM Jr, Alheit J, Oozeki Y, Roy C (eds) Climate change and small pelagic fish. Cambridge University Press, Cambridge, pp 191−255

Brander KM (2005) Cod recruitment is strongly affected by climate when stock biomass is low. ICES J Mar Sci 62:339–343. doi:10.1016/j.icesjms.2004.07.029

Carr ME (2001) Estimation of potential productivity in eastern boundary currents using remote sensing. Deep-Sea Res 49:59–80. doi:10.1016/S0967-0645(01)00094-7

Castillo-Guerrero JA (2003) Respuestas del bobo de patas azules (*Sula nebouxii*) a las características del hábitat, con énfasis en las relaciones interespecíficas, en isla El Rancho, Sinaloa, durante la temporada reproductiva 2003. Tesis de Maestría. CICESE, Ensenada, México, 98 pp

Chan F, Barth JA, Lubchenco J, Kirinich A, Weeks H, Peterson WT, Menge BA (2007) Emergence of anoxia in the California current large marine ecosystem. Science 319:920. doi:10.1126/science.1149016

Chavez FP, Ryan J, Lluch-Cota SE, Niquen CM (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299:217–221. doi:10.1126/science.1075880

Cisneros-Mata MA, Nevárez-Martínez MO, Montemayor-López G, Santos-Molina JP, Morales R (1991a) Pesquerías de sardina en el golfo de California 1988/1989–1989/1990. Instituto Nacional de la Pesca-CRIP Guaymas, Guaymas

Cisneros-Mata MA, Nevárez-Martínez MO, Montemayor G, Santos JP, Morales R (1991b) Pesqueria de la sardina en el Golfo de California 1988/1989 1989/1990. Boletin del Centro Regional de Investigacion Pesquera de Guaymas. Guaymas, Sonora: Instituto Nacional de Pesca, Secretaria de Pesca, 80 pp

Cisneros-Mata MA, Hammann MG, Nevárez-Martínez MO (1995) The rise and fall of the Pacific sardine, *Sardinops Sagax* caeruleus in the Gulf of California. Mex Cal Coop Ocean Fish 36:136–143

Conover DO, Munch SB (2002) Sustaining fisheries yields over evolutionary time scales. Science 297:94–96. doi:10.1126/science.1074085

Cury P, Bakun A, Crawford RJM, Jarre-Teichmann A, Quiñones RA, Shannon LJ, Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES J Mar Sci 210:603–618. doi:10.1006/jmsc.2000.0712

Daskalov GM (2002) Overfishing drives a trophic cascade in the Black Sea. Mar Ecol Prog Ser 225:53–63. doi:10.3354/meps225053

de Anda-Montañez A, Seijo JS (1999) Bioeconomics of the Pacific sardine (*Sardinops sagax*) fishery in the Gulf of California. CalCOFl Rep 40:170–178

Diffenbaugh NS, Snyder MA, Sloan LC (2004) Could CO2-induced land-cover feedbacks alter near-shore upwelling regimes? Proc Natl Acad Sci USA 101:27–32. doi:10.1073/pnas.0305746101

Dorry N, Cufone M, Mossness A, Hocevar J, Shapson M, Gormen PL, Pagano L, Ayers J, Mann C, Keifer R, Navarro Barnetche A (2008) Letter from the NGO community to the Marine Stewardship Council

Dumont H, Shiganova T (2003) The invasion of the Black, Mediterranean and Caspian Seas by the ctenophore, *Mnemiopsis leidyi*: a NATO Workshop held in Baku (Azerbaijan) on 24–26 June 2002. Globec International Newsletter 9(1): 13–20. http://web.pml.ac.uk/globec/products/newsletter/newsletter.htm Accessed 4 May 2009

Freon P, Cury P, Shannon L, Roy C (2005) Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes. Bull Mar Sci 76:385–462

García-Rodríguez FJ, Aurioles-Gamboa D (2004) Spatial and temporal variation in the diet of the California sea lion (*Zalophus californianus*) in the Gulf of California, Mexico. Fish B-NOAA 102:47–62

Gonzalez-Suarez M, McCluney KE, Aurioles D, Gerber LR (2006) Incorporating uncertainty in spatial structure for viability predictions: a case study of California sea lions (*Zalophus californianus californianus*). Anim Conserv 9:219–227

Hammann MG, Cisneros-Mata MF (1989) Range extension and commercial capture of the northern anchovy, *Engraulis mordax* Girard, in the Gulf of California, Mexico. Calif Fish Game 75(1):49–53

Hernandez A, Kempton W (2003) Changes in fisheries management in Mexico: effects of increasing scientific input and public participation. Ocean Coast Manage 46:507–526. doi:10.1016/S0964-5691(03)00032-2

Hjermann DO, Stenseth NC, Otterson G (2004) The population dynamics of Northeast Arctic cod (*Gadus morhua*) through two decades: an analysis based on survey data. Can J Fish Aquat Sci 61:1747–1755. doi:10.1139/f04-115

Holmgren-Urba D, Baumgartner TR (1993) A 250-year history of pelagic fish abundances from the anaerobic sediments of the central Gulf of California. Cal Coop Ocean Fish 34:60–68

Hsieh C, Glaser SM, Lucas AJ, Sugihara G (2005) Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. Nature 435:336–340. doi:10.1038/nature03553

Hsieh CH, Reiss CS, Hunter JR, Beddington JR, May RM, Sugihara G (2006) Fishing elevates variability in the abundance of exploited species. Nature 433:859–862. doi:10.1038/nature05232

Huato-Soberanis L, Lluch-Belda D (1987) Mesoscale cycles in the series of environmental indices related to the sardine fishery in the Gulf of California. Cal Coop Ocean Fish 28:128–134

Hutchings JA (2001) Influence of population decline, fishing and spawner variability on the recovery of marine fish. J Fish Biol 59(supplement A):306–322. doi:10.1111/j.1095-8649.2001.tb01392.x

IATTC (2008) Tunas and billfishes in the Eastern Pacific Ocean in 2006. IATTC Fishery Status Report No. 5

Instituto Nacional de la Pesca (2006) Peces Pelágicos Menores. In: Sustentabilidady Pesca Responsable en México:Evaluación y Manejo. Secretaria Deagricultura, Ganaderia,Desarrollo Rural, Pesca Y Alimentación, pp 263–302

Jaquet N, Gendron D (2002) Distribution and relative abundance of sperm whales in relation to key environmental features, squid landings and the distribution of other cetacean species in the Gulf of California, Mexico. Mar Biol (Berl) 141(3):591–601. doi:10.1007/s00227-002-0839-0

Jiménez-Castro CM (1988) Hábitos alimenticios, requerimientos energéticos y consumo alimenticio del pelicano café en la Bahía de La Paz, B.C.S., México. Tesis de Licenciatura, UABCS, 62 pp

Jørgensen C, Enberg K, Dunlop ES, Arlinghaus R, Boukal DS, Brander K, Ernande B, Gardmark A, Johnston F, Matsumura S, Pardoe H, Raab K, Silva A, Vainikka A, Dieckmann U, Heino M, Rijnsdorp AD (2007) Managing evolving fish stocks. Science 318:1247–1248. doi:10.1126/science.1148089

Katsukawa T, Matsuda H (2003) Simulated effects of target switching on yield and sustainability of fish stocks. Fish Res 60:515–525. doi:10.1016/S0165-7836(02)00083-8

Kelleher K (2005) Discards in the world's marine fisheries. An update. FAO Fisheries Technical Paper No 470, Rome, FAO, 2005, 131 p

Levin SA (1998) Ecosystems and the biosphere as complex adaptive systems. Ecosystems (N Y, Print) 1:431–436. doi:10.1007/s100219900037

Levin SA (1999) Fragile dominion: complexity and the commons. Perseus Books, Reading

Lluch-Belda D, Magallón FJ, Schwartzlose RA (1986) Large fluctuations in the sardine fishery in the Gulf of California: possible causes. Cal Coop Ocean Fish 27:136–140

Lluch-Belda D, Crawford RJM, Kawasaki T, MacCall AD, Parrish RH, Schwartzlose RA, Smith PE (1989) Worldwide fluctuations of sardine and anchovy stocks: the regime problem. S Afr J Mar Sci 8:195–205

Lluch-Belda D, Schwartzlose RA, Serra R, Parrish RH, Kawasaki T, Hedgecock D, Crawford RJM (1992) Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. Fish Oceanogr 1:339–347. doi:10.1111/j.1365-2419.1992.tb00006.x

Lluch-Cota SE (2000) A proposal of the basis for an environmental fishery information system for the sardine fishery of the Gulf of California. Cent. de Investigaciones Biologicas del Noroeste, La Paz, p 43

Lluch-Cota SE, Lluch-Cota DB, Nevárez-Martínez MO, Páres-Sierra A, Lluch-Belda D, Hernández-Vázquez S (1999) Variability of sardine catch as related to enrichment concentration and retention processes in the central Gulf of California. CalCOFl Rep 40:184–190

Lluch-Cota SE, Aragón-Noriega EA, Arreguín-Sánchez F, Aurioles-Gamboa D, Bautista-Romero JJ, Brusca RC, Cervantes-Duarte R, Cortés-Altamirano R, Del-Monte-Luna P, Esquivel-Herrera A, Fernández G, Hendrickx ME, Hernández-Vázquez S, Herrera-Cervantes H, Kahru M, Lavín M, Lluch-Belda D, Lluch-Cota DB, López-Martínez J, Marinote SG, Nevárez-Martínez MO, Ortega-García S, Palacios-Castro E, Parés-Sierra A, Ponce-Díaz G, Ramírez-Rodríguez M, Salinas-Zavala CA, Schwartzlos RA, Sierra-Beltrá AP (2007) The Gulf of California: review of ecosystem status and sustainability challenges. Prog Oceanogr 73:1–26

López-Martínez J, Nevárez-Martínez MO, Molina-Ocampo RE, Manrique-Colchado FA (1999) Overlap in the type and size of the prey that compose the diet of the Pacific sardine Sardinops caeruleus, thread herring *Opisthonema libertate* and Northern anchovy *Engraulis modax* in the Gulf of California. Cien Mar 25:541–556

Lynam CP, Gibbons MJ, Axelsen BJ, Sparks CAJ, Coetzee J, Heyward BJ, Bierly SS (2006) Jellyfish overtake fish in a heavily fished ecosystem. Cur Biol 16(13):R492–R493

MacCall AD (2009) A short scientific history of the fisheries, Chapter 2. In: Checkley DM Jr, Alheit J, Oozeki Y, Roy C (eds) Climate change and small pelagic fish. Cambridge University Press, Cambridge, pp 9–11

Maldonado JE, Davila FO, Stewart BS, Greffen E, Wayne RK (1995) Intraspecific genetic differentiation in California sea lions (*Zalophus californianus*) from southern California and the Gulf of California. Mar Mamm Sci 11:46–58

Marinone SG (2003) A three dimensional model of the mean and seasonal circulation of the Gulf of California. J Geophys Res 108:3325

Markaida U (2006) Population structure and reproductive biology of jumbo squid *Dosidicus gigas* from the Gulf of California after the 1997–1998 El Niño event. Fish Res 79:28–37

Markaida U, Sosa-Nishizaki O (2003) Food and feeding habits of jumbo squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae) from the Gulf of California, Mexico. J Mar Biol Assoc UK 83:507–522

Mayr E (1982) The growth of biological thought. Harvard Univ. Press, Cambridge, p 974

Mellink E, Dominguez J, Luévano J (2001) Diet of eastern pacific brown boobies *Sula leucogaster brewsteri* on isla San Jorge, north-eastern Gulf of California, and an April comparison with diets in the middle Gulf of California. Mar Ornithol 29:23–28

Mendelssohn R, Schwing FB (2002) Common and uncommon trends in SST and wind stress in the California and Peru-Chile current systems. Prog Oceanogr 53:141–162

Nevárez-Martínez MO (2000) Varibilidad de la Poblacíon de Sardina Monterey Sardinops caeruleus en el Golfo de California, Mexico. Doctor of Marine Science Thesis, Instituto Politécnico Nacional, Centro Interdisciplinario de Ciensias Marinas (CICIMAR), La Paz, B.C.S., Mexico, 77 pp + 25 Appendix Figures

Nevárez-Martínez MO, Chávez EA, Cisneros-Mata MA, Lluch-Belda D (1999) Modeling on the Pacific sardine Sardinops caeruleus fishery of the Gulf of California, Mexico. Fish Res 41:273–283

Oskin M, Stock J (2003) Miocene to Recent Pacific-North America plate motion and opening of the Upper Delfin Basin, northern Gulf of California, Mexico. 2003. Geol Soc Am Bull 115:1173–1190

Overland J, Alheit J, Bakun A, Hurrell J, Mackas D, Miller A (2009) Climatic forcing of marine ecosystems and fish populations. J Mar Sys (in press)

Pikitch EK, Santora C, Babcock EA, Bakun A, Bonfil R, Conover DO, Dayton P, Doukakis P, Fluharty D, Heneman B, Houde ED, Link J, Livingston PA, Mangel M, McAllister MK, Pope J, Sainsbury KJ (2004) Ecosystem-based fishery management. Science 305:346–347

Polovina JJ (2005) Climate variation, regime shifts and implications for sustainable fisheries. Bull Mar Sci 76(2):233–244

Rice J (1995) Food web theory, marine food webs, and what climate change may do to northern fish populations. In: Beamish RJ (ed) Climate change and northern fish populations. Can Spec Pub Fish Aquat Sci 121: 561–568

Richardson AJ, Bakun A, Hays GC, Gibbons MJ (2009) The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. Trends Ecol Evol 24(6):312–322

Rodríguez-Sánchez R, Lluch-Belda D, Villalobos H, Ortega-García S (2003) Dynamic geography of small pelagic fish populations in the California Current System on the regime time scale (1931–1997). Can J Fish Aquat Sci 59:1980–1988

Rojas-Bracho L, Reeves RR, Jaramillo-Legorreta A (2006) Conservation of the vaquita. Mammal Rev 36:179–216

Salvadeo CJ (2008) Análisis de la comunidad de odontocetos y la relación con su ambiente en el extremo sur-occidental del Golfo de California, México (2003–2006). Tesis de Maestría CICIMAR-IPN, La Paz, B.C.S., México, 63 pp

Sánchez-Velaso L, Shirasago B, Cisneros-Mata MA, Avalos-Garcia C (2000) Spatial distribution of small pelagic fish larvae in the Gulf of California and its relation to the El Niño 1997–1998. J Plankton Res 22:1611–1618

Schwartzlose RA, Alheit J, Bakun A, Baumgartner T, Cloete R, Crawford RJM, Fletcher WJ, Green-Ruiz Y, Hagen E, Kawasaki T, Lluch-Belda D, Lluch-Cota SE, MacCall AD, Matsuura Y, Neváres-Martínez MO, Parrish RH, Roy C, Serra R, Shust KV, Ward NM, Zuzunaga JZ (1999) Worldwide large-scale fluctuations of sardine and anchovy populations. S Afr J Marine Sci 21:289–347

Schwing FB, Mendelssohn R (1997) Increased coastal upwelling in the California Current System. J Geophys Res 102:3421–3438

Shannon V, Crawford RJM, Pollock DE, Hutchens L, Boyd AJ, Taunton-Clark J (1992) The 1980s—a decade of change in the Benguela ecosystem. In: Payne AIL, Brink KH, Mann KH, Hilborn R (eds) Benguela Trophic Functioning. S Afr J Mar Sci 12: 271–296

Soutar A, Isaacs JD (1974) Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediment off the Californias. Fish Bull (U.S.) 72:257–273

Suazo-Guillén E, Mellink E (2004) Diet, maximum diving depth, and diving time by brown boobies in Isla San Jorge, Sonora, Mexico, 2003. 31st Reunión Annual del Pacific Seabird Group. La Paz, B.C.S

Szteren D, Aurioles D, Gerber LR (2006) Population status and trends of California sea lion (*Zalophus californianus californianus*) in the Gulf of California, Mexico. In: Trites AW, Atkinson SK, DeMater DP, Firtiz LW, Gelatt TS, Rea LD, Winne KM (eds) Sea lions of the world. Alaska Sea Grant College Program, University of Alaska, Fairbanks, pp 360–384

Tershy BR, Breese D, Alvarez-Borrego S (1991) Increase in cetacean and seabird numbers in the Canal de Ballenas during an El Nino-Southern Oscillation event. Mar Ecol Prog Ser 69:299–302

Torres-Rojas Y, Hernández-Herrera A, Galván-Magaña F (2006) Feeding habits of the scalloped hammerhead *Sphyrna lewini* in Mazatlan waters, Southern Gulf of California, Mexico. Cybium 30(4):85–90

Trenberth KE, Large WG, Olson JG (1990) The mean annual cycle in global ocean wind stress. J Phys Oceanogr 20:1742–1760

Tripp-Valdez A (2005) Ecología Trófica del dorado *Corhyfaena hippurus* (Linnaeus, 1758) en dos áreas del sur del Golfo de California. Tesis de Maestría CICIMAR-IPN, La Paz, B.C.S., México

Urbán RJ, Flores RS (1996) A note on Bryde's Whales (*Balaenoptera edeni*) in the Gulf of California, Mexico. Rep Int Whal Commn. 46:453–457

Van der Lingen CD (1994) Effect of particle size and concentration on the feeding behavior of adult pilchard, *Sardinops sagax*. Mar Ecol Prog Ser 109:1–13

Vecchi GA, Soden BJ (2007) Global warming and the weakening of tropical circulation. J Clim 20:4316–4340

Vecchi GA, Soden BJ, Wittenberg AT, Held IM, Leetmaa A, Harrison MJ (2006) Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. Nature 441:73–76

Velarde E, Ezcurra E, Cisneros-Mata MA, Lavin MF (2004) Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. Ecolog Appl 14:607–615

Weeks SJ, Currie B, Bakun A, Peard KR (2004) Hydrogen sulphide eruptions in the Atlantic Ocean off southern Africa: implications of a new view based on SeaWiFS satellite imagery. Deep-Sea Res I 51:153–172

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ENDANGERED SPECIES RESEARCH
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Contribution to the Theme Section 'Responses of animals to habitat alteration'

Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific

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ABSTRACT: Increasing water temperatures due to global warming mean that specific isotherms are shifting polewards. This may cause the poleward shifts in the range limits of species that are only found in specific thermal habitats. Such range shifts have been recorded in a number of plant and animal species. In the last 3 decades, we observed a decline in the presence of Pacific white-sided dolphin *Lagenorhynchus obliquidens* in the southwest Gulf of California (GOC), which is considered the southern boundary of their distribution. Considering that the thermal environment is physiologically important to animals, we believe that this poleward shift in the usual geographic range of the Pacific white-sided dolphin is due to long-term changes in the local climate. To obtain the conceptual framework needed to discuss such a hypothesis, we summarize and analyze current knowledge about Pacific white-sided dolphins in the southwest GOC, and sea surface temperature variability at a regional scale.

KEY WORDS: Climate change · *Lagenorhynchus obliquidens* · Poleward shift · Northeastern Pacific · Gulf of California

INTRODUCTION

Climate change is affecting biodiversity and places additional pressures on already over-used, degraded, and fragmented ecosystems, undermining their resilience. In particular, some species, especially polar and mountain species, have already experienced severe range contractions as they try to remain within their preferred climatic envelopes by changing their distributions (Parmesan & Yohe 2003, Root et al. 2003). Cetacean species' ranges are likely to change in a similar manner as a result of increases in water temperature. For individual cetacean species, it can be predicted whether their ranges will expand, shift poleward, or contract based on their current distributions and on the characteristics of the niches they occupy (MacLeod 2009). In particular, certain characteristics place some species at greater risk from such changes than others. These include a range that is restricted to non-tropical waters (including temperate species) and a preference for shelf waters such as shown by most porpoises and *Lagenorhynchus* species (MacLeod 2009). Such range shifts in response to climate change are most likely to be detected at the edge of the current distribution of a species, since this is where any changes are likely to occur first.

The Pacific white-sided dolphin *Lagenorhynchus obliquidens* is restricted to the temperate waters of the North Pacific Ocean, and does not occur in tropical and Arctic waters. In the eastern Pacific, large groups of this species are frequently seen in the California Current System (CCS; Leatherwood et al. 1984, Stacey &

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Baird 1990, Keiper et al. 2005). The southern boundary of the distribution of Pacific white-sided dolphins is the Gulf of California (GOC), where the species has been observed only in the southwest area during the temperate season (from December to June; Aurioles et al. 1989).

In the CCS and GOC, water temperatures are known to have increased over the last century (Lluch-Belda et al. in press; see Fig. 2). Given this water temperature rise at the southern edge of its distribution, if the range of the Pacific white-sided dolphin is being affected by climate change in the manner suggested by MacLeod (2009), we would predict that its distribution would have declined in the GOC in recent years. To test this prediction, we examined the occurrence of Pacific white-sided dolphins in the GOC between 1980 and 2009 based on data from 2 separate sources. While these surveys have different spatial coverage, they provide data collected in a consistent manner for an overlapping area in the GOC over a sufficiently long period to assess whether any changes in distribution have occurred at the southern edge of this species' distribution in the northeast Pacific.

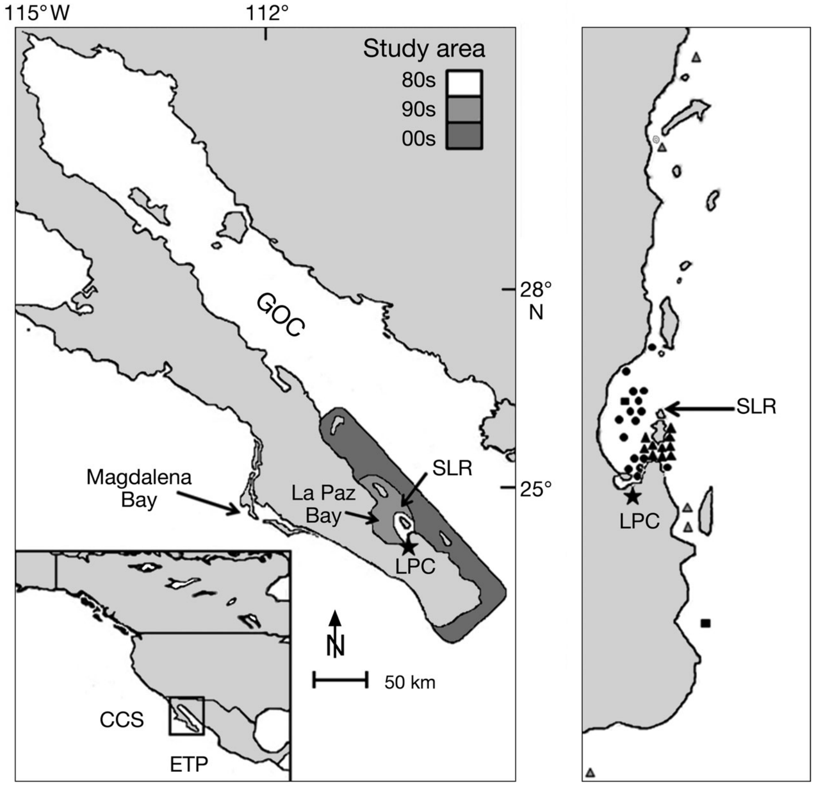

Fig. 1. Study area and sighting positions from 1978–1988 (80s) (small white area within dark gray shaded area; all triangles, where gray triangles indicate opportunistic sightings reported by Aurioles et al. 1988, 1989 and not taken in to account for numerical analysis), 1989–1999 (90s) (●), and 2000–2009 (00s) (■). CCS: California Current System; ETP: Eastern Tropical Pacific; GOC: Gulf of California; LPC: La Paz City; SLR: sea lion rookery

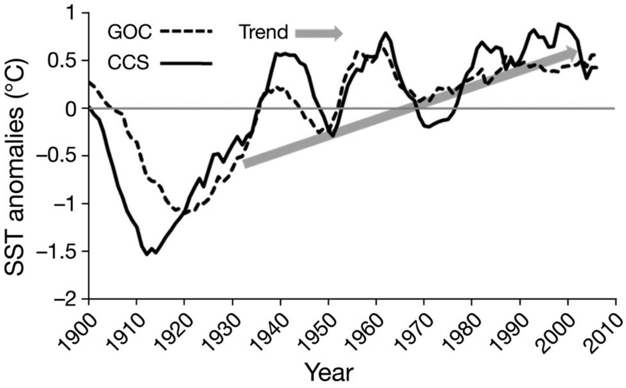

Fig. 2. Sea surface temperature (SST) anomalies (10 yr Hamming smoothed series) in the Gulf of California (GOC) and California Current System (CCS) from Lluch-Belda et al. (in press)

MATERIALS AND METHODS

The study area is located in the southwest GOC along the eastern coast of the Baja California Peninsula (Fig. 1). This area is structurally complex. The continental shelf is irregular and narrow with the presence of basins, sea mounts, and several volcanic islands. North-northwesterly winds prevail during the temperate season, promoting upwelling along the gulf's eastern coast (Maluf 1983). Such upwelling fertilizes the whole gulf through a system of eddies that carry enriched waters from the eastern to the western coast (Beier 1997). These hydrographic features promote a higher and homogeneously distributed productivity throughout the study area.

We compared sightings of the Pacific white-sided dolphin in the southwest GOC during temperate seasons (when this species is most likely to be present) from the last 3 decades. These sighting data came from 2 separate sources. We primarily used data from Aurioles et al. (1989) to provide information on the occurrence of Pacific white-sided dolphins in the surveyed area during the 1980s. These data were collected during trips to the sea lion rookery situated on Espiritu Santo Island in La Paz Bay (Fig. 1). During each trip, observers searched for animals and recorded all species sighted (D. Aurioles pers. comm.). These surveys were initiated in 1978 and have continued until the present time. The second data set used included sightings collected over a 20 yr period between 1989 and 2009 by the Universidad Autónoma de Baja California Sur (UABCS). These sightings were collected during sampling trips that followed a consistent but non-random search method, in which the boat ran in a straight line at cruising speed (11 knots) following a predetermined track trying to cover most of the study area, with less than Beaufort 3 wind scale conditions (higher conditions significantly reduce the capacity of observers to detect cetaceans). During each sampling trip, 3 observers were located on the boat, 1 at the front and 1 on each side of the boat for cetacean searching, and stops were made every 30 min for a 360° binocular (7 × 50) scan. When a cetacean was sighted, the date, time, species, location, number of animals, behavior, and association with other marine species (birds, fishes, mammals, and turtles) were recorded. For the purposes of this study, this data set was divided into 2 time periods, the 1990s and the 2000s. The 1990s data were obtained exclusively from sampling trips in the La Paz Bay area and adjacent waters, while in the 2000s, the area covered was larger (Fig. 1). While the data for the 1990s (1998–1999) and 2000s (2000–2009) came from larger sampling areas than those covered by the data from the 1980s (1978–1988), these later surveys also covered the same area as the 1980s surveys, meaning that there is at least some spatial consistency over time. In addition, as the Pacific white-sided dolphin is generally more abundant in open waters, this species is likely to be more abundant in these wider areas than in La Paz Bay itself. Therefore, the wider coverage would be expected to have increased rather than decreased the encounter rate with this species.

Sighting data from the UABCS surveys collected from 1989 to 2009 were used to calculate seasonal dolphin relative abundance (animals h^{-1}) for each year as an indicator of the species' presence in GOC waters for the 1990s and 2000s. Data from Aurioles et al. (1989) were not included in this calculation, because they were presented as accumulated monthly observations from the period 1978 to 1988; thus we could not calculate the relative abundance and effort for each year alone. In addition, effort was presented as the number of transects. For this reason, before we were able to compare their data to the UABCS data, it was necessary to transform the number of transects into the total time spent (3 h for each transect; D. Aurioles pers. comm.).

To compare records among the 3 decades, for each we calculated the following: (1) the total effort hours, total sightings, and total number of animals; (2) the mean, maxima, and minima of the dolphin group size; and (3) the relative abundance (number of sightings and animals h^{-1} of effort). Also, the monthly accumulated effort and number of animals were calculated for the 1990s and 2000s, to compare the monthly presence pattern between decades.

To assess possible causes for any changes in the occurrence of Pacific white-sided dolphins, 3 additional data sets were investigated. Firstly, information on the occurrence of other cetacean species collected during the same surveys was investigated. This allowed an assessment of whether any decline in occurrence was restricted to the main species of interest, or whether other species were also affected. If only Pacific white-sided dolphins were affected, then this would suggest the change is unlikely to be driven by factors such as bycatch, changes in productivity, or decline in ecosystem productivity, which would be expected to also affect other cetacean species.

Secondly, data from annual landings of small pelagic fish (mostly Pacific sardine *Sardinops sagax caerulea*) in the GOC and the west coast of Baja Peninsula (Magdalena Bay and Ensenada) were used as an approximation of regional prey availability. We used annual sardine landings as they are considered a good index of sardine abundance, due to a high degree of similarity between sardine landings and biomass estimation (Norton & Mason 2005). These data were provided by the Laboratorio de Edad y Crecimiento at the Centro Interdisciplinario de Ciencias Marinas-Instituto Politécnico Nacional (CICIMAR-IPN). This allowed us to assess whether changes in prey availability could be influencing the occurrence of Pacific white-sided dolphins within the surveyed areas.

Finally, in order to directly assess whether any changes in the occurrence of Pacific white-sided dolphins since the 1980s were related to changes in water temperature, data on sea surface temperature (SST) in the CCS and southern GOC region were obtained from Lluch-Belda et al. (in press). The authors constructed annually averaged sea surface temperature (SST) anomalies in 2 × 2° quadrants at the GOC and CCS using the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, Release 2.0, available at http://icoads.noaa.gov/) and the NOAA Extended Reconstructed SST (ERSST) data set (NOAA Satellite and Information Service, http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php).

RESULTS

The data show that despite the increase in the spatial (Fig. 1) and temporal (Fig. 3, Table 1) effort, the occurrence (sightings and animals h^{-1} of effort) of this dolphin species has decreased during the last 3 decades (Fig. 3, Table 1). This decline in occurrence is most evident at the decadal scale.

In the 1980s, Pacific white-sided dolphins were regularly sighted in the surveyed areas between La Paz City and the sea lion rookery in La Paz Bay (Fig. 1).

Table 1. *Lagenorhynchus obliquidens.* Accumulated historical data from the southwest Gulf of California for the last 3 decades. Effort (h); sightings: number of occasions when the species was observed; mean, minimum (min.), maximum (max.), and SD for group size; sightings h^{-1} and animals h^{-1}: abundance relative to effort; 1980s: 1978–1988; 1990s: 1989–1999; 2000s: 2000–2009

Period	Effort	Sightings	Animals	Mean	Min.	Max.	SD	Sightings h^{-1}	Animals h^{-1}
1980s	252	10	647	65	2	200	67	0.039	2.56
1990s	1659	16	316	20	1	45	12	0.010	0.19
2000s	1986	2	50	25	20	30	7	0.001	0.03

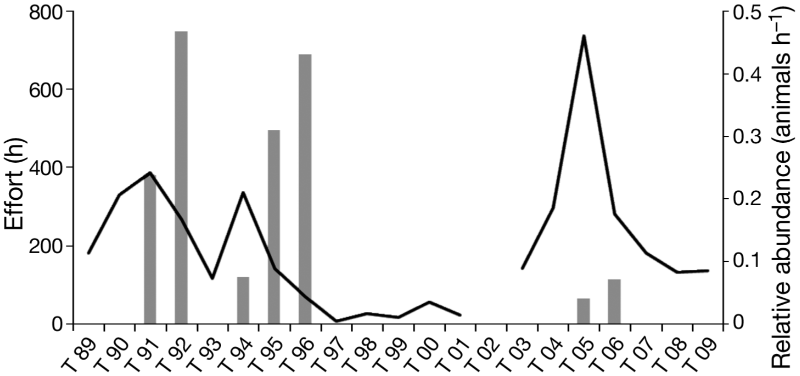

Fig. 3. *Lagenorhynchus obliquidens.* Relative abundance (animals h^{-1}, gray bars) and effort (h, black line) during the temperate season (T, followed by the respective year)

They were recorded throughout the cold season from January to June (Figs. 4 & 5). For the 1980s as a whole, the sighting rates and relative abundance were 0.039 and 2.56 h^{-1} of effort, respectively. Group sizes ranged from 2 to 200 with a mean of 65 animals.

During the 1990s, Pacific white-sided dolphins were recorded between February and May (Figs. 4 & 5) in groups between 1 and 45 animals (mean: 20). The sighting rate was 0.01 h^{-1}, and the relative abundance was 0.19 ind. h^{-1} of survey effort for the area surveyed. In addition, there were few sightings recorded within the area covered during the 1980s surveys (Fig. 1).

In the 2000s, only 2 groups of Pacific white-sided dolphin were recorded, 1 of 20 animals and 1 of 30 animals. These sightings occurred in March and April, respectively. The sightings rate was 0.001 groups h^{-1} of survey effort, and the relative abundance was 0.03 ind. h^{-1}. In addition, no sightings were recorded in the area that had been surveyed in the 1980s (Fig. 1).

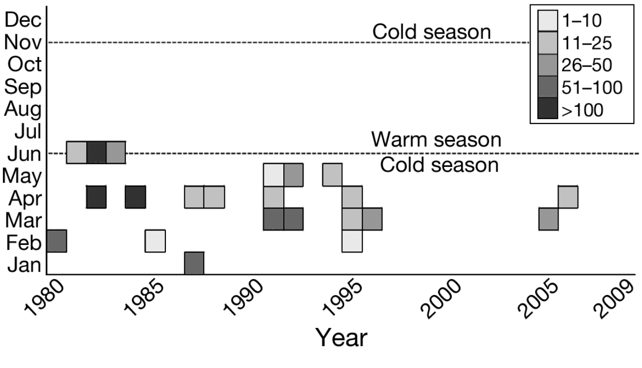

Fig. 4. *Lagenorhynchus obliquidens.* Historical number (total) of dolphins sighted per month in the surveyed areas (see Fig. 1)

Therefore, based on these data sets, 3 changes in the occurrence of Pacific white-sided dolphins in the GOC over time can be identified. These are: (1) a decrease in seasonal occurrence from the entire cool season (January to June) in the 1980s to only the central months of the cool season (March and April) in the 2000s; (2) a decrease in maximum and average group sizes from 200 and 65 animals, respectively, in the 1980s to 30 and 25, respectively, in the 2000s; (3) a decrease in sighting rates and relative abundances from 0.039 sightings and 2.56 ind. h^{-1} of survey effort in the 1980s to 0.001 sightings and 0.03 ind. h^{-1} of survey effort in the 2000s. While some of these changes could have resulted from a change in survey coverage between the 3 time periods, when only the area covered in 1980s was compared, this change is still evident, with half as many sightings during the 1990s as during the 1980s and none during the 2000s.

Other cetacean species encountered in the study area included common dolphins *Delphinus* spp., bottlenose dolphin *Tursiops truncatus*, pilot whale *Globicephala macrorhynchus*, sperm whale *Physeter macrocephalus*, fin whale *Balaenoptera physalus*, Bryde's whale *B. edeni*, and as seasonal visitors the blue whale *B. musculus* and the humpback whale *Megaptera novaeangliae*. None of these other cetacean species show evidence of a similar decline (Salvadeo 2008, Troyo-Vega 2008, Pardo 2009). For example, common dolphins, which are warm-temperate water species not close to the edge of their range, have not changed in terms of their seasonal occurrence, group size, or relative abundance. In addition, the population of sea lions at La Paz Bay has grown in recent years (Szteren et al. 2006). This suggests that the observed changes in Pacific white-sided dolphin occurrence are not driven by ecosystem factors such as changes in productivity.

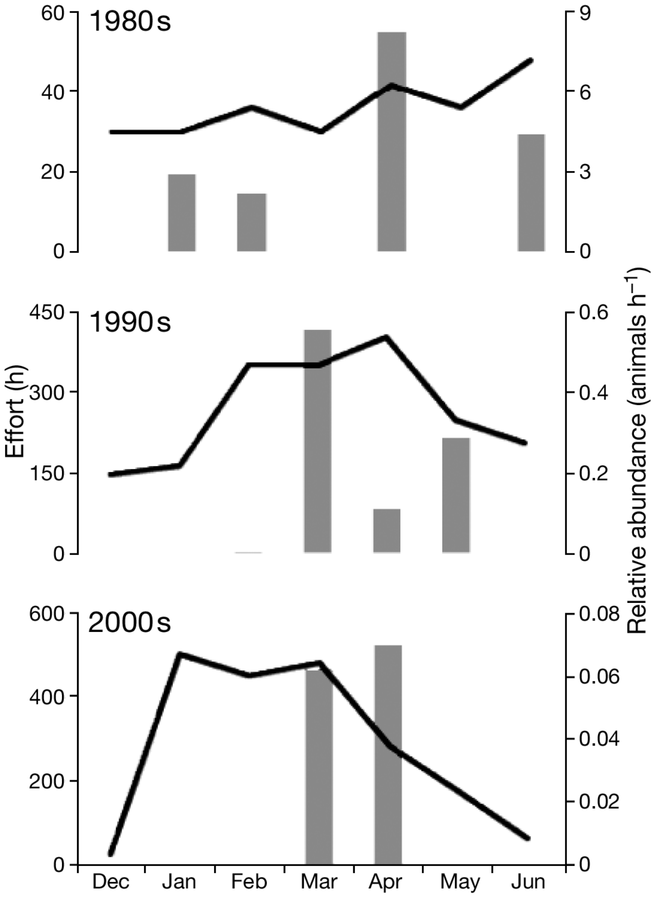

Fig. 5. *Lagenorhynchus obliquidens.* Accumulated relative abundance (animals h^{-1}, gray bars) and effort (h, black line) per month for each decade. Note the different scales

Similarly, sardine landings in the GOC did not show a consistent decline between the 1980s and the 2000s. Instead, they showed a decline between 1989 and 1993, followed by an increase from 1993 to 2007 (Fig. 6). Sardine landings from neighboring areas outside the GOC showed a consistent increase from the 1980s to 2007. Therefore, the changes in the occurrence of Pacific white-sided dolphins in the GOC did not occur in concert with a decline in local fish stocks.

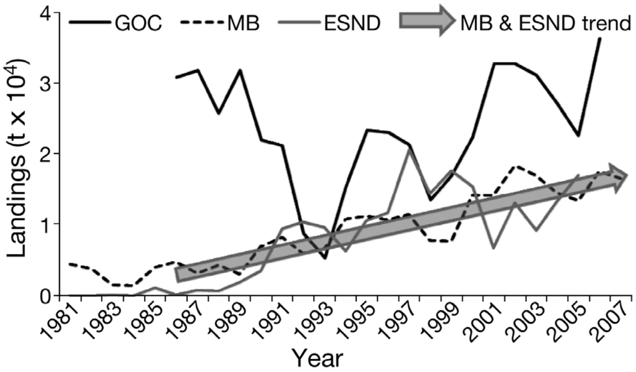

Fig. 6. Annual sardine landings from the Gulf of California (GOC) and from the west coast of Baja Peninsula represented by Magdalena Bay (MB; see Fig. 1) and Ensenada (ESND) located near the USA border; MB and ESND data were multiplied by 3 for comparative purposes

In terms of water temperatures, there has been a trend to increasing water temperatures in the GOC and the CCS since the mid-1910s (Fig. 2). This is consistent with the observed changes in the Pacific white-sided dolphin occurrence being related to an increase in water temperatures.

DISCUSSION

In the Northeastern Pacific, there are several Pacific white-sided dolphin populations that show relatively complex patterns in their seasonal distributions. However, north–south and inshore–offshore movements have been recorded in several areas. These seasonal patterns are thought to be related to seasonal movements in prey species and changes in water temperature (Leatherwood & Walker 1982, Aurioles et al. 1989, Stacey & Baird 1990, Reeves et al. 2002, Keiper et al. 2005). In the southwest GOC, Aurioles et al. (1989) considered the Pacific white-sided dolphin to be a seasonal visitor during the temperate season (winter to spring; Figs. 4 & 5), when the cooling of GOC waters allows them to enter from the CCS. In addition, their seasonal presence in the southwestern GOC matches with high abundances of small pelagic fish (potential prey) due to seasonal movement of sardine inside the GOC (Hammann et al. 1998). These small pelagic fishes, in turn, attract fish-eating predators such as small cetaceans and sea birds to the southwest GOC (Salvadeo 2008).

Our study suggests that the occurrence of the Pacific white-sided dolphin has decreased by approximately 1 order of magnitude per decade since the 1980s, (Figs. 3 & 5, Table 1). This difference remains even if only areas surveyed in all 3 decades (La Paz Bay) are considered. For example, Pacific white-sided dolphins were rarely recorded in the area around La Paz during the survey conducted here since the year 2000 (Fig. 1). In addition, Pacific white-sided dolphins have not been sighted during recent trips to the sea lion rookery, where data were collected in the 1980s (D. Aurioles pers. comm.).

This decline in the occurrence of Pacific white-sided dolphins in the GOC has not been associated with declines in other marine mammals, such as common dolphins or California sea lions from the La Paz Bay colony, nor has it been associated with a decline in sardine landings (a good index of sardine biomass). This suggests that the decline in Pacific white-sided dolphin occurrence is not related to factors such as a decline in available prey or a reduction in productivity. In addition, the level of bycatch in Pacific white-sided dolphins is relatively low (<10% of calculated biological removal; Carretta et al. 2008), and therefore is unlikely to be a major driving force behind the decline in occurrence that we identified in this study. Similarly, there is no evidence of increased industrial or military noise within the region that could contribute to this decline. Finally, the principal activities in the southern peninsula are artisanal and sport fisheries, and ecotourism; these activities have a low or no impact on marine mammals around the area.

However, the decline in occurrence has occurred during a period of warming in the local region. This suggests that changes in water temperature may be associated with the decline in occurrence. This possibility is further supported by the seasonal contraction in occurrence to the coolest times of the year as temperatures have increased.

While variations in water temperature may be associated with short-term climatic events, such as El Niño and Pacific Decadal Oscillations (PDO), there has been a consistent increase in temperature throughout the period from 1980 to 2009. This suggests that the main driving force behind these changes in water temperature is global climate change rather than more regional and mid-term climatic events.

Thus, if we consider the GOC as the southern boundary of the Pacific white-sided dolphin range, the decrease in their abundance and group size between 1980 and 2009 (Table 1, Figs. 3 to 5) and their monthly contraction to cooler months (Figs. 4 & 5), are evidence consistent with a poleward shift in their range.

Therefore, these observations are consistent with the northward shift in the range of the Pacific white-sided dolphin predicted by MacLeod (2009). This possibility of a poleward shift in the range of the Pacific white-sided dolphin in the northeastern Pacific is further supported by evidence that Pacific white-sided dolphins increased in occurrence on the west coast of Canada from 1984 to 1998 (Morton 2000). Therefore, throughout the northeast Pacific, there is evidence of a poleward shift in occurrence at both the northern and southern range limits of this species, associated with increases in water temperature.

This poleward shift in the range of the Pacific white-sided dolphin in response to climate change is likely to have implications for conservation and management of the GOC marine environment. In particular, the species' shift away from the GOC may be indicative of other climate-induced changes in local ecosystems. In addition, it has implications for the conservation and management of the Pacific white-sided dolphin in the northeastern Pacific. In particular, it is likely to become increasingly rare in southern portions of its current range, especially in Mexican waters.

Finally, this is the second of the 6 species of the genus *Lagenorhynchus* in which evidence of a climate change-induced range shift has been identified (MacLeod et al. 2005), supporting the hypothesis that members of this genus may be particularly at risk from the negative effects of climate change (MacLeod 2009).

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LITERATURE CITED

Aurioles D, Leatherwood S, Muñoz E (1988) Pacific white-sided dolphins (*Lagenorynchus obliquidens*) in the Sea of Cortez. Bull South Calif Acad Sci 87:44–45

Aurioles DG, Gallo-Reynoso JP, Muñoz EL, Ejido JV (1989) El delfín de costados blancos (*Lagenorhynchus obliquidens,* Gill 1865) (Cetacea: Delphinidae) residente estacional en el suroeste del Golfo de California, México. An Inst Biol Univ Nac Auton Mex Zool 60:459–472

➤ Beier E (1997) A numerical investigation of the annual variability in the Gulf of California. J Phys Oceanogr 27: 615–632

Carretta JV, Forney KA, Lowry MS, Barlow J and others (2008) United States Pacific marine mammal stock assessment: 2008. NOAA Tech Memo NMFS-SWFSC-434

Hammann MG, Nevárez-Martínez MO, Green-Ruíz Y (1998) Spawning habitat of the Pacific sardine (*Sardinops sagax*) in the Gulf of California: egg and larval distribution 1956–1957 and 1971–1991. CCOFI Rep 39:169–179

➤ Keiper CA, Ainley DG, Allen SG, Harvey JT (2005) Marine mammal occurrence and ocean climate off central California, 1986 to 1994 and 1997 to 1999. Mar Ecol Prog Ser 289: 285–306

Leatherwood S, Walker WA (1982) Population biology and ecology of the Pacific whitesided dolphin *Lagenorhynchus obliquidens* in the northeastern Pacific. Part I: Distribution, seasonal movements and abundance with a bibliography and summary of specimen material. NOAA, NMFS, SWFC Admin Rep LJ-82-18C

Leatherwood S, Reeves RR, Bowles AE, Stewart BS, Goodrich KR (1984) Distribution, seasonal movements and abundance of Pacific white-sided dolphins in the eastern North Pacific. Sci Rep Whales Res Inst 35:129–157

Lluch-Belda D, Del Monte Luna P, Lluch-Cota SE (in press) 20th century variability of the Gulf of California SST. CCOFI Rep

➤ MacLeod CD (2009) Global climate change, range changes and potential implications for the conservation of marine cetaceans: a review and synthesis. Endang Spec Res 7: 125–136

➤ MacLeod CD, Bannon SM, Pierce GJ, Schweder CS, Learmonth JA, Herman JS, Reid RJ (2005) Climate change and the cetacean community of north-west Scotland. Biol Conserv 124:477–483

Maluf LI (1983) The physical oceanography. In: Case TJ, Cody ML (eds) Island biogeography in the Sea of Cortez. University of California Press, Berkely, CA, p 26–45

➤ Morton A (2000) Occurrence, photo-identification and prey of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in the Broughton Archipelago, Canada 1984–1998. Mar Mamm Sci 16:80–93

Norton JG, Mason JE (2005) Environmental influences on California sardine abundance. CCOFI Rep 46:83–92

Pardo M (2009) Condiciones fisicoquímicas y biológicas que modulan la abundancia de cetáceos sobre la Cuenca Alfonso, Golfo de California. MSc thesis, CICIMAR-IPN, La Paz

➤ Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Reeves RR, Stewart B, Clapham PJ, Powell JA (2002) National Audobon Society guide to marine mammals of the world. Knopf, New York, NY

➤ Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

Salvadeo CJ (2008) Análisis de la comunidad de odontocetos y la relación con su ambiente en el extremo sur-occidental del Golfo de California, México (2003–2006). MSc thesis, CICIMAR-IPN, La Paz

Stacey PJ, Baird RW (1990) Status of the white-sided dolphin, *Lagenorhynchus obliquidens*, in Canada. Can Field Nat 105:219–232

Szteren D, Aurioles-Gamboa D, Gerber L (2006) Population status and trends of the California sea lion (*Zalophus californianus californianus*) in the Gulf of California, Mexico. In: Trites AW, Atkinson S, DeMaster D, Fritz L, Gelatt L, Wynne K (eds) Sea lions of the world. Alaska Sea Grant College Program, University of Alaska, Fairbanks, AK, p 369–384

Troyo-Vega V (2008) Distribución y diversidad de cetáceos en el extremo suroccidental del Golfo de California, 2005. MSc thesis, UABCS, La Paz

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ARTÍCULO POR INVITACIÓN

THE IMPORTANCE OF GREY LITERATURE IN FISHERIES ECOLOGY: AN EXAMPLE BASED ON THE TROPHIC ROLE OF SMALL PELAGICS IN THE GULF OF CALIFORNIA

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RESUMEN. La literatura gris suele considerase como una fuente de información cuestionable en revistas y publicaciones científicas debido a que carece de una revisión especializada y a que puede constituirse de documentos difíciles de rastrear. Sin embargo, brinda información detallada y de calidad que no se encuentra en las publicaciones con arbitraje estricto. Con el objetivo de ilustrar la importancia de la literatura gris en el ámbito de la ecología pesquera, se realizó una búsqueda en línea de publicaciones en revistas indexadas, en tesis de grado, reportes técnicos y resúmenes de congresos donde se reportan las relaciones tróficas de los pelágicos menores con especies de diversos taxa en el Golfo de California. Se obtuvieron 57 referencias bibliográficas de las cuales 36 son consideradas como literatura gris. Excluir los datos contenidos en estas fuentes de los análisis que se lleven a cabo sobre el tema, podría representar una pérdida de más del 60% de la información disponible. Este sesgo tiene el potencial de producir conclusiones incompletas o erróneas en los estudios de la dinámica trófica de los pelágicos menores en el Golfo de California.

Palabras clave: Pelágicos menores, Golfo de California, revistas no arbitradas, revistas ISI.

La importancia de la literatura gris en la ecología pesquera: un ejemplo basado en el papel de los pelágicos menores en el Golfo de California

ABSTRACT. Grey literature has been, in general, rejected from peer reviewed journals due to the lack of specialized revision and because they are difficult to trace. However, this information may contain detailed data that cannot be found in commercial reviewed journals. In order to assess the importance of grey literature in fisheries ecology, we made an online survey of indexed journals as well as thesis dissertations, technical papers and abstracts from proceedings reporting the trophic relationships of small pelagic fish in the Gulf of California. We obtained 57 bibliographic references from which 36 are considered grey literature, and these would represent a loss of more than 60% of information. This bias can lead to erroneous conclusions in studies and applications derived from such information.

Keywords: Small pelagic, Gulf of California, non-indexed journals, ISI journals.

Tripp-Valdez, M. A., S. E. Lluch Cota, P. Del Monte Luna & C. Salvadeo. 2010. The importance of grey literature in Fisheries Ecology: an example based on the trophic role of small pelagic in the Gulf of California. *CICIMAR Oceánides*, 25(1): 59-71.

INTRODUCTION

The main way in which scientists communicate their research results is through peer reviewed scientific journals. This allows the generated knowledge to be subjected to a rigorous review process and validation from specialists and also to be widely distributed among the scientific community.

Scientific research also produces an important amount of information as technical reports, atlases, congress and symposium proceedings, taxonomical keys and thesis dissertations. Such sources of information, generated at all levels of government, academy, business and industry, that are not controlled by commercial publishing circuits, is known as

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"grey literature" (opposed to the "white" or "open literature" that includes journal articles or books; Cassell, 2005; De Castro, 2006). Despite that this literature may contain valuable information, it tends to be rejected as much as possible from peer reviewed journals, mainly because it is not indexed and thus it can be very difficult to trace and acquire. Also, the lack of strict editorial controls cast doubt on the veracity of its contents (Lacanilao, 1997; Mathews, 2004).

Although the peer reviewed system has been a rather efficient quality control for scientific publications, it is not flawless. Students and researchers keep publishing only their more relevant results or those that have some importance for economical o political issues (Bank, 2006).

Grey literature may fill this gap because it contains detailed information (equipment description, proceedings, raw data, tables, graphics, etc.) which is usually not published in peer reviewed journals due to space limitations or because this information is not useful for a wider audience (De Castro, 2006).

In recent times, the world wide web has facilitated the publication of raw data or supplementary material in journals, however, in Latin America and other developing countries grey literature still plays an important role because scientist, especially graduate students, still use and produce this information, but do not usually publish their results in peer reviewed journals (De Castro, 2006; Thatje *et al*., 2006).

For instance, Sáenz-Arroyo *et al*. (2005) made an exhaustive search of fishery reports from international, national and local libraries (*i.e*., grey literature) and interviews with local fishermen to address the status of the gulf grouper (*Mycteroperca jordani*). They found that there is a considerable decrease in abundance of this species inside the Gulf of California, contrary to what has been found using fisheries models. Thatje *et al*. (2006) found that grey literature is a very valuable source of information about the ENSO effects in the Humboldt Current System. More than half of this information is in Spanish, which represents an important barrier for its worldwide dispersion.

In this study, we illustrated the importance of using grey literature, *i.e*., graduate and post graduate dissertations and technical reports, focusing on the trophic relationships of small pelagics in the Gulf of California.

METHODS

We made an online bibliographic survey in several databases: the ISI Web of Knowledge, Google Scholar web search engine and FISHBASE (www.fishbase.org) using the words "prey", "Gulf of California", "Feeding ecology" and "small pelagic". Likewise we surveyed the FISHBASE database for feeding habits of many of pelagic fish of economical importance in the Gulf of California.

We also searched for graduate and post graduate dissertations addressing the trophic ecology, feeding habits, biology and abundance of several species related with the small pelagics in the Gulf of California. Our search was conducted in the on-line public libraries of different research institutions: CIBNOR (www.cibnor.gob.mx), UABCS (http://biblio.uabcs.mx/), UABC (http://sia.mxl.uabc.mx/), CICESE (http://.biblioteca.cicese.mx) and CICIMAR (www.biblioteca.cicimar.ipn.mx/oacis) for postgraduate dissertations. Electronic versions of the documents (PDF) were obtained.

We made a database including the species that feed upon small pelagics and the region of the Gulf of California and the date when the information was obtained, the importance of small pelagics in the diet composition (percentage), and the species that comprise the diet.

We made a list of the main fishery journals in the Science Citation Index 2008. Guides for authors were revised to identify the policy of each journal concerning grey literature, *i.e.*, if they allow the use of dissertations, technical reports, abstracts, etc. In the case of those journals that do not specify the use of grey literature, we made a thorough revision of all articles from the two most recent issues of each journal looking for trends in the use of grey literature. Finally we analyzed the amount of whole database that woud be eliminated in case of rejection of grey literature.

RESULTS

From the bibliographic online survey, we obtained information of 36 species from four different taxa that feed upon small pelagics in the Gulf of California (Table 1 on the appendix) contained in 57 documents from which 21 are articles published in peer reviewed journals or doctoral (PhD) theses, both considered as white literature; 23 are Master´s (MSc) thesis; 8 Bachelor´s degree (BSc) theses; two conference proceedings and three technical reports.

Eight of the indexed journals do not allow the use of any kind of grey literature in their reference list; unpublished data must be cited as such in the text or as personal communication. The *Canadian Journal of Fisheries and Aquatic Science* allows the use of MSc and PhD theses, while *Fisheries Research* only permits the use of PhD theses. Both allow the use of personal communication and unpublished data must be cited in the text but not in the reference list (Table 2 on the appendix).

Journals that are not specific on the use of grey literature (Table 2) revealed that even if it is possible to include MSc theses, technical reports and proceedings, these appeared very rarely, however PhD theses were widely cited.

As shown in Table 1, if grey literature was excluded from the study of the trophic relationships in small pelagics in the Gulf of California, it would represent a loss of 67.3% of the whole information of species related to this group. Elasmobranchii would be the most affected group because only three out of 13 references are white literature and thus can be reported in a journal that rejects grey literature. Information on bonny fish and marine birds would also be reduced considerably. For each group, only two out of ten references can be reported as white literature. Cephalopods and marine mammals are the less affected group since most of the reports are referred in indexed journals (Fig. 1).

Because some journals allow the use of MSc theses in the references, we also analyzed the database considering only white literature and MSc thesis. We observed a considerable increase of information that can be included especially in the taxa of elasmobranchii and marine birds (Fig. 1)

DISCUSSION

This study revealed that, although there is a tendency to avoid the use of grey literature in scientific publications (Wilbur, 1990; Lacanilao, 1997), these sources of information may give more detailed data than that found in peer reviewed articles, as illustrated in specific aspects of the trophic ecology of small pelagics in the Gulf of California.

As seen in table 1 and figure 1, by disregarding MSc thesis, technical reports and proceedings, there can be a potential loss of valuable information concerning the importance of the small pelagic as part of the diet of several species of fishes, elasmobranchii, marine mammals and birds in the Gulf of California. This situation may gain momentum at the time

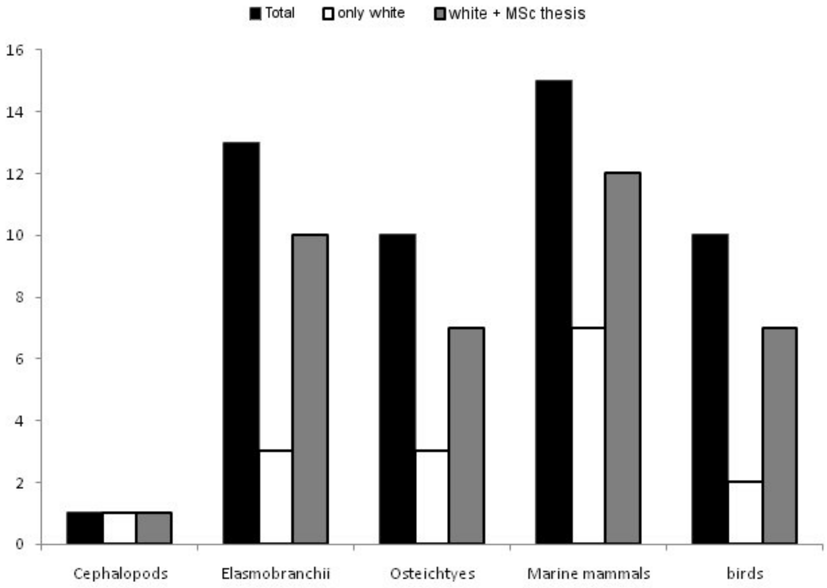

Figure 1. Number of references for each taxa reported in literature: Total; considering only white literature; and considering white literature and MSc theses

of integrating ecological information for the development of management strategies for small pelagics (see for example Velarde *et al*., 2004).

In our evaluation, more than half of the information gathered came from postgraduate theses, mainly MSc. However, the results obtained in these theses could not be found published in journals in ISI or the Google Scholar search engine. This supports the idea described by Lacanilao (1997) and Sáenz-Osuna (2009) that information gathered by graduate dissertations in developing countries are seldom transferred to peer reviewed journals.

This highlights the need that institutions have to produce grey literature and to encourage their staff to prepare the results of their investigations in journal publications. Institutions should also instruct their researchers (authors) about the quality and ethical standards of the journals (Wilbur, 1990) if the main objective is the generation of more useful information and its publication among the scientific community.

CONCLUSIONS

This study shows that grey literature is a useful tool in the scientific work because it contains data that may not be available in commercial scientific journals, giving a wider perspective of the research of our choosing as well as the hypothesis testing process. Important efforts should be placed to increase efforts to publish grey literature in order to avoid the loss of substantial amounts of information due to its inaccessibility.

REFERENCES

Abitia-Cárdenas, L. A. 1992. *Espectro trófico energético del marlin rayado Tetrapturus audax (Philippi, 1887) y marlin azul Makaira mazara (Jordan & Snider, 1901), del área de Cabo San Lucas, BCS, México.* MSc Thesis: Centro Interdisciplinario de Ciencias Marinas-IPN. 76 p.

Aguilar-Castro, N. A. 2004. *Ecología trófica de juveniles del tiburón martillo Sphyrna lewini (Griffin & Smith, 1834) en el Golfo de California.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 111 p.

Aguilar-Palomino, B. 1993. *Espectro trófico del dorado Coryphaena hippurus Linnaeus 1758 (OSTEICHTHYES: CORYPHAENIDAE), capturado en la Bahía de La Paz y Cabo San Lucas, Baja California Sur, México, durante 1990 y 1991*. MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 102 p.

Aguilar-Palomino. B., F. Galvan-Magaña, A. Abitia-Cárdenas, A.F. Muhlia-Melo & J. Rodríguez-Romero. 1998. Feeding aspects of the dolphinfish *Coryphaena hippurus* Linnaeus, 1758 in cabo San Lucas, Baja California Sur, Mexico. *Cien. Mar*., 24: 253-265.

Andrade, Z. 2005. *Hábitos alimenticios del tiburón Carcharhinus falciformis en el Océano Pacífico Oriental. Mast*er Thesis: Centro Interdisciplinario de Ciencias Marinas-IPN. 120 p.

Angulo-Gastélum, U. T. 2008. *Biología reproductiva y efecto del tamaño de colonia del gallito marino Thalasseus maximus en la isla El Rancho, Sinaloa, durante la temporada 2007*. MSc Thesis. Centro de Investigación Científica y de Educación Superior de Ensenada. 53 p.

Arizmendi-Rodríguez, D. I. 2004. *Hábitos alimenticios del pez vela Istiophorus platypterus (Shaw & Nodder, 1791) en el área de Mazatlán Sinaloa, México*. MSc Thesis: Centro Interdisciplinario de Ciencias Marinas-IPN. 89 p.

Arizmendi-Rodríguez, D. I., L. A. Abitia-Cárdenas, F. Galván-Magaña & I. Trejo-Escamilla. 2006. Food habits of sailfish *Istiophorus platypterus* off Mazatlán, México. *Bull. Mar. Sci*., 79: 777-791.

Armendáriz-Villegas, J. 2005. *Hábitos alimenticios del Calamar Gigante (Dosidicus gigas; Orbigny, 1835) en el Centro del Golfo de California durante los años 2002 y 2003*. BSc Thesis. Universidad Autónoma de Baja California Sur. 80 p.

Aurioles-Gamboa, D. & F. García-Rodríguez 1999. Fluctuaciones de la población de lobo marino y la pesquería de sardina en el Golfo de California. 19-22, *In: Resúmenes de la XXIV Reunión Internacional pa-*

ra el estudio de los Mamíferos Marinos. Mazatlán, México.

Aurioles-Gamboa D., F. García-Rodríguez, M. Ramírez-Rodríguez & C. J. Hernández-Camacho. 2003. Interaction between the California sea lion and the artisanal fishery in La Paz Bay, Gulf of California, Mexico. *Cien. Mar.*, 29: 357-370.

Banks, M. A. 2006. Towards a continuum of scholarship: The eventual collapse of the distinction between grey and non-grey literature. *Publishing Res. Quart.*, 22(1): 4-11.

Busquets-Vass, G. 2008*. Variabilidad de isótopos estables de nitrógeno y carbono en piel de ballena azul (Balaenoptera musculus).* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 84 p.

Caraveo, J. 1991. *Hábitos Alimenticios de la "pierna" (Caulolatilus princeps) Jenyns, 1842 (Pisces Branchiosteguidae) en Bahía de La Paz, BCS, México.* BSc Thesis. Universidad Autónoma de Baja Californa Sur. 75 p.

Cassell, K. A. 2005. Report on the 6th international conference o grey literature, New York. *Collection Building*, 24 (2): 70-71

Castillo-Guerrero, J. A. 2003. *Respuestas del bobo de patas azules (Sula nebouxii) a las características del hábitat, con énfasis en las relaciones interespecíficas, en isla El Rancho, Sinaloa, durante la temporada reproductiva 2003*. MSc Thesis. Centro de Investigación Científica y de Educación Superior de Ensenada. 98 p.

Conde-Moreno, M. 2009. *Ecología trófica del tiburón bironche, Rhizoprionodon longurio, en dos zonas del Pacífico Mexicano.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 80 p.

Davis, R. W., N. Jaquet, D. Gendron, U. Markaida, G. Bazzino & W. Gilly. 2007. Diving behavior of sperm whales in relation to behavior of a major prey species, the jumbo squid, in the Gulf of California, Mexico. *Mar. Ecol. Prog. Ser.*, 333: 291–302.

De Castro, P. 2006. Scientists produce and use grey literature, but are they aware of the implications of doing so? *Eur. Sci. Edit.*, 32(4): 95-97.

Del Ángel Rodríguez, J.A. 1997. *Hábitos alimentarios y distribución espaciotemporal de los rorcuales común (Balaenoptera phisalus) y azul (Balaenoptera musculus) en la Bahía de La Paz, BCS, México.* MSc Thesis Centro Interdisciplinario de Ciencias Marinas-IPN. 73 p.

Díaz-Gamboa, R. 2004. *Diferenciación entre Tursiops truncatus costeros y oceánicos en el Golfo de California por medio de isótopos estables de carbono y nitrógeno.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 62 p.

Escobar-Sánchez, O. 2004. *Hábitos alimentarios del tiburón ángel Squatina californica (Ayres, 1859) en el suroeste del Golfo de California, México*. Master's Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 99 p.

Escobar-Sánchez, O., L. A. Abitia-Cárdenas & F. Galván-Magaña. 2006. Food habits of the pacific angel shark *Squatina californica* in the sohutern Gulf of California, México. *Cybium*, 30: 91-97.

Fitch, J.E. & R. Brownell Jr. 1968. Fish Otholits in Cetacean Stomachs and Their Importance in Interpreting Feeding Habits. *J. Fish. Res. Board of Canada*, 25: 2561-2574.

Galvan-Magaña, F., H. J. Nienhuis & A. P. Klimley. 1989. Seasonal abundance and feeding habitats of sharks of the lower Gulf of California, Mexico. *Cal. Fish and Game,* 75: 74-84.

García-Rodríguez, F. J. 1999. *Cambios espaciales y estacionales de la estructura trófica y consumo del lobo marino de California, Zalophus californianus, en la región de las grandes islas, Golfo de California*. MSc Thesis: Centro Interdisciplinario de Ciencias Marinas-IPN. 85 p.

García-Rodríquez, C. & D. Aurioles-Gamboa. 2004. Spatial and temporal variation in the diet of the California sea lion *Zalophus californianus* in the Gulf of California, Mexico. *Fish. Bull.* 102: 47–62.

Gendron, D. 1993 Índice de avistamiento y distribución del género *Balaeneptera* en el Golfo de California, México, durante febrero, marzo y abril de 1988. *Rev. Inves. Cien. Special number SOMEMMA*, 1: 21-29.

Guevara Medina, M. A. 2008. *Variación interanual en los parámetros reproductivos del rabijunco de pico rojo (Phaethon aethereus) en las temporadas 2004 y 2007 en la isla Farallón de San Ignacio, Sinaloa*. MSc Thesis. Centro de Investigación Científica y de Educación Superior de Ensenada. 48 p.

Hacohen-Domene, A. 2007. *Ecología alimentaria del tiburón ballena (Rhincodon typus, Smith 1828) en la costa occidental del Golfo de California, México.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 57 p.

Jaquet, N. & D. Gendron. 2002. Distribution and relative abundance of sperm whales in relation to key environmental features, squid landings and the distribution of other cetacean species in the Gulf of California, Mexico. *Mar. Biol.* 141: 591-601

Jaume-Schinkelm, S. 2004. *Hábitos alimentarios del rorcual común Balaenoptera physalus en el Golfo de California mediante el uso de isótopos estables de nitrógeno y carbono.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 64 p.

Jiménez-Castro, C. M. 1988. *Hábitos alimenticios, requerimientos energéticos y consumo alimenticio del pelicano café en la Bahía de La Paz, B.C.S., México.* BSc Thesis. Universidad Autónoma de Baja California Sur. 62 p.

Ketchum, J. T. 2003. *Distribución espacio temporal y ecología alimentaria del tiburón ballena (Rhincodon typus) en Bahía de La Paz y zonas adyacentes en el suroeste del Golfo de California*. MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 91 p.

Lacanilao, F. 1997. Continuing problems with gray literature*. Environ. Biol. Fishes*, 49: 1-5.

Markaida, U. 2006. Food and feeding habits of jumbo squid *Dosidicus gigas* in the Gulf of California and adjacent waters after the 1997-98 El Niño event. *Fish. Res.* 79: 16-27.

Markaida, U. & O. Sosa-Nishizaki. 2003. Food and feeding habits of jumbo squid *Dosidicus giga*s (Cephalopoda: Ommastrephidae) from the Gulf of California, Mexico. *J. Mar. Biol. Assoc. U.K.*83: 507–522.

Mellink, E., J. Dominguez & J. Luévano 2001. Diet of eastern pacific brown boobies *Sula leucogaster brewsteri* on isla San Jorge, North-Eastern Gulf of California, and an April comparison with diets in the middle Gulf of California. *Mar. Ornithol.,* 29: 23–28.

Mendez-Loesa, I. 2004. *Hábitos alimenticios de los cazones Mustelus californicus y Mustelus lunulatus (Triakidae) en el alto Golfo de California.* BSc Thesis. Universidad Autónoma de Baja California. Ensenada, Baja California. 57 p.

Ochoa-Díaz, M. R. 2006. *Hábitos alimenticios del tiburón martillo Sphyrna zigaena (Linnaeus, 1758) en Baja California Sur*. BSc Thesis. Universidad de Guadalajara. 99 p.

Páez-Osuna, F. 2009. How much and where do Mexican scientist publish their research in environmental science? *Environ. Pollut.,* 157: 1764-1766.

Peláez-Mendoza, A. K. 1997. *Hábitos alimenticios de la Cabrilla Sardinera Mycteroperca rosacea Streets, 1877 (Pices: Serranidae) en la Bahía de La Paz, B.C.S. y zonas adyacentes*. BSc Thesis, Universidad Autónoma Baja California Sur. 62 p.

Pérez Cortés-Moreno, H., G.K. Silber & B. Villa-Ramírez. 1996. Contribución al conocimiento de la alimentación de la vaquita, *Phocoena sinus*. *Cien. Pesq*. 13: 66-72.

Porras-Peters, H. .2004. *Nivel, amplitud y superposición trófica de las colonias de lobo marino Zalophus californianus del Golfo de California, México.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 55 p.

Román-Rodríguez, M.J. 1990. Alimentación de *Totoaba macdonaldi* (Gilbert) (Pisces: Sciaenidae) en la parte norte del Alto Golfo de California. *Ecológica*, 1: 1–9.

Sáenz-Arroyo, A., C.M. Roberts & M. Cariño-Olvera. 2005. Using fisher´s anecdotes, naturalist´s observations and grey literature to reassess marine species at risk: the case of the Gulf grouper in the Gulf of California, Mexico. *Fish. Fish*., 6: 121-133.

Salinas-Zacarías, M. A. 2005. *Ecología de los tursiones, Tursiops truncatus, en Bahía de La Paz, BCS.* PhD Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 102 p.

Salvadeo, C., S. Flores-Ramírez, A. Gómez-Gallardo, S. Jaume-Schinkel, J. Urbán & D. Lluch-Belda. 2007. The Bryde´s whale *(Balaenoptera edeni)* in La Paz Bay, México and its relationship with climatic changes and prey availability. *In*: *Abstracts book of 1st CLIOTOP International Symposium. 3-7 December 2007, La Paz, México, Baja California Sur, México*.

Salvadeo, C. J. 2008a. Importancia trófica de los pelágicos menores en aguas del Golfo de California. *Informe técnico interno del proyecto SEMARNAT-2002-C01-0278.* 14 p.

Salvadeo, C. J. 2008b. *Análisis de la comunidad de odontocetos y la relación con su ambiente en el extremo sur-occidental del Golfo de California, México (2003-2006).* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas- IPN. 63 p.

Sampson, T. L. 2007*. Dieta, posición trofica y variación en la señal isotópica de Mobula thurstoni y Mobula japanica en el suroeste del Golfo de California.* MSc Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 60 p.

Suazo-Guillén, E. .2004. *Biología reproductiva y hábitos de forrajeo del bobo café, Sula leucogaster, en dos islas del golfo de California, 2003 – 2004*. Master Thesis. Centro de Investigación Científica y de Educación Superior de Ensenada., 74 p.

Szteren, D. & D. Aurioles-Gamboa. 2006. Population Status and Trends of the California Sea Lion (*Zalophus californianus californianus*) in the Gulf of California, Mexico. *In: Sea Lions of the World. Alaska Sea Grant College Program AK-SG-06-01*. 384 p.

Tershy, B. R., D. Breese & S. Alvarez-Borrego. 1991. Increase in cetacean and seabird numbers in the Canal de Ballenas during an El Nino-Southern Oscillation event. *Mar. Ecol. Prog. Ser*. 69: 299-302

Thatje, S., J. Laudien, O. Heilmayer & C. Nauen. 2007. Understanding El Niño-The importance of grey literature in coastal ecosystem research and management. *Mar. Pol*., 31(2): 85-93

Torres-Huerta, A. M. 2004. *Distribución, abundancia y hábitos alimenticios de juveniles del tiburón martillo Sphyrna lewini (Griffin & Smith, 1834) en la costa de Sinaloa, México durante el evento de El Niño 1997-98*. MSc Thesis. Universidad del Mar, Oaxaca. 91 p.

Torres-Rojas, Y, A. Hernández-Herrera & F. Galván-Magaña. 2006. Feeding habits of the scalloped hammerhead *Sphyrna lewini* in Mazatlan waters, Southern Gulf of California, Mexico. *Cybium*, 30: 85-90.

Tripp-Valdez, A. 2005. *Ecología Trófica del dorado Coryphaena hippurus (Linnaeus, 1758) en dos áreas del sur del Golfo de California*. Master Thesis. Centro Interdisciplinario de Ciencias Marinas-IPN. 125 p.

Urbán, R. J. & R. S. Flores. 1996. A note on Bryde's Whales (*Balaenoptera edeni*) in the Gulf of California, Mexico. *Reports of the International Whaling Commission,* 46: 453–457.

Vázquez-Morquecho, E. I. 1997. *Distribución espacio-temporal, fidelidad al área y tamaño poblacional del calderón de aletas cortas Globicephala macrorhynchus (Gray 1846) en la Bahía de La Paz, B.C.S. México (1989-1995). BSc Thesis.* Universidad Autónoma de Baja California Sur. 66 p.

Vázquez-Sánchez, R. I. 2008. Hábitos alimenticios del pargo amarillo *Lutjanus argentiventris* (Peters, 1869) (Percoidei: Lutjanidae) en la Bahía de La Paz, México. *Rev. Biol. Mar. Oceanogr*., 43: 295-302.

Velarde, E., E. Ezcurra, M. A. Cisneros-Mata & M. F. Lavín. 2004. Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. *Ecol. Appl.* 14: 607–615.

Velarde, E., M. S. Tordesillas & L.V. Rocio Esquivel 1994 Seabirds as indicators of important fish populations in the Gulf of California. *CalCOFI Rep.* 35: 137-143.

Velasco, P. M. 2003. *Hábitos alimenticios del dorado, Coryphaena hippurus, Linnaeus 1758. (Osteichthyes Coryphaenidae), capturado en Punta Lobos y Los Barriles, B.C.S. México, durante 2000 y 2001*. BSc Thesis. Universidad Autónoma de Baja California Sur. 75 p.

Wilbur, R. L. 1990. Gray literature: A professional dilemma. *Fisheries*, 15(5): 2-5

APPENDIX

Table 1. Bibliographic review of the importance (as percentage) of small pelagic fishes in the diet of predators in the Gulf of California, including reported sampled area (southern=S, center=C, eastern=E, western=W, and entire Gulf of California=GOC), period and relevant observations. References to peer reviewed journal articles are marked in bold, and grey literature classified as: [1] Graduate thesis (BSc); [2] Master degree thesis; [3] Doctoral degree thesis; [4]Technical reports; and [5]Abstracts.

Predator	Area	Period	%	Prey	Observations	Bibliography
Cephalopods						
Jumbo squid (*Dosidicus gigas*)	CS	1995-2000	< 0.3	Clupeidae +Engraulidae (Herrings, Sardines and Anchovies)	%IRR	Markaida *et al*., 2003; Markaida., 2006
	CSW	2002-2003	26	Engraulidae (Anchovies)	%IRR	Armendáriz-Villegas, 2005[1]
Elasmobranchii						
Scalloped hammerhead	SE	2000-2004	0.31	*S. caeruleus* (Pacific sardine)	%IRR	Torres-Rojas *et al*., 2006
(*Sphyrna lewini*)			0.25	Engraulidae		
Juvenile scalloped hammerhead *(Sphyrna lewini)*	CSW	2001-2002	2.52	*S. caeruleus*	%IRR	Aguilar Castro, 2004[2]
			9.49	*Scomber japonicus* (Chub Mackarel)		
Juvenile scalloped Hammerhead *(Sphyrna lewini)*	S	El Niño	1.1	*Ophistonema libertate* (Pacific thread herring)	%IRR	Torres-Huerta, 2004[2]
		97-98				
Scalloped hammerhead *(Sphyrna zygaena)*	SW	2000-2004	2.96	*S. caeruleus*	%IRR	Ochoa-Díaz, 2006[1]
Scalloped hammerhead (*Sphyrna* sp.)	SW	1981-1982		—	Small pelagic fishes were not identified in stomach contents	Galvan-Magaña *et al*., 1989
Pacific sharpnose shark (*Rhizopriononodon longurio*)	S	2003-2004	24.1	*Opisthopterus dovii* (Longfinherring)	%IRR	Conde-Moreno, 2009[2]
Whale shark (*Rhincodon typus*)	W	1995-2005	—	—	no report of predation on small pelagic fishes	Ketchum, 2003[2]; Hacohen, 2007[2]
Smooth hound shark (*Mustelus californicus*)	N	2002	1.7	*Cetengraulis mysticetus* (Pacific anchoveta)	%IRR	Mendez-Loesa, 2004[1]
Smooth hound shark (*Mustelus californicus*)	SW	1981-1982	—	—	Small pelagic fishes were not identified in stomach contents	Galvan-Magaña *et al*., 1989
Smooth hound shark (*Mustelus californicus*)	N	2002	0.12	*C. Mysticetus*	%IRR	Mendez-Loesa, 2004[1]
Silky shark *(Carcharinus falciformis)*	S	1992-1994	0.46	*S. caeruleus*	%IRR	Andrade, 2005[2]
Smooth-tail mobula (*Mobula* sp.)	SW	2002-2007	—	—	no report of predation on small pelagic fishes	Sampson, 2007[2]
Pacific angel shark *(Squatina californica)*	S	2000-2003	0.03	*S. caeruleus*	%IRR	Escobar-Sánchez, 2004[2]
			4.23	*Etrumeus teres* (Round herring)		Escobar-Sánchez *et al*., 2006
Osteichthyes						
Ocean whitefish (*Caulolatilus princeps*)	SW	1986-1987	<5	Clupeidae	%IRR	Caraveo, 1991[1]
Yellow snapper (*Lutjanus argentiventris*)	SW	2003	23.7	*Harengula thrissina* (Pacific Flaitron herring)	%IRR	Vázquez-Sánchez, 2008

Table 1. Continued.

Predator	Area	Period	%	Prey	Observations	Bibliography
Common dolphinfish (*Coryphaena hippurus*)	S	1990-1991	0.2	*S. caeruleus*	%IRR	Aguilar-Palomino, 1993[2]
			1.2	*S. japonicus*		Aguilar-Palomino *et al*., 1998
	S	2000-2003	0.02	Clupeidae	%IRR	Tripp-Valdéz, 2005[2]
			0.22	*H. thrissina*		
			0.03	*Ophistonema sp*		
			0.05	*S. caeruleus*		
			0.17	Engraulidae		
			0.01	*Anchoa sp*		
			0.06	*S. japonicus*		
	SW	2000-2001	42.43	*H. thrissina*	%IRR	Velasco, 2003[1]
			0.01	*S. japonicus*		
Leopard grouper *(Mycteroperca rosacea*)	SW	1991	34	*H. thrissina*	%IRR	Peláez-Mendoza, 1997[1]
			6.18	*Clupeidae*		
			0.67	*Engraulidae*		
Totoaba macdonaldi	N	1986-1989	30.9	*C. Mysticetus*	%IRR	Román-Rodríguez, 1990
Sail fish (*Istiophorus platypterus*)	SE	2002-2003	0.01	*S. caeruleus*	%IRR	Arizmendi-Rodríguez, 2004[2]; Arizmendi-Rodríguez *et al*., 2006
			3	*Ophistonema sp.*		
			0.41	*O. libertate*		
			0.15	*E. mordax*		
			0.41	*S. japonicus*		
Striped marlin (*Tetrapturus audax*)	SW	1988-1989	23.17	*S. caeruleus*	%IRR	Abitia-Cárdenas, 1992[2]
			0.24	*O, libertate*		
			5.32	*E. teres*		
			1.65	*Clupeidae*		
			43.66	*S. japonicus*		
Blue marlin (*Makaira mazara*)	SW	1988-1989	0.14	*S. caeruleus*	%IRR	Abitia-Cárdenas, 1992[2]
			0.003	*E. teres*		
			0.001	*Clupeidae*		
			0.02	*S. japonicus*		
Marine mammals						
California sea lion (*Zalophus californianus)*	SW	1980-1993	0		% relative abundance	Aurioles-Gamboa *et al*., 2003
	CN	1995-1996	10.16	*S. caeruleus*	%IRR	García-Rodríguez, 1999[2]
			5.96	*E. mordax*		García-Rodríguez & Aurioles-Gamboa, 2004
			1.39	*S. japonicus*		
			1.98	*C. mysticetus*		
			1.47	*Trachurus symetricus* (Jack mackerel*)*		
	C	1989-1992	—	Clupeidae	Population trends related with sardine trends	Aurioles-Gamboa & García-Rodríguez, 1999[5]; Szteren *et al*., 2006
	GOC	2002	11.78	*C. mysticetus*	Important prey index	Porras-Peters, 2004[2]

Table 1. Continued.

Predator	Area	Period	%	Prey	Observations	Bibliography
California sea lion (*Zalophus californianus)*			5.61	*T. symetricus*		
			5.47	*S. caeruleus*		
			5.35	*E. mordax*		
			2	*E. japonicus*		
Vaquita *(Phocoena sinus)*	N	1967, 1986-1993	27.2	*Anchoa sp.*	%IRR	Fitch & Brownell, 1968; Pérez-Cortez *et al*., 1996
Bryde's whale *(Balaenoptera edeni)*	SW	1988-1995	—		Feed on small pelagic fishes	Urbán & Flores, 1996
	SW	1988-2006	—		Presence related with sardine trends	Salvadeo et al., 2007[5]
Fin whale *(Balaenoptera physalus)*	SW	1988	—		Feed on small pelagic fish and plankton	Gendron, 1993
	SW	1993-1995	—		Feed on plankton	Del Ángel, 1997[2]
	GOC	2001-2002	—	*S. caeruleus*	Isotopic signal during the warm season	Jaume, 2004[2]
Blue whale *(Balaenoptera musculus)*	GOC	1993-2007	—		Feed on plankton	Del Ángel, 1997[2]; Busquets Vass, 2008[2]
Sperm whale *(Physeter macrocephalus)*	GOC	1998-2004	—		Feed on jumbo squid	Jaquet & Gendron, 2002; Davis *et al*., 2007
Pilot whale *(Globicephala macrorhynchus)*	SW	1989-2006			Feed on jumbo squid	Vázquez-Morquecho, 1997[1]; Salvadeo, 2008[4]
Common dolphin (*Delphinus sp.)*	SW	2003-2006			Feed on small pelagic fishes	Salvadeo, 2008[2]
Bottlenose dolphin *(Tursiops truncatus)*					Feed on fishes and squid	Díaz-Gamboa, 2004[2]; Salinas, 2005[3]
Fish eating cetaceans (*Balaenoptera edeni; Delphinus delphis)*	C	1983-1985			Increased numbers in the Canal de Ballenas during an El Niño event	Tershy *et al*., 1991
Birds						
Heermann's gull *(Larus heermanni)*	C	1983-1992	33	*S. sagax*	% of total prey	Velarde et al 1994[4]; Velarde *et al*., 2004
			65.3	*E. mordax*	Diet predicted from commercial landins	
Elegant tern *(Sterna elegans)*	C	1983-1992	24	*S. sagax*	% of total prey	Velarde et al 1994[4]; Velarde *et al*., 2004
			70	*E. mordax*	Diet predicted from commercial landings	
			3	*S. japonicus*		
Red-billed tropic bird *(Phaethon aethereus)*	SE	2004-2007	2.3	*O. libertate*	% of total prey	Guevara-Medina, 2008[2]
Royal tern *(Thalasseus maximus)*	SE	2007	29	*Anchoa sp.*	% of total prey	Angulo-Gastélum, 2008[2]
			20	*C mysticetus*		
Brown booby *(Sula leucogaster)*	C	1998-2000	2.4	*O. libertate*	% of total prey	Mellink *et al*., 2001
			1	*Lile stolifera*	San Jorge island	
			3.4	Clupeidae		
			6.6	*S. japonicus*		
			10.2	*Anchoa sp.*		

Table 1. Continued.

Predator	Area	Period	%	Prey	Observations	Bibliography
Brown booby *(Sula leucogaster)*			44	*C. mysticetus*		
	C	1999-2000	5.6	Clupeidae	% of total prey	Mellink *et al*., 2001
			18	*Anchoa sp.*	San Idelfonso and San Pedro Martir island	
			49	*C. mysticetus*		
			15	*S. japonicus*		
Blue booby *(Sula nebouxii)*	C	2003	64	*O. libertate*	Regurgitated frequency	Castillo-Guerrero, 2003[2]
			2	*Anchoa exigua*		
			13	*C. mysticetus*		
Brown booby *(Sula leucogaster)*	C	2003-2004	27.4	*S. caeruleus*	% of total prey	Suazo-Guillén, 2004[2]
			2.2	*Leuresthes sardina*		
			1.1	*O. libertate*		
			0.6	*E. teres*		
			20.6	*C. Mysticetus*		
			30.9	*Anchoa sp*		
Brown pelican *(Pelecanus occidentalis)*	SW	1984-1986	2.8	*H. thrissina*	Regurgitated frequency	Jiménez-Castro, 1988[1]
			1.95	*O. libértate*		
			15	*Anchoa ischana*		
			42	*S. japonicus*		
Marine birds *(S. nebouxii; S. leucogaster)*	C	1983-1985			Increased numbers in the Canal de Ballenas during an El Niño event	Tershy *et al*., 1991

Table 2. List of Peer review journals with their ISSN, impact factor and their policy on grey literature

Journal	Impact Factor (2008)	Policy on grey literature
Fish and Fisheries	3.158	Not allowed
Fisheries Oceanography	2.812	Not allowed
Reviews in Fisheries Science	2.375	Not allowed
Canadian Journal of Fisheries and Aquatic Sciences	2.276	Only MSc and PhD thesis allowed
Reviews in Fish Biology and Fisheries	1.792	Not Specified
Fisheries	1.712	Not Specified
Ices Journal of Marine Science	1.661	Not allowed
Transactions of the American Fisheries Society	1.569	Not allowed
Marine and Freshwater Research	1.5	Not allowed
Fisheries Research	1.434	BSc & MSc thesis not allowed
Fisheries Management and Ecology	1.404	Not Specified
Journal of Fish Biology	1.246	Not allowed
Fishery Bulletin	1.19	Not Specified
California Cooperative Oceanic Fisheries Investigations Reports	1.091	Not Specified
North American Journal of Fisheries Management	0.811	Not allowed
Fisheries Science	0.781	Only PhD thesis allowed
Journal of Applied Ichthyology	0.638	Not Specified

***CICIMAR Oceánides* 26(1): 51-62 (2011)**

ARTÍCULO POR INVITACIÓN

ECOSYSTEM-LEVEL EFFECTS OF THE SMALL PELAGICS FISHERY IN THE GULF OF CALIFORNIA

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ABSTRACT. Documentary scientific evidence supports the notion that the small pelagics fishery in the Gulf of California does not measurably affect the physical habitat or the functional relationships between the species comprising the pelagic ecosystem. Also, there is little information that suggests any negative effects of the small pelagic fishery operations on critically endangered, endemic species, *i.e.*, vaquita and totoaba. Under the current management regime, small pelagics fishery in the Gulf of California has recovered twice from collapses during the last 30 years. Although the small pelagics abundance varies greatly, the long-term productivity of the target species and the structure and function of the pelagic ecosystem are not compromised because the fishery relies on a suitable logistic and administrative platform, which is consistent with international standards for responsible fisheries, precautionary approach and ecosystem-based fisheries management principles.

Keywords: Climate change, collapse, ecological modeling, Pacific sardine, recovery, trophic relationships.

Efectos a nivel ecosistema de la pesquería de pelágicos menores en el Golfo de California

RESUMEN. Existe documentación científica suficiente como para suponer que la pesquería de pelágicos menores en el Golfo de California no afecta significativamente el hábitat ni las relaciones funcionales entre las especies que conforman el ecosistema pelágico del cual depende. Tampoco hay información que indique interferencia entre las operaciones de la pesquería de pelágicos menores y especies amenazadas o en peligro de extinción, específicamente la vaquita y la totoaba. Adicionalmente, bajo el sistema actual de manejo, esta pesquería no sólo ha logrado recuperarse exitosamente en dos ocasiones durante los últimos 30 años sino que también cuenta con la plataforma logística y administrativa necesarias para asegurar un aprovechamiento racional de las especies objetivo y la productividad de la propia actividad en el largo plazo, en congruencia con los estándares internacionales de pesca responsable y enfoque precautorio.

Palabras clave: Cambio climático, colapso, modelación ecológica, , recuperación, relaciones tróficas, sardina monterrey.

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APPROACH

The most common way of investigating functional relationships between species is based on their feeding habits. Within an ecosystem, some species interfere with others through competition and predation, while others benefit from feeding in different systems across their migratory routes, compelling other species to follow them as they migrate. This situation results in a complex trophic web in each ecosystem with its own particular dynamic, defined by the less vagrant species with bridges formed to other webs by the most mobile species.

In the Gulf of California, functional relationships have been studied with two complementary approaches. The first involves a description of the feeding habits for the main commercial species (fish resources) and conservation-relevant species (*i.e.*, marine tetrapods). The second approach is a more holistic one, based on the mathematical representation of energy and biomass fluxes among the functional groups in the ecosystem (herbivores, carnivores, planktophages, etc.), that allows for the examination of effects of fishing at levels of integration above that of the population (Christensen & Walters, 2004). During the last decade, several trophic models of various regions of the gulf have been developed (*e.g.*, Arreguín-Sánchez *et al*., 2002; Arreguín-Sánchez & Calderón-Aguilera, 2002; Morales-Zárate *et al*., 2004; Lercari & Arreguín-Sánchez, 2009).

In the gulf's pelagic ecosystem, the dominant functional fish group in terms of biomass consists of the small pelagics, and within this group the Pacific sardine (*Sardinops sagax caeruleus*) is the most abundant species, representing on average 55% of the total catch (Table 1; Figure 1). This species is therefore of great economic and ecological importance. Small pelagics, marine amniotes and some invertebrates such as shrimps have been the focus of the aforementioned approaches during the last 30 years. Bakun *et al.* (2009) regard trophic in-

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Table 1. Catch composition (%) of small pelagics in the main landing ports in the Gulf of California; A) Mazatlán Sinaloa; B) Yavaros y Guaymas, Sonora; extracted from Instituto Nacional de la Pesca (2006).

Species/Authority	Common name	A	B
Opisthonema libertate (Berry & Barret)	Pacific thread herring	30	+17.4
Opisthonema bulleri (Regan)	Slender thread herring	30	17.4
Opisthonema medirastre (Berry & Barret)	Middling thread herring	30	17.4
Cetengraulis mysticetus (Günther)	Pacific anchovy	70	20.7
Sardinops sagax caeruleus (Jenyns)	Pacific sardine	-	55.9
Scomber japonicas (Gmelin)	Chub mackerel	-	3.8
Engraulis mordax (Girard)	Californian anchovy	-	0.7
Etrumeus teres (DeKay)	Round herring	-	0.8
Oligoplites spp.	Longjaw leatherjack	-	0.7

teractions, particularly the one where sardines are a source of food for predators, as key elements that should be incorporated into any ecosystem-based management system.

There is a increasing concern regarding the impact that fishing foraging species may have on the structure of marine ecosystems (Bakun *et al*., 2009), however efforts for integrating available evidence for some ecologically relevant systems are lacking. In the present study we made a thorough literature survey in order to determine whether there is documentary information suggesting that the small pelagics fishery negatively affects the throphic relationships in the pelagic ecosystem of the Gulf of California, or the critically endangered species and their habitats that are or might be in contact with this fishery. We also examined the role of the small pelagics management system on the fishery behavior and productivity. In the following sections we present a review of tropho-dynamic studies, ecological modeling of small pelagics and environmental impact of this fishery in the Gulf of California, as well as our interpretations of this research in the context of ecosystem functional relationships and fisheries management.

FUNCTIONAL RELATIONSHIPS

Invertebrates and fish

There are more than 40 scientific publications on the feeding habits of several species in different zoological groups that feed upon small pelagics in the region. These references (mostly grey literature) are summarized in (Tripp-Valdéz *et al*., 2010).

With respect to invertebrates, the jumbo squid (*Dosidicus gigas*) is considered to be the

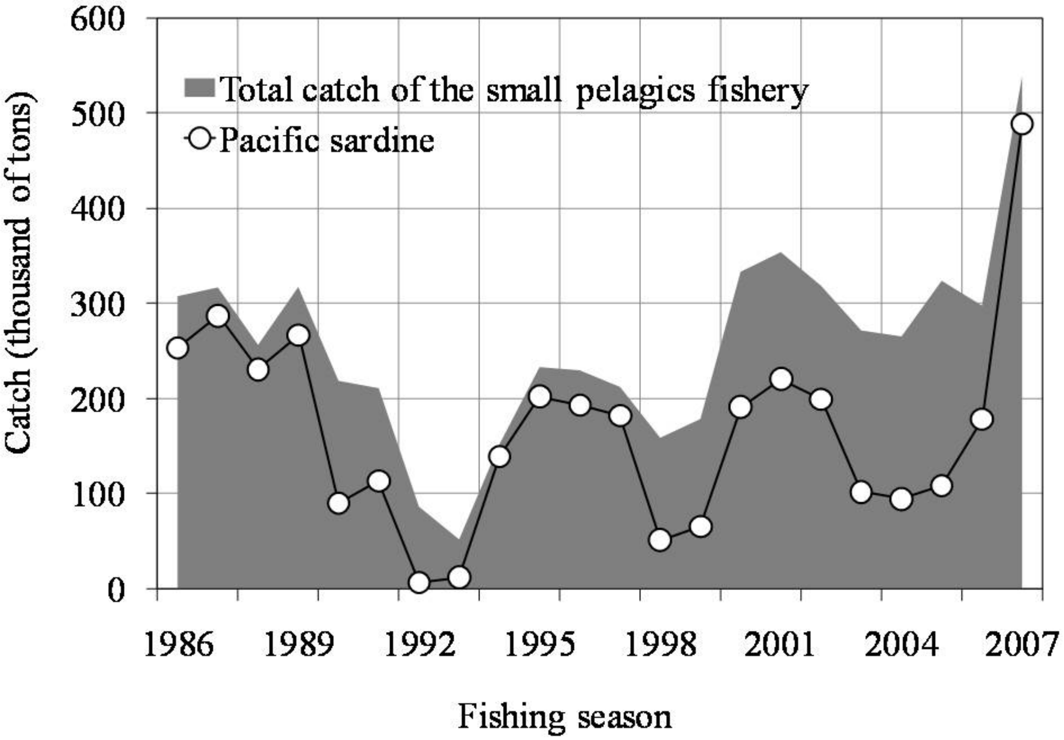


Figure 1. Comparison between the historical total catch of the small pelagics fishery in the Gulf of California and that of the Pacific Sardine in the same region.

most abundant cephalopod in the gulf (>45,000 tons per year since 2000). Its migratory movements, and therefore the interannual variation of its abundance, are thought to be linked to environmental fluctuations, interactions with other fisheries (Instituto Nacional de la Pesca, 2006) and the seasonal displacement of small pelagics inside the gulf. However, these hypotheses have yet to be proved. For instance, descriptions of the jumbo squid's diet indicate that mychtophid fish and red crabs are the best represented groups while sardines, although present, do not seem to be such an important (Figure 2) or ecologically relevant component (Rosas-Ruíz *et al.,* 2008). Nevertheless, Bakun *et al*. (2009) suggested that the migratory movement of jumbo squid could influence the mortality and growth rates of sardines, in addition to their reproductive success.

From the available literature, ten species have been identified that feed upon small pelagics. Six of these species include the pacific sardine in less than 3% (Index of Relative Importance) of their diet while just one, the striped marlin (*Tetrapturus audax*) has the sardine representing 24% of its diet. The remaining species feed upon other small pelagics (*O. libertate*, *E. teres,* and *Opisthonema* spp.) in no more than 5% of their diets, except for the sharpnose shark (*Rhizopriononodon longurio*) and the yellow snapper (*Lutjanus argentiventris*) for whom small pelagics comprise up to 25% of the diets, however their preys -*Opisthopterus dovii* and *Harengula thrissina*, respectively, are not target species. Moreover, it is well documented that large pelagics that prey on the sardine show distribution patterns similar to those of teutophagous cetaceans (Salvadeo, 2008a).

There is evidence of a strong seasonal signal in the abundance of striped marlin in the southwest gulf, similar to that observed for ichthyophagous cetaceans such as the common dolphin (*Delphinus* spp.), with a winter/spring maximum (Figure 3) coinciding with the southward movement of the sardine (Lluch-Belda *et al.,* 1986; Cisneros Mata *et al.*, 1995a; Hammann *et al.,* 1998; Ortega-García *et al*., 2005; Salvadeo, 2008b). It is noticeable that the period in which the stomach contents of the striped marlin were sampled (1988-1989) was anomalously cold, consistent with an increase in sardine abundance and residence time in the southern portion of the gulf (Lluch-Belda *et al.*, 2005). In terms of functional relationships this can be translated into higher, yet casual, food availability for large pelagic predators.

Marine amniotes

Marine amniotes have a larger proportion of small pelagics in their diets, and the avai-

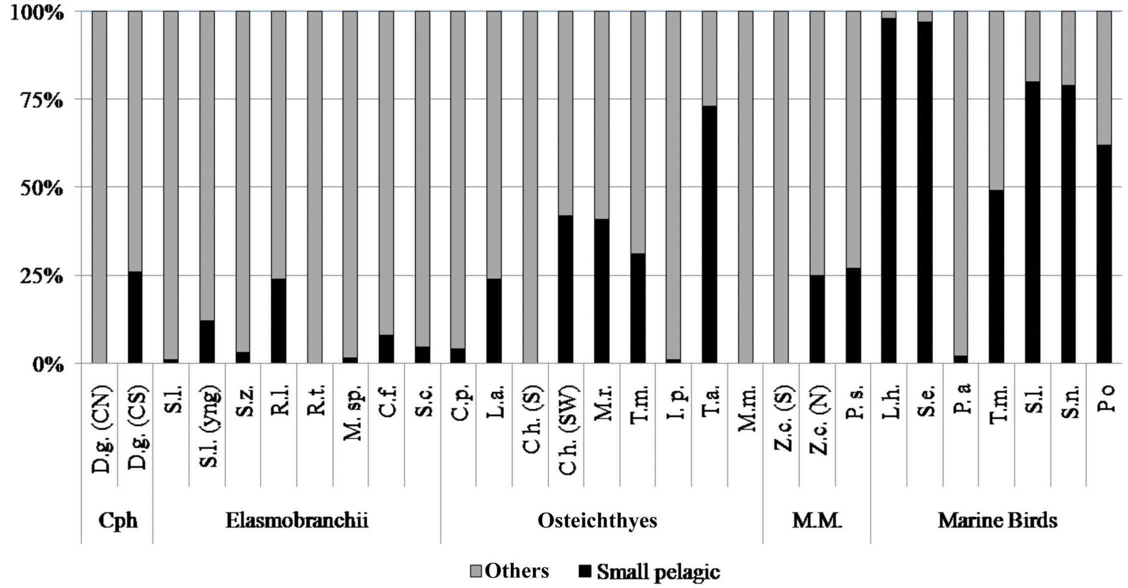
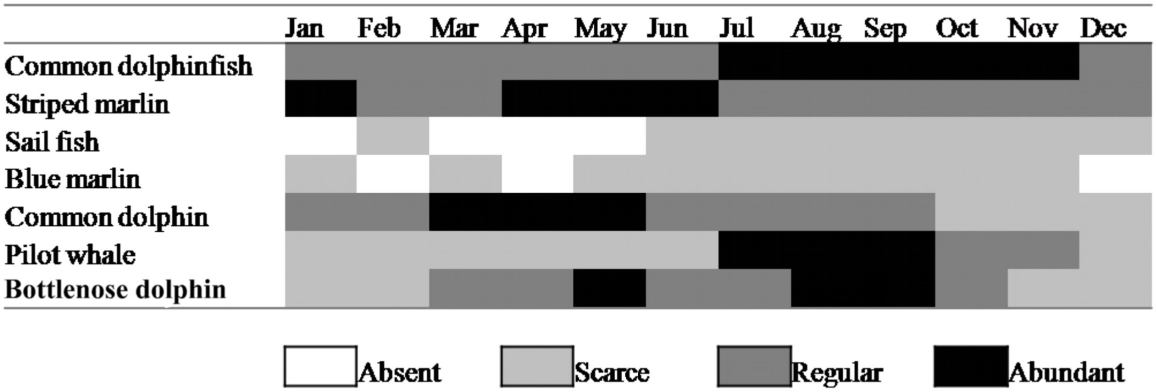


Figure 2. Percentage prevalence of small pelagics (sardine and anchovy = Clupeidae) in the diet of large pelagics in the Gulf of California; Chp (cephalopods), MM (marine mammals), D.g. (*Dosidicus gigas*), S.l. (*Sphyrna lewini*), S.z. (*Sphyrna zygaena*), R.l. (*Rhizoprionodon longurio*), R.t. (*Rhincodon typus*), M.sp (*Mustelus* sp.), C.f. (*Carcharhinus falciformis*), S.c. (*Squatina californica*), C.p. (*Caulolatilus princeps*), L.a. (*Lutjanus argentiventris*), C.h. (*Corhyphaena hippurus*), M.r. (*Mycteroperca rosacea*), T.m. (*Totoaba macdonaldi*), I.p. (*Istiophorus platypterus*), T.a. (*Tetrapturus audax*), M.m. (*Makaira mazara*), Z.c. (*Zalophus californianus*), P.s. (*Phocoena sinus*), L.h. (*Larus heermanni*), S.e. (*Sterna elegans*), P.a. (*Phaethon aethereus*), T.m. (*Thalasseus maximus*), S.l. (*Sula leucogaster*), S.n. (*Sula nebouxii*), and P.o. (*Pelecanus occidentalis*); CN (center-north), CS (center-south), yng (young), S (south), SW (southwest), N (north) from the Gulf.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Common dolphinfish	▒	▒	▒	▒	▒	▒	■	■	■	■	■	▒
Striped marlin	■	▒	▒	■	■	■	▒	▒	▒	▒	▒	▒
Sail fish	□	░	□	□	□	░	░	░	░	░	░	░
Blue marlin	░	□	░	□	░	░	░	░	░	░	░	□
Common dolphin	▒	▒	■	■	■	▒	▒	▒	▒	░	░	░
Pilot whale	░	░	░	░	░	░	■	■	■	▒	▒	░
Bottlenose dolphin	░	░	▒	▒	■	▒	▒	■	■	▒	░	░

□ **Absent** ░ **Scarce** ▒ **Regular** ■ **Abundant**

Figure 3. Temporal occurrence of large pelagic species for sport fishing in Cabo San Lucas area: common dolphinfish (*Coryphaena hippurus*), striped marlin (*Tetrapturus audax*), sail fish (*Istiophorus platypterus*) and blue marlin (*Makaira mazara*), extracted and modified from Ortega-Garcia *et al*. (2005); marine mammal occurrence in the southwest Gulf of California: common dolphin (*Delphinus* sp.), pilot whale (*Globicephala macrorhynchus*) and bottlenose dolphin (*Tursiops truncatus*); extracted from Salvadeo (2008a).

lability of these species as a food resource is related to their seasonal movement across the gulf. For two out of the seven marine birds (*Larus heermanni*) and (*Sterna elegans*) that feed upon small pelagics, the northern anchovy (*E. mordax*) corresponds to 70% of their total consumption. However, this species represents less than 1% of the total catch of small pelagics in the central Gulf of California. The pacific sardine comprises the remaining 30%. Furthermore, depending on their relative abundance, there seems to be a shift in the proportion of sardines and anchovies in the birds' diets: when sardines are abundant, the anchovy becomes a less important food item and vice versa (Velarde *et al.,* 1994), resulting in a constant food supply regardless of the ecological regime.

The diets of the blue-footed booby (*Sula nebouxii*) and the brown booby (*Sula leucogaster*) in the central gulf are mainly (57%) composed of Peruvian anchovy, which comprises 20% of the total catch of small pelagics in the region. In one of only two available studies addressing the feeding habits of the brown booby (Suazo-Guillén, 2004), The Pacific sardine represents 41% of the diet. The rest of the dietary components of these and other marine birds such as the brown pelican (*Pelecanus occidentalis*) the royal tern (*Sterna maxima*) and the red-billed tropic bird (*Phaethon aethereus*) consist of small pelagics that are poorly represented or absent in the total catch *Anchoa* spp.*, A. exigua, A. ischana* and *Lile stolifera*. This suggests that the brown booby has sufficient trophic plasticity to switch between different preys according to their spatial availability, and even though the small pelagics fishery and marine birds do share some target species, there is no evident interference between them due to the low proportion of these kinds of fish in the catch and in their diets, respectively.

Regarding marine mammals, the sea lion (*Zalophus californianus*) has no dietary preference for small pelagics and feeds upon benthic and mesopleagic species. However, *S. sagax* is the main food item in four of the 13 breeding colonies of sea lions situated around the Midriff Islands, where the size of local sea lion populations (which was declining until 2004; Szteren & Aurioles, 2006) is positively correlated with that of the sardine. For this reason it is imperative to highlight the factors affecting the abundance of small pelagics in the Gulf of California.

The effects of fishing on the population dynamics of small pelagics in the Gulf of California are not fully understood (Wolf, 1992; Cisneros-Mata *et al.*, 1995a). However, there is little doubt about the influence of environmental conditions, particularly the interannual variability (*i.e.*, El Niño/La Niña), on the abundance of these species (Lluch-Belda *et al.*, 1989, 1995; Nevárez-Martínez *et al.*, 2001). To illustrate this relationship, Lluch-Cota *et al.* (1999) forecasted with reasonable accuracy the sharp decline (1992) and later recovery (1996) of the pacific sardine in the Gulf of California using an upwelling index, the sea surface temperature and the reproductive success of the stock (derived from the abundance of eggs and larvae) as the only predictors for the total catch. This may indicate that the observed negative population trend in the four sea lion breeding colonies indirectly responds to environmental fluctuations, in the form of changes in prey availability, more than to dynamics of the fishing effort exerted on small pelagics.

Small pelagics are also important food

items in the diets of common dolphins (*Delphinus delphis*) and (*D. capensis*, Salvadeo, 2008b) and the Bryde's whale (*Balaenoptera edeni*, Urban & Flores, 1996). Similar to what is observed in sea lion breeding colonies, there is a correlation between the presence of these whales and oceanographic interannual variability, mediated by the sardine stock abundance (Salvadeo *et al.*, 2007). Larger cetaceans such as the sperm whale (*Physeter macrocephalus*) and the pilot whale (*Globicephala macrorhynchus*) chiefly consume squid (Jaquet & Gendron, 2002; Salvadeo, 2008b), while the blue whale (*Balaenoptera musculus*) eats zooplankton (Busquets-Vass, 2008). However, species such as the fin whale (*Balaenoptera physalus*) and the bottle-nose dolphin (*Tursiops truncatus*) may benefit from having small pelagics as a dietary component (Gendron, 1993; Jaume, 2004; Salinas, 2005). Fifteen out of 30 cetacean species observed in the Gulf of California are occasional visitors, and of the remaining half only three species, the most abundant ones in the region, feed upon small pelagics in addition to many other groups. None of these predators are included as threatened or endangered on international conservation lists.

Critically endangered species

Regarding the functional relationship between small pelagics and endangered species such as the vaquita (*Phocoena sinus*) there are some available studies that describe feeding habits (for instance, Culik 2004 and www.vaquitamarina.org), although most of them are based on no more than four original articles (Fitch & Brownell, 1968; Silber, 1990; Vidal *et al.,* 1995; Pérez-Cortés Moreno *et al.*, 1996). Only the latter mentions the presence of two small pelagics in the vaquita's diet: the slender anchovy *(A. ischana*) and the gulf anchovy (*A. helleri*) neither of which have been registered by catch or incidental catch in the Gulf of California small pelagics fishery. Moreover, the vaquita is considered to be an opportunistic consumer, preying upon small demersal fish and invertebrates such as the squid.

Another species that is endemic to the Gulf of California, and regarded as critically endangered by the International Union for the Conservation of Nature is the totoaba, (*Totoaba macdonaldi*) which in its adult stage preys upon small pelagics, particularly the pacific sardine (Román-Rodríguez, 1990). The low population numbers of the totoaba are attributable to effects from different factors such as habitat loss, incidental catches of the shrimp fishery, poaching and natural environmental changes (Cisneros-Mata, 1995b; Lercari & Chávez, 2007). Regarding the latter cause, it has been suggested that certain large-scale climate patterns observed over the Mexican Pacific are positively correlated with regional regimes of sea temperature in the upper Gulf of California. The ecological effects of such changes may be revealed, via trophic web and reproductive success, in the sardine stock abundance and therefore in its availability as prey. The importance of each of these factors on the totoaba's abundance is currently unknown. However, the relative weight of the functional relationship between this species and the sardine is determined by factors that are unrelated to small pelagics fishery.

Ecological modelling

There are several studies addressing the dynamics of trophic flows in the Gulf of California, but only four explicitly including the small pelagics (*i.e.*, *S. sagax*, Arreguín-Sánchez & Calderón-Aguilera, 2002; Arreguín-Sánchez & Martínez-Aguilar, 2004; Rosas-Ruíz *et al.*, 2008; Lercari, 2006). In the first one, the authors recognized environmental variability as a key element for deriving stock biomass estimations for the pacific sardine in the pelagic ecosystem. The second one represents an improvement of the previous model. The authors modified the sardine´s vulnerability to predation (*i.e.*, changes in predation rate on sardines) and directly incorporated the sea surface temperature and upwelling index as forcing factors on the sardine's natural mortality. Although such amendments reduced the magnitude of the residuals between the observed and estimated biomass, they did not help to capture the main signals observed in the biomass time series for the sardine. This may be due to the internal structure of the current model, which only allows the incorporation of forcing factors in a linear manner. Del Monte-Luna *et al*. (2007) suggested that changes in sardine abundance over time do not entirely rely on the trophic flow dynamics within the ecosystem, but instead on the non-linear effects of temperature and upwelling on the sardine stock, particularly on its reproductive success (Lluch-Cota *et al.*, 1999).

The third study addresses the role of the giant squid in the pelagics ecosystem in the middle of the Gulf of California. The authors highlight that there is no significant functional relationship between the two species despite the fact that small pelagics are part of the diet of the giant squid. The last of these works explores the effects of fishing (including small pelagics fishery) on different species inhabiting the upper gulf, *i.e.*, vaquita and totoaba. The results indicate that small-scale fishery and shrimp fishery directly interfere with these two species through fishing mortality, and indirectly through trophic flows. Small pelagics fishery, nonetheless, appeared to be harmless (Lercari, 2006).

Impacts on habitat and selectivity

Two of the less desirable effects of any fishery are alterations in habitat and the direct or incidental mortality of non-target species. Some fishing gears and fishing operations, such as the trawling nets, have the potential to directly affect the immediate benthic habitat and its occupants by traction over the sea floor. Moreover, because of the low selectivity of the equipment, several other species are caught in addition to the commercial sought ones during fishing operations. Such incidental catches may become significant when species have biological traits that render them more vulnerable to external perturbations or when their population numbers are extremely low.

In general, the fishing operations used for small pelagics fishery are virtually harmless to the habitat and to other species because they are performed at the core of the water column, between depths of 30 m and 200 m, using surface or mid-water-column purse seine nets that directly target small pelagics. For example, the Pacific sardine fishery in Washington State (15,000 metric tons in 2002) extracts no more than four non-target species whose total numbers, on average, do not exceed 1000 individuals per year, with most of these being returned alive to the water (Washington Department of Fish and Wildlife, 2002). In Australia, the incidental catch of purse seine nets is negligible. Even when using mid-water trawling nets, the by-catch represents less than 1% of the total catch (Australian Fisheries Management Authority, 2005).

In the Gulf of California, interference with other fisheries and the environmental effects of the small pelagics fishery are minimal. In this region, purse seine nets are deployed at depths between 40 m and 100 m. Additionally the characteristics of fishing gear and boats are regulated by law (NOM-003-PESC-1993) to minimize the extraction of juvenile individuals. According to at-sea direct sampling and interviews with fishermen, discarding and incidental fishing rarely occur. Discards are generally comprised of the same target species and take place when the size of the fish school surpasses the vessel's storage capacity. Besides small pelagics, the purse seine fishing fleet may capture other species such as the jumbo squid and *Oligoplites* spp., which account for no more than 1% of the total catch (Instituto Nacional de La Pesca, 2006).

Another potentially adverse ecological effect caused by fishing activities is the reduction of a stock´s recovery potential when exploited species are driven to very low population levels (depensation or Allee effect) because this may further accelerate the collapse. In gregarious species such as small pelagics, depensation may weaken the aggregation capacity of the organisms, which then would tend to associate with other species to form dense schools (Morales-Bojórquez & Nevárez-Martínez, 2005). In the case of sardines, low probability of egg fertilization is a consequence of depensation (Cisneros-Mata *et al.*, 1995a). Nevertheless, the estimated threshold value for negative effects on the population growth of the species in the Gulf of California is considerably below the historical minimum (1993-1994) of spawning and adult abundance (Morales-Bojórquez & Nevárez-Martínez, 2005). In summary, there is no available evidence that the pacific sardine had or will display the Allee effect in the near future.

Regarding the relationship between the small pelagics fishery and threatened or critically endangered species, there is no documented evidence of incidental mortality or any other kind of harm. It is possible that the northern limit for the geographic distribution of the Pacific sardine in the East coast of the gulf (Rodríguez-Sánchez & Ponce-Díaz, 1986) is located near (+100 km) a zone where one vaquita was once sighted, southwest of Punta Peñasco. However, the northern terminus of the geographic distribution for the commercial catch of small pelagics is relatively far from the historical southern limit of the vaquita (Figure 4).

With respect to other vulnerable species, simple matching of distribution maps suggests that the geographic range of *T. macdonaldi* overlaps with that of the commercial fleet that fishes small pelagics. However, the *modus operandi* of the purse seine fishery and the physical characteristics of its fishing gear have little or no effect on the sea floor (Fletcher & Head, 2006), where the entire life cycle of the totoaba takes place (Cisneros-Mata *et al.*, 1995b, 1997). Therefore, this species is out of reach of the purse seine nets. The observed fishing mortality for this species is a result of the shrimp fishery by-catch, gill nets from the small-scale fishery and poaching (Pedrín-Osuna *et al.*, 2001). Other factors unrelated to the small pelagics fishery may play an important role in regulating the totoaba population; such factors include the loss of spawning habitat resulting from a reduction in the discharge volume from the Colorado River and natural climatic oscillations (Lercari & Chávez, 2007).

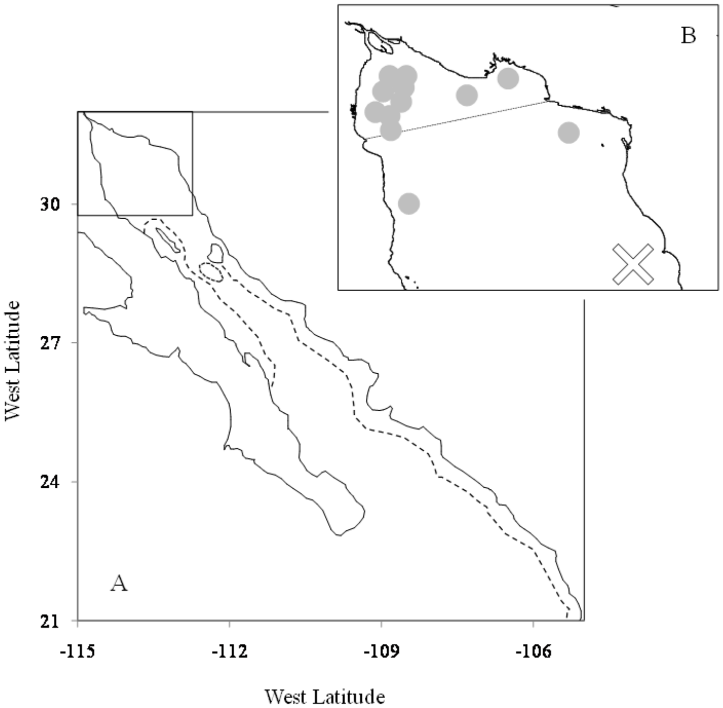


Figure 4. (A) Geographical distribution of the commercial pelagics fishery in the Gulf of California (dotted line). (B) Upper Gulf of California Biosphere Reserve and Colorado River Delta (solid line); sighting distribution of the vaquita (*Phocoena sinus*; solid circles) and observed southern limit of the Pacific sardine in the Gulf of California (white cross). Taken from INP (2006); Map Library from the National Commission of Natural Protected Areas CONANMP, http://www.conanp.gob.mx); Culik (2004) www.vaquitamarina.org, and Rodríguez-Sánchez and Ponce-Díaz (1986).

Fish productivity and fishery management

To realize the recovery capacity for a natural population, the population must transit from low to high levels of abundance or re-colonize its original range after a substantial reduction in geographic distribution. These events are fueled by a combination of factors such as the biological traits of the species, the condition of the immediate environment and the implementation of appropriate and adequate management actions. A common feature that characterizes small pelagics around the world is their large abundance fluctuations, sometimes unrelated to fishing dynamics, in time scales ranging from the interannual to multi-decadal that are synchronized with the expansion and contraction of populations along their geographical range (Lluch-Belda *et al.*, 1989; Chávez *et al.*, 2003).

The small pelagics in the Gulf of California are no exception. During the history of the fishery in the region, the total catch has shown drastic reductions. The first and most important drop was registered in the early 1990's, just before catches reached a historical maximum (1988-1989). In no more than four years the catch dropped from 294,000 tons to 7,000 tons (97% reduction), which, under the current context of fishery management, may be considered a severe collapse. We should clarify that the sardine did not really collapse in the strict sense (population decline to dangerously low levels as a response to uncontrolled, intense, fishing). Instead, schools were restricted to their usual distribution around the Midriff islands and did not expand south to the customary fishing grounds along the eastern coast of the gulf (Lluch-Cota *et al.*, 2007; Bakun *et al.*, 2009).

By the mid 1990's yields had increased to 215,000 tons. Assuming that in this case the total landing of sardines may be used as an index of abundance, then the population would have recovered by 75%. The second reduction occurred a few years later (1998-2000), when the catch dropped to 55,000 tons (a 74% reduction). Between 2000 and 2003, landings built up to 203,000 tons, representing a 94% recovery relative to the previous maximum. Since then, the total catch of small pelagics has shown a positive trend. It must be stressed that after 1990, the fishing effort has been fairly constant (Instituto Nacional de La Pesca, 2006).

Although this situation indicates that the fluctuations in the stock of small pelagics may not be fully explained by the dynamics of the fishing effort, these changes have been attributed to the effects of fishing and to the competition between small pelagics and other species (Cisneros-Mata *et al*., 1995a). Alternatively, Lluch-Belda *et al.* (1986, 1989 and references thereafter) linked these fluctuations to environmental stress, manifested as spatial displacements of the adult stock (Rodríguez-Sánchez *et al.*, 2002) and as variations in spawning activity (Morales-Bojórquez & Nevárez-Martínez, 2005). Whatever the cause, the Mexican government along with the fishing industry, NGOs and the academic sector have jointly defined and implemented different management actions aimed at the stock's recovery and maintenance of its long term biological potential, based on quantitative population assessments and frequent fishing surveys that determine the success of recruitment . Furthermore, there is sufficient information available for applying proactive management measures in accordance with international standards for a precautionary approach. Under such management schemes, the populations of small pelagics in the Gulf of California have successfully recovered twice from "collapsing" during the last 20 years. Whether such fluctutions are part of the stock natural variability, fostered by the current management regime, or a combination of both, is not yet fully understood.

After the dramatic decline in 1990, specific management actions included reducing the industrial fishing fleet by half (from 77 to 32 boats), establishing the length at first catch for the principal target species and closing areas (*i.e*., Loreto Marine Park) to fishing (either totally or partially) during August and September in order to protect the spawning stock. Currently the exploitation of small pelagics in Mexico is regulated by Mexican Official Norm NOM-003-PESC-1993. This norm limits the amount of fishing north of 21° N, including the Gulf of California, and authorizes the substitution of active fishing boats with new and improved ones with better refrigeration systems. In addition, the norm specifies the length at first catch for the Pacific sardine (150 mm), the slender thread herring (160 mm) and the anchovy (100 mm). The effectiveness of such actions can be corroborated with the magnitude of landings during 2010 (surpassing 500,000 tons), the number of active fishing boats (which oscillates between 26 and 32), and the proportion of individuals below the legal length (no more than 30%) that are incidentally caught.

On the other hand, given the large variations in stocks of small pelagics over time, it may be inadequate to define target and limit reference points by fixing catch quotas. Instead, management actions based on harvest rates (catch-biomass ratio), without compromising the stock productivity, may be more appropriate (Caddy & Mahon, 1995; Bakun *et al.*, 2009). For the Pacific sardine, for instance, this ratio (proportional to fishing mortality) must not exceed a threshold value of 0.26 per year, and the proportion of individuals below 150 mm in the total catch should not be greater than it currently is (30%). For the rest of the small pelagic species, there exist reliable estimates for reference points or, at least, the necessary information to derive them from survey data. As for other relevant reference points, the minimum viable (spawning) population size of the Pacific sardine is estimated to be 287 million individuals and the historically observed minimum is ~1000 million (Morales-Bojórquez & Nevárez-Martínez, 2005).

Additionally, every three months, the fishing and academic sectors and federal authorities gather together to analyze developments in the small pelagics fishery on the basis of information generated from constant stock and environmental monitoring and, if necessary, to adopt proper management actions in a consensual manner. Such a scheme has created a cooperative political climate, noticeable not only in the common approval of management actions but also in the financial support given to regional fisheries research from the fishing industry.

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REFERENCES

Arreguín-Sánchez, F. & L.E. Calderón-Aguilera. 2002. Evaluating harvesting strategies for fisheries in the Central Gulf of California ecosystem. *Fish. Centre Res. Rep*., 10:135-141.

Arreguín-Sánchez, F, E. Arcos-Huitrón & E.A. Chávez-Ortíz. 2002. Flows of biomass and structure in an exploited benthic ecosystem in the Gulf of California, Mexico. *Ecol. Model*., 156: 167-183

Arreguín-Sánchez, F. & S. Martínez-Aguilar. 2004. Manejo adaptativo de la pesquería de sardina, *Sardinops caeruleus* del Golfo de California, 1-16. En: Quiñonez-Velázquez C. & J. Elorduy-Garay (Eds.) *Ambiente y pesquería de pelágicos menores en el Noroeste de México*. Centro Interdisciplinario de Ciencias Marinas-IPN, 186 p.

Australian Fisheries Management Authority. 2005. *Small Pelagic Fishery. Bycatch Ac-*

tion Plan 2005. Revised Draft, Australia, 25 pp. Disponible en línea: http://www.afma.gov.au/environment/bycatch/draft/spf_draft_BAP_2005.pdf.

Bakun, A., E.A. Babcock, S.E., Lluch-Cota, C. Santora, & C.J. Salvadeo. 2009. Issues of ecosystem-based management of forage fisheries in ‘‘open’’ non-stationary ecosystems: the example of the sardine fishery in the Gulf of California. *Rev. Fish Biol. Fisher*., 20(1): 9-29.

Busquets-Vass, G. 2008. *Variabilidad de isótopos estables de nitrógeno y carbono en piel de ballena azul (Balaenoptera musculus).* Tesis de Maestría. Centro Interdisciplinario de Ciencias Marinas-IPN, 84 p.

Caddy, J. & R. Mahon. 1995. Reference points for fisheries management. *FAO Fish. Tech. Pap. No. 347*, 83 p.

Chavez, F. P., Ryan, J., Lluch-Cota, S. E. & Niquen C. M. (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*, 299(5604): 217–221.

Christensen, V. & C.J. Walters. 2004. Ecopath with ecosim: methods, capabilities and limitations. *Ecol. Model*., 172(2-4): 109–139.

Cisneros-Mata, M.A., M.O. Nevárez-Martínez & M.G. Hammann. 1995a. The rise and fall of the Pacific sardine, *Sardinops sagax caeruleus* Girard, in the Gulf of California, Mexico. *CalCOFI Rep.*, 36(1): 136-143.

Cisneros-Mata, M.A., G. Montemayor-López & M.J. Román-Rodríguez. 1995b. Life History and Conservation of *Totoaba macdonaldi*. *Conserv. Biol.*, 9(4): 806-814.

Cisneros-Mata, M.A., L.W. Botsford & J.F. Quinn. 1997. Projecting viability of *Totoaba macdonaldi*, a population with unknown age-dependent variability. *Ecol. Appl.*, 7(3): 968-980.

Culik, B.M. 2004. Review of small cetaceans. Distribution, behavior, migration and threats. *Marine Mammal Action Plan /Regional Seas Reports and Studies No. 177*, 343 p.

Del Monte-Luna, P., F. Arreguín-Sánchez & D. Lluch-Belda. 2007. Marine Ecosystem Analyses in the Gulf of Ulloa: BAC meets ECOPATH. *Fish. Centre Res. Rep*., 15(6): 114-133.

Fitch, J.E. & R.L. Brownell Jr. 1968. Fish Otholits in Cetacean Stomachs and Their Importance in Interpreting Feeding Habits. *J. Fish. Res. Can*., 25: 2561-2574.

Fletcher, W. J. & F. Head. 2006. *State of the Fisheries Report 2005/06*. Department of Fisheries, Western Australia, 8 p.

Gendron, D. 1993. Índice de avistamiento y distribución del género *Balaenoptera* en el Golfo de California, México, durante febrero, marzo y abril de 1988. *Revista de Investigación Científica, Serie Científica, UABCS, Número especial SOMEMMA,* 1: 21-29.

Hammann, M.G., M.O. Nevárez-Martínez & Y. Green-Ruíz. 1998. Spawning habitat of the Pacific sardine (*Sardinops sagax*) in the Gulf of California: Egg and larval distribution 1956-1957 and 1971-1991. *CalCOFI Rep*., 39(1): 169-179.

Instituto Nacional de la Pesca. 2006. *Sustentabilidad y Pesca Responsable*. Evaluación y Manejo. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, México, 543 p.

Jaquet, N. & D. Gendron. 2002. Distribution and relative abundance of sperm whales in relation to key environmental features, squid landings and the distribution of other cetacean species in the Gulf of California, Mexico. *Mar. Biol*., 141(3): 591-601.

Jaume-Schinkelm, S. 2004. Hábitos alimentarios del rorcual común *Balaenoptera physalus* en el Golfo de California mediante el uso de isótopos estables de nitrógeno y carbono. Tesis de Maestría. Centro Interdisciplinario de Ciencias Marinas-IPN, 64 p.

Lercari, D. 2006. *Manejo de los recursos del ecosistema del norte del Golfo de California: integrando explotación y conservación*. Tesis de Doctorado. Centro Interdisciplinario de Ciencias Marinas-IPN, 173 p.

Lercari, D. & E.A Chávez. 2007. Possible causes related to historic stock depletion of the totoaba, *Totoaba macdonaldi* (Perciformes: Sciaenidae), endemic to the Gulf of California. *Fish. Res.*, 86(2-3): 136-142.

Lercari, D. & F. Arreguín-Sánchez. 2009. An ecosystem modelling approach to deriving viable harvest strategies for multispecies management of the Northern Gulf of California. *Aquat. Conserv.*, 19(4): 384-397.

Lluch-Belda, D., B.F.J. Magallón & R. Schwartzlose. 1986. Large fluctuations in the sardine fishery in the Gulf of California: possible causes. *CalCOFI Rep.*, 27(1): 136-140.

Lluch-Belda, D., R.J.M. Crawford, T. Kawasaki, A.D. MacCall, R.H. Parrish, R.A. Schwartzlose & P.E. Smith. 1989. Worldwide fluctuations of sardine and anchovy stocks: the regimen problem. *S. Afr. J. Marine Sci.*, 8(1): 195–205.

Lluch-Belda, D., J. Arvizu, S. Hernández-Vázquez, D.B. LLuch-Cota, C.A. Salinas-Zavala, T. Baumgartner, G. Hammann, V.A. Cota, C.E. Cotero, F.W. García-Franco, O. Pedrín, S. Lizárraga, M.A. Martínez, R. Morales, M.O. Nevárez-Martínez, J.P. Santos-Molina, R. Ochoa, S.R. Rodríguez, J.R. Torres & F. Páez. 1995. *Atlas Pesquero de México. Pesquerías Relevantes*. Secretaría de Pesca/Instituto Nacional de la Pesca/ Universidad de Colima. Instituto Nacional de la Pesca, 234 p.

Lluch-Belda, D., D.B. Lluch-Cota & S.E. Lluch-Cota. 2005. Changes in marine faunal distributions and ENSO events in the California Current. *Fish. Oceanogr.*, 14(6): 458–467.

Lluch-Cota, S.E., D.B. Lluch-Cota, D. Lluch-Belda, M.O. Nevárez-Martínez, A. Parés-Sierra & S. Hernández-Vázquez. 1999. Variability of sardine catch as related to enrichment, concentration and retention processes in the central Gulf of California. *CalCOFI Rep.*, 40(1): 184-190.

Lluch-Cota SE, E.A. Aragón-Noriega, F. Arreguín-Sánchez, D. Aurioles-Gamboa, J.J. Bautista-Romero, R.C. Brusca, R. Cervantes-Duarte, R. Cortés-Altamirano, P. Del Monte-Luna, A. Esquivel-Herrera, G. Fernández, M.E. Hendrickx, S. Hernández-Vázquez, H. Herrera-Cervantes, M. Kahru, M. Lavín, D. Lluch-Belda, D.B. Lluch-Cota, J. López-Martínez, S.G. Marinote, M.O. Nevárez-Martínez, S. Ortega-García, E. Palacios-Castro, A. Parés-Sierra, G. Ponce-Díaz, M. Ramírez-Rodríguez, C.A. Salinas-Zavala, R.A. Schwartzlose, A.P. Sierra-Beltrán. 2007. The Gulf of California: review of ecosystem status and sustainability challenges. *Prog. Oceanogr.*, 73: 1–26.

Morales-Bojórquez, E. & M.O. Nevárez-Martínez. 2005. Spawner-recruit patterns and investigation of Allee effect in Pacific sardine *Sardinops sagax caeruleus* in the Gulf of California, Mexico. *CalCOFI Rep.*, 46(1): 161-174.

Morales-Zárate, M.V., F. Arreguín-Sánchez, J. López-Martínez, & S.E. Lluch-Cota. 2004. Ecosystem trophic structure and energy flux in the Northern Gulf of California, México. *Ecol. Model.*, 174: 331-345.

Nevárez-Martínez, M. O., D. Lluch-Belda, M.A. Cisneros-Mata, J.P. Santos-Molina, M.A. Martínez-Zavala & S.E. Lluch-Cota. 2001. Distribution and abundance of the Pacific sardine (*Sardinops sagax*) in the Gulf of California and their relation with the environment. *Prog. Oceanogr.*, 49(16): 565-580.

Ortega-García, S., M.S. Zuñiga-Flores & J.P. Arias-Aréchiga. 2005. Boletín Informativo 4° trimestre de 2004. Centro Interdisciplinario de Ciencias Marinas-IPN, API, Cabo San Lucas, México.

Pedrín-Osuna, O.A., J.H. Córdoba-Murueta & M. Delgado-Machena. 2001. Crecimiento y mortalidad de la totoaba, *Totoaba macdonaldi*, del alto Golfo de California. *Ciencia Pesquera*, 14: 131-140.

Pérez Cortés-Moreno, H. G.K. Silber & B. Villa-Ramírez. 1996. Contribución al conocimiento de la alimentación de la vaquita, *Phocoena sinus*. *Ciencia Pesquera*, 13: 66-72.

Rodríguez-Sánchez, R. & G. Ponce-Díaz 1986. *Resultados sobre dinámica poblacional de las principales especies de sardina en la costa Pacífica de la península de Baja California y en el Golfo de California, durante octubre de 1984 a marzo de 1986*. Informe Técnico. Centro Interdisciplinario de Ciencias Marinas-IPN, 86 p.

Rodríguez-Sánchez, R., D. Lluch-Belda, H. Villalobos & S. Ortega-García. 2002. Dynamic geography of small pelagic fish populations in the California Current System on the regime time scale (1931–97). *Can. J. Fish. Aquat. Sci.*, 59(12): 1980–1988.

Román-Rodríguez, M.J. 1990. Alimentación de *Totoaba macdonaldi* (Gilbert) (Pisces: Sciaenidae) en la parte norte del Alto Golfo de California. *Ecológica*, 1: 1–9.

Rosas-Ruíz, R., C.A. Salinas-Zavala, V. Koch, P. Del Monte-Luna & V. Morales-Zàrate. 2008. Importance of jumbo squid *Dosidicus gigas* (Orbigny, 1835) in the pelagic ecosystem of the central Gulf of California. *Ecol. Model.*, 218(1-2):149-161.

Salinas-Zacarías, M.A. 2005. *Ecología de los tursiones,* **Tursiops truncatus***, en Bahía de La Paz, BCS*. Tesis de Doctorado . Centro Interdisciplinario de Ciencias Marinas-IPN, 102 p.

Salvadeo, C.J., S. Flores-Ramírez, A. Gómez-Gallardo, S. Jaume-Schinkel, J. Urban & D. Lluch-Belda. 2007. The Bryde´s whale (*Balaenoptera edeni*) in La Paz Bay, México and its ralationship with climatic changes and prey availability. *Abstracts book of 1st CLIOTOP International Symposium.* 3-7 December 2007, La Paz, México, Baja California Sur, México.

Salvadeo, C.J. 2008a. Importancia trófica de los pelágicos menores en aguas del Golfo de California. Informe técnico interno del proyecto SEMARNAT-2002-C01-0278. 14 p.

Salvadeo, C.J. 2008b. *Análisis de la comunidad de odontocetos y la relación con su ambiente en el extremo sur-occidental del Golfo de California, México (2003-2006)*. Tesis de Maestría. Centro Interdisciplinario de Ciencias Marinas-IPN, 63 p.

Silber, G.K. 1990. *Distributional relations of cetaceans in the northern Gulf of California, with special reference to the vaquita,* **Phocoena sinus**. Tesis de Doctorado. University of California, 158 p.

Suazo-Guillén, E. 2004. *Biología reproductiva y hábitos de forrajeo del bobo café,* **Sula leucogaster***, en dos islas del Golfo de California, 2003 – 2004*. Tesis de Maestría. Centro de Investigación Científica y de Educación Superior de Ensenada, 74 p.

Szteren, D., & D. Aurioles-Gamboa. 2006. Population Status and Trends of the California Sea Lion (*Zalophus californianus californianus*) in the Gulf of California, Mexico*. Sea Lions of the World*. Alaska Sea Grant College Program AK-SG-06-01. 384 p.

Tripp-Valdéz, M.A., S.E. Lluch-Cota, P. Del Monte-Luna & C.J. Salvadeo. 2010. The importance of grey literature in fisheries ecology: an example based on the trophic role of small pelagics in the Gulf of California. *CICIMAR-Oceánides*, 25(1): 73-75.

Urbán, R.J. & R.S. Flores. 1996. A note on Bryde’s Whales (*Balaenoptera edeni*) in the Gulf of California, Mexico. *Reports of the International Whaling Commission,* 46: 453– 457.

Velarde, E., M.S. Tordesillas & L.V. Rocío Esquivel. 1994. Seabirds as indicators of important fish populations in the Gulf of California. *CalCOFI Rep.*, 35(1): 137-143.

Vidal, R.B., R.L. Brownell Jr. & L.T. Findley. 1995. Vaquita -*Phocoena sinus* Norris & McFarland, 1958, 357-378. En: R. Harrison & S. Ridgway (Eds.) *Handbook of Marine Mammals Volume 6, The Second Book of Dolphins and Porpoises*. Academic Press San Diego.

Washington Department of Fish and Wildlife. 2002. *Summary Report of the 2002 Trial Purse Seine Fishery for Pacific Sardine (Sardinops sagax)*. Washington Department of Fish and Wildlife*.* Intergovernmental Resource Management. 5 p.

Wolf , P. 1992. Recovery of the Pacific sardine and the California sardine fishery. *CalCOFI Rep.*, 33(1): 76-86.

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Bryde's whale (*Balaenoptera edeni*) in the southwestern Gulf of California: Relationship with ENSO variability and prey availability

El rorcual de Bryde (*Balaenoptera edeni*) en el suroeste del Golfo de California: Su relación con la variabilidad de ENOS y disponibilidad de presas

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ABSTRACT. Interannual changes in the occurrence of Bryde's whale (*Balaenoptera edeni*) have been observed in La Paz Bay (southwestern Gulf of California, Mexico) over the last 20 years. We suggest that these changes could be driven by natural fluctuations in food resources that are related to climate variability. We compared monthly Bryde's whale occurrence in La Paz Bay from 1988 to 2006 to climate variability at seasonal and interannual time scales and its effect on prey availability. The results showed that Bryde's whales do not have a well-defined pattern of seasonal occurrence; however, large numbers of whales were consistently recorded during La Niña conditions when the Gulf of California sardine population is distributed further south within the gulf. In contrast, fewer whales were recorded during El Niño and neutral conditions. This indicates that changes in the occurrence of Bryde's whales at La Paz Bay are driven by the El Niño-Southern Oscillation interannual variability and are probably mediated by their prey availability.

Key words: climate variability, Pacific sardine, sardine distribution, cetacean occurrence.

RESUMEN. En los últimos 20 años se han observado cambios interanuales en la presencia del rorcual de Bryde (*Balaenoptera edeni*) en la Bahía de La Paz (suroeste del Golfo de California, México). Se sugiere que estos cambios pueden ser causados por fluctuaciones naturales de los recursos alimenticios relacionadas con la variabilidad climática. Por ello, se contrastó la ocurrencia mensual del rorcual de Bryde en la Bahía de La Paz entre 1988 y 2006 con la variabilidad climática a las escalas temporales estacional e interanual, y el efecto de esta variabilidad climática sobre la disponibilidad de presas. Los resultados mostraron que los rorcuales de Bryde no tienen un patrón de ocurrencia estacional bien definido; sin embargo, un mayor número de ballenas se registró consistentemente durante condiciones de La Niña, cuando la población de sardinas del Golfo de California se encuentra distribuida más al sur dentro del golfo. En contraste, muy pocos rorcuales se registraron durante condiciones neutrales y de El Niño. Esto muestra que los cambios en la ocurrencia de rorcuales de Bryde en la Bahía de La Paz están influenciados por la variabilidad interanual de El Niño Oscilación del Sur y probablemente estén mediados por la disponibilidad de sus presas.

Palabras clave: variabilidad climática, sardina del Pacífico, distribución de sardina, ocurrencia de cetáceos.

INTRODUCTION

Climate variability affects animal and plant communities at different spatial and temporal scales, and marine mammals are no exception. Potential impacts can be divided into direct and indirect effects. Direct effects include, for example, the effects of reduced sea ice and rising sea levels on seal haul-out sites or those that impact species tracking a specific range of water temperatures in which they can physically survive, while indirect effects include the potential impacts on reproductive success, distribution, abundance, migration, and community structure of marine mammal prey at specific locations (Learmonth *et al.* 2006).

Bryde's whales (*Balaenoptera edeni*) are distributed in tropical, subtropical, and temperate waters throughout much of the world (Reeves *et al.* 2002). In the Gulf of California

INTRODUCCIÓN

La variabilidad climática afecta a las comunidades de plantas y animales a diferentes escalas espaciales y temporales, y los mamíferos marinos no son la excepción. Los impactos potenciales pueden dividirse en efectos directos e indirectos. Los efectos directos incluyen, por ejemplo, los efectos de la reducción de la cobertura de hielo y el aumento en el nivel del mar en los sitios de agregación de focas, o aquellos que impactan a las especies que siguen un intervalo determinado de temperatura en el que pueden sobrevivir físicamente, mientras que los efectos indirectos incluyen los impactos potenciales sobre el éxito reproductivo, la distribución, abundancia, migración y estructura comunitaria de las presas de mamíferos marinos en áreas específicas (Learmonth *et al.* 2006).

(GC), year-round sightings of the species suggest the presence of a resident population (Tershy *et al.* 1990, 1993; Urbán and Flores-Ramírez 1996). In La Paz Bay (southwest GC), interannual changes in the occurrence of Bryde's whales have been observed over the last 20 years. We suggest that these changes could be driven by natural fluctuations in food resources that are related to climate variability.

In the GC, Bryde's whales prey on small schooling fish, such as Pacific sardines (*Sardinops sagax caeruleus*) (Tershy 1992, Gendron 1993, Urbán and Flores-Ramírez 1996). This forage fish is the most abundant small pelagic species and a key component of the regional ecosystem, and presents a north–south movement inside the GC related to seasonal environmental changes. In addition to such seasonal expansions and contractions, the abundance and distribution of Pacific sardine inside the GC varies due to the effects of El Niño-Southern Oscillation (ENSO) (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Velarde *et al.* 2004, Bakun *et al.* 2009).

The aim of the present study was to analyze the sighting records of Bryde's whales and the environmental variability in the GC to obtain a conceptual framework needed to: (i) identify seasonal and interannual changes in the occurrence of Bryde's whales in La Paz Bay, Baja California Sur (fig. 1), as an indicator of the occurrence of this species in the southern GC, and (ii) test whether changes in occurrence are related to interannual variability in sea surface temperature and chlorophyll concentration, as well as prey availability.

MATERIAL AND METHODS

We analyzed sightings of Bryde's whales at La Paz Bay, Baja California Sur, Mexico (fig. 1a, b), recorded between 1988 and 2006 by staff from the Marine Mammal Research Program of the Autonomous University of Baja California Sur (UABCS). All data were collected using mid-size fishing boats (length < 50 ft) as research platforms during Beaufort sea state 3 or less (higher conditions significantly reduce our capacity to detect cetaceans). A consistent search method was followed, in which the boat ran in a straight line at cruising speed (11 kn) following a predetermined track (fig. 1b), trying to cover most of the study area in about three days. During each sampling trip, three observers (one located at the front and one on each side of the boat) searched for cetaceans, and stops were made every 30 min for a 360º binocular (7 × 50) scan. When a cetacean was sighted, the date, time, species, location, number of animals, behavior, and association with other marine species (birds, fishes, marine mammals, and sea turtles) were recorded. These data were used to calculate the monthly relative abundance (RA = animals per effort hour) of Bryde's whales as an indicator of the occurrence of this species in La Paz Bay and adjacent waters. To do this, we calculated the total number of whales sighted and the effective effort hours per month sampled.

To assess whether any changes in the interannual and seasonal occurrence of Bryde's whales were related to any

Los rorcuales de Bryde (*Balaenoptera edeni*) habitan aguas tropicales, subtropicales y templadas de todo el mundo (Reeves *et al.* 2002). En el Golfo de California (GC), los avistamientos de esta especie a lo largo del año sugieren que existe una población residente (Tershy *et al.* 1990, 1993; Urbán y Flores-Ramírez 1996). En los últimos 20 años, se han observado cambios interanuales en la presencia de esta ballena en Bahía de La Paz (suroeste del GC). Se supone que estos cambios pueden estar influenciados por fluctuaciones en el alimento, relacionadas con la variabilidad climática.

En el GC, los rorcuales de Bryde depredan sobre cardúmenes de pelágicos menores, como las sardinas del Pacífico (*Sardinops sagax caeruleus*) (Tershy 1992, Gendron 1993, Urbán y Flores-Ramírez 1996). Esta sardina es la especie de pelágicos menores más abundante del GC y, por lo tanto, un componente clave en el ecosistema regional. Dentro del GC, esta especie presenta movimientos de norte a sur relacionados con cambios estacionales en el ambiente. Además de estos movimientos estacionales, la sardina del Pacífico presenta cambios en su abundancia y distribución dentro del GC que se deben a los efectos de El Niño Oscilación del Sur (ENOS) (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Velarde *et al.* 2004, Bakun *et al.* 2009).

El objetivo del presente estudio fue analizar los registros de avistamientos del rorcual de Bryde y la variabilidad ambiental en el GC para obtener el marco conceptual necesario para desarrollar los siguientes puntos: (i) identificar los cambios interanuales e interestacionales en la ocurrencia de rorcuales de Bryde en la Bahía de La Paz, Baja California Sur (fig. 1), como un indicador de la presencia de la especie en el suroeste del GC, y (ii) probar si los cambios en su ocurrencia se relacionan con la variabilidad interanual en la temperatura superficial del mar y la concentración de clorofila, así como la disponibilidad de las presas.

MATERIALES Y MÉTODOS

Se analizaron los avistamientos de rorcuales de Bryde en la Bahía de La Paz, Baja California Sur, México (fig. 1a, b), registrados entre 1988 y 2006 por personal del Programa de Investigación de Mamíferos Marinos de la Universidad Autónoma de Baja California Sur (UABCS). Todos los datos se recolectaron desde embarcaciones medianas (eslora < 50 pies) que se utilizaron como plataformas de investigación bajo condiciones inferiores o igual a 3 en la escala de Beaufort (las condiciones por arriba de este valor reducen significativamente la capacidad de detectar cetáceos). Se siguió un método consistente de búsqueda, en el cual la embarcación se condujo en línea recta, a velocidad crucero (11 nudos), siguiendo un recorrido predeterminado (fig. 1b) y tratando de cubrir la mayor parte del área en un lapso de tres días. Durante cada viaje de muestreo, tres observadores (uno al frente y uno a cada lado de la embarcación) buscaron cetáceos, y el bote se detuvo cada 30 min para hacer una revisión de las aguas vecinas barriendo los 360º circundantes al

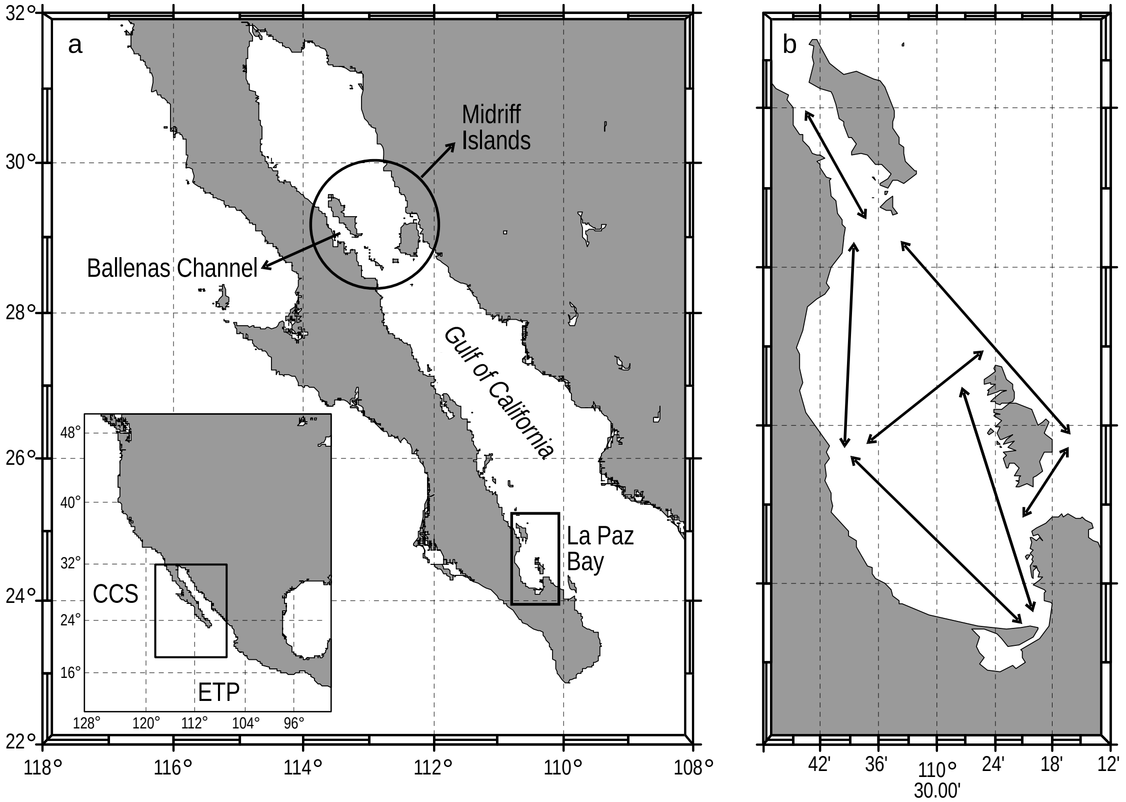

Figure 1. Study area. (**a**) Geographic location: CCS, California Current System; ETP, eastern tropical Pacific. (**b**) La Paz Bay and predetermined sampling track (black arrows).

Figura 1. Área de estudio. (**a**) Localización geográfica: CCS, Sistema de la Corriente de California; ETP, Pacífico oriental tropical. (**b**) Bahía de La Paz y rutas predeterminadas de muestreo (flechas negras).

environmental variability between 1988 and 2006, three additional data sets were obtained: (1) monthly mean sea surface temperatures (SST), with 1º × 1º spatial resolution, for La Paz Bay as an indicator of seasonal and interannual variations at local scale, using the NOAA_OI_SST_V2 data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (www.cdc.noaa.gov/cdc/data.noaa.oisst.v2.html; downloaded on 7 January 2009); (2) monthly values of the Northern Oscillation Index (NOI), as an indicator of the ENSO-related interannual variability in the northeastern Pacific (from the GC to the Gulf of Alaska), provided by the Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html; downloaded on 28 October 2009); and (3) monthly values of the Pacific Decadal Oscillation (PDO) Index, as an indicator of North Pacific decadal variability, provided by the Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu/pdo/PDO.latest; downloaded on 7 January 2009). Also, SST anomalies (SSTA) at La Paz Bay were obtained by subtracting the seasonal signal (calculated by least-squares fitting) from the monthly mean SST time series, as an indicator of interannual variability at local scale. Additionally, monthly mean sea surface chlorophyll concentrations, for the period 1997–2006, were used as a proxy of seasonal and

mismo con binoculares (7 × 50). Al avistarse un cetáceo, se registraron la fecha, la hora, la especie, la localización, el número de animales, el comportamiento y su asociación con otras especies (aves, peces, mamíferos marinos y tortugas). Estos datos se utilizaron para calcular la abundancia relativa mensual del rorcual de Bryde (AR = animales por hora de esfuerzo) como un indicador de la ocurrencia de esta especie en Bahía de La Paz y aguas adyacentes. Para ello, se calculó el número total de ballenas avistadas y el número efectivo de horas por mes muestreado.

Para evaluar si los cambios en la ocurrencia interanual y estacional de los rorcuales se relacionaron con la variabilidad ambiental entre los años 1988 y 2006, se obtuvieron tres grupos de datos adicionales: (1) promedios mensuales de la temperatura superficial del mar (TSM) para la Bahía de La Paz, con una resolución espacial de 1º × 1º, como un indicador de la variación interestacional e interanual a escala local, usando los datos NOAA_OI_SST_V2 proporcionados por la NOAA/OAR/ESRL PSD, Boulder, Colorado, EE.UU. (www.cdc.noaa.gov/cdc/data.noaa.oisst.v2.html; obtenidos el 7 de enero de 2009); (2) valores mensuales del Índice de la Oscilación del Norte (ION), como un indicador de la variabilidad interanual relacionada con ENOS en el Pacífico noreste (desde el GC hasta el Golfo de Alaska), proporcionados por interannual patterns of primary productivity at La Paz Bay; these data were obtained from SeaWiFS satellite images of 9 × 9 km spatial resolution (http://oceancolor.gsfc.nasa.gov/cgi/l3; downloaded on 7 January 2009). To emphasize the prevailing large-scale conditions, a one-year (12-month) running mean for each month was applied to the NOI, PDO, and SSTA data.

For the statistical and descriptive analysis, we used only the data from months when at least two sampling trips were made (table 1). These RA values were first grouped by months in a "standard year" and plotted to assess a possible seasonal pattern in the occurrence of Bryde's whales in La Paz Bay. They were then grouped by temperate season (December to May) and warm season (June to November), and the Mann-Whitney U test was used to detect significant differences in the occurrence of whales between both seasons. Additionally, the SST and chlorophyll values were grouped in a "standard year" and plotted to describe the seasonal pattern of these environmental variables.

To characterize interannual changes in the occurrence of Bryde's whales, the monthly RA values were grouped based on the SSTA values: cold (SSTA ≤ –0.5 ºC), warm (SSTA ≥ 0.5 ºC), and neutral (–0.5 ºC < SSTA < 0.5 ºC) interannual conditions. These groups were also regrouped in a "standard year" and plotted again to assess possible changes at the seasonal scale during each interannual SST condition. Then, to identify interannual changes in the occurrence of Bryde's whales and test whether these changes were related to climate variability, we examined the monthly data (RA, SSTA, NOI, and PDO) using generalized linear and additive models. As the results obtained from these models were not as clear cut as we would have hoped, we decided to perform a straightforward linear analysis (Redfern *et al.* 2006). As the RA of Bryde's whales was not normally distributed, Spearman correlations were performed to evaluate the relationships observed between the RA and the different measures of environmental variability (SSTA, NOI, and PDO).

RESULTS

The SST data showed a well-defined seasonal pattern at La Paz Bay (fig. 2a): a temperate season (SST < 24.20 ºC)

Table 1. Basic statistics for the number of sampling trips, effective effort hours, and number of whales per month (for months with at least two trips).

Tabla 1. Estadísticos básicos para el número de viajes de muestreo, horas de esfuerzo efectivo y número de rorcuales registrados por mes (para aquellos meses en los que se efectuaron al menos dos viajes de muestreo).

	n	Mean	Minimum	Maximum	SD
Trips	88	3.5	2.0	5.0	0.9
Effort hours	88	29.9	11.8	68.3	9.0
Whales	88	2.5	0.0	17.0	3.5

el Laboratorio para el Medio Ambiente de las Pesquerías del Pacífico de la NOAA (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html; obtenidos el 28 de octubre de 2009); y (3) valores mensuales del Índice de la Oscilación Decadal del Pacífico (ODP), como un indicador de la variabilidad decadal del Pacífico Norte, proporcionados por el Instituto para el Estudio de la Atmósfera y el Océano (http://jisao.washington.edu/pdo/PDO.latest; obtenidos el 7 de enero de 2009). Adicionalmente, se calcularon las anomalías de la TSM (ATSM) para la Bahía de La Paz restando la señal estacional (calculada mediante ajuste de mínimos cuadrados) de la serie de tiempo de valores mensuales de TSM. Esos datos se usaron como un indicador de la variabilidad interanual a escala local. Finalmente, se tomó el promedio mensual de la concentración superficial de clorofila, para el periodo 1997–2006, como un indicador de los patrones estacionales e interanuales de la productividad primaria en Bahía de La Paz; estos valores se obtuvieron a partir de imágenes del satélite SeaWiFS con una resolución espacial de 9 × 9 km (http://oceancolor.gsfc.nasa.gov/cgi/l3; obtenidos el 7 de enero de 2009). Para resaltar las condiciones prevalentes de gran escala, se efectuó un promedio móvil de 12 meses en cada mes para los datos de ION, ODP y ATSM.

Para los análisis descriptivos y estadísticos, se analizaron los datos de aquellos meses que presentaron al menos dos viajes de muestreo (tabla 1). Estos valores de AR se agruparon por meses en un "año estándar" y se graficaron para evaluar la existencia de un posible patrón estacional en la ocurrencia de rorcuales de Bryde en la Bahía de La Paz. Posteriormente, estos valores mensuales se agruparon por estación templada (diciembre a mayo) y estación cálida (junio a noviembre), y se efectuó una prueba U de Mann-Whitney para detectar diferencias significativas en la ocurrencia de rorcuales entre ambas estaciones. A su vez, los valores de TSM y clorofila se agruparon en un "año estándar" y se graficaron para describir el patrón estacional de estas variables ambientales.

Para caracterizar cambios interanuales en la ocurrencia de rorcuales de Bryde, los valores mensuales de AR se agruparon acorde a los valores de ATSM: condiciones interanuales frías (ATSM ≤ –0.5 ºC), cálidas (ATSM ≥ 0.5 ºC) y neutras (–0.5 ºC < ATSM < 0.5 ºC). Estos datos se reagruparon en un "año estándar" y se graficaron nuevamente para detectar posibles cambios a la escala estacional durante cada condición interanual de TSM. Posteriormente, se analizaron los valores mensuales de las variables de interés (AR, ATSM, ION y ODP) mediante modelos lineales y aditivos generalizados para identificar cambios interanuales en la ocurrencia de estas ballenas y probar si estos cambios se relacionaron con la variabilidad climática. Como los resultados de estos análisis no fueron consistentes con los requerimientos que estos modelos deben cumplir, se decidió efectuar un análisis de correlación simple (Redfern *et al.* 2006). Puesto que la AR del rorcual de Bryde no mostró distribución normal, se efectuaron correlaciones de Spearman para evaluar las during the boreal winter and spring (December to May) and a warm season (SST > 24.2 ºC) during the boreal summer and autumn (June to November). At interannual scale, SSTA closely follows the ENSO phenomenology represented by the NOI (Pearson $R = -0.8$, $P < 0.05$), with negative anomalies during La Niña conditions and positive during El Niño conditions (fig. 3a). Sea surface chlorophyll concentrations (fig. 2b) were highest during the first half of the year, and accentuated at the beginning of the warm season (June) during interannual neutral conditions and in the middle of the temperate season (February) during interannual cold conditions. The lowest concentrations occurred at the end of the warm season during interannual cold and neutral conditions, and throughout the year during interannual warm conditions (fig. 2b).

The annual occurrence of Bryde's whales did not show any seasonal pattern (fig. 2c), and there were no statistical relaciones observadas entre su AR y las diferentes medidas de variabilidad ambiental (ATSM, ION y ODP).

RESULTADOS

Los datos de TSM mostraron un patrón estacional bien definido en la Bahía de La Paz. (fig. 2a): una estación templada (TSM < 24.20 ºC) durante el invierno y la primavera boreal (diciembre a mayo) y una estación cálida (TSM > 24.20 ºC) durante el verano y el otoño boreal (junio a noviembre). A escala interanual, la ATSM sigue muy de cerca la fenomenología de ENOS representada por el ION (Pearson $R = -0.8$, $P < 0.05$), con anomalías negativas durante las condiciones de La Niña y anomalías positivas durante condiciones de El Niño (fig. 3a). Las concentraciones de clorofila en la superficie del mar (fig. 2b) mostraron concentraciones mayores durante la primera parte del año, y

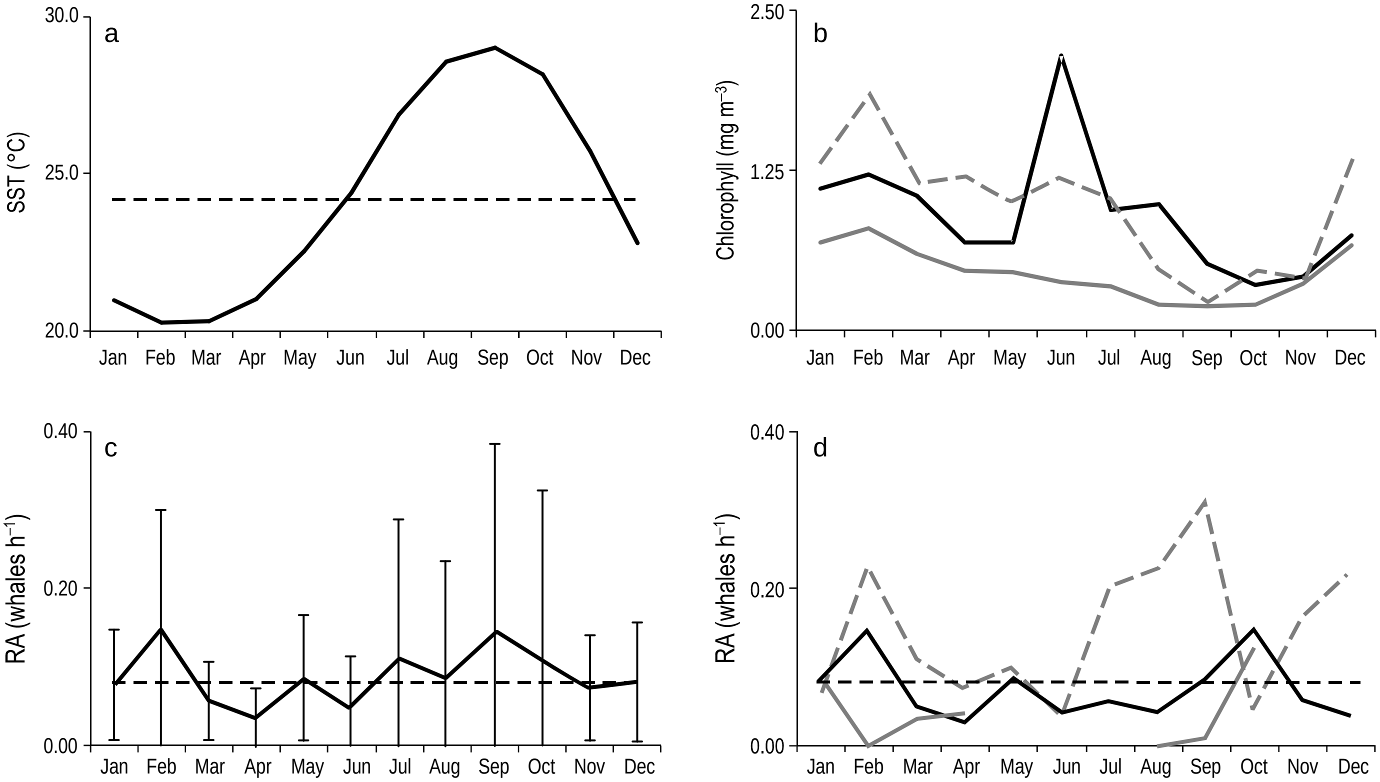

Figure 2. (**a**) Sea surface temperature (SST) climatology (solid line) and annual mean (dashed line) for La Paz Bay. (**b**) Monthly chlorophyll concentration for La Paz Bay (obtained from SeaWiFS satellite images for 1997 to 2006) during cold (dashed gray line), warm (solid gray line), and neutral (solid black line) interannual conditions. (**c**) Monthly mean and standard deviation of the relative abundance (RA) of Bryde's whales (solid black line) and overall mean for all the study period (dashed black line). (**d**) Monthly mean RA of Bryde's whales during cold (dashed gray line), warm (solid gray line), and neutral (solid black line) interannual conditions, and overall mean for all the study period (dashed black line).

Figura 2. (**a**) Climatología de la temperatura superficial del mar (SST, línea sólida) y promedio anual (línea discontinua) para la Bahía de La Paz. (**b**) Concentración mensual de clorofila superficial para la Bahía de La Paz (obtenida a partir de imágenes del sátelite SeaWiFS de 1997 a 2006) durante condiciones interanuales frías (línea gris discontinua), cálidas (línea gris sólida) y neutrales (línea negra sólida). (**c**) Promedio mensual y desviación estándar de la abundancia relativa (RA) del rorcual de Bryde (línea negra sólida) y su promedio global para todo el periodo de estudio (línea negra discontinua). (**d**) Promedio mensual de la RA del rorcual de Bryde durante condiciones interanuales frías (línea gris discontinua), cálidas (línea gris sólida) y neutrales (línea negra sólida), y promedio global para todo el periodo de estudio (línea negra discontinua).

differences in RA between both seasons (Mann-Whitney test: Z = –0.89, $P = 0.37$, $n_1 = 45$, $n_2 = 42$). The lack of a defined seasonal pattern was also observed during cold, warm, and neutral interannual conditions (fig. 2d); however, the highest RA values were recorded during cold La Niña conditions and the lowest during warm El Niño conditions (fig. 2d).

The overall mean monthly RA was 0.09 animals per effort hour (table 2). Throughout the study period, the occurrence of Bryde's whales varied temporally, showing high, low, and even null RA values (fig. 3b). A relationship was observed between their occurrence and the SSTA related to ENSO phenomenology (large numbers of whales were consistently recorded during cold La Niña conditions). The Spearman correlation between RA and the different measures of environmental variability confirmed this assessment, showing that the occurrence of Bryde's whales was only

se acentuaron al inicio de la estación cálida (junio) durante condiciones interanuales neutrales, así como hacia la mitad de la estación templada (febrero) durante condiciones interanuales frías. Las concentraciones más bajas de clorofila se presentaron hacia el final de la estación cálida durante condiciones interanuales frías y neutrales, y a lo largo de todo el año durante condiciones interanuales cálidas (fig. 2b).

La ocurrencia anual de rorcuales de Bryde no mostró ningún patrón estacional (fig. 2c), y no se registraron diferencias estadísticas en su AR entre estaciones (prueba de Mann-Whitney: Z = –0.89, $P = 0.37$, $n_1 = 45$, $n_2 = 42$). La ausencia de un patrón estacional definido también se observó durante condiciones interanuales frías, cálidas y neutrales (fig. 2d); sin embargo, los valores más elevados de AR se registraron durante condiciones frías de La Niña y los valores más bajos durante condiciones cálidas de El Niño (fig. 2d).

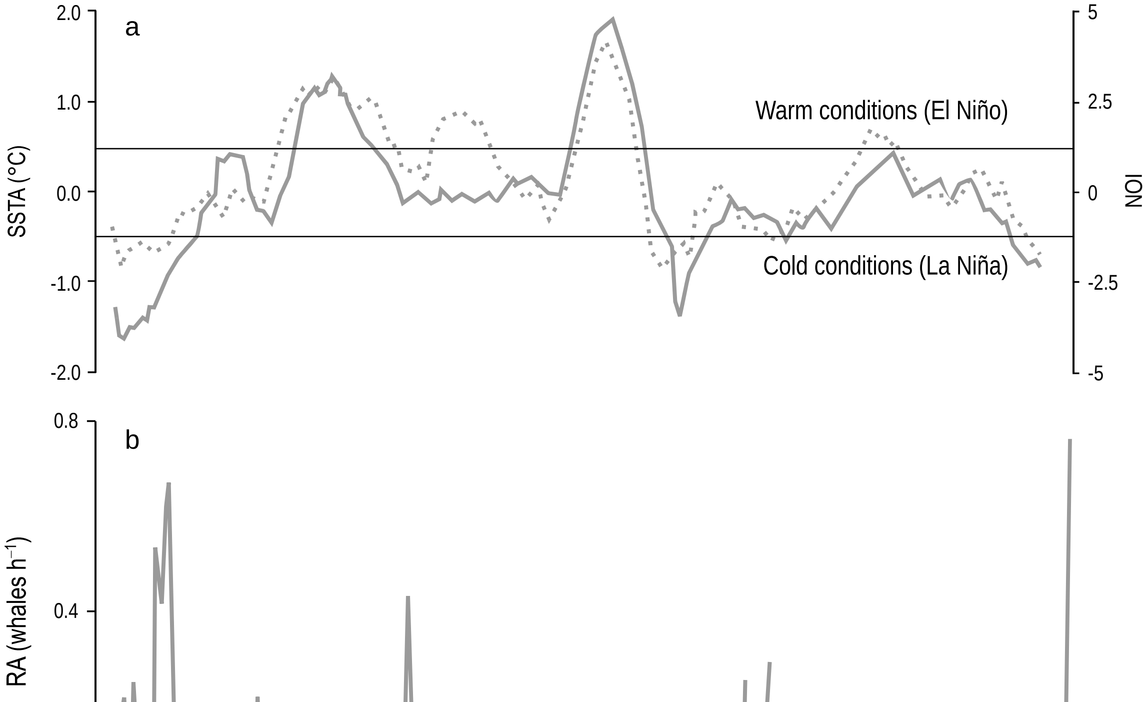

Figure 3. (**a**) Sea surface temperature anomaly (SSTA) at La Paz Bay (solid gray line) and North Oscillation Index (NOI, dotted gray line); the latter was multiplied by –1 for comparative purposes. (**b**) Monthly relative abundance (RA) of Bryde's whales (solid gray line) and overall mean (dashed gray line) for all the study period; dashed and solid boxes on the *x* axis represent cold La Niña and warm El Niño conditions, respectively, and years without boxes are neutral years.

Figura 3. (**a**) Anomalía de la temperatura superficial del mar (SSTA) en la Bahía de La Paz (línea gris sólida) e Índice de la Oscilación del Norte (NOI, línea gris punteada); este último fue multiplicado por –1 con propósitos comparativos. (**b**) Abundancia relativa (RA) mensual del rorcual de Bryde (línea gris sólida) y su promedio global (línea gris discontinua) para todo el periodo de estudio; los recuadros discontinuos y sólidos en el eje *x* representan condiciones frías de La Niña y cálidas de El Niño, respectivamente, y los años neutrales se muestran sin recuadro.

related to SSTA (R = –0.25, P < 0.05, n = 88) and NOI (R = 0.25, n = 88). Mean RA was one order of magnitude higher during cold conditions (La Niña) than during the other two interannual conditions (table 2). This relationship was also observed in the annual occurrence of Bryde's whales (fig. 2d): fewer whales relative to the overall mean were observed throughout the year during El Niño conditions, while more whales than the overall mean were observed during La Niña conditions.

DISCUSSION

At the seasonal scale, two distinct seasons can be identified in the GC: the highly productive temperate period during the boreal winter and spring, and a warmer, less productive period during the boreal summer and autumn (Álvarez-Borrego and Schwartzlose 1979, Soto-Mardones *et al.* 1999, Lluch-Cota *et al.* 2007). North-northwesterly winds prevail during the temperate season, promoting upwelling along the gulf's eastern coast that fertilizes the whole GC, while south-southeasterly winds predominate during the warm season and weak upwelling occurs along the peninsular coast (Soto-Mardones *et al.* 1999, Lluch-Cota *et al.* 2007). However, a marked drop in net productivity occurs at most gulf localities during the warm season due to the intrusion of oligotrophic waters from the subtropical North Pacific, the intense solar radiation, and weak winds (Jiménez-Illescas *et al.* 1997, Obeso-Nieblas 2003). In contrast to the rest of the GC, primary productivity near the Midriff Islands (fig. 1) remains high throughout the year because of strong tidal mixing (Lluch-Cota *et al.* 2007). In La Paz Bay, the same seasonal pattern described for the rest of the GC is followed by SST (fig. 2a), but it is not so clear in the case of primary productivity (fig. 2b). High chlorophyll concentrations associated with GC enrichment processes occur in the temperate season, but the most prominent chlorophyll peak occurs at the beginning of the warm season, especially during neutral years (fig. 2b). This high productivity is due to the hydrography of the bay, making it an important cetacean aggregation site, when the surrounding areas are more oligotrophic (Pardo 2009).

Table 2. Basic statistics for monthly relative abundance of Bryde's whale during cold (La Niña), warm (El Niño), and neutral interannual conditions, and all months combined.

Tabla 2. Estadísticos básicos para la abundancia relativa mensual del rorcual de Bryde durante condiciones interanuales frías (La Niña), cálidas (El Niño) y neutras, y para todos los meses en conjunto.

Month	*n*	Mean	Minimum	Maximum	SD
Cold	21	0.15	0.00	0.62	0.18
Warm	9	0.06	0.00	0.13	0.05
Neutral	58	0.07	0.00	0.67	0.11
All	88	0.09	0.00	0.67	0.13

El promedio global de la AR mensual de rorcuales de Bryde fue de 0.09 ballenas por hora de esfuerzo (tabla 2). En todo el periodo de estudio, la ocurrencia de estas ballenas cambió temporalmente, observándose valores altos, bajos y nulos en su AR (fig. 3b). Se evidenció una relación entre la ocurrencia de rorcuales de Bryde y la ATSM asociada a la fenomenología de ENOS (se registraron consistentemente un gran número de animales durante condiciones frías de La Niña). La correlación de Spearman entre la AR y las distintas medidas de variabilidad ambiental confirmó esta observación, mostrando que su ocurrencia se relacionó únicamente con la ATSM (R = –0.25, P < 0.05, n = 88) y con ION (R = 0.25, n = 88). El promedio de la AR de rorcuales de Bryde fue un orden de magnitud superior durante condiciones frías (La Niña) que durante condiciones cálidas (El Niño) y neutras (tabla 2). Esta relación también se observó para la ocurrencia anual de rorcuales de Bryde (fig. 2d): se observaron menos rorcuales respecto al promedio global a lo largo del año durante condiciones de El Niño, mientras que se observaron con mayor frecuencia respecto a la media global durante condiciones de La Niña.

DISCUSIÓN

A escala temporal, se observaron dos estaciones muy marcadas en el GC: un periodo templado y muy productivo durante el invierno y la primavera boreal, y un periodo cálido y menos productivo durante el verano y el otoño boreal (Álvarez-Borrego y Schwartzlose 1979, Soto-Mardones *et al.* 1999, Lluch-Cota *et al.* 2007). Durante la estación templada prevalecen vientos del nor-noroeste que promueven la formación de surgencias en la costa este del GC, fertilizando todo el golfo, mientras que durante la estación cálida predominan los vientos del sur-sureste y se generan surgencias ligeras a lo largo de la costa peninsular (Soto-Mardones *et al.* 1999, Lluch-Cota *et al.* 2007). Sin embargo, se presenta un descenso marcado en la productividad primaria en la mayoría de las localidades del golfo durante la estación cálida debido a la intrusión de aguas oligotróficas provenientes del Pacífico Norte subtropical, a la radiación solar intensa y a los vientos débiles (Jiménez-Illescas *et al.* 1997, Obeso-Nieblas 2003). En contraste con el resto del GC, la productividad primaria en la región de las Grandes Islas (fig. 1) permanece elevada a lo largo de todo el año debido a la fuerte mezcla de aguas por corrientes de mareas (Lluch-Cota *et al.* 2007). En la Bahía de La Paz la TSM siguió el mismo patrón estacional descrito para el resto del GC (fig. 2a), pero este patrón no es tan claro para el caso de la productividad primaria (fig. 2b). Durante la estación templada se encuentran concentraciones de clorofila altas relacionadas con procesos de enriquecimiento del mismo golfo, pero el pico más prominente de clorofila se presenta al inicio de la estación cálida, especialmente durante los años neutrales (fig. 2b). Esta alta productividad se debe a la hidrografía propia de la Bahía de La Paz, que la hace un área importante de agregación de cetáceos, cuando las áreas circundantes son más oligotróficas (Pardo 2009).

In general, the occurrence and movement patterns of marine mammals are well defined and are related to the seasonal variability that determines the availability of their prey (e.g., Lusseau *et al.* 2004, Keiper *et al.* 2005, Mercuri 2007). However, Bryde's whales did not present a well-defined seasonal pattern at La Paz Bay during the study period (fig. 2c; Mann-Whitney test: Z = –0.89, *P* = 0.37, n_1 = 45, n_2 = 42). They seem to be present throughout the year, but are more abundant at the beginning of the temperate season and most of the warm season, especially during cold periods (fig. 2d). This lack of seasonality may be due to the ecology of the species itself, since it does not undertake migrations between high and low latitudes and, in general, little is known of its migratory movements (Kato 2002, Reeves *et al.* 2002). Bryde's whales do not appear to form breeding aggregations and it is believed that the reproductive cycle of this rorqual differs slightly from that of other members of the Balaenopteridae family in that there is no regular calving season (Leatherwood *et al.* 1988). Nevertheless, seasonal occurrence patterns of this species have been observed in some regions including the GC, suggesting migratory movements (Rice 1974; Cummings 1985; Tershy *et al.* 1990, 1993; Zerbini *et al.* 1997; Kato 2002). In Ballenas Channel (fig. 1), Tershy *et al.* (1990, 1993) observed a larger number of animals during the warm season than during the temperate season. They propose that during the temperate season Bryde's whales move to other areas of the GC, most probably southwards. This hypothesized migratory movement coincides with the seasonal displacement of sardine schools in the GC. During the warm season, sardines restrict their distribution to the highly productive waters near the Midriff Islands, whereas during the temperate season the expansion of productive waters allows sardine schools to occupy the entire gulf (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Bakun *et al.* 2009).

The apparent absence of migratory patterns in La Paz Bay (southern GC) shown by our results was also identified in an earlier study (Flores-Ramírez *et al.* 1997). This may be due to the presence of two population stocks in the southern GC that visit the bay at different times of the year, as suggested by Urbán and Flores-Ramírez (1996). This idea is supported by the preliminary results of a genetic study by Dizon *et al.* (1995), which pointed to the possible presence of an internal GC population and an external stock distributed in the waters of the eastern tropical Pacific (ETP). Rice (1974) proposed that the Bryde's whale population of the ETP is migratory, wintering in equatorial waters and moving to the North Pacific in the summer. Thus, the whales observed during the warm season could correspond mainly to this stock, which probably takes advantage of the fractions of the sardine populations off the west coast of Baja California that move to the south of the peninsula and southern GC (Félix-Uraga *et al.* 2005). On the other hand, the whales observed during the temperate season could, according to the seasonal movements proposed by Tershy *et al.* (1990, 1993), correspond

En general, los patrones de ocurrencia y movimientos de mamíferos marinos están bien definidos y se relacionan con la variabilidad estacional que determina la disponibilidad de sus presas (e.g., Lusseau *et al.* 2004, Keiper *et al.* 2005, Mercuri 2007). Sin embargo, los rorcuales de Bryde no presentaron un patrón estacional bien definido en la Bahía de La Paz durante el periodo de estudio (fig. 2c; prueba de Mann-Whitney: Z = –0.89, *P* = 0.37, n_1 = 45, n_2 = 42). Estos rorcuales parecen estar presentes todo el año, siendo más abundantes al inicio de la estación templada y la mayor parte de la estación cálida, especialmente durante periodos frios (fig. 2d). Esta falta de estacionalidad puede deberse a la propia ecología de la especie, pues el rorcual de Bryde no efectúa migraciones entre latitudes altas y bajas y, en general, se sabe poco acerca de sus movimientos migratorios (Kato 2002, Reeves *et al.* 2002). Estas ballenas no parecen formar agregaciones reproductivas y se cree que su ciclo reproductivo es ligeramente distinto al del resto de los miembros de la familia Balaenopteridae, en el sentido de que no tienen una estación de reproducción y crianza (Leatherwood *et al.* 1988). No obstante, se han observado patrones estacionales de la presencia de esta especie en algunas regiones, incluyendo el GC, que sugieren movimientos migratorios (Rice 1974; Cummings 1985; Tershy *et al.* 1990, 1993; Zerbini *et al.* 1997; Kato 2002). En el Canal de Ballenas (fig. 1), Tershy *et al.* (1990, 1993) registraron un mayor número de rorcuales de Bryde durante la estación cálida que durante la estación templada. Estos autores proponen que durante la estación templada los rorcuales de Bryde se desplazan a otras áreas del GC, probablemente hacia el sur. Esta migración hipotética coincide con el desplazamiento estacional de los cardúmenes de sardina dentro del GC. En particular, durante la estación cálida las sardinas restringen su distribución a aguas productivas en la región de las Grandes Islas, mientras que durante la estación templada la expansión de las aguas productivas permite a los cardúmenes de sardina ocupar todo el GC (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Bakun *et al.* 2009).

La falta de un patrón estacional en la Bahía de La Paz (sur del GC) que se observa en los resultados de este estudio también fue observada en un estudio previo (Flores-Ramírez *et al.* 1997). Esto puede deberse a la presencia de dos poblaciones de esta especie en el sur del GC que visitan la Bahía de La Paz en distintos momentos del año, como lo sugieren Urbán y Flores-Ramírez (1996). Esta idea ha sido sustentada por resultados preliminares de un estudio genético efectuado por Dizon *et al.* (1995), que indica la posible presencia de una población interna al GC y una población externa distribuida en el Pacífico oriental tropical (POT). Rice (1974) propuso que la población de rorcuales de Bryde del POT es migratoria: pasa el invierno en aguas ecuatoriales y se desplaza al Pacífico Norte en el verano. Así, las ballenas observadas en la Bahía de La Paz durante la estación cálida podrían pertenecer principalmente a esta población, la cual probablemente aprovecha las fracciones de las poblaciones mainly to the GC stock, which follows the movements of the GC sardine population.

At the interannual scale, ENSO is considered the most important influence on climate variability in the GC, affecting SST and primary productivity (Bernal *et al.* 2001, Lluch-Cota *et al.* 2007). As in the rest of the GC, in La Paz Bay, SST decreases and primary productivity increases during cold La Niña conditions, whereas SST increases and primary productivity decreases during warm El Niño conditions (fig. 3a). Moreover, in the GC the abundance of sardine varies due to large fluctuations in recruitment related to ENSO. During El Niño events, recruitment of Pacific sardine is affected by the intrusion of warm waters that reduce the spawning habitat, while the opposite occurs during La Niña events (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Bakun *et al.* 2009). In relation to this climate variation, the occurrence of Bryde’s whales showed a significant relationship with the ENSO phenomenon, indicated by the correlation with SSTA ($R = -0.25$, $P < 0.05$, $n = 88$) and NOI ($R = 0.25$, $P < 0.05$, $n = 88$). Our results show that, regardless of the season, large numbers of whales were consistently recorded during La Niña conditions, when the GC sardine population is distributed further south within the gulf. In contrast, fewer whales were recorded during El Niño and neutral conditions (table 2; figs. 2d, 3b). In a prior study about Bryde’s whales in La Paz Bay, Urbán and Flores-Ramírez (1996) noted a peak in abundance during the 1989 La Niña event, followed by a decrease in the subsequent years (1990–1991), but they did not confirm the relationship with the ENSO phenomenon due to limited data (three years). Shifts in the abundance and distribution of cetacean populations related to climate variability are most likely due to the effects on the abundance and availability of prey (e.g., Manzanilla 1989, Shane 1995, Keiper *et al.* 2005, Ballance *et al.* 2006, Learmonth *et al.* 2006). Large whales require large and dense prey patches, so their distribution, abundance, and movements are influenced by the dynamics of their prey (Learmonth *et al.* 2006). In addition, as active predators, whales are able to disperse in response to perturbations; for example, whales were observed to move as far as the Bering Sea to feed during the 1997–1998 El Niño (Tynan 1999). In GC waters, Tershy *et al.* (1991) observed a greater presence of fish-eating cetaceans (including Bryde’s whales) in Ballenas Channel (fig. 1) during the 1982–1983 El Niño, and proposed that this area of high productivity and prey abundance served as refuge during adverse periods. Our results agree with those of Tershy *et al.* (1991), with fewer whale sightings in La Paz Bay during El Niño conditions, when the sardine distribution contracted to the northern GC. During cold La Niña conditions, large numbers of whales were consistently sighted, coinciding with the southward expansion of the GC sardine population (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998). Our results suggest that, regardless of the origin of the whale population (from the GC or ETP), the occurrence of Bryde’s whales in La Paz Bay

de sardinas en la costa oeste de Baja California que se mueven hacia el sur de la península y del GC (Félix-Uraga *et al.* 2005). Por otro lado, los rorcuales observados durante la estación templada pueden corresponder, según los movimientos estacionales propuestos por Tershy *et al.* (1990, 1993), principalmente a la población del GC, la cual sigue los movimientos de la población de sardinas del GC.

A escala interanual, ENOS se considera la influencia más importante sobre la variabilidad climática dentro del GC, afectando la TSM y la productividad primaria (Bernal *et al.* 2001, Lluch-Cota *et al.* 2007). Como en el resto del GC, en la Bahía de La Paz la TSM disminuye y la productividad primaria se incrementa durante las condiciones frías de La Niña, mientras que durante las condiciones cálidas de El Niño la TSM aumenta y la productividad primaria disminuye (fig. 3a). Adicionalmente, en el GC la abundancia de sardinas varía debido a grandes fluctuaciones en su reclutamiento relacionadas con ENOS. Durante los eventos de El Niño, el reclutamiento de la sardina del Pacífico es afectado por la intrusión de aguas cálidas que reducen el hábitat de desove, mientras que durante los eventos de La Niña sucede lo opuesto (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998, Bakun *et al.* 2009). En relación a esta variación en el clima, la ocurrencia del rorcual de Bryde mostró una relación significativa con el fenómeno de ENOS, indicada por su correlación con los valores de ATSM e ION. Los resultados del presente estudio muestran que, independientemente de la estación, se registró un mayor número de rorcuales de manera consistente durante las condiciones frías de La Niña, cuando la población de sardina del GC se distribuye más al sur dentro del golfo. En contraste, se registraron menos rorcuales durante condiciones de El Niño y neutrales (tabla 2; figs. 2d, 3b). En el último estudio sobre rorcuales de Bryde en Bahía de La Paz, Urbán y Flores-Ramírez (1996) notaron un pico de abundancia durante condiciones frías de La Niña en 1989, seguido por un decremento en la abundancia durante los años siguientes (1990–1991), pero no pudieron confirmar la relación entre la abundancia de la especie y el fenómeno de ENOS debido a una serie de datos limitada (tres años). Los cambios en la abundancia y distribución de las poblaciones de cetáceos relativos a la variabilidad climática se deben, en su mayor parte, a los efectos sobre la abundancia y disponibilidad de sus presas (e.g., Manzanilla 1989, Shane 1995, Keiper *et al.* 2005, Ballance *et al.* 2006, Learmonth *et al.* 2006). Los grandes rorcuales requieren grandes y densos parches de presas, por lo que su distribución, abundancia y sus movimientos están influenciados por la dinámica de sus presas (Learmonth *et al.* 2006). Además, como depredadores activos, los rorcuales son capaces de desplazarse en respuesta a perturbaciones; por ejemplo, se observaron rorcuales desplazarse hasta el Mar de Bering para alimentarse durante El Niño de 1997–1998 (Tynan 1999). En aguas del GC, Tershy *et al.* (1991) observaron una mayor presencia de cetáceos ictiófagos (incluyendo rorcuales de Bryde) en el Canal de Ballenas (fig. 1) durante El Niño de 1982–1983, y sugirieron (southern GC) is driven by ENSO-related changes in prey availability. Unfortunately we cannot discern population origin of the whales sighted to determine whether the greater presence during La Niña conditions is because of the entry of animals from the ETP population or GC population attracted to the bay and adjacent waters due to enhanced prey availability. Further population studies (e.g., photo-identification or genetic studies) are recommended to clarify the importance of both populations in the southwestern GC.

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REFERENCES

Álvarez-Borrego S, Schwartzlose RA. 1979. Water masses of the Gulf of California. Cienc. Mar. 6: 43–63.

Bakun A, Babcock EA, Lluch-Cota SE, Santora C, Salvadeo CJ. 2009. Issues of ecosystem-based management of forage fisheries in "open" non-stationary ecosystems: the example of the sardine fishery in the Gulf of California. Rev. Fish. Biol. Fisheries. doi:10.1007/s11160-009-9118-1.

Ballance LT, Pitman RL, Fiedler PC. 2006. Oceanographic influences on seabirds and cetaceans of the eastern tropical Pacific: A review. Prog. Oceanogr. 69: 360–390.

Bernal G, Ripa P, Reguera JC. 2001. Oceanographic and climatic variability in the lower Gulf of California: Links with the tropics and North Pacific. Cienc. Mar. 27: 595–617.

Cummings WC. 1985. Bryde's whale *Balaenoptera edeni*. In: Ridgway SH, Harrison R (eds.), Handbook of Marine Mammals. Vol. 3. The Sirenians and Baleen Whales. Academic Press, pp. 137–154.

Dizon AE, Lux CA, Leduc RG, Henshaw M, Brownwell RL. 1995. An interim phylogenetic analysis of sei and Bryde's whale mitochondrial DNA control region sequences. Paper SC/47/NP23 presented to the International Whaling Commission Scientific Committee (unpublished), 12 pp.

Félix-Uraga R, Quiñónez-Velázquez C, Kevin T, Hill KT, Gómez-Muñoz VM, Melo-Barrera FN, García-Franco W. 2005. Pacific sardine (*Sardinops sagax*) stock discrimination off the west coast of Baja California and southern California using otolith morphometry. CalCOFI Rep. 46: 113–121.

Flores-Ramírez S, Urbán RJ, Delgado-González O, Vargas-Salinas J. 1997. Avistamientos de rorcual tropical, *Balaenoptera edeni* (Cetacea: Balaenopteridae) y temperatura del agua, en Baja California Sur, México. Rev. Biol. Trop. 45: 1209–1214.

Gendron D. 1993. Índice de avistamiento y distribución del género *Balaeneptera* en el Golfo de California, México, durante febrero, marzo y abril de 1988. Rev. Invest. Cient. Univ. Autón. Baja Calif. Sur (Ser. Cienc. Mar.), No. Esp. SOMMEMA 1: 21–29.

Hammann MG, Nevárez-Martínez MO, Green-Ruíz Y. 1998. Spawning habitat of the Pacific sardine (*Sardinops sagax*) in the Gulf of California: Egg and larval distribution 1956–1957 and 1971–1991. CalCOFI Rep. 39: 169–179.

Jiménez-Illescas R, Obeso-Nieblas M, Salas de León A. 1997. Oceanografía física de la Bahía de La Paz. In: Urbán RJ, Ramírez RM (eds.), La Bahía de La Paz, Investigación y Conservación. UABCS-CICIMAR-SCRIPPS, México, pp. 31–41.

Kato H. 2002. Bryde's whales *Balaenoptera edeni* and *B. brydei*. In: Perrin WF, Würsig B, Thewissen JGM (eds.), Encyclopedia of Marine Mammals. Academic Press, San Diego, pp 171–177.

Keiper CA, Ainley DG, Allen SG, Harvey JT. 2005. Marine mammal occurrence and ocean climate off central California, 1986 to 1994 and 1997 to 1999. Mar. Ecol. Prog. Ser. 289: 285–306.

Learmonth JA, Santos MB, Pierce GJ, Crick HQP, Robinson RA. 2006. Potential effects of climate change on marine mammals. Oceanogr. Mar. Biol. Annu. Rev. 44: 431–464.

Leatherwood S, Reeves RR, Perrin WF, Evans WE. 1988. Ballenas, delfines y marsopas del Pacífico nororiental y de las aguas árticas adyacentes: Una guía para su identificación. Comisión Interamericana del Atún Tropical (IATTC), Inf. Esp. No. 8, La Jolla, California, 245 pp.

que esta área con alta productividad y abundancia de presas sirve como refugio durante periodos adversos. Nuestras observaciones son consistentes con lo propuesto por Tershy *et al.* (1991), al registrarse menos rorcuales de Bryde en la Bahía de La Paz durante condiciones de El Niño, cuando la distribución de sardina se contrae al norte del GC. Durante las condiciones de La Niña se observaron, consistentemente, grandes números de rorcuales de Bryde, coincidiendo con la expansión hacia el sur de la población de sardinas al interior del GC (Lluch-Belda *et al.* 1986, Hammann *et al.* 1998). Los resultados del presente estudio sugieren que, independientemente de cual sea su población de origen (del GC o del POT), la ocurrencia de rorcuales de Bryde en la Bahía de La Paz (sur del GC) está influenciada por los cambios en la disponibilidad de presas relacionados con ENOS. Desafortunadamente, no se puede discernir de que poblaciones provienen los rorcuales avistados para determinar si la presencia de un mayor número de ballenas durante condiciones de La Niña se debe a la entrada de animales provenientes de la población del POT o si es el resultado de una mayor permanencia de la población del GC en la Bahía de La Paz y aguas adyacentes debido a la mayor disponibilidad de presas. Se recomienda desarrollar estudios poblacionales (e.g., estudios genéticos o de fotoidentificación) para clarificar la importancia de la presencia de ambas poblaciones en el suroeste del GC.

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Lluch-Belda D, Magallón BFJ, Schwartzlose RA. 1986. Large fluctuations in the sardine fishery in the Gulf of California: Possible causes. CalCOFI Rep. 27: 136–140.

Lluch-Cota SE, Aragón-Noriega EA, Arreguín-Sánchez F *et al.* 2007. The Gulf of California: Review of ecosystem status and sustainability challenges. Prog. Oceanogr. 73: 1–26.

Lusseau D, Williams R, Wilson B. 2004. Parallel influence of climate on the behaviour of Pacific killer whales and Atlantic bottlenose dolphins. Ecol. Lett. 7: 1068–1076.

Manzanilla SR. 1989. The 1982–1983 El Niño event recorded in dentinal growth layers in teeth of Peruvian dusky dolphins (*Lagenorhynchus obscurus*). Can. J. Zool. 67: 2120–2125.

Mercuri M. 2007. Varamiento de mamíferos marinos en isla Magdalena, BCS, México, y su relación con factores físicos y biológicos. M.Sc. thesis, CICIMAR-IPN, La Paz, BCS, Mexico,107 pp.

Obeso-Nieblas M. 2003. Variabilidad espaciotemporal de las condiciones oceanográficas de la Bahía de La Paz, BCS, México. Ph.D. thesis, CICIMAR-IPN, La Paz, BCS, Mexico, 337 pp.

Pardo MA. 2009. Condiciones fisicoquímicas y biológicas que modulan la abundancia de cetáceos sobre Cuenca Alfonzo, Golfo de California. M.Sc. thesis, CICIMAR-IPN, La Paz, BCS, Mexico,101 pp.

Redfern JV, Ferguson MC, Becker EA, Hyrenbach KD, Good C, Barlow J, Kaschner K, Baumgartner MF, Forney KA, Ballance LT, Fauchald P, Halpin1 P, Hamazaki T, Pershing AJ, Qian SS, Read A, Reilly SB, Torres L, Werner F. 2006. Techniques for cetacean-habitat modeling. Mar. Ecol. Prog. Ser. 310: 271–295.

Reeves RR, Stewart B, Clapham PJ, Powell JA. 2002. Guide to Marine Mammals of the World. Knopf, New York, 527 pp.

Rice DW. 1974. Whales and whale research in the eastern North Pacific. In: Schevill WE (ed.), The Whale Problem. A Status Report. Harvard Univ. Press, Cambridge, Massachusetts, pp. 170–195.

Shane SH. 1995. Relationship between pilot whales and Risso's dolphins at Santa Catalina Island, California, USA. Mar. Ecol. Prog. Ser. 123: 5–11.

Soto-Mardones L, Marinone SG, Parés-Sierra A. 1999. Time and spatial variability of sea surface temperature in the Gulf of California. Cienc. Mar. 25: 1–30.

Tershy BR. 1992. Body size, diet, habitat use, and social behaviour of *Balaenoptera* whales in the Gulf of California. J. Mammal. 73: 477–486.

Tershy BR, Breese D, Strong CS. 1990. Abundance, seasonal distribution and population composition of Balaonopterid whales in the Canal de Ballenas, Gulf of California, Mexico. Rep. Int. Whal. Comm. (Special Issue) 12: 369–375.

Tershy BR, Breese D, Alvarez-Borrego S. 1991. Increase in cetacean and seabird numbers in the Canal de Ballenas during an El Niño-Southern Oscillation event. Mar. Ecol. Prog. Ser. 69: 299–302.

Tershy BR, Urbán-Ramírez J, Breese D, Rojas L, Findley LT. 1993. Are fin whales resident to the Gulf of California? Rev. Invest. Cient. Univ. Autón. Baja Calif. Sur (Ser. Cienc. Mar.), No. Esp. SOMMEMA. 1: 69–72.

Tynan CT. 1999. Redistributions of cetaceans in the southeast Bering Sea relative to anomalous oceanographic conditions during the 1997 El Niño. PICES Sci. Rep. 10: 115–117.

Urbán RJ, Flores-Ramírez S. 1996. A note on Bryde's whales (*Balaenoptera edeni*) in the Gulf of California, Mexico. Rep. Int. Whal. Comm. 46: 453–457.

Velarde E, Ezcurra E, Cisneros-Mata A, Lavín MF. 2004. Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. Ecol. Appl. 14: 607–615.

Zerbini AN, Secchi ER, Siciliano S, Simões-Lopes PC. 1997. A review of the occurrence and distribution of whales of the genus *Balaenoptera* along the Brazilian coast. Rep. Int. Whal. Comm. 47: 407–417.

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Review of Long Term Macro-Fauna Movement by Multi-Decadal Warming Trends in the Northeastern Pacific

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1. Introduction

Worldwide marine ecosystems are continuously responding to changes in the physical environment at diverse spatial and temporal scales. In addition to the seasonal cycle, other natural patterns occur at the interannual scale, such as El Niño-La Niña Southern Oscillation (ENSO) with a period of about three to five years (Wang & Fiedler, 2006). When ocean conditions stay above or below the long-term average for periods of 10 to 20 years we recognize decadal fluctuations (Mantua et al., 1997), and those with periods longer than 50 years are known as regime (Lluch-Belda et al., 1989). On the ocean, marine populations respond to these variations in different ways, such as changes in their distribution and abundance. Evidence suggests that this multi-decadal scale climate variations are cyclic, which generates recurrent changes in the production level of marine ecosystems in ways that may favor one species or a group over another.

Abrupt changes between multi-decadal phases are known as regime shifts (Overland et al., 2008). The best documented regime shift in the North Pacific occurred in the mid-1970, with strong physical and biological signals, including ocean productivity (Ebbesmeyer, et al., 1991; Roemmich & McGowan, 1995), strong biomass and distribution changes in sardine and anchovy populations (Kawasaki, 1983; Lluch-Belda et al., 1989), and several other fish populations (Beamish et al., 1993; Mantua et al., 1997; Holbrook et al., 1997). These changes impacted marine food webs and ultimately affected the distribution and survival of marine top predators such as seabirds and marine mammals (Trites & Larkin, 1996; Veit et al., 1997; Trites et al., 2007). In this work we review published reports on long term macro-fauna (nekton) movements as related to multi-decadal temperature trends in the Northeastern Pacific.

2. Long term ocean surface variability on the southern California current system

The study area (Fig 1) is under the influence of the California Current System, where, several authors have observed environmental and biological multi-decadal climate signals

(Lluch-Belda et al., 1989; Ware, 1995; Mantua et al., 1997). To describe the environmental conditions on the California Current System, monthly gridded (2x2 degree) sea surface temperatures (from January 1900 to December 2010) were analyzed for the area limited by the 20-42°N latitude and 102-140°W longitude (Fig. 1). The data base is known as "Extended Reconstructed Sea Surface Temperature" and was obtained from the National Oceanic and Atmospheric Administration (NOAA) web site (http://lwf.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php).

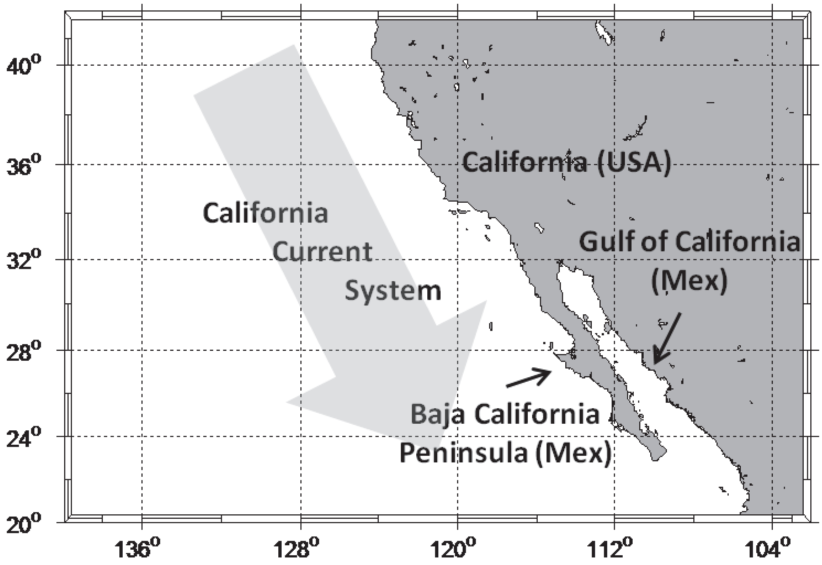


Fig. 1. Study area; USA: United States of America; Mex: Mexico.

To isolate scales of variability from the SST time series, we computed the long term mean and the seasonal signal by fitting annual and semiannual harmonics to the 110-year monthly mean time series (Ripa, 2002). Then we computed SST anomalies as residuals containing sub-seasonal (meso-scale) and low frequency variability (interannual and large scales) after extracting the long term mean and seasonal signals at each grid point. To analyze the regional modes of SST anomalies over the study area (Fig. 1), an empirical orthogonal functions analysis (EOF) was conducted using SST anomalies. The EOF decomposes the variability of the anomalies in a set of *N* uncorrelated orthogonal functions; each *n*-function represents an independent "mode of variability" (Björnsson & Venegas, 1997; Venegas, 2001).

The first EOF mode of SST anomalies explains 48% of the total variance over the study area.

The spatial pattern shows a typical distribution of a global mode, where the surface temperature increase (decrease) in the whole area at the same time and according to the sign of the EOF time series, which explains up to 50% of the unseasonal SST variability off California and Baja California Peninsula (Fig. 2, upper panel). This mode shows a great interannual and multi-decadal variability in its time series (Fig. 2, lower panel). Two long warming trends and two long cooling trends are evident. Warming trends occurred between the late 1910s and the end of the 1930s, and from 1975 until the end of the 1990s, while the cooling trend occurred from the beginning of the twentieth century to the late 1910s, and between the early 1940s and 1975. The strong warming event at the end of the 1950s was not considered as a long term trend, because this was caused by the strong El Niño 1958-59 event, and a few years later the SST recovered its cooling trend until 1975. Also, our results suggested a new cooling trend beginning with the new century. The origin of these multi-decadal trends is subject to debate. In this regard, several studies and hypothesis have been developed to explain the physic mechanisms that are underlying this multi-decadal variability, but are not the matter of this work.

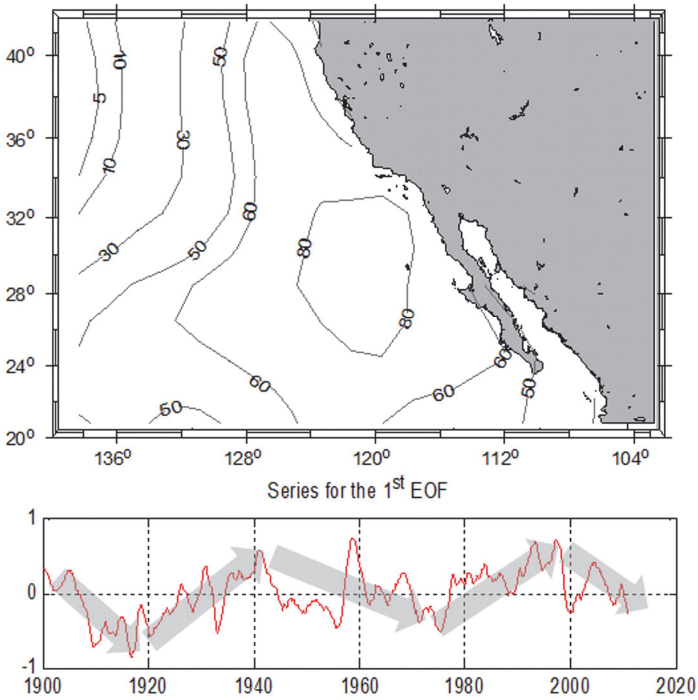


Fig. 2. Local explained variance (%) and temporal patterns of the first EOF mode of SST anomalies.

3. Long term macro-fauna movement

The California sardine (*Sardinops sagax caeruleus*) is the most abundant fish species in the northeast Pacific. It is a key component of the California Current pelagic ecosystem, being the main prey of several pelagic species such as seabirds, marine mammals, predatory fishes and squid (Bakun et al., 2010). This sardine has two core centers of distribution, one in the west coast of the Baja California Peninsula, and the other inside the Gulf of California. From these centers, schools may expand into the surrounding waters when environmental conditions are suitable. This species tends to have large interannual fluctuations in its abundance, due to strong variations in recruitment related primarily to environmental variability in their spawning areas (Lluch-Belda et al., 1986; Hammann et al., 1998). In addition to these interannual fluctuations, this group has a not yet totally understood regime shift time scale (~60 years) of global alternation between sardine and anchovy populations, due to the expansion and contraction of their populations (Fig. 3; Kawasaki, 1983; Lluch-Belda et al., 1989; Baumgartner et al., 1992; Chavez et al., 2003; Bakun et al., 2010). These can be seen in the commercial landings of California state (USA) waters (Fig. 4) and in fossil records over the last 2000 years (Baumgartner et al., 1992). Chavez et al (2003) related this regime shift to the SST variability in the northeast Pacific. This relationship is evident in the sardine landings (Fig. 4), where increases are evident during warming trends (1920-1940 & 1975-2000) and a decrease during the cooling trend (1940-1975).

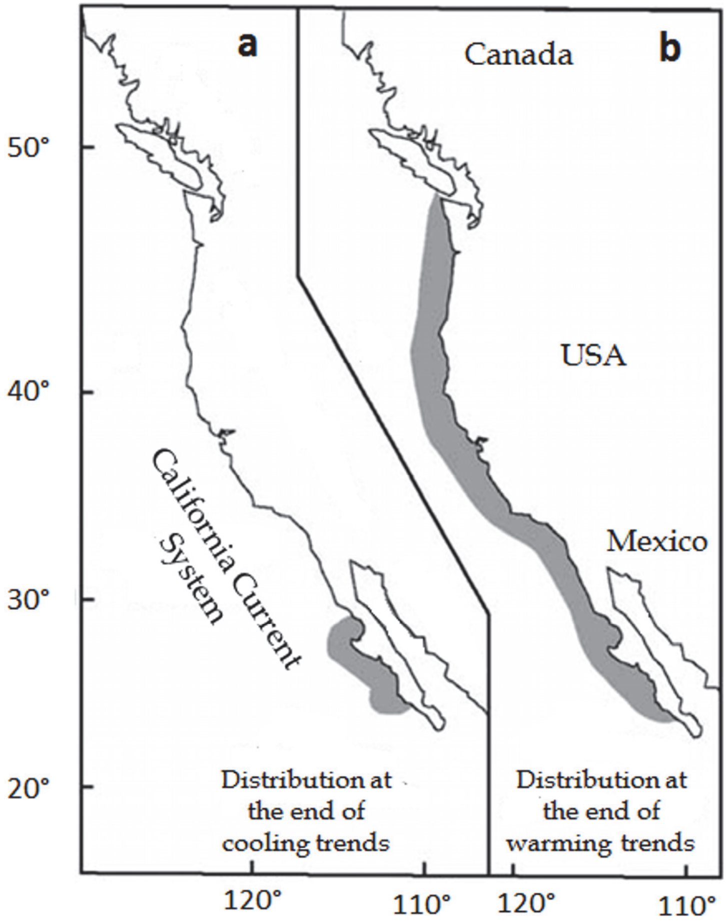


Fig. 3. Contraction (a) and expansion (b) of California sardine populations in the Northeast Pacific at the end of cooling and warming periods respectively (Bakun et al., 2010).

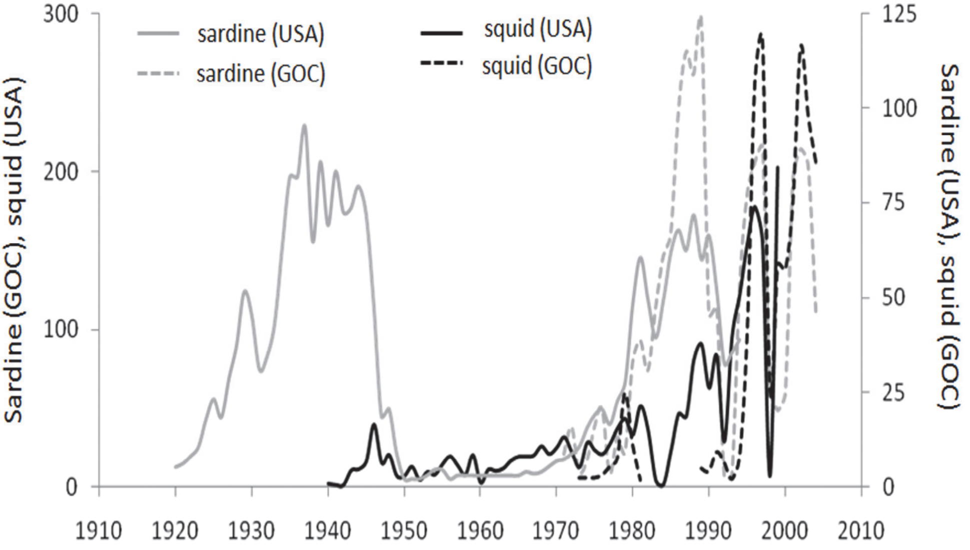
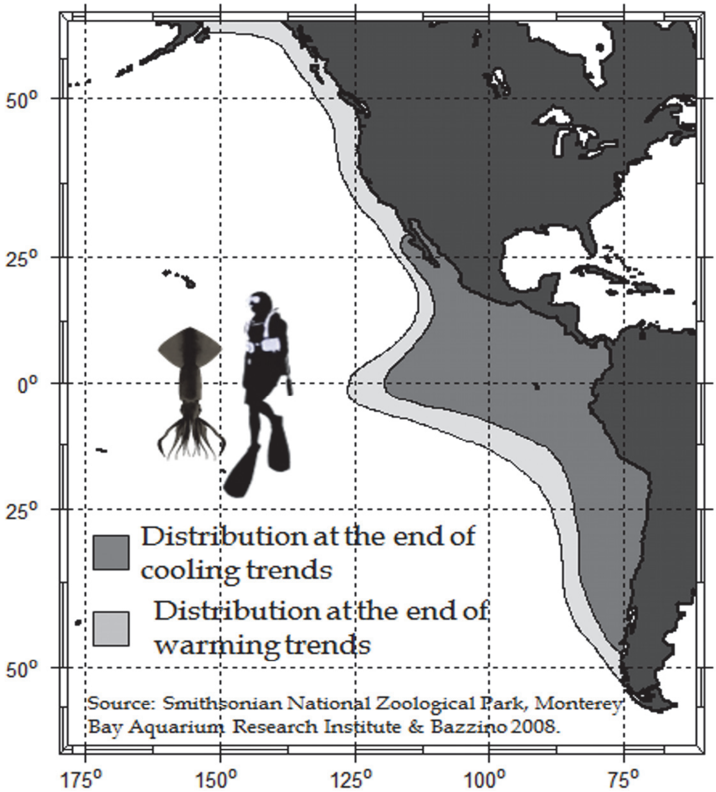


Fig. 4. California sardine landings at California waters (USA; thousands of tons) from FAO (1997), and for Gulf of California waters (GOC; thousands of tons) from SAGARPA; jumbo squid landings at California waters (USA; millions of pounds) from NOAA web page (http://www.pfeg.noaa.gov/research/climatemarine/cmffish/cmffishery.html), and Gulf of California (GOC; thousands of tons) from SAGARPA.

The Jumbo squid (*Dosidicus gigas*) is a large ommastrephid (up to 50 kg mass and overall length of 2.5 m) endemic to the Eastern Tropical Pacific. This squid is an important component of the marine food web that prey on small pelagic and mesopelagic fishes, crustaceans and squids (Markaida & Sosa-Nishizaki, 2003; Armendáriz-Villegas, 2005; Field et al., 2007); being an energy transfer from the mesopelagic food web to higher trophic level species as tunas, billfish, sharks, and marine mammals (Galván-Magaña et al., 2006; Field et al., 2007). The jumbo squid maintain the largest squid fishery in the world, which operates off the coasts of Peru, Chile and Central America, and in the Gulf of California (Morales-Bojórquez et al., 2001; Waluda & Rodhouse 2006). Recent scientific publications, anecdotal observations and fisheries landings pointed out a range expansion of jumbo squid throughout the California Current and southern Chile over the past decade (Fig. 4 & 5; Cosgrove, 2005; Chong et al., 2005; Wing, 2006; Zeidberg & Robinson, 2007). This sustained range expansion has generated hypotheses related to changes in climate-linked oceanographic conditions and reduction in their competing top predators (Zeidberg & Robinson, 2007; Waters et al., 2008). However, the coincidence of the recent poleward range expansions in both hemispheres, and the reports of the increases in the abundance off the west coasts of North and South America in the late 30s (Rodhouse, 2008), (just at the end of the 1910-1940 warming trend), suggests a physically-induced forcing mechanism. This may be related with long term warming trends and the poleward expansion of their primary habitat (Bazzino, 2008).



Source: Smithsonian National Zoological Park, Monterey Bay Aquarium Research Institute & Bazzino 2008.

Fig. 5. Jumbo squid expansion during multi-decadal environmental trends.

The sperm whale *(Physeter macrocephalus)* is the largest odontocete, or toothed whale. This predator can be found in all world oceans in deeper waters, feeding largely on epi- and mesopelagic squid species (Whitehead, 2003). Groups of females and immatures are distributed on tropical and temperate waters, while solitary males are distributed on polar waters and only go to lower latitudes to breed. In the California Current System, Barlow & Forney (2007) showed that the abundance of sperm whales is temporally variable, and the two most recent estimates (2001 and 2005) were markedly higher than the estimates for 1991−96. Related to this increased in whales abundance, Jaquet et al. (2003) noted that few sightings of sperm whales were reported during the 1980s along the Baja California Peninsula; then their abundance appeared to increase since 1992. Actually these whales occur into the Gulf of California year-round and the high proportion of mature females and first-year calves suggests that this area is an important breeding and feeding ground for the sperm whale (Jaquet et al., 2003). As sperm whales are known to forage on jumbo squid, these authors coincided that the increased in the presence of sperm whale in both regions could be related with the expansion of jumbo squid in the California Current System and in the Gulf of California during the past two decades. Concurrently, a decrease in sperm whale abundance in the Galapagos Islands since the early 1990s has been observed (Whitehead et al., 1997), as well as animals from Galapagos have been spotted inside the Gulf (Jaquet et al., 2003), suggesting a northward shift in their distribution.

The Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) is an average-sized oceanic dolphin (from 2 to 2.5 m) found in temperate waters of the North Pacific Ocean, feeding on small pelagic and mesopelagic fish and squid. In the eastern Pacific, large groups of this species are frequently seen in the California Current System (Leatherwood et al., 1984; Stacey & Baird, 1990; Keiper et al., 2005). The southern boundary of the distribution of Pacific white-sided dolphins is the Gulf of California, where the species has been observed only in its southwest area during the winter and spring (Aurioles et al., 1989). During the last 3 decades, Salvadeo et al. (2010) documented a decline in the presence of this dolphin species in the southwest Gulf of California, just during the end of the last warming trend in the California Current System (Fig. 2). Considering that the thermal environment is physiologically important to animals, the authors listed three evidences consistent with a poleward shift in their range: 1) The occurrence of this dolphin has decreased by approximately 1 order of magnitude per decade since the 1980s, (Table 1); 2) their monthly contraction to cooler months of the year (Fig. 6); and 3) the occurrence of this dolphin has increased on the west coast of Canada from 1984 to 1998 (Morton, 2000).

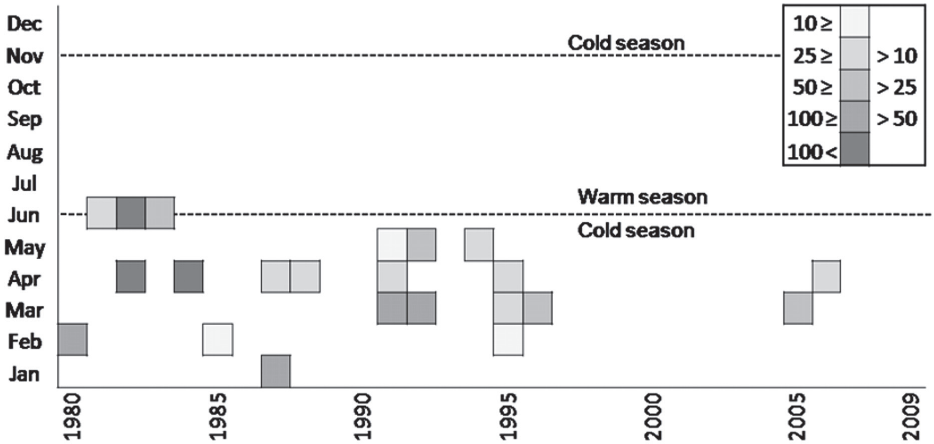


Fig. 6. Historical numbers of animals per month of Pacific white-sided dolphin from the southwest Gulf of California (Salvadeo et al. 2010).

Period	Effort	Sightings	Animals	Mean	Min.	Max.	SD	Sightings/hrs	Animals/hrs
1980s	252	10	647	65	2	200	67	0.039	2.56
1990s	1659	16	316	20	1	45	12	0.010	0.19
2000s	1986	2	50	25	20	30	7	0.001	0.03

Table 1. Pacific white-sided dolphin: accumulated historical data from the southwest Gulf of California for the last 3 decades. Effort (h); sightings: number of occasions when the species was observed; mean, minimum (min.), maximum (max.), and SD for group size; sightings h–1 and animals h–1: abundance relative to effort; 1980s: 1978–1988; 1990s: 1989–1999; 2000s: 2000–2009 (Salvadeo et al., 2010).

The gray whale (*Eschrictius robustus*) is a medium sized baleen whale reach 14 m in length and weigh of 45 metric tons. Some pods of gray whales breed every boreal winter at three lagoons along the Baja California Peninsula. At the end of the breeding season, the whales migrate to the feeding grounds in the Bering and Chukchi Seas, where they feed on benthic fauna (Rice & Wolman, 1971). The population of gray whales seems to have reached carrying capacity, with population size fluctuating between 20,000 and 22,000 animals (Rugh et al., 2008). As the Pacific white-sided dolphin, the evidences pointed out a possible poleward shift of the gray whale distribution related to the last warming SST trend. These evidences are: 1) there is an apparent long term tendency in the use of breeding lagoons, increasing at the northern lagoon and decreasing at the southern lagoon (Urbán et al., 2003a); 2) the decrease in the numbers of whales at the breeding lagoons during the last years, also observed from shore-based surveys at Piedras Blancas during the northbound migration (Urbán et al., 2010); 3) an increase in calf sightings at California (USA) correlating with warmer sea surface temperature anomalies (Shelden et al., 2004); 4) a range expansion into Arctic waters (Moore and Huntington, 2008); 5) during warming El Niño years the whales tend to use northern areas more intensively than in normal years (Gardner & Chávez-Rosales, 2000; Urbán et al., 2003b); 6) the unusual sighting of a gray whale in the Mediterranean Sea, it is another possible effect of their expansion to the north, which allows them to cross the Arctic to the Atlantic (Scheinin et al., 2011); and 7) in spite of having an increasing population of gray whales in the eastern Pacific, the observations of individuals inside the Gulf of California has been consistently declining (Salvadeo et al., 2011).

4. Conclusions

Two well defined long term climate warming trends were observed in the SST anomalies, these appear to be part of cyclical changes that include cooling trends over the study area (Fig 2). Changes in the SST are indicators of more complex ocean processes related to alterations in oceanic and atmospheric circulations, which ultimately affect the enrichment of superficial waters. The biological responses to those ocean processes are complex and not well understood.

There are evidences which indicate that distribution shifts related to long term ocean warming had occurred for some species, including poleward shifts (gray whale and Pacific white-sided dolphin), range expansions (California sardine and jumbo squid) and redistribution (sperm whale). The distributions of most species are defined by interactions between available environmental conditions and the ecological niches that they occupy on the ecosystem (Macleod, 2009). For gray whales and Pacific white-sided dolphins the cause of their range shift is apparently driven by the importance of thermal environment for the species. This poleward shift caused by thermal niche was also recorded in stranding records of dolphin species in the north-eastern Atlantic Ocean (Macleod et al., 2005). For the sperm whale it seems to be related with a trophic link, because their redistribution appears to be coupled with the range expansion of their primary prey, the jumbo squid. Multi-decadal range shift related with trophic interactions was also observed in the north-eastern Atlantic Ocean, from the subpolar gyre variability via plankton, to marine top predators (Hátún et al., 2009)

For the California sardine and the jumbo squid, their range expansions appear to be related with the extension of suitable habitat for their reproduction and recruitment. These range shifts seems to be cyclical, where their populations retract to subtropical areas during cooling trends and expand to temperate areas during warming trends. For cetacean species, this cycle was not observed yet, possibly due to the lack of information, so maybe this could also happen. These recurrent populations' changes also were observed on small pelagic fish and squids in other world oceans current systems (Fig. 7), and show the links between multi-decadal global ocean climate variability and regional fish and squid populations (Lluch-Belda et al., 1989; Schwartzlose et al., 1999; Sakurai et al., 2000; Tourre et al., 2007). These synchronous population shifts are consequence of cyclic changes on the environment that affect the production level of marine ecosystems in ways that may favor one species or group of species over another, affecting the marine food web structure and function.

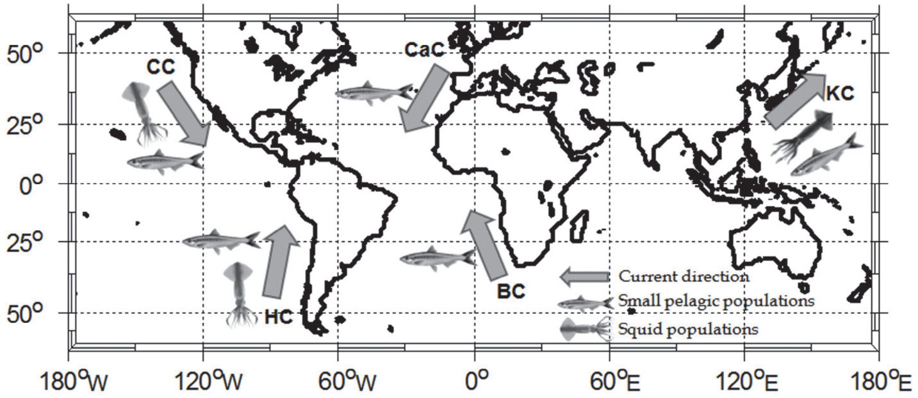


Fig. 7. Oceans current systems, where distribution shift were recorded on small pelagic fish and squid populations; ocean currents: California (CC), Canary (CaC), Kuroshio (KC), Humboldt (HC) and Benguela (BC); source: Lluch-Belda et al., 1989; Schwartzlose et al., 1999; Sakurai et al., 2000; Tourre et al., 2007, Bazzino 2008.

In conclusion, there are evidences that distribution shift occurred for some species due to long term ocean warming. Future scientific studies need to focus on understand the mechanisms of these long term cyclic variations and their effects on marine fauna, and incorporate this knowledge into the management and conservation approaches of the living marine resources.

Finally, the first EOF mode of SST anomalies showed a cooling trend for the last 10 years (Fig. 2). If the observed trends during the past are replicated, we should expect the beginning of a new ecological cycle, forced by climate tendencies that will restrict the distribution of California sardine to the west coast of the Baja California peninsula; and will move the jumbo squid range southward, forcing lower squid population levels at the west coast of the Baja Peninsula and the Gulf of California; related with this, a subsequent movement of sperm whales to other areas of the Pacific would occur, and the return of white-sided dolphins and gray whales as seasonal visitors of the Gulf of California.

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6. References

Armendáriz-Villegas, J. (2005). Hábitos alimenticios del Calamar Gigante (Dosidicus gigas; Orbigny, 1835), en el Centro del Golfo de California durante los años 2002 y 2003, Bachelor Thesis, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., México

Aurioles D. G., Gallo-Reynoso J. P., Muñoz E. L. & Ejido J. V. (1989). El delfín de costados blancos (Lagenorhynchus obliquidens, Gill 1865) (Cetacea: Delphinidae) residente estacional en el suroeste del Golfo de California, México. *Anales del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología* Vol.60, pp.459–472, ISSN 0368-8720

Bakun, A., Babcock, E. A., Lluch-Cota, S. E., Santora, C. & Salvadeo C. J. (2010). Issues of ecosystem-based management of forage fisheries in "open" non-stationary ecosystems: the example of the sardine fishery in the Gulf of California. *Reviews in Fish Biology and Fisheries* Vol.20, No.1, pp. 9-29. ISSN 1573-5184

Barlow, J. & Forney K. A. (2007). Abundance and density of cetaceans in the California Current ecosystem. Fishery *Bulletin* Vol.105, pp. 509–526. ISSN 0090-0656

Baumgartner, T. R., Soutar, A. & Ferreira-Bartrina V. (1992). Reconstruction of the history of Pacific sardine and Northern Pacific anchovy populations over the past two millennia from sediments of the Santa Barbara basin. CalCOFI Reports Vol.33, pp. 24-40. ISSN 0575-3317

Bazzino, G. (2008). Estructura poblacional, movimientos horizontales y migraciones verticales del calamar gigante en el Golfo de California y en el Océano Pacífico frente a la Península de Baja California. PhD. Thesis, Centro de Investigaciones Biológicas del Noroeste, La Paz, B.C.S., México. 126 pp.

Beamish, R. J. & Bouillon, D. R. (1993). Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences Vol.50, pp. 1002–1016. ISSN 1205-7533

Björnsson, H. & Venegas S. A. (1997) A manual for EOF and SVD analyses of climatic data, McGill University, Retrieved from http://www.geog.mcgill.ca/gec3/wp-content/uploads/2009/03/Report-no.-1997-1.pdf

Chavez F. P., Ryan J., Lluch-Cota S. E. & Niquen C. M. (2003). From anchovies to sardines and back: multi-decadal change in the Pacific Ocean. Science Vol.299, pp. 217–221. ISSN 1095-9203

Chong, J., Oyarzun, C., Galleguillos, R., Tarifeño, E., Sepúlveda R. & Ibáñez, C. (2005). Fishery biology parameters of jumbo squid, Dosidicus gigas (Orbigny, 1835) (Cephalopoda: Ommastrephidae), in Central Chile coast (29°S-40°S) during 1993-1994. Gayana Vol.69, No.2, pp. 319-328. ISSN 0717-652X

Cosgrove, J. A. (2005). The first specimens of Humboldt squid in British Columbia. PICES Press Vol.13, No.2, pp. 30–31. ISSN 1195-2512

Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H. & Redmond K. T. (1991). 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. Seventh annual Pacific climate (PACLIM) workshop, Asilomar, California, USA, April 1990

FAO. (1997). Review of the state of world fishery resources: marine fisheries. FAO Fisheries Circular No.920 FIRM/C920, ISSN 0429-9329, Rome, Italy.

Field, J. C., Baltz, K., Phillips, A. J. & Walker, W. A. (2007). Range expansion and trophic interactions of the jumbo squid, Dosidicus gigas, in the California Current. CalCOFI Reports Vol.48, pp. 131-146. ISSN 0575-3317

Galván-Magaña, F., Olson, R. J., Bocanegra-Castillo, N. & Alatorre-Ramirez, V G. (2006). Cephalopod prey of the apex predator guild in the epipelagic eastern Pacific Ocean In: The role of squid in open ocean ecosystems, Olson, R. J. & Young, J. W. (Eds.), pp. 45-48, GLOBEC international project, ISSN 1066-7881, Honolulu, Hawaii, USA

Gardner, S. C. & Chávez-Rosales, S. (2000). Changes in the relative abundance and distribution of gray whales (Eschrichtius robustus) in Magdalena Bay, Mexico during an El Niño event. Marine Mammal Science Vol.16, pp. 728–738, ISSN 0824-0469

Hammann M. G., Nevárez-Martínez M. O. & Green-Ruíz, Y. (1998). Spawning habitat of the Pacific sardine (Sardinops sagax) in the Gulf of California: Egg and larval distribution 1956-1957 and 1971-1991. CalCOFI Reports Vol.39, pp. 169-179, ISSN 0575-3317

Hátún, H., Payne, M. R., Beaugrand, G., Reid, P. C., Sandø A. B., Drange, H., Hansen, B, Jacobsen, J. A. & Bloch D. (2009). Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. Progress in Oceanography Vol.80, pp. 149–162, ISSN 0079-6611

Holbrook, S., Schmitt, R. & Stephens, J. (1997) Changes In An Assemblage of Temperate Reef Fishes Associated With A Climate Shift. Ecological Applications Vol.7, pp. 1299-1310, ISSN 1051-0761

Jaquet, N., Gendron, D. & Coakes, A. (2003). sperm whales in the gulf of California: residency, movements, behavior, and the possible influence of variation in food supply. Marine Mammals Science Vol.19, No.3, pp.545-562, ISSN 0824-0469

Kawasaki, T. (1983). Why do some pelagic fishes have wide fluctuations in their numbers? - biological basis of fluctuation from the viewpoint of evolutionary ecology, In: Reports of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources. Sharp, G. D. & Csirke J. (eds.), pp. 1065-1080, FAO Vol.91, No.2-3, Rome, Italy

Keiper, C. A., Ainley, D. G., Allen, S. G. & Harvey J. T. (2005). Marine mammal occurrence and ocean climate off central California, 1986 to 1994 and 1997 to 1999. Marine Ecology Progress Series Vol.289, pp. 285–306. ISSN 1616-1599

Leatherwood, S., Reeves, R. R., Bowles, A. E., Stewart, B. S. & Goodrich, K. R. (1984). Distribution, seasonal movements and abundance of Pacific white-sided dolphins in the eastern North Pacific. Science Report Whales Research Institute Vol.35, pp. 129–157

Lluch-Belda, D., Magallón, B. F. J. & Schwartzlose, R. A. (1986). Large fluctuations in the sardine fishery in the Gulf of California: possible causes. CalCOFI Reports Vol.27, pp. 136-140, ISSN 0575-3317

Lluch-Belda, D., Crawford R. J. M., Kawasaki, T., MacCall, A. D., Parrish, R. H., Schwartzlose, R. A. & Smith P. E. (1989). Worldwide fluctuations of sardine and anchovy stocks: the regime problem. South Africa Journal of Marine Science Vol.8, pp. 195–205, ISSN 1814-2338

MacLeod, C. D. (2009) Global climate change, range changes and potential implications for the conservation of marine cetaceans: a review and synthesis. Endangered Species Research Vol.7, pp. 125-136, ISSN 1613-4796

MacLeod, C. D., Bannon, S. M., Pierce, G. J., Schweder, C., Learmonth, J. A., Reid, R.J. & Herman, J. S. (2005) Climate change and the cetacean community of northwest Scotland. Biological Conservation Vol.124, pp. 477–483, ISSN 0006-3207

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific decadal climate oscillation with impacts on salmon. Bulletin of the American Meteorological Society Vol.78, pp. 1069-1079, ISSN 0003-0007

Markaida U, Sosa-Nishizaki O (2003) Food and feeding habits of jumbo squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae) from the Gulf of California, Mexico. Journal of the Marine Biological Association of the United Kingdom Vol.83, pp. 507–522, ISSN 0025- 3154

Moore, S. E., & Huntington, H. P. (2008). Arctic marine mammals and climate change: impacts and resilience. Ecological Applications Vol.18, pp. 157–165, ISSN 1051-0761

Morales-Bojórquez, E., Cisneros-Mata, M. A., Nevarez-Martínez, M. O. & Hernández-Herrera, A. (2001). Review of stock assessment and fishery biology of Dosidicus gigas in the Gulf of California, Mexico. Fisheries Research Vol.54, pp. 83-94, ISSN 0165-7836

Morton, A. (2000). Occurrence, photo-identification and prey of Pacific white-sided dolphins (Lagenorhynchus obliquidens) in the Broughton Archipelago, Canada 1984–1998. Marine Mammals Science Vol.16, pp. 80-93, ISSN 0824-0469

Overland, J., Rodionov, S., Minobe, S., & Bond, N. (2008). North Pacific regime shifts: Definitions, issues and recent transitions. Progress In Oceanography Vol.77, No.2-3, pp. 92-102, ISSN 0079-6611

Rice, D. W., & Wolman, A. A. (1971). The life history and ecology of the gray whale (Eschrichtius robustus). American Society of Mammalogists, Special Publication No.3 Stillwater, Oklahoma, USA

Ripa, P. (2002). Least squares data fitting. Ciencias Marinas Vol.28, pp.79-105,ISSN: 0185-3880

Roemmich, D. & McGowan, J. (1995). Climate warming and the decline of zooplankton in the California Current. Science Vol.267, pp. 1324-1326. ISSN 1095-9203

Rodhouse P. G. (2008). Large-scale range expansion and variability in ommastrephid squid populations: a review of environmental links. CalCOFI Reports Vol.49, pp. 83-89, ISSN 0575-3317

Rugh, D. J., Breiwick, J., Muto, M. M., Hobbs, R. C., Sheldon, K. W., D'Vincent, C., Laursen, I. M., Rief, S. L., Maher, S. L., & Nilson, S. D. (2008). Report of the 2006–2007 census of the eastern North Pacific stock of gray whales. Alaska Fisheries Science Center, Retrieved from www.afsc.noaa.gov/Publications/ProcRpt/PR2008-03.pdf

Sakurai, Y., Kiyofui, H., Saitoh, S., Goto, T. & Hiyama, Y. (2000). Changes in inferred spawning areas of Todarodes pacificus (Cephalopoda: Ommatrephidae) due to changing environmental conditions. ICES Journal of Marine Science Vol.57, pp. 24-30, ISSN 1095-9289

Salvadeo C. J., Lluch-Belda, D., Gómez-Gallardo, A., Urbán-Ramírez, J. & MacLeod, C. D. (2010). Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific. Endangered Species Research Vol.11, pp. 13-19, ISSN 1613-4796

Salvadeo C. J., Lluch-Cota, S., Maravilla-Chavez, M. O., Alvarez-Castañeda S. T., Mercuri, M. & Ortega-Rubio, A. (2011). Impact of climate change on gray whale populations, whale watching, and conservation. Conservation Science Symposium, Loreto, BCS, Mexico, May 25-28, 2011

Scheinin, A. P., Kerem, D., MacLeod, C. D., Gazo, M., Chicote C. A. & Castellote, M. (2011). Gray whale (Eschrichtius robustus) in the Mediterranean Sea: anomalous event or early sign of climate-driven distribution change?. Marine Biodiversity Records Vol.4, e28, ISSN 1755-2672

Schwartzlose, R. A., Alheit, J., Bakun, A., Baumgartner, T. R., Cloete, R.,. Crawford, R. J. M., Fletcher, W. J., Green-Ruiz, Y. Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S., MacCall, A. D., Matsuura, Y., Nevarez-Martinez, M. O., Parrish, R. H., Roy, C., Serra, R., Shust, K. V., Ward, M. N. & Zuzunaga, J. Z. (1999). Worldwide large–scale fluctuations of sardine and anchovy populations. South Africa Journal of Marine Science, Vol.21, pp. 289–347, ISSN 1814-2338

Shelden, K. W., Rugh, D. J., & Schulman-Janiger, A. (2004). Gray whales born north of Mexico: indicator of recovery or consequence of regime shift? Ecological Applications Vol.14, pp. 1789–1805, ISSN 1051-0761

Stacey, P. J. & Baird, R. W. (1990). Status of the white-sided dolphin, Lagenorhynchus obliquidens, in Canada. Canadian *Field-Naturalist* Vol.105, pp. 219–232, ISSN 0008-3550

Tourre, Y. M., Lluch-Cota, S. E. & White, W. B. (2007). Global multi-decadal ocean climate and small-pelagic fish population. Environmental Research Letters Vol.2, doi:10.1088/1748-9326/2/3/034005, ISSN 1748-9326

Trites, A. W. & Larkin, P. A. (1996). Changes in the abundance of Steller sea lions (Eumetopias jubatus) in Alaska from 1956 to 1992: how many were there? Aquatic Mammals Vol.22, pp. 153-166, ISSN 0167-5427

Trites, A. W., Deecke, V. B., Gregr, E. J., Ford, J. K. B. & Olesiuk P. F. (2007). Killer whales, whaling and sequential megafaunal collapse in the North Pacific: a comparative analysis of dynamics of marine mammals in Alaska and British Columbia following commercial whaling. Marine Mammal Science Vol.23, pp. 751-765, ISSN 0824-0469

Urbán, R. J., Rojas, L. B., Pérez-Cortéz, H., Gómez-Gallardo, A. U., Swartz, S. Ludwing, S. & Brownell, L. (2003a). A review of gray whales on their wintering grounds in Mexican waters. Journal of Cetacean Research and Management Vol.5, pp. 281–295, ISSN 1561-0713

Urbán, R. J., Gómez-Gallardo, U. A. & Ludwig, S. (2003b). Abundance and mortality of gray whales at Laguna San Ignacio, Mexico, during the 1997–98 El Niño and the 1998–99 La Niña. Geofisica Internacional Vol.42, pp. 439-446, ISSN 0016-7169

Urbán, R. J., Gómez-Gallardo U. A., Rojas-Bracho, L. & Swartz S. L. (2010). Historical changes of gray whales abundance in San Ignacio and Ojo de Liebre breeding lagoons, Mexico. IWC Scientific Committee Paper, SC/62/BRG36, ISSN-0255-2760

Venegas S. A. (2001). Statistical methods for signal detection in climate. Danish Center for Earth System Science Report No.2, Retrieved from www.atmos.colostate.edu/~davet/AT655/notes/VenegasNotes.pdf

Veit, R. R., Mcgowan, J. A., Ainley, D. G., Wahls, T. R., & Pyle, P. (1997). Apex marine predator declines ninety percent in association with changing oceanic climate. Global Change Biology Vol.3, pp. 23–28, ISSN 1365-2486

Waluda, C. M. & Rodhouse, P. G. (2006). Remotely sensed mesoscale oceanography of the central Eastern Pacific and recruitment variability in *Dosidicus gigas*. Marine Ecology Progress Series Vol.310, pp. 25–32. ISSN 1616-1599

Wang, C. & Fiedler, P. C. (2006). ENSO variability and the eastern tropical Pacific: A review. Progress in Oceanography Vol.69: 239-266. ISSN 1369-9350

Ware, D. M. (1995). A century and a half of change in the climate of the NE Pacific. Fisheries Oceanography Vol.4, pp. 267-277, ISN 1365-2419

Waters, G. M., Olson, R. J., Field, J. C. & Essington T. E. (2008). Range expansion of the Humboldt squid was not caused by tuna fishing. PNAS Vol.105, No.3, E5, ISSN 1091-6490

Whitehead, H. (2003). "*Sperm Whales*: *Social Evolution in the Ocean*." University of Chicago Press, ISBN 9780226895178, Chicago USA

Whitehead, H., Christal, J. & Dufault , S. (1997). Past and distant whaling and the rapid decline of sperm whales off the Galápagos Islands. *Conservation Biology* Vol.11, pp. 1387-1396, ISSN 0888-8892

Wing, B. L. (2006). Unusual invertebrates and fish observed in the Gulf of Alaska, 2004–2005. PICES Press Vol.14, No.2, pp. 26–28

Zeidberg L. D. and B. H. Robinson. 2007. Invasive range expansion by the Humboldt squid, Dosidicus gigas, in the eastern North Pacific. PNAS Vol.104, No.31, pp. 12948-12950, ISSN 1091-6490