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GRAY WHALE (*Eschrichtius robustus*) ABUNDANCE DURING ITS MIGRATION IN ENSENADA, BAJA CALIFORNIA, DURING THREE SEASONS (2003-2006)

TESIS

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Resumen aprobado por:

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Abundancia de ballena gris (*Eschrichtius robustus*) durante su migración en Ensenada, Baja California, en tres temporadas (2003-2006).

Actualmente sólo existen dos poblaciones de ballena gris que han pasado por momentos en donde se les consideró casi extintas. La población del Pacífico Occidental, que se encuentra a lo largo de las costas asiáticas, aún se considera en peligro de extinción. La población del Pacífico oriental se ha recuperado y ha sido monitoreada desde los años cincuenta. Este estudio se enfoca en esta población. La ruta migratoria anual de esta ballena es a lo largo de las costas de Norteamérica, desde los mares de Chuckchi y Beaufort hasta las lagunas costeras de Baja California Sur, México. Su extensa ruta migratoria hace de la ballena gris un recurso compartido entre tres naciones, y por lo tanto, la contribución para su conservación debe ser una responsabilidad de todas ellas. Los conteos de ballena gris durante su migración no se habían realizado en México antes del presente estudio. Nuestros objetivos fueron determinar los tiempos de la migración (inicio, máximo, fin) al sur y al norte, y estimar el tamaño poblacional con base en las ballenas contadas en la migración al sur. Se llevaron a cabo censos durante tres años (diciembre a mayo 2003-2006) desde la costa en Ensenada, Baja California, México. Los tiempos de la migración se determinaron para las migraciones al sur y al norte por medio de un índice de abundancia relativa (número de ballenas por hora de esfuerzo de observación). Para la estimación de abundancia se tomaron en cuenta factores que podrían sesgar la estimación final: ballenas no observadas durante horas de esfuerzo, corrección por tamaño de grupo y por sesgo del observador, ballenas no observadas durante periodos sin esfuerzo (f_t) por medio de polinomiales de Hermite, distancia de la costa (por medio de recorridos en barco) y variación de la tasa migratoria entre el día y la noche. Los conteos promedio fueron de 3.97, 3.87 y 3.56 ballenas/hr en 2003-2004, 2004-2005 y 2005-2006, respectivamente. Los tiempos de migración fueron consistentes en 2003-04 y 2005-06, y se presentaron fechas medianas del 23 al 29 de enero. Las fechas medianas para 2004-05 fueron una semana más temprano, entre el 17 y el 18 de enero. Para los tres años, la consistencia permaneció para la fecha en la cual se registró el 90% de los avistamientos (13 de febrero). La migración al norte mostró una serie de tiempo más prolongada, y se dividió en migración al norte sin crías y migración sólo de parejas hembra/cría. La migración al norte sin crías ocurrió desde mediados de febrero hasta principios de abril con conteos de 1.03, 1.50 y 0.52 ballenas/hr en los respectivos años de 2003 a 2006. El segundo grupo de migrantes (parejas hembra/cría) pasaron por Ensenada desde principios de abril hasta principios de mayo con conteos menores (0.43, 0.19 y 0.26 parejas hembra/cría por año). El traslapo entre los dos periodos de migración al norte fue a principios de abril. Se contaron un total de 661, 773 y

661 ballenas durante la migración al sur en 2003-04, 2004-05 y 2005-06, respectivamente, Los recorridos en barco mostraron que 56% de los avistamientos de ballenas grises que pasan por Ensenada no pueden ser observadas desde tierra porque pasan a más de 5km de la costa; por lo tanto, se aplicó un factor multiplicativo general de 1.56. Se obtuvieron valores altos de f_t: 12.46 (2003-04), 12.96 (2004-05) y 9.77 (2005-06)). La estimación final de la abundancia de ballena gris en Ensenada fue de 24,862 individuos en 2003-04, 29,786 en 2004-05 y 19,436 ballenas en 2005-06.

Palabras clave: Ballena gris, *Eschrichtius robustus*, abundancia, estimación, migración, factores de corrección.

ABSTRACT of the thesis presented by **Melba De Jesús Huerta**, as a partial requirement to obtain the degree in MASTER OF SCIENCE in MARINE ECOLOGY, Ensenada, Baja, California, Mexico, October 2006.

Abstract approved by:

Gisela Heckel Dziendzielewski, Ph.D.

Gray whale (*Eschrichtius robustus*) abundance during its migration in Ensenada, Baja California, during three seasons (2003-2006).

In present time, there are only two extant gray whale populations that have gone through critical points of near extinction. The Western Pacific stock, found along eastern Asian coasts, still remains endangered. The Eastern stock has recovered and has been monitored systematically since the 1950's. The present study is focused on this population. This whale's annual migration route is along the North American coasts, from the Chukchi and Beaufort seas to coastal lagoons in Baja California Sur, Mexico. Its extended migration route makes gray whales a common resource shared among three nations. Therefore, contribution for its conservation should be a three-nation responsibility. Gray whale counts during its migration in Mexico had not been attempted prior to this study. Our objectives were to determine the south- and northbound migration timing (beginning, peak, end) and to estimate the population size based on southbound migrating whale counts. We carried out onshore censuses during three years (December to May 2003-2006) in Ensenada, Baja California, Mexico. Migration timing was determined for southbound and northbound migration periods with a relative abundance index (number of whales per hour of observation effort). Abundance estimation took into account factors that may bias the final estimation: whales missed during effort periods, bias corrected pod size and observer bias, whales missed during off-effort periods (f_t) with Hermite polynomials, distance offshore (by means of boat surveys), and day/night travel rate. Mean counts varied from 3.97, 3.87, to 3.56 whales/hr in 2003-2004, 2004-2005, and 2005-2006, respectively. Migration timing was consistent in 2003-04 and 2005-06, with median dates ranging from 23-29 January. Median dates for 2004-05 were about a week earlier on 17-18 January. For all three years, consistency prevailed in the observed date (13 February) on which 90% of the southbound sightings were recorded. The northbound migration showed a more prolonged time series, splitting it into northbound migration without calves and migration with only cow/calf pairs. Northbound migration without calves lasted from mid-February to early April with mean counts of 1.03, 1.50, and 0.52 whales/hr in the respective years from 2003-2006. The second set of migrants (cow/calf pairs) traveled past Ensenada from early April to early May with lower mean counts of 0.43, 0.19, and 0.26 cow/calf pairs day^{-1} per year. The overlap in the two northbound migration groups was in early April. A total of 661, 773, and

661 whales were counted in 2003-04, 2004-05 and 2005-06, respectively, for the southbound migration. Boat surveys revealed that 56% of gray whale sightings cannot be observed from land because the whales are traveling beyond 5km from shore; therefore, a correction factor of 1.56 was calculated as a general multiplicative factor. High f_t values were obtained: 12.46 (2003-04), 12.96 (2004-05), 9.77 (2005-06). Final estimated gray whale abundance in Ensenada was 24,862 whales in 2003-04, 29,786 whales in 2004-05 and 19,436 whales in 2005-06.

Key words: Gray whale, *Eschrichtius robustus*, abundance, estimation, migration, correction factors.

IN SPECIAL DEDICATION TO:

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RESUMEN EJECUTIVO

I. INTRODUCCIÓN

La larga ruta migratoria de la población del Pacífico nororiental de la ballena gris (*Eschrichtius robustus*; Lilljeborg, 1861), hace de este misticeto un recurso compartido por tres naciones: Canadá, Estados Unidos y México. Independientemente del acuerdo que exista entre las naciones para manejar un recurso, el principio básico para manejarlo es el conocer la salud y estado del mismo así como también del ambiente que lo rodea. La migración anual y costera de la ballena gris, que es la más larga de los mamíferos, resulta conveniente para el constante monitoreo de esta especie permitiendo conteos anuales desde tierra. Con base en los conteos es posible estimar el tamaño de esta población. Sin embargo, las estimaciones pueden estar sesgadas por factores que puedan afectar los conteos. Aunque se han realizado estimaciones en California (Granite Canyon) casi cada año desde la década de los sesenta, desde 2002-2003 esta información no se registró. En el presente estudio se estimó el tamaño de la población de ballena gris del Pacifico Nororiental en tres temporadas (2003-04, 2004-05, 2005-06), tomando en cuenta los factores que sesgan la estimación final. En México, este método de estimación de abundancia no se había aplicado. El estudio se podría tomar como un indicador de participación por parte de México en el monitoreo de un recurso que también le pertenece.

Caza de la ballena gris del Pacifico nororiental

A mediados del siglo XIX, una de las especies de ballenas más afectadas por la caza fue la ballena gris. Existían tres poblaciones de ballena gris distribuidas alrededor del hemisferio norte antes de que iniciara la caza: en el Atlántico, el Pacifico nororiental y el Pacífico noroccidental. La caza intensa posiblemente fue de los mayores contribuyentes en la extinción del stock del Atlántico (Bryant, 1995), y actualmente sólo existen los dos stocks del Océano Pacífico (Rice and Wolman, 1971). Éstos han pasado por un punto de agotamiento. La caza incontrolada fue probablemente la causa principal en agotar el stock del Pacifico noroccidental, al grado de que se había llegado a dudar de su existencia (Mizue 1951; Bowen, 1974). Aun existente, este stock se encuentra en peligro de extinción (Brownell and Chun, 1977; Blokhin, *et al.*, 1985). De los tres stocks que pasaron por niveles de agotamiento, el único en recuperarse ha sido el de la ballena gris del Pacifico oriental. Su caza comercial inició en 1846 y sólo se extendió hasta 1874 debido a una intensa caza no controlada. En 1937, se dio protección a esta especie en Estados Unidos, donde se incluyó en la lista de especies en peligro de extinción (U.S. Endangered and Threatened Wild Life List, Federal Rule 59 FR 31095; MBC Applied Environmental Science, 1989; COSEWIC, 2004). En México se ha considerado como una especie protegida desde 1994, además de que sus lagunas de reproducción se han protegido desde 1972 (SEMARNAT, 2002). Hoy en día, esta población se ha recuperado y se ha ubicado en la categoría de "baja preocupación" de la Lista Roja de la Unión para la Conservación de la Naturaleza y Recursos Naturales (IUCN por sus siglas en inglés; Cetacean Specialist Group 1996).

Información general e importancia de la población del Pacifico Nororiental

La ballena gris (*Eschrichtius robustus*) es la única especie representativa de la familia *Eschrichtiidae*. No presenta una aleta dorsal, y en su lugar tiene una pequeña "joroba", seguida de 6 a 14 protuberancias. La longitud de la ballena gris es de aproximadamente 4.6-4.9m al nacer y en promedio de 14m en la etapa adulta; donde las hembras son de mayor tamaño que los machos (Jones and Swartz, 2002; Reeves *et al*., 2002). Como todas las ballenas, esta especie es longeva y alcanza la madurez sexual a los ocho años. Su reproducción es bienal y se caracteriza por migrar grandes distancias para llevarla a cabo. Anualmente, la ballena gris migra entre 8,000 y 10,000 km. (Rugh *et al*., 2001) desde su zona de alimentación (mares de Bering y Chuckchi) a las lagunas de reproducción en Baja California, México. Se le considera una especie clave en el ecosistema Bering-Chuckchi. Ecológicamente, esta especie toma importancia en eventos sucesivos bentónicos debido a sus hábitos alimenticios, ya que aspira el sedimento del fondo marino, donde viven sus presas preferidas, los anfípodos bentónicos. Su importancia se extiende más allá de lo ecológico, puesto que también se le atribuyen valores económicos y culturales. En lo que a lo económico se refiere, los ingresos monetarios provienen de avistamientos turísticos de ballena gris a lo largo de su ruta migratoria. La importancia cultural prevalece en las zonas de alimentación, donde la cazan aborígenes con con fines de subsistencia.

Antecedentes

Antes de los métodos que actualmente se conocen, la única forma de conocer la población de ballenas era por medio de registros de captura por unidad de esfuerzo, es decir, por registros de caza (Allen, 1980). Con el tiempo, los métodos evolucionaron y hoy en día se puede estimar el tamaño de la población mediante conteos desde tierra. La metodología se ha vuelto meticulosa y se han contemplado factores que puedan sesgar la estimación del tamaño de la población. Se han hecho modificaciones detalladas de estas correcciones para precisar la estimación final a un número cercano a la realidad. En su mayoría, estos estudios se han realizado en Granite Canyon, California. Reilly *et al*. (1983) realizaron un estudio de una serie de tiempo de 13 años, y estimaron el tamaño de la población para cada temporada. Estos autores iniciaron el cálculo de factores para corregir errores o sesgos en la estimación, tales como ballenas no observadas durante horas sin esfuerzo, sesgo en la estimación del tamaño de grupo por variaciones entre los observadores, así como por factores ambientales y variación en la tasa de nado entre el día y la noche. Este último factor no pudo ser corregido por estos autores debido a un sesgo en la hora inicial de esfuerzo. La corrección fue determinada por Perryman *et al*, (1999) quienes mediante el uso de sensores de imágenes térmicas, determinaron un factor de corrección en la variación de la tasa nado en la noche de 1.0875 (f_n^* = 1.0875).

El sesgo en detectar un grupo de ballenas y determinar su tamaño también se ha contemplado desde los estudios de Reilly *et al*. (1980). Además, Rugh *et al*. (1990), condujeron un experimento con observaciones pareadas determinar el número de ballenas que no se observan durante horas de esfuerzo (probabilidad de detección). Este estudio fue detallado en 1993 por Rugh *et al*., extendiendo el tiempo del experimento y desarrollando un algoritmo de puntaje para determinar la probabilidad de detectar la ballena.

Un factor que puede resultar de gran importancia si el corredor migratorio es amplio es el número de ballenas no observadas debido a que pasan a una distancia a la costa tan amplia que no es posible detectarlas. Shelden y Laake (2002) realizaron un estudio mediante censos aéreos en Granite Canyon, California, y determinaron que no era necesario corregir este factor, puesto que más del 90% de la población pasaba a la vista del observador, a menos de 5.6km de la costa. Sin embargo, en sitios como Washington esto no sucede. Green *et al*. (2005) determinaron que el ancho del corredor migratorio se extiende ahí a 40 km de la costa.

El tamaño de la población se subestima si el número de ballenas que pasan fuera de horas de esfuerzo no se toma en cuenta. Para esto, se han desarrollado métodos menos complejos que el uso de la distribución Gamma. Buckland (1992) diseñó un algoritmo utilizando polinomios de Hermite para interpolar sobre la distribución de los avistamientos obtenidos y así contemplar el número de ballenas no observadas durante periodos fuera de esfuerzo.

Importancia del trabajo

Se sabe que las poblaciones no son constantes y esto se evidencia en las fluctuaciones de la población de ballena gris del Pacífico nororiental, a lo largo de los años que se han estudiado. En las temporadas que se contemplaron en este estudio desde el 2003 al 2006, no se conocen registros de conteos o estimaciones del tamaño de la población. Las últimas estimaciones se realizaron en el 2002 y, según Rugh *et al*. (2005), la población disminuyó desde el 2001. El presente trabajo puede contribuir al conocimiento de la abundancia de la población en los años en los cuales no se registró alguna estimación. Aunado a esto, en México esta información es casi nula, por lo tanto este estudio puede proporcionar una contribución preliminar de estimación de abundancia de ballena gris.

HIPÓTESIS

La población de ballena gris del Pacífico nororiental ha pasado por cambios importantes. Springer (2002) resalta un posible decremento de 30% en el ecosistema de Bering-Chuckchi en los últimos 30 años. Por lo tanto, esta población pudo haber disminuido desde el 2002, el último año en que se registró una estimación en California.

OBJETIVOS

Objetivo General

Con el fin de generar nueva información en México y en la serie de tiempo anual sobre la abundancia de la ballena gris, este estudio estimó la abundancia de ballena gris del Pacífico nororiental durante su migración al sur en tres temporadas (diciembre a mayo 2003-2004, 2004-2005, y 2005-2006).

Objetivos específicos

- Determinar el tiempo de la migración al sur y al norte (inicio, máximo y fin) en Ensenada con base en un índice de abundancia relativa (número de individuos/hora de esfuerzo de observación).
- Estimar el tamaño de la población de ballena gris con base en conteos desde tierra durante las tres temporadas de la migración al sur (2003-2004, 2004-2005, y 2005-2006), tomando en cuenta los factores de corrección que influyen y afectan la estimación final.

II. MÉTODO

Los conteos desde tierra se realizaron en Costa Azul, aproximadamente a 28 km al norte de Ensenada, a una altura de 59m sobre el nivel del mar. El esfuerzo contempló un periodo de diciembre a mayo para cubrir en su mayor parte todo el periodo migratorio, sin embargo, las horas de esfuerzo variaron según la temporada (norte o sur). Las horas de esfuerzo para ambas temporadas fueron de 7:00 a 14:00 horas. Sin embargo los días de esfuerzo fueron de tres días a la semana para la migración al sur y seis días por semana para la migración al norte. La metodología consistió en realizar conteos de ballenas grises (generalmente avistadas por soplos), registrando las condiciones ambientales, tamaño de grupo, hora, observadores a cargo, comportamientos, y en caso de ser posible, las posiciones geográficas con el uso del teodolito.

Existía la incertidumbre del ancho del corredor migratorio de la ballena gris en esta zona, por lo que, cuando se presentaba la posibilidad, se realizaron seguimientos de ballena gris con el teodolito. Además, en 2007 se realizó un experimento de transectos lineales en barco hasta 40 km de la costa para determinar el ancho del corredor migratorio y, por lo tanto, el porcentaje de ballenas que no se logran ver desde tierra.

El tiempo de la migración de la ballena gris se determinó mediante el uso de un índice de abundancia relativa.

La abundancia de ballena gris se determinó tomando en cuenta los factores de corrección relativos a las ballenas no observadas durante horas de esfuerzo (probabilidad de detección) y sesgo en la estimación del tamaño de grupo debido a la variabilidad entre observadores, ballenas no observadas debido a la distancia de la costa, variación en la tasa de nado entre el día y la noche, y ballenas no observadas durante horas sin esfuerzo.

III. RESULTADOS

Tiempo de la migración.

Se observó una constancia en los tiempos migratorios registrados en 2003-04 y 2005-06 (Fig. 4, Tabla V y VIII). El tiempo de la migración de la ballena gris varió sólo en la temporada 2004-05. En este año se observó que todo el periodo de migración fue más largo que en los otros dos años. Para la migración al sur de este mismo año se observó un adelanto de una semana en el inicio (10% de los avistamientos) de la migración al sur, así como un adelanto en la fecha mediana (fecha en la que se registra el 50% de las observaciones). El fin de la migración, cuando se registró el 90% de los avistamientos, se presentó a inicios de mayo, mientras que en 2003-04 y 2005-2006 esta fecha se presentó a finales de abril. La migración al norte de parejas madre-cría también tardó en pasar por Ensenada durante el año 2004-05.

Estimación de abundancia.

En este estudio, se presenta una pre-estimación del número de ballenas no observadas durante horas de esfuerzo, puesto que no se realizaron observaciones pareadas para determinar la probabilidad de detección y la variabilidad en la estimación del tamaño de grupo. Se estimó un número de ballenas no observadas durante horas de esfuerzo de 1,176 individuos durante la temporada 2003-04, 1,355 ballenas para 2004-05 y 1,173 ballenas en la temporada 2005-06. Las estimaciones se calcularon utilizando las correcciones por tamaño de grupo y la corrección promedio por grupos no observados en los estudios de Rugh *et al*. (2005).

No fue necesario calcular un factor de corrección por variación en la tasa de nado, pues ya fue determinado por Perryman *et al*. (1999). El factor que determinaron estos autores, a partir de sensores de imágenes térmicas, fue de 1.0875 y se utilizó en este estudio.

Según los resultados de las trayectorias de tierra, el observador tiene una campo visual que se extiende hasta 5.5 km de la costa. Después de realizar una prueba ji cuadrada (χ^2 = 8.33, df = 6, p>0.001) se observó que no existían diferencias en la distribución de datos en los intervalos de distancia desde tierra según la temporada. Con esto se supone que la distribución de los avistamientos no vario entre años. Una vez conocida esta información, fue posible la aplicación de un solo factor de corrección para ballenas no observadas por distancia a la costa para los tres años. Es decir, el factor de corrección calculado a través de los avistamientos obtenidos desde tierra y desde barco, pudo ser empleado para las tres temporadas. Según los avistamientos obtenidos desde barco, los observadores en tierra sólo ven el 44% de la población (Tabla XI). Por lo tanto, es necesario un factor de corrección por distancia, debido a que el 56% de la población pasa más allá del campo visual del observador. Para corregir esta discrepancia se calculó un factor de corrección de 1.56 para los tres años.

Para corregir el número de ballenas no observadas durante horas en las que no se realizó algún esfuerzo fue necesario el uso de intervalos de tiempo similares, es decir, fracciones del tiempo de esfuerzo con características ambientales similares. Con base en esto, y conociendo el número de individuos dentro de cada intervalo, fue posible hacer uso del algoritmo desarrollado por Buckland (1992) mediante el programa *gwnormf77*. Los factores de corrección que se obtuvieron fueron de 12.46 para el 2003-04, 12.96 para el 2004-05 y 9.77 para la última temporada (2005-06).

IV. DISCUSIÓN

Tiempo de la migracion

Según este estudio, el año que más variación presentó fue el 2004-05, las dos temporadas restantes presentaron fechas similares. El tiempo de la migración de la ballena gris puede ser afectado por factores ambientales o por simple comportamiento de la población. Eventos de retraso o adelanto en el inicio del tiempo migratorio no son raros. A lo largo de su misma ruta migratoria pueden ocurrir variaciones. En 2000, LeBoeuf *et al.* reportaron que las ballenas se distribuyeron más al sur de la península de Baja California, con lo que era de esperarse que su migración al norte se retrasara. Sin embargo, se reportó que en Granite Canyon (donde se han venido realizando las estimaciones de esta población) no hubo alguna variación en las fechas medianas del registro de avistamientos. Una posible causa que puede explicar que se adelante la migración es la formación temprana y rápida de la capa de hielo en sus zonas de alimentación. Cuando esta capa cubre el mar, impide que la alimentación por parte de la ballena gris se siga llevando a cabo. Esto dejaría la única alternativa de iniciar la migración más temprano de lo normal. Lo contrario sucede si la formación del hielo es lenta. Por otra parte, no todas la ballenas migran al norte hasta las zonas de alimentación, unas permanecen al sur se Alaska. Si estas ballenas inician la migración, entonces la porción que permanece al sur de Alaska podría explicar el registro temprano de ballenas en nuestro sitio de observación.

Estimación de abundancia

Entre las correcciones necesarias para determinar el tamaño de la población de ballena gris, la corrección por ballenas no observadas durante horas de esfuerzo fue imposible de estimar para este estudio por falta de un experimento de observaciones pareadas. Si se excluyera esta corrección, la abundancia final sería subestimada. Aunque se conoce que existen diferencias en los sitios, se supone que la probabilidad de detección es la misma para ambos (Costa Azul y Granite Canyon). Si la probabilidad de detección es mayor en Costa Azul entonces la población se estaría subestimando. Se hace una suposición de cómo serían nuestras estimaciones si nuestra probabilidad de detección fuera menor en un 10%, 15% y 20% de la calculada en Granite Canyon (Tabla XII). Por ejemplo, si nuestra probabilidad de detección fuera 10% más baja, la estimación final sería de 22,376 para el 2003-04, 26,807 para 2004-05 y 17,493 para el 2005-06. Las estimaciones serían aún más bajas si el sesgo fuese de 20% (por ej. 15,549 ballenas en 2005-06). Si bien la variación en la estimación de la población no se explica sólo con este factor, entonces el número de ballenas no observadas por distancia es tan amplio que podría incluir este tipo de sesgos.

En este estudio se observó que el corredor migratorio es muy ancho en Ensenada, extendiéndose hasta 40 km de la costa. A lo largo de toda la ruta migratoria este ancho del corredor puede variar. En comparación con otros estudios, este factor no es un problema en Granite Canyon, puesto que el corredor migratorio es muy angosto y los observadores alcanzan a ver más del 90% de la población dentro de los primeros 5.6km (Shelden y Laake 2002). Lo contrario se reporta en Washington según Green *et al.* (2005). Estos autores reportan que en Washington al ancho migratorio se extiende a 40km de la costa y en parte lo atribuyen a la fisiografía. Según la comparación de avistamientos realizados desde tierra y desde barco en este estudio, el 56% de la población pasa más allá de la capacidad de avistamiento de los observadores en tierra, que es de 5.5km en este estudio. Si bien las ballenas se guían por fisiografía, la batimetría frente Ensenada y zonas adyacentes pueden explicar el ancho del corredor migratorio (Fig. 15). Desde Rosarito (al norte de Ensenada) se observan profundidades someras (≈100 m) que se extienden a 18 km de la costa. Estas mismas características se observan al sur del sitio de observación, en Punta Banda y la plataforma de Santo Tomás. Ensenada se encuentra dentro de la Bahía de Todos Santos, y las islas Todos Santos se alinean con Punta Banda; por lo tanto, es posible que para disminuir el gasto energético las ballenas podrían estar tomando una ruta más directa hacia las zonas de reproducción.

El factor de corrección por distancia aumentó en 1.56 el número de ballenas en la estimación final del estudio. Sin embargo, la corrección de ballenas no observadas en horas de no esfuerzo también fue una fuerte contribución en la estimación. En comparación con otros estudios en los que este factor no sobrepasa de cinco, aquí se calcularon factores que sobrepasan el doble de esta cantidad (por ej. 12.96 en 2004-05). Estos valores altos en parte se pueden explicar por el tiempo de esfuerzo, el cual es de sólo tres días en Ensenada y en Granite Canyon los días de esfuerzo son el doble, y las horas de esfuerzo por día son más. Aunque se realizaron intervalos de tiempo meticulosos, no se debe descartar que posiblemente exista un error en la base de datos, según los intervalos de tiempo, ya que el registro de las condiciones ambientales pudo variar según el grupo de observadores que realizó el esfuerzo.

Aunque estos factores fueron contemplados para este estudio, el hecho de no tener una probabilidad de detección propia del área de estudio, pudo sesgar la estimación. Este mismo factor impidió un cálculo inmediato de los coeficientes de variación (CV) de las estimaciones. Por lo tanto, en este estudio se aproximaron CVs de 0.20, 0.35 y 0.50. Comparando con otros estudios (Rugh *et al.*, 2005), las estimaciones obtenidas con un CV mayor a 0.35 arrojaron estimaciones muy bajas. Con base en esto, se podría decir que nuestro CV se encuentra entre un 20 y 35%. Independientemente de la probabilidad de detección, un patrón es evidente en las estimaciones de abundancia: un incremento en el tamaño poblacional para el año 2004-05 y una disminución para la última temporada (2005-06). Si bien es cierto que la población parece acercar su capacidad de carga o de su equilibrio (Hobbs et al., 2004; Wade, 2002), entonces las fluctuaciones de la población podrían ser resultado del efecto *Allee*, en el cual la población varía (aumenta y disminuye) alrededor de la capacidad de carga. Son necesarios estudios más detallados para poder mejorar la estimación de la población en Costa Azul, y entre estos detalles, cabe mencionar que sería importante aplicar un factor de corrección por fatiga del observador.

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I. INTRODUCTION

I.1. General Introduction

The eastern Pacific gray whale (*Eschrichtius robustus*; Lilljeborg, 1861) is a cetacean belonging to the *Eschrichtiidae* family. As a mysticete, or baleen whale, grays share similarities with other great whales yet they have unique physical and demographic characteristics. Among these, there is the long annual migration they make, along the western coasts of the North American continent which in turn is convenient for its monitoring.

Specifically, the eastern Pacific stock has been monitored ever since it was first considered endangered due to whale hunting and its recovery has been followed up-to-date with modeled census data and population size estimates. Whaling has seized for this stock and today the gray whale is only hunted for subsistence by aboriginal groups with a limited annual quota. The quota is stated by the International Whaling Commission and the feedback for this decision comes, in part, from abundance estimates.

Population estimates have been assessed by the National Marine Mammal Laboratory in California (U.S.), nevertheless, the long migratory route of the Eastern Pacific gray whale stock makes us consider it as a common resource shared among three nations: Canada, United States, and Mexico. It is hard enough to assess a resource belonging to one sole nation; therefore, assessment becomes more complex when it comes to a shared resource. Despite the agreement among the nations, the basic path for a good assessment is through the knowledge of the resource's health and status, as well as the ecosystem which surrounds it. To scientific convenience, gray whales show a particular biology and ecology which allow a better understanding of its population dynamics and a more complete contribution to the monitoring of its status (Rice and Wolman, 1971). Stock assessment is achieved through data monitoring and is fundamental for their conservation and management. The gray whale has come to be an important resource for all three countries and its conservation is then of mutual interest. Therefore, this study is a contribution to gray whale monitoring by estimating the population size during a three year time series. The factors already known to affect the estimation are considered and the calculation of these corrections is part of the sharpening of these estimates.

Abundance estimation may have certain biases due to natural causes or survey methods (Reilly *et al*. 1983; Reilly, 1984; Buckland *et al.*, 1993; Hobbs *et al.*, 2002; Rugh *et al.*, 2005). This study aims to estimate the eastern gray whale abundance including migration timing for every surveyed season and the population size. Population size was based upon shore counts in Ensenada, Baja California, during three seasons of its southbound migration: 2003-2004, 2004-2005, and 2005-2006. In order to have a good estimate of the population size, the factors that may bias the estimation were taken into account for this study. In California, nearly annual censuses have been reported, though for these three seasons no data were collected. The data generated from this study can shape out the three missing years in the gray's abundance time series.

I.1a. Eastern North Pacific Gray Whale Hunting

Gray whale populations are clear examples of what has happened, what is happening, and what would happen with an exploitable resource depending on the assessment and management it is given. Gray whaling history portrays the importance of assessing a resource and taking conservation measures.

At the beginning of the nineteenth century, when Pacific whale stocks were discovered by American and European whalers, one of the stocks to be severely affected was that of the gray whale. Although they knew it was one of the most dangerous whales to hunt because of its aggressive reactions to hunters (especially mothers protecting calves), whalers went after it for its high commercial revenue (Henderson, 1984). Three gray whale (*Eschrichtius robustus*; Lilljeborg, 1861) stocks were distributed along the northern hemisphere before whaling occurred: Eastern Pacific stock, Western Pacific stock (found on the eastern coast of Asia) and the Atlantic stock (possibly distributed throughout the northern Atlantic Ocean). Intense whaling extinguished the Atlantic stock, and today only two geographically separated gray whale stocks are recognized with a limited distribution along the eastern and western coasts of the Northern Pacific Ocean (Rice and Wolman, 1971).

Excessive unsupervised whaling was probably the main contributor to the extinction of the North Atlantic gray whale population in the early 17th century (Bryant, 1995), and Pacific gray populations were both nearing the same fate. When the eastern Pacific grays were going through depletion in the mid 19th century, the Korean stock remained “intact” (Mizue, 1951). Uncontrolled whaling activities and lack of management later exhausted the

Western North Pacific stock to the point that some authors came to question its existence (Mizue 1951; Bowen, 1974). The still extant stock (Brownell and Chun, 1977; Blokhin, *et al.*, 1985) is presently considered endangered and has failed to recover from its depletion, in 1934 (Mizue, 1951; Rice and Wolman, 1971; Clapham, *et al.*, 1999). However, out of the three known stocks of gray whale, only one well-monitored stock has recovered from whaling depletion (Eastern North Pacific).

Commercial gray whale hunting in the Eastern North Pacific Ocean started in 1846. As whalers found out more about the gray's breeding grounds in Baja California Sur, Mexico, the population's core was found, and Eastern stock whaling only lasted about 11 winters (1845-1865) with profitable results. By the end of the 1873-74 migrating season, gray whale harvests were so little that many whalers were forced to abandon their activity. A total of 573 whale ships were settled and approximately 8,090 gray whales were killed, of which only between 7,025 and 7,078 individuals were captured, in the elapsed time from the discovery of this resource to its depletion (Scammon, 1874; Henderson, 1984). Protection for this stock was not given until 1937, as it was categorized as an endangered species in the U.S. Endangered and Threatened Wild Life List (Federal Rule 59 FR 31095; MBC Applied Environmental Science, 1989; COSEWIC, 2004). Mexico has protected the gray whale breeding grounds since 1972, and included this species in the Mexican list of protected species since 1994 (SEMARNAT, 2002). Even after it was seriously depleted, and with better luck than the other two gray whale stocks, the Eastern Pacific stock has recovered and is in the "lower concern" category in the Red List of the Union for Conservation of Nature and Natural Resources (IUCN) (Cetacean Specialist Group 1996). This was accepted on 16 June 1994, year in which it was removed from the U.S.

Endangered and Threatened Wild Life List (Hobbs *et al*., 2004). This stock, in particular, is a vivid example of positive feedback to the management measures it has been given (NOAA Fisheries, 2002). Today, Eastern Pacific gray whales are captured under regulation for subsistence use (meat, culture, health; IWC 2007b) of aboriginal groups. More on aboriginal quotas will be further explained in the following section. The positive feedback would not have been possible without the assessment of this stock, which needs to rely on monitored abundance data. The present research was focused on abundance estimation of the Eastern North Pacific stock during three southbound migration seasons (2003-2004, 2004-2005, 2005-2006) past Ensenada, Baja California.

I.1b. General Information and Importance of the Northeastern Pacific population

In general, the gray whale (*Eschrichtius robustus*; Lilljeborg, 1861) is the only baleen whale species representative of the *Eschrichtiidae* family. Unique in this species, is the lack of a dorsal fin which in turn has a hump with 6 to 14 "knuckles" running from the hump to the caudal peduncle. Its elongated slender body may range in size from an adult male (13m) to an adult female (cow) (14.1m) and with a ranging weight of 16,000 to 45,000kg. At birth, gray whale calves may range from 4.6 to 4.9m in length. Like all great whales, grays are long-lived organisms with slow sexual maturity. Sexual maturity is in average reached at the age of eight. Its reproductive cycle takes place every two years with a 12 to 13-month gestation period; although some authors have reported that some females may take as long as three years to calve (Jones and Swartz, 2002; Reeves *et al*., 2002).

This, however, turns out to be quite inconvenient for the growth of a population, since it makes it more vulnerable to depletion, which in turn may bring about negative effects on the zones it inhabits.

Particularly, Eastern Pacific grays are known for setting the longest migration route than any other mammal in one long period of time (Rice and Wolman, 1971). They migrate around 8,000km from Unimak Pass (Alaska) all the way through to the winter breeding grounds in the Baja California lagoons in Mexico in approximately 54 days, and an even longer time and path for those coming from the Beaufort Sea traveling more than 10,000km (Rugh *et al.,* 2001). As a migratory species, gray whales have a broad distribution all along the western coasts of the North American continent. During the summer, they feed on the shallow Bering, Chukchi and Beaufort Sea floors to be able to take on their annual migration. Feeding only occurs in the summer; grays generally do not feed during the entire migration period (Rice and Wolman, 1971) though they have been observed feeding along the route (Le Boeuf *et al*., 2000; Rugh *et al.,* 2001). Therefore, it is important for them to forage plenty of energy in order to make it back to the feeding grounds. This is especially essential for pregnant females which must feed their calves at the breeding grounds.

The long trip for grays starts in autumn, at the beginning of October and November, although they have left the feeding grounds as late as September (Rugh *et al*., 2001). The first whales to leave the feeding grounds past Unimak Pass are pregnant females, second are adult males, followed by immature females and lastly immature males (Rice and Wolman, 1971). From Unimak Pass, they go past the Aleutian Islands and head south along the Canadian and United States coasts. By December, they accomplish the first half of their migration journey in Mexican lagoons and bays along the western Baja California region

(Rice and Wolman, 1971) to reproduce and give birth to new recruitment (calves). The main breeding zones are Guerrero Negro, Ojo de Liebre, and San Ignacio lagoons, and Magdalena bay, although some whales have also been reported as far south as Cabo San Lucas and in the Gulf of California (Gilmore *et al.*, 1967; Rice and Wolman, 1971; Reilly, 1984; Findley and Vidal, 2002).

Migration back to the feeding grounds starts in February, although some whales have been spotted still on their southbound migration during that time (Rugh *et al.,* 2001). This time, conceived females are the first to leave the breeding grounds back to the feeding grounds followed by adult males, behind them are mestrous, anestrous, and immature females, and right after them are all immature males (Rice and Wolman, 1971). It is worth mentioning the importance for conceived females to get to the feeding areas before all the other whales, since they are in a pregnancy state (embryo development). The last whales to leave Mexican waters are females with calves (cow/calf pairs). These whales and their youngsters remain a longer period of time in Mexican lagoons, feeding, nursing, and preparing them for their long journey back to the feeding grounds. In general, the northbound migration, which lasts about 3 months, is slower than the 2-month southbound migration (Pike, 1962).

Gray whales from the Eastern Pacific stock are of great importance in benthic-arctic ecosystems, due to the ocean floor modifications it causes with its feeding strategies. They feed every summer on the Arctic benthos, preferably amphipods buried in the ocean floor. Hence, frequent disturbance on these ocean floors, caused by feeding, is followed by succession of benthic organisms (Oliver and Slattery, 1985; Highsmith and Coyle, 1992; Le Boeuf *et al*., 2000). This feeding ground is one of the most productive areas worldwide

(Springer, 2000). Considering the number of whales feeding there and the amount of food consumption required by their metabolism, the removal of this stock could cause greater abundance of benthic organisms, leading to space competition, among other possible derived causes. In fact, the gray whale has even been stated as a keystone species of arctic benthic communities for maintaining its structure on the invertebrates it feeds upon (Oliver and Slaterry, 1985). Biologically and ecologically, they play an important role in ocean-floor modifications, structurally modifying its feeding ecosystem and are hosts to many parasites (mainly barnacles; *Cryptolepas rhachianecti*). In fact, out of all great whales, grays are the most parasitized (Jones and Swartz, 2002). The importance of these animals goes beyond its ecological magnitude. COSEWIC (2004) state a cultural and economic importance, of which the cultural importance will be slightly discussed later on and the economic importance relies mainly on whale watching, especially at the summer and winter grounds.

Gray whale abundance may determine that of other organisms, especially those in benthic communities in the arctic zone, due to its feeding strategies (Oliver and Slattery, 1985; Highsmith and Coyle, 1992); therefore, the source of its abundance variation itself should be of concern. Gray whale abundance may vary depending on the nature of the causes. Naturally speaking, these variances may be due to climatic conditions; current climate change, El Niño and La Niña events, among other causes (Le Boeuf *et al*., 2000). Anthropogenic causes are the second nature of whale abundance variability. A third cause of population decline may be due to incidental deaths caused by fishing operations (Baird *et al*., 2002) or aboriginal subsistence whaling, as mentioned earlier.

Although commercial whaling is no longer permitted, subsistence whaling still takes place and is of great cultural importance to some aboriginal groups in the Northern part of North America and along the Siberian coasts. Understanding the importance of subsistence whaling for these aboriginal groups, this type of whaling is limited to aboriginal groups in Alaska and the eastern coast of Russia (NOAA Fisheries, 2002; IWC, 2007a and b).

Stock assessment is a means of stock status monitoring (abundance, maximum net production rate, population trends), and so management decisions regarding its actual status or subsistence whaling quotas may be determined. The International Whaling Commission (IWC, 2007a) had previously established the eastern stock quota to be an average of 120 individuals caught per year and it would be valid and intact through a five-year period (2003-07). Up-to-date, subsistence whaling is restricted to a harvest quota, split among the Alaskan and Siberian aborigines of the two countries (USA and Russia), of 620 whales in a five-year period from 2008-2012. A maximum of 140 individuals can be harvested in one of these years (IWC, 2007a and 2007d). Depending on the annual harvest, the quota for the following year is determined and it shall not exceed 140 individuals nor shall this harvest be repeated during the five-year period. In order to establish the above five-year total harvest, the IWC needs information to base upon and decide over aboriginal whaling quotas. Information on abundance estimates can give a general idea of population behavior and perhaps an idea on the population's health.

I.2. Previous works

Before methods used nowadays, one of the main sources to determine whale populations was through catch per unit of effort information (CPUE; Allen, 1980). Methods evolved, and today the main source for assessing whale populations is through direct observations from shore, boat, and/or aerial means (Hubbs and Hubbs, 1967; Gard, 1974; Reilly *et al*., 1983; Reilly, 1984; Green *et al.*, 1995; Shelden and Laake, 2002). In California, onshore census surveys have been taking place since 1967. However, the eastern population of gray whales was first surveyed in 1887 by Townsend (Reilly, 1984). Townsend (1887) was one of the pioneers to point out the factors that influence total abundance estimation based on onshore counts: unseen whales passing during the night, before and after a census takes place, and those whales passing way beyond the observer's visual sight. At that time, these factors were solely a concern. With time, methods to account for these discrepancies were developed and improved to near abundance estimates as close as possible to true population abundance.

Reilly *et al.* (1980) made a preliminary estimate of the gray whale eastern Pacific stock based on a 12-year observation effort. The main concerns in their study were observer bias, what percent of the population was passing beyond the observer's eye sight, and diel and weather variation. Their research fully explored the first two concerns, the other two remained unexplored. Later, in 1983, Reilly *et al.* published an assessment for this population adding one more year to their previous study in Reilly *et al.* (1980), analyzing 13 years. Their study took into account those factors that may bias the estimation of the population. In order to certain their estimate, they point out the possibility of bias due to diel variation. Unfortunately this latter factor was not proven by them, given that there was a bias on the first hour of the census. The estimation to correct for this factor was pioneered with the study of Swartz *et al.* (1987). Buckland *et al*. (1993) used this information to correct for the travel rate inconsistency (f_n^*) and they found that the whales' travel speed was slightly faster at night (f_n^*= 1.020). Later in 1999, Perryman *et al.*, edged this correction after running a thermal imagery experiment. Though they found similar results in travel rates, they complemented the study by contemplating data containing the fraction of whales migrating after the median date (when 50% of the sightings are reported) rather than a "fixed calendar day" (15 January). The newly estimated correction factor (f_n^* = 1.0875) has been used in recent abundance estimations (Rugh *et al.*, 2005).

Observer discrepancies occur and were first studied in Reilly *et al*. (1980) in California. An experiment of data comparison between observations made by 12 observers making individual counts and data taken as "true counts" from simultaneous observations made during aircraft surveys was the first step to consider this bias. Furthermore, in 1990, Rugh *et al*. conducted new experiments making paired independent counts at Granite Canyon, California, during the peak of the 1986 southbound migration season (effort time 60 hr). Their results showed that a great percentage of whales was being missed within the viewing area by single observers. In their study, they found that of all whales passing the viewing area, 21% was being missed or uncounted by observers and that a greater percent of whales was missed than groups were undercounted. This study was only based on a 6-day experiment. Rugh *et al*. (1993) extended and sharpened this research, again, using a "mark-recapture" experiment, though this time effort consisted in a complete 2-month period. A scoring algorithm was devised to match sightings and find the percent sightings being missed. Similar results, comparing with Rugh *et al*. (1990), were found in this study, as they found that most seen whales were within a 1.5 to 4.4km offshore range (Rugh *et al*., 1990, report a range of 0.5 to 3.7 km offshore). The number of whales missed by observers was found to be 19%.

Sighting records have also shown that observers miss a percent of whales because of distance from shore. Boat and aerial experiments have been used to correct for this missed percentage. Reilly *et al.* (1980) flew an aircraft running parallel transect line surveys, perpendicular to the coast near the Granite Canyon survey station in California. As a result, they reported that 90% of grays were passing within 2 n.m. of their research station. Shelden and Laake, (2002) later obtained different results in their aerial surveys. They conducted 6 aerial surveys near Granite Canyon, at the same time onshore surveys took place, during the peak of the southbound migration in 1996. Most of their observations were within 3 n.m. Green *et al*. (1995) followed a similar experiment in Oregon and Washington in 1990 to find the gray whale's migration corridor. Contrary to other known survey sites, the whale's migration corridor was very wide. Most of the gray whales were passing beyond 10 km from the coast (66%). At the same time, whales were passing further offshore (13 km) at Washington than at Oregon. Aerial surveys provide means to determine the migration corridor; hence, if needed, correct for a percent of whales missed due to distance. However, they are very costly, and might not always fit in the budget. Rugh *et al*. (2002) conducted paired independent surveys using fix-mounted 25-powered binoculars to evaluate yearly variations in migration corridors (offshore distribution). They suggested this method as an alternative to aerial surveys.

Distance from shore can also be analyzed from boat surveys. Due to the different conditions, the equipment used in boat surveys is a Global Positioning System, an angle board and binoculars edged with reticles. Kinzey and Gerodette (2003) present "accuracy and precision of distances measured at sea."

Observations are not possible all 24 hours. There are times in which no effort can be undertaken. Calculation for this factor first consisted in fitting a normal density curve of sightings with a gamma function (Reilly, 1983). These calculations were eased later on by Buckland (1992) with the introduction of the use of Hermite polynomial extrapolation to account for missed periods. This method was again used in abundance estimations in Buckland *et al*. (1993) and this has been the method used up to recent studies.

Variation in gray whale abundance

Reilly *et al.* (1983) concluded that the population had an annual increase of 2.5%. Although there was an annual increase rate, these authors reported a season of low estimates (1971-72) and they attributed it, in part, to poor visibility due to a "stormier year" than usual.

According to Reilly *et al*. (1983), NOAA Fisheries (2002) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2004) reports, the eastern gray whale stock has a mean annual increase of 2.5%. On the other hand, serious death increases have also been reported for certain years (Le Boeuf *et al.*, 2000; Gulland *et al*., 2005; IWC, 2007c), and also a recent delay in its onset migration time (Rugh *et al*., 2001). High mortalities and low recruitments both coincided in the 1998-99 season (Le Boeuf *et al.*, 2000). Mortalities reported during the 1998-99 season "exceed any other reported in previous years" down to 1985 (Le Boeuf *et al*., 2000). During 1975-2006, IWC (2007c) reports 1,892 stranded whales along its migratory route. Two stranding peaks can be pointed out during the time series from 1985 to 1999: one in 1991 and a second one in 1999. It is well-known that females compose an important part of a population's recruitment and the strandings for those seasons, according to Le Boeuf *et al*. (2000), were mainly females. Female losses may lower the incoming components of a population (recruitment) and so it was seen that calf recruitment was a low 1.7% compared to a variable 4.6-4.7% in previous years (Perryman *et al*., 2002). Also, when observers expected to sight twice the number of mothers and calves in March (*i.e*. 92 in 1996 mother/calf pairs), during the study reported in 2002, they only observed in average 45 mother/calf pairs (Le Boeuf *et al.*, 2000).

High mortalities were also followed in the subsequent year with a 1.1% recruitment rate (COSEWIC, 2004 and Le Boeuf *et al*., 2000). Despite this decrease, death rates went back to normal in 2001 (Perryman, 2002), notwithstanding that the annual recruitment was still low at 1.4%. Totally different rates were reported for 2002 and 2003 with percentages of 4.8 and 4.4% respectively (COSEWIC, 2004). The population estimates, however, for 2001 and 2002, were 18,761 individuals for 2001, and 17, 414 for 2002 (Rugh *et al*., 2005). The population for 2002 still showed a decrease in number despite its recruitment increase. The latter resulted in a 10% population decrease since 1998 (COSEWIC, 2004).

Le Boeuf *et al.* (2000), Springer (2000), and Rugh *et al.* (2001) agreed on a starvation conclusion due to climate shifts. They also reported a change in primary productivity as an effect of global warming. It is agreed that a shift in primary productivity will affect, in turn, benthic communities. Le Boeuf *et al*. (2000) cited 3 authors (giving information on arctic productivity) of which Springer (2000) reports a 30% decrease in the past 30 years for the Chukchi-Bering ecosystem. Other possible climatic effects are reported in Le Boeuf *et al*. (2000) with a relation found between sea surface temperatures and El Niño, which may be, in part, a plausible cause of the decline in the Bering Sea amphipod communities.

NOAA Fisheries (2002) states an annual Potential Biological Removal[1] for this stock of 575 individuals, which is based upon a minimum number of individuals. It is also reported that this number is not exceeded by the total number of individuals killed incidentally by fishing operations and the aboriginal hunt summed together.

The eastern gray whale stock has considerably reduced in numbers during three consecutive years, since 1999. It is quite known that without recruitment, growth, in any population, will be poor. Therefore, low recruitment in the mentioned years could be contributing to the 10% decrease COSEWIC (2004) reports.

As an observation from past estimates (1999-2002), recruitment has been seriously affected. Mean birth rate in *Eschrichtius robustus* is one calf per adult (twins are rare) and it presents a biennial reproductive cycle (Rice y Wolman, 1971). This implies a constant monitoring for this stock due to its ecologic importance and the fact that aboriginal groups depend on it as well. Regardless of the nature of deaths, populations are being varied either by anthropogenic causes or as in recent years (such as the high mortalities in 1999) by natural causes. This is true for almost, if not all populations, since they are never constant, rather they are always changing and need constant monitoring.

[1] According to NOAA Fisheries (2002), “the Potential Biological Removal is defined as the product of the minimum population estimate, one-half the maximum theoretical net productivity rate, and a recovery factor.”

I.3. Rationale

Aside from being one of the basic parameters in studying and learning about the dynamics of a population, abundance is also important and necessary in resource assessment. It is quite true, as mentioned earlier, that populations are not constant, and this is evident in the fluctuations of gray whale abundance throughout its known history.

Just when it was thought that the population had recovered from depletion and in addition that it had reached its carrying capacity, the eastern gray whale stock went through important decreases in the past years (Rugh *et al*., 2005). Besides effects on the Bering-Chukchi ecosystem, aboriginal groups that depend on this resource would also be seriously affected, should this resource be negatively altered in numbers.

The information up-to-day of census data is available only until 2002. This study will bring out an idea of the population fluctuation on the subsequent three seasons (2003-2006) lacking census efforts on the population at Granite Canyon, California. It is also very important to note that related studies, in the understanding of gray whale abundance, are almost inexistent in the southern part of its migration route in Mexican waters, with the exception of the calving areas. The Baja California peninsula is, in particular, an important region for the recruitment of this population, and as a country partially responsible for this resource, it is important for it to develop its own data to aid in the knowledge of what is also its resource. Hence, it would also develop its own back-up information and this study should be a preliminary contribution of gray whale abundance in Mexico.

I.4. Hypothesis

The gray whale eastern Pacific stock has gone through some important changes. Springer (2002) reports a 30% decrease in the Bering-Chukchi ecosystem in the past 30 years. Therefore, this stock could possibly have continued diminishing since 2002, last census-reported year in California.

I.5. Objectives

I.5.a. General Objective:

In order to generate new information in Mexico and in the time series regarding the gray whale's annual population abundance, this study focused on the estimation of gray whale abundance of the eastern Pacific stock during its southbound migration in three seasons (December to May 2003-2004, 2004-2005, and 2005-2006).

I.5.b. Specific Objectives:

- To determine the south and northbound migration timing (beginning, peak, and end) in Ensenada based upon a relative abundance index (number of individuals/observation hour).
- To estimate the population size of the gray whale based upon onshore counts during three southbound seasons (2003-2004, 2004-2005, and 2005-2006) along with the correction factors that influence and affect the final estimation.

II. METHODS

II.1. Study area

Surveys took place about 23km north of Ensenada at Costa Azul. Costa Azul is situated on the northwestern side of the Baja California peninsula, Mexico, at 31º 58"95'N, 116º 50"16'W (Fig. 1). The Ensenada region falls within the Southern California Bight, since the latter extends from Point Conception, California (USA), to Punta Colonet, Baja California. (Hickey, 1993). The continental shelf coasting the Ensenada region extends 2km from the coastline, dropping into a steep continental slope ≈ 360 m deep (CSDS, 1971). The port of Ensenada is located within Todos Santos Bay, having a small peninsula (Punta Banda) protuberating from the coastline. North of Punta Banda lies a steep 550m-deep submarine canyon, separating Punta Banda from the Todos Santos volcanic islands (Heckel, 2001; CSDS, 1971).

Weather in the study area is Mediterranean-like; dry in the summer and rainy in the winter. Annual mean temperature is 16.5°C though it ranges from 14.0°C in December to 16.3°C in May (elapsed time of a survey season). The lowest mean temperatures are given in January with 13.3°C. Precipitation is highest in January (42.5mm) and in May it lowers to 3.4mm totaling 190.4mm annually. Wind also plays an important role in this region. Annually, from September through May, polar wind masses prevail (Energía Costa Azul, 2007).

Ensenada's location yields mainly humid weather with cold winds in the winter time. These weather characteristics are important in determining effort periods.

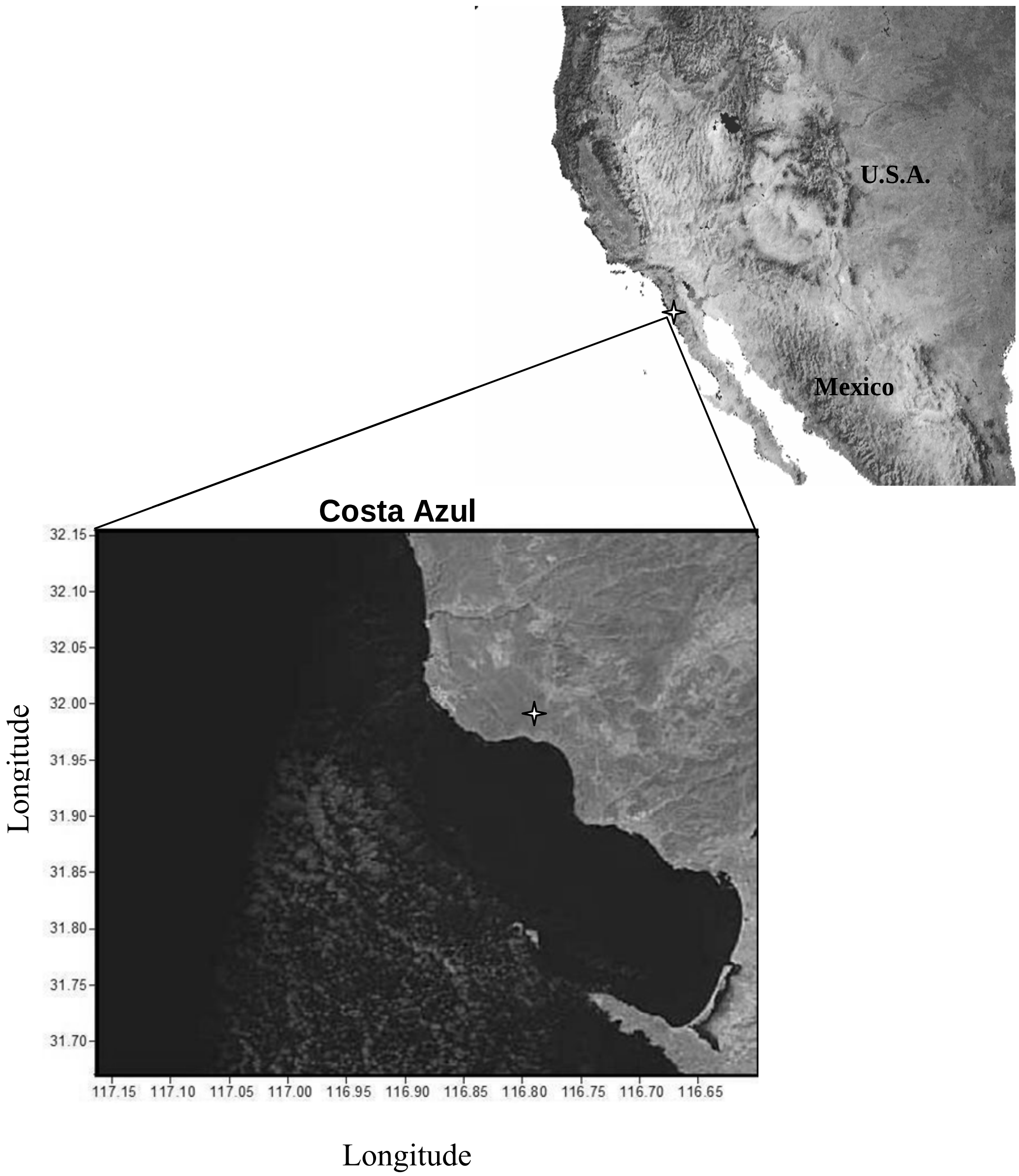

Figure 1. Location of the study area at Costa Azul, Ensenada (Mapa de Mexico, 2007).

Figura 1. Localización del área de estudio en Costa Azul, Ensenada (Mapa de Mexico,2007).

II.2. Survey methods

II.2a. Onshore surveys

Since gray whales are well known for migrating close to the shore (Gilmore, 1960, Pike, 1962, Rice and Wolman, 1971), shore-based censuses are made possible from December through May each year throughout regions of its migratory corridor. There are unknown census studies for abundance estimation on gray whales in this study area. The methods followed in this study were settled upon those followed at Granite Canyon, California (Reilly *et al*., 1983; Rugh 2005), and stick as close as possible to their design for future comparison.

Observations were made from a fixed semi-enclosed platform, 59 meters above sea level, at Costa Azul, with the aid of 7x50 and 10x50 binoculars, and a Topcon DT-102 theodolite (with a 30X telescope). The base (platform) allowed a wide 120° field of view for the observers. On average, 11 observers took part throughout the survey seasons, acquiring experience from the beginning of the first census. Nevertheless, some observers had previous experience with whale observations, and no more than one naïve observer was allowed per day of effort. Regardless of the many observers available, a limited number of 4 or 5 observers were assigned to a given effort day, due to the difficult access to the study area.

Total effort consisted in 3 days a week for the southbound migration and 6 days per week for the northbound migration. The recommended hours for onshore surveys, by the MBC Applied Environmental Sciences (1989), were applied for this study's effort, from

07:00 to 14:00 hours. Though a 7 hour time interval was implemented, weather conditions restricted our effort periods hence a variation in effort times. Whenever climatic conditions were unfavorable (rainy days, null visibility), and in view of the fact that there was little shelter from the elements, effort was partially or completely canceled, depending on the severity. Effort began each day after reporting the start time, observer positions, and environmental conditions of the study area. Henceforth, any change in these climatic conditions was reported at the time it occurred, and after agreement on these changes was conferred among the observers.

The information for environmental conditions included sea state (Beaufort scale), visibility (km), swell, and cloud cover. It is relevant to note that visibility was not recorded as distance from the coast to the horizon but as the distance from Costa Azul to four geographical reference points (Punta San Miguel, 11km; Todos Santos Islands, 19km; Banda Point, 27km; Santo Tomás Point, 49km). Cue distances for visibility were taken from the observation point to the 4 reference points from a chart of the study area. These distances solely indicated how well the observer could see given the presence of fog, mist or dust. Distance was, therefore, not a measurement from the observation station to the horizon but an empiric idea of day clearness. That is, the distance to the four reference points gave an idea of how clear the day was. Only distance to the reference points were true measurements, all others recorded were subjectively measured from those points. For example, the closest reference point was 11km (Punta San Miguel) from the observation station, this being a true measurement, but if fog made this reference point invisible to the eye, an approximate distance was conferred among observers, *e.g.* 6km. Visibility then ranged from 3 km in a foggy day to 49 km in a clear day. Regarding visibility as a whole, other factors that may have affected the observer's view were contemplated: cloud cover, swell and sea state. Cloudiness, as in observer visibility, was conferred among observers as the percent of sky covered by clouds; 0% being a clear sky and 100% complete overcast. Swell was either present or absent and sea state was measured based on the Beaufort scale. Often, whale blows were confused with white caps and observation to the naked eye became poor. Effort was canceled after wind exceeded 3 in the Beaufort scale, so sightings obtained with Beaufort greater than 3 were null.

Whale searching was done by all observers, nonetheless this main objective was broken down into specific tasks divided among them which consisted in a constant scanning of the area, keeping track of pods, note taking, tape recording and theodolite tracking. Two observers were responsible for constantly scanning the study area in a north-south direction. Gray whales were sighted whenever a blow, print, back or tail was seen, and if there was uncertainty of the species, verification was done with the theodolite's telescope. If a blow was spotted far at the horizon, uncertainty arose and it was reported as an unidentified whale, therefore not included on analyses for this study. Immediately after spotting a gray whale, the observer with the format sheet was responsible for reporting the sighting specifying its corresponding information: sighting number, species, pod size estimate, time, behavior, migration direction (north or south), environmental conditions, and if possible the angles given by the person standing at the theodolite. Whenever more than one pod was sighted, these observers were also responsible for keeping track of the pods already counted to avoid any duplicate counts.

Sometimes theodolite tracking was possible, and for this task, two different observers (the cassette recorder and the person in charge of the theodolite) focused on tracking the whale pods. The observer recording was equipped with a stop watch, a cassette recorder and 7X50 binoculars fixed on a tripod to track the whale. From the moment the pod was sighted until it was no longer seen, the recorder reported the time the pod surfaced, to the nearest second, and the angles dictated by the person tracking with the theodolite, as well as any environmental change or whale behavior. Naturally, the 7X50 binoculars gave the observer recording a wider visual area; consequently he/she aided the theodolite tracker not to loose the pod being followed since the theodolite has a reduced field of view.

II.2b. Boat surveys

To estimate the width of the gray whale's migratory corridor, aerial surveys are usually preferred over boat surveys since it is easier to sight a whale. However, budget and administrative limitations lead this study to carry on with boat surveys. All the same, boat line transect surveys have certain advantages such as reducing the possibility of loosing an individual due to speed. Also, the boat may come to a complete stop and verification of species identification.

Field methods followed general distance sampling protocols (Buckland *et al*., 2001). The study was designed according to Shelden and Laake (2002). Five 20km-long transect lines (inshore lines) were surveyed perpendicular to the Costa Azul coast, where the onshore surveys took place (Figure 2). In addition, line C, which was directly in front of the shore survey site, was extended 20km from point C6, turning out into a new transect line (D). The same is true for lines E and G, totaling 7 transect lines, of which two fused to a 40km expansion from the coast. The two long transects (offshore transect lines) were deliberated to be ran in front of the site, under the assumption that that is where the observer's eyes focused most of the time. All transect lines had a strip width of 1km and distance between line transects was 2km.

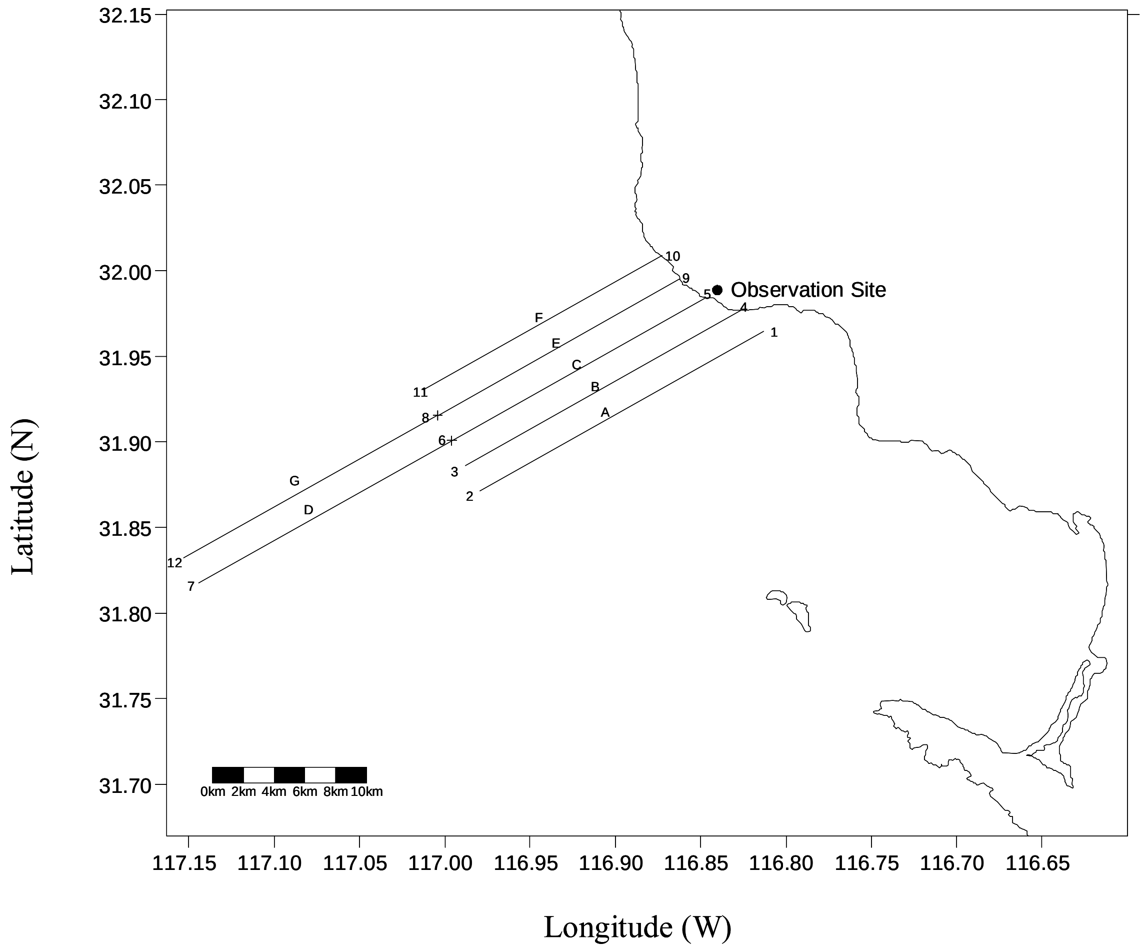

Figure 2. Design of transect lines for boat surveys about the onshore observation area.

Figura 2. Diseño de los transectos lineales para los conteos desde barco en el área del puesto de observación de tierra.

Boat surveys were designed to take place, in 2007, about the peak dates of the southbound migration in Ensenada, Baja California, *i.e.* between mid-January and mid-February. Two to four transect lines were ran per day of effort at an average speed of 15.5km/hr aboard the *Quest* vessel, with a 165hp Diesel engine, 13m in length. Onboard, the observer team consisted of four people of which three were on watch and one remained at rest, ready to relay any of the three observers on duty. The observer team was equipped with three 7X50 binoculars edged with reticles, a GPS (global positioning navigation system), three angle boards, and format sheets for data recording. On the roof of the boat's bridge, three observers on duty sat facing the bow. Eye height average was 5.5m above sea level, measured from sea surface to the average eye level of observers.

Though all observers kept watch, particularly the observer in the middle was in charge of the GPS, and recording data into the format sheet. Both observers with lateral positions were equipped with binoculars and an angle board in front of them. The field view for the lateral observers was 90°, having the bow set as 0°, and the observer in the middle had a 60° field of view; 30° to the right, and 30° to the left of the bow. Observer positions were shifted every transect line (approximately 60 minutes).

At the beginning of each survey effort, time, observer positions and environmental conditions were recorded (Beaufort sea state, cloud cover, swell, and visibility), as well as any change hereafter. Time was also recorded at the beginning and end of each transect line. On the spot of a gray whale blow, a sighting number was assigned, and all information was gathered on the format sheet. The waypoint was recorded on the GPS, and the observer that saw the whale was responsible for reporting the angle where it was seen, and the reticle line (lines edged on binoculars). The angle was taken from the angle board attached to the floor, therefore sightings could only be spotted within a 0-90° angle view, being 90° directly aside of the lateral position. The reticle line was defined after setting the first line on the horizon and the line taken was read from that line down to the last one set over the sea surface level of the whale blow (sighting). Distance values for each reticle line are taken from Kinzey and Gerrodette (2001) and the values used in this study are shown on Table I.

Table I. Reticle distance values used in this study after Kinzey and Gerodette (2001).

Tabla I. Valores de la distancia de las retículas utilizados en este estudio de acuerdo a Kinzey y Gerrodette (2001).

7X50 Binoculars	
Reticle	**km**
0	8.37
1	0.90
2	0.50
3	0.35
4	0.26
5	0.21
6	0.18
7	0.16
8	0.14
9	0.12
10	0.11
11	0.10
12	0.09
13	0.09
14	0.08

The data entries reported when a marine mammal was sighted were: time, waypoint, environmental conditions, species, number of individuals, reticle line, angle where it was sighted, navigation bearing, and comments (*e.g.* unusual behavior). It is relevant to say that double counts were not a factor to take care of since the boat traveled at a very slow speed and sufficient time elapsed between transect lines. Besides, we navigated the lines in a south-north direction, therefore whales counted in a previously ran southern line would have passed by the time we ran the next line.

II.3. Analytical methods

Early abundance analyses (Reilly *et al*., 1980, 1981) have been modified through time with the introduction of new mathematical procedures. Recent methods developed by Buckland *et al*. (1993), Hobbs *et al*. (2004), and Rugh *et al*. (2005) were followed for the abundance analyses in this work.

Data from three consecutive seasons of shore-based surveys (2003-04, 2004-05, and 2005-06) were analyzed to estimate the eastern Pacific gray whale stock in Ensenada. Analyses here were split into two sections: first, a description of the migration timing for 2003 through 2006, and secondly, abundance estimation for the respective years.

II.3a. Migration timing

It is well known, beforehand, that the gray whale migration has two main periods; a southbound migration, which comprises the time the population takes to travel to its reproduction sites, and a northbound migration comprising the time it takes to travel to the feeding areas. Though in all, each survey season lasted from 9 December through mid-May, two weeks after the last gray whale sighting, the time span analyzed depended on the analysis, survey season, and the direction of the migration. Data were therefore split according to the corresponding period, eliminating from the analysis sightings that were far from those time intervals. Further, data for the northbound migration were divided into two phases, separating the migration of whales without calves and that with only cow/calf pairs. It is relevant to mention that northbound migration data were treated separately from those of the southbound migration, and were used here solely for migration timing analyses.

As a migratory species, evaluation for gray whale abundance includes a description of its migratory rate. Migration rate was described with a relative abundance index (number of whales counted per time effort) to determine the beginning, peak and end of both southbound and northbound migration periods (Rugh *et al*., 2001). All sightings were arranged into number of whales per day and number of whales per hour, henceforth a calculation of the cumulative percentage of sightings per time effort was obtained. The onset of the migration was considered to be the time when 10% of the sightings were reported, according to the respective onshore survey season. For this study, the peak date is taken as a median date (when 50% of the sightings had been obtained at Costa Azul in a survey season) and the end of the migration is the date when 90% of the sightings had been recorded.

II.3b. Abundance Estimation

Simple extrapolation from raw data gives a faux estimation of the true number of individuals in a population, especially when the population is so mobile along such an extended route. Variations within survey areas along with other factors hinder a direct estimation from raw data, grounding biases to take into account before a final estimation. Such biases included are day/night travel rate, whales missed within effort periods (due to observer fatigue and detection probability), pod size bias, whales passing beyond the observer's sight, and whales missed during off-effort hours (Reilly *et al.*, 1983, Buckland *et al.*, 1993, Rugh *et al.*, 1993, Hobbs *et al.,* 2004). Raw data are then extrapolated to a total abundance estimate using correction factors that diminish these biases.

Diel variation

The latest experiment to investigate the diel variation in travel rate was carried out by Perryman *et al*. (1999) with gray whale thermal imagery, and their correction was used in this analysis for southbound whales (f_n^* = 1.0875).

Whales missed within effort hours and pod size correction

In Granite Canyon, California, independent paired counts have been carried out since 1967 to estimate the correction factor for missed pods during effort times and recorded pod size bias (Rugh *et al*., 1993; Buckland *et al*., 1993; Rugh *et al*., 2005). Capture-recapture data are obtained to compare and match the sightings between two independent observation sheds. The resulting matches are made by the use of a scoring algorithm developed by Rugh *et al*. (1993) based on time, offshore distance and pod size (Rugh *et al*., 1993, Hobbs *et al*., 2004). Probability of detection is obtained through iterative logistic regression (Buckland *et al*., 1993). A linear model is then fit, considering the different covariates affecting the probability of detecting a pod. The best model is used to "estimate the detection probability of the i^{th} pod of size *e* passing" during usable effort periods, p_{ei} (Hobbs *et al*., 2004, Rugh *et al*., 2005). A better extended description of these methods is in Rugh *et al*. (1993), Buckland *et al*. (1993), Hobbs *et al*. (2004), and Rugh *et al*. (2005). Calculation of the "total number of pods of size *e* passing during effort periods of the survey" ($\hat{M}_e$; Eq. 1) is obtained to finally calculate the "total number of pods passing the field site" while observation took place, $\hat{M}$. The detailed development of the equations is shown in Annex I (Hobbs *et al*., 2004). After Hobbs *et al*. (2004) and Rugh *et al*. (2005), $\hat{M}_e$ is calculated by

$$\hat{M}_e = \sum_{i=1}^{m_e} \frac{1}{p_{ei}}, \qquad \textbf{Eq. (1)}$$

where:

m_e = number of pods of size *e* sighted from the primary site.

p_{ei} = Detection probability of the i^{th} pod of size *e* passing during usable effort periods.

$\hat{M}$ is needed to estimate $\hat{W}_e$ (Eq. 2), the total number of whales passing the site during effort periods represented by pods of size *e*, and it is calculated by Hobbs *et al*. (2004) and Rugh *et al*. (2005) as

$$\hat{W}_e = \hat{M}_e(e + b_e), \qquad \textbf{Eq. (2)}$$

where:

$\hat{W}_e$ = Total number of whales passing the site during effort periods by pods of size e,

b_e = estimated additive bias correction for *e* from Laake *et al*. (1994).

Before this, a correction for bias in estimated pod size needs to be computed, to correct the fact that underestimation of pod size occurs.

Because the counts for this study were initially made with a different objective (theodolite tracking) and having that it was the first time ever making these counts in Ensenada, paired counts were not made in these years of censuses for the southbound migration. Nevertheless, it is absolutely fundamental to include these corrections in the whale's abundance estimate. In order to account for this inconvenient lack of information, the correction estimates for pod size bias and whales passing the site within usable effort hours obtained at Granite Canyon (Rugh *et al*., 2005) were used for this analysis.

Distance offshore

Before this study, no research on how far whales were migrating from Costa Azul was undertaken. Depending on the research area, one of the factors that may strongly affect the estimated number of gray whales is lacking the awareness of the whale's migratory corridor width; that is, distance from shore. Although this species is well known for being a coastal traveler, a percentage of whales is still being missed because of a limited field of view. Abundance may be under- or overestimated if the migration corridor is unknown and distance is not taken into account. Distance from shore of gray whale sightings was calculated from both boat and onshore surveys to correct for this inconvenience.

Onshore theodolite tracking

Onshore surveys provided data to scrutinize the observer's viewing capacity. Information consisted in gray whale paths, which were gathered from theodolite tracking. Methods for theodolite tracking are explained in the above section. It was practically impossible to track all whales seen with the theodolite, for sometimes more than 3 pods were sighted at the same time, and only one could be followed. However, it was intended to get as many paths as possible.

The theodolite gives out two angles; the vertical angle and the azimuth, which is the horizontal angle from the true northern orientation. These angles were transferred to program T-Track (Cipriano, 1980), which gave northing and easting positions (in relative meter units). With this information, the exact geographic position of the whale can be computed, but for the interest of this study, the distance of the given geographic position from the survey site is most relevant. Paths were drawn, based on the geographical points, with *AUTOCAD* computer program. A standard line was drawn parallel to the coast, and distance perpendicular to the coastline, where the survey site was located, to the whale migration paths was measured (Figure 3).

Once all measurements were done, analytical measures followed. For the first survey season, all sightings that were more than 7km away were excluded from analyses, since it was the first season and misidentification was most probable, as was learned from later experience. Also, transects not falling within the southbound migration period were not included in this analysis.

Distances were arranged in different categorical bins, depending on comparisons. In order to compare to Shelden and Laake's 2002 article, bins of precisely 1.3705km (0.74nm) distance intervals up to 40km (21.6 n.m.) from shore were also analyzed. Chi-square tests were run to test for significant differences at a 95% level among distance intervals and also contingency tables were made to test independence of distance from shore among the surveyed years (Spatz and Johston, 1989), in order to assess if it was correct to apply the same correction factor to abundance estimates for all three observation years.

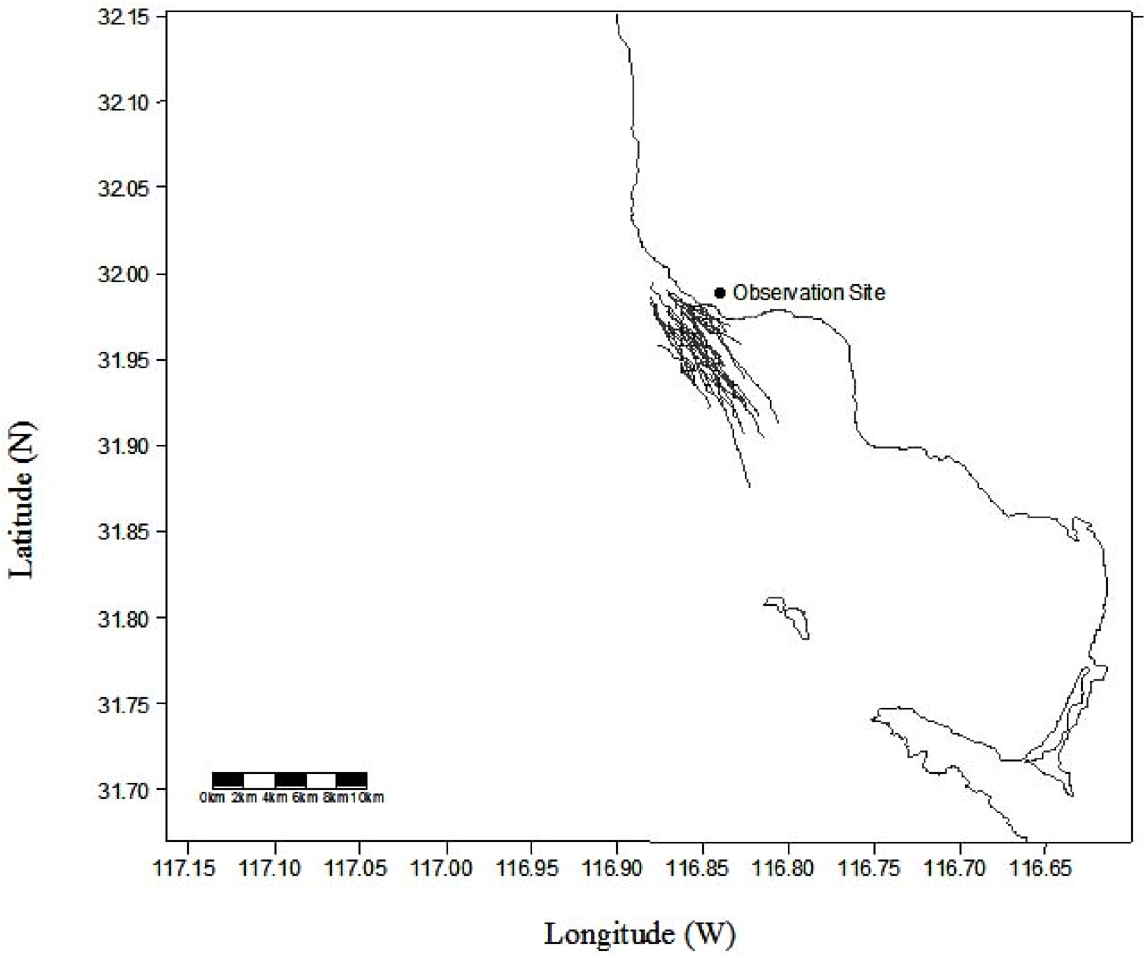

Figure 3. Map showing gray whale tracking lines taken from the theodolite from surveys.

Figura 3. Mapa con las trayectorias de ballena gris tomadas con el teodolito de los conteos desde tierra.

Boat surveys

Data obtained from the boat transects were analyzed in a similar way as the shore-based theodolite tracking. Waypoints were set on a map and distance was measured from the coastline to the waypoint. It is important to mention that waypoints not falling within the strip width (1km) were excluded from the analyses. Also, to avoid taking data not falling within the strip width and for better confidence, sightings that were recorded with reticle line zero or 0.5 were removed from final analyses. Once this distance was obtained, and with the angles reported from the angle boards, basic trigonometric computations provided a true distance of the sighting from shore.

These data were arranged into distance bins, to find the gray whale's migration corridor. Chi-square tests of independence followed to find yearly and inter-bin significant differences. After comparing sightings from theodolite tracking and from boat surveys the percent of sightings missed from the shore station because of distance was estimated.

Missed whales during off-effort hours (f_t)

Twenty-four daily hours of counts are impossible due to variable reasons. Weather conditions are not constant throughout the day and effort time was usually limited or conditioned by climate variations. Effort was usually partially canceled when Beaufort 3 sea state was present, rain came along, or fog was too dense, and it was resumed when these conditions improved. In the worst of cases, that is, if these conditions remained unfavorable for two hours, effort for that day was canceled. Also, recalling the field methods, count surveys for the southbound migration took place three days per week rather than all seven days; therefore, there are days on which no surveys were undertaken. Adding to these missing data, count surveys only took place during the day, from 0700-1400h leaving empty counts any time before and after each survey (nocturnal hours are included in this missing time of effort). According to Buckland (1992) and Breiwick (pers. comm. [2]),

[2] National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle, Washington 98115 USA.

the performed effort time is categorized or grouped into time interval data sets. The resulting count periods, with gaps in between (periods in which no effort or counts were performed), are then frequency counts of whales passing the survey area within that time interval. These frequency counts form the basis for the analysis to correct for missed counts during off-effort hours.

Code design for time intervals

Since count periods are needed to follow on with the use of the *FORTRAN Gwnormf*77 program (Breiwick, pers. comm.) for the computation of f_t (pods missed during off-effort periods), they should be categorized in a systematic manner in order to have reasonable results. It is true that if a single visibility code contemplating the environmental conditions (sea state, cloud cover, fog, among others) is assigned the moment the sighting was recorded; these count periods can easily be grouped. Single code assignment (contemplating these factors as a whole) on the spot of a pod, was not done for the surveys analyzed in this study. This study used a different method developed from the recorded data to generate the count periods needed. Environmental conditions were recorded individually, rather than into a single code, from the beginning of a day's effort and anytime henceforth a change occurred. Since environmental conditions do not vary simultaneously, a sighting may have been done at the time all environmental conditions changed, or, with change in at least one of these factors. Consequently, categorization of time intervals would be difficult due to the many resulting data groups. To discard the many possible groups, a code design was developed to group the counts into proper time intervals. The general visibility code was designed, based on a frequency criterion. Frequencies were based on number of sightings per environmental condition.

There were three obvious possibilities in viewing conditions according to the environmental factors recorded: best, acceptable and worst (Table II). The best of conditions was a day with a clear sky, no fog nor swell and sea state under Beaufort one. The worst possible working conditions are shown in Table II. Data was arranged into frequency counts according to each of the four recorded environmental condition. These percentages gave an idea of how each condition influenced on the sighting of a pod. Each of the categorized conditions (best, acceptable and worst) was then subcategorized into specific environmental conditions, given the resulting frequencies. Codes (1-3) were then assigned to each of these categorized conditions according to the required subcategorized environmental factors (see Table III). Hence, a pod could be single-coded according to the environmental factors under which it was recorded. For example, a sighting with a "best categorized condition" had to occur under Beaufort 1, visibility within a range of 31 to 50 km, and 40% or less cloud cover in order to yield *code 1*. Presence of swell was independent since 95% of sightings were recorded under this condition (see percentages in Table III). The codes were used to set the time intervals at which pods were sighted under alike environmental conditions.

Table II. Classification of three known possible conditions under which the environment could yield best, acceptable, and worst environmental conditions. Basic criteria for categorized environmental conditions.

Tabla II. Clasificación de tres posibles condiciones bajo las cuales las condiciones ambientales pueden clasificarse como buenas, aceptables o malas. Criterios básicos para la categorización de condiciones ambientales.

Conditions	Beaufort (1-3)	Swell (present/absent)	Visibility (km)	Cloud cover (%)
Best	1	0	49	0
Acceptable	2	1/0	27	50
Worst	3	1	0	100

Table III. Code criteria, based on environmental factors, for three categorized conditions. Categories show the conditions required to yield a respective code. Percent values reflect percent sighting frequencies under the respective environmental condition. (Swell: 0=absent and 1=presence).

Tabla III. Criterios para códigos, basados en los factores ambientales para tres condiciones categorizadas. Las categorías muestran las condiciones necesarias para llegar a su respectivo código. El valor porcentual refleja la frecuencia de avistamientos bajos la condición ambiental respectiva. (Mar de fondo: 0=ausencia y 1=presencia.)

Beaufort	Swell 1 = 95% 0 = 5%	Visibility (km)	Cloud cover (%)	Code	No. sightings per code
1 (90%)	0/1	31-50 (18%)	0-40 (49.7%)	1	262
2 (9%)	0/1	11-30 (69%)	41-80 (24.26%)	2	1251
3 1(%)	0/1	0-10 (13%)	81-100 (25%)	3	582

Computing the correction factor f_t

Proceeding after the codes, a three-column matrix was generated yielding time intervals in decimal days (start and end time taking 01 December as day one) and number of whales reported within that time interval. The passing whales within missed effort hours can be accounted for with a correction factor (f_t) computed after modeling the sightings' density curve (Buckland, 1992). Buckland (1992) describes a method using Hermite polynomials, in which parameterization of a model is fit to the data, using these polynomials to adjust when there is a lack of good fit. The three-column matrix was therefore used to run the FORTRAN *Gwnormf*77 program, and adjust the resulting density with a Hermite polynomial-fitted normal density function (Eq. 3). Equation three is taken after Buckland *et al*. (1993). Hermite polynomials adjust for skewness, kurtosis, and higher moments (Buckland, 1993). The resulting graph is a normal distribution indicating the passage rate of whales. The rate function $q(t)$ is the number of expected whales per day integrated to adjust or correct for missed periods. The final correction factor for missed periods (f_t) is defined to be "the ratio of the total area under the function, Q, to the sum over all watch effort periods of the area under the function during each effort period" (Buckland *et al*, 1993; Hobbs *et al.*, 2002).

$$f(x) \cong \alpha(x_s) \cdot \left(1 + \sum_{j=1}^{b} a_j H_j(x_s)\right) / \beta, \qquad \textbf{Eq.(3)}$$

where:

$x_s = (x - \mu)/\sigma$ = a standardized x value,

$\alpha(x_s) = \exp(-x_s^2/2)$ = key function,

$H_j(x_s)$= j^{th} Hermite polynomial, j =1,…, h,

a_j = 0 (if term *j* of $p_j(y_s)$ is not required,

β = normalizing function of the parameters.

An assumption is essentially necessary for this method, though, and that is that the passage rate during effort periods does not differ significantly from the overall rate (Buckland , 1992). A parametric model is fitted first to the data, and if the fit is not ample, then polynomial adjustments follow.

Abundance

Total abundance was estimated from onshore sightings and corrections were included in the final estimate. Such corrections are total whales missed within effort hours ($\hat{W}$ from Rugh *et al.*, 2005), missed whales due to distance offshore (f_d = 1.56, from this study), whales missed during off effort periods (f_t), and nocturnal travel rate (f_n= 1.0875, from Perryman, 1999). Thus, the estimated population size for the Eastern Pacific Stock ($\hat{N}$) in this study was obtained through the following equation:

$$\hat{N} = \hat{W} \cdot f_d \cdot f_t \cdot f_n . \qquad \textbf{Eq. (4)}$$

III. RESULTS

III.1. Migration timing

Three years of census data (2003-2006) were analyzed to determine migration timing of the gray whale (*Eschrichtius robustus*) in Ensenada, Baja California. Overall, effort hours spent for every season are shown in Table IV. Number of hours spent in each survey increased with years.

Table IV. Effort times are given for each migration season as well as the number of pods and whales counted during the southbound surveys.

Tabla IV. Tiempo de esfuerzo para cada temporada así como el número de grupos de ballenas y el total de ballenas contadas durante los conteos de la migración al sur.

Season	Total effort hours	Northbound effort hours	Southbound effort hours	No. of pods counted during the southbound period	No. of whales counted during the southbound survey
2003-04	341.7	163.9	177.8	389	661
2004-05	448.32	255.95	192.37	441	773
2005-06	488.48	255.93	232.55	395	661

Total migration timing is shown in Figure 4, from December through May. An overlap of migration periods (southbound and northbound) can be seen in most years around the beginning of February, except for 2004/05. Northbound migration timing for that year seems to have started at around the peak of the southbound migration, *i.e.* the third week of January. The relative abundance distribution also shows that the northbound migration was also more extended in time, for that same year. The two most visible bell-shapes are noticed for the southbound and northbound migration of this same season. Alone, the northbound migration does not show a well defined bell-shaped distribution, rather it has a more prolonged shape with two overlapped "bells" of different magnitude (Figs. 4 and 5) and two separate peaks; one for the northbound migration without calves and a second one corresponding only to cow/calf pairs.

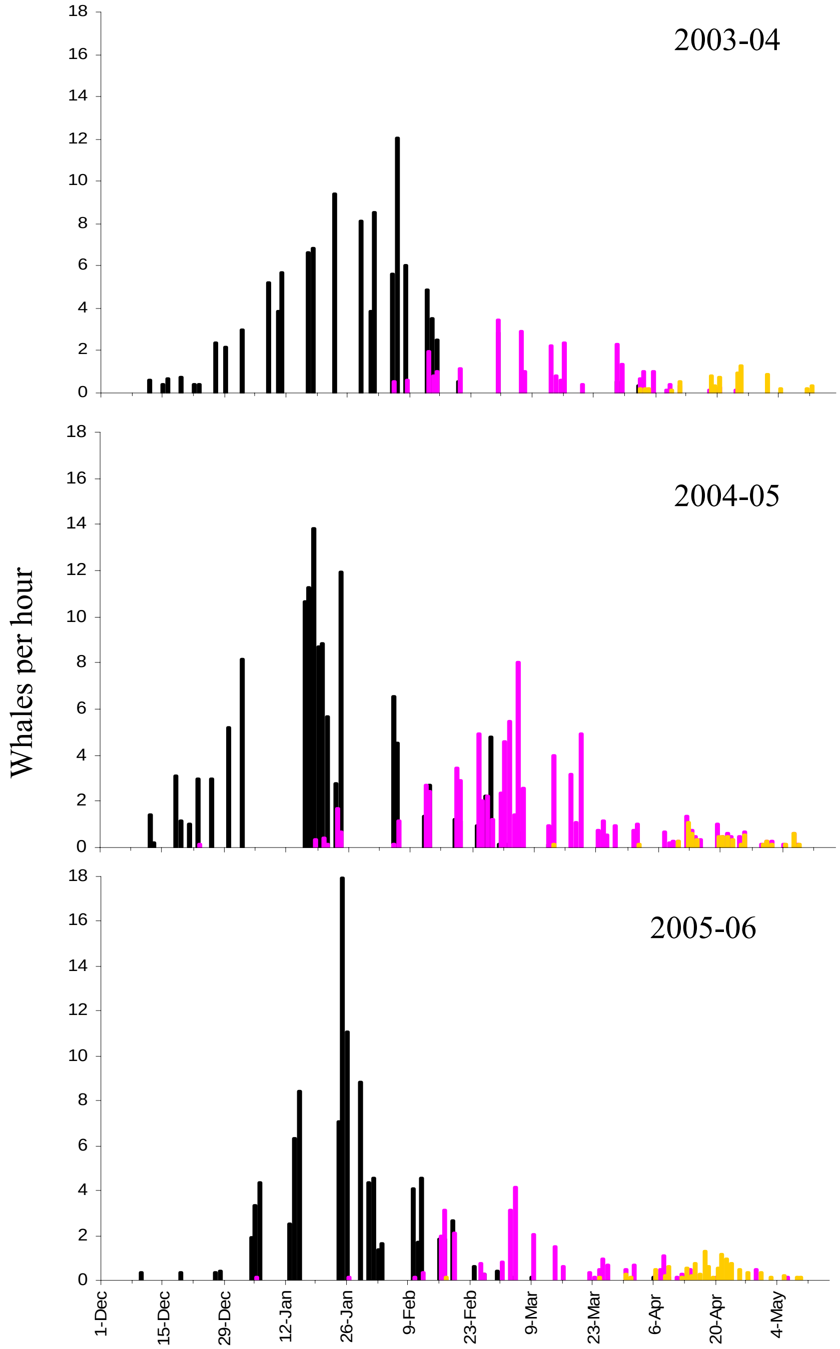

Figure 4. Distribution of gray whale sightings recorded per effort hour during the three surveyed seasons (2003-2006). Black = southbound, pink = northbound without calves, and yellow = northbound cow/calf pairs.

Figura 4. Distribución de avistamientos de ballena gris por hora de esfuerzo para cada una de las tres temporadas (2003-2006). Negro = sur, rosado = norte sin crías y amarillo = norte parejas hembra/cría.

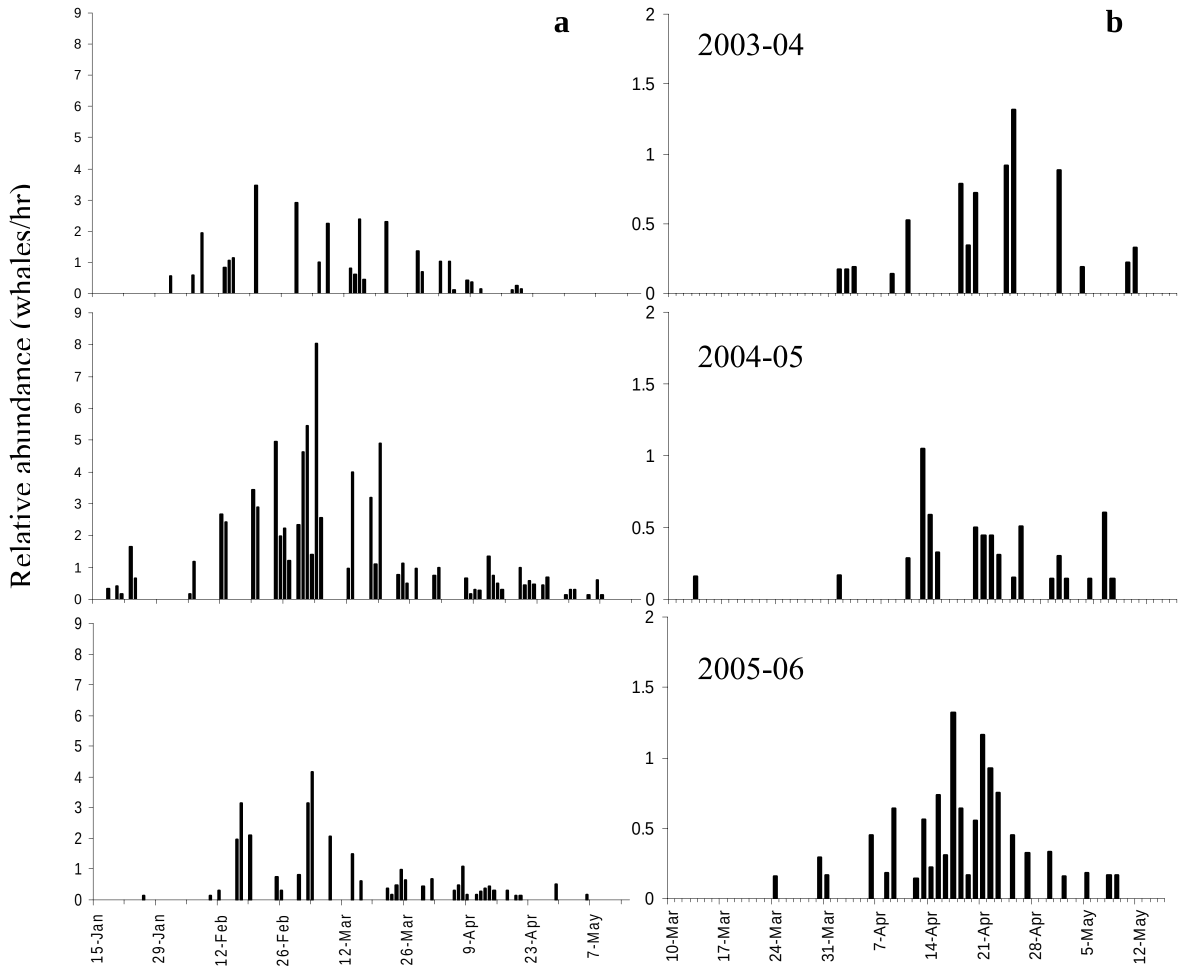

Figure 5. Distribution of northbound migrating whales sighted per hour of effort during the three surveyed seasons (2003-2006), including cow/calf pairs. a) Whales without calves, b) cow/calf pairs.

Figura 5. Distribución del número de ballenas registradas por hora de esfuerzo en la migración al norte durante las tres temporadas de muestreo (2003-2006). a) Ballenas sin crías, b) parejas madre/cría.

III.1a. Southbound migration timing

Data analyzed for the southbound migration were taken from resulting survey information obtained from 9 December through 15 March in order to make annual comparisons. A total of 661 whales were seen (389 pods) during 177.8 hours of effort time spent for the 2003-04 southbound season (Table IV). An increase in number of whales (773 whales; 441 pods) was observed for 2004/05, yet for the following year this number decreased to a similar number of whales as seen in the first survey year. However, effort time was also increased from the first survey year to the last and considering this, fewer whales were seen (661) for the 2005-06 southbound survey, regardless of the increase in number of observation hours (232.55h) (Table IV).

The relative abundance of southbound grays is depicted in Figure 6 as number of observed whales per hour during a two-month period. It reflects the passage rate of whales, with a bell-shaped distribution, during effort hours. From this rate, the timing at which a percent of the population is passing Ensenada can be estimated. Timing for the southbound abundance distribution in this study was from December to early March in every survey season (Fig. 6). The bell-shaped graphs reflect the gray’s southbound migration passage rate as an initial flux (the onset of whales passing Ensenada), rising to a peak, and then smoothly declining, marking the end. The end is assumed to be when most whales have traveled south past Ensenada, and the southbound migration there is considered to be over. The tails of the migration in Ensenada are shown on Table V.

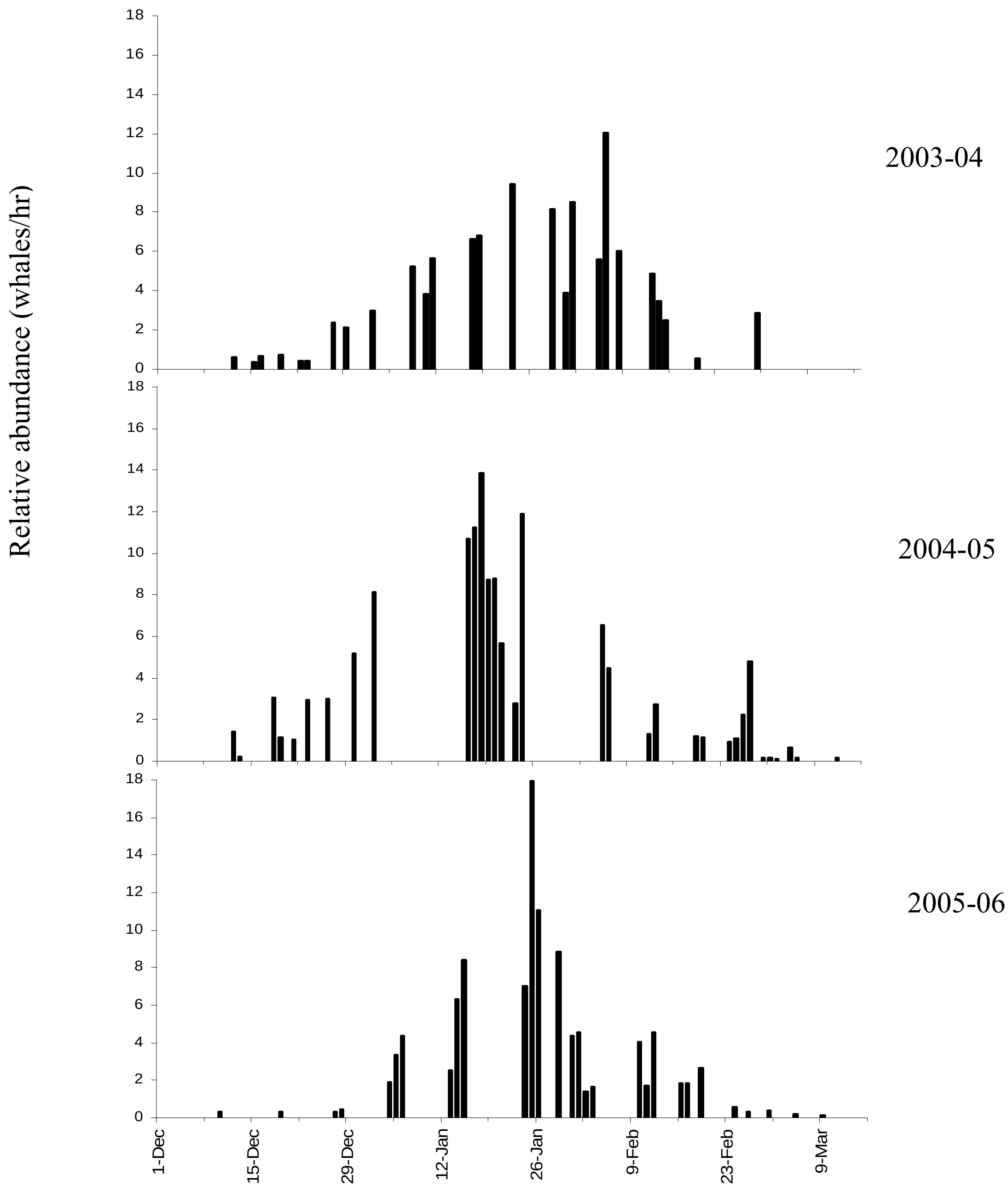

Figure 6. Distribution of southbound gray whales sighted per effort hour during the three surveyed seasons. Time is shown from 01-Dec. to 15-Mar.

Figura 6. Distribución de avistamientos de ballena gris por hora de esfuerzo en la migración al sur para las tres temporadas de muestreo, del 1 de diciembre al 15 de marzo.

Table V. Dates of occurrence of the tails of the southbound migration and median dates (50%) taken from the relative abundance index, for each migration season.

Tabla V. Fechas de las proporciones extremas (10% y 90%) de la migración al sur y fechas medianas (50%), tomadas del índice de abundancia relativa para cada temporada.

Season	10%	50%	90%
2003/04	02 January	23-29 January	13 February
2004/05	25 December	17-18 January	13 February
2005/06	06 January	25 January	12 February

There seems to be a head-start of about a week or two in the onset of the 2004/05 (Dec. 25) migration season, time at which 10% of the sightings had been recorded. This early arrival is also seen for the median dates on that same year (17-18 January), notwithstanding the dates obtained for the other two years, which are in late January. However, the end of the migration fell on the same day (12-13 February) for all three years. After averaging the relative abundance for the southbound migration (table VI), it is noted that counts did not

Table VI. Mean relative abundance index showing whales per hour during the three migration seasons (2003-2006).

Tabla VI. Índice promedio de abundancia relativa mostrando numero de ballenas por hora durante las tres temporadas de migración (2003-2006).

	Mean southbound		Mean northbound		Mean northbound	
	whales/day	whales/hr	whales/day	whales/hr	CC/day	CC/hr
2003/04	24.59	3.97	4.78	1.03	1.28	0.43
2004/05	23.42	3.87	8.94	1.53	1.37	0.19
2005/06	22.79	3.56	3.71	0.62	1.59	0.26

rise in 2004-05. Therefore, it cannot be said that whales were passing at a faster rate than usual and hence the early arrival.

The peak of the migration (date with maximum rate of whales per hour) coincides with the median date for every respective year. Even though the peak date is seen to have varied in all three years, it was more noticeable in 2004-2005 (Fig. 6) where a week-delay was observed.

III.1b. Northbound migration timing

The northbound migration has a different behavior from the southbound migration; therefore, it is treated separately. Migration in the northbound direction is divided into two sets of migrants; migration without calves and migration with only cow/calf pairs. Whales falling within the first northbound migrating group are early pregnant females, adult males, mestrous, anestrous and immature females, and immature males (Rice and Wolman, 1971). Behavior for this data shall be described first.

The period for the northbound migration without calves took place from early February to early April (Figs. 4 and 5a). The beginning for the migration without calves was not variable for the first two seasons; dates coincided early in 12-13 February (Table VII). A later date in mid- February is reported for the onset of the 2005-06 northbound flux. Consistency in median dates is shown for 2004-05 and 2005-06; sightings for those two years fell within the same median date, 04 March. The same pattern in date consistency is obtained for the end of the migration, where 90% of the sightings are reported between 9-10 April. In fact, despite that counts were higher in 2004/05 (1.53 whales/hr; table VI), migration timing for this period was also longer. During the last survey season, a delay in the initial flux seemed to have shifted around 3 to 5 days from the other two surveys. This is more noticeable for the second set of migrants.

Table VII. Dates of percent sightings obtained during the northbound migration in every season; no cow/calf pairs.

Tabla VII. Fechas del porcentaje de avistamientos registrados en la migración al norte durante cada temporada; sin crías.

Season	10%	50% (median dates)	90%
2003/04	12-13 February	06-08 March	02 April
2004/05	12-13 February	04 March	10-12 April
2005/06	16-17 February	04-05 March	09 April

The second set of the northbound migrants (cow/calf pairs) follows after the first group and may overlap in dates (Fig. 4). The migration rate for these migrants is slower than the northbound migration without cow/calf pairs and similarly this latter is slower than the southbound migration rate (see Figure 5b and Table VI). The northbound migrating whales, including solely cow/calf pairs, start passing Ensenada in early April, just after the first northbound whales are at the end of their migration past these waters (Fig. 5b). Median dates did not vary from year to year. A tendency in date variation is poorly observed for these sightings (Table VIII). There is a constant behavior in the data for this migration since the start is shown to be in early April and the median dates are quite similar for 2003-04 and 2004-05. Comparing the first season with the following two, there is a two-day difference at the beginning of the migration. The earliest starting date is observed on the last survey season, showing a four-day variation from the second season. Precise dates are not shown for this part of the northbound migration, though in all, they all have similar dates (18-19 April). The resulting dates for the end of the cow/calf pair migration are soon after median dates, in late April. However, this date is prolonged to early May in 2004-05.

Table VIII. Dates of percent sightings obtained during the northbound migration in every season; cow/calf pairs.

Tabla VIII. Fechas del porcentaje de avistamientos registrados en la migración al norte durante cada temporada; sólo parejas madre/cría.

Season	10%	50% (median date)	90%
2003/04	08 April	19-23 April	30 April
2004/05	10 April	19-20 April	04-05 May
2005/06	06 April	17-18 April	25-27 April

Gray whales are last seen in Ensenada waters, until the next season, with the end of the cow/calf pair migration. Therefore, total migration, here, ends in early May. Particularly, it ended at a later time in the 2004-05 season.

III.2. Abundance Estimation

III.2a. Pods missed during effort hours

Corrections for pod size estimation and for missed pods within effort periods were taken from values reported in Rugh *et al*. (2005). A pre-estimation was obtained based on these corrections. Average correction for missed pods varied among the three years of their study

(1997-98, 2000-01 and 2001-02). Therefore, the estimation of whales passing the survey site ($\hat{W}_e$) is calculated using the mean of the correction estimated for the last two years in Rugh *et al*. (2005) for each survey season analyzed in this study (Table IX).

Table IX. Estimation of total number of whales passing the survey site ($\hat{W}$), in each surveyed season, using corrections for missed pods within effort periods and pod size bias due to observers as reported in Rugh *et al*. (2005). $\hat{W}_e$ = No. whales in pods of size *e*.

Tabla IX. Estimación del total de ballenas que pasaron el sitio de observación ($\hat{W}$), en cada temporada, utilizando las correcciones para grupos no observados dentro de horas de esfuerzo y sesgo de los observadores por tamaño de grupo, tal como lo reportan Rugh *et al*. (2005). $\hat{W}_e$ = No. ballenas en grupos de tamaño *e*.

Pod size	Average Correction for missed pods	Bias-corrected pod size	No. of pods 2003-04	$\hat{W}_e$	No. of pods 2004-05	$\hat{W}_e$	No. of pods 2005-06	$\hat{W}_e$
1	1.28	1.94	203	504.35	237	588.82	238	591.31
2	1.229	2.65	114	370.72	120	390.23	102	331.70
3	1.156	3.61	55	229.33	51	212.65	26	108.41
4	1.1015	4.25	10	46.81	21	98.31	12	56.18
5	1.0525	5.25	1	5.53	8	44.21	8	44.20
6	1.043	5.25	2	10.95	2	13.04	3	16.43
7	1.0285	7.25	-	-	1	7.46	1	7.46
8	1.028	8.25	1	8.48			2	16.96
All	**1.25**	**2.43**	**386**		**440**		**392**	
$\hat{W}$				**1,176.2**		**1,354.7**		**1,172.6**

The corrections used in this study's final estimation are the latest reported correction estimates (2000-01 and 2001-02; Rugh *et al*., 2005). The pre-estimations for our study were

1,176, 1,355 and 1,173 individuals for the respective 2003/04, 2004/05 and 2005/06 survey season results. An early tendency can be seen as an increase of individuals in 2004/05 and then a decrease in 2005/06 similar to estimates calculated in 2003/04.

III.2b. Pods missed due to distance from shore

Onshore theodolite tracking

For the 2003/04 survey, a total of 49 sightings were tracked with the theodolite, 39 were tracked in 2004/05 and during the last survey season (2005/06), 58 tracks were gathered. Sightings were categorized into distance interval bins of 1.375km, the equivalent to 0.74nm (Table X**)**. Table X shows percent of sightings observed per distance interval for every year as well as the respective chi-square value to test for differences in distance intervals (each bin represents a distance interval).

Distance intervals are rounded to two digits after the decimal point, though this was only done to ease the view and reading of graphic and table results. In analyses, this numbers were used to the precision of 0.74 nautical miles. There was a statistically significant difference in the number of sightings among bins in each of the three seasons (2003-2004: $\chi^2 = 32.74$, 2004-2005: $\chi^2 = 43.95$, 2005, 2006: $\chi^2 = 81.66$; df=4, $p<0.001$).

Table X. Number and percent of tracked sightings recorded per distance interval during each surveyed season. Chi square tests revealed a significant difference in the number of sightings between intervals for every year ($p<0.001$).

Tabla X. Número y porcentaje de avistamientos registrados según el intervalo de distancia. La prueba ji-cuadrada mostró diferencias significativas en el número de avistamientos entre los intervalos para cada año ($p<0.001$).

	2003/04		2004/05		2005/06	
Distance intervals (km)	No. of tracked sightings	Percent tracked sightings	No. of tracked sightings	Percent tracked sightings	No. of tracked sightings	Percent tracked sightings
0-1.37	13	26.5	6	15.39	15	25.86
1.37-2.76	22	44.9	23	58.97	37	63.79
2.76-4.15	12	24.5	9	23.08	5	8.620
4.15-5.54	2	4.1	1	2.56	1	1.72
5.54 and on	0	0.0	0	0	0	0
Total	49	100.0	39	100	58	100
χ^2	**32.74**		**43.95**		**81.66**	

A greater number of sightings is reported between the 1.37-2.76 km distance interval. From this interval, a tendency of decrease in number of sightings, as distance from the coast increases, is seen in all three years (Figure 7). No theodolite tracks are reported beyond 5.5km, and more than 95% of the sightings recorded from land are reported between zero and 4.15 km. This figure also shows a similar tendency is observed in Shelden and Laake's 2002 results (Fig. 7).

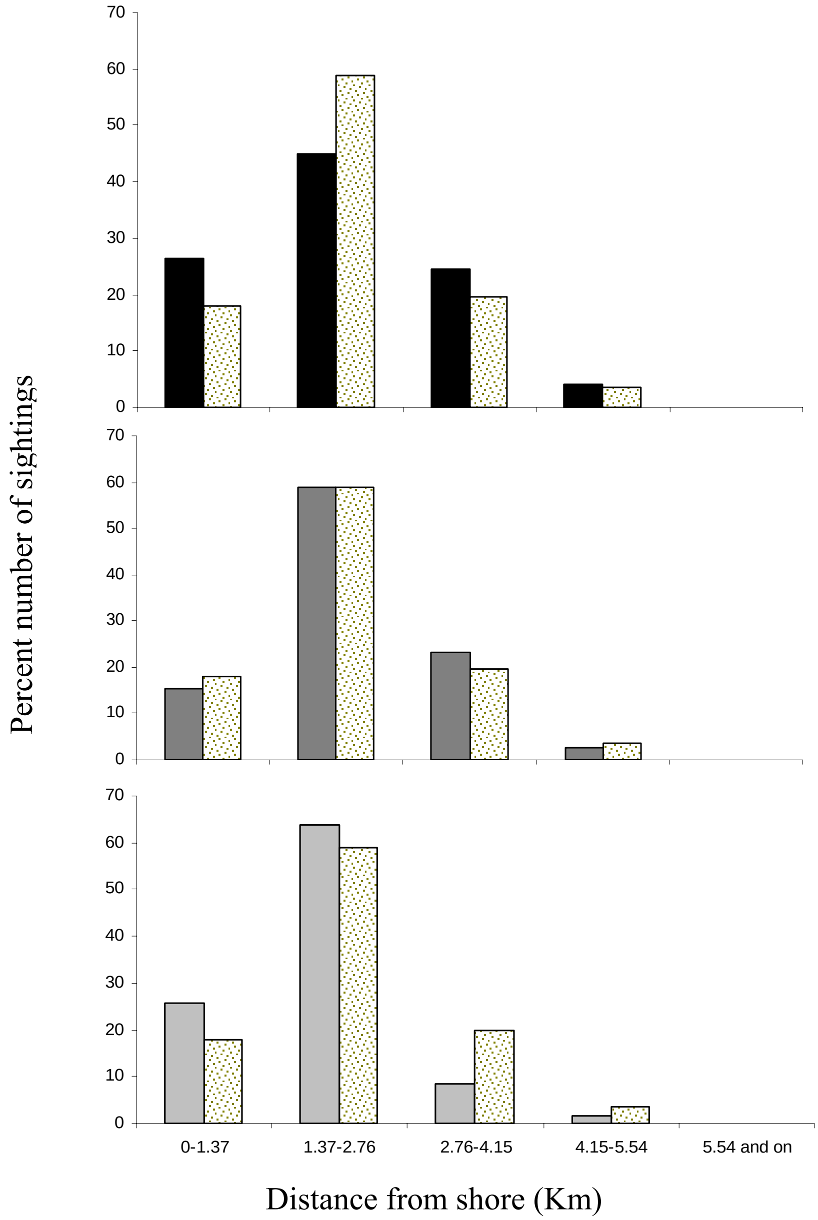

Figure 7. Comparison of the distribution of sightings per distance interval obtained from onshore theodolite tracking at Costa Azul (black = 2003-04; gray = 2004-05; light gray = 2005-06) with the results from aerial surveys at Granite Canyon, California (dotted bars) (Shelden and Laake, 2002).

Figura 7. Comparación de la distribución de los avistamientos obtenidos con el teodolito desde tierra en Costa Azul, según el intervalos de distancia, (negro = 2003-04; gris = 2004-05; gris claro = 2005-06) y los resultados de recorridos aéreos en Granite Canyon, California (barras punteadas) (Shelden y Laake, 2002).

Inter-annual comparisons in data distribution were also tested for independence among years, resulting in a rejection of the null hypothesis. Hence, the theoretical assumption was accepted (χ^2 = 8.33, df = 6, n = 146 p>0.001), inferring that the spatial distribution of gray whales reported from shore did not differ among the three years (2003-2006). That is, there was no difference in the distribution of percent sightings in the categorical bins among the years analyzed from onshore theodolite tracking.

Boat surveys

Surveys were done from 22 January to 9 February running a total of 31.5 inshore and 6 offshore transect lines. On average, three to four transect lines were ran per day. Survey time extension and number of transects surveyed in a day were both consequences of weather variations and limitations. Throughout the entire study period, 118 sightings of gray whales (207 gray whales sighted) were gathered, though after data treatment, sample size reduced to 78 usable sightings.

Marine mammals observed during these surveys, other than gray whales, were short-beaked common dolphin (*Delphinus delphis*), long-beaked common dolphin (*Delphinus capensis*), bottlenose dolphin (*Tursiops truncatus*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), fin whale (*Balaenoptera physalus*), California sea lion (*Zalophus californianus. californianus*), and harbor seal (*Phoca vitulina richardsi*). Also, and to a surprise, a gray whale cow/calf pair was sighted at the end of one of the long transects (40km from shore; 07 February, 2007), though it was not included in the analyses because it was at a yet further distance and did not fall within the sampling area.

As a first exploratory analysis, data were divided into 5-km distance intervals. Most gray whale observations were between 5 and 10km, observations dropped drastically beyond this point (Figure 8). Furthermore, data were split into onshore (23 sightings between 0-4.15km) and offshore (55 sightings between 4.16-40km). There was a highly significant difference in the number of sightings between the two intervals (χ^2 = 0.837, df=1, n=78 p<0.001**)**. That is, distribution of sightings was not homogeneous and only 29.5% of recorded sightings fell within the inshore categorical bin, indicating that the majority of sightings were recorded offshore.

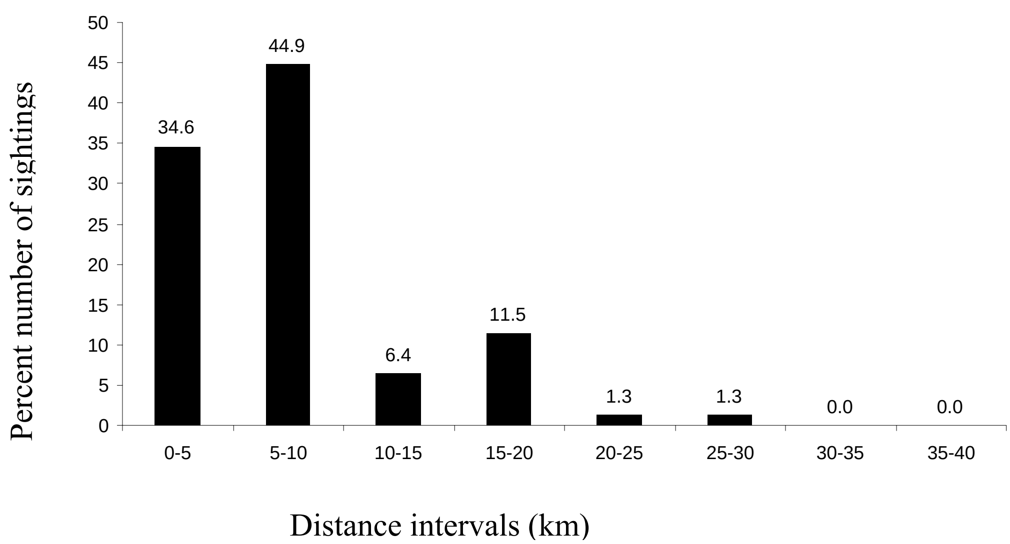

Figure 8. Offshore distance of gray whale sightings per distance interval according to boat survey results

Figura 8. Proporción de avistamientos de ballena gris según los intervalos de distancia de la costa registrados desde el barco.

As in Shelden and Laake (2002), inshore data were subcategorized into 1.3705km distance intervals (the equivalent to their 0.74nm) up to 5.5 km from the coastline (Fig. 9). Inshore sighting distribution rejected homogeneity (χ^2 = 5.76; df=3, n=34 p<0.001**)**. Not many sightings were obtained in the first kilometer from shore, yet number of sightings increased with distance.

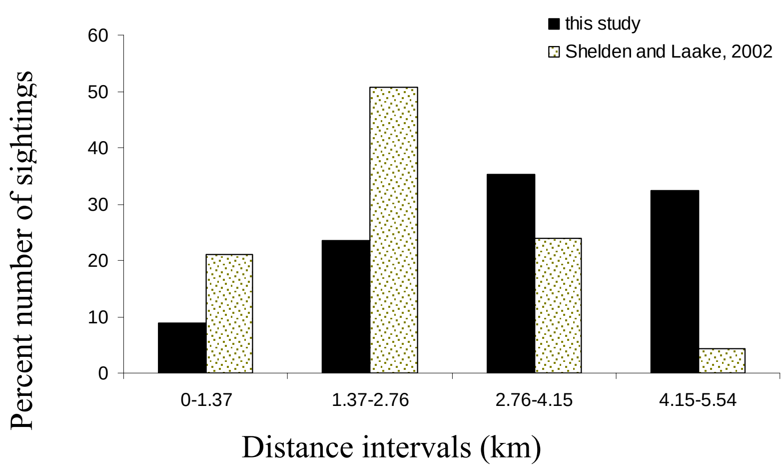

Figure 9. Distribution of percent sightings obtained within 5.54km from shore and divided into 1.3705km intervals (0.74nm), to compare with results from Shelden and Laake's (2002) aerial surveys at Granite Canyon, California.

Figura 9. Distribución del porcentaje de avistamientos dentro de los primeros 5.54km de la costa y divididos en intervalos de 1.3705km (0.74nm), para comparar con los resultados de censos aéreos en Granite Canyon, California, por Shelden y Laake (2002).

Comparison of onshore and boat surveys: Correction factor (f_d)

Inshore and offshore distances were initially categorized based on information from Shelden and Laake's (2002) study. Nevertheless, results from onshore distance analyses (theodolite tracking) determined that percent sighting distribution was similar to results reported in Shelden and Laake's (2002) study (Figure 8). Observers at Costa Azul recorded more than 95% of the tracks below 4.15km and no recordings were reported at a further distance than 5km. However, boat survey results indicated that numerous whales were still passing beyond this distance. Eyesight limitation from shore to sea was then determined to be at 5.5km for this study. Nonetheless onshore and boat surveys together determine true observer eyesight from the observation point to be at 4.15 km. For this study, observer eyesight was taken to be the distance where most sightings (>90%) were being recorded by observers. Table XI shows the observer viewing limitation when compared to the percent sightings obtained from boat surveys. A comparison of the 2007 boat survey results with the three years of shore-based surveys shows the cumulative percent sightings from boat surveys compared with the cumulative percent sightings obtained with the theodolite from land. The cumulative percent comparison was made with results obtained up to 20km since there very few sightings recorded beyond this distance (Figure 10).

Table XI. Percent sightings obtained from theodolite tracks, per distance interval, according to year. Mean percent land sightings are compared with boat survey sightings obtained within the distance intervals. During boat surveys, 56% of sightings were recorded at more than 5.5 km, beyond shore observer eyesight.

Tabla XI. Porcentaje de avistamientos obtenidos de las trayectorias con teodolito por intervalo de distancia, según el año. El porcentaje promedio de avistamientos obtenidos desde tierra se compara con los avistamientos del barco. Los recorridos en barco indican que el 56% de los avistamientos se obtuvo a más de 5.5 km de la costa.

Distance intervals (km)	% sightings from theodolite tracks according to year			Mean % of all 3yrs.	Boat survey sightings (2007)	Boat survey % sightings
	2003-04	2004-05	2005-06			
0-1.4	26.53	15.38	25.86	23.29	3	3.85
1.4-2.8	44.90	58.97	63.79	56.16	8	10.26
2.8-4.1	24.49	23.08	8.62	17.81	12	15.38
4.1-5.5	4.08	2.56	1.72	2.74	11	14.10
5.5-9.9	-	-	-	-	28	35.90
10-15	-	-	-	-	5	6.41
15-20	-	-	-	-	9	11.54
20-25	-	-	-	-	1	1.28
25-30	-	-	-	-	1	1.28
30-35	-	-	-	-	0	0.00
35-40	-	-	-	-	0	0.00
n	49	39	58	100	78	100

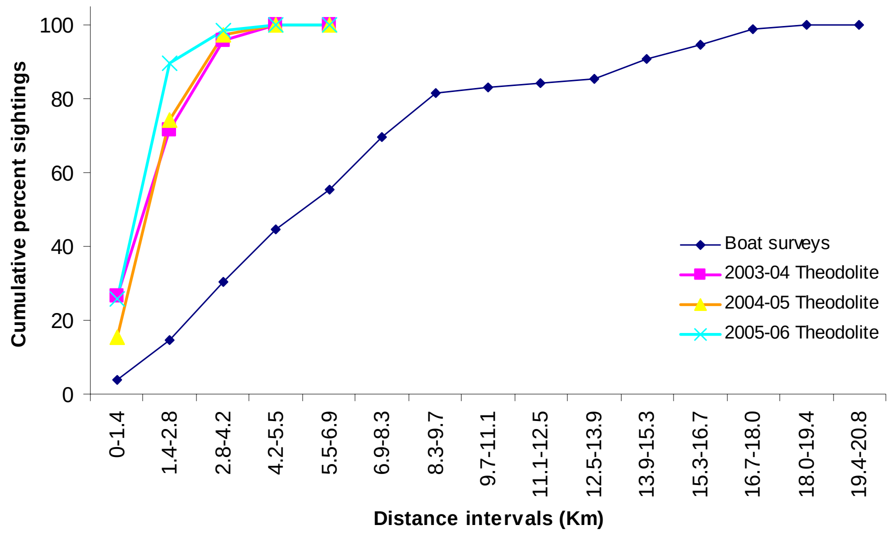

Figure 10. Cumulative percent sightings from boat surveys and those obtained from land with the theodolite (per season). More than 50% of boat sightings were recorded beyond 5.5km, the distance at which the shore observer is able to record with the theodolite.

Figura 10. Porcentaje acumulado de los avistamientos obtenidos de barco y desde tierra con el teodolito (por temporada). Más del 50% de avistamientos desde barco se registran a más de 5.5km, distancia máxima a la que el observador en tierra logra registrar con el teodolito.

Nevertheless, Figure 11 shows a comparison of the average percent sightings obtained during the three years of onshore surveys against the percent sightings obtained in all transect lines ran in the 2007 boat surveys. As shown in Table XI, 56% of the sightings are recorded beyond the shore observer eyesight (5.5km). This can be better portrayed in the comparison shown in Figure 10. As a result, a single-general correction factor of 1.56 was determined to be used in all three years for abundance estimation.

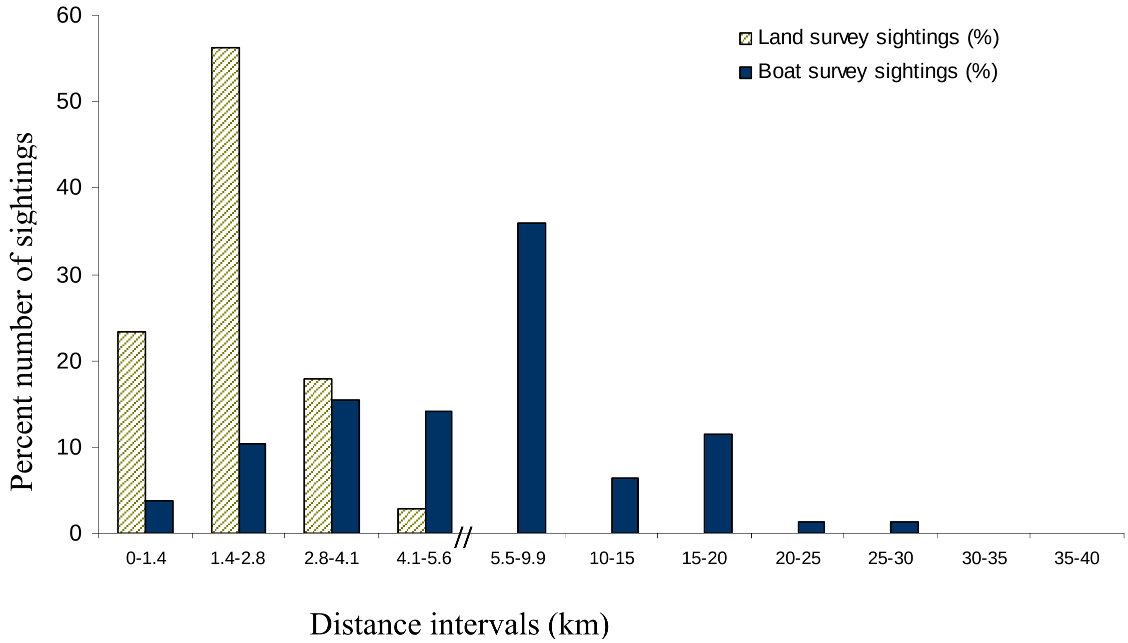

Figure 11. Percent sightings obtained in the 2007 boat survey and the average percent sightings obtained from the three years of onshore theodolite tracks; 56% of boat sightings occurred at more than 5.5km and were missed from land.

Figura 11. Resultados de los censos de barco en 2007 y el porcentaje promedio de avistamientos obtenidos en los tres años desde tierra; 56% de los avistamientos del barco ocurrieron a más de 5.5km y no se observaron desde tierra.

III.2d. Missed whales during off-effort hours (f_t)

Environmental conditions

According to the classification of environmental factors (Beaufort, swell, visibility, and cloud cover, Table III), sightings were given a code. In general, most sightings (90%) were obtained under Beaufort 1, 50% with cloud cover <25, 69% under fair observer visibility (11-30km), and 95% in the absence of swell (Table III). Few sightings were done under code 1. Most sightings were done under fair or worse conditions. Worse conditions, here, are not meant to be unacceptable viewing conditions but conditions in which the elements were not so good yet they allowed effort to go on. In this study, it was meant to work only under good or acceptable conditions and weather forecast was usually checked before going out on the field. This avoided unusable effort hours during the analyses and those hours were considered to be off-effort periods. Sighting frequencies were useful for single-coding environmental conditions. Figures 12-14 show the adjusted passage rate for the respective survey seasons using Hermite polynomials. The correction factors (f_t) were 12.46, 12.96, 9.77 for the respective years from 2003-2006.

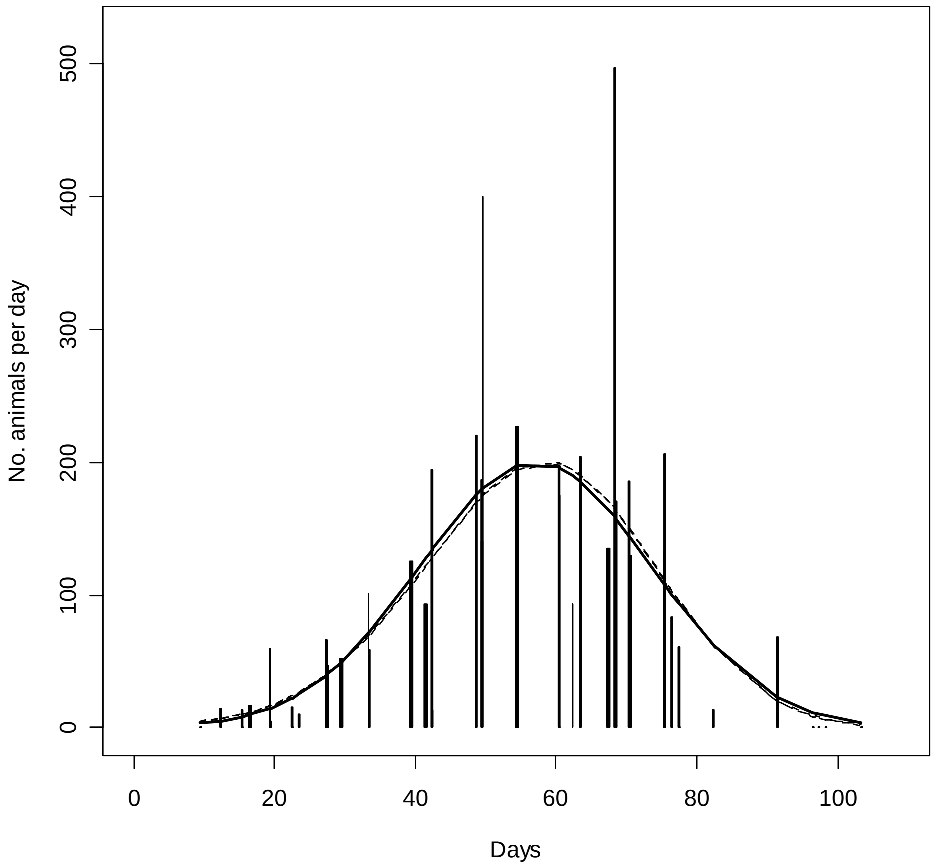

Figure 12. Fitted distribution (using Hermite polynomials) of estimated number of whales per day passing the survey site for the 2003-04 season (solid line).

Figura 12. Distribución ajustada (utilizando polinomios de Hermite) del número estimado de ballenas que pasaron por el sitio de observación en la temporada 2003-04 (línea continua).

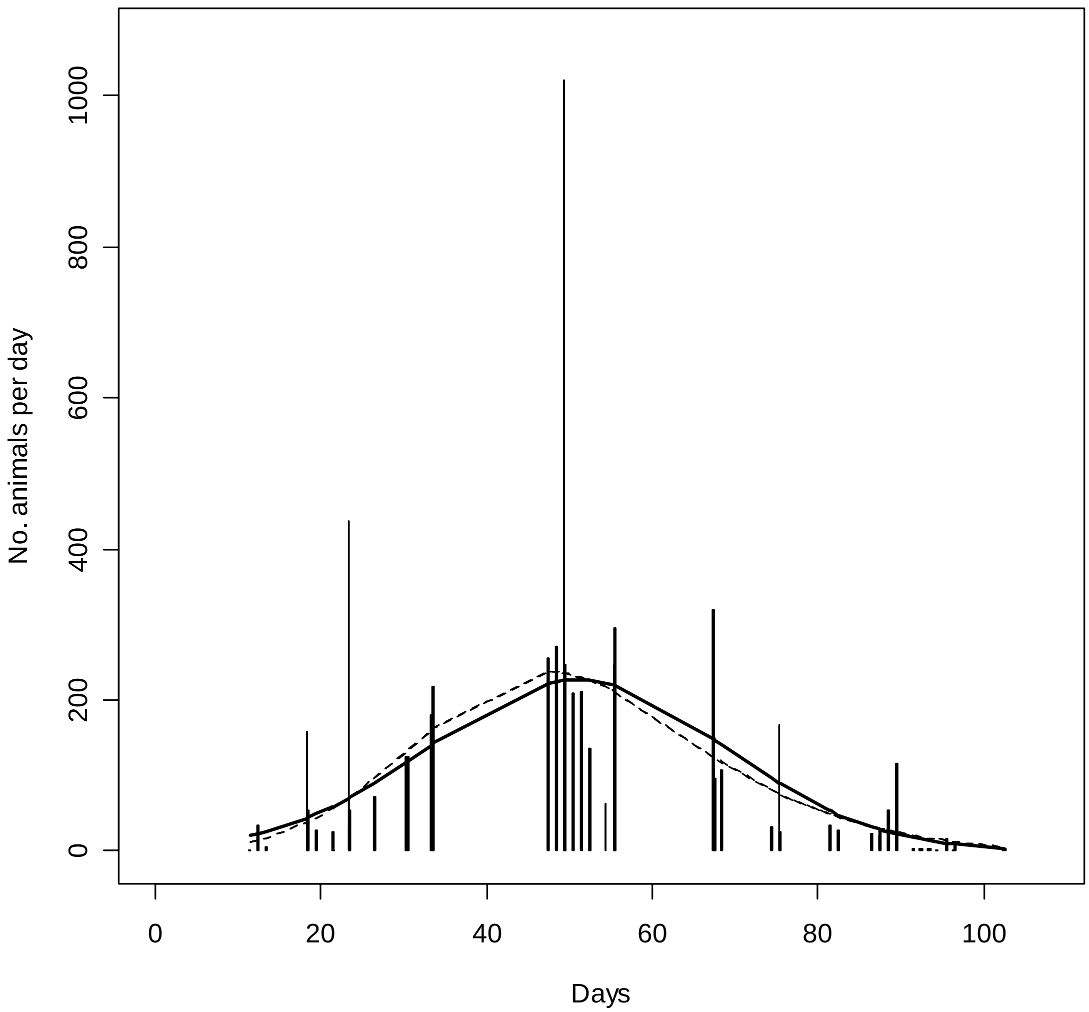

Figure 13. Fitted distribution (using Hermite polynomials) of estimated number of whales per day passing the survey site for the 2004-05 season (solid line).

Figura 13. Distribución ajustada (utilizando polinomios de Hermite) del número estimado de ballenas que pasaron por el sitio de observación en la temporada 2004-05 (línea continua).

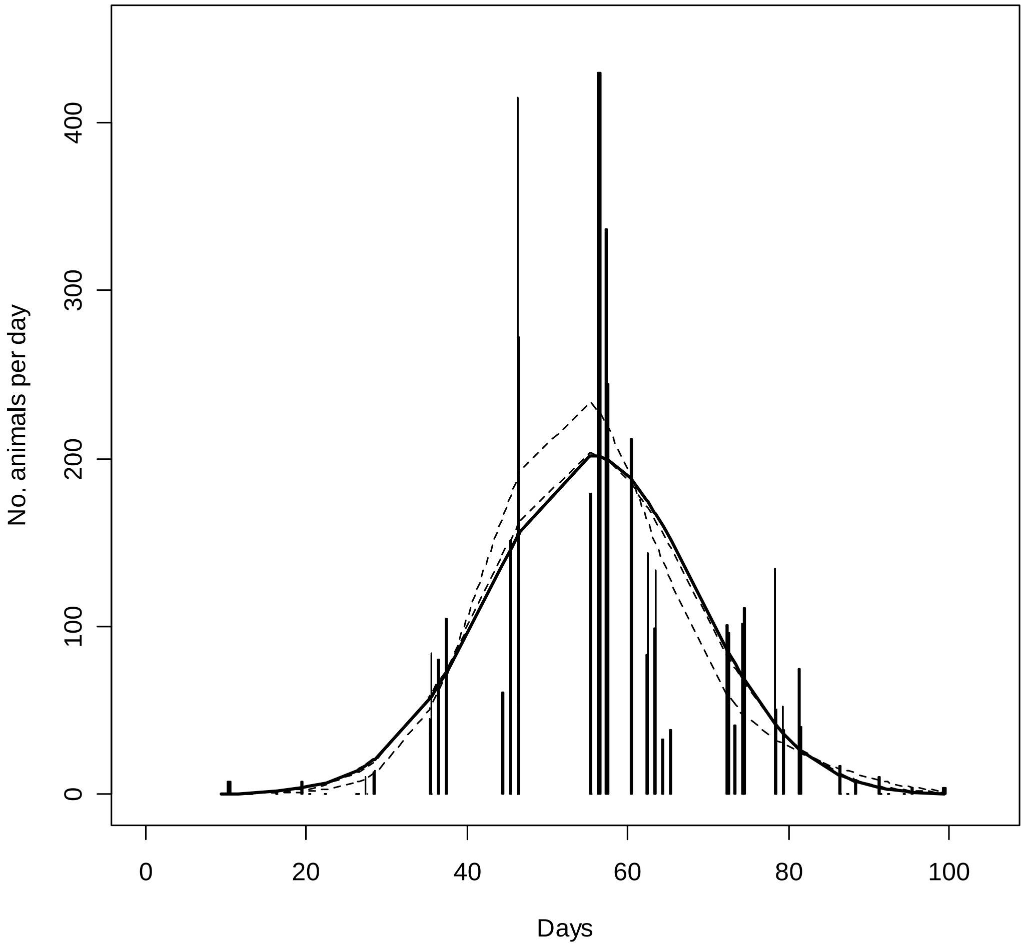

Figure 14. Fitted distribution (using Hermite polynomials) of estimated number of whales per day passing the survey site for the 2005-06 season (solid line).

Figura 14. Distribución ajustada (utilizando polinomios de Hermite) del número estimado de ballenas que pasaron por el sitio de observación en la temporada 2005-06 (línea continua).

III.3. Abundance

Total abundance estimated in this study resulted in 24,862 individuals for 2003/04, 29,786 whales in 2004/05, and 19,436 whales in 2005/06. Taking in mind that correction for missed pods within effort periods was taken from a different study, an approximate estimate was calculated if our corrections were off by 10%, 15%, and 20% (Table XII).

Table XII. Estimated population size (N) for every surveyed year and an approximated estimate if this study was off by 10%, 15% and 20% from the correction factor for missed pods within effort periods.

Tabla XII. Tamaño estimado de la población (N) para cada año de conteos y estimación aproximada si este estudio estuviera sesgado por un 10%, 15% y 20% del factor de corrección por ballenas no observadas durante periodos de esfuerzo.

Season	Population size (N)	Estimate off by 10%	Estimate off by 15%	Estimate off by 20%
2003-04	24,862	22,376	21,133	19,890
2004-05	29,786	26,807	25,318	23,829
2005-06	19,436	17,493	16,521	15,549

There are no true confidence intervals given for these estimates as the true variations in missed pods within effort periods and pod-size correction bias are unknown for the data in this study. These multiplicative corrections were taken from Rugh *et al.* (2005) (see Methods); therefore, a true variation should yet be determined.

However, based on coefficients of variation (CVs) reported in previous studies (Buckland *et al.*, 1993; Hobbs *et al.*, 2004, Rugh *et al.*, 2005, etc.), and taking a conservative approach, approximated CVs were calculated at 20, 35 and 50% from population size N along with the respective confidence intervals (see table XIII).

Table XIII. Population size (N) for each year with confidence intervals of approximated Coefficient of Variations (CV).

Tabla XIII. Tamaño de la población (N) para cada año con intervalos de confianza a partir de Coeficientes de Variación (CV) aproximados.

Season	Population size N	CV = 0.20		CV = 0.35		CV = 0.50	
		lower	upper	lower	upper	lower	upper
2003-04	24,862	19,890	29,835	16,161	33,564	12,431	37,294
2004-05	29,786	23,829	35,743	19,361	40,211	14,893	44,679
2005-06	19,436	15,549	23,324	12,634	26,239	9,718	29,154

IV. DISCUSSION

IV.1. Migration timing

The timing of the migration for the 2003/04 and 2005/06 survey seasons showed a consistency. On the other hand, the second survey season (2004-2005) resulted in earlier migration timing, yet 90% of the sightings, for all three seasons, passed Ensenada at about the same timing. Delays or early arrivals are not said to be rare, rather they are a reflection of the population's behavior to changes in their environment. Rugh *et al*. (2001) analyzed data from different sources and estimated an up to 7-day delay in the gray whale's southbound migration as well as a delay in the onset of their northbound migration (since 1967). They discuss climate variability and feeding causes, and comment on a "climate regime shift" occurring in 1970 that may have been linked to the delay. The latter may explain the low number of individuals estimated by Reilly *et al.* (1983) in the 1971-72 season. This last statement is not contradicting the conclusion made by Reilly *et al.* in their 1983 paper, in which they attribute the low estimate to poor visibility conditions. Also, reported dates cannot de said to be punctual throughout the migration route. Though it was reported that migration timing was not unusual at Granite Canyon in 1999, LeBoeuf *et al*. (2000) find that gray whales were distributed further south in Baja California. According to this study, whales should have been expected to arrive at a later date in the northbound migration, yet, no unusual behavior in migration timing was reported for that year.

Data for this study indicate an earlier arrival of the southbound migration in Ensenada for 2004/05. Bad weather and mechanical problems may explain the gaps in the obtained data plots about the median dates in the 2004/05 southbound season as well as the entire migration extension. There was a strong rainy season in January 2005, and the station provided little protection from the elements. Thus, effort was usually canceled for consecutive days under bad weather conditions; rainy days in this case. Also, technical transportation problems limited access to the station for several days and consequently no effort was undertaken. Nevertheless, more effort hours were dedicated during this season, in comparison to the previous, and the idea that other external (environmental) factors may have caused its early arrival cannot be rejected. This can be seen in the migratory relative abundance index for 2004/05, where the overlap of migration periods is seen during the mean dates of the southbound migration. Northbound sightings were reported early, just as the southbound migration had an early arrival. Early or late ice arrival may affect the timing of grays arriving at certain areas of the migration route. They may be delayed if the ice cap formation is slow in a given year, having that they may remain more time at the feeding grounds foraging. On the other hand, one of the factors, aside from daylight (Rugh *et al*., 2001), that may trigger an early migration could be a quick ice formation. The covering of the feeding grounds by quick ice formation may leave whales no alternative but to start migrating south in the lack of easy food access hence the early arrivals at some sites. Also, some whales do not always make it all the way back to the feeding grounds; rather they may only make it as far north as southern Alaska (Rugh *et al*., 2001). These whales may head the southbound migration and hence it may seem that the southbound migration timing is having an early arrival at the observation site. Apart from the above, distance could also take part in peak date determination, since 56% of whales are passing unseen offshore.

When the southbound distribution of sightings was adjusted with Hermite polynomials of order 3, the plots did not differ from the adjusted normal bell-shaped curve (Figs. 12-14). Especially for the 2003/04 plot, the difference is barely noticed. There were possibly no corrections for missed whales during off-effort periods before the first or after the last effort day since surveys started early and ended until no more southbound whales were seen. This is true for the southbound migration only, since surveys were still followed for acquisition of northbound migration data. Rugh *et al*. (2005) found the southbound migration to be normal in 1997/98 (mean date = 18 January) and 2001/02 (15 January). The previous year (2000/01) showed a delay in median dates (median = 25 January) and they mentioned that it was the most delayed in the past 25 years. In fact, whales were still reported three weeks after the normal ending date. If whales travel at a speed of 147km/day, then they should be arriving at Ensenada in approximately 4 days from Granite Canyon. When compared to the latest surveys, median dates at Granite Canyon coincided with the median dates obtained during survey years at Costa Azul. However, this is only true for the first and last season, for 2004/05 appeared to be about a week earlier (17-18 January).

IV.2. Abundance estimation

VI.2a. Missed whales within effort hours

The calculated corrections for missed whales within effort hours in Granite Canyon have been meticulously studied for years. By using their correction factors, this study contemplates a correction for bias in pod size determination by observers and for missed whales within effort hours as a presumption of what the estimation would be like had those studies been experimented at Costa Azul. Detection probability is assumed to be the same as that in Granite Canyon. At least two factors are true, the recorded sightings are nearly all obtained within the inshore interval, and weather conditions do not vary drastically. Unfortunately, the census stations were both at different heights, Costa Azul being the highest at 59m above sea level. This height is rather advantageous for allowing a greater view for it is far higher by more than twice the height than that in Granite Canyon. In 1998, harsh weather washed out the road to Granite Canyon and a different site was used. Rugh et al. (2005) made a correction for using a different site (Point Lobos). In 2002, simultaneous observations took place in both stations and data were compared based on sightings according to the expected arrival time form one site to the other. A correction for site difference between Costa Azul and Granite Canyon was not possible because no simultaneous observation were undertaken. Despite the facts that in 2007 observations were underway at Granite Canyon and also at Costa Azul, the existing data from both sites cannot be comparable. Height difference, weather variability, and offshore distance hinder analysis to find a precise correction factor. Hence, the corrections used in Rugh *et al.* (2005) are not fully representative of this area and a true correction factor cannot be derived for these data. This is why detection probability can only be assumed to be the same when using the Granite Canyon corrections for missed whales during effort periods and bias correction in pod size. If detection probability is higher at Costa Azul then abundance is being underestimated. Assuming that this study is overestimating the counted whales and our correction (had this study calculated these corrections) would be off by 10%, the final estimate would then be 22,376 for 2003/04, 26,807 for 2004/05 and 17,493 for 2005/06. Estimates would be even lower if this study was off by 20% totaling 19,890, 23,829, and 15,549 for the respective years from 2003-2006 (Table XII). If, in fact, detection probability of a pod is about the same at Costa Azul, then under- or overestimation of the population may be explained with the 56% percent passing offshore.

VI.2b Pods missed due to distance from shore

The migration corridor can vary between years and at the same time distance offshore can vary between sites. At Granite Canyon, studies have recorded that observers there are seeing most of the passing whales, and in fact most of the population passes within the inshore distance interval (5.6km) (Shelden and Laake, 2002). On the contrary, there are sites in which whales expand their migration corridor such as Washington and Oregon (Green *et al*., 1995), where whales were observed 40km from the coast. Observers at Costa Azul are missing a great percentage of whales due to distance, needing a correction factor for missed whales (f_d =1.56). Surprisingly, most grays are passing further from shore than what was initially expected.

Ensenada forms a bay, and perhaps, as an energy-saving mechanism, whales may be taking a straight migration route rather than wasting energy by shoring the bay. In their study, Green *et al*. (1995) suggest that a portion of the gray whale population takes a more direct offshore route in Washington, U.S.A. Green *et al*. (1995) also hypothesize the possibility of whales migrating according to depth, *i.e.* they tend to follow shallow 100-150 m deep waters rather than crossing the deep Juan de Fuca submarine canyon (250-650 m). That is, it may seem that gray whales are crossing the Juan de Fuca submarine canyon, in the southern Gulf of Alaska, "at its narrowest point" by following an offshore route towards Washington and maintain that offshore route, since the shallow waters here "extend 75km from shore" (Green *et al*., 1995).

Cartography in northern Mexico shows shallow waters extending ≈18km from the Rosarito (a town ≈50km north of Costa Azul) coast (Legg, 1985). A steep slope drops off 5km from the Ensenada coast to a depth of 250m (Fig. 15). Shallow waters (≈ 100 m) are again seen <5km from Punta Banda and further south the underwater Soledad Ridge (≈40km south from the observation point) allows a ≈ 100 m deep shallow region ≈18km from the continental coast. These shallow depths follow south to the wide Santo Tomás shelf (located ≈50km from Costa Azul and ≈10km from Punta Banda). If whales are routing by topography, then they may be following a direct path from Rosarito town to the shallow waters in any of the Punta Banda coast, Soledad ridge or Santo Tomás shelf points (Fig. 15). Further, the Todos Santos islands found west of Todos Santos bay are almost aligned with the Punta Banda peninsula. This may form a small barrier

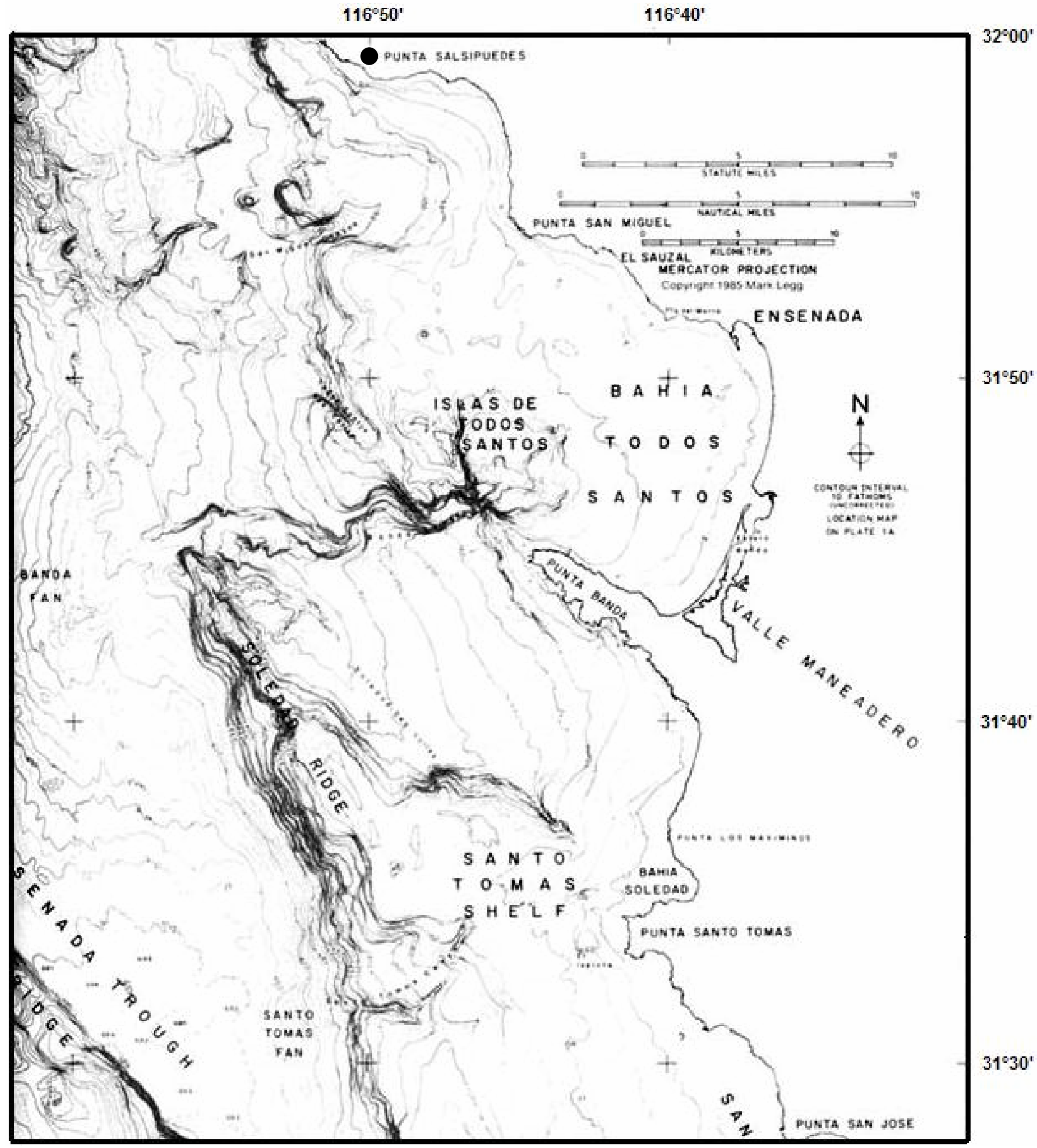

Figure 15.- Bathymetry map south of the observation site showing Santo Tomás shelf and Soledad Ridge. This study's observation point is located near punta Salsipuedes (Legg, 1985).

Figura 15.- Mapa batimétrico del sur del sitio de observación mostrando la plataforma de Santo Tomás y la cresta de la Soledad. El punto de observación de este estudio se localiza cerca de punta Salsipuedes (Legg, 1985).

for whales to migrate closer to the shore as it may seem as a coastal route for grays and therefore a direct southward route may be taken. If so, this may, perhaps, be a mean of saving energy cost by evading entrance to the Ensenada bay. In fact, the mother and calf pair that was observed at about 40km from the coast heading south can possibly evident this thought. A more profound study is recommended to test this hypothesis.

Onshore and boat surveys were both used to find the percent of whales missed due to a limited distance view. If all gray whale sightings with a position from the theodolite had been analyzed then perhaps, a greater percentage could have been recorded further off the coast. According to boat survey results, whales were still reported from 30 to 35km, though they were not included in the analysis because they did not fall within the strip width. Boat survey sample size would have been greater if all sightings had fallen within the strip width, nonetheless and even if more than half the recorded sightings were not included, sample size was sufficient. When exploring all sightings, the distribution was not much different from the valid sample size results.

Other studies (Shelden and Laake 2002) have found that the migration corridor may vary between years yet this cannot be confirmed at Costa Azul only from shore observations, in view of the wide migratory corridor at this site as boat survey results showed. The correction factor for distance from shore elevated the total number of whales estimated for this population. Abundance estimates may be overestimated if distance is underestimated and the reverse is also true (Kinzey and Gerrodette, 2003). Variations in this correction may be present because no paired boat surveys were done to account for observer discrepancies here. Kinzey and Gerrodette (2003) analyzed the precision of measuring distance at sea using reticles in binoculars. A possible bias may occur in determining the reticle line, especially under swell conditions. The above mentioned authors found that underestimation occurs from using reticle measurements and although refraction may affect, swell height, Beaufort Sea state and wind speed caused greater affects on reticle measurements. Paired boat surveys were not possible due to a budget limitation, nevertheless having that an important number of whales is being missed this correction factor should be considered valid, until new research is done in this zone. During the boat surveys, at Ensenada, bad weather prevailed and it is most probable that the resulting reticle measurements are biased due to swell height and Beaufort Sea state. If distance obtained from reticle measurements is underestimated, then this in part explains the high abundance estimates for all three years.

Percent sighting distribution within inshore distances in Ensenada turned out the same as that in Shelden and Laake (2002), which is the distance where most observations are reported. Observers are seeing most of the recorded sightings within inshore (5.5km). As a result, from theodolite tracks, the observer is seeing only up to 5.5km, this defines the eye sight limitation from shore to sea. This gives away the distance of the field viewing range at the observation site. Observer eye sight limitation can be taken as such distance, since comparisons with boat survey results indicate that there are significant numbers of whales still passing beyond this distance. Although the theodolite's telescope (30X) does aid to identify at a greater distance than regular 7X50 binoculars, observers still have a limited view range. The migration corridor in Ensenada can be said to be quite ample, from 1km off the coast extending to perhaps more than 30km out sea, at least for 2007. Gray whales show to be coastal migrants only at certain sites of their migration route or so is seen in compared results (Figure 9) from aerial surveys at Granite Canyon and reports in Green *et al*. (1995).

VI.2c. Missed whales during off-effort periods

The use of Hermite polynomials became rather advantageous allowing interpolation within a density curve, accounting for periods on which no counts took place. Unlike Hermite polynomials, other methods, such as Kernal estimation, will not allow any computations unless there are no gaps in our data (there are no missing effort periods). Polynomial adjustment is used if the parametric fit is not adequate. Estimation remains reliable even if, as in this case, effort was not done all 7 days a week or if visibility is a "serious handicap" (Buckland, 1992). Of all correction factors estimated in this study, this is the most confident. Visibility periods were meticulously categorized for the output data used in the *gwnormf77* FORTRAN R statistical program. Though a confident estimated correction factor, the elevated number of individuals could have come from these estimations. Nonetheless, the source error could have also derived from the database in the first place. There are high numbers of individuals in such small time intervals, when compared to the other two years. These high numbers are indicated on the plots for 2004/05 data (Fig. 13). Since Hermite fitting adjusts the curve and hence interpolation is possible then, perhaps, the high peaks are sourcing the error. Abundance estimates were quite high in 2004/05 and very low in 2005/06. Biases may have altered the numbers, though a pattern of ascent and descent is evident.

VI.2d. Abundance

Gray whale abundance in Ensenada during three migration seasons (2003-2006), had an apparent increase in 2004-05 (29,786), with respect to the preceding year (24,862, and a drop of a bit over 10,000 individuals in the subsequent year (19,436). The high numbers may be attributed to bias in analyses due to lack of experiments to correctly or precisely account for factors that determine final estimates. Nevertheless, this indicates that there might have been an increase of animals from the last estimates reported in 2002. Springer (2000), discuss that there has been a 30% decrease in the Chuckchi-Beaufort ecosystem and other authors claim the Eastern Pacific stock of gray might be reaching an equilibrium level (Hobbs et al., 2004; Wade, 2002). Considering this, the drop in number of individuals in the 2005/06 season may have been due to the natural behavior of a population after reaching *k*. If food availability has dropped in the past years and the number of whales has increased considerably, then this is the major limiting factor controlling the population. The ecosystem can bear only a certain amount of whales. Le Boeuf *et al.* (2002) state that the high mortality rates reported in 1999 may have been due to a "decrease in their principle prey." In fact, Rugh *et al*. (2001) report that some whales have been sought feeding further north of the Beaufort Sea, near Canada, meaning that whales are traveling further north in the seek of food.

If the behavior of gray whale population size in the past years (1996-2006) is viewed in a graphic manner (*e.g.* Fig. 16), this fluctuation would be pictured as the number of individuals in a population moving above and below the carrying capacity level. The population would be found in a stable balance point, according the *Allee* effect

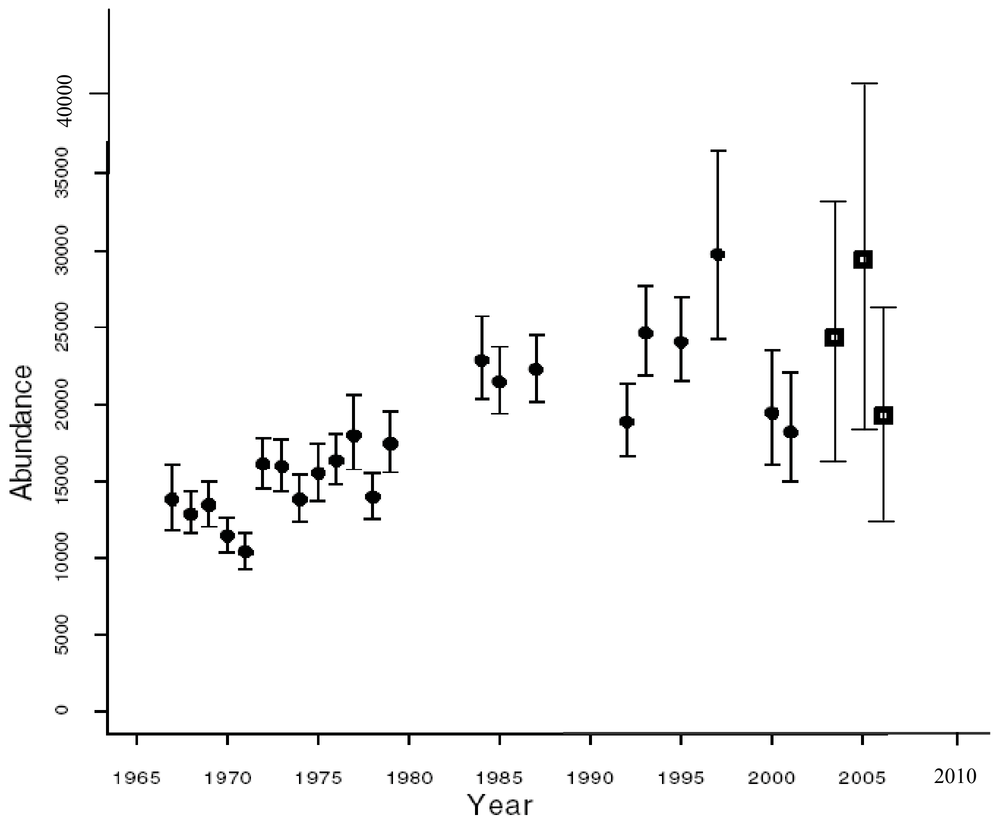

Figure 16. Gray whale population size time series from studies at Granite Canyon taken from Alaska Marine Mammal Stock Assessment (2005), including the estimates in this study (squares). Confidence intervals were not calculated; however, a conservative 35% coefficient of variation is shown.

Figura 16. Serie de tiempo del tamaño de la población de la ballena gris tomado de Alaska Marine Mammal Stock Assessment (2005), incluyendo las estimaciones de este estudio (cuadros). No se calcularon intervalos de confianza; sin embargo, se muestra un coeficiente de variación conservador del 35%.

theory. According to Hobbs *et al.* (2004), 22,263 estimated whales passed Granite Canyon in the 1995/96 season, and Rugh *et al*. (2005) report 29,758 whales for the 1997/98, with an abrupt drop in 2000/01 (19,448) and a slighter drop in the following season (18,178). If the pattern is followed with the results from this study, then an increase in number of individuals is observed in 2003/04 reaching a peak in the subsequent year (29,786) and a decrease is followed in 2005/06 (Fig. 16).

Coefficients of variation (CVs) were not calculated in this study because average corrections for missed pods during effort hours (detection probability) and pod size observer bias were taken from studies at Granite Canyon (Rugh *et al.*, 2005). A true CV calculation should be made taking this factor into account. Approximated CV values gave an idea of this study's CV range. Coefficients of variation greater than 35% gave off very low values in the lower confidence intervals (*e.g.* 12,634 whales in 2005-06). Also, past abundance estimates (Reilly *et al*., 1983; Buckland *et al*., 1993, Hobbs *et al*., 2004 and Rugh *et al*., 2005), have not reported confidence intervals below 13,000 or beyond 40,000 individuals (CVs ranged from 0.20 to 0.35). Given the confidence intervals in table XIII and from past reports at Granite Canyon, our estimates might range in a 20 to 35% CV. The final estimated population size (N) of every season is higher than the latest reports from Granite Canyon (2000-01: 19,448 whales; 2001-02: 18,178 whales; Rugh *et al*., 2005) though the N reported in the last season (19,436) is not far off from the last estimated year there (2001/02). The estimation of that year was 18,178 whales with 95% confidence intervals ranging from 15,010 to 22,015 (Rugh *et al*., 2005).

V. CONCLUSIONS

Migration timing

- Timing for the southbound migration varied a few days in the three years of this study, though for 2004/05 this variation was more noticeable with an early start of nearly a week (December 25 vs. January 2 and 6).
- The early arrivals in migration timing could be explained by quick ice formation at the feeding grounds, forcing whales to leave before the usual timing. Also, whales residing south of Alaska may head the southbound migration, and so early dates.
- Northbound gray whales without calves, migrating back to the feeding grounds, past Ensenada around similar dates (18-19 April).
- While in the first and last surveyed years mothers and calves had ended their migration past the station in late April, in 2004/05 migration ended in 05 May. This showed an ample migration distribution for this year.

Abundance estimation

- Gray whale abundance consisted in separate analyses; correction factors (day/night travel rate, pod size and missed pods within effort periods, missed pods because of distance, and missed pods during off-effort periods) were used in the final estimated population size. The corrections for whales missed within effort periods were taken from results of past experiments at Granite Canyon because no such research was done during the three mentioned years. For missed pods because of distance offshore, an experiment was done in 2007 about the dates of the peak of the migration. This experiment included boat surveys near the onshore survey station and gray whale theodolite tracks. Missed pods during off-effort periods were accounted for by fitting the sighting's distribution with Hermite polynomials.

- Though most correction factors were taken into account, other correction factors, such as observer fatigue, should still be taken into account in further research.
- Some possible biases in the final estimation may have derived from using the detection probability obtained at Granite Canyon and observer fatigue. Nevertheless, a great percentage of missed whales was corrected for with the results from boat surveys. Observers are missing 56% of the population because they are passing too far offshore. It may be assumed that topography is playing a role in the offshore distribution as in other sites (*e.g.* Washington, U.S.A.).
- Hermite polynomial fitting also provided an increase in the final estimation, since surveys did not take place everyday of the week and off-effort periods were frequent. Although bias may have come mainly from missed whales during effort periods, the analyses indicate a small pattern.
- Gray whale abundance in Ensenada was estimated to be 24,862, 29,786, and 19,436 during the years 2003-2004, 2004-2005, and 2005-2006.
- Coefficients of variation were approximated for the final population size, as a lack of experiment and data did not allow a true CV estimation. However it should be noted that our CV may range from 20 to 35%. In all, the population fluctuated in these three years and it seemed to have decreased in the last surveyed year. Comparisons should still be done with the estimation obtained at Granite Canyon for 2006/07 to see how biased these estimations are.

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ANNEX I

Equations used in the calculation of whales passing the survey within effort hours [3]

Total number of pods of size *e* passing during the effort periods, $\hat{M}_e$:

$$\hat{M}_e = \sum_{i=1}^{m_e} \frac{1}{p_{ei}} \qquad \textbf{Eq. (5)}$$

and its variance is obtained through:

$$Var\left(\hat{M}_e\right) = \sum_{i=1}^{m_e} \left[\frac{1-p_{ei}}{p_{ei}^2} \right] + D_\beta\left(\hat{M}_e\right)^T \hat{\Sigma}_\beta D_\beta\left(\hat{M}_e\right) \qquad \textbf{Eq. (6)}$$

p_{ei} = detection probability of the *i*th pod of size *e*.

m_e = number of pods of size *e* sighted from the primary site.

β = vector of parameters

$D_\beta\left(\hat{M}_e\right)$ = vector of partial derivatives of $\hat{M}_e$ with respect to β.

$\hat{\Sigma}_\beta$ = estimated variance-covariance matrix of the vector of parameter estimates ($\hat{\beta}$).

(c.f. Borchers et al, 1996).

[3] All equations and description of variables are after Hobbs *et al.*, 2004.

Total number of pods passing while systematic efforts were underway, $\hat{M}_e$:

$$\hat{M} = \sum_{e=1}^{E} \hat{M}_e \qquad \textbf{Eq. (7)}$$

$$^4 Var\left(\hat{M}\right) = \sum_{e=1}^{E} Var\left(\hat{M}_e\right) + 2\sum_{j=1}^{E-1} \sum_{k=j+1}^{E} D_\beta\left(\hat{M}_j\right)^T \hat{\Sigma}_\beta D_\beta\left(\hat{M}_K\right) \qquad \textbf{Eq. (8)}$$

Total number of whales passing the observations site during effort periods represented by pods of size *e*, $\hat{W}_e$:

$$\hat{W}_e = \hat{M}_e\left(e + b_e\right) \qquad \textbf{Eq. (9)}$$

$$Var\left(\hat{W}_e\right) = Var\left(\hat{M}_e\right)\left(e + b_e\right)^2 + \hat{M}_e^2 \hat{\sigma}_{b_e}^2 + \hat{M}_e s_e^2 \qquad \textbf{Eq. (10)}$$

b_e = estimated additive bias correction for *e* from Laake *et al*. (1994).

$\hat{\sigma}_{b_e}^2$ = bootstrap estimate of the variance of b_e.

s_e^2 =bootstrap estimate of the standard deviation of the bias estimation samples for pods estimated as size *e*.

Total number of whales, $\hat{W}$, passing the site during usable effort periods:

$$\hat{W} = \sum_{e=1}^{E} \hat{W}_e \qquad \textbf{Eq. (11)}$$

$$CV\left(\hat{W}\right) = \frac{1}{\hat{W}} \sqrt{\sum_{e=1}^{E} Var\left(\hat{W}_e\right) + 2\sum_{j=1}^{E-1} \sum_{k=j+1}^{E} \left[\left(j + b_j\right) D_\beta\left(\hat{M}_j\right)^T \hat{\Sigma}_\beta D_\beta\left(\hat{M}_k\right)\left(k + b_k\right) + \hat{M}_j \hat{M}_k \hat{\sigma}_{bjk}\right]} \qquad \textbf{Eq. (12)}$$

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[4] All equations and description of variables are after Hobbs et al., 2004).