

# APPENDIX A: DATA GATHERING REVIEW, RESULTS AND BALANCING

## Outline of provided data and methods

The accumulation of data sources led to several successive iterations of the Eastern and Western Subarctic (ESA and WSA) ECOPATH models. Initial data gathering led to the creation of “unbalanced” models which were adjusted for balance prior to and during the 2001 BASS/MODEL Workshop in Honolulu (Appendix D). During and after the meeting, additional data sources were made available. Changes made to the model solely for the purpose of thermodynamic balance are described under “Balancing the models”, below.

Further changes were made to the models due to the provision of new data by workshop participants, the discussion of studies containing differing range of values, or if work with ECOSIM projections revealed “pathological” results. Even at late stages of the simulation process during and after the 2002 BASS/MODEL Workshop in La Paz (Appendix F), new data sources continued to be provided. Some of these data sources became available after a significant number of the ECOSIM simulations and scenarios had been projected and discussed, and some of these data were provided in response to the results themselves.

The approach taken for the purposes of this publication, was to “freeze” the models in the state that they existed at the beginning of the La Paz Workshop, as the bulk of the results in the main section of this report stemmed from that meeting. To aid in duplication and expansion of results, the complete list of model parameters Tables in the Appendix B represent these La Paz models. However, in this Appendix, sources of data that might supercede the parameters in the La Paz models are indicated. Future researchers are encouraged to explore differences in modeled outcomes arising from using these differing values.

Tables B1-B3 contain the primary literature values and references used for the primary parameters of

biomass (B), production/biomass (P/B) and consumption/biomass (Q/B) for all functional groups in the WSA and ESA models. In cases where a value could be taken directly from the literature with no changes excepting a unit, time, or area conversion, the original references are listed in these tables and not noted in the text. The conversion of yearly instantaneous mortality estimates (Z) to P/B values are considered a unit conversion.

Cases where additional calculations, assumptions or conversions were required to transform literature values into model parameters are indicated with a (\*) on Tables B1-B3. Descriptions of the methods used for these parameters can be found under “Model data review”, below, under the section for the appropriate species group. Text descriptions of parameters by species groups are also included if the majority of the data used was unpublished. Diet data and references are described generally in the text and complete diets are shown in Tables B7-B8.

Data were graded for quality and uncertainty by workshop discussions of the literature search results. The quality ranking of each parameter depended on the data source and included consideration of collection methodology, coverage, and appropriate time period. The criteria for ranking were based on a “pedigree” methodology described for ECOPATH by Christensen and Pauly (1992). Table A1 shows the criteria used to assign a rank to each parameter, and the uniform range about each point parameter estimate associated with each quality rank (as a proportion of the point estimate). The overall “uncertainty” of the model is illustrated in Table B4 where the assessed uncertainty ranges of all parameters are shown.

Tables B5-B8 contain parameters as they were entered into the WSA and ESA models, including diet information and detrital flow assumptions, formatted as ECOPATH input tables.

**Table A1** Criteria for ranking data quality for each parameter from good (rank 1) to poor (rank 8). Number in parenthesis is assumed range for each rank, as a proportion of the input parameter.

Rank	Biomass	P/B	Q/B	Diet
1.	Assessment with thorough data (0.1)	Same group, same system (0.1)	Same group, same system (0.1)	Quantitative, detailed, same time (0.1)
2.	Sampling with high precision (0.1)	Same group, similar system (0.2)	Same group, similar system (0.2)	Quantitative but limited (0.3)
3.	Sampling with low precision (0.5)	Similar group, same system (0.3)	Similar group, same system (0.3)	Quantitative, different time (0.5)
4.	Higly variable population (0.5)	Similar group, similar system (0.4)	Similar group, similar system (0.4)	Qualitative for specific prey (0.6)
5.	Approximate or indirect method (0.5)	Empirical relationship (0.5)	Empirical relationship (0.8)	Qualitative for broad prey (0.7)
6.	Guesstimate (0.8)	From other ECOPATH model (0.6)	From other ECOPATH model (0.6)	General knowledge of same group (0.8)
7.	From other ECOPATH model (0.8)	Guesstimate (0.7)	Guesstimate (0.7)	From other ECOPATH model (0.8)
8.	Estimated by ECOPATH (0.8)	Estimated by ECOPATH (0.8)	Estimated by ECOPATH (0.8)	General knowledge of related group (0.8)

The data in these tables should be sufficient to reproduce the models described in the text. Estimated ecotrophic efficiency (EE) and growth efficiency (GE) values are included in these tables for confirmation purposes. These models are also available from the primary author (Kerim Aydin, Kerim.Aydin@noaa.gov) as ECOPATH input (.eii) files.

### Balancing the models

#### *Migration*

While the oceanography of the subarctic Pacific provides some biological basis for bounding the Eastern and Western Subarctic Gyres, both ecosystems are characterized by having top trophic level species that are extraordinarily migratory. Marine mammals and birds are only present part of the year in the ecosystems (Springer *et al.*

1999), while Pacific salmon possess a complex life cycle for which the gyres are an important but not isolated habitat.

ECOPATH is generally designed to model a closed system; however, several methods are provided for the inclusion of migration data. Migration rates may be added explicitly, feeding may be assigned to diet “import”, or biomass, production and consumption rates may be scaled for the portion of the year that each species spends in the gyres.

All of these methods give similar results for the ECOPATH “balance” model; however, all of these methods are known to lead to unrealistic projections in dynamic ECOSIM (Aydin unpublished). The method selected to minimize errors was the last method mentioned above, that of scaling biomass for residence time (for marine

mammals and birds) or biomass, production, and consumption (for Pacific salmon), as described below.

### ***Diet scaling***

Diet data for higher trophic levels, especially birds and mammals, tended to be highly aggregated and contained insufficient resolution to cover all potential prey items in the models. For example, it was common for prey to be apportioned in literature between “fish” and “squids” without further taxonomic resolution. In these cases, the diet of each predator that the literature apportioned to a major taxon, for example to “fish”, was split among all fish groups in the model with a “neutral” preference, *i.e.*, split in proportion to the biomass of each fish type in the model.

However, this “neutral preference” approach could not be used directly due to data gaps in the forage species biomass, specifically for “other” forage fish and micronektonic squid. For these species, biomass estimates were unavailable and thus biomass was to be estimated from consumption requirements. However the preference method noted above used biomass estimates to estimate consumption, thus introducing a circular estimation problem.

This circular data gap was resolved iteratively as follows: micronektonic squid and fish were considered to be a small proportion (~10%) of squid and fish in diets of top predators for which the preference model was used. In most cases this led to “unbalanced” ( $EE > 1$ ) predation rates on specific (non-forage) fish and squid groups. When this occurred, the diets of predators were gradually shifted from specific fish and squid to the more general categories, and the biomass of these general categories increased in estimation accordingly.

Thus, the estimated consumption of specific fish and squid groups in the model is close to the maximum possible under constraints balance, *i.e.*, under constraints of production being equal to or greater than consumption for each individual group. On the other hand, the biomass of the general forage species are estimated to be the minimum required for providing the remainder of

dietary requirements to upper trophic levels. The low grading of the diet data reflects the uncertainty inherent in this method.

### ***Additional adjustments***

The stepwise shifting of top predator diets from specific fish to general “forage” fish, in conjunction with allowing micronektonic squid and forage fish to be estimated based on demand, generally ensured that most of the species were thermodynamically “in balance” in the models (with  $EEs < 1.0$ ) without further drastic adjustments. As mentioned in “Diet scaling” above, overly high EEs of fish species such as salmon and large squid led to shifting diets of top predators towards forage fish. This repeated shifting was necessary mainly for sharks and Pacific whitesided dolphin.

In addition to the general balancing, six other changes were made in the biomass levels of groups due to the specific needs of balancing the model. Five of these changes were due to perceived mismatches in coverage; either because existent data was dominated by mismatching border region data rather than central gyre data, or due to lack of seasonal data. Balance was achieved in these cases by scaling biomass estimates as appropriate for the gyre as a whole over the whole year. The sixth change was due to the difficulty of capturing cannibalism in a highly productive species. The changes were as follows:

1. Predation by toothed whales (Orca) included predation on mammals and birds, which caused EEs of some mammals and birds to be too high (between 2 and 3). Feeding on birds and mammals is a characteristic of “transient” types of Orcas which are thought to be low in numbers and shore-based. Toothed whale biomass was reduced by 80% from the initial (shore-based) estimate.
2. The EE of Pacific sardines in the WSA model was initially too high (EE greater than 5). This was primarily due to predation by Pacific pomfret. Both pomfret and sardines are predominantly southern species with biomass levels that are much higher in the Kuroshio Current. In this case, the diet information

came from southern sampling where the pomfret/sardine connection would be strong, but the biomass of sardines in the model came from Kamchatka Current studies and reflected their low presence in the northern gyre regions. The biomass of Pacific sardines was increased from 0.017 to 0.05 t/km<sup>2</sup> to account for the influence of the “southern” regions of the model. To aid in selecting appropriate adjustments for sardines, several ECOSIM scenarios were explored which allowed for “invasions” of sardines in response to possible regime-scale shifts in abundance.

3. Chaetognaths in the WSA were the source of a great deal of predation and led to an imbalance in several zooplankton groups, including amphipods, pteropods and euphausiids. The initial chaetognath biomass estimate came from studies in the Kamchatka Current and was calculated to be 53 t/km<sup>2</sup>, higher than copepods or microzooplankton. This biomass was cut approximately in half to 25 t/km<sup>2</sup> which was the maximum that allowed balance. This puts chaetognath biomass in a similar range as other large predatory zooplankton in the central gyre.
4. WSA microzooplankton biomass as estimated from Kamchatka Current data was half copepod biomass and possessed an EE > 1. Microzooplankton biomass was set equal to copepod biomass as a first approximation.
5. Overall in the WSA, the EEs of amphipods, pteropods, and euphausiids were higher than 1.0 even after chaetognath reduction, while the EE of copepods was extremely low (less than 0.2). This was considered to be partially due to seasonal sampling: very little dietary sampling captured spring periods when copepods might dominate the diets of large zooplankton such as shrimp and chaetognaths. For these highest trophic levels of zooplankton, predation on amphipods, euphausiids and pteropods was decreased, and predation on copepods increased. Finally, 10% of copepod consumption on microzooplankton was shifted to phytoplankton. As WSA phytoplankton was “top-down”

balanced, the resulting phytoplankton biomass levels were set as sufficient to fuel the system.

6. Flying squid in the ESA initially had an EE greater than 4, but almost all of this was due to cannibalism. Cannibalism, when it occurs, would be best modeled by creating two biomass pools and having adult flying squid feed on juveniles, as juveniles would have a higher production rate and therefore be able to balance the demand. Due to lack of data on squid recruitment dynamics, this method was not pursued. Instead, 50% of the “cannibalism” in flying squid diets was shifted to micronektonic squid, which might include juvenile flying squid.

In the initial versions of the model, two species, Spiny dogfish and daggertooth, were included as separate groups but were dropped from the models during the balancing process. Spiny dogfish do occur in the gyres and have been caught in central gyre research gillnets with catch rates similar to those for some large squid species (Pearcy *et al.* 1999). Also, examination of dogfish stomachs near ocean Station P has revealed evidence of recent zooplankton consumption in these regions (Pearcy, unpublished data; Aydin, unpublished). However, it was felt that these animals might be migratory with little residence time or feeding effort expended in the central gyres (McFarlane and King, in press). The combination of low production rates and assumptions of predation by larger animals made the species difficult to balance reasonably, and they were removed. Daggertooth (sp), even at maximum reasonable assumptions of density, were less than 1% of the biomass of any trophic level and less than 0.5% of any species’ predation mortality and were thus dropped from the model due to lack of data and importance of the species as a whole.

Initial versions of the model had substantial nutrient groups as detrital pools to simulate nitrogen cycling in conjunction with NEMURO. However, the ECOSIM formulations are generally unsuited for fast turnover rates required for nutrient pool dynamics (Walters, pers. comm). Therefore, detrital pools were simplified into dissolved organic matter (NH<sub>3</sub>) and particulate

organic matter (POM) which were fed on by bacteria, and represent the only accounting detrital recyclers in the final model. A considerable proportion of lower trophic-level regulation in the gyres may be due to nutrient recycling (Harrison *et al.* 1999). The current ECOPATH models should not be used to explore hypotheses based on specific mechanistic lower-trophic level links, for which a model such as NEMURO would be more appropriate.

## Model data review

### *Physical variations*

Two gyres dominate Subarctic Pacific: the Eastern gyre and the Western gyre. In the Eastern Gyre, the centre of the gyre is at approximately 52°N, 155°W, and the gyre extends westward nearly to the dateline. Much of the research on lower trophic levels for the Eastern gyre was carried out in its southeast corner at Ocean Station P (50°N, 145°W). The Western Gyre is northeast of Japan, southeast of Kamchatka Peninsula, at 155–165° E, 45–50° N. The gyres are bounded to the south by the slow, eastward flowing Subarctic Current at approximately 45–50°N, formed in the west by the convergence of the Oyashio and Kuroshio Currents. The Subarctic Current splits at approximately 48°N, 130°W, and becomes the northward flowing Alaska Current, and the southward flowing California Current.

The Aleutian Low atmospheric system dominates the region in winter. Winds peak in winter at 12 m/s, and decrease to 7 m/s in July. High precipitation, low evaporation and freshwater land runoff result in an upper layer with a strong shallow halocline and winter mixed layer depths in the center of the Eastern Gyre to 75–100 m. Surface cooling and winter wind mixing cause mean surface temperature to be <6°C in February. Also in February, salinity peaks at 32.7 psu, the mixed layer deepens to ~120 m, and nitrate and silicate levels increase.

Severe winter storms and the dominant Aleutian Low result in upwelling in the gyres, which maintains high nutrient concentrations in surface waters. Harrison *et al.* (1999) noted that the

Subarctic North Pacific is one of 3 major high-nitrate-low-chlorophyll regions.

Sea surface temperatures in the Western Gyre (3–9.5°C) are colder than in the Eastern Gyre (6–12°C). Nitrate, Nitrite, Silicate and Phosphate concentrations are higher in the Western than in the Eastern Gyre. The Western Gyre has higher nutrient concentrations, higher chlorophyll concentrations than the Eastern Gyre, but similar summer primary productivity. In summer the mixed layer depth and photic zone are shallower in the Western than in the Eastern Gyre. Mean chlorophyll concentrations are twice as high in the Western than the Eastern Gyre, but depth-integrated chlorophyll concentrations are nearly equal, as the photic zone is deeper in the Eastern than it is in the Western Gyre (Harrison *et al.* 1999). An area about 500 km in radius around Station P has been sampled for spatial nutrient and temperature variations. Water temperatures increase to the east and south of Station P. Nutrients increase to the west and north (toward the centre of the Eastern Gyre). Salinity increases to the north, south and west.

Interannual and interdecadal changes in nutrients have been observed in the Eastern Gyre. During the 1989 La Niña, Station P was cold, less saline and had nitrate-rich surface water in the winter. During the transition to El Niño from 1991 to 1994, the surface waters at Station P warmed by 2°C, became 0.3 psu more saline, and 30% lower in nitrate. A seaward extension of the nitrate-depleted surface layer occurred in 1994, due to a reduction in winter nitrate concentrations. This reduction was caused by an intrusion of warmer, lower nitrate water from the south during El Niño. Lower winter nitrate levels are estimated to have reduced new production by 40% and possibly shifted phytoplankton community structure. From the 1970s to the 1990s, winter silicate and nitrate uptake has declined by 3.6  $\mu\text{m}$  and 2.5  $\mu\text{m}$  respectively, which may indicate an iron supply reduction in the last twenty years.

### *Species groups*

Species inhabiting each gyre system were identified using existing reviews on the ecosystem dynamics of both areas (Taniguchi 1999; Mackas

and Tsuda 1999; Brodeur *et al.* 1999; Beamish *et al.* 1999; Springer *et al.* 1999; Hunt *et al.* 2000). The species groups selected were equivalent for the Eastern and Western Gyre systems with five exceptions: Minke whales, common dolphins, Japanese anchovy and Pacific sardine were in the Western Gyre model only, and northern elephant seals were in the Eastern Gyre model only. Highly aggregated groups such as “micronektonic squid”, “other forage fish”, or “copepods” would likely differ in species composition between the gyres but are treated as functionally equivalent between the two models.

Biomass, diet composition and production estimates were compiled using published estimates, and when possible, using data collected from 1990-1993, or as close to this time period as possible. Estimates are annual values and are made from data collected in offshore areas only. While biomass estimates differed between gyres, the P/B and Q/B ratios for each species group were assumed to be equivalent for both gyre models. This latter assumption was made due to data limitations, but within the Subarctic climate regime, P/B and Q/B values for species would be expected to be more similar than different. Diet composition data are expressed as percentage of biomass.

### **Marine mammals**

Cetaceans were divided into nine functional groups, each one containing a single species. Seven of these groups are present in both the Eastern and Western Gyres: sperm whale (*Physeter catodon*); orca (*Orcinus orca*); fin whale (*Balaenoptera physalus*); sei whale (*Balaenoptera borealis*); Dall’s porpoise (*Phocoenoides dalli*); Pacific white sided dolphin (*Lagenorhynchus obliquidens*) and northern right whale dolphin (*Lissodelphis borealis*). The additional two groups, minke whale (*Balaenoptera acutorostrata*) and common dolphin (*Delphinus delphis*) were present in the Western Gyre only.

Two pinniped groups were used in the Eastern Gyre model: northern fur seal (*Callorhinus ursinus*) and northern elephant seal (*Mirounga angustirostris*). Only one pinniped group (northern fur seal) was used in the Western Gyre

model. Although actual routes of migration are not well understood, Springer *et al.* (1999) noted that in general, pinnipeds remain close to shore throughout the year, and are not considered to be part of the fauna of the subarctic gyres. Some other species of whales and pinnipeds have also been reported in the Western Gyre (Springer *et al.* 1999), but have not been included in the models due to low numbers.

Most species of cetaceans are highly migratory, particularly the Mysticetes which reside in higher latitudes in the summer for feeding, and move to lower latitudes in winter for breeding. They are widespread and appear to be equally abundant in both the gyres. Most biomass estimates reported were available for the North Pacific as a whole, or in the case of pinnipeds, based on counts at breeding sites, throughout the Pacific rim. Migration patterns have been suggested as one indication of differences in marine mammalian behaviour between regions of the Pacific. For example, in the western Pacific region, Dall’s porpoise have a larger migration, from the Sea of Okhotsk in summer, to the Japan/East Sea, and northwestern North Pacific regions in winter. On the east side of the North Pacific they have been observed migrating smaller distances, onshore/offshore only (Springer *et al.* 1999).

The migration of species was taken into account by performing a broad North Pacific synthesis to scale North Pacific abundance and body weight estimates by residence time in both gyres, and spread across the gyres (Table A2). P/B values for marine mammals were all taken from estimates of yearly mortality (Z) as cited in Table B1. Q/B values came from daily allometric energy requirements listed in Hunt *et al.* (2000, Appendix 9) and caloric energy densities of typical prey types (Table A3).

Diet estimates for marine mammals were highly aggregated. A review by Hunt *et al.* (2000) indicated no source of data for marine mammals that was specific to the ESA or WSA. For these regions, the only source of data was Pauly *et al.* (1998), who reviewed general marine mammal diets around the world. They divided marine mammal prey into 8 categories: benthic invertebrates, pelagic zooplankton, small squid,

large squid, small epipelagic fish, mesopelagic fish, misc. fish, and birds and mammals. Prey proportions by predator are found in Hunt *et al.* (2000, Table 10.6-10.7). As described above,

diets in the ESA and WSA models were split to species within each broad category in proportion to the biomass of the species (Tables B7-B8).

**Table A2** Synthesis of North Pacific abundance estimates and area residence times for marine mammals, used to provide biomass estimates for ESA and WSA models.

Species	Values used for estimate and literature sources
Sperm whale	Kato <i>et al.</i> (1997) give 2,300 individuals in WSA only; Pauly and Christensen (1996) give 2,000 in North Pacific. Since feeding occurs in the Bering Sea also (Aydin <i>et al.</i> 2002) we assumed population was N. Pacific overall. Used 2,000 individuals * 18,518 kg/individual (Kato <i>et al.</i> 1997) * ½ year / 20 million km <sup>2</sup> (total N. Pacific area); this is most likely a minimal estimate.
Toothed whales	The only available estimates of ESA orca biomass were from Pauly and Christensen (1996) and covered the “transient” type of orca (mammal-consumer) only. These species were left in the model and reduced for balance, although it is not known if this life-history type feeds in the subarctic gyres.
Fin whale	20,000 individuals * 55,590 kg/individual (Evans 1987; Gambell 1985a) * ½ year / 20 million km <sup>2</sup> (total N. Pacific area).
Sei whale	14,000 individuals * 16,811 kg/individual (Gambell 1985b) * ½ year / 20 million km <sup>2</sup> (total N. Pacific area).
Minke whale	In the initial model a minimal estimate of 0.001 t/km <sup>2</sup> was assumed. Buckland <i>et al.</i> (1992) estimate of 5,841 individuals over 2.1 million km <sup>2</sup> (WSA area) for half the year (0.009 t/km <sup>2</sup> ).
Northern fur seal	Springer <i>et al.</i> (1999) estimate 175,000 over 20 million km <sup>2</sup> (total N. Pacific area) south of the Aleutian Islands for half the year. (Compare to 190,000 from Buckland <i>et al.</i> 1993). An average body weight of 28 kg is given by Hunt <i>et al.</i> (2000). Small and DeMaster (1995) give a population of 1 million individuals in the Pribilof Islands while Bigg (1990) notes that 10-15% of these travel into the gyres for half the year or less.
Elephant seal	Stewart <i>et al.</i> 1994 give a eastern North Pacific estimate of 127,000; however only adult males forage in the Eastern Gyre. Scaling gives 8,400 animals at 371 kg body weight over, 3,600,000 km (eastern Pacific), for ½ year.
Dall’s porpoise	1,925,000 (Hunt <i>et al.</i> 2000 Table 9.11); compare to 1,200,000 from Buckland <i>et al.</i> 1993 * 61 kg each/ 20 million km <sup>2</sup> (subarctic and transition zones).
Pacific whitesided dolphin	1 million at 79 kg each/20 million km <sup>2</sup> (Buckland <i>et al.</i> 1993). Estimate may be high due to vessel attraction during surveys (Angliss <i>et al.</i> 2001).
Northern right whale dolphin	740,000 (Hunt <i>et al.</i> 2000, Table 9.7) at 105 kg each over 20 million km <sup>2</sup> (subarctic and transition zones), compare to 68,000 for ESA (Buckland <i>et al.</i> 1993).
Common dolphin	Minimal estimate of 0.001 t/km <sup>2</sup> was used.

**Table A3** Values used to compute yearly consumption/biomass (Q/B) rates for marine mammals. Calculated values are italicized. Energy required and body weight are taken from Hunt *et al.* (2000). Prey energy density is assumed for two feeding modes, zooplanktivorous and piscivorous, with ESA fish and zooplankton energy densities from Davis *et al.* (1998).

Species	Energy required (kcal/day)	Prey density (kcal/g)	Prey consumed (kg/day)	Body weight (kg)	Q/B (daily)	Q/B (yearly)
Sperm whales	502,867	1.5	<i>335.24</i>	18518	<i>0.01810</i>	<i>6.61</i>
Toothed whales (orca)	104,539	1.5	<i>69.69</i>	2280	<i>0.03057</i>	<i>11.16</i>
Fin	694,768	1.0	<i>694.77</i>	55590	<i>0.01250</i>	<i>4.56</i>
Sei	283,325	1.0	<i>283.33</i>	16811	<i>0.01685</i>	<i>6.15</i>
Minke	139,990	1.0	<i>139.99</i>	6566	<i>0.02132</i>	<i>7.78</i>
Northern fur seals	4,491	1.5	<i>2.99</i>	28	<i>0.10693</i>	<i>39.03</i>
Elephant seals	16,890	1.5	<i>11.26</i>	371	<i>0.03035</i>	<i>11.08</i>
Dall's porpoise	7,000	1.5	<i>4.67</i>	62	<i>0.07526</i>	<i>27.47</i>
Pacific white sided dolphin	8,385	1.5	<i>5.59</i>	79	<i>0.07076</i>	<i>25.83</i>
Northern right whale dolphin	10,416	1.5	<i>6.94</i>	105	<i>0.06613</i>	<i>24.14</i>
Common dolphin	(values unknown, averaged Q/B from other dolphins)					

**Table A4** Bird residency days in the WSA and ESA, and body weights, used to weight total bird biomass by percentage of each species. Data is from Hunt *et al.* (2000).

Species	Body weight (kg)	WSA residency days	WSA percent	Species	ESA residency days	ESA percent
Laysan Albatross	3.04	1,100,000	40.8%	Sooty Shearwater	1,600,000	45.7%
Sooty Shearwater	0.79	3,100,000	29.7%	Northern Fulmar	470,000	9.3%
Tufted Puffin	0.79	892,000	8.5%	Tufted Puffin	255,000	7.2%
Northern Fulmar	0.54	600,000	4.0%	South-Polar Skua	160,000	6.7%
Black-legged kittiwake	0.41	610,000	3.0%	Black-legged kittiwake	440,000	6.5%
Short-tailed Shearwater	0.53	430,000	2.8%	Long-Tailed Jaeger	440,000	4.7%
Fork-tailed Storm Petrel	0.06	3,600,000	2.4%	Short-tailed Shearwater	220,000	4.3%
South-Polar Skua	1.15	150,000	2.1%	Fork-tailed Storm Petrel	1,900,000	3.8%
Leach's Storm Petrel	0.04	3,500,000	1.7%	Leach's Storm Petrel	2,200,000	3.2%
Pormarine Jaeger	0.69	190,000	1.6%	Black-footed Albatross	23,000	2.6%
				Laysan Albatross	21,000	2.3%

### **Birds**

Total bird biomass density in the gyres is reported to be 0.0008 in the ESA and 0.0038 in the WSA (Hunt *et al.* 2000). To weight this total by different bird groups, species were weighted by residency days in the gyres and body weight to find the percentage of the total bird biomass consisting of each species. Species representing the cumulative 95% of the bird biomass were

included in the model, groups as albatrosses, shearwaters, storm petrels, kittiwakes, fulmars, puffins, skuas and jaegers (Table A4).

Mortality rates were not obtained and taken to be similar to eastern Bering Sea estimates of 0.05 to 0.075 for large predatory birds, and 0.1 for smaller birds (Aydin *et al.* 2002). Consumption rates and diets were taken from Hunt *et al.* (2000) (which reported allometric energy requirements and prey

by general categories) and weighted by biomass of prey species within each category.

### Cephalopods

Neon flying squid (*Ommastrephes bartrami*), boreal clubhook squid (*Onychoteuthis borealijaponica*), large gonatid squid (Family Gonatidae), and micronektonic squid were used in each gyre model. Biomass for clubhook and large gonatid species in the ESA was calculated from measurements of catch-per-unit-effort in Hokkaido University research gillnet studies from the 1994-1999, published yearly (for example, Faculty of Fisheries Hokkaido 2000). The CPUE values were reported for Pacific salmon and other fish of similar size, including pomfret and large squid (as individuals per unit of research net). It was assumed that the ratio of CPUE (non-salmon species) / CPUE (total salmon) was equal to the ratio of biomass (non-salmon species) / biomass (total salmon). To solve for the biomass of non-salmon species, the biomass of salmon species used was that from the run reconstruction method detailed below. Neon flying squid biomass was reported by Shimizaki (1986). In the WSA, squid biomass was taken from Russian sources cited in Table B2. P/B ratios for all of the large squid was taken to be the same as reported for neon flying squid, of 0.07 per 10 days or 2.555 per year (Murata and Shimazu 1982). Q/B ratios from Brodeur *et al.* (1999) are reported as 0.02 per day for clubhook and large gonatid squid (7.3/year) and 0.017 for neon flying squid (6.2/year). Squid diets were from research gillnet studies (Ishida unpublished data).

Micronektonic squid, primarily gonatids such as *Berryteuthis anonychus* and *Gonatus onyx* are an extremely important food source for species across the subarctic gyres, especially in the Subarctic Current (Pearcy *et al.* 1988; Aydin *et al.* 1998). No estimate for their biomass was available so it was estimated by setting their EE to 0.90 in both models. References for P/B and Q/B ratios are given in Table B2.

### Fish

**Pacific salmon.** Six species of Pacific salmon were included in the models as separate groups:

steelhead (*Onchorhynchus mykiss*); chinook salmon (*O. tshawytscha*); coho salmon (*O. kisutch*); sockeye salmon (*O. nerka*); chum salmon (*O. keta*); and pink salmon (*O. gorbuscha*). Due to their commercial importance salmon were the species with the most data available, however much of this data is concentrated around the early or late stages of their life cycle outside of the gyres.

For biomass, two basic methods were available. The first was to use run (returning salmon) reconstruction records (catch + escapement) for Pacific Rim stocks in conjunction with mortality and migration studies, to determine the percentage of each salmon stock's life-history cycle in the gyres. The second was to use direct survey estimates. The first method has the advantage of taking into account all seasons and life stages of the salmon, as well as allowing for reconstruction historical biomass levels. Its disadvantage is that it relies on indirect measures of migration such as non-quantitative tagging studies. The second method provides a direct point estimate of a catch-per-unit-effort, but this may be difficult to calibrate to biomass and in addition may cover only brief periods of the year.

Initially, the first method was used for both gyres combining Pacific-wide stock-specific run reconstructions from 1950-1998 (Rogers 1999) with salmon body weight by month (Ishida *et al.* 1993), mortality estimates (Pauly and Christensen 1996) and tagging studies (Myers *et al.* 1996). The values are averaged for the period 1990-98 and shown in Table A5. For the ESA, the run reconstruction values show a pattern similar to results from Pauly and Christensen (1996).

In the WSA, two additional sources of data were provided from surveys. The first, a combination of values from Shuntov *et al.* (1993 a,b) and Shuntov *et al.* (1995) was used in the final model. These data were collected from the northwest sections of the WSA near Kamchatka. However, original data from research cruises (TINRO 1998 a,b) provided finer spatial resolution; when "Kamchatka Current" stations were removed the results were a synthesis of TINRO data sources that were oriented towards the central gyres. The biomass levels from this TINRO synthesis are

more similar to run reconstruction values than Shuntov *et al.* (1993 a,b; 1995), especially in showing a lower level of pink salmon biomass.

Overall, the run reconstruction methods showed a considerably higher proportion of sockeye and chum salmon in gyres, and a lower proportion of pink salmon, when compared with survey methods. This is because the surveys are geared

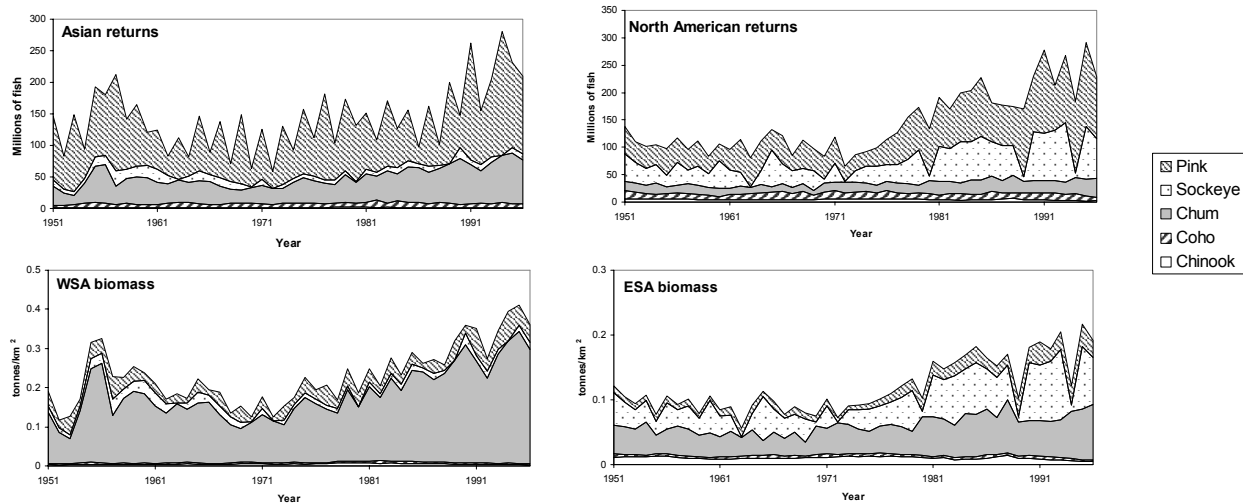
towards catching adult (maturing) salmon while the reconstructions take into account the juvenile biomass present in the multi-year life history of chum and sockeye salmon.

For historical fitting found in the main text, the run reconstructions for both the ESA and WSA were used to estimate gyre salmon biomass between 1951-1996 (Fig. A1).

**Table A5** Estimated 1990s biomass of Pacific salmon in the WSA and ESA according to different estimation methods. Values used in the final model are shown in bold.

	WSA			ESA	
	Shuntov <i>et al</i> 1993 a,b; 1995.	TINRO synthesis	Run reconstruction	Run reconstruction	Pauly and Christensen 1996
Sockeye	<b>0.00310</b>	0.0223	0.0283	<b>0.0897</b>	0.109
Chum	<b>0.0152</b>	0.112	0.303	<b>0.0541</b>	0.051
Pink	<b>0.197</b>	0.0981	0.020	<b>0.0233</b>	0.083
Coho	<b>0.0058</b>	0.0209	0.00304	<b>0.00445</b>	1.830
Chinook	<b>0.0039</b>	0.00628	0.00438	<b>0.00930</b>	0.335
Steelhead	<b>0.0039(*)</b>			<b>0.00930(*)</b>	0.100

(\*) Steelhead values not available so assumed equal to chinook.



**Fig. A1** Top Panels: Run sizes (returns) of North American and Asian Pacific salmon (catch+escapment); from Rogers (1999); and reconstructed biomass densities (averaged throughout year for all age-classes) for the WSA and ESA. Bottom panels: Notice difference in scales between two bottom panels.

P/B and Q/B values for Pacific salmon were constructed from detailed bioenergetics models (Aydin 2000) based on growth rates reported by Ishida *et al.* (1998). The freshwater and early ocean, and late (fishery) stages are not included, so this model does not capture the dynamics of the salmon fisheries implied by management of escapement and hatcheries, and no fishing of salmon is modeled.

Diet habits of Pacific salmon for the 1990s can be found for the ESA in detail in Aydin (2000), and in summary in Kaeriyama *et al.* (2000); the original data from these studies were pooled to construct the ESA diet tables. WSA salmon diet data from similar studies were provided by Y. Ishida.

**Other fish.** The other piscivorous fish in the ESA and WSA models were sharks, primarily salmon sharks (sp) and pacific pomfret (*Brama japonica*). As mentioned under “Balancing the model” above, Pacific dogfish (*Squalus acanthias*) and daggertooth (*Anotopterus pharao*) were included in initial model drafts but later dropped.

Several forage fish groups were modeled in the two systems. Mesopelagic fish (mainly myctophidae, particularly *Stenobrachius leucopsarus*, see Beamish *et al.* 1999c for species lists); miscellaneous forage fish (mainly sticklebacks *Gasterosteus aculeatus*); and saury (*Cololabis saira*) were modeled in both systems. There were two additional teleost groups in WSA gyre model: Pacific sardine (*Sardinops sagax*) and Japanese anchovy (*Engraulis japonica*).

The data sources for biomass, P/B, and Q/B for these species are listed in Table B2; the exception is for ESA pomfret biomass which was estimated by computing its CPUE ratio to total salmon biomass as described in the section on squids, above.

### **Plankton**

For the ECOPATH model, zooplankton were divided into eleven groups: microzooplankton (zooplankton <200  $\mu\text{m}$ , typically meroplanktonic larvae and copepod nauplii); copepods;

euphausiids; pteropods; amphipods (mainly hyperiids); sergestidae; chaetognaths; salps; ctenophores; large jellyfish; and an other group (mainly Larvaceans and Polychaetes). A bacterial component was included in the initial balancing stages and in the model for Appendix B; however this group was not used for ECOSIM simulations that included seasonal dynamics.

ECOPATH model estimates for lower trophic levels were taken from outputs from the NEMURO model (Tables A6-A10). NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography) is a lower trophic level model (LTL) of a marine ecosystem that was developed by the PICES CCCC MODEL Task Team during a modeling workshop held in Nemuro, Japan, in 2000 (Eslinger *et al.* 2000, Megrey *et al.* 2000). NEMURO simulates the annual dynamics of phytoplankton, zooplankton and nutrient concentrations for two locations in the North Pacific, Ocean Station P (50°N 145°W) and station A7 (41.30°N 145.30°E) off the “A-line”, an oceanographic sampling line off Hokkaido Island, Japan. For the ECOPATH models, only Ocean Station P results were used. The diet composition for zooplankton groups were very similar in both gyre models. Copepods, microzooplankton and phytoplankton are generally the major component of zooplankton diet. Large jellyfish, chaetognaths, sergestid shrimp and amphipods feed mainly on copepods (60-80%). The remaining zooplankton groups feed on copepods (25-40%), microzooplankton (20-40%) and phytoplankton (25-70%). Microzooplankton diet is composed of small phytoplankton (75%) and bacteria (25%).

The annual, gyre-scale averages used for zooplankton in the ECOPATH models cover a wide range of spatial, seasonal, and interannual variability which was not explicitly modeled. Mackas and Tsuda (1999) found that timing of spawning and age at first maturation for zooplankton have been later, slower and more narrowly seasonal in the northern parts of both gyres, particularly in the cold waters of the high latitude western marginal seas. They further suggested that in all regions the annual biomass peak of mesozooplankton coincides with the time

**Table A6** Results of NEMURO/MATLAB Box model simulations.

Variable	NEMURO Group (ECOPATH Groups)	Model Value
P/B daily P/B annual B mean	PS (Small phytoplankton)	0.108-0.636 /d mean = 0.355/d ~ 0.12
P/B daily P/B annual B mean	PL (Large phytoplankton)	0.032-0.212/d mean = 0.116/d ~0.11
P/B daily P/B annual B mean	ZS (Microzooplankton)	0.081-0.222/d mean = 0.134/d ~0.055
P/B daily P/B annual B mean	ZL (Copepods)	0.026-0.127/d mean = 0.065/d ~0.055
P/B daily P/B annual B mean	ZP (Euphausiids, amphipods, pteropods)	0.001-0.015/d mean = 0.007/d ~0.08
Q/B	ZS (Microzooplankton)	0.387-1.06/d mean = 0.639/d
Q/B	ZL (Copepods)	0.124-0.604/d mean = 0.308/d
Q/B	ZP (Euphausiids, amphipods, pteropods)	0.004-0.070/d mean = 0.033/d

**Table A7** Estimates of Station P primary production.

Method	Average Daily PP (gC/m <sup>2</sup> /d)	Annual PP (gC/m <sup>2</sup> /yr)	Source
C14		140	Wong <i>et al.</i> 1995
Nitrate depletion		133	Wong <i>et al.</i> 1995
Particle flux		120	Wong <i>et al.</i> 1995
Chl a	0.55	199	Longhurst <i>et al.</i> 1995
Secchi disc data		167	Falkowski & Wilson 1992

**Table A8** Average annual biomass (B1-B4), P/B, and annual primary production (PP) for PS and PL.

Group	B1 μmolN/l	B2 μmolC/l	B3 gC/m <sup>3</sup>	B4 gC/m <sup>2</sup>	P/B d <sup>-1</sup>	PP gC/m <sup>2</sup> /yr
PS	0.12	0.792	0.0095	0.760	0.355	98.5
PL	0.11	0.726	0.0087	0.697	0.116	29.5
PS + PL	0.23	1.518	0.0182	1.457		128

Calculations:

1. B2 = 6.6 (Redfield ratio) x B1.
2. B3 = 0.012 x B2 (Table 6).
3. B4 = 80 m x B3 (Table 7).
4. PP = P/B x B4 x 365 d.

**Table A9** Conversion factors.

Variable	Value	Source
C/N (Redfield)	6.6	Wong <i>et al.</i> 1995
C/N	7.8	Kawamiya <i>et al.</i> 1997
N/Chl a	7.5	Kawamiya <i>et al.</i> 1997
C/Chl a	50	Kawamiya <i>et al.</i> 1997

**Table A10** Station P characteristics.

Variable	Value	Source
Euphotic zone	80 m	Wong <i>et al.</i> 1995
Average Chl a (annual)	0.4 mg/m <sup>3</sup> (μg/L)	Wong <i>et al.</i> 1995
f-ratio	0.25	Wong <i>et al.</i> 1995
f-ratio (summer)	0.25-0.52	Wong <i>et al.</i> 1998

period when late copepodites of *Neocalanus* spp. are the most abundant above the pycnocline (sometime between May and July).

Taniguchi (1999) noted that the Eastern Gyre area generally has the lowest chlorophyll levels (0.3 μg/L) in the North Pacific, while Western Gyre levels are slightly higher (0.5 μg/L). Station P exhibits a consistently low biomass with little seasonality. Chlorophyll concentrations are very low but annual primary productivity is quite high, primarily from small phytoplankton <5 μm (prasinophytes, prymnesiophytes, cryptophytes and cyanobacteria). The productivity is derived mainly from regenerated production, and about 21% from new production. Taniguchi (1999)

reported nitrate levels of 16 μg/L in winter, and 8 μg/L in summer.

Nitrogen uptake rates are influenced by light, temperature, available nitrogen sources, iron concentration, and competition from bacteria. Harrison *et al.* (1999) suggest that nitrogen uptake by larger (>5 μm) diatom cells may be influenced by iron concentration, which can be introduced to the gyre system by various sources, one of the most important being atmospheric transport of dust from land sources.

Harrison *et al.* (1999) found that small cells in the Eastern Gyre can grow at near maximum growth rates, and are grazer controlled. Small

phytoplankton are controlled by grazing microzooplankton, which can grow rapidly to respond to changes in growth rate of the small phytoplankton, and may exert a greater control than mesozooplankton grazing.

Harrison *et al.* (1999) reported greater seasonality in phytoplankton in the Western Gyre compared to the Eastern Gyre. Diatom cells have been reported in higher numbers in the Western than in the Eastern Gyre in spring and summer. Picoplankton (<2 µm) are predominant in the summer, but when chlorophyll concentrations are over 1 µg/L, phytoplankton >10 µm make up 60% of the total chlorophyll concentration. There is a late autumn increase in chlorophyll concentration in the Western Gyre, but summer productivity values are similar between the Western Gyre and values obtained at Station P.

One iron enrichment study in the Western Gyre indicated that iron may limit primary productivity of large cells in this gyre as well. Larger cells are dominated by *Thalassiosira*, unlike the Eastern Gyre where pennate diatoms were observed with iron enrichment. The 10 µM ambient nitrate was depleted in 5 days, and ambient chlorophyll increased from 1.3 to 5 µg/L with the introduction of iron. Surface iron concentrations in the Western Gyre are low during the low dust season (summer and fall), at which time the iron levels are similar to those found in the Eastern Gyre. Deposition of dust has been suggested to result in an increase in primary productivity during the dusty season.

Taniguchi (1999) suggested the Western Gyre contains a similar percent contribution from micro-sized dinoflagellates to total flagellate biomass as is found in the Eastern Gyre. He also noted that the Western Gyre has more standing stock of microzooplankton than the Oyashio Region, but less than the Eastern Gyre. Microzooplankton grazing may control

phytoplankton in most regions of the subarctic Pacific, except in the Oyashio region.

Harrison *et al.* (1999) reported inshore stations in the Eastern Gyre have diatom dominated spring and summer blooms, when growth rate is likely limited by nitrogen, and sedimentation occurs as diatoms sink out. Oceanic stations show little seasonality in biomass; however, they have a pronounced seasonal cycle in primary production. The biomass is dominated by small cells. Sedimentation is low compared to inshore stations. Higher diatom abundance is recorded occasionally, maybe indicating variation in the iron supply.

Mackas and Tsuda (1999) found higher population biomass and individual growth rates of zooplankton near land and on the Asian side of the basin, consistent with the hypothesis that the rate of supply of iron from land limits some primary productivity.

Brodeur and Ware (1992) found an increase in the biomass of mesozooplankton in the Gulf of Alaska (ESA) from 113 mg wet weight/m<sup>3</sup> in 1956-1962, to 194 mg wet weight/m<sup>3</sup> in 1980-1989. Findings by Mackas and Tsuda (1999) are in agreement, indicating that the summer season biomass of mesozooplankton in the Eastern Gyre was a factor or two higher in the 1980s than in the 1950s and 1960s, and these changes correlated with large scale atmospheric and oceanographic changes, as well as interdecadal changes in pelagic fish production.

Brodeur and Ware (1995) reported that biomass for the Eastern Gyre was 213 mg wet fish weight/m<sup>3</sup> before 1980, and 168 mg wet weight/m<sup>3</sup> after 1980. Mackas and Tsuda (1999) found a similar decrease in zooplankton from the mid-1960s – early 1970s through to the late 1970s and 1980s in the Kuroshio-Oyashio transition area of the Western North Pacific.