Spatial Heterogeneity of Sea Surface Temperature Trends in the Gulf of Alaska

Steven J. Bograd[1*], Roy Mendelssohn[1], Franklin B. Schwing[1] and Arthur J. Miller[2]

[1]*NOAA, Pacific Fisheries Environmental Laboratory*
Pacific Grove, California, 93950-2097 USA
[2]*Scripps Institution of Oceanography, La Jolla, California, USA*

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ABSTRACT *State-space models were used to derive non-parametric sea surface temperature (SST) trends from 26 locations in and around the Gulf of Alaska for the period 1950–97. The SST trends reflect important large-scale climate impacts associated with El Niño events and regime shifts, but also reveal significant spatial heterogeneity across the region. The SST trends cluster into five distinct regions that define a robust zonal and meridional asymmetry. The meridional differences reflect the relative impact of El Niño events, while the zonal differences reflect variations in the timing and amplitude of a region-wide post-1970 warming trend. The 1976 regime shift is evident primarily as an accelerated warming in the northern and eastern portions of the Gulf of Alaska. The climate signals identified in the SST series are of sufficient magnitude and duration that they could potentially foster changes in lower trophic productivity and structure, which could lead to a broader ecosystem reorganization. Regional differences in Steller sea lion population trends may have resulted from a spatially heterogeneous upper-ocean response to large-scale climate variability.*

RESUMÉ *[Traduit par la rédaction] On a utilisé des modèles d'espace d'états pour dériver les tendances non paramétriques de la température de la surface de la mer (TSM) en 26 endroits situés dans le golfe d'Alaska ou à prox0imité pour la période 1950-1997. Les tendances de la TSM reflètent d'importants effets climatiques à grande échelle associés aux évènements de El Niño et aux changements de régime mais révèlent aussi une grande hétérogénéité spatiale à travers la région. Les tendances de la TSM se regroupent en cinq régions distinctes qui mettent en évidence une asymétrie zonale et méridionale marquée. Les différences méridionales reflètent l'effet relatif des évènements de El Niño alors que les différences zonales sont liées aux variations dans le moment et l'ampleur d'une tendance au réchauffement à la grandeur de la région après 1970. Le changement de régime de 1976 se manifeste surtout comme un réchauffement accéléré dans les parties nord et est du golfe d'Alaska. Les signaux climatiques relevés dans les ensembles de données de TSM sont d'une force et d'une durée suffisantes pour éventuellement favoriser des changements dans la productivité et la structure trophiques inférieures, ce qui pourrait mener à une plus vaste réorganisation de l'écosystème. Les différences régionales dans les tendances des populations de lions de mer de Steller peuvent avoir été causées par une réaction spatialement hétérogène des couches supérieures de l'océan à la variabilité climatique à grande échelle.*

1 Introduction

Recent research has revealed the importance of long-term climate fluctuations on marine ecosystem structure (Benson and Trites, 2002; McGowan et al., 2003; Chavez, 2005). Particular attention has been paid to rapid, large-scale climate shifts, such as those proposed to have occurred in the North Pacific around 1976 (Miller et al., 1994; Polovina et al., 1994; Trenberth and Hurrell, 1994), 1989 (Hare and Mantua, 2000), and 1999 (Schwing and Moore, 2000; Peterson and Schwing, 2003). In each of these cases, large shifts in biological production and ecosystem community structure were reported over wide areas of the eastern North Pacific, even though the mechanisms responsible for the physical and biological changes were not fully understood (Mantua et al., 1997; Hare and Mantua, 2000; Benson and Trites, 2002; McGowan et al., 2003; Peterson and Schwing, 2003). In fact, there were substantial differences in the physical and biological changes associated with each of these shifts (Hare and Mantua, 2000; Bond et al., 2003). Detailed analyses of the morphology of climate regimes, and the transitions between them, are necessary to understand the ecosystem impacts of large-scale climate variability.

One of the most prominent recent ecological changes was the greater than 80% decline in Steller sea lion populations in the Gulf of Alaska (GoA) and around the Aleutian Islands

*Corresponding author's e-mail: steven.bograd@noaa.gov

between the late 1970s and 1990s (Trites and Larkin, 1996). A number of potential causes for this decline have been proposed, including epidemic diseases and increased predation by killer whales (Trites and Donnelly, 2003; Trites et al., 2005). A leading theory for the decline is that a compositional change in the prey available to the sea lions (from energy-rich fatty fish such as herring to less nutritional lean fish such as pollock) had an adverse effect on their metabolism, resulting in reduced growth, reproduction, and survival (Rosen and Trites, 2000; Trites and Donnelly, 2003). Changes in the quality, quantity, and accessibility of the dominant prey may have resulted from shifts in ecosystem structure at lower trophic levels, driven by changing oceanic conditions such as those experienced following the regime shift of the 1970s (Trites et al., 2005; Miller et al., 2005). Steller population trends have shown a notable east-west asymmetry, however, with the larger western population (west of ~144°W) declining dramatically while the separate, smaller eastern population (east of ~144°W) increased slightly (Trites and Donnelly, 2003). This implies regionally varying impacts in sea lion habitat across the GoA, which may be reflected in environmental parameters such as sea surface temperature (SST).

Here we examine seasonal and long-term trends in SST in the portion of the north-east Pacific dominated by the cyclonic circulation and Ekman pumping of the GoA. This region encompasses most of the habitat utilized by both the western and eastern Steller sea lion populations. SST is used because of its availability as well as its prior use as an indicator of large-scale regime shifts (Mantua et al., 1997). Our objectives are to describe warming and cooling trends of sufficient length and magnitude to accommodate changes in ecosystem structure, to identify periods of relatively abrupt SST change, and to quantify regional differences in the timing and amplitude of SST variability. Long-term SST trends reflect important climate forcing that may influence lower trophic productivity and community composition, leading to changes in the dominant fish species and the observed decline in the western population of Steller sea lions.

2 Data and methodology

a *Data Sources*

Monthly mean SSTs were obtained from the Comprehensive Ocean-Atmoshere Data Set (COADS) (Woodruff et al., 1987) in 1° boxes for the region bounded by 130°–170°W and 50°–60°N for the period 1950–97. The number of months with SST observations in this region and period ranged from fewer than 100 in parts of the eastern Bering Sea to well over 500 in the transitional domain south of 52°N (Fig. 1). Analyses were performed using data from boxes at every 3° latitude-longitude square, which covers a wide spatial domain of the north-east Pacific Ocean while providing sufficient data for the analyses. A state-space statistical model, described in the following section, was applied to the monthly time series of SST from each of these locations to investigate long-term trends at each location and temporal variability common to the entire region.

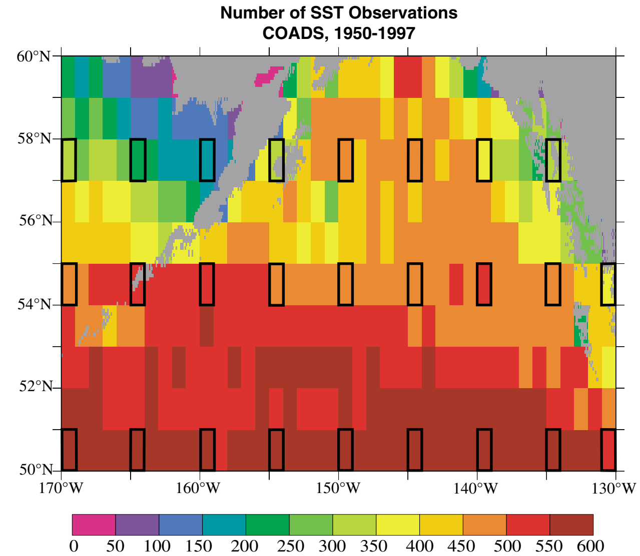

Fig. 1 Number of months with SST observations in the north-east Pacific from COADS data for the period 1950–97. Black outlines indicate the 1° boxes used in this study.

b *State-Space Decomposition*

A number of recent studies have shown how state-space models can be used to decompose environmental time series into components that differentiate long-term trends and changes in the phase and amplitude of the seasonal cycle (Schwing and Mendelssohn, 1997; Mendelssohn and Schwing, 1997; Durand and Mendelssohn, 1998; Bograd et al., 2002; Mendelssohn and Schwing, 2002; Mendelssohn et al., 2003). In these analyses we assume that each observation *y(t)* is the sum of four components,

$$y(t) = T(t) + S(t) + I(t) + e(t), \qquad t = 1, \tau$$

where, at time *t*, *T(t)* is the time-dependent mean-level (non-linear and non-parametric), *S(t)* is the seasonal component (non-stationary and non-deterministic), *I(t)* is the irregular term (containing any stationary autocorrelated part of the data), and *e(t)* is the stationary uncorrelated component, which can be viewed here as "observation" error. (A complete description of state-space decompositions of time series can be found in Durbin and Koopman (2001), Harvey (1989), Shumway and Stoffer (2000), and in the appendix of Schwing and Mendelssohn (1997).) Piecewise continuous smoothing splines are used to estimate the unobserved components. The trend term can be viewed as an unknown function of time, and parametrized as

$$\nabla^k T(t) \approx N\left(0, \sigma_T^2\right), \qquad t = 1, \tau$$

where the notation $x \approx N(a,b)$ means a random variable that is normally distributed with mean *a* and variance *b*, and $\sigma_T^{\,2}$ (to be estimated) controls the smoothness of the estimated trend.

The other terms are parametrized in a similar way. For our analyses we use $k = 1$ in the trend term. The non-parametric trend computed for each time series gives an estimate of the non-linear changes in the mean level, and can be used to identify significant change points in the series.

c *Subspace Identification and Regional Trends*

Kitagawa and Gersch (1984, 1985) show how these assumptions can be put into a state-space model and solved using a combination of the Kalman filter and maximum liklihood estimation, which can be calculated using the Expectation-Maximization algorithm (Dempster et al., 1977; Shumway, 1988). After subtracting the estimated seasonal and irregular terms from each time series (in each case the seasonal cycle was nearly deterministic and had little effect on the final analysis), subspace identification techniques (Aoki, 1990; Aoki and Havenner, 1997) were used on the partial residual (trend plus error terms) to estimate common non-parametric trend terms from the collection of time series. The subspace identification method proceeds by calculating the Hankel matrix of the covariance between the past and future of the series, and then uses a canonical variate methodology to find the linear combination of the future that is best predicted (in a correlation sense) by a linear combination of the past. These components are referred to here as common trends. It was found that the first four components from this common trend analysis reproduced the main features of the estimated univariate SST trends. It should be noted that these common trends, though analogous to principal components, are not restricted to being orthogonal, nor is total contemporaneous variance explained the criterion used to find the common trends. Details of the analysis methods applied here can be found in Schwing and Mendelssohn (1997) and Mendelssohn et al. (2003).

In addition to the state-space analyses, a complete-linkage cluster analysis was performed on the factor loadings of the second to fourth common trend components in order to examine the spatial patterns of SST variability further. The first common trend was not included in the cluster analysis as it represents a weighted mean of the series (see following) and includes scale effect. The higher order common trends can be viewed as an analysis of variance; they are like treatment effects in the Analysis of Variance (ANOVA), showing which locations differ from the (weighted)-mean effect in a similar manner.

3 Results

The time series of the first SST common trend, which includes scale and can be considered a spatially weighted mean, features a strong episodic warming associated with the 1957–58 El Niño event, followed first by a cooling trend during the 1960s, then a significant warming trend beginning in the early 1970s (Fig. 2a). The latter warming trend accelerated around 1976, the time of the well-documented regime shift in North Pacific climate (Miller et al., 1994; Polovina et al., 1994; Trenberth and Hurrell, 1994). Almost all El Niño events are characterized by positive peaks or rising temperatures. The loadings for this component are positive at all locations, indicating that these long-term cooling and warming periods occurred throughout the region. The linear increase from north-west to south-east in the amplitude of the loadings reflects generally warmer SSTs in the south-eastern portion of the GoA.

Although the first common trend represents the highest canonical correlations and explains most of the total variance in the series, the higher components, which are not constrained to be orthogonal, compensate for this trend at locations and times that represent regional differences in SST variability. The time series of the second common trend has characteristics much like the first, with a declining trend beginning in the late 1950s, a low point in the late 1960s to early 1970s, and a rising trend until the end of the record. At the locations with positive loadings (an axis from the south-eastern Bering Sea, through the central GoA, to the south-eastern GoA; Fig. 2b), these climate trends are accentuated, while they are mitigated in locations with strong negative loadings (the south-western and northern GoA). In particular, the regions with strong positive loadings experienced a strong and relatively abrupt warming in the early 1970s followed by a steady warming trend until the end of the record. The 1976 warming event is de-emphasized in this component.

The most prominent features in the time series of the third SST common trend are the sharp peak in the late 1950s followed first by a rising trend and then a declining trend (Fig. 2c). The spatial structure of this component is clearly zonal, with positive loadings in the western portion of the domain and negative loadings throughout the central and eastern GoA. This component, therefore, enhances the warming episode of the late 1950s at several locations in the central and northern GoA (strong negative loadings), and mitigates its effect in the western GoA and Bering Sea (strong positive loadings). This warming event may have been associated with the strong 1957–58 tropical El Niño event. However, the magnitude and longevity of this event imply that it transcends the relatively ephemeral effects of an El Niño event; a similar long-lived warming episode has been observed in upper ocean temperatures in the California Current (Mendelssohn et al., 2003). The steady warming trend that began in the early 1970s and continued until the end of the record (Fig. 2a) is emphasized in the south-eastern Bering Sea and western transitional zone, where the loadings are most strongly positive. As with the first two common trends, the change point for the most recent warming trend was the early 1970s, not 1976–77.

The fourth SST common trend captures much of the higher-frequency (interannual) variability, some of which appears to be associated with tropical El Niño events (Fig. 2d). An interesting result is that there does not appear to be a unique El Niño response in the GoA. Three of the strongest El Niño events (1965–66, 1972–73, and 1982–83) are associated with negative peaks in this component, implying an accentuation of these warming eposides in the southern and eastern GoA where there are negative loadings. All other El Niño events are associated with weak-to-moderate positive peaks or rising

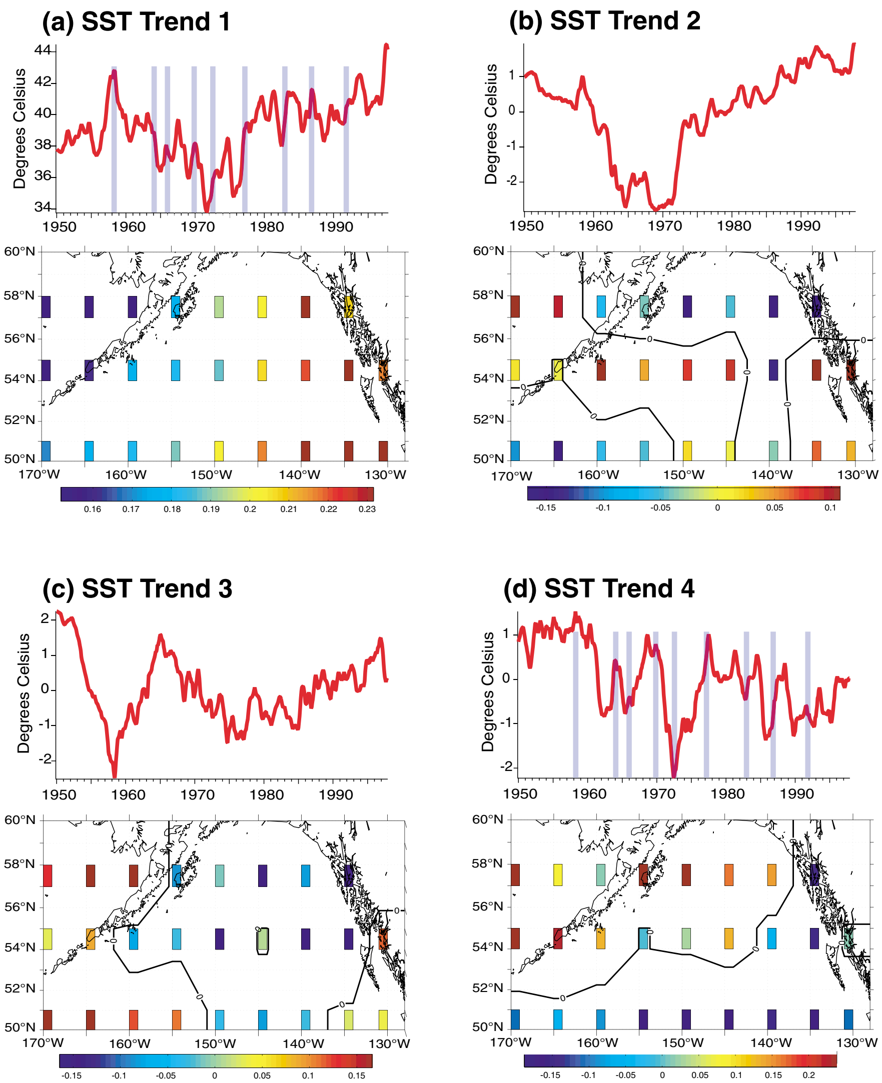

Fig. 2 Time series and distributions of loadings for the first four components of the SST common trend analysis. Colors in 1° boxes show factor loadings at each location; contours show zero crossings. Times of strong El Niño events are marked on the first and fourth common trend time series.

trends, which suggests that the associated warming is more widespread through the region (i.e., there is still strong warming in the south and east, as depicted in the first common trend, but the other regions experienced similar or even stronger warming). These classifications of a variable extratropical response to El Niño events are entirely consistent with results from the California Current (see Table 4 and Fig. 10 of Mendelssohn et al., 2003), and may reflect the nature of the teleconnections between the tropics and the north-east Pacific.

Not all El Niño events show up strongly in the fourth common trend, and there are large peaks or change points not associated with El Niño events. This component is picking up variability at higher frequencies than the decadal trends, and this variability includes, but is not limited to, El Niño events. Spatially, this trend clearly separates the southern and northern halves of the region, with coastal British Columbia and the eastern transitional zone (strong negative loadings) being most influenced by the strong El Niño events and having greater overall variance. As seen in the first two common trends, this component also indicates a significant change point in the early 1970s.

A cluster analysis of the SST loadings for common trends 2–4 further defines the spatial structure of SST variability in the region, revealing five geographical clusters within which there is common variability (Fig. 3). This clustering emphasizes both north-south differences (primarily the relative impact of El Niño events, as reflected in common trend 4) and east-west differences (primarily the timing and amplitude of the post-1970 warming trend, as reflected in common trends 2 and 3) in the SST time series, consistent with the common trend analysis. Thus, the GoA and eastern Bering Sea cluster separately from the transitional zone, and the eastern and western halves of the GoA cluster separately.

The trends and change points identified in the common trend and cluster analyses are apparent from sample reconstructed SST series representing the five geographical clusters (Fig. 4).

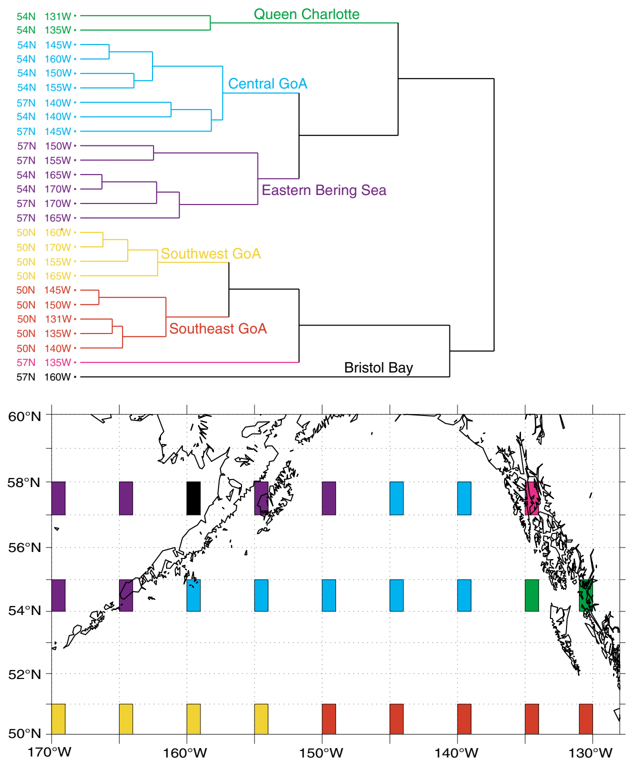

Fig. 3 Cluster dendogram and map showing regional differences in SST variability from a cluster analysis of the loadings from common trends 2–4. Map shows colours represented on the cluster tree.

The sharp, geographically broad warming around the time of the 1957–58 El Niño event is evident in all areas except the south-western GoA (yellow boxes in Fig. 3 and yellow line in Fig. 4), and is especially prevalent in the eastern and central GoA (green, blue) and eastern transitional zone (red). The eastern and central GoA then experienced a decadal cooling trend, which was less pronounced in the eastern (red) and western (yellow) regions of the transitional zone and the eastern Bering Sea (purple). The relative importance of the 1976 regime shift, in terms of SST change, differs in the western and eastern halves of the GoA. Although all regions experienced an accelerated warming after 1976, it was most pronounced in the northern and eastern GoA. It is interesting to note, however, that the warming trend that continued to the end of the record commenced at most locations in the early 1970s, prior to the regime shift as defined by a change in sign of the Pacific Decadal Oscillation (PDO; Mantua et al., 1997).

Similar analyses were performed on the seasonal components of the SST time series (not shown). Although some regional differences in seasonal amplitude and phase were found, the differences were small. Most regions showed a relatively stationary seasonal cycle in SST, in contrast to the highly non-stationary behaviour of upper-ocean temperatures in the California Current (Mendelssohn et al., 2004). These regional differences in SST seasonality are similar to that found for sea level pressure in the north-east Pacific; the seasonal cycle of the Aleutian Low was relatively stationary over the same time period, while that of the North Pacific High was highly non-stationary (Bograd et al., 2002).

4 Discussion and Conclusions

Non-parametric trends of SST were estimated from a state-space decomposition of COADS data from 26 locations in and around the GoA. These trends reflect important large-scale climate impacts, associated both with El Niño events and the regime shift of the 1970s. But they also reveal significant spatial heterogeneity in long-term SST trends across the region. Not all El Niño events have the same regional response, and the 1957–58 El Niño, in particular, appears to be associated with a broader, long-lived warming event. We also see regional differences in the timing and amplitude of the regime shift of the 1970s. The SST time series cluster into five distinct regions, with common variability within the eastern GoA, the western GoA, and the transitional zone to the south. In particular, the leading common trend components reveal a robust east-west asymmetry.

The SST trends experienced in the GoA for the period 1950–97 were both prolonged, lasting up to two decades, and significant, amounting to changes of up to 2°C. Throughout most of the GoA, SST cooled during the 1960s, following the high-amplitude event of the late 1950s. The entire region has warmed since the early 1970s, with an accelerated warming in the eastern half of the domain following 1976. It is particularly interesting to note that the recent warming trend commenced several years prior to the 1976 regime shift, as indexed by the PDO (Mantua et al., 1997). This is consistent with a number of fishery time series, which also show population shifts prior to 1976 (Hare and Mantua, 2000). One interpretation is that a regime shift may be an evolving phenomenon whose signals may "propagate" into different regions, depths, and fields having different response times. Thus, it may be possible that either the forcing responsible for such a shift, or the ocean response to such forcing, may not be as abrupt as the PDO (and other large-scale indices) imply. It should also be noted that the 1976 regime shift is the time of the zero crossing in the PDO time series, rather than the earlier, and potentially more significant, inflection point. Regardless of the physics behind these shifts, complex trophic interactions would likely result in lags between environmental changes and population fluctuations at higher trophic levels (Bakun, 2005).

The climate signals identified in this SST analysis are of sufficient magnitude and duration that they could potentially foster changes in lower trophic productivity. Fisheries catch in the GoA has changed from being shrimp-dominated in the 1960s–70s, during the cool regime, to being gadid (pollock)-dominated during the 1980s–90s, as temperatures warmed (Anderson and Piatt, 1999). These changes likely reflect a broader trophic reorganization, and suggest that a warmer climate supports a less favourable diet source for Steller sea lions. The observed SST trends may reflect a more substantial change in upper-ocean heat content, mixed layer depth, and water column stratification, all of which may lead to a changing community structure of primary and secondary producers.

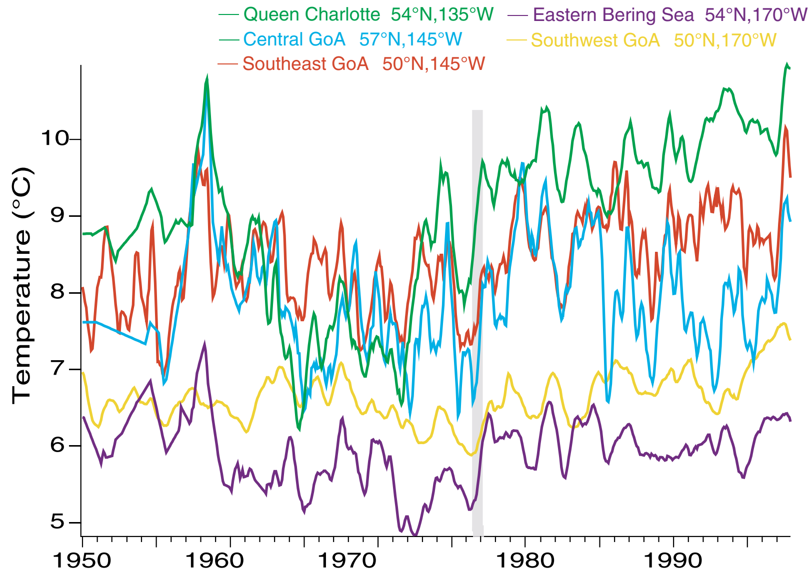

Fig. 4 Reconstructed SST time series (non-parametric trend term from the state-space decomposition) for locations representative of the five geographical clusters of Fig. 3. Winter 1976–77 is marked by a grey line.

In fact, Freeland et al. (1997) have documented a substantial declining trend in winter mixed layer depth in the north-east Pacific, forced in part by reduced surface layer stability as a result of surface warming. Although a shallower mixed layer would tend to reduce the entrainment of nutrients into the upper ocean each winter, it could also enhance surface layer iron concentrations, whose primary source is atmospheric deposition. Higher iron concentrations favour the production of larger phytoplankton species (e.g., diatoms) over smaller species, potentially triggering broader ecosystem changes. Similarly, different regional climate trends, as seen in GoA SSTs, might be expected to force different local ecosystem responses. Although the present analysis is not adequate to infer a direct environmental impact on Steller sea lions, the spatially heterogeneous SST trends are broadly consistent with the observed regionally varying population trends. A more complete investigation of this hypothesis will require coupled physical-ecosystem models that are carefully tuned to regional conditions and that adequately reproduce the observed environmental variability.

The subarctic Pacific SST analysis has some similarities to analyses of water column structure in the California Current System (Mendelssohn et al., 2003). Both regions show a long-term upper-ocean warming trend, beginning in the early 1970s (particularly evident below the surface layer and in the northern portion of the California Current) and accelerated in the surface layer after 1976, superimposed on a spatially heterogeneous response to large-scale climate shifts and El Niño events. A follow-up study will investigate further the timing of significant North Pacific climate change points as a function of region, depth, and environmental property. Anticipating the ecosystem response to future climate change requires a careful delineation of the timing and spatial structure of large-scale climate events.

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