Monitoring North Pacific Heat Content Variability; An Indicator of Fish Quantity?

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Abstract.

Fields of modeled sea surface heights and temperatures are used to develop an algorithm to monitor the low frequency heat content variability of the North Pacific’s mid-latitudes associated with regime shifts in the circulation patterns of the Alaskan and the California currents. Data from altimetric and infrared satellites are then used to apply the method using observational measurements. The model shows that the mid latitude Pacific subsurface circulation variability is primarily due to large, low frequency horizontal north/south gyre movement. The changes may also be due to large scale atmospheric changes in wind patterns, local mixing as well as internal dynamics. It is proposed that this type of monitoring might be useful to help with understanding the variability in fisheries.

1. Introduction

The low frequency variability of the ocean’s circulation and its relationship to the variability of marine populations has been explored to first order [McGowan et al., 1998; Schwing et al., 2000]. In these papers, the authors explored the relationship between the long period changes in sea surface temperature (SST) with disturbances in the coastal ecosystems. Large scale interdecadal shifts of SST and atmospheric pressure are associated with a southward shift and intensification of the Aleutian Low. Along with the atmospheric pressure shift is a shift in the location of the prevailing westerlies over the midlatitude central and eastern North Pacific. These shifts also cause changes in the sea surface height (SSH) field a lower height corresponding to cooler, denser water below the surface and which also may reflect an increase in mixing of nutrient rich waters. These papers refer to two phases: “A”, where the Aleutian low is shallow, and the central gyre ocean is relatively warm and “B” with cool water and a deep Aleutian low. The basic circulation pattern of the North East Pacific [McGowan et al., 1998] can be described as the North Pacific Current (West Wind Drift) flowing into both the Alaska Current system (cyclonic) and the California Current (Figure 1). The strength of the Alaska current system is in phase with this fluctuation while there appears to be no distinct phasing relationship with the California system. Here, we consider whether a space-based monitoring system can be developed to monitor and predict of the size of various fish stocks by watching the North Pacific heat content progress through these phases. This would be similar to how we monitor the tropical SSH pattern and its relation to changes in SST [Chambers et al., 1998].

Figure 2 illustrates the relationships between the marine populations, the ocean heat content and the atmospheric conditions and their changes over time. The marine populations are represented by the salmon catch off of Alaska and the heat content is represented by the changes in the height of the sea surface. The North Pacific (NP) index is representing the strength of the wind forcing. The NP Index is defined by Trenberth and Hurrell, [1994] as the area-weighted sea level pressure over the region 30N-65N, 160E-140W. The first half of the time series indicates a relatively large increase in the ocean’s heat content at 160°W, 35°N in 1987/88 and may be connected to the large decrease in the fish catch. The last half of the record appears to be more strongly correlated with the atmospheric conditions than the first half. If these gyre changes to the ocean’s heat content portend a trend in the fish catch in the northeastern Pacific, then monitoring the SSH low frequency signal could be useful.

This paper discusses how an empirical technique of combining SSH anomaly measurements and SST measurements can be used to monitor the low frequency change of heat content in the eastern North Pacific. Near realtime measurements of satellite derived SST (Advanced Very High
Figure 1. Correlation of the applied heat flux to SST of the model; low values are uncorrelated. The gray lines are a schematic of the currents. The weight of the gray lines indicate the type, stronger northward flow for a “Type B” pattern. The black line is the transect for sampling the model and data.

Figure 2. SSH anomaly signal at 160°W, 35°N: gray, thick line; compared to total Salmon catch for Alaska: black line with stars. The numbers for 2000-2002 (dashed line) are estimated or predicted. Also included on the plot is the NP index: thin, black line with circles. Salmon data is from National Marine Fisheries Service, Fisheries Statistics and Economics Division, Silver Spring, MD and Alaskan Department of Fish and Game (2002). 2002 is a forecast; 2000 and 2001 are preliminary values.
Resolution Radiometer - AVHRR on the NOAA operational satellites) [Smith, 1996] and altimetric (TOPEX/Poseidon - T/P and ERS) [Koblinsky et al., 1998] derived SSH anomaly (SSH', sea surface’s deviation from a 9+ year mean) measurements are used in combination to create a proxy heat content estimate. An eddy-permitting ocean model [Tokmakian and Challenor, 2000] is used to test the feasibility of the method and also to extend the time series back in time from the period when high quality altimeter measurements have become available.

2. Surface Observations

Along the subtropical convergence zone, the output of simulations (covering 20 years, 1979-1998) shows that the heat content and SST are uncorrelated with the applied heat flux variability, as given by the meteorological fields produced by the European Centre for Medium Weather Forecasts (ECMWF) (Figure 1). This same lack of correlation can be found with heat flux fields and SST as measured by space-based satellite infrared instruments. The uncorrelated region covers approximately a wedge shaped area and is defined for the Pacific Ocean so that it begins in the west at a location approximately 22°N, 140°E and broadens to the east covering, at 120°W, an area between about 30°N to 42°N. Within this wedge SST is highly correlated with the heat content of the upper layers and with the upper steric height, as discussed by Koblinsky et al. [1998], for a given location and time and dominated by the seasonal cycle.

The relationship between heat content (storage) and upper steric height anomaly is defined at a location as

\[ H' = \rho c_p \int_{-300}^{0} T'(z) dz, \]  

if we assume that \( \rho \) and \( c_p \), the density and heat capacity, change by less than 1%. Direct substitution, therefore, gives

\[ H' = \frac{\rho c_p}{\alpha} \eta_s'. \]

The low frequency signal can be monitored by using a combination of remotely sensed measurements of SSH and SST. This signal is discussed, for example, in Zhang [1998] who note the changes in the temperature field at 400 meters and describe the decadal "see-saw" pattern in the midlatitudes and subtropics circulating in the North Pacific with a period of 20 years. We are proposing to monitor these integrated changes in the subsurface fields by using as a proxy - an adjusted sea surface height field.

3. Testing the method using a model

To test this approach, the output from an eddy-permitting high resolution (1/4°) primitive equation ocean model [Tokmakian and Challenor, 2000] is used to create a proxy heat content field from the anomalies of the model’s SSH and SST anomalies (SST'). The proxy field is then compared to the model’s own estimate of \( \eta_s' \) and \( \eta_{lower}' \) to see how well it represents the low frequency heat content signal in the subsurface layers of the ocean. In the example, the above quantities are extracted from the model fields along the transect shown in Figure 1. Figure 3 shows \( \eta_s' \) (a) and \( \eta_{lower}' \) (b), SSH' (c), and d) the estimate of the low frequency variability.

Figure 3d, the proxy "heat content" field (see equation 4), is created by computing

\[ \eta_s' = \alpha \cdot SS'H' - \beta \cdot SST'. \]

where \( \alpha \) and \( \beta \) are the optimal values from a set that corresponds to the regression of SSH' and SST' on both \( \eta_s' \) and \( \eta_{lower}' \). Physically, these coefficients represent the percentage of total signal that can be represented by either the SSH’ time series and the SST anomaly time series.

Figure 3a clearly shows the seasonal surface signal. The underlying interannual signal is difficult to detect, except for the especially strong "propagating" signal in the east between 1986 and 1990.
Figure 3. a-d are time-'longitude index' plots of the time varying anomalies of a) upper steric height of model (0-300m) b) lower steric height of model (300-bottom) c) model SSH d) computed "proxy heat content" using model SSH + model SST such that $\alpha*(\text{SSH}' - \beta*\text{SST}')$ e,f) same as a and b, except with altimeter data for 1992-2001 g) same as f, except with zonal SSH mean removed. Latitudes correspond to transect along the diagonal in Fig. 1. Units are in centimeters.
In Figure 3, the goal is to try to estimate the low frequency signal of the ocean’s heat content with real time products through the removal of the changes in the near surface seasonal effects. Optimal values are set for \( \alpha \) as 0.6 and for \( \beta \) as 0.5, \( \gamma' \). Figure 3d, can then produced and shows corrected SSH anomalies in centimeters, rather than in units of heat content. The coefficients vary somewhat across the section and average values are used rather than location specific values. This is due to the fact that our model, although fairly realistic, does not represent the true relationships in the ocean.

The skill (correlation squared) of the model (also described as the percentage of the variance explained) in Figure 3b in explaining Figure 3d is on the order of 0.6 (60%) for the points between 160°E and 210°E. The section between 210°E and 225°E is closer in its representation to Figure 3a, with the heat flux component removed (not shown), describing up to 80% of the variance. If it assumed that there are 20 independent points (20 year time series) then the SSH corrected series (Figure 3d) across the section are significantly \( \rho_{\text{critical}} = 0.44 \) correlated with the lower portion of the water column. The section between 210°E and 225°E is significantly correlated with the upper portion of the water column.

In the steric height field of the lower portion of the water column (Figure 3b), the unfiltered, monthly mean fields show many anomalies moving east to west, with a large increase in the height occurring mid-gyre, between the years 1987 and 1992. Figure 3c and d show the SSH monthly fields from the model without and with the correction considering the SST quantity. Figure 3c clearly shows the deeper interannual signal seen in Figure 3b. By examining the corresponding velocity vectors, the smaller spatial propagating signals are related to gyre movement north and south, while the large "warming" event is related to weaker winds in this region (seen in the model’s momentum fields) and result in less deep mixing.

The model output clearly shows that with adequate sampling of SSH and SST from satellites, it is possible to monitor the low frequency changes of the subtropical gyre, including changes in the deeper subsurface layers.

First, west of 175°E, (and thus, below 25°N) the variability in the water column changes similarly for the upper and the deeper waters below 300 m.

Second, east of 175°E and west of about 205°E (north of 30-30°N), the lower portion of the water column contributes most to the SSH variability. This is due to the strong influence of mixing to deeper levels and the variation of the winter mixing in different years. This strong, deep winter time mixing is forced by the anomalously strong wind forcing, indicated by the NP index value in Figure 2, thin black line with circles. The strong interannual variation in winter mixing extends further north, but the model simulation shows in the section east of 205°E and west of 225°E, that the upper ocean is the strongest contributor to the surface variability. This can be visually seen in Figure 3d between years 1986 and 1990 by the high anomaly feature which is stationary in space at 220°E. This feature may or may not be realistic, but in the model, this upper ocean signal is due the accumulation and some advection of heat in the upper layers of the model.

And finally, at the eastern edge, both the upper and lower portions contribute equally to the surface height variability.

How realistic is using an SSH 'corrected' by the satellite SST measurements in estimating the heat content of the subsurface layers? It has been suggested that the method is equivalent to removing the zonal mean of SSH from the SSH estimate. (Note, removing the zonal mean of SST produces a similar plot to Figure 3d). To understand the difference between removing zonal SSH signal and removing the local SST signal, a plot similar to Figure 3d was produced and an analysis of the difference was done. The comparison shows that west of about 180°E (and thus south of about 30°N), the two methods produce largely equivalent signals. East of 180°E (and north of 30°N), the two methods diverge, reflecting that the heat content variability is not just a change in the steric component forced by the atmospheric heat flux alone. To illustrate the difference, Figure 4 shows a time series extracted along 200°E for the SSH quantity corrected by SST (heavy red line), the SSH with a zonal mean removed (thin red line with stars), the heat content of the upper layers (black line) and the heat content associated with the lower layers (blue line). The heat content series are multiplied by a thermal expansion coefficient to convert to units of centimeters. The figure shows that there are similarities and differences between the two red lines and how they each reflect the heat content in the upper and lower model levels. The major differences exhibit themselves during the 1988 through 1994 period and during 1996-1998 period. In the first period, the difference shows that the zonal mean removes the signal that relates to the deeper waters. The zonal mean removal technique shows cooler ocean during the first period and a warmer ocean during the second period. The removal of the zonal SSH mean removes a portion of the interannual signal that is of interest.

From detailed analysis of the time series at all longitudes consisting of computing regressions and correlations, it is found that the method which best corrects SSH to reflect the heat content along the whole section uses the local SST values rather than a zonal mean SSH.

Next, the modeled SSH were replaced with satellite measured SSH, the average of available T/P and ERS data (10/1992 - 2001). The modeled SST is replaced with AVHRR
SSTs. The same adjustment to the SSH* fields is made as described above. The resulting three plots are shown in Figure 3e (the model plus altimeter SSH fields), f (the adjusted model plus altimeter SSH fields using the SST correction, and g (the SSH field adjusted using a zonal SSH mean). The first portions (1979-1992) of each plot are identical to Figure 3c and d and the rest (late 1992 through 2001) is the satellite data. For the latter portion of the record, it can be seen that the model fields are similar to what the satellites have measured. The difference between the plots with the SST correction and the zonal mean correction shows that removing a zonal mean SSH from each point results in a somewhat warmer ocean during the "cold" period centered around 1998/1999.

4. Independent Observations

To validate our estimates of changes in low frequency heat content as measured by satellites, an independent, in situ data set of ocean temperatures is compared to the proxy heat content. Available temperatures from ship observations, either CTD or XBT data have been incorporated into an on-line data set maintained by the Pacific Fisheries Environmental Laboratory (PFEL, NOAA). These data are provided via the PFEL - Live Access Server - and are monthly means of MEDS (Canada’s Marine Environmental Data Service) and other subsurface temperature observations received from NODC (NOAA’s National Oceanographic Data Center). The temperature data have been averaged on a 1 degree latitude/longitude grid and interpolated to 19 standard depth levels. 3 data sets make up the database: 1) Monthly real-time GTSP - for the period 1999-2001, 2) Best Copy GTSP - higher resolution delayed-mode data which often duplicates or supercedes real-time profiles for the period 1991-1998, and 3) World Ocean Data (Levitus) for 1979-1990. More data for a particular time period is incorporated into the database as time passes, resulting in less data for the recent past in contrast to five or ten years ago. For the purpose of providing an independent validation of the technique to estimate heat content, an average temperature anomaly change is then calculated for the top 300 meters and for the data available below 300m.

Figure 5 shows the two time-longitude plots along the same diagonal as before, but now extracted for subsurface in situ temperatures. This independent data set of subsurface temperatures shows that the eastern basin of the subtropical gyre is warmer after 1999, than between 1994 and 1999. The upper layers in Figure 5a clearly shows the seasonal cycle that is seen in Figure 3 for the modeled fields for the period when the data was from the World Ocean Data set (Levitus) (1979-1990). In the lower portion of the water col-
Figure 5. a) average temperature anomaly over top 300m from GTSP data set b) average temperature between 300 and 1000m from GTSP data set (note some depths may be missing)

umn (Figure 5b), the model has replicated the change seen in the observations which appear to propagate from east to west (for example 1984–1988). The observations also clearly indicate a cooling of the North Pacific in the east during the early 1990's with a tendency towards warming in 1999/2000 - similar to the altimeter estimates.

Figure 6 shows a similar time series to Figure 4 but with the modeled heat content replaced by the estimated fields from the data (Figure 5) and with the modeled SSH fields replace from October 1992 with satellite measured SSH (Figure 3f). We see that the satellite estimate appears to do a reasonable job with estimating the increase in the average temperature along 200°E. The plot also shows that the model contains a difference in an estimate of heat content between 1986 and 1990 from what the data shows. This is the model failing to reproduce the observed low frequency signal. After 1992, the SSH is from signal observed by the altimeters. The altimeter derived low frequency signal shows that it is reproducing qualitatively the change in heat content seen in the observations (a drop in heat content followed by a steep rise). The differences could be due to the sparse observational data set available at this time as compared to the first have of the time series shown. For completeness, a third line, the thin red line with stars, represents the change in heat content along 200°E with a zonal SSH mean removed from the SSH signal (extracted from Figure 3g). This line produces a similar result, with 1998 showing a warmer ocean than is calculated when just the SST signal is removed. Further investigations will be conducted to understand the usefulness of this estimate to both physical and biological oceanographers; including how this information might be useful to fishery science. A much longer time series of modeled fields, satellite data, and observational data is necessary to test the method further.

5. Discussion and Conclusions

Through the use of the output from the four dimensional ocean circulation model, we are able to explore further aspects of the circulation. Both coastal systems are significantly correlated with the variation in the North Pacific Current and its heat transport, with about 40% of the coastal flow prescribed by this large, low frequency, North Pacific signal (correlations are on the order of 0.6/0.7). During the early portion of our modeled simulation (1980s), both the Alaskan Current and the California Current show a relative increase in their transports (a period of a strong Aleutian Low and relatively low NP indexes, and a strong, warm Alaskan current).

In contrast, the period between 1988 and 1989, shows relatively weaker flow in both directions. This middle period is
the period with higher than average NP Index values (relative to the period 1979 - 2002) [Trenberth and Hurrell, 1994], indicating weaker mixing and warmer mid-gyre temperatures ("Type A" circulation pattern [McGowan et al., 1998]).

In the late 1990’s, the pattern returned to something similar to the early 1980’s with generally strong westerlies and "Type B" circulation patterns. This is consistent with what Qiu [2002] found when looking only at the T/P data for the 1990s. Now in the 2000’s, the westerlies have weakened again (with a NP index relatively higher than the mid-1990s) and the mid-gyre SSH anomaly is positive through late 2001 and the coast region a cooler, "Type A" regime. On average, the flow northward during the early 1980’s and late 1990’s is relatively strong as compared to the early 1990’s The temporal change in the strength of the flow to the south appears to also follow this same pattern, but modified by the El Niño signal.

To understand how the SSH anomaly information might be useful in predicting the available fish catch for a future year, the total salmon catch off of Alaska (Personal communication from the National Marine Fisheries Service, Fisheries Statistics and Economics Division, Silver Spring, MD, 2002 www.st.nmfs.gov/st1) is compared with the low frequency SSH anomaly in the middle of the gyre, seen initially in Figure 2. It is, also, a well known fact that the the Alaskan salmon catch time series is out of phase with the Washington/Oregon catch [Mantua et al., 1997]. During the early 1980’s the Alaskan catch, relative to our plus 20 year time series, is low. The Alaskan catch begins to increase from the mid to late 1980’s into the mid 1990’s, where it then fluctuates through the late 1990’s into the 2000’s. The mid-gyre, indicating a "Type B" pattern (early 1980’s,1990’s), corresponds to a trend towards increasing Salmon catch in the Alaskan Gyre. The series also reflects a slight drop in the fish catch during a short "Type A" phase at the end of the 1980’s and then again in the 2000’s. The estimated SSH anomaly signal from the mid-gyre region indicates that central Northeast Pacific is warming (higher SSH values) significantly from late 1998 and continuing on into 2002. The "type A" phase thus indicates cooler waters off the Alaskan coast and less nutrient rich water supply from the mid-gyre, and weaker northward flow leading to a reduction in the stock available for catch. Off the Oregon and Washington coast, the salmon catch tends to fluctuate in the opposite sense.

In summary, an empirical technique which monitors the low frequency changes in SSH and associated heat content along a transect in the North Pacific has been developed and tested using both simulated fields and space-based measurements. By comparing to in situ data, the paper shows that using SST fields to remove the surface signal in the upper heat content of the oceans is a reasonable way to estimate the changes in the strength of the mid-gyre of the North Pacific and might contribute to a better estimate of predicting fish catch in the North East Pacific ocean. Given the estimate of the SSH anomaly for the end of 2001 (Figure 3f), it suggests that the trend is for a decrease in the salmon catch off of Alaska and an increase in catch off Oregon and Washington.

Acknowledgments.

This work is funded by grants from NASA JSMAT, DOE, and from NOAA GLOBEC -North Eastern Pacific. Computer computations for model simulations provided by NCAR. Thanks to Koblnsky, et al., for altimeter pathfinder data, to JPL for AVHRR Pathfinder data (MC SST), and to PFEL (Lynn DeWitt). The author thanks the two reviewers for their time and the suggestion from one to look at how the method differs from a method which removes a zonal mean.

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Received Dec, 2002; revised May, 2003; accepted June, 2003.