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Analysis of AVHRR, CZCS and Historical *In Situ* Data Off the Oregon Coast (NAGW-869)

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Final Report

Introduction

The original scientific objectives of this grant were to: 1) characterize the seasonal cycles and interannual variability of phytoplankton concentrations and sea surface temperature (SST) in the California Current using satellite data; and 2) to explore the spatial and temporal relationship between these variables and surface wind forcing. An additional methodological objective was to develop statistical methods for forming mean fields, which minimize the effects of random data gaps and errors in the irregularly sampled CZCS (Coastal Zone Color Scanner) and AVHRR (Advanced Very High Resolution Radiometer) satellite data. A final task was to evaluate the level of uncertainty in the wind fields used for the statistical analysis. Funding in the first year included part of the cost of an image processing system to enable this and other projects to process and analyze satellite data.

As proposed, monthly mean fields of surface pigment and SST were to be formed from processed CZCS and AVHRR data made available to us by JPL in the West Coast Time Series (WCTS). Gridded wind fields formed from a mix of observations and models were to be obtained from the Navy's FNOC (Fleet Numerical Oceanography Center) archive and from the National Center for Atmospheric Research archive. Measured winds were to be obtained from the National Data Buoy Center (NDBC) for specific locations in order to evaluate which gridded wind product was more accurate. Historical *in situ* surface pigment data were to be obtained from Bill Pearcy at OSU. These data were to be analyzed using the methods of time series analysis: harmonic analysis, cross-correlation, optimal interpolation, empirical orthogonal functions (EOF), and principal estimator patterns (PEP).

As described below and in the appendices, the above plans were carried out and the objectives were achieved, with the exception of the AVHRR data analysis. The analysis of coincident AVHRR and CZCS data was not possible, since the WCTS of AVHRR data was not processed and made available to us. Because the biological component of this interdisciplinary study was the more unique aspect, however, we were able to accomplish most of our goals without the AVHRR data. In lieu of the AVHRR analysis, the biological component was extended to include zooplankton as well as phytoplankton. *In situ* zooplankton biomass data were obtained from the CalCOFI

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(California Cooperative Oceanic Fisheries Investigations) archive and their annual and interannual variability were described. In addition, sea level height data were used as a proxy for oceanic currents and SST and compared to the alongshore wind stress at the time of the onset of seasonal upwelling, as the SST would have been. Finally, AVHRR data from 1987-1988 (which was being analyzed under separate, ONR funding) were used to compare the typical summertime spatial patterns of SST to those of the historical (1979-1986) CZCS mean fields, allowing us to relate AVHRR and CZCS data to each other. Thus, the lack of historical AVHRR data did not diminish the quantity or quality of the research accomplished under this grant, although it changed the way in which we sought to achieve the original goals. Work supported wholly or partially by this grant resulted in 5 refereed papers, a Masters thesis, a chapter in the Coastal Ocean Prediction Systems (COPS) report, and 12 presentations at professional conferences or universities (see Appendix A).

The rest of this report consists of summaries of the major projects carried out with all or partial support from this grant. The appendices include a list of papers and professional presentations supported by the grant, as well as reprints of the major papers and reports.

Analysis of *In Situ* Zooplankton Data

A 32-year record (1951–1982) of zooplankton displacement volume was obtained from the CalCOFI archive. Data were analyzed over the region within several hundred kilometers of the coast from approximately 24°N–37°N (Baja to central California). A comparison between zooplankton biomass and geostrophic transport was made for both the seasonal and interannual time scales. Details are presented in Appendix B. The conclusions of the study are:

1. Seasonal variability of zooplankton biomass shows maxima and minima that are nearly coincident with maxima and minima of southward transport in the California Current. Thus, the seasonal variability is largely controlled by advection of the biomass over most of the region.
2. Nonseasonal variability of $\log_e$ transformed zooplankton biomass is dominated by a low-frequency (3–5 year period) signal. In the northern part of the domain, this variability is associated with variations in the geostrophic transport of biomass, as it was for seasonal variability. In the southern part of the domain, there is a time lag between advection and zooplankton response, implying that biomass responds to environmental changes in nutrients, temperatures, etc. brought on by advection, rather than simply advection of biomass. Analysis of species and age-class distributions supports this conclusion.
3. Nonseasonal variability of non-$\log_e$ transformed zooplankton biomass is dominated by much shorter period (3-4 month) episodic bursts of biomass, followed by rapid decrease in biomass. These burst may be linked to the episodic injection of nutrients into the core of the California Current by offshore filaments north of the study region. Evidence for this hypothesis comes from one period in 1980, when the CZCS

sensor showed offshore patches of surface pigment in February and the CalCOFI data indicated a burst of zooplankton biomass in April–May.

Evaluation of Alternate Wind Fields

Three types of gridded wind fields were obtained: 1) FNOC winds formed from observations every six hours with grid spacing of approximately 380 km; 2) LFM (Limited-Area Fine Mesh) 6-hour forecast winds with grid spacing of approximately 180 km; 3) NGM (Nested Grid Model) 6-hour forecast winds with the same grid spacing as the LFM. Winds from NDBC buoys were in hand at OSU from other projects for the period 1980-1983 and 1987-1988. The NGM winds are a newer product, beginning in 1986, and cannot be used with the 1979-1986 CZCS data. They were included in the comparison as a possibility for future use. They are calculated on a grid with twice the spatial resolution of the LFM winds, although they are only archived on the same grid as the LFM. They have a better boundary layer parameterization and may represent surface winds better.

Details of the comparison of the gridded fields to each other and to the buoy winds can be found in Appendix C. The conclusions of the comparison are as follows:

1. RMS differences between instantaneous LFM and FNOC winds are 3.5–5.5 m s^{-1}, caused somewhat more by differences in direction than speed. RMS Differences between longer averages, such as monthly means, are lower, in the range of 1–3 m s^{-1}. Thus, it may make less difference which winds are used for climatological studies than for shorter "events".
2. Correlations between the gridded fields and the buoys are slightly higher for FNOC and NGM winds than for LFM. Correlations are higher 200-500 km from the coast than they are over the shelf 10 km from the coast. In the 1980-1983 period, RMS differences between the buoys and LFM winds are 3–6 m s^{-1}; RMS differences between the buoys and FNOC winds are 2–5 m s^{-1}. In both cases RMS differences are lower in summer and farther offshore than they are over the shelf. Although the LFM winds produced slightly lower correlations and slightly higher RMS differences, their orientation over the shelf was more alongshore, like the buoy winds, than were the orientations of the FNOC winds.
3. Spatial differences in the alongshore winds over alongshore distances greater than 600–900 km are well represented by both LFM and FNOC fields. Spatial differences in the cross-shelf winds are not as well represented. The increased spatial resolution of the LFM fields does not increase their ability to accurately resolve smaller scale wind features.
4. Fields of wind stress curl from both LFM and FNOC both have a band of positive curl near the coast in summer south of 44 °N, as expected from ship observations, but not north of 44 °N, which is thought to be in error. The band of positive curl is too broad and the values are too weak, but the temporal correlation with the few measurements available is significant (0.7). Thus, time series of LFM and FNOC

curl represent about 50% of the day to day variability of the real curl, but with magnitudes that are 4–10 times too small.

5. Fields of wind stress curl formed from the NGM winds have a narrower band of curl that extends all along the US coast in summer, with higher values than those from the LFM or FNOC winds. Thus, studies of the ocean for the period from 1986 on should use these winds rather than the LFM and FNOC winds.

From these comparisons, we concluded that there would be little difference in results caused by using monthly averages of either the LFM or FNOC winds. For shorter periods, the FNOC winds appear slightly better. Starting in mid-1986, the NGM winds are better.

Analysis of *In Situ* Surface Pigment Concentrations

Surface pigment concentrations were collected during cruises in May– September 1980–1985. These data were collected on cross-shelf transects that were widely spaced in the alongshore direction. Although these data were initially gridded and contoured, the alongshore sampling proved too coarse to interpret the data as complete fields with any confidence. The data did prove useful, however, for two purposes. First, coincident pairs of satellite and *in situ* surface pigment allowed an estimate of the accuracy of the satellite pigment concentrations. The agreement was in the usual range of a factor of 2, but perhaps slightly larger. Secondly, the pattern of interannual variability seen in the satellite data was supported by a similar pattern in the *in situ* values, giving more confidence to the conclusions based on the satellite data.

Atmospheric Forcing of the Spring Transition

In many years, an abrupt change in the wind patterns occurs in spring that begins the spring–summer upwelling regime. The oceanic response is also abrupt and has been found to be persistent off Oregon and less so as one goes south to southern California, where it may not appear at all. As part of our interdisciplinary exploration of the connection between the atmosphere and the coastal ocean, we used the methods of compositing events to look at the progression of patterns of surface pressure fields over the North Pacific and North America. We also examined the fields of 500 mb height to see if the atmospheric event was driven by, or extended to, changes in the jet stream. The compositing method was supplemented by EOF and PEP analysis, using sea level heights as a proxy for oceanic currents and temperatures. Besides providing scientific insight into this coupled atmosphere-ocean event, this analysis gave us experience with the principal estimator technique using strictly physical variables, where we expected the connection between variables to be tighter than it would be when we included satellite-derived pigment. If AVHRR data had been available, it would have provided a physical oceanic variable with which to test the PEP method. The sea level height data was available from previous projects and provided us a means of circumventing the lack of AVHRR data. Under separate funding, the examination of the spring transition was extended to the CZCS data set to determine the biological response to this surface forcing.

Details of the analysis can be found in the paper included as Appendix D. The conclusions of the analysis are:

1. There is both a gradual seasonal buildup of high pressure over the northeast Pacific and an abrupt expansion and intensification of that high pressure coincident with the increase in upwelling-favorable winds and the drop in sea level characteristic of the transition.
2. This buildup of high pressure is coincident with a change in the 500 mb height fields, causing a ridge over the high pressure that lasts for 5–10 days.
3. After the initial 5–10 day period, the stability of the high pressure is not due to a classic "atmospheric blocking" pattern. Instead, the high pressure in the northeast Pacific is part of a dipole pair (high pressure south of low pressure) that is upstream of an opposite sign dipole pair (high pressure north of low pressure) over the North American continent, which sits under a diffluent pattern in the jet stream. This double vortex pair, under a diffluent jet has been found to be quite stable in numerical models of geophysical fluids.

Annual/Interannual Variability of Surface Pigment Concentrations

This was the main thrust of the proposal and received the most attention, although progress was slow due to initial delays in getting the CZCS data and subsequent questions about the quality of the data. The details are presented in the paper found in Appendix E. The conclusions of the study are:

1. As originally processed, the WCTS CZCS data cannot be used to look at seasonal cycles, since the single-scattering Rayleigh algorithm produces unrealistically high values in high latitudes in winter. To account for this effect, we first formed a correction function from a north-south strip as far offshore as possible. The assumption was that surface pigment values were low all year long in the region far from the coast, so any signal with a maximum in winter was a signature of the algorithm failure. The first EOF of the offshore strip had a maximum in winter and a monotonic increase from south to north. This EOF explained 70% of the variance and was used to correct the CZCS data as a function of time and latitude. Values for the months November–February were still suspect and this period was excluded from most of the analysis.
2. Using March–October monthly means of the corrected CZCS data, a reasonable seasonal progression was found that includes 1) a double maximum off Washington (spring bloom, die-down and late summer max); 2) a summer maximum off Oregon; 3) a large-scale spring bloom off California from 35°N–43°N that covers a large offshore region, followed by a decrease in offshore values in summer, limiting the high pigment areas to a narrower, scalloped region within 100–200 km of the coast, followed by an expansion to a more diffuse region of moderately high values in fall; 4) very low values with almost no seasonal variability in the southern California

Bight (32°N–35°N); 5) a seasonal progression off Baja California that is similar to that off northern California.

3. From approximately 35°N–45°N, there is a northward progression of the spring–summer maximum that is similar to the northward progression of both upwelling favorable winds and the maximum of positive wind stress curl. Thus coastal and/or offshore upwelling of nutrients is the likely cause of the spring–summer bloom. North of 45°N, the early spring bloom coincides with the seasonal decrease in wind mixing power, suggesting that an increase in stratification allows the phytoplankton bloom, as it does in the north Atlantic. We plan to test the hypothesis that different mechanisms are responsible for phytoplankton dynamics in different regions using the global CZCS data set in a proposal presently under review by NASA.
4. After removing the seasonal cycle, the interannual variability of the monthly anomalies was found to be dominated by the 1982–1983 El Niño, producing the appearance of a single cycle of a long-period fluctuation over the 1980–1986 period. Simple correlations between monthly anomalies of pigment concentration and various wind variables were only marginally significant. EOF and PEP analysis showed that over the larger-scale California Current, the wind variable most closely related to pigment was the wind stress curl. Over the region within 100 km of the coast, the upwelling- favorable alongshore wind stress and the wind mixing power were the more important wind variables and it was not possible to separate their effects, since the two are so closely correlated to each other.
5. Only 25% of the nonseasonal pigment variability could be related to wind variability. This confirmed our expectation that connections between biological variables and physical forcing is much weaker than the connections between physical forcing and physical responses. For instance, 90% of the sea level variability was related to alongshore wind stress by the first two PEP patterns (Appendix D). The weaker connection between physical forcing and biological variability may be partly due to greater noise in the CZCS data than in sea level data. It is also a reflection of the greater natural variability of biological variables and their episodic, non-linear response to forcing.

Estimation of Mean Fields from Irregularly Sampled Satellite Data

In this study, a method of quantifying the error in estimates of time averages formed from irregularly sampled data at one location was developed. The method was used to compare the usual "composite averages" of CZCS data to an "optimal estimate" of the average. The optimal estimate of a temporal mean is an extension of the more conventional optimal interpolation technique of estimating a point value from irregularly sampled data. It requires a knowledge of the variances and correlation functions of the chlorophyll signal and the CZCS measurement errors. The composite averages were compared to the optimal estimates for known time series that have been subsampled with the actual CZCS sampling pattern at two locations. Thus, by knowing the true temporal means, the level of error of the estimates was quantified. Details are presented in the paper in Appendix F. The conclusions are:

1. The accuracy of the composite average is very sensitive to the actual sampling pattern, the measurement error-to-signal variance ratio, the averaging period, and the measurement error correlation time scale. The optimal estimate is much less sensitive and much more accurate.
2. If the true variances and correlation functions are not known and assumed values are used, the estimates become "suboptimal estimates". Comparison of the optimal and suboptimal estimates shows the suboptimal estimates to be only weakly dependent on the measurement error-to-signal variance ratio and the signal correlation function, but strongly dependent on the measurement error correlation time scale. Suboptimal estimates become much less accurate than optimal estimates if the measurement errors are correlated on times scales greater than a week, but are still more accurate than composite averages.
3. The length of the averaging period over which the optimal estimate can be made accurately depends on the measurement error-to- signal variance ratio. For values of 1.5, as assumed here, 30-day mean optimal estimates are good, but 10-day means are too smooth. Shorter mean optimal estimates become acceptable as this ratio is reduced.

Comparison of Historical CZCS Patterns with SST and Surface Currents

Under ONR funding, P. T. Strub participated in the Coastal Transition Zone (CTZ) experiment, which looked at the biological and physical structure of the filaments which appear in both the CZCS and AVHRR images in summer. One of the conclusions from that work was that the filaments are often the result of a meandering jet, which separates the warmer and oligotrophic offshore waters from the colder and more eutrophic water next to the coast.

The biological effect of this meandering current was made clearer by comparing the historical mean summer CZCS fields to the 1987-1988 AVHRR fields. The scalloped nature of the high pigment region next to the coast in summer was found to correspond quite well to the locations of offshore meanders (seen as SST and pigment filaments) and onshore meanders, which in some instances occurred on the northern side of anticyclonic eddies. These anticyclonic eddies appear as the low pigment regions of the scalloped pattern.

The fact that these meanders and eddies have preferred locations was demonstrated by the fact that they can be seen in longer term (4-year) means of the CZCS data. The CZCS images also clarified the biological implications of the meandering jet i.e., that the jet separates the richer inshore water from the poorer offshore water but at the same time carries the richer water along on the inside of its offshore meanders, extending 300 km or farther offshore. Thus, data and effort funded by the present NASA grant allowed us to extend the interpretation of the 1987-1988 AVHRR data. Conversely, the ONR funded CTZ project allowed us to make the connection between SST and pigment, as originally proposed in this NASA grant, even though the historical AVHRR data did not become available. The final paper describing the nature of the filaments is included in Appendix G.

APPENDIX A – Publications and Presentations

Refereed Journal Papers

Roesler, C. S., and D. B. Chelton. Zooplankton variability in the California Current, 1951–1982. *CalCOFI Rep.*, **23**, 59-96, 1987.

Strub, P. T. and C. James. Atmospheric conditions during the spring and fall transitions in the coastal ocean off western United States. *J. Geophys. Res.*, **93**, 15561-15584, 1988.

Strub, P. T., C. James, A. C. Thomas and M. R. Abbott. Seasonal and non-seasonal variability of satellite-derived surface pigment concentration in the California Current. *J. Geophys. Res.*, **95**, 11,501-11,530, 1990.

Chelton, D. B., and M. G. Schlax. Estimation of time-averaged chlorophyll concentration from irregularly-spaced satellite observations. *J. Geophys. Res.*, (submitted), 1990.

Strub, P. T., P. M. Kosro, A. Huyer, and the CTZ Group. The nature of the cold filaments in the California Current System. *J. Geophys. Res.*, (submitted), 1990.

Reports

Roesler, C. S. Zooplankton variability in the California Current, 1951–1982. *M.S. Thesis*, Oregon State University, 1987.

Strub, P. T. Evaluation of surface wind fields over the coastal ocean off the western U.S. in, The Coastal Ocean Prediction Systems Program: Understanding and Managing our Coastal Ocean, **II**, Overview and Invited Papers, 146–165, 1990.

Presentations

Chelton, D. B. The Coastal Zone Color Sensor: Theory and oceanographic applications. Ball Aerospace Corporation, Seminar (Invited). Boulder, Colorado, June, 1985.

Strub, P. T. Monthly fields of chlorophyll off Oregon and Washington in summer 1981-83. NASA Workshop on Ocean Color Remote Sensing, Sterling Forest, New York, May, 1986.

Roesler, C. S. and D. B. Chelton. The spatial and temporal structure of nonseasonal zooplankton variability. CalCOFI Conference. Lake Arrowhead, California, October 1986.

Strub, P. T. Large-scale horizontal variation in the coastal ocean wind forcing. IUGG (IAPSO) XIX General Assembly, Vancouver, Canada, August, 1987.

Strub, P. T. The atmospheric event associated with the spring transition in the coastal ocean. American Geophysical Union, Fall Meeting, San Francisco, California, December, 1987.

Roesler, C. S., and D. B. Chelton. Zooplankton variability in the California Current, 1951–1982. American Geophysical Union,Fall Meeting. San Francisco, California, December, 1987.

Chelton, D. B. Large-scale, low frequency physical and biological interaction (Invited). American Geophysical Union, Fall Meeting. San Francisco, California, December, 1988.

Chelton, D. B. CalCOFI: A 40-year survey of the California Current System. (Invited Presentation) David Taylor Naval Research Center, Deep-Sea Observatory Meeting, Bethesda, Maryland, November, 1989.

Strub, et al. The nature of the cold filaments in the California Current – squirts or meanders? et al.) American Geophysical Union, Ocean Sciences Meeting, New Orleans, Louisiana. February, 1990.

Strub, P. T., C. James, and A. C. Thomas. The seasonal cycle of CZCS- derived surface pigment concentration in the California Current. American Geophysical Union, Ocean Sciences Meeting, New Orleans, Louisiana, February, 1990.

Strub, P. T., C. James, and A. C. Thomas. Interannual variability of satellite-derived surface pigment concentration in the California Current. Canadian Meteorology and Oceanographic Society; 24th Annual CMOS Congress, Victoria, B.C., Canada, May, 1990.

Chelton, D. B. Estimation of time-averaged chlorophyll concentration from irregularly speed satellite observations. University of Colorado, Aerospace Engineering Sciences Seminar, Boulder, Colorado, July, 1990.