Investigation of the seasonal-to-interannual variabilities of the ocean by assimilating satellite altimetry and ancillary data into numerical ocean models

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We study the physical processes underling ocean circulation variations derived from satellite data and in-situ measurements. Our approach is to estimate the currents, temperature, salinity and other properties throughout the ocean (the complete three-dimensional state) by combining satellite altimeter observations, other measurements, and numerical models of ocean circulation. Mechanisms of the mean and time-varying ocean circulation are examined, with particular focus on identifying dominant processes that control seasonal-to-decadal changes of the Pacific Ocean (e.g., El Niño/ La Niña, Pacific Decadal Oscillation).

The heat and fresh water exchange between the oceans and the atmosphere dictate the impact of the ocean on climate at seasonal-to-decadal time-scales. Understanding how the ocean transports, stores, and releases heat and water to the atmosphere is fundamental to advancing our knowledge of the ocean's role in climate change. However, large discrepancies exist among different estimates of ocean circulation. The reason for these discrepancies are 1) incomplete observations, and 2) temporal variations in the global ocean state between observations. For instance, interannual variability in the Tropical Pacific Ocean in the 1980s appears to be different from those in the early 1990s. The prolonged persistence of warm conditions over the Tropical Pacific Ocean in the early 1990s may be due to influx of anomalously warm waters from the Subtropical Pacific Ocean [Gu and Philander, 1997]. The El Niño event of 1997-98 appears to be different from those in the early 1990s, but similar to that of 1982-1983.
In particular, changes in sea level suggest that a possible climate shift occurred in 1999 associated with the Pacific Decadal Oscillation (http://topex-www.jpl.nasa.gov/discover/PDO.html).

Changes in sea level, to a large extent, reflect changes in vertically integrated heat content, and therefore altimetric measurements can shed much light on how heat is transported. Jason-1, together with TOPEX/POSEIDON which has been operational since September 1992, will provide a continuous record of observations that offers an unprecedented opportunity to examine the temporal changes of the ocean's heat content, in particular, the seasonal-to-interannual variability of heat transport over the last decade.

In spite of its global coverage, altimetric sea level measurements alone cannot reveal the inherently three-dimensional nature of ocean circulation. Numerical ocean circulation models can help extrapolate information obtained from satellite observations into the ocean interior and can combine them further with those from in situ measurements. These models can be thought of as providing theoretical relationships among various properties of the ocean. Assimilation of observations with numerical models amounts to solving a set of simultaneous equations, many of which are nonlinear and have enormous dimensions owing to the ocean being a vast continuum (on the order of hundreds of millions of equations). Various approaches have been advanced to efficiently solve such complex computational problems [Fukumori, 2000].

Data assimilation provides optimal descriptions of the complete state of ocean circulation, allowing estimates of various properties including those that are not directly measurable. For instance, figure 1 compares temporal changes in subsurface circulation estimates made from altimeter data [Fukumori et al., 1999]. The impact of altimeter data is evidenced by the assimilated estimates (blue) being in closer agreement with independent in situ measurements (black) than the unconstrained model estimates (red) are. Improved estimates of temperature and velocity give better understanding of the ocean's mass

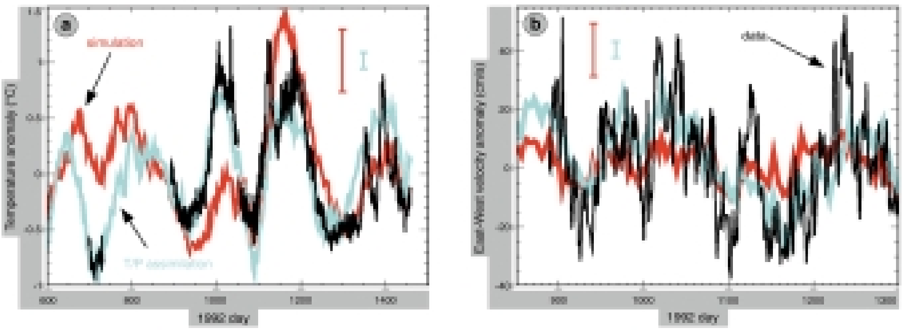

Figure 1: Comparisons of temporal variability; (a) temperature anomaly at 200 m 8°N 180°E, (b) east-west velocity anomaly at 120 m 0°N 110°W. Curves are in-situ data (black), TOPEX/POSEIDON altimeter assimilation (blue), and unconstrained model estimate (red). Bars denote expected errors of respective model estimates.

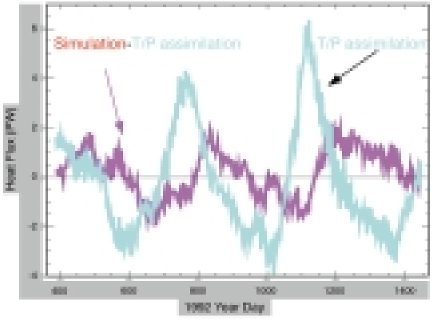

Figure 2: Variability of zonally integrated northward heat flux (peta watts) in the Pacific Ocean along 2°N. The curves are estimates from a TOPEX/POSEIDON altimeter assimilation (blue) and its difference from an unconstrained model estimate (magenta).

and heat transport and their balance. Figure 2 shows the variability of zonally integrated northward heat flux estimated across the Pacific Ocean. The large seasonal cycle reflects changes in wind-driven surface circulation. Differences resulting from assimilation are due to corrections of model errors at depth and amount to a fair fraction of the total variability that would lead to significant differences in how the ocean affects the atmosphere.

The comprehensive description of the ocean by models helps quantitatively evaluate and understand processes in the ocean. Figure 3 shows an example comparing estimates of different processes affecting anomalies of sea surface temperature in the eastern equatorial Pacific ("Niño3" region). Sea surface temperature dictates surface heat flux from the ocean to the atmosphere, and is therefore a central quantity of interest. Figure 3 indicates that advection (in particular, the east-west component) was the primary cause of the positive sea surface temperature anomaly associated with the 1997-1998 El Niño event. Such evaluation would be difficult without a physically consistent description of the entire state of the ocean.

Analyses of circulation pathways provide additional insight into mechanisms of ocean circulation. Model-based solutions are particularly valuable in such assessment owing to their high spatial and temporal resolution. Figure 4 shows an example describing pathways of water parcels estimated over a two-year period released in January 1985 along 24°N and 24°S. Such analysis helps distinguish different dynamic regimes that determine water mass evolution and improves our understanding of how changes in one part of the ocean might affect another. For example, the figure illustrates that water reaching the equator originates in the eastern half of the subtropical basin (red and green) with most of it traversing the energetic western boundary region before reaching the equator.

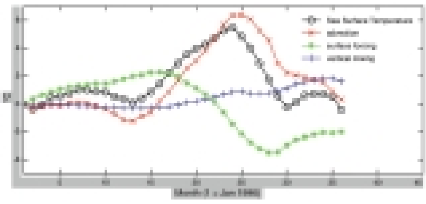

Figure 3: Comparison of processes affecting sea surface temperature variability in the eastern equatorial Pacific (210°E-270°E, 5°S-5°N) from January 1996 to December 1998; sea surface temperature (black circle), advection (red cross), vertical mixing (blue plus), surface forcing (green star).

These analyses above will be expanded with the advent of Jason-1. The inclusion of more observations together with further improvements in modeling and data assimilation will lead to increasingly more accurate and complete descriptions of ocean circulation. Advancements will also allow assimilated analyses to be produced routinely so as to provide a monitoring tool for events such as the El Niño. Routine descriptions will enable predictability studies of the coupled ocean-atmosphere system, by providing initial conditions of the oceanic state. Estimates of oceanic advection and mixing will also facilitate understanding tracer distribution that is critical in modeling biogeochemical processes of the ocean.

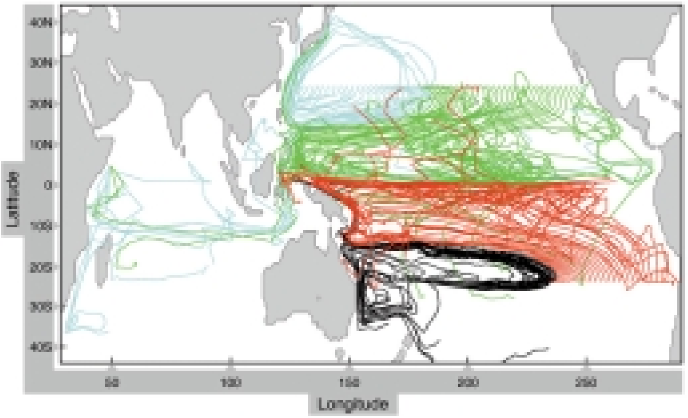

Figure 4: Trajectory of water parcels originating at 50 m, 24°S and 24°N, from 1985 to 1997. Colors indicate different origins; trajectories originating in the eastern (western) half of the domain are in red (black) and green (blue) at 24°S and 24°N, respectively.

References

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