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Estimating the ocean flow field from combined sea surface temperature and sea surface height data

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Final Project Report

The primary focus of this project was on the estimation of the three-dimensional, absolute and time-evolving general circulation of the global ocean from a combined analysis of remotely sensed fields of sea surface temperature (SST) and sea surface height (SSH). The synthesis of those two fields was performed with other relevant physical data, and appropriate dynamical ocean models with emphasis on constraining ocean general circulation models by a combination of both SST and SSH data.

This effort is directly related to an attempt to describe the mechanisms which give rise to observed SST and its variability on seasonal and inter-annual timescales, its relation to ocean-atmosphere interaction, and the dynamical coupling between the ocean mixed layer and the deep interior ocean. This is one of the fundamental climate related questions being pursued currently under the CLIVAR Program. Because of the strong turbulent mixing associated with atmospheric fluxes of momentum, heat and freshwater through the sea surface, the ocean forms a shallow surface boundary layer — the mixed layer — which is largely homogeneous in its constituents. The relation between the temperature of the remotely sensed "skin" and the bulk of the mixed layer is largely understood (Reynolds and Smith 1994; Emery et al., 1995). However, because the surface mixed layer is effectively decoupled from the underlying ocean dynamics, an interpretation of satellite SST observations in isolation and in direct use for dynamical studies is very difficult. As a result, the impact of SST data on the understanding of ocean variability and related dynamical processes has been only minor, as compared to the (much shorter) altimeter data set.

The central goal of the project was therefore to improve our understanding and modeling of the relationship between the SST and its variability to internal ocean dynamics, and the overlying atmosphere, and to explore the relative roles of air-sea fluxes and internal ocean dynamics in establishing anomalies in SST on annual and longer time scales. An understanding of those problems will feed into the general discussion on how SST anomalies vary with time and the extend to which they interact with the atmosphere. Most specifically we aimed at understanding the relations between the SST anomalies and subsurface current fluctuations which can be used to constrain the internal ocean flow field in combination with other data such as SSH. At the same time this insight can lead to an improved understanding of ocean surface heat fluxes and their errors.

The data sets analyzed as as part of this project were primarily the Reynolds and Smith (1994) SST analysis as provided by the National Center for Environmental Prediction (NCEP) on a weekly basis, and 10-day averaged SSH fields observed by the TOPEX/POSEIDON altimeter mission. We used those fields alone for data-based studies and in combination with NCEP surface forcing fields. We also used them in combination with a numerical model in model-data assimilation approaches. But to make quantitative use of SST data in constraining OGCMs, one needs to understand in particular mixed layer processes which lead to observed SST in response to surface momentum, and buoyancy fluxes. Various different approaches are here possible.

Our approach was therefore first to investigate the SST data in combination with other data sets to explain observed SST variations in terms of surface fluxes and ocean dynamics. The next steps included the improvement of mixed layer formulations in the MIT ocean model and the assimilation of SST and SSH data into the same model. The emphasis here was on constraining ocean general circulation models by a combination of both SST and SSH data sets to obtain a dynamically consistent picture of the ocean state. This work build on previous efforts in constraining ocean circulation models by altimeter observations (Stammer and Wunsch, 1996; Stammer et al., 1997)

Given the different goals of this project, the work during time frame March 1998 to December 1999 fell naturally into the following the following sub-categories of statistical analysis and data assimilation.

1) Statistical Analysis:

Purely empirical methods are a necessary first step to test the remote sensing data against in-situ ocean observations and against models of the upper ocean physics build into general circulation models. During this step the space-time variability of SST on sub-annual, annual, and inter-annual timescales was studied in relation to sea surface flux estimates provided, e.g., by meteorological centers, and observations of SSH. This analysis included the computation of various statistical quantities such as global and regional SST frequency and wavenumber spectra, a common EOF analysis of SSH and SST as well as a detailed study of atmospheric forcing fields and their relation to SST and SSH variability.

A full summary of the respective work and results are given in the attached paper by Leeuwenburg and Stammer (2000). In that paper, we investigate regional and global-scale correlations between observed anomalies in sea surface temperature and height. A strong agreement between the two fields is found over a broad range of latitudes for different ocean basins. Both time-longitude plots and wavenumber-frequency spectra suggest an advective forcing of SST anomalies by a first-mode baroclinic wave field on spatial scales down to 400 km and time scales as short as 1 month. Even though the magnitude of the mean background temperature gradient is determining for the effectiveness of the forcing, there is no obvious seasonality that can be detected in the amplitudes of SST anomalies. Instead, individual wave signatures in the SST can in some cases be followed over periods of two years.

The phase relationship between SST and SSH anomalies is dependent upon frequency and wavenumber and displays a clear decrease of the phase lag toward higher latitudes where the two fields come into phase at low frequencies. Estimates of the damping coefficient are larger than generally obtained for a purely atmospheric feedback. From a global frequency spectrum a damping time scale of 2-3 month was found. Regionally results are very variable and range from 1 month near strong currents to 10 month at low latitudes and in the sub-polar North Atlantic. Strong agreement is found between the first global EOF modes of 10 day averaged and spatially smoothed SST and SSH grids. The accompanying time series display low frequency oscillations in both fields.

2) Mixed layer model implementation and Data Assimilation:

To understand observed SST variability, it is important to have the best possible representation of mixed layer dynamics implemented in our ocean general circulation models. For that purpose we implemented the KPP mixed layer model (Large et al., 1994) into the MIT ocean circulation model to study the local variation of SST in relation to surface forcing, heat content, and salt and mixed layer depth. These studies were performed in combination with ocean observations, e.g., from the subduction experiment (B. Weller, pers. communication). With only a traditional convective adjustment parameterization, the heat uptake in the model is limited to the top model layer. In contrast, the implementation of the KPP model leads to quite an accurate development of the mixed layer depth and heat uptake during the late summer deepening phase.

One of the major reasons for observing the global ocean is to infer the transport properties of quantities important to climate, including heat, freshwater, carbon, oxygen, etc. Our focus during this project was on the time-evolving global circulation as it emerges primarily from altimetric measurements, SST fields and an ocean general circulation model. Computations were performed during which the MIT circulation model was constrained over the 6 year period 1992 through 1997. Data constrains include the absolute and time-varying T/P data (relative to the EGM-96 geoid model; see *Lemoine et al.*, [1997]) from October 1992 through December 1997, SSH anomalies from the ERS-1 and ERS-2 satellites, and the time-varying NCEP Re-Analysis fluxes of momentum, heat and freshwater. Monthly means of the model state are required to remain within assigned bounds of the monthly mean Levitus et al. (1994) climatology, and NSCAT estimates of wind stress errors (*D. Chelton*, pers. communication, 1997) are being employed. To bring the model into consistency with the observations, the following control parameters are modified: the initial potential temperature (θ) and salinity (S) fields, as well as the surface forcing fields over the entire 6 year period.

To study the impact of SST data on the estimated state monthly mean SST data (Reynolds and Smith, 1994) have been included in the estimation procedure as part of this project. Results summarized in Stammer et al. (2000) show that the overall model-data misfit is substantially reduced through the inclusion of SST data, especially when a full KPP mixed layer model was used.

To gain more insight and confidence into the boundary layer parameterization, an experiment was set up in collaboration with Robert Weller at WHOI which has as its goal to test the full MIT GCM in a small sub-domain of the Atlantic centered at the

Subduction Experiment. In that area substantial amounts of near-surface data exist and will be used in the regional assimilation experiment. Surface boundary conditions were changed from a flux to a Bulk formulation which allows now to estimated flux changes consistent with the physical coupling between latent and sensible heat changes and wind stress variations.

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