GLOBAL OCEAN MODELING AND STATE ESTIMATION IN SUPPORT OF CLIMATE RESEARCH

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1 – INTRODUCTION

During the last decade it has become obvious that the ocean circulation shows vigorous variability on a wide range of time and space scales and that the concept of a "sluggish" and slowly varying circulation is rather elusive. Increasing emphasis has to be put, therefore, on observing the rapidly changing ocean state on time scales ranging from weeks to decades and beyond, and on understanding the ocean's response to changing atmospheric forcing conditions. As outlined in various strategy and implementation documents (e.g., the implementation plans of WOCE AMS, CLIVAR, and GODAE) a combination of the global ocean data sets with a state-of-the-art numerical circulation model is required to interpret the various diverse data sets and to produce the best possible estimates of the time-varying ocean circulation. The mechanism of ocean state estimation is a powerful tool for such a "synthesis" of observations, obtained on very complex space-time pattern, into one dynamically consistent picture of the global time-evolving ocean circulation. This process has much in common with ongoing analysis and reanalysis activities in the atmospheric community. But because the ocean is, and will remain for the foreseeable future, substantially under-sampled, the burden put on the modeling and estimation components is substantially larger than in the atmosphere. Moreover, the smaller dynamical eddy scales which need to be properly parameterized or resolved in ocean model simulations, put stringent requirements on computational resources for ongoing and anticipated climate research.

Process-oriented model studies are now a routine part of physical oceanography, and models are run regionally with up to $1/12°$ horizontal resolution and better and globally with $1/6°$ resolution or better. In comparison, the field of ocean state estimation is still in its early stages. However, substantial progress has been achieved over the last few years which give rise to great expectations of what can be achieved in the near future. Several attempts are now underway to estimate the time-evolving ocean state for up to a decade in various basins and globally, and with methods which cover a wide range of complexities. Examples include synthesis activities in the Indian Ocean, the Pacific, and the Atlantic, as well as on global scale. Those activities have shown recently that a continuous ocean state estimation on global scales and with a $1°$ spatial resolution and better is now feasible for a time span of about a decade.

Results will be used

- to study observed and unobserved ocean state variables;
- for a complete dynamical analysis of the data, such as estimates of climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences (similar

for tracer and oxygen, silica, nitrate), location and rate of ventilation, and of the ocean response to atmospheric variability;

- to assess errors in data, surface forcing fields, and internal model parameters, including initial conditions and lateral boundary conditions;

- and to design and improve an operational long-term ocean observing system.

Many more applications are anticipated and have begun already, such as real-time now-casting and prediction for seasonal-to-interannual and ENSO-related changes, or studies of the marine geoid and the ocean's impact on the earth angular momentum budget. But because most of those applications will be covered in other chapters, we will focus here on the climate issues of a global observing and assimilation system.

What is needed from ocean modeling and ocean state estimation in support of climate research? With ever growing computer power, we can anticipate that we will soon be able to constrain models on a routine basis globally and with a resolution sufficient to address urgent dynamical and climate related questions in the ocean. At the same time, coupled climate models are being developed, and we can expect that in due time we will be able to run climate models over time intervals and with spatial resolution sufficient to simulate the climate system in process-oriented settings. However, considerable experience is needed in assessing the realism of ocean and climate models and in assessing the performance and design of climate observing systems. Both areas will benefit greatly from global data sets and from fully-developed global ocean state estimation efforts.

To bring the ongoing activities forward into what is required of a basin-scale or global climate-oriented observing and modeling system and to make the best-possible use of global data sets, four parallel, but interleaved activities are required: (1) model improvements, (2) process-oriented modeling activities, (3) ocean state estimation activities, and (4) coupled ocean-atmosphere experiments. We will briefly touch on each of these themes below.

2 – MODEL DEVELOPMENTS

The prerequisite for any quantitative model and ocean state estimation is an evaluation of models with respect to their realism in simulating observed processes. These studies are required to determine the models' consistency with ocean data, determine errors in the models, and ultimately lead to their improvements where needed (e.g., see *Fu and Smith*, 1996; *Stammer et al.*, 1996). Two examples are shown here which indicate that models, at least in some of their state variables, show an intriguing agreement with what is actually been observed in the ocean.

Figure 1 shows in its left panel a comparison of a sea surface height time series simulated by the POCM 4C model (R. Tokmakian, pers. communication, 1999) with data from 5 tide gauge stations on the west coast of the America's. The model is simulating most of the observed climate events, at least qualitatively (the correlation coefficients vary between 0.57 and 0.88). Amplitudes are generally lower in the model, though. A similar encouraging result can be found from a comparison of velocity fields from the MIT model (*Marshall et al.*, 1997a,b) with TOGA-TAO velocity data at 0N, 140W (Fig. 1, right panel). The model was run at JPL with a spatial resolution of near 1/3° near the equator (T. Lee, pers. comm., 1999). The comparison indicates reasonable skill in simulating the time mean and variability of the upper equatorial Pacific circulation, an important prerequisite for using the model to study seasonal to interannual variability. The mean flow field shows some biases, however, in the core of the undercurrent.

Uncertainties in prescribed mixing coefficients and surface forcing fields are believed to cause the observed model-data differences in Fig. 1. Model development efforts aim at reducing those and other differences in order to provide a best possible model for process oriented studies and data assimilation.

It is quite likely that process-oriented studies have different priorities for model improvements than, e.g., large-scale ocean state estimation, but there appears to be a substantial overlap. From the discussions given in *WOCE IPO* (1998) and *Stammer et al.* (1998) the following issues are deemed important (with no priority attached).

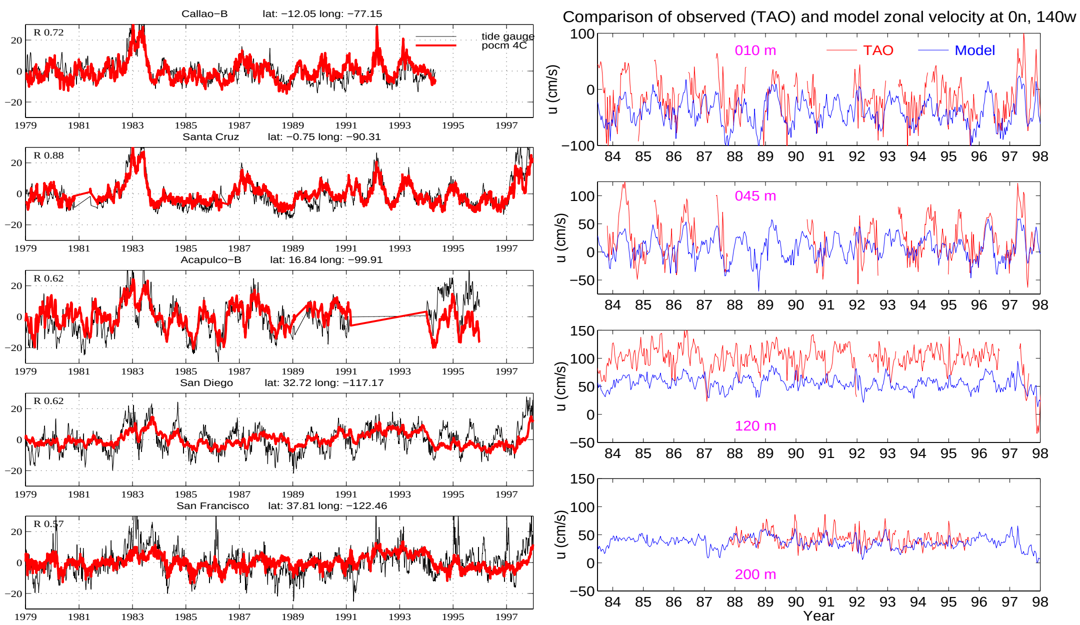

Figure 1: left: Comparison of POCM 4C simulated sea surface height fields with time series of 5 tide gauge stations located along the west coast of the Americas from south to north. Only anomalies are displayed which indicate the ability of the model to simulate various climate events such as the observed El Niño/La Niña pattern as well as short-period anomalies. (R. Tokmakian, pers. communication, 1999.)
right: Comparison of model zonal velocity at four depths with current meter measurements obtained from a TOGA-TAO mooring at 0N, 140W. The comparison indicates reasonable skill in simulating the time mean and variability of the upper equatorial Pacific circulation, an important prerequisite for using the model to study seasonal to inter annual variability. (T. Lee, pers. communication, 1999.)

Model Resolution: Until sufficient computational resources are available to constrain high-resolution models, enhanced resolution near western boundaries and near the equator is desirable. As an example, *Fanning and Weaver* (1997) show that the resolution of an ocean model impacts the realism of heat transport. The transports are much more realistic with a 1/4° resolution model than at lower resolutions. This potentially includes enhanced resolution both in the vertical and the horizontal. More generally, this leads to the concept of adaptive grid estimation (e.g., see *Blayo and Dereu*, 1998).

Topography Representation: Improved representations of straits and sills is important for deep ocean water mass budgets. A few examples are the Denmark-Scotland overflow and its impact on the NADW formation, the Strait of Gibraltar, and the Romance Fracture Zone and its role in ventilating the deep eastern North Atlantic, and the Indonesian Throughflow region. The recently released topography of *Smith and Sandwell* (1997) shows enhanced structure of the ocean's bathymetry. Fault lines along the mid-Atlantic, for example, are enhanced, and unmapped or incorrectly mapped sea mounts in the Southern Ocean are now defined.

Boundary Layer Representation: Improvements are needed in both surface and benthic boundary layers, specifically with regard to flow over steep topography. Maintenance of the thermocline, clearly an essential aspect of ocean modeling given its controlling influence on biogeochemical processes, is largely a matter of correctly simulating seasonal changes in surface boundary layer depth. Correct boundary layer representation is also important for estimating T,S surface boundary conditions in water mass formation regions.

Coupling to ice models: Ice models are essential for correctly simulating horizontal and vertical freshwater fluxes in the polar oceans. Given that density near the freezing point is almost exclusively controlled by salinity, these fluxes have a strong effect on convective events and thus on deep water formation.

Mixing processes: Required is information about the three-dimensional structure of tracer diffusion coefficients in the ocean. On long time scales, mixing across isopycnals returns the deep and bottom water to the thermocline and ultimately back to the surface. The cross-isopycnal mixing representation in numerical models remains therefore one of the major issues. During WOCE, several experiments directly measured mixing rates, and a comparison of these results with current parameterization attempts hopefully will lead to useful representations of upper-ocean processes and cross-isopycnal mixing which are urgently needed to make long-term climate simulations feasible.

Surface Fluxes: As the ocean is driven primarily at its surface through a combination of buoyancy and momentum fluxes, an essential step toward improved ocean models will come through improved estimates of surface fluxes of heat, freshwater and momentum and a better understanding of upper-ocean and boundary layer physics. The meteorological centers (ECMWF and NCEP) now provide surface forcing fields as byproducts of their reanalysis efforts which are more realistic than the operational products, but still have serious deficiencies.

It should be noted that ocean state estimation encompasses estimation of surface flux fields that bring the model into consistency with ocean observations. Resulting estimates need to be consistent with Met center-provided fields and their uncertainties and any inconsistency will shed light on to errors in the atmospheric and ocean models.

3 – PROCESS-ORIENTED STUDIES

Diapycnal mixing is important for closing the meridional overturning circulation. (It is worth pointing out, however, that lack of diapycnal mixing by itself will not shut down the Meridional Overturning Circulation. Experiments with isopycnic coordinate models driven by realistic wind and buoyancy forces show that turning off diapycnal mixing in non-convective regions –

convectively driven mixing cannot be turned off in hydrostatic models because this model class cannot handle static instabilities – leads to some weakening but not total suppression of the MOC.)

Modeling technology has made great strides towards eliminating numerically induced diapycnal mixing. These advances allow us today to study in detail how diapycnal mixing affects the buoyancy-driven circulation. Preliminary experiments along these lines indicate that neither a constant mixing coefficient nor one inversely proportional to the buoyancy frequency is capable of maintaining the presently observed water mass distribution in models driven with realistic wind and buoyancy forces. The problem, in short, is that neither parameter choice appears to be capable of striking the right balance between mixing in the thermocline and mixing in the abyssal ocean (*Bleck, pers.comm.)*

Direct measurements (*Polzin et al.*, 1997) suggest that deep ocean diffusivities may vary geographically by several orders of magnitude, and that barotropic tides impinging on rough topography and generating internal waves could be a major source of energy enhancing these vertical diffusivities. Given these observations and other studies (*Munk and Wunsch*, 1998), it is now considered mandatory that tidal mixing be included in ocean circulation models either implicitly or explicitly. Barotropic tide and tidal current modeling have done major progress especially in conjunction with the advent of high precision altimetry (*Le Provost et al.*, 1995). The good strategy seems to be to parameterize tidal mixing via 3-D maps of diffusivities which have to be computed from high resolution global ocean tide models. Preliminary attempts have been recently developed (*Egbert*, 1997, *Church et al.*, 1999).

To make further headway on this issue, there is a clear need for (a) measuring oceanic mixing in various geographic locations differing in bottom roughness, tidal amplitude, and other properties known to affect mixing; (b) developing mixing coefficient parameterizations complex enough to incorporate the above-named influences, yet simple enough to be suitable for OGCMs; and (c) directly estimate a suitable 3-dimensional structure of the parameters, and (d) systematic process studies aimed at validating these schemes. Bulk measures of the success of a diapycnal mixing parameterization are (a) its ability to reduce model drift, as expressed by temporal changes in the water mass census, and (b) qualitative reproduction of the major features of the MOC. The latter requires processing of model output in a way that mimics procedures used by the observational community. An example of the latter type of diagnostics is shown in Fig. 2 which quantitatively depicts the meridional overturning circulation, rendered in terms of four density classes, in a near-global, coarse-mesh, isopycnic model simulation.

A different and likewise urgent problem is the resolution of eddies and eddy variability and the associated effect on momentum and water mass transfer, as well as the possibility of parameterizing the related effects. Eddies play a fundamental role in shaping the general circulation of the ocean, especially in the Southern Ocean where the mean flow is near-zonal and hence is a relatively ineffective meridional transport agent. Realistic simulation of eddies needs to be of high priority (see *WOCE IPO* (1998) for more details).

As an example, Fig. 3 shows the trajectories for water parcels originating at +/- 24°N, 50 m depth (D.Menemenlis, pers. communication, 1999). Water parcels are tracked for a period of 13 years (1985-1997) using time-mean model velocity (top panel) and real-time model velocity (bottom panel) of the same run as used in Fig. 2, which due to its low resolution does not simulate any mesoscale energy in mid and high latitudes. Colors indicate four different regimes: North/South recirculation (blue/black) and tropical extra-tropical exchange (green/red). Such

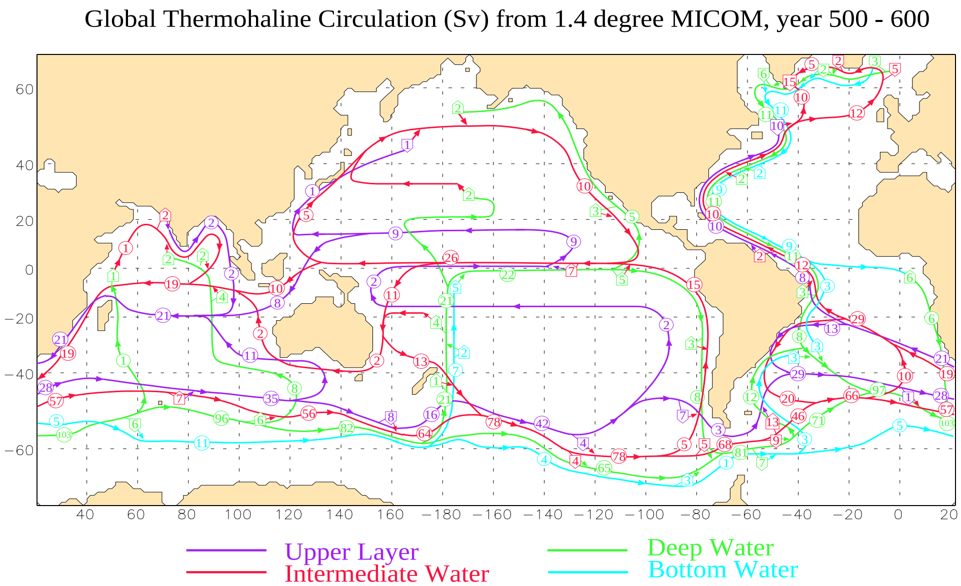

Figure 2: Quantitative rendition of thermohaline-driven flow in 4 density classes, extracted from a near-global MICOM simulation at 1.4°resolution and 16 layers. From *Sun et al.* (1999).

trajectories are used to study the possible role of tropical-extra-tropical exchange in decadal climate variability.

Despite the fact that the model substantially underestimates the effect of ocean eddies, the differences between the top and bottom panels clearly illustrate the danger of using time-mean fields to understand long-term effects of the ocean circulation on water mass and tracer distributions. For example, most water parcels subducted at 24°N, East of the Date Line (green), eventually find their way through the Indonesian passage to the West Coast of Africa when time-mean velocity fields are used (top panel). The picture obtained when using real-time model velocity (bottom panel) is very different, especially in the amount of water exchange between the Pacific and the Indian Ocean.

Using the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM) it has been possible to run simulations of major ocean basins at resolutions up to 1/64° (1.7 km) for each variable (*Hurlburt and Hogan*, 1999). As the model resolution is increased, the pathways of current systems become much more accurate, ocean fronts become sharper and extend much farther to the east across major ocean basins, eddies fill the entire model domain, the large-scale shape of basin-scale ocean gyres is altered, and the global thermohaline circulation is modified, including inter-basin exchanges, and the pathways of global scale currents and their transports. These results, obtained with a model which achieves computational efficiciency through coarse vertical resolution (typically 6 layers) and omission of shelf seas, indicate that very high horizontal resolution in ocean models (10 km or better) is relevant to larger-scale as well as regional climate simulation.

Very fine resolution of mesoscale flow instabilities allows more, stronger, and smaller eddies which fill the model domain, but more importantly it provides a means to strongly couple upper ocean currents to abyssal currents and the bottom topography, even when the upper ocean currents do not directly impinge on the topography. In essence mesoscale flow instabilities (especially baroclinic instability) in the upper ocean transfer energy to the abyssal layer and drive deep currents which are contained to follow the f/h (Coriolis parameter/depth) contours of the bottom topography. These abyssal currents in turn steer the upper ocean currents and

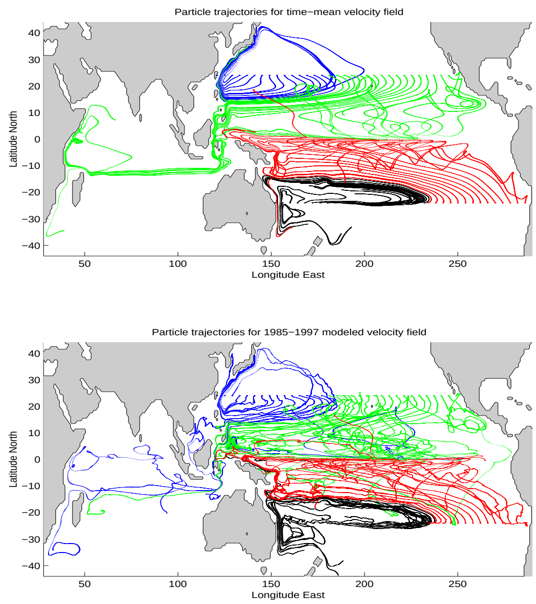

Figure 3: Trajectories for water parcels originating at +/- 24°N, 50 m depth. Water parcels are tracked for a period of 13 years (1985-1997) using time-mean model velocity (top panel) and real-time model velocity (bottom panel). Colors indicate four different regimes: North/South recirculation (blue/black) and tropical extra-tropical exchange (green/red). Such trajectories are used to study the possible role of tropical-extratropical exchange in decadal climate variability. (D. Menemenlis, pers. communication, 1999.)

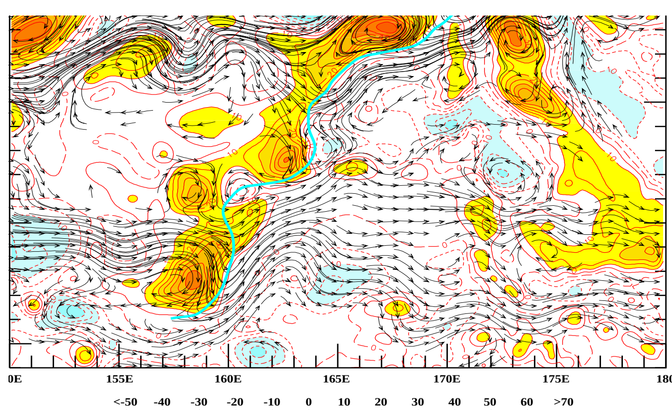

Figure 4: Relationship between upper ocean and abyssal currents in the Shatsky Rise Region of the Pacific (from *Hurlburt and Metzger*, 1998)

strongly impact the mean pathways of upper ocean currents. See *Hurlburt et al.* (1996) for a more complete discussion. Using equilibrated global ocean simulations with up to 1/16° resolution, *Shriver and Hurlburt* (1998) also find that mesoscale flow instabilities, particularly baroclinic instability, can affect the global thermohaline circulation, as described above, via isopycnal flattening, i.e., transfer of potential energy of the mean flow to eddy potential energy.

To date, simulations using NLOM have run with resolutions up to 1/64° for the North Atlantic (*Hurlburt and Hogan*, 1999) and the Japan/East Sea (*Hogan and Hurlburt*, 1999). In both cases major improvements in the simulations were seen at resolutions up to 1/32° (3.5 km) and more modest improvements with a further increase to 1/64° resolution. In the Japan/East Sea 1/32° resolution was required for strong upper ocean - topographic coupling which greatly affected the separation of the East Korea Warm Current from the coast as well as other circulation features. In the Atlantic, simulation of the Gulf Stream between Cape Hatteras and the Grand Banks, the nonlinear recirculation gyre on the south side of the Gulf Stream, and the C-shape of the subtropical gyre were substantially improved with resolution increases up to 1/32° An example is shown in Fig. 4 from *Hurlburt and Metzger* (1998) which illustrates the bifurcation of the Kuroshio Extension at the Shatsky Rise, where both upper ocean - topographic coupling and the ability to simulate the eastward penetration of an inertial jet are critical. A resolution of a 1/16° is essentially required to obtain the illustrated degree of detail and structure.

4 – OCEAN STATE ESTIMATION

A truely optimal estimate of the ocean state will be obtained by utilizing the full suit of ocean data, including altimetry, hydrography, float and drifter velocities, and ultimately tracer and nutrient data, in a way consistent with their errors and with errors of models.

Mathematically, the ocean state estimation problem can in practice be identified as one of least-squares. A solution $\mathbf{x}$ over time t is sought that minimizes a sum of model-data misfits and deviations from model equations,

$$J = \sum_t (\mathbf{y}(t) - \mathbf{E}\mathbf{x}(t))^T \mathbf{R}(t)^{-1} (\mathbf{y}(t) - \mathbf{E}\mathbf{x}(t)) + \sum_t (\mathbf{x}(t+1) - \mathcal{L}[\mathbf{x}(t)])^T \mathbf{Q}(t)^{-1} (\mathbf{x}(t+1) - \mathcal{L}[\mathbf{x}(t)]) \tag{1}$$

Here $\mathbf{y}$ stands for noisy ocean data with $\mathbf{Ex}$ its model's equivalent, and $\mathcal{L}$ defines the operator that steps the model state $\mathbf{x}$ forward in time. Matrices $\mathbf{R}$ and $\mathbf{Q}$ are weights, that statistically correspond to error covariances of data ($\mathbf{y}(t) \approx \mathbf{Ex}(\mathbf{t})$) and model ($\mathbf{x}(t+1) \approx \mathcal{L}[\mathbf{x}(t)]$) constraints, respectively.

While empirical methods such as Optimal Interpolation and "nudging" are computationally simple, their relationship with the underlying optimization problem Eq (1) is not obvious. Arbitrary assumptions can lead to physical inconsistencies, such as invoking heat sources and sinks within the ocean interior that would render analyses of ocean heat transport difficult. If we are to learn from ocean state estimation and reanalysis efforts, a dynamically and statistically consistent solution is required which preserves our basic understanding of the ocean. Among the rigorous methods that solve the estimation problem are the Kalman Filter-Smoother and the adjoint method, both of which are computationally demanding.

4.1 – Ongoing Work Most of the present focus in ongoing ocean state estimation is on the time-evolving large-scale circulation using primarily altimetric observations. Precise and accurate TOPEX/POSEIDON (T/P) sea surface height observations are now available on a routine basis for 6+ years covering the period September 1992 through present. Combined with a general circulation model, they carry unprecedented information about ocean circulation. Information from WOCE in situ data, such as XBTs, floats, and the WOCE hydrography, are mostly being used as independent information to test the altimetric assimilation. Here we will mention only a few examples which seem to be relevant for climate research. One of the examples is the attempt of an ocean state estimation on global scale as it results from an an ongoing effort at MIT, SIO, and JPL. The state estimation system is based on a general circulation model and a dual assimilation approach utilizing the model's adjoint and an approximate Kalman filter and smoother. The forward component is the general circulation model developed by John Marshall and his group and is described in *Marshall et al.* (1997a,b). The adjoint component is obtained from the forward model by using the Tangent-linear and Adjoint Compiler (TAMC) which was written by Ralf Giering (*Giering and Kaminsky,* 1997). This compiler has proven to be extremely flexible since it allows one to easily regenerate the adjoint code whenever a change in the forward code is necessary (*Marotzke et al.*, 1999). The approximate filter is an extension of the reduced-state filter described by *Fukumori and Malanotte-Rizzoli* (1995).

Ongoing computations include a 6-year estimate of the time-evolving ocean circulation (1992 through 1997) with up to 1°spatial resolution, a complete mixed layer model (*Large et al.*, 1994) and an eddy parameterization (*Gent and McWilliams*, 1990). Data include the absolute and time-varying T/P data from October 1992 through December 1997, SSH anomalies from the ERS-1 and ERS-2 satellites, monthly mean SST data (*Reynolds and Smith*, 1994), time-varying NCEP Reanalysis fluxes of momentum, heat and freshwater, and NSCAT estimates of wind stress errors are being employed. Monthly means of the model state are required to remain within assigned bounds of the monthly mean *Levitus et al.* (1994) climatology. To bring the model into consistency with the observations, the initial potential temperature (θ) and salinity (S) fields are modified, as well as the surface forcing fields. Changes in those fields (often referred to as "control" terms) are determined as a best-fit in a least-squares sense of the model state to the observations and their uncertainties over the full data period. In the current configuration, there are 10^8 elements in the control vector. See *Stammer et al.* [1997] and the web page http://puddle.mit.edu/∼detlef/OSE/OSE.html for details on this work.

Results are summarized in Fig. 5, showing the estimated mean surface velocity and sea surface height field for the Atlantic and Pacific Oceans. Once converged to an optimal solution, the estimated time-varying model state and consistent surface flux fields will be available for the entire estimation period and will be the basis for a wide variety of climate and societal application in the open ocean as well as in coastal areas. In particular; transports of mass, heat and freshwater in the ocean will be computed and compared to what is shown in Fig. 2 from process-oriented forward models. The differences will bear strong indications of model errors and hint at potential improvement areas.

In the framework of the AGORA and GANES European projects, the LEGOS and CERFACS groups in Toulouse have been setting up a global data assimilation system. The methodology (SOFA system; De Mey, 1999) is based on four-dimensional reduced-order Optimal Interpolation. OI is a very economical method for large-scale problems, but it does not explicitly enforce

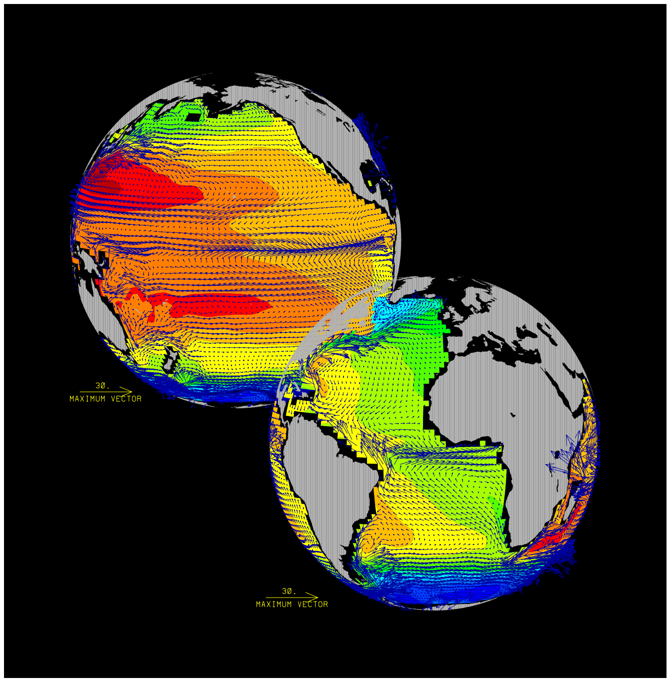

Figure 5: Mean surface velocity and sea surface height field for the Atlantic and Pacific Oceans estimates from 6 years of absolute TOPEX/POSEIDON data, SST fields, surface fluxes and the monthly mean Levitus hydrography fields. See *Stammer et al.* (1997) for details.

dynamical constraints as in (2), and is therefore not as physically-consistent as the Kalman Filter and adjoint methods. However, the physical and statistical relationships between variables are introduced via the basis functions of the reduced space. The use of isopycnal coordinates for the basis functions seems promising (e.g. *Gavart and De Mey*, 1997) and consistent with the conservation of large-scale properties (*Cooper and Haines*, 1996) in particular in the perspective of climate research.

The primitive equations model used in AGORA and GANES is the OPA global model (*Blanke and Delecluse*, 1993). The average resolution is 2° x1.5°, with higher resolution in the Tropics. Horizontal diffusion is isopycnal for the tracers and harmonic for the velocity. The horizontal viscosity is minimum at the equator and increases the-wards and near the coasts. A 1.5D turbulent kinetic energy closure is used to determine the vertical viscosity and diffusivity. ECMWF 6-hour winds, heat flux, solar penetrative flux and freshwater flux force the model. The average fluvial contributions are also taken into account. Model sea surface temperature is relaxed towards weekly satellite data (*Reynolds and Smith*, 1994). Model sea surface salinity is relaxed towards the Levitus climatology. Deeper than 1500m, a relaxation towards the climatological monthly temperature and salinity of *Levitus et al.* (1994) is imposed.

Examples are shown in Fig. 6 obtained after the assimilation of TOPEX/POSEIDON and ERS altimetry in the '90s taken from *Greiner et al.* (1999). Assimilation runs coupled with the ARPEGE atmospheric model have also been conducted by Rogel et al. (1998) in the perspective of seasonal forecasting.

A highly eddy-resolving 1/16° Pacific Ocean model has been used in an observing system simulation experiment, an experiment designed to investigate the feasibility of using satellite altimetry and a data-assimilative version of the Pacific model to map the evolution of mesoscale features. In this experiment, error free altimeter data were simulated by the NRL 1/16° six-

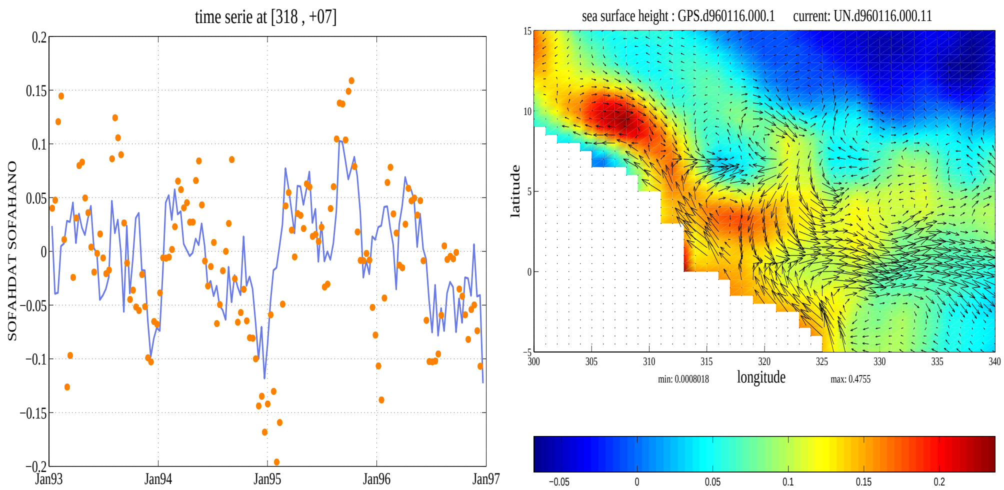

Figure 6: Left: Time series of 10-day forecast sea-level anomalies from the Toulouse global assimilation system at 42W,7N (solid line) vs. TOPEX/POSEIDON (dots). The assimilation allows the description of seasonal to interannual fluctuations. TOPEX/POSEIDON extrema (mostly due to tidal aliasing) are rejected by the data assimilation system.
Right: Analyzed sea-surface height and 100m depth currents on Jan 16, 1996 from the Toulouse global assimilation system, for the same area of the Tropical Atlantic as Fig. LEGOS-1. The analysis presents the typical oscillations of the North Tropical currents and the complex circulation of the western boundary.

layer Pacific Ocean model which covers the Pacific north of 20°S (*Hurlburt et al.*, 1996; Section 3). The model realistically simulates a strongly meandering Kuroshio current system and numerous eddies. It was spun-up to statistical equilibrium, then run 1990 - present forced by 12 hourly winds from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), where the temporal mean was replaced by the annual mean from Hellerman and Rosenstein (1983). Then simulated altimeter data from 80 days in model year 1994 were assimilated into model year 1997, a time when the Kuroshio pathway was quite different. 1994 winds were used during the assimilation.

The goal was to determine how well the simulation during 1994 could be reproduced given only SSH along altimeter ground tracks and the correct wind forcing only during the assimilation time frame. Of particular interest was the ability to reproduce mesoscale variability that tends to be a nondeterministic response to atmospheric forcing due to flow instabilities. A variety of experiments were performed using different combinations of simulated altimetric satellites, including ERS (35-day repeat tracks), Geosat (17-day repeat) and TOPEX/POSEIDON (T/P) (10-day repeat). Even one altimeter is quite effective (5-6 cm rms in the Kuroshio region, 3 cm rms over the whole domaine), with the Geosat and ERS orbits giving lower error than T/P. Reduced error is found by having up to 3 satellites (3-4 cm, rms in the Kuroshio region, 2 cm rms overall), but little further improvement is obtained by having 5 of them in this test. Using the correct wind forcing without the altimetric assimilation gave little improvement over persistence of the initial state or using winds from the wrong year in these 80-day tests. See *Hurlburt et al.* (1999), *Smedstad et al.* (1999) and *LeTraon et al.* (this volume) for additional information on these experiments and nowcast/forecast experiments using real ERS-2 and T/P data.

4.2 – A Priori and A Posteriori Error Evaluations The weights **R** and **Q** in Eq (1) define the mathematical problem of ocean state estimation. As such, suitable specification of these weights is essential to obtaining sensible solutions and is a fundamental issue in ocean state estimation. In fact, while further advances in computational capabilities will resolve many of the technical issues of estimation, the improvements will not resolve the weight identification problem. Different weights represent different physics, thereby leading to different solutions. Misspecification of the weights will cause models to err in fitting the data, which in turn will result in inaccuracies or even outright "failures" of the estimation.

There is substantial need for the general community to come up with proper estimates of data and model error covariances, including those for atmospheric forcing fields. Special attention needs to be paid to the hydrographic data weights, which in principle requires knowledge of the 3 dimensional frequency-wavenumber spectrum of the ocean temperature and salinity field. Improved understanding is also needed concerning incorporation of Lagrangian data sets into model. Ultimately one needs error covariance estimates for all components involved, including the model itself and the atmospheric forcing fields provided by meteorological centers.

Statistical considerations suggest a suitable choice of the weights being a priori error *covariances* of the respective terms in Eq (1). (The particular form of Eq (1) assumes temporally uncorrelated errors.) Specifically, weights **R** and **Q** should be regarded as errors in data and model *constraints* rather than merely data and model errors. A case in point is the so-called representation error (e.g., *Lorenc*, 1986), which corresponds to real processes that affect measurements but are not represented or resolvable by the models. For instance, inertial oscillations and tides are not represented by the physics of quasi-geostrophic models. Variabilities with scales smaller than the model resolution also contribute to representation error. To the extent that representation errors are formally inconsistent with (not represented by) models but contribute to measurements, errors of representativeness should be considered part of the uncertainties of the data constraint (**R**) instead of those of the model constraint (**Q**).

In most practical applications, representation error is in fact the largest component of data constraint error **R**, and is much larger than the instrumental accuracy of any observing system. That is, for most of what we can observe of the ocean, we can measure far more accurately than what models can represent. However, in most situations, the nature of representation error is inadequately known. For instance, variables in finite difference models are loosely understood to represent averages in the vicinity of model grid points. However, the exact averaging operator is rarely stated. A better understanding of what models and observing systems respectively do and do not represent is arguably the most urgent and important issue in estimation.

In practice, a priori uncertainty estimates are often simply guesses, and the validity of the assumptions must be carefully assessed to assure the quality and integrity of the estimates. If estimation problems are set up (specification of prior uncertainties) and solved consistently, resulting estimates should necessarily be more accurate than model simulations. An estimation's success needs to be assessed by examining the calculation's consistency. Useful measures of consistency include formal error estimates, the model-data residuals, and comparisons with respect to independent observations. *Fukumori et al.* (1999) discusses examples of such measures with regard to an assimilation of TOPEX/POSEIDON data into a global ocean circulation model using a reduced-state Kalman filter and smoother. For some of the parameters, prior error statistics can be computed by use of a joint error estimation technique which incorporates the use of multiple data sets as demonstrated by *Tokmakian and Challenor* (1999). With minimal assumptions, the derived weights provide a realistic guide as to where an ocean model needs to be corrected. Available data sets are available for computing error statistics for both SSH and SST using this method.

If assimilation problems are set up (specification of prior uncertainties) and solved properly, assimilated estimates should necessarily be more accurate than model simulations. The success of the assimilation in this regard needs to be assessed by examining the calculation's consistency. Useful measures of consistency include formal error estimates, the model-data residuals, and comparisons with respect to independent observations. The assessment requires proper accounting of prior assumptions, such as error magnitudes and their covariances, and identification of the differences between model state errors and model representation errors.

Given an assimilation system and a posteriori error residuals, the complementary use of adaptive approaches such as the Adaptive Kalman Filter has been suggested in order to "whiten" the innovation sequence and extract from it as much information as possible (e.g. *Blanchet et al.*, 1997, in the Tropical Pacific).

4.3 – Observing System Design and Sensitivity Studies In order to achieve maximum return from long-term climate observations, a proper design of an observing system is required. Ocean models and data assimilation systems are beginning now to support the design of such an observing system and to test its usefulness to measure climate-relevant quantities in a quantitative and yet cost-efficient way.

A posteriori errors with and without particular data sets provide one measure of the impact of certain observing systems. For instance, *Carton et al.*, (1996), by comparing separate ocean estimations using different data sets, found TOPEX/POSEIDON altimeter data to have the largest impact in resolving intra-seasonal variability of the tropical Pacific Ocean than data from a mooring array or a network of expendable bathythermographs (XBTs).

Forward model experiments provide a means to simulate an observing system. For instance, Stammer and Hurlburt independently conducted global simulation experiments of float dispersion in support of planning for a global float array (Array for Real-time Geostrophic Oceanography, ARGO).

Forward simulations also allow testing sensitivity of model solutions to varying forcings, initial conditions, and/or model parameters, by deducing effects of particular aspects of the circulation on other elements of the model. In comparison, the model's adjoint can be utilized to examine the reverse sensitivity, namely the dependence (rather than effect) of properties on other elements of the model. An example of such use of the adjoint is shown in Fig 8 (*Marotzke et al.*, 1999). The figure shows the sensitivity of the annual mean heat transport across 29°N in the North Atlantic with respect to changes in initial temperature and salinity fields near the surface and at depth, respectively. The figure clearly identifies the hydrography along the boundaries as the most important measurement for deducing the heat transport at this latitude.

Ensemble methods (e.g. *Evensen and van Leeuwen*, 1996) could also prove helpful in designing observing systems and sensitivity studies, in particular for the highly nonlinear climate problems

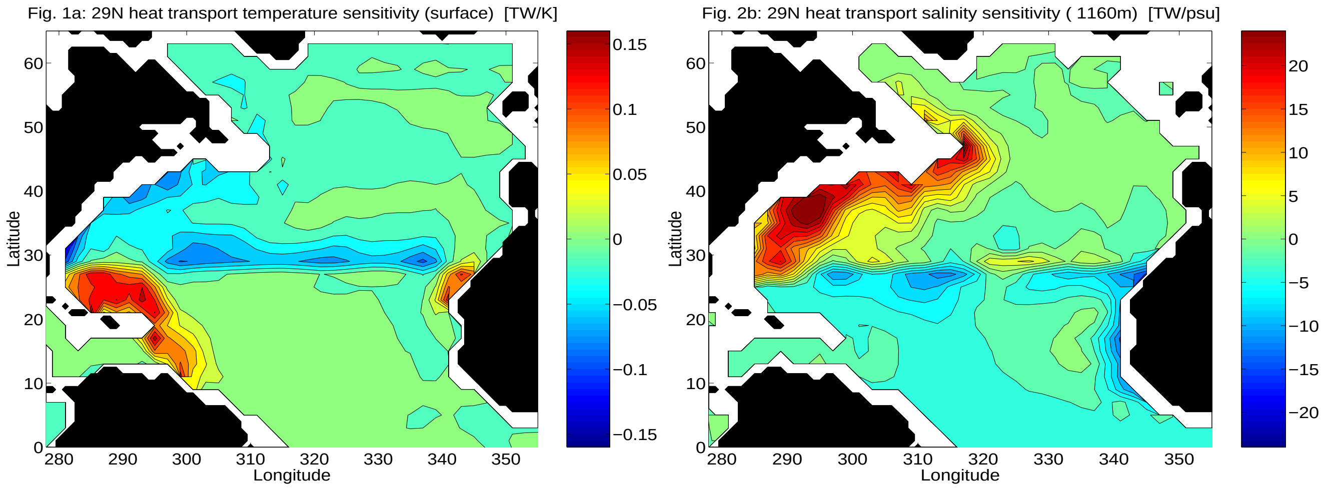

Figure 7: (a) Sensitivity of Atlantic heat transport across 29°N (1993 mean), to surface temperature on 1. January 1993. Contour interval is 0.02 x 10^{12} W/K. (b) Sensitivity of Atlantic heat transport across 29°N (1993 mean), to salinity at 1160m depth, on January 1993. Contour interval is 0.02 x 10^{12} W/psu. See *Marotzke et al.* (1999) for details.

and coupled forecasting. Using these methods in a coastal ocean model, *Echevin et al.* (1999) calculated approximate representer functions in an ocean model, which give insight into the influence of individual observations and observational arrays in a state estimation procedure.

5 – COUPLED OCEAN-ATMOSPHERE MODELS

The need for multiple surface forcing data sets could in principle be eliminated by coupling ocean models to an atmospheric GCM, in which case the only input to be specified is solar energy. Unfortunately, atmospheric models have not reached a degree of realism where this strategy would be advisable. The most notorious problem encountered in today's AGCMs, from the ocean modelers perspective, is their inability to control the escape of water vapor from the atmospheric boundary layer. This makes it very hard to form and maintain stratus clouds. The absence of low-level marine stratus in AGCM simulations today is the biggest source of SST errors in coupled simulations. The problem of insufficient "shading" of the sea surface has been masked somewhat by the tendency of traditional level-type ocean models to diffuse heat down the water column and deposit it in the thermocline. The new generation of layer models, which are better able to control this downward heat diffusion, respond to the lack of stratus clouds over the eastern sub-tropical basins with SST errors in excess of 5°C.

Another error seen in coupled simulations, which makes it inadvisable to attach ocean models to AGCMs for the sake of generating surface boundary conditions, is the amplification of meridional heat flux errors. In a coupled model, the atmosphere tends to react to erroneous oceanic heat fluxes by changing its storm tracks. This modifies wind stress patterns and ocean gyre boundaries which is likely to further accentuate the heat flux error. A goal is therefore to use the ocean state estimated by bringing models and data together, as the best possible ocean solution to properly initialize climate models. However, much has to be learned about the technical details of the initialization step, and related activities are now being launched in the context of CO_2 and anthropogenic climate change studies. Ultimately, the goal is to constrain not just ocean models, but the coupled system as a whole, and to use the dynamically balanced solution for climate studies.

Sea ice affects the ocean's circulation by contributing to the formation of Antarctic Bottom Water (AABW) in the Southern Ocean. Polynyas located offshore, such as the Weddell Polynya of the mid-1970s, are surface manifestations of open-ocean deep convection and contribute to ventilating the deep ocean. *Comiso and Gordon* (1998) suggest that coastal polynyas and the rate of AABW formation are both related to the passage of the Antarctic Circumpolar Wave (*White and Peterson*, 1996). *Zhang and Hunke* (1999) show, using a coupled ice/ocean model forced with realistic winds, that there are interannual changes in ice formation. Such changes affect the thermohaline circulation of the Arctic ocean and the outflow of the Arctic waters into the Atlantic.

6 – OUTLOOK

Ocean data assimilation has long been a focus of theoreticians and modelers, and we are very much aware of the tremendous efforts of the community that bring us to where we are now. As an example, there are now several ongoing assimilation efforts in the U.S., including those at NCEP, GSFC, and LDEO/SIO (all in support of ENSO prediction), at U. of Maryland, Oregon State U. (directed primarily at tidal problems), and at NRL in support of Navy needs. See *Malanotte-Rizzoli* (1996) for an overview of recent activities. It is important now to bring the ongoing international work into the mature phase required to realize successful ocean climate observing and modeling systems and this - with the required computational support - will be central to the success of programs such as CLIVAR and GODAE.

To address the present and future needs of CLIVAR and GODAE, two consortia have been formed recently in the U.S. under sponsorship of the US National Ocean Partnership Program (NOPP). Funding is being provided from NSF, NASA, and ONR. One of those efforts is a consortium for "Estimation of the Circulation and Climate of the Ocean" (ECCO) which is building on the already existing MIT/SIO ocean state estimation efforts and parallel ones at JPL. This consortium of scientists at the Massachusetts Institute of Technology (MIT), the Jet Propulsion Laboratory (JPL), the Scripps Institution of Oceanography (SIO) and the Max-Planck Institut für Meteorologie (MPI) and proposes to elevate global ocean state estimation from its current experimental status to a quasi-operational tool. In addition to developing data assimilation models and routine tools, the consortium will provide a novel experiment in integrating the modeling and observational communities.

The scientific goal is to describe and contribute to the understanding of the global general circulation of the oceans and its role in climate by combining modern large-scale data sets with a state-of-the-art general circulation model (GCM). The central technical goal of ECCO is a complete global-scale ocean state estimation over the 15 year period 1985-2000 at the highest possible resolution along with a complete error description. But to develop the technical understanding required to incorporate all available data types, develop associated error covariances, and to continue to improve models in support of the global estimate, ECCO will begin with coarser-resolution global and basin-wide models and develop near-real time capabilities in support of the climate community needs.

A second multi-institutional NOPP effort in support of GODAE and CLIVAR focusses on the development and evaluation of data assimilation in a hybrid isopycnal-sigma-z coordinate ocean model (called HYbrid Coordinate Ocean Model or HYCOM). The partner organizations in this case are the U. of Miami/RSMAS, NRL, NOAA/AOML, the U. of Minnesota, the Los Alamos National Laboratory, Planning Systems Inc., Orbital Image Corp. and the U.S. Coast Guard. The hybrid coordinate, in the context of the proposed work, is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The theoretical foundation for implementing such a coordinate was set forth by *Bleck and Boudra* (1981) and *Bleck and Benjamin* (1993). The capability of assigning additional coordinate surfaces to the oceanic mixed layer allows the slab-type Kraus-Turner mixed layer of MICOM to be replaced by a more sophisticated closure scheme, such as K-Profile Parameterization (KPP) (*Large et al.*, 1994, 1997). A prototype of HYCOM, developed from MICOM (Miami Isopycnic Coordinate Ocean Model), has been successfully tested at coarse resolution in the Atlantic, and will be shortly configured on a global domain.

The global model configuration is the one adopted by the Los Alamos National Laboratory (LANL) in a comparison between HYCOM and POP (Parallel Ocean Program). Since POP will become the oceanic component in the next generation of the National Center for Atmospheric Research (NCAR) Climate System Model (CSM), this ensures that HYCOM's set-up and forcing parameterizations conform to the latest consensus on climate modeling. Coarse resolution model-based reanalysis of archived observational data will provide a comprehensive picture of the dynamics and thermodynamics of the global ocean during recent decades. Expertise on the model's behavior with an eddy-resolving grid will be gained by running the model in basin-scale configurations using lateral boundary conditions provided by the global simulations, initially focusing efforts on the Atlantic Ocean. By 2003, the project should be able to address the US-GODAE principal objective of depicting the 3-D ocean state at fine resolution in near real time. A new web-based tool that allows quicker access to both data and software will facilitate the availability of those products to the user community.

An eddy-resolving data-assimilation effort based on the NRL 1/16°near-global Layered ocean Model (NLOM) is under development at NRL. The output from this system should be available on the U.S. GODAE data server at Fleet Numerical Meteorology and Oceanography Center (FNMOC) in near-real time starting in 2002. A history of archived output from 1993 (the beginning of T/P data) to the present should also be available. This will provide an opportunity to investigate effects of very high resolution on climate related issues as discussed in Section 3. The model domain covers the global ocean from 72°S to 65°N, excluding the Arctic Ocean and shelf regions.

The ocean modeling group at the Naval Postgraduate School (NPS) has several ongoing projects related to climate research. Relatively high resolution global ocean and ice models are being run, simulating the ocean's circulation for a twenty year period. Surface fluxes derived from the European Centre for Medium Weather Forecasting reanalysis (79-93) and operational (94-98) data produces a forcing data set for studying the low frequency changes in the ocean which may give an insight into climate changes. Additionally, NPS is working with the Naval Research Laboratory to investigate the usefulness of the high resolution primitive equation models in short term predictions. The ocean model (POP) will eventually be coupled to the Navy's atmospheric model, NOGAPS and will include code for assimilating data into both the atmosphere and into the ocean model. The resolution of these ocean models is/will be between 1/3° and 1/10° depending upon the computer resources available. Although the work with NRL is for short term predication, much of what will be learned in the coupled regime can be applied to climate related studies.

At the Goddard Space Flight Center, the NASA Seasonal-to-Interannual Prediction Project (NSIPP) has been initiated with the objectives of i) demonstrating the utility of satellite observations in predictions of short-term climate variations, and ii) establishing both the cost-effective blend of remote surface observations and subsurface data necessary for a seasonal-to-interannual climate prediction capability, and the assimilation and coupled model systems that will provide the most reliable prediction. To achieve these objectives, ocean data assimilation capabilities based on both OI, where the steady-state error covariances are estimated through Monte Carlo simulations (e.g., *Rienecker et al.*, 1999), and the Ensemble Kalman Filter (EnKF, e.g., *Evensen and van Leeuwen*, 1996) have been developed for the Poseidon quasi-isopycnal ocean model (e.g., *Schopf and Loughe*, 1995). The time-varying multivariate error covariance structures estimated from the EnKF, with their built-in dynamical consistency, will be compared with those estimated for OI. The global model resolution is 2/3 x 1.25 x 20 layers. Currently a 32-member ensemble for the Pacific has been implemented on a T3E and is being tested by assimilation of TAO temperature data (e.g., Figure 8 from *Keppenne and Rienecker*, 1999). For prediction purposes, the sequential filter assimilation is appropriate, however for climate ocean state estimates, an Ensemble Kalman Smoother will be used.

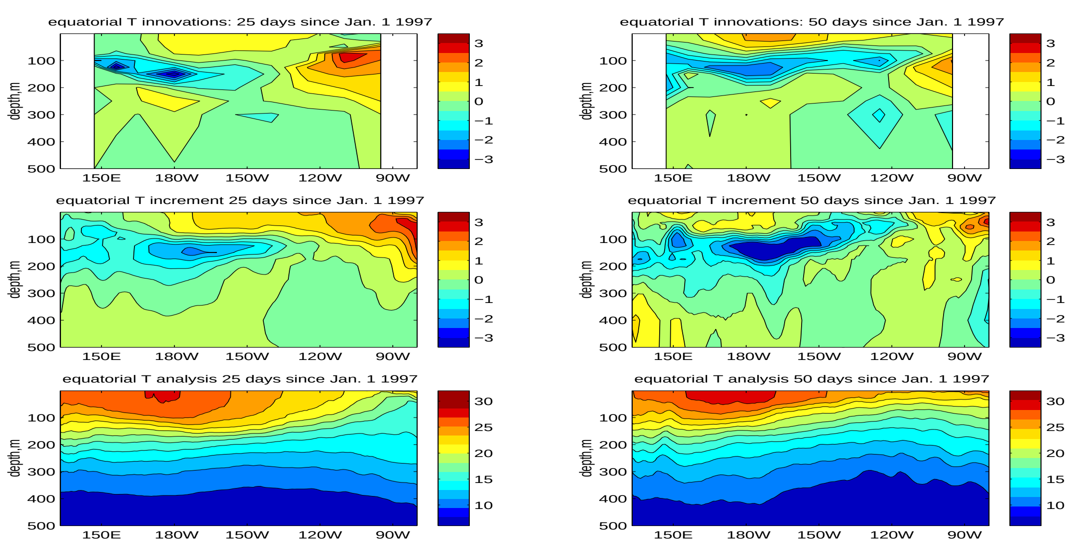

Figure 8: Upper panels: Ensemble mean innovations (observations - forecast) from comparing the Poseidon ocean model forced by SSMI winds with TAO temperature data along the equator. Middle panels: Ensemble mean temperature increment along the equator from a 32-member ensemble integration. Bottom panels: Ensemble mean temperature analysis along the equator. The left hand panels are for January 25, 1997, 25 days after the assimilation procedure has been initialized; the left hand panels are for February 19, 1997.

A coordinated effort is underway in France to develop an integrated system aimed at producing an ocean state estimate routinely in near real time and in a pre-operational mode. This MERCATOR project is split in two components: a global ocean component and a regional North

Atlantic component including the Mediterranean Sea. The objectives of the global component are to provide ocean state estimates for initialization of seasonal climate prediction models, to provide boundary conditions for the regional component (and other future regional applications), and to provide the best ocean state estimates for the scientific community, especially for climate studies. The objectives of the regional North Atlantic component are more related to pre-operational applications: open ocean applications of the French Navy, such as 15–30 day forecasts of mesoscale ocean dynamics, and coastal ocean applications (where most industrial, commercial and environmental impacts are found). They are also related to ecosystem modeling with the aim to provide 3-D ocean transport fields for bio-geochemical studies, and more generally to the research community interests, especially those relating to the impact of mesoscale phenomena.

The forward component of both subsystems is the general ocean circulation model developed by LODYC (Madec et al., 1998) and by the CLIPPER project (*Treguier et al.*, 1999). The preliminary version of the global system relies on a 1/4° horizontal resolution Mercator grid and 31 levels on the vertical. The coverage is global, including the Arctic Ocean where the grid is distorted in order to avoid the pole singularity. The Atlantic/Mediterranean Sea system is based on a rotated grid allowing an almost uniform horizontal resolution of 5 to 7 km, and 43 levels on the vertical.

Because of the size of the state vector and the computational resources initially available, both subsystems will first assimilate observations using an improved version of the reduced-order OI scheme already in use in Toulouse (see Section 4.1; *De Mey*, 1999). Immediate developments concern the observation operators, representativeness errors, consistency with atmospheric fluxes, and physically consistent order-reduction operators. The sequencing and parallelization of tasks will be handled by PALM, a tool derived from atmosphere/ocean model couplers. In the medium term, it is planned to add an adaptive loop (see comment in Section 4.2) to estimate parameters of the model and forecast errors in the OI system. Both global and Atlantic/Mediterranean subsystems will first incorporate altimetry and SST, and will be in position to assimilate vertical profiles (ARGO, XBTs), SSS and absolute topography measurements when they become available early in the next decade. Verification plans (*Le Provost*, 1999) include real-time comparisons with local and larger-scale in situ experiments in 2000-2001 as well as cross-comparisons with other ocean state estimation systems.

Resources: One of the ironies is that ongoing ocean state estimation efforts already have outgrown computer resources presently available to the oceanographic community. In the U.S., much of the ongoing work is based on annual allocations made in response to proposals to computer centers, such as NCAR or SDSC. By now the fundamental limitation to making further and faster progress is widely being appreciated. However a fast remedy of this dangerous situation is not yet in sight. In the US, there has been a recommendation for the formation of a NOPP ocean data analysis and assimilation center with a powerful computer facility as its central component. Plans for this are still under development.

Semtner (1999) gives a detailed list of requirements for future climate research involving coupled ocean/atmosphere modeled systems. For ocean state estimation, a multiple of those resources and substantial increase in memory/storage is required. Ensemble approaches need to run many parallel estimates, while the adjoint model requires about 4 times the CPU time of the forward model and needs to be optimized iteratively, with typically 50 to 100 iterations necessary, yielding increases requirements on resources by a factor of 100-1000 relative to a forward model run. And while a process-oriented approach can normally cope with multi-user center environments, ocean state estimation will need dedicated computer resources, similar to what is the practice in meteorological forecast centers.

For a 1° solution of the MIT adjoint model, about 200 CPU days are required on a CRAY T90. Within the next 5 years the goal is to run a global optimization with 1/4° resolution over 15+ yrs. This requires a factor of about 1000 more compute capacity than the ongoing optimization.

For programs such as CLIVAR many state estimates will have to be provided, and yet none of the required computer time is available, nor does it seem to have been included in the planning process. Provision of adequate computational resources will determine the success of future climate research and planning at the national levels is urgently required. With such resources, the ocean assimilation community has already made significant progress towards providing modeling and assimilation tools in support of climate research goals.

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