Research and climate applications

Jens Schröter[1] Ichiro. Fukumori[2], Detlef Stammer[3], Manfred Wenzel[1], Dieter Wolf-Gladrow[1]

[1]Alfred Wegener Institute for Polar and Marine Research,
Postfach 161 120, 27515 Bremerhaven, Germany
jschroeter@awi-bremerhaven.de

[2]Jet Propulsion Laboratory
MS 300-323, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A

[3]Scripps Institution of Oceanography
9500 Gilman Dr.; La Jolla, CA 92093-0230, U.S.A

1 Introduction

Three years after the Global Ocean Data Assimilation Experiment (GODAE) conference "OCEANOBS 99" in Saint Raphael it is timely to review ocean state estimation aimed at describing and better understanding oceanic processes and climate. The ocean is a major element in the climate system, is responsible for the major part of meridional heat transport, a reservoir for carbon, and a focus of biological productivity, among other roles. Ongoing and planned oceanic and climate research activities are intended to measure, describe, understand, and eventually predict, variations in the ocean and its interaction with the atmosphere, biosphere, and cryosphere on long time scales. Substantial problems exist for any system of observing and simulating the rapidly changing flow field and associated properties such as temperature or carbon and their consequences. We will focus on efforts which involve much longer time scales than those necessary for operational prediction of the oceans. Usually a lot of attention is paid on the upper ocean which can be observed to some extent. The deep ocean is, however, of equal importance when we wish to calculate budgets, fluxes and finally flux divergences. For these calculations our data basis is much too sparse and we have to rely on estimations of the ocean state which put individual measurements into a common context and help in understanding oceanic processes.

Rigorous global ocean state estimation methods are now being used to produce dynamically consistent time-varying syntheses of model and measurement. Early results begin to form the basis for studies of a variety of scientifically important problems. A complete ocean observing and synthesis system includes global observations and state-of-the-art ocean general circulation models. The global observing system envisioned for GODAE is presented at this conference and has previously been described in detail in Smith and Koblinsky (2001) with a similar status report of ocean modelling given by Griffies et al. (2000). Here we report on the third component of state estimation: the synthesis of the observations and models into unified, dynamically consistent, estimates. In contrast to state estimates in support of short term predictions of the upper ocean we focus on annual to decadal periods which necessarily includes the deep ocean. We describe some of the first applications, and discuss future directions in support of the wider oceanographic community and related disciplines. Both Climate Variability and Predictability and GODAE programs are being designed and built to a great extent around the assumed availability of routine state estimates. A recent summary of ongoing international assimilation efforts in support of CLIVAR (http://www.clivar.org) and GODAE (http://www.bom.gov.au/GODAE) can be found in Stammer et al. (2002) and Fukumori (2002).

In this context, ocean state estimation has as its goal to obtain the best possible description of the changing ocean by combining, in some suitably optimum way, all the diverse ocean observations, with theoretical knowledge of the ocean circulation as embodied in numerical ocean circulation models. If carried out properly, the result is a dynamically self-consistent estimate of the time-evolving ocean circulation, one which has greater information and forecast skill than does either model or data alone. GODAE is the experiment that will prove the feasibility of ocean forecasting. As such it has a clear focus. The value of GODAE for CLIVAR and other research projects, however, is much larger than short term ocean state estimation and forecasting. Longer term applications are grouped around GODAE which will profit greatly from the availability of data and model output. The research described here differs from the regular GODAE focus in

- A full depth analysis as opposed to a concentration on the upper ocean.
- Global approach versus regional studies.
- A retrospective analysis (re-analysis) versus real time description and forecast.
- Use of all data, including those that will reach the data centres in “delayed mode”.
- Accurate error characterisation and quality control for both model and data.
- Consistent evolution as opposed to a sequence of synoptic state estimates.
- Understanding versus describing change.

Oceanic applications are complemented by providing important information and links to other scientific fields:

- A consistent estimate of long term trends such as in the sea level, the fresh water budget and in earth rotation parameters.
- Better understanding of the role of the ocean in the biogeochemical system, especially the carbon cycle.
- A consistent physical state estimate including mixed layer depth and advection rates for use in ecosystem models.
- A model, properly initialized, for coupling to models of the atmosphere and cryosphere.

A formidable effort is required to carry out rigorous global ocean state estimation. In the US a consortium has been formed called "Estimating the Circulation and Climate of the Ocean" (ECCO) with funding provided by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Office of Naval Research (ONR) under the National Oceanographic Partnership Program (NOPP). ECCO intends to transform existing ocean state estimation efforts from their present experimental status into quasi-operational applications that can support scientific, societal and navy needs alike. ECCO's ultimate goal is to employ rigorous methods of ocean/data syntheses in a sustained form to describe the global ocean circulation at time scales of days to decades, using data of any type and the best available models. ECCO activities are based on the MIT general circulation model. An overview can be found in Stammer et al., (2002b). Ongoing efforts of the ECCO Consortium are now aiming to produce two major, sustained analysis products: (1) global state estimation as a full synthesis of all available data (ECCO-1). (2) A near-real time analysis at the highest practical resolution (ECCO-2). Both products will be routinely distributed through the project data server (http://www.ecco-group.org/las).
Efforts in Europe concerned with global ocean state estimation are much less developed. They rely on different models run by various groups. Some programs are already operational but in general they mostly concentrate on short range forecasting of the ocean state and are presented in detail during this GODAE conference. More and more the necessity of combining the skills of many groups in Europe is becoming clear and has already lead to a European effort for a joint ocean state estimation and forecasting consortium.

2 Physical consistency

All data assimilation methods deal, in principle, with a vector $\mathbf{x}_t$ representing a time-dependent model simulation of the state of the ocean. These state vectors include, typically on a regular grid, the values of temperature, salinity, pressure and velocity required by a general circulation model for temporal integration subject to appropriate boundary conditions. From the state vector, one can compute any derived quantity (e.g., enstrophy, potential vorticity or enthalpy flux, etc.) of interest. All oceanic measurements can be associated with its model equivalent through a functional relationship that can be written as,

$$\mathbf{y}_t = \mathbf{H}_t\,\mathbf{x}_t + \mathbf{n}_t$$

$\mathbf{y}_t$ is the vector of observations. Operator $\mathbf{H}_t$ relates the model state to the model equivalent of the observations and $\mathbf{n}_t$ is the measurement error including data noise. An estimated time-dependent solution, $\hat{\mathbf{x}}_t$ is then sought, that minimizes the model-data misfits. Simplified methods (e.g., nudging, robust diagnostics and objective mapping), intended to find approximate solutions by relaxing the model constraints, are easy to set up and are computationally inexpensive. However, the temporal evolution of such ad hoc solutions are not necessarily consistent dynamically and usually imply internal sinks and sources of momentum, heat and freshwater. Rigorous methods, such as 4DVAR or smoothing methods are computationally much more demanding. We note, however, that they are needed to obtain dynamically self-consistent ocean estimates useful for understanding the physics of the system by exploiting all the information contained in the data.

Understanding mechanisms and processes governing the ocean is a central problem in climate analyses. However, the temporal evolution of most data assimilated solutions is not physically consistent, limiting the usefulness of such analyses for climate studies. Physical inconsistency is an important deficiency that is often forgotten and/or ignored. Figure 1 describes the problem by illustrating a typical temporal evolution of an element of the model state as a function of time. All sequential assimilation methods, including the statistically optimal Kalman filter, involve integrating the model state in time shown in black and correcting the states according to observations when available shown in red (Fukumori, 2002). The black evolution can physically be accounted for, such as by advection, mixing, and external forcing. However, the red data correction is not identified by any particular process. Instead, the correction reflects an implicit combination of the effects of various model errors (errors in advection, mixing, and forcing). Mathematically, the problem can be understood by the equation governing the evolution of the assimilated solution:

$$\hat{\mathbf{x}}_t = \mathbf{A}\hat{\mathbf{x}}_{t-1} + \mathbf{G}\hat{\mathbf{u}}_{t-1} + \mathbf{K}_t\left(\mathbf{y}_t - \mathbf{H}_t\left(\mathbf{A}\hat{\mathbf{x}}_{t-1} + \mathbf{G}\hat{\mathbf{u}}_{t-1}\right)\right)$$

Vectors $\hat{\mathbf{x}}_t$, $\hat{\mathbf{u}}_t$, and $\mathbf{y}_t$ denote estimates of the model state and various controls (e.g., boundary conditions, sources of model errors, etc.), and the assimilated observations at time *t* (subscript), respectively. (Prior estimate of model errors are typically nil.) Operators **A** and **G** represent the model physics describing how the state and various controls determine the evolution of the dynamic system. $\mathbf{K}_t$ denotes the assimilation operator (e.g., the Kalman filter). The first two terms on the right hand side describe the black physical evolution whereas the third term is the red data correction in Figure 1 that implicitly corresponds to errors in the first two terms. As such, the temporal evolution of the data assimilated estimate is physically inconsistent because of the undetermined nature of this data correction term.

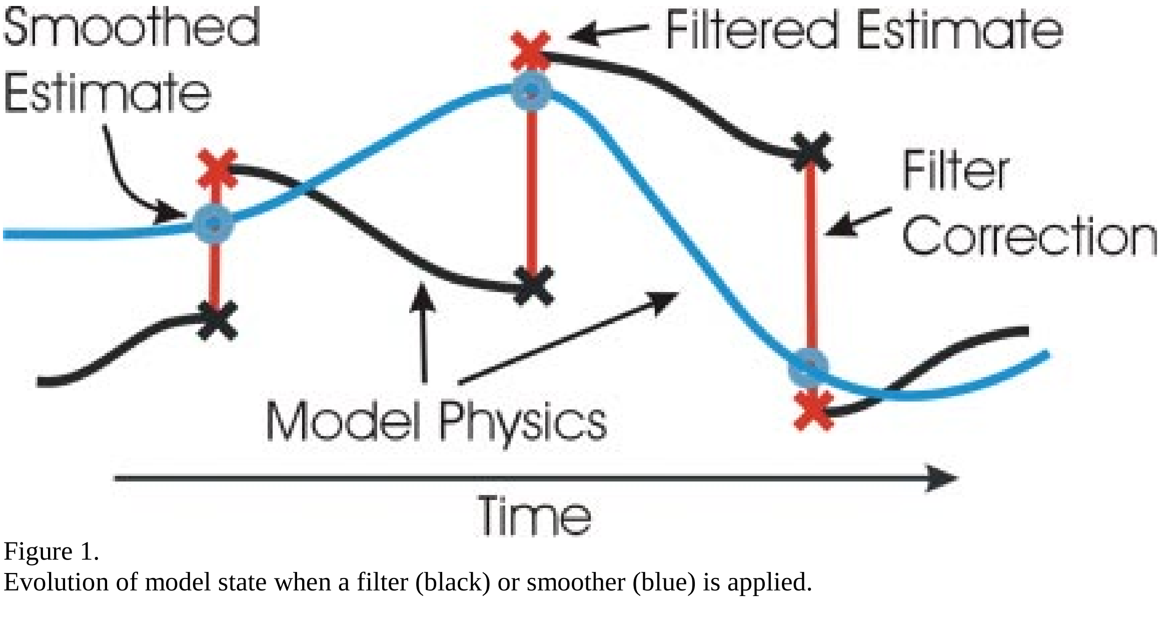

Figure 1.
Evolution of model state when a filter (black) or smoother (blue) is applied.

Physical inconsistencies limit the usefulness of such estimated states for understanding mechanisms and processes relevant for climate studies. For instance, imbalance in heat budget makes analyses of global and regional heat transport difficult. Violation of continuity render tracing pathways and the evolution of water masses uncertain. The cause of low frequency changes in the oceanic state (e.g., sea level and temperature) can be difficult to discern because of the unknown nature of the data correction term.
A physically consistent estimate is derived by inverting data correction (third term) at each time-step, correcting explicit physical processes (the state and the control, i.e., first and second terms) backwards in

time (Fukumori et al., 2002). Mathematically, the procedure is known as smoothing, and common methods include 4DVAR and sequential smoothers. Smoothing employs formally future observations to correct the state and control in the past. In comparison, the assimilation above describes filtering that utilizes present and past observations to correct only the model state. Smoothed estimates are physically consistent such that its state evolution can be explained by explicit physical processes (advection, mixing, and forcing);

$$\mathbf{x}_t = \mathbf{A}\mathbf{x}_{t-1} + \mathbf{G}\mathbf{u}_{t-1}\,.$$

The evolution of the smoothed estimate $\hat{\mathbf{x}}_t$ is illustrated by the blue curve in Figure 1. Most existing smoother applications typically only concern the state $\hat{\mathbf{x}}_t$ but not the control $\hat{\mathbf{u}}_t$. However, a consistent description of the state's evolution requires both state and control estimates that satisfy physical principles. In particular, this illustrates the importance of modeling model errors (process noise, $\hat{\mathbf{u}}_t$) by explicit physical processes (e.g., errors in external forcing, parameterization, finite differencing, etc) so as the smoothed control estimate is physically sensible. It should be noted that such a smoothed estimate is not equivalent to a solution of the so-called strong constraint assimilation. The smoothed estimate is a weak constraint solution but one with explicit model error estimates. An example how inconsistent and consistent assimilation methods lead to different oceanographic interpretations is given below in the section on the carbon cycle (Figure 5).

3 Applications

Having a consistent description enables diagnosis to be made of the physical processes controlling the observed changes of the ocean. For instance, the left panel in Figure 2 describes contributions to changes in the average sea surface temperature (black curve) of the eastern equatorial Pacific ("Nino3" region) of the ECCO-2 smoothed product over a four year period covering the 97-98 El Nino event (Lee et al., 2002). Advection (red) and mixing (green) are found to act in concert to warm the Nino3 mixed layer, while the atmosphere (blue) has a tendency to cool the ocean in this region. Effects of the circulation on temperature change are generally larger than those of mixing. The right panel describes a decomposition of the dominant advective contributions, and shows vertical circulation playing the primary role in controlling interannual temperature change in the Nino3 region. The examples illustrate what can be accomplished by consistent state estimation: inference is made about unobserved quantities from sparse observations, with the estimated state evolution being dynamically consistent in the sense that changes can be attributed to a sum of explicit physical processes. The relative role of these processes is *a priory* unknown. After assimilation we understand much better the governing mechanisms.

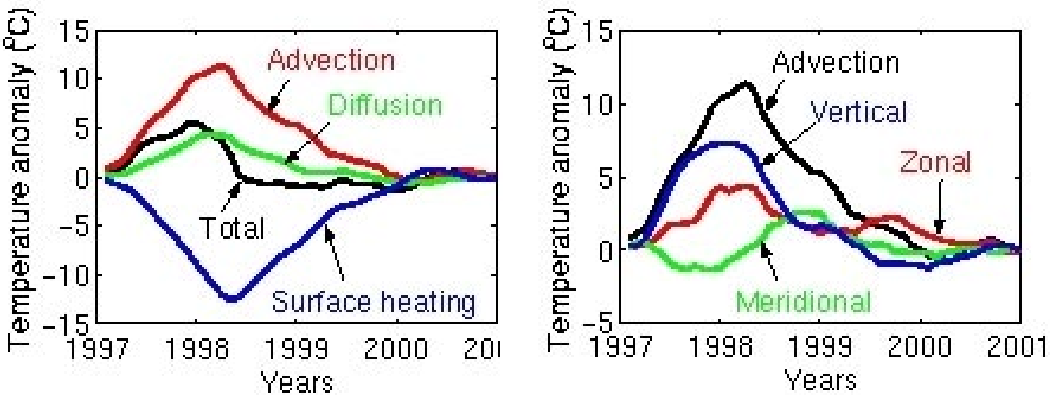

Figure 2
Contributions of various terms to the tendency of the mixed layer temperature heat balances in the eastern tropical Pacific as described by Lee et al. (2002).

Other important applications are the estimation of driving forces on the ocean. These forces can be used as control $\mathbf{u}_t$. Knowledge of upper boundary conditions is not only crucial for the ocean model. Atmospheric models need lower boundary conditions for their temporal integration. Preferably both boundary conditions should be consistent. A word of cautions is necessary at this place. Assimilation methods like 4DVAR will not only find reasonable and meaningful adjustments to the first guess forcing fields. Additionally model error will be projected on the control variables. It is therefore important to analyse the results carefully and distinguish between model error and physically meaningful adjustment. As an example the mean net surface heat flux field resulting from a different ECCO optimisation over a 9 year period (see Stammer et al., 2002a, 2002b for details) is displayed in the upper panel of Fig.3. The adjustment relative to the prior National Center for Environmental Prediction (NCEP) estimate is also shown that is required to bring the model state into consistency with the ocean data. Modifications of the net NCEP heat fluxes are of the order of 20 W m^{-2} over large parts of the interior oceans. Maximum changes occur along the boundary currents in the Northern Hemisphere where changes of up to 100 W m^{-2} can be found. Most of the eastern boundary currents now show a significant heat uptake. The same is true in the Arabian Sea, where the off-shore Ekman transport brings up cold water, and which is then heated by the atmosphere. Strong warming occurs over Flemish Cap, in the North Pacific, and along most of the Antarctic Circumpolar Current. Note that the optimisation also removes some of the small-scales visible in the eastern Pacific in the initial NCEP estimates of buoyancy flux fields; these originate from Gibbs effects in the spectral representation of mountain ranges such as the Andes. Stammer et al. (2002b) conclude that combined ocean observations and dynamics provide a route to improving air-sea flux estimates, complementary to those from atmospheric models, or from direct observational campaigns.

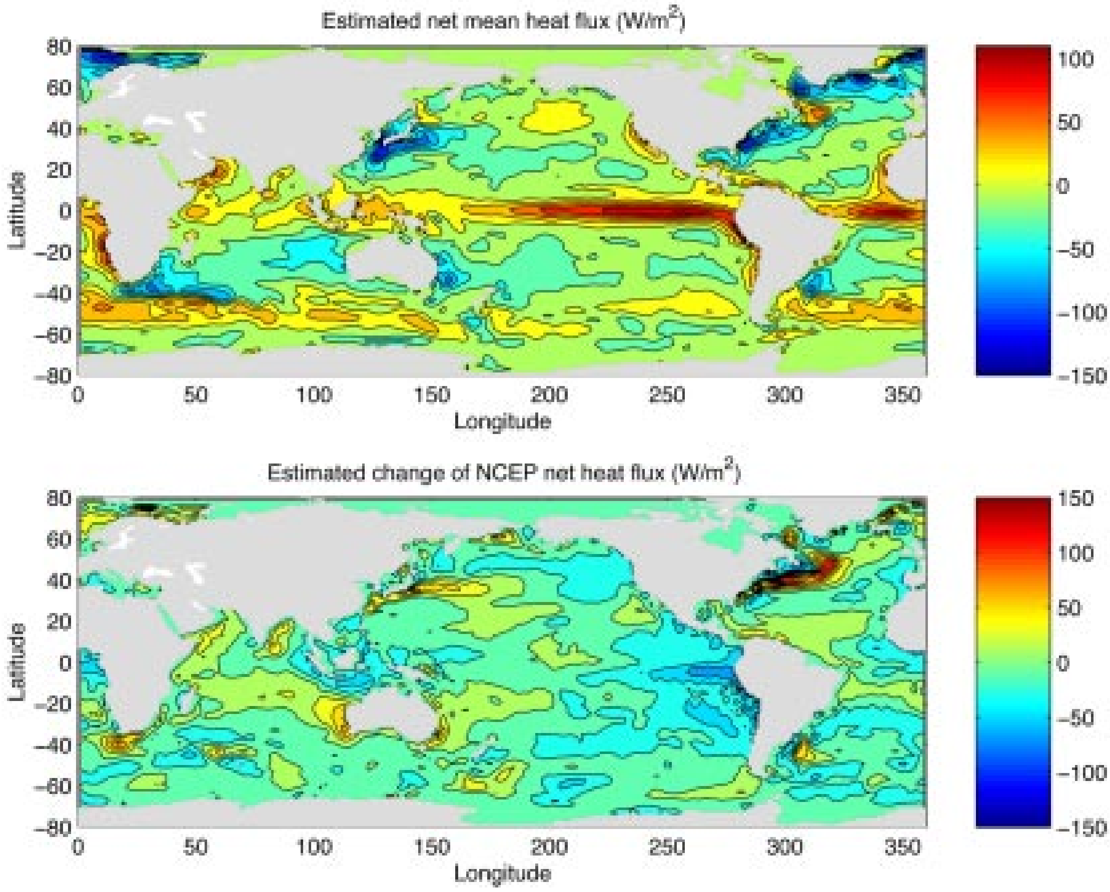

Figure 3

Above: Mean estimated net surface heat flux required to bring the model into consistency with data [Wm^{-2}]
Below: Mean estimated adjustment of the NCEP net surface heat flux required to bring the model into consistency with data. Contour interval: 20 W m^{-2}.

A by-product of the adjoint method is the estimate of the adjoint solution. This solution represents a nearly complete description of sensitivity to data, and of the flow of information in the model. Obviously this is an ideal tool for observational design. Use of this solution, to examine the controlling factors on oceanic meridional heat flux, was described by Marotzke et al. (1999). New applications will be to decide whether operational profiling floats (ARGO) which may possibly also measure during the period they stay at depth should preferably follow isopycnals during their drift or should better stay at given depth levels. Similarly we will learn in which locations and at what time intervals additional measurements would be most valuable simply by analysis of the adjoint solution.

4 Understanding long-term climate variability and change

Sea level rise and its prediction is one of the greatest public concerns in the context of global change. Despite its importance sea level change is not well enough understood. During the last decade we have, for the first time, continuous observations by satellite altimetry on a global scale. Before this period even estimating the global sea level remained a difficult task. Gaps in spatial and in temporal coverage make estimates uncertain to some extent. It is difficult to distinguish between interannual to decadal oscillations and longer term trends. It is one of the prime targets of long-period state estimation within GODAE to derive continuous and global timeseries of sea level evolution consistent with ocean dynamics and with observed data.

For predictive purposes it is most important to understand and distinguish different processes leading to local sea level variations. A global model with a resolution of 2^O was used to study sea level changes due to thermal expansion, haline contraction, fresh water fluxes and oceanic circulation during the last decades. Data assimilation was applied to first derive an ocean state with no significant remaining drift and consistent with the average annual cycle of temperature and salinity over the whole depth of the ocean (Wenzel et al., 2001). For this experiment the monthly mean values of wind-stress, air temperature and precipitation-evaporation were used as control variables. The model was subsequently forced with anomalies from NCEP reanalysis for 50 years. Precipitation and evaporation are taken into account by exchanging fresh water (i.e. mass) with the atmosphere. Inflow by rivers is included (Wenzel and Schröter, 2002).

The thermal expansion played a minor role in comparison with the net influx of fresh water into the ocean. An interesting result of the modeling is the role of salt. While salt itself is strictly conserved as a global mean, salinity may change locally. Halo-steric effects do play a considerable role in the local sea level variations even on decadal time scales. Figure 4 shows the difference in sea surface height between the 1970ies and 1990ies which is due to halosteric contraction, i.e. local changes in salinity. Strong signals are found mostly in the Atlantic Ocean. It is worth noting that in general halosteric effects have a strong (negative) correlation with thermosteric expansion which dominates sea level evolution. Observed changes of the total sea level are therefore likely to be of opposite sign than given in Figure 4 and caused by local heating/cooling. Our experience from global state estimation leads us to the conclusion that sea level anomalies should not simply be seen as anomalies in the local heat content. The role of salinity and of changes in the local circulation patterns must be taken into account as well.

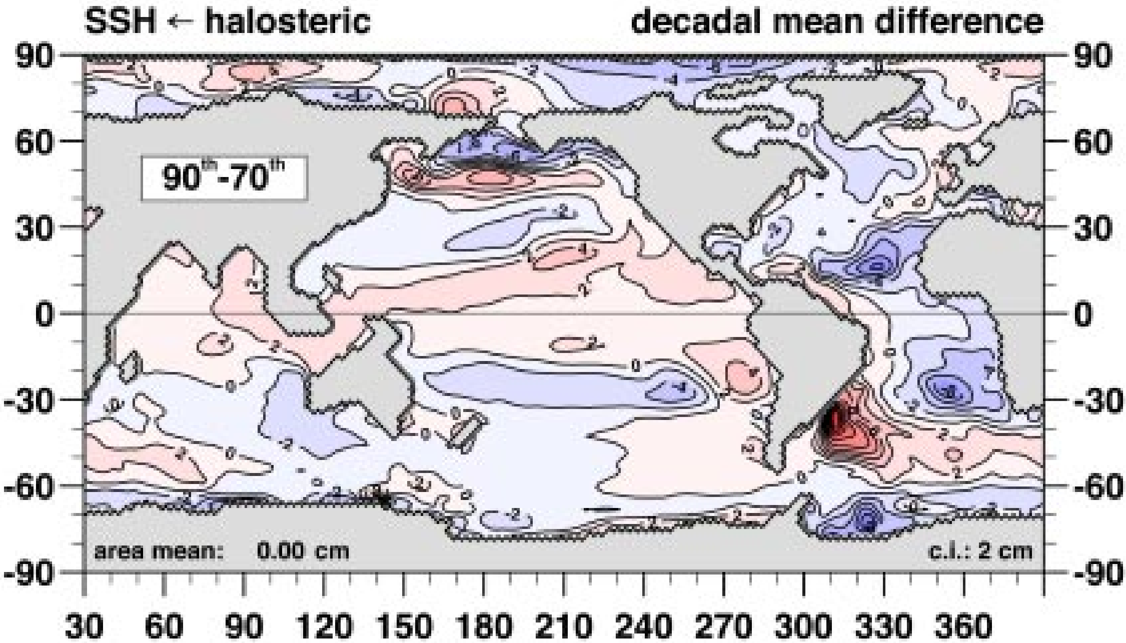

Figure 4
Sea level change due to variations in salinity (halo-steric contraction) between the 1970ies and the 1990ies. calculated from a global circulation model after assimilation (Schröter et al., 2002). Most of the ocean shows little change while in the North Pacific and in the Atlantic Ocean strong interdecadal signals are detected.

In the discussion about sea level rise the angular momentum of the globe has found renewed interest (Munk, 2002). Melting of high latitude ice-sheets leads to a redistribution of mass on the globe and has a prominent signal in the length of day. Changes in this length and polar motion can be calculated from global atmosphere and ocean models. They explain a certain, fluctuating part of the time series based on observations of satellite orbits and stellar positions. Ponte et al. (2001) demonstrated that the optimised solution derived by ocean state estimation produces a significantly increased fraction of the observed rotation variance. Improved state estimates of the ocean for the last decades which includes mass redistribution and sea level rise enables us to make crucial comparisons. Sea level change may be constrained effectively by observed angular momentum. On the other hand oceanic data resulting from the state estimate performed within GODAE can be used to separate different effects within the angular momentum budget and help to better understand processes in the solid earth. Ultimately, measurements of polar motion and rotation will be used to constrain the ocean flow field, as will be measurements of gravity fluctuations and changes in the ocean mass field expected to originate from the upcoming Gravity Recovery and Climate Experiment (GRACE) mission. In this context it is interesting to note that standard atmospheric reanalysis projects do not conserve the mass of the dry air. This is the effect of using a filter for atmospheric state estimations instead of a smoother which would be more consistent as discussed above. Angular momentum is one of the fields where oceanography and meteorology meet with hydrology and the sciences of solid earth and cryosphere in a fruitful way for their mutual benefit.

5 Ecosystem modelling and the global carbon cycle

A key element in the global carbon cycle regulating climate is the exchange of CO_2 between atmosphere and oceans. Currently, the oceans take up around 2 Pg C ($2*10^9$ tons of carbon) each year which equals one third of anthropogenic emissions due to burning of fossil fuels. The estimate of global oceanic uptake of CO_2 is still based on biogeochemical general circulation models (BGCMs) or on interpretations of atmospheric O_2/N_2 ratios, although more and more measurements of pCO_2 and of dissolved inorganic carbon (DIC) were made in the sea during the last decade and the impact of increased atmospheric CO_2 on oceanic CO_2 levels has been clearly demonstrated for certain regions. Orr et al. (2001) compared four BGCMs and gave a value of 1.85 +- 0.35 Pg C / a for the global uptake (average for 1980 - 1989).

Although the scatter in global uptake rates between models appears to be small, the differences in the regional distributions of annual mean air-sea flux and vertical integral (inventory) of anthropogenic CO_2 are quite large. The models still need much improvement before we can trust in the calculated uptake values. Since about a decade the O_2/N_2 ratio in the atmosphere is measured with extremely high precision (Keeling and Shertz, 1992; Heimann, 2001). Under certain assumption (stoichiometry of land plants, no change in the strength of the marine biological C pumps, etc.) the uptake of anthropogenic CO_2 by the physical (solubility) carbon pump can be inferred from the trend in atmospheric O_2/N_2 (Keeling et al., 1996).

Changes in oceanic circulation or temperature lead to changes in outgassing or uptake of O_2 and CO_2. These effects have to be taken into account when interpreting of the O_2/N_2 time series. Once again, physical consistency is particularly relevant in using assimilation products. Figure 5 illustrates such flux estimates in the tropical Pacific Ocean during the 97-98 El Nino event based on a biogeochemical model employing circulation estimates (advection and mixing) of the filtered and smoothed ECCO-2 products (McKinley, 2002). Inconsistencies in the filtered advection field result in unrealistic sea to air CO_2 fluxes (left) whereas such anomalies are absent in the estimate based on the smoother (right) consistent with independent observations. These results clearly illustrate the need for a consistent data assimilation method when we aim for understanding processes and supporting other disciplines.

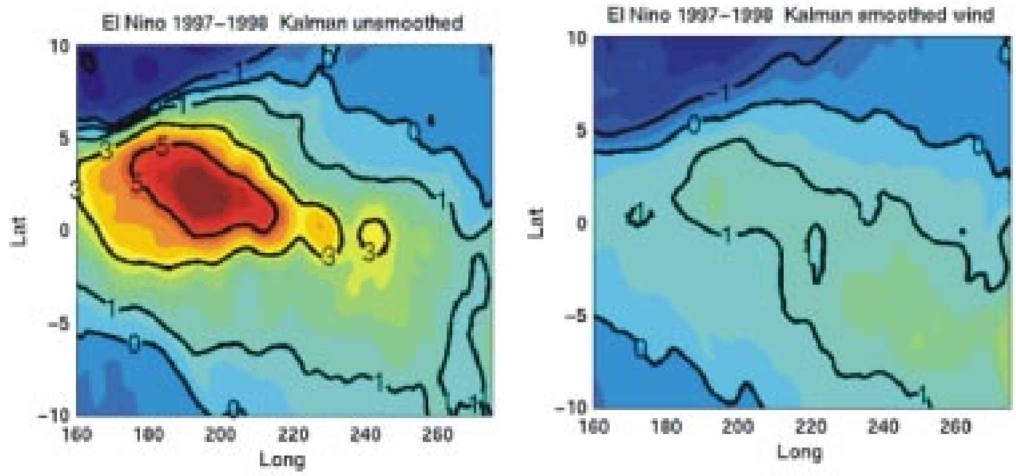

Figure 5.
Average air sea flux of CO_2 calculated from the ECCO-2 ocean model. Left: estimates derived from assimilation with the Kalman Filter method. Right: same as left but calculated with a consistent estimate by Kalman Smoother.

Global BGCMs still have coarse spatial resolution (1^O x 1^O at most, but typically 2^O x 2^O or even coarser) and therefore are not able to explicitly resolve meso-scale eddies. Eddy-permitting models have been set up on the regional scale as, for example, for the whole North Atlantic. It has been shown that meso-scale dynamics may lead to much higher (compared to coarse scale models) nutrient supply from deeper layers (McGillicuddy et al., 1998; Oschlies and Garcon, 1998). Models with even higher resolution (eddy-resolving models) might provide more surprises in the near future. Eddy-permitting and eddy-resolving models should be coupled with biogeochemical models that include carbon (and not only nitrate or phosphate). Fine-scale resolution model will hopefully also show a better representation of heat flux and mixing. Oceanic CO_2 uptake is closely related to heat flux divergences (Watson et al., 1995) and the ratio between meridional overturning and vertical mixing rate in the North Atlantic determines whether the northern North Atlantic is a sink or source for anthropogenic CO_2 (Völker et al., submitted). We learn that major questions about CO_2 uptake in the ocean cannot be answered by biogeochemistry only. Ocean state estimation plays an important role in providing proper boundary conditions and physical background for biogeochemical modelling.

The carbonate system in BGCMs is described by prognostic equations for dissolved inorganic carbon (DIC) and total alkalinity (TA). DIC in the ocean is affected by CO_2 gas-exchange with the atmosphere, by the formation and remineralization of organic matter, and by the biogenic precipitation and dissolution of calcite and aragonite. TA is affected mainly by $CaCO_3$ precipitation and dissolution and by nitrate and ammonium uptake and release. Gas exchange has no effect on TA. Currently, the marine biota is simulated by very simple approaches (four compartment models NPZD = nutrient, phytoplankton, zooplankton, detritus). We know, however, that different functional groups of phytoplankton (Falkowski, 1999) such as, for example, silicifiers (diatoms), calcifiers (coccolithophorides), N-fixers (cyanobacteria) have different impacts on DIC and TA and are influenced differently by the abundance of nutrients. They should thus be taken into account when simulating the marine carbon cycle. Plankton models with a higher functional diversity are currently developed, implemented into BGCMs and analyzed (Moore et al., 2001). The model parameters of such plankton models can be constrained more and more by observed physiological and ecological properties of key organisms but optimization of parameter values by data assimilation will be still required for the representation of bulk properties. For the latter purpose data from time stations (Hawaii, Bermuda, Kerguelen, etc.) and from remote sensing (ocean colors) is strongly requested. Additionally it would be highly welcome if ARGO floats can be equipped with sensors for CO_2 and pH.

Mitigation of further atmospheric CO_2 increase by large-scale iron fertilization of the ocean has been discussed in the context of the Kyoto protocol and Markels, an American scientist and entrepreneur, has already applied/registered several patents with respect to oceanic fertilizations (compare references in Markels and Barber, 2001). Several scientific iron fertilization experiments conducted in recent years in HNLC (high nitrate low chlorophyll) regions such as the equatorial Pacific and large parts of the Southern Ocean have clearly demonstrated that addition of dissolved iron has a stimulating effect on phytoplankton. Yes, iron is the limiting element in HNLC regions. We are far from the point where we are able to make predictions on the impact of large-scale and long-time iron fertilization and thus many marine scientists are concerned of this mitigation strategy (Chisholm et al., 2001). The fate of phytoplankton blooms is still not known because all experiments have been too short because of ship time limitations. Future longer, multi-ship experiments will answer this and many other open questions such as functioning of marine ecosystems or glacial-interglacial differences in ecosystem structure.

In Figure 6 the velocity field and the ocean patch influenced by iron fertilization in the Southern Ocean during EISENEX is depicted. Note the fine resolution and the complex structures. In this context it is immediately clear that EISENEX and follow on experiments will greatly profit from an Ocean Forecasting System. Position and strength of eddies or rings in the southern Ocean can first of all be diagnosed before the expedition begins. Some estimate is available about what the fate of any ocean patch will be. So we can design experiments according to forecasted ocean dynamics saving ship time helping hypothesis testing.

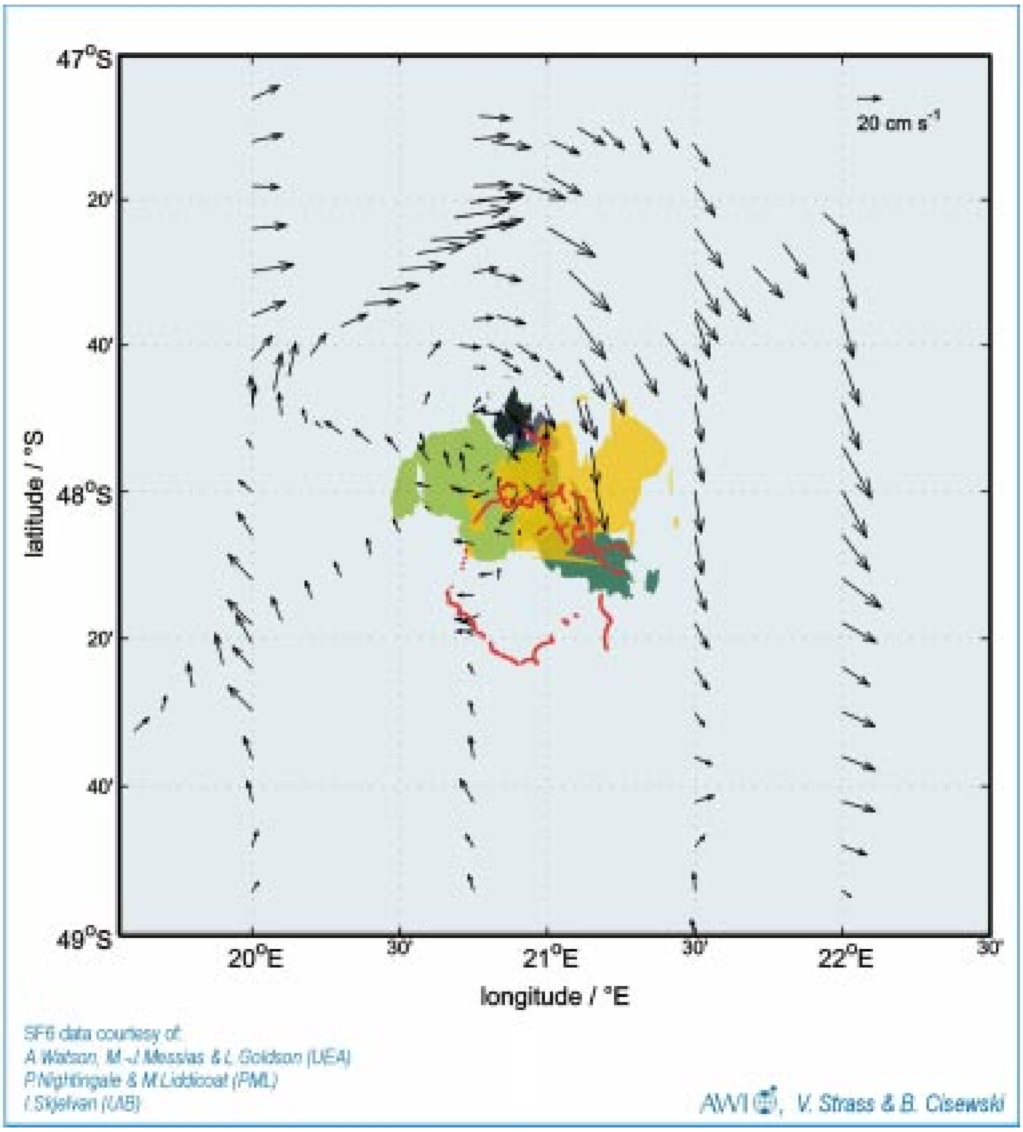

Figure 6
The ocean patch influenced by iron fertilisation during the EISENEX experiment. Arrows indicate current velocities.

6 Outlook

The "New Paradigm" for sharing ocean data in almost real time which was proposed at OCEANOBS 99 has found a lot of support. It is being extended by voluntarily sharing their operational or offline estimates over the internet. This new data sharing policy is found more and more natural in the community on ocean state estimation. Physical oceanography is entering a new era in which there will be a far greater reliance on global observations and ocean state estimation as a synthesis tool to provide the community with estimates of the time-evolving ocean and climate state. The preliminary results reported here show that the existing data-base and the available modelling and computing capability have advanced to the point where true three dimensional, skilful estimates of the global time-evolving general circulation are practical. To a large extent, this statement is a vindication of the vision which drove the World Ocean Circulation Experiment that such estimates could become possible by about the year 2000, and that they would be necessary for the advancement of the science. We strongly emphasize however, that we are at the very beginning of what will be a long process of improvements and enlargement of the scope of oceanic state estimation. The analogous effort in numerical weather prediction has already spanned several decades. With expected advances in computer power and numerical algorithms, models with greatly increased spatial resolution, and more sophisticated and complete physical parameterisations will come. Regional estimates at extremely high resolution with open boundaries are already underway. Global estimates at $1/4^{O}$ are envisioned as being feasible in two-to-three years. A much fuller exploration of the control vector space will be undertaken, including adjustments to internal parameters such as diffusion and viscosity coefficients, and external parameters such as the bottom topography and sidewall boundary condition relationships. The information contained in adjoint solutions remains to be more fully exploited.

Looking further into the future, one can envision ongoing global estimates of coupled ocean/atmosphere/cryosphere models with sufficient skill that true climate forecasting (that is, with skill estimates) will be possible. At the same time, we envision a vigorous interaction between estimation activities and the biogeochemical and physical observation efforts now being designed. A critical element for enhanced understanding of biological processes in the ocean is the availability of a realistic flow field such as that which becomes available from ocean state estimation. The greatest challenge of all to the oceanographic community may well be to find a way to sustain the long term observing systems, model development and synthesis activities which are all essential to reaching our goal.

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