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D. Stammer

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1) Executive Summary:

A first CLIVAR workshop on ocean reanalysis was held at NCAR, Boulder, from November 8 to 10, 2004. The workshop was solicited by the CLIVAR SSG and organized under the auspices of GSOP. It was sponsored financially by NASA, NSF, NOAA, WCRP, and was arranged in coordination with GODAE and OOPC. The meeting was called because high-quality data assimilation capabilities are required as a firm element of CLIVAR's observing and data synthesis strategies and because CLIVAR has to make sure that a respective and suitable reanalysis support of its research is organized.

In general terms, CLIVAR needs ocean reanalysis:

1) To develop improved data bases and reference data sets for climate studies.
2) As a basis to study the climate dynamics in the ocean over the last several decades.
3) As initial conditions of coupled models on seasonal-to-interannual and decadal and longer time scales.

In particular, global reanalysis efforts are required within CLIVAR to build a global framework in which regional/basin scale research efforts, such as process studies, can be embedded. Those global reanalysis efforts will be used to estimate the state of the ocean through the assimilation of in situ and remotely-sensed data such that the resulting fields are dynamically consistent with the model dynamics and can be used as the basis for CLIVAR's scientific studies to study ocean variability, its dynamics, its transport properties and its interaction with the atmosphere.

To meet all those goals, the objectives of the workshop were accordingly to:

- Review the status of ongoing and planned ocean synthesis (reanalysis) efforts.
- Establish the requirements for ocean state estimation and reanalysis in climate research within the remit of CLIVAR.
- Promote the use of existing reanalyses.
- Review the synergy between ocean and atmospheric reanalysis activities with specific focus on improving surface flux fields.
- Review coupled ocean-atmosphere model syntheses in support of climate prediction.

The 3-day meeting was open to the community but limited in size to about 80 participants. The meeting consisted of plenary sessions with invited talks followed by working sessions in which discussions were held that focus on addressing the meeting's goals. A complete meeting agenda is provided in Appendix B. In the plenary sessions review-talks were presented to provide a basis for the discussions in the working groups. Although the workshop's primary focus was on ocean syntheses/reanalysis, atmospheric re-analysis activities were reviewed as well with specific focus on surface flux estimations so as to link the two individual approaches, which currently are pursued separately in the ocean and in the atmosphere. Ultimately climate-focused reanalysis activities need to be approached as a coupled problem and the workshop needs to discuss the implications of this.

The outcomes of the workshop can be summarized as follows:

CLIVAR needs to promote the development and wider use of global ocean reanalyses to adequately address climate-related questions and for applications with significant societal relevance. The spectrum of applications of ocean reanalyses for climate variability and prediction purposes spans over seasonal-to-interannual, decadal-to-centennial, and even millennial time scales. Examples of climate-relevant applications requiring high quality ocean reanalysis products include:

1) Studies of sea level change
2) Input for the 5thIPCC assessment in terms of initial conditions for next assessment runs, as well as basis for climate change studies, such as sea level change over the past 50 years or changes in ocean heat content.
3) Investigations of the oceans role in CO2 sequestration
4) Characterizing and understanding important climate processes and dynamics
5) Initial conditions and boundary conditions for higher-resolution approaches intended to elucidate regional impacts.
6) Initializing coupled models for seasonal to seasonal to interannual and for decadal and centennial forecasting.
7) Observing System Experiments (OSE) required for designing ocean elements of the climate observing system

These applications pose a range of accuracy and robustness requirements on ocean reanalyses. Consequently, they necessitate somewhat different data assimilation approaches and evaluation. While there are a small number of sustained efforts institutionalized for seasonal-to-interannual forecasting and respective ocean assimilation work (see Appendix A), there are critically few sustained activities in place to provide needed climate-quality hindcasts/reanalyses, climate model initializations for decadal to millennial time-scale problems, and other products.

While there are some needs common across the multiple applications outlined above, optimal approaches have not yet been established for any of these major climate-research related applications of ocean reanalyses. It is therefore likely that different approaches and methods will need to coexist for some time in support of these applications. In some cases, such as ENSO predictions, specialized suboptimal efforts might work better than using the most dynamically consistent ocean data assimilation estimate. It is also recognized that focused infrastructure developments will be required to address the gaps between ocean reanalysis needs and current capabilities. Lastly, an earnest fundamental R&D program needs to be maintained in order to continue improving ocean reanalysis efforts so that these improvements could eventually be transitioned into coupled reanalysis and forecasting frameworks.

An urgent next step needed as a basis for a well–defined CLIVAR reanalysis effort requires the evaluation of existing reanalyses in terms of their quality for each of the above application areas. Such an evaluation includes determining uncertainties within a model ensemble framework. This needs to be completed in close collaboration with WGOMD, GODAE and the CLIVAR basin panels (model-model; model-data; prediction, residuals). A working group needs to define the current capabilities of ocean reanalysis for climate purposes as well as the respective requirements to meet CLIVAR needs. The most important requirements that should be addressed include data quality, assemblage, and distribution, surface and lateral fluxes of heat, momentum, and freshwater (incl. freshwater run off and ice), data assimilation methodologies, ocean model physics and approximations.

Several enabling activities for ocean reanalysis need to be coordinated in support of all requirements. For example, seasonal-to-interannual ocean analysis efforts, which require only a modest amount of recent and real-time data (and generally have less stringent data quality requirements), have a well–organized data stream. Portions of this resource are being used by other ocean reanalyses efforts, but assembling data streams and data QC becomes a significantly large issue for decadal reanalyses efforts. Consequently, interactions between different assimilation developers, contributors, and users needs to be enhanced to address a wider spectrum of needs, particularly to meet the needs of applications requiring longer integrations, more observations, and more complex assimilation systems. A working group needs to define data needs and work with the CLIVAR DACs on implementing them for reanalyses and other CLIVAR purposes.

Surface flux (i.e. momentum, heat, and freshwater, including run off and ice volume advection) uncertainties remain a large issue. Reanalyses efforts need to work with WGOMD and the WCRP Working Group on Surface Fluxes (WGSF) on identifying the best surface flux products to utilize in ocean reanalyses efforts. Such an evaluation should include satellite vector wind stress and SST.

Regional impact studies have to be performed. The major new feature of ocean data assimilation efforts in the next decade and beyond will be its multi-disciplinary and multi-scale as the separation between physical, chemical and biological applications become transparent. Inter-disciplinary coupled models are the venue of the future.

Changes of the ocean observing system exist and their impact on long-term ocean reanalyses must be qualified (atmospheric reanalyses are also affected by this problem). OSE's can help to understand such impacts and can also help to determine requirements on the observing system. However, caution has to be used while interpreting OSE results since they depend on the underlying model fidelity and model setup, as well as on the science question (metric) under investigation.

Above all, a major challenge remains as to how ocean reanalysis efforts can be moved forward and become integrated within coupled approaches that are suitable to produce the best possible initial conditions for coupled climate forecasts, e.g. those that use the entire ocean-atmosphere-cryosphere-terrestrial observing system.

Several GSOP actions are underway in response to this workshop. These include (at the time of this writing):

1. Working group on data quality requirements for reanalyses and ocean data system to produce recommendations for CLIVAR DACS. A respective working group was formed by GSOP and a white paper is in preparation.
2. Working group on reanalysis evaluation studies (in partnership with GODAE, WGOMD and CLIVAR panels). This would initially be done in a pilot inter-comparison process to be developed in the coming year. A respective white paper was written after the workshop and the effort is anticipated to start late in 2005.
3. Preparation of recommendations for model standards and surface fluxes that should be used by reanalysis efforts. A small group was formed by GSOP and action is underway in close cooperation with CLIVAR-WGOMD and Flux WG.

2) Background:

As a legacy of WOCE, ocean data assimilation has evolved into a quantitative approach of combining ocean circulation models with ocean observations. If performed in a mathematically rigorous way, data assimilation will extract maximum information from the relatively sparse and expensive climate observing system and results will lead to a best possible and dynamically self-consistent estimate of the time-varying ocean circulation, and its interaction with other components of the climate system. In the context of CLIVAR, reanalysis efforts are required:

1) To develop improved data bases and reference data sets for the climate community.
2) To provide a basis to study the climate dynamics in the ocean over the last several decades.
3) To provide the basis for the initialization of coupled models on seasonal-to-interannual and decadal and longer time scales.
4) As a global framework to embed in regional/basin scale research efforts.

To live up to this expectations on ocean data assimilation within CLIVAR's research, ocean data assimilation/ reanalysis needs to be viewed as an intricate element of its observing strategy, and data assimilation needs to be performed in a way consistent with the data and ocean circulation models, and uncertainties in both. In particular, data assimilation needs to be carried out in a way that results can be used to study climate dynamics over time scales from a few months to decades, to understand the interaction of the ocean with the atmosphere and other parts of the climate system (e.g., the cryosphere) and to initialize climate forecast studies. There are also many other applications that involve data assimilation or build on its result, the ultimate goal being the need for predictions and understanding of ocean dynamics on multiple space and time scales as part of a coupled earth system. Carbon sequestering in the ocean and predictions of the carbon content in the climate system is yet another important application with societal implications, as is the prediction of regional and global sea level increase over the next century.

Although substantial progress has been made in recent years, major challenges remain which need to be overcome before the objective of routine ocean state estimate in support of CLIVAR's research can fully be met. To this end, the CLIVAR community must define the usefulness of the current status of data assimilation for its research, must think about ways forward to remedy those short comings but must also take action to sustain data assimilation as an intricate part of CLIVAR's observing system – at least as long as CLIVAR's duration. However, as a legacy of CLIVAR, ocean reanalysis efforts must have demonstrated the importance of sustained climate observing and synthesis efforts as an indispensable element of coupled data assimilation efforts that are required to initialize coupled clime forecast models.

To expedite this process and at the same time to promote the use of data assimilation as an intricate elements of a climate observing strategy in support of CLIVAR's research, a workshop was called for by the CLIVAR SSG and was organized under the auspices of CLIVAR's "Global Synthesis and Observations Panel" (GSOP), aiming to review the status of ongoing and planned ocean synthesis (reanalysis) efforts, to establish CLIVAR's requirements for ocean state estimation and reanalysis and to start organizing respective data flow structures and reanalysis efforts. Among the goals of the workshop was also to review the synergy between ocean and atmospheric reanalysis activities with specific focus on improving surface flux fields, and to review coupled ocean-atmosphere model syntheses in support of climate prediction.

The 2-day meeting was open to the community but limited in size to about 80 participants. A list of workshop participants is provided in Appendix C. The meeting consisted of plenary sessions with invited talks, followed by working sessions in which discussions that focus on addressing the meeting's goals were held. Review-talks were provided in plenary, aiming at providing a basis for the discussions during working groups during day two of the meeting (a complete meeting agenda is provided in the Appendix B).

Plenary talks included the following topics:

- Ocean synthesis requirements, benefits and strategies for CLIVAR (C. Wunsch).
- Status of atmospheric reanalyses (ECMWF (ERA-40), NCEP, GMAO, SURFA) (S. Schubert) .
- Status of surface fluxes estimates (C. Fairal)
- GODAE support for CLIVAR (N. Smith)

Plenary talks were followed by a presentation on ongoing reanalysis activities in the ocean (listed below), their accomplishments, problems and data requirements:

1. HYCOM (C. Thacker)
2. ENACT (Mike Davy; A.T. Weaver)
3. ECCO (Ichiro Fukumori, Carl Wunsch)
4. GFDL (Leetmaa, Rosati)
5. U Maryland (J. Carton)

6. NCEP (D. Behringer)
7. MEXT (Toshiyuki Awaji)
8. BlueLink (A. Schiller)
9. GMAO (M. Rienecker; contribution was cancelled)
10. Mercator (Eric Greiner)
11. ECMWF (Magdalena Balmaseda)
12. UKMO (Bruce Ingleby)

These review talks were concluded by a summary on the historical data archiving project performed at NODC (Hernan Garcia). Brief outlines of all those efforts are provided in Appendix A.

During the second day of the workshop, meeting participants were subdivided into four working group to allow in-depths discussions of key issues of reanalysis. The working groups covered the following 4 themes:

I) Applications of reanalysis efforts (chaired by A. Treguir and I. Fukumori)
II) Fluxes from Atmospheric reanalyses (chaired by R. Weller and W. Large)
III) Ocean observing system for CLIVAR (chaired by M. McPhaden and V. Zlotnicki)
IV) Uncertainties and biases (chaired by A. Bennett and A. Weaver)

The working group discussions addressed in particular the following issues: What have we learned from existing results, what will we learn? What are useful methods for CLIVAR and useful for what? What deliverables are available from ongoing efforts and who are their users? What is the status of data availability, their quality, and the data stream? What are the uncertainties of data and models, and what are the synergies to Atmosphere/ Fluxes Coupled Assimilation?

Challenges for the future were discussed in a final plenary session during the morning of the last day (chaired by D. Anderson and M. Reinicker), which was followed by a summary of workshop outcomes and a conclusion.

3) Plenary Talks and Working Group Results

In this section, the plenary overview talks will be summarized and conclusions that have been drawn from working group discussions will be highlighted.

Plenary Talk 1:

Ocean synthesis requirements, benefits and strategies for CLIVAR

Speaker: C. Wunsch (presented by D. Stammer).

The earliest WOCE planning documents discussed the idea that diverse global data sets would require their combination with global numerical circulation models to obtain a most complete description of the changing ocean circulation. Although not called a reanalysis at that time (there is still no "analysis" to be reanalyzed), the focus of this workshop is clearly what was in the minds of the WOCE pioneers. Because numerical models are meant to encompass all theoretical knowledge of the ocean circulation, synthesis products should be more accurate than individual estimates obtained from models, or data alone. Failure to do state estimation would imply either a complete lack of confidence in our theoretical knowledge, or in the information content of observations. On the other hand, ocean field experiments/ observation systems are very expensive, and worth a considerable investment in appropriate design. True experiment designs needs to be done quantitatively, and generally involves optimizing a function of a hypothetical state variable.

One particular goal of a climate program is to understand predictability, and then to predict what is possible. Thus a major question concerns finding the time horizon of prediction for various elements of the ocean circulation. That is, given a perfect atmosphere, how far into the future can one calculate oceanic heat uptake? What is the carbon uptake of the global ocean? What are fresh water and heat flux divergences and how do they change with time? Answers to those questions will depend both upon the underlaying model's accuracy, precision, and physical stability, but also upon the errors of its initialization and representation. These can only be found through a rigorous estimation procedure. CLIVAR's success therefore fundamentally depends on the fidelity of its analysis procedures. Science questions to be answered using CLIVAR's global analysis efforts include global and regional sea level issues: global warming, change of mass, post-glacial isostatic adjustment of the solid Earth, melting of continental ice sheets, and water storage on land. Model issues include approximation, topography and flow field, and coupled ocean-ice-atmosphere problems.

To reach those goals, there are several reasons for CLIVAR to undertake a global synthesis (state estimate): Data are diverse (altimeters, hydrography, floats, current meters, meteorological variables, boundary current transports) and some kind of synthesis is required to use all data together in a dynamically and statistically consistent way. Because the oceanic climate state is global, ultimately the state and its changes in any part of the system could/would affect all regions at various times. CLIVAR therefore needs a global synthesis to connect its regional observing and process studies: Regional programs (Brazil Basin, or Subduction Experiments are good examples) are affected by the surrounding, otherwise unobserved, ocean.

Other examples that advocate for global synthesis to be coordinated by CLIVAR:

- State estimates of the larger scales are necessary to interpret climatologically important flows except on the shortest of time scales (internal wave studies do not require a knowledge of the distant ocean, but general circulation scales will be affected by every region if one waits long enough);
- Initialization of global coupled climate models requires global ocean reanalyses;
- Description of a complex local flow field and its interaction with biology;
- Description of the interaction of the ocean with the atmosphere and associated changes in the flow fields, ocean properties, etc. (analysis);
- Use of estimated flow field for studies of CO2 sequestration, regional impacts, sea level, among others.

There are seemingly many vastly varying approaches to state estimation. However, when one cuts through the fog of jargon that seems particularly to surround this subject, state estimation or "data assimilation" (nudging, 4DVAR, 3DVAR, adjoint, OI, OM, Kalman filter, RTS smoother, ensemble KF, AD, Pontryagin principle, relaxation, line-searches, breeding vectors, SVD, optimals, Hessians, quelling, dual) is, in practice just least-squares fitting of models to data. The apparently different methods are variant algorithms used to find the minimum of an objective (or cost) function, the extent to which an approximation to that minimum is acceptable, and whether one seriously seeks an estimate of the error of the result. This seems not to be widely understood. The advantage of regarding the ocean analysis problem as one of formal 'state estimation' is that it ties the problem into the more mature fields of estimation and control theory, optimization, etc. both for concepts, notation, jargon reduction, and existing software. (Reserve the term "data assimilation" for the particular meteorological methods used for their purposes, which are rather special.)

There are many methods for solving least-squares problems, either exactly, by iteration, or sequentially. A nearly religious fervor seems to grip some practitioners of different methods, but it is important to remember that most of the argument is about algorithms not about the goal. So far, most attention has been paid to:

- "Sequential" methods (Kalman filters in various incarnations, and less commonly, on completing the job with a smoother). The atmospheric focus on prediction---for which the Kalman filter is optimal (up to linearization) underlies a lot of the interest in this approach
- Lagrange multiplier methods ("adjoint" or "4DVAR") because of the reduced computing load and availability of semi-automatic differentiation (AD) tools.

The bottom line is that both approaches work and choices for their use in state estimation often depends on the particular application. However, there are circumstances under which state estimation is not worthwhile:

1. The model has no known skill (Unconstrained model and data differ so greatly that they are not describing the same physical universe. Example: describing internal waves with a geostrophically balanced model.)
2. The unconstrained model completely reproduces the data within its estimated errors (the data carry no information not already present in the model).
3. The fields (and their noise) are so non-Gaussian that conventional minimum variance estimation makes no sense. (Implies not that state estimation should not be carried out, but only that one cannot use the most conventional approaches.)

None of the above appears to be true today for the ocean general circulation. Again, the bottom line is that both methods (and others) "work". A choice can be based primarily on convenience (What is locally available? Is the focus primarily on forecasting? Is the model workable with an available AD tool? How important are the error estimates? How near to a true optimum does one need to be?) A fast, efficient system producing adequate nowcasts/forecasts is not intended for the same purpose as a system attempting to give the best possible state and control vector estimates, satisfying known dynamics over a finite time interval. In the latter problem, it may well be worth a very heavy burden of computational overhead and much more careful specification of data/model error covariances than is the case for operational forecasting. These are different problems, requiring different methodologies. These two different approaches also use data in a different way.

In summary, state estimation (or reanalysis) is a necessity and is the basis for climate-related analysis efforts because it constitutes methods for combining theoretical (model) knowledge with actual data for every purpose involving the ocean. While in 1981, at the beginning of the WOCE planning, oceanic applications of these methods were pure speculation (almost no data existed, and only very primitive numerical circulation models were available – let alone computational platforms that were rudimentary in their capabilities), ten years ago the oceanic observational stream jumped by orders of magnitude, and the models became far more realistic. Given the progress thus far in the global observing capabilities, the technology development in numerical modeling, state estimation and especially computer hardware, the remaining difficulties of existing ocean analysis efforts, while not trivial, do not look insurmountable. To perform multi-decadal ocean state estimates as part of CLIVAR seems inevitable, although questions remain e.g.: how fast, how clever, and how adequate? Next questions follow immediately: How long can it be ocean only? Or when would CLIVAR need to think about coupled analyses, including ocean-ice, ocean-atmosphere, and the full Earth system.

The following CLIVAR-related issues of ongoing analysis efforts are worth highlighting:

I) We lack an adequate population of practitioners who are familiar with ocean models, ocean data, and estimation methods. This problem may be the rate-setting one.

II) Computing power remains a serious obstacle. Is full eddy resolution necessary, and if necessary, is it everywhere, for adequate realism for (1) understanding the ocean/climate and/or (2) forecasting what is known to be predictable?

III) There seems to be no fundamental advantage to any of the various estimation methods. They differ in convenience, degree of development, computational load, extent of their approximations, but all, when used sensibly, and without overstating claims, can produce useful results.

IV) Data quality control/error estimates can be widely distributed and shared. It would be possible to parcel out particular data types and responsibilities to various estimation groups, as well as share, at least in part, some software tools and parameterization packages (e.g., Gent-McWilliams); adjoint tools (AD tools); ice physics). These have to be supported by specific funding to make sure they get done. Ocean state estimation has to be sustained indefinitely somewhere (unless the data stream stops), and funding agencies need to know that one or more groups must be established, and remain stably, to carry it on. Unfortunately, the open-ended nature does not fit well with conventional academic departments or oceanographic institutions.

V) What CLIVAR does in terms of methodologies and products will be taken up for state estimation by biological/chemical, and paleoclimate communities? It is worth linking generic efforts (software, method development) to these other groups, for funding and manpower support. Are important elements of the ocean state estimate problem (best atmospheric estimates, ice dynamics and thermodynamics, hydrologic cycle inputs) in sufficiently good hands that the ocean community needs not pay direct attention? Greatly simplifying if true.

Plenary Talk 2

Status of atmospheric reanalyses (ECMWF (ERA-40), NCEP, GMAO, SURFA)

Speaker: S. Schubert (presented by P. Arkin)

Because the climate of the Earth is not fixed but varies essentially on all space and time scale, we need a comprehensive atmospheric information system to:

- Integrate and analyze global observations;
- Describe and monitor climate variations and their causes as they occur;
- Understand and model the changes and their origins;
- Predict future developments;
- Assess impacts of climate changes regionally: on environment, human activities and sectors such as agriculture, energy, fisheries, water resources, etc.

To reach those goals, we need more comprehensive climate observations, but at the same time we must make more efficient use of those that are and will be available. In particular the latter goal requires the existence of a comprehensive observing system approach (beyond a network of observing instruments), which includes:

- Climate observations from both space-based and in situ platforms taken in ways that address climate needs and adhere to the ten principles outlined by the NRC (1999);
- A global telecommunications network and satellite data telemetry capacity to enable data and products to be disseminated;
- A climate observations analysis capability that produces global and regional analyses of products for the atmosphere, oceans, land surface and hydrology, and the cryosphere, based on four dimensional data assimilation capabilities that process the multivariate data in a physically consistent framework to enable production of the analyses: for the atmosphere and oceans, land surface and so on;
- Global climate models that encompass all parts of the climate system and which are utilized in data assimilation and in making ensemble predictions.

Given the continuing improvement in our understanding of climate observations and the need for long time series, reprocessing of routinely available analyses of the atmospheric observing system produced as part of operational numerical weather prediction systems is a hallmark of every climate observing system. Europe, Japan and the US have ongoing efforts, but risks and limitations abound. A workshop on "Ongoing Analysis of the Climate System" was held in Boulder, Colorado, 18-20 August 2003 (see http://www.joss.ucar.edu/joss_psg/meetings for a pdf version of its report and further background information). The Workshop concluded that the U.S., similar to Europe and Japan, must establish a National Program for Ongoing Analysis of the Climate System to provide a retrospective and ongoing physically consistent synthesis of earth observations in order to:

- Design and guide operation of observing systems;
- Produce and sustain the growing climate record;
- Reconcile disparate climate observations and to characterize analysis uncertainty;
- Establish initial conditions for climate prediction;
- Validate prediction and projection models on all time scales;
- Provide long time series of global and regional (North American) climatic analyses for all types of prediction and projection verification.

Currently ongoing and recent atmospheric reanalysis efforts include:

- ERA40 (completed - http://www.ecmwf.int/research/era/) covering the period 1957-2001. Results are available from NCAR;
- NOAA/NCEP NARR (completed - http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/), covering the period 1979-2003; results are available from NCDC and JOSS;
- JRA-25 (expected completion date 2005 - http://www.jreap.org/indexe.html) covering the period 1979-2004. Some data already available via web;
- NASA/MERRA (covering the period 1979-present - http://gmao.gsfc.nasa.gov/merra.php). Production will start in 2006.

With respect to MERRA-NASA/GMAO (Modern Era Reanalysis for Research and Applications, led by M. Bosilovich), the focus will be on the modern satellite era (1979-present) with a science focus on the water and energy cycles. To that end, precipitation and total precipitable water, together with other parameters relevant to the water cycle, will be assimilated. More generally, MERRA will emphasize the role of remote sensing observations and observing system experiments (OSEs), and the effort will utilize a next generation GEOS-5 DAS (under ESMF), which includes a unified GEOS-5 AGCM, a catchment-based LSM, NCEP's new GSI analysis system, and in its validation component a strong link to CEOP. Results will be made available through Goddard DAAC.

Plans for reanalysis in the near future at ECMWF encompass an interim reanalysis, covering the period from 1989 onwards. It will start in 2005 and will be the baseline for future developments, including extra constituents. The underlying model will be T159L91, 4D-Var initialization procedure, and the latest version of the forecasting system. The setup will be more experimental, to validate new versions of forecasting system, to allow high-resolution re-analyses for specific cases and to perform observing system experiments. An extensive new reanalysis (ERA-70?) at ECMWF is not planned before 2009 or beyond.

A proposed extension to MERRA ("Understanding and Quantifying the 1970s Climate Transition in the Presence of a Rapidly Changing Observing System"; Investigators: Schubert, Suarez, Dee, Lee, Kumar, Hoerling; collaborators: Trenberth, White, Kistler, Bosilovich, Simmons, Uppala) will aim at assessing uncertainties and bias (observing system experiments; model impact - utilize ESMF; test bias correction techniques) and to assess the role of SSTs in the coupled system and the nature of SST observed changes.

The overall strategy for future reanalysis efforts is that a complete climate observing system requires both ongoing, near-real time analyses of the physical climate together with periodic reanalyses that use improved data sets and data assimilation methods. Both are essential components of a long-term climate observing strategy. So far, climate analysis and reanalysis efforts have focused principally on the atmosphere. A longer-term strategy must be developed to analyze and eventually bring together all the components of the Earth system (oceans, land, cryosphere, hydrology, biosphere) through coupled model assimilation. This will enable a more comprehensive synthesis and understanding of the climate system. In addition and in parallel, efforts to analyze/reanalyze components/subregions of the total Earth System are being developed. These efforts must be coordinated and mutually support one another! Moreover, international coordination is absolutely essential to a successful program – GEOSS must have an OACS!

Plenary Talk 3

Status of surface fluxes estimates

Speaker: Chris Fairall.

Recent interest in global fields of surface forcing of the ocean led to WCRP/SCOR working group for surface flux evaluation. Their findings (in the form of a comprehensive report, a conference proceedings, and a special issue in JOURNAL OF CLIMATE 16 (4): FEB 2003. 18 Articles) are now available. We will briefly summarize here those and subsequent conclusions. Here we will consider the turbulent, radiative, and precipitation fluxes (components of the surface heat, momentum, and mass budgets). The 'products' we will consider are in situ measurements, satellite, and NWP flux estimates. For in situ sources, we consider both direct and indirect estimates. Indirect methods applied to COAPS/VOS-data are the main source of data for global in situ flux products (such as the Southampton Climatology). For example, turbulent fluxes may be estimated with direct covariance computations from measurements of the high-speed turbulent components or by bulk methods derived from measurements of local wind speed, air temperature and humidity, and sea surface temperature (SST). Numerous NWP products (operational and reanalysis) are available and the time series goes back several decades. Satellite products are still experimental and are not produced operationally. Limited time periods are presently available from 4-5 research groups.

For turbulent fluxes, much progress has been made in the last 5 years and direct and indirect in situ methods have uncertainties less than 5-10% for time scales on the order of a week. However, to achieve such accuracies with bulk methods requires heroic efforts to determine the bulk variables with sufficient accuracy. Both satellite and NWP products are essentially based on bulk relationships; both have shown significant problems when compared to high-quality surface in situ references. For example, two different satellite products disagree by 80 W/m2 for annual averages of latent heat flux near the equator. Comparable disagreements can be found between in situ and NWP products in the mid-latitude storm tracks. Surface stress is by far the best flux from these methods (although there are still questions about the stress direction versus the wind direction and the relationship to local wave fields).

For radiative fluxes, present seagoing pyranometer/pygreometer databases are very limited and do not achieve the accuracy available from land-based standards. Indirect in situ methods (based on cloud observer assessments and radiative parameterizations) suffer from conceptual problems, but may be regionally tunable to direct method accuracies for sufficiently long time averages (this is still debated in the community). Satellite methods (which essentially relate observations of upward flux to downward flux via radiative transfer models) are very good for solar flux on weekly – monthly time scales. For downward IR flux, the connection to upward flux is weaker (particularly in the presence of clouds) and the variability of the IR flux is particularly problematical. Where NWP products have trouble representing the clouds (e.g., equatorial upwelling zones) they have biases in radiative fluxes.

For precipitation (or evaporation-precipitation), none of the present products appear to be suitable for ocean reanalysis purposes. Island measurements are considered to be biased estimators of open ocean precipitation. Direct in situ methods from seagoing platforms are subject to exposure and wind errors that suggest even highly massaged research-grade measurements are only good to 10%. Radar, microwave, and IR-based methods must be considered to be uncertain by nearly 50% at any specific location, but accuracy may be improved with increasing spatial averaging. Because of its highly intermittent nature, sampling is a uniquely critical problem for precipitation. Even space-based radars (e.g., TRMM) may be poorly sampled on 1-month time scales. NWP products have similar qualities to satellite products, although computations of E-P might give much better results in regions with good network sampling of atmospheric profiles. Ocean reanalysis efforts would certainly benefit from the development of a blended flux product. However, the error/decorrelation characteristics of each of the products must be determined in a systematic way.

The following table gives some crude estimates of the best accuracy of research- grade in situ measurements (which we consider a reference point for satellite and NWP methods).

Absolute in situ accuracy			
	Direct	Indirect	~ 1-day decorrelation scale
Precipitation	10% and 0.1 mm/d	Z-R 50% Pol, q-Conv 25%	5 km
Hs+Hl	5% and 3 W/m^2	Similar *	100 km
Rsd	2% and 1 W/m^2	Poor	20 km
Rld	2.5 W/m^2	Fair	50 km

Accuracy requirements for bulk variables:

$du = 0.2$ m/s
$dT_s = 0.2$ °C
$dT_a = 0.2$ °C
$dq_a = 0.2$ g/kg (1% tropics, 6% polar)

Plenary Talk 4

The Global Ocean Data Assimilation Experiment: Relevance to climate research/CLIVAR (and vice versa)

Speaker: N. Smith.

The primary objective of the Global Ocean Data Assimilation Experiment (GODAE) is to provide a practical demonstration of real-time global operational oceanography by providing regular comprehensive descriptions of the ocean circulation at high temporal and spatial resolution, and at climate scales. Results should be consistent with a suite of remote and in-situ measurements and appropriate dynamical and physical constraints. Accordingly, GODAE product lines anticipate:

- Real-time and delayed-mode remote sensed and in situ data products.
- Real-time ocean monitoring and short-term forecasts.
- High-Resolution Model Products.
- (Near-)Real-time ocean monitoring
- Lower-Resolution Climate reanalysis Products

SERVING THE USER COMMUNITY is being established, by maintaining Up-to-date Product Catalogues and Servers; through timeliness and dependability, liability and responsibility; through full scientific assessment of GODAE products, and through training and capacity building, e.g., summer schools. The GODAE Common has proved an effective method for sharing knowledge, including of users knowledge and internal metrics.

With respect to this CLIVAR reanalysis workshop and to GSOP efforts in general, both GODAE and CLIVAR have plans for ocean re-analyses, that in detail overlap in the sense that it is actually the same groups that serve both. GODAE and CLIVAR do have to overcome infrastructure issues related to datasets and analysis products. A direct collaboration between GODAE and CLIVAR with respect to data assembly and preparation of input data sets as well as prior error information therefore seems inevitable. This includes joining forces for new data products (e.g., SST) and sharing ideas for a quality control, and address the latter in joint projects. This also encompasses a joint discussion about surface forcing fields and their uncertainties, which can best be addressed in a joint evaluation effort which aims at identifying strengths and weaknesses of existing reanalysis products for climate and other applications.

In summary: There are several specific areas related to re-analysis where the work of GODAE could benefit CLIVAR, and vice versa. Firstly, joint inter-comparison projects are required. They will define uncertainty of climate analysis/reanalysis products through inter- comparison and will facilitate applications of reanalysis products. Furthermore, it will shed light on additional observations needed through product inter-comparison (e.g., to identify areas that the products differ significantly and that have insufficient observations for validation. The objectives of such an intercomparison would be to:

1. To evaluate the quality and consistency of various global ocean (climate) assimilation products.
2. To identify the common strengths and weaknesses of these systems and the differences among them.
3. To facilitate potential applications by the climate research community.

Among other things, such an intercomparison studies could facilitate the use of reanalysis products in future IPCC assessments and would thereby also demonstrate the necessity of a climate observing system for societal needs.

The preparation of datasets for re-analysis is a significant undertaking. This holds both for assimilation and for testing. IGST 9 proposed enhanced coordination between GODAE and CLIVAR to

1. Ease burden and maximize the quality of datasets;
2. Identify source data being used for GODAE re-analysis experiments;
3. Identify any additional value-adding exercises that are being used to clean/quality control datasets and the degree to which such results can be made available to others;
4. Identify any consolidation/assembly activities whereby data are being merged from different sources and redundancy/duplication isolated;
5. Provide a recommendation on whether a global data assembly project is warranted (i.e., ENACT but with broader participation); and

6. Participate in the preparation of (a part of) a white paper for GODAE and, perhaps, GSOP on re-analysis datasets.

A common data infrastructure would include serving processed data of different quality control levels and the quantification of "data errors". An exploration of climate applications for real-time meso-scale products is also required as are seasonal-interannual predictability studies using climate-related reanalysis products.

Other efforts of common interest include:

1. Observing system sensitivity experiments (OSSE).
2. Surface forcing comparison.
3. Improvement of model errors.

GODAE has a final lifetime and will soon end. However, the GODAE community will continue to exist and we are working on sustaining this effort. Options for a scientific extension include: (Global) biogeochemistry, ecosystems, extended weather (and hazard) prediction and coastal assimilation and predictability: CODAE. A particular point of concern is the lack of global R&D, which needs to be the focus for future.

Working Group 1

Ocean (and ice) variability and processes as seen in prognostic simulations and reanalyses.

Chairs: A.-M. Treguir and I. Fukumori

The aim of this working group was to document the potential of using reanalysis results to study climate variability, to identify open questions and to suggest strategies to improve future ocean reanalysis efforts. Questions there were discussed in this context included:

- Model biases and changes in ocean circulation and T/S properties.
- Seasonal to interannual variations of heat (salt) transport and content, budgets.
- The role of eddies in the circulation and in reanalysis efforts.
- Outputs needed for climate studies and metrics able to measure the quality of results.
- Perspectives for improved representation of variability and processes in future reanalysis efforts.

Recommendations that emerged during the working group discussion can be summarized as follows:

1) The following is a list of examples of what global reanalyses efforts needs to bring for CLIVAR. Reanalysis efforts need to be able to resolve those and other important processes without a distortion of the underlaying dynamics through the assimilation procedure:

- Dynamics in the tropics, seasonal prediction (this topics was not discussed in detail, but was presented during the first meeting day).
- Better understanding of dynamics of sea level change than can be obtained from data alone.
- A description of the relationship between changes in the surface forcing and local or remote deep variability. An example here would be the deep signature of NAO forcing, if it exists.
- A description of required additional observations or redundant data sets to optimize the global observing system.
- The diagnostics of non-observable quantities like heat transport, MOC or other integral quantities (usefulness depends on assimilation methods).

Many existing reanalysis efforts do provide some elements of those examples. However, all those examples require a dynamically consistent description of the time-varying ocean circulation over several decades, implying that mathematically rigorous assimilation approaches would be required as a basis for those studies.

2) The following recommendations can be given for CLIVAR-suitable reanalysis efforts:

- CLIVAR reanalysis should be cutting-edge efforts, i.e., they should be based on the best possible and state of the art model and sub-grid scale formulations that are defined as standard by WGOMD.
- Within CLIVAR it could in particular be useful to use IPCC ocean models for reanalysis since those would produce estimates of the ocean, i.e., initial conditions for coupled models that could be used in next IPCC assessment runs. This issue does imply a dedicated R&D effort, since IPCC models are not being used in ocean-alone approaches, neither are they set up for data assimilation efforts.
- Every reanalysis effort should start from best possible forcing fields (or estimate it) to ensure global balance (NWP products have large imbalances).
- Every reanalysis run should be accompanied by an unconstrained run with the same model and results should be available to the public to evaluate the drift.
- Every reanalysis effort should estimate balances, estimate the water mass transformation due to

assimilation, compare balances in runs with and without assimilation and provide results to the community.
- Users of reanalysis results should be provided with estimate of the fraction of variability or just drift that is coming from the model alone (i.e., not from the data) and what variables are actually strongly constrained by observations.

3) A few of possible other model issues were discussed, but we don't have the elements to answer the question yet:

- Do we need non-Boussinesq models for sea level modeling? Perhaps not in terms of removing biggest uncertainties. However, to make the models consistent with novel gravity observations it would be convenient, since it seems now fundamental obstacle and would not reduce numerical efficiency.
- Every model should be driven by freshwater rather than virtual salt fluxes.
- Do we need eddies in reanalysis efforts? We do know that there is internally generated (eddy, waves –driven...) interannual variability (in heat transport, content...). It is not obvious that we can parameterize this in coarse-resolution models (time-variable GM coefficient for ex.). To the extend that time-varying eddy activity is involve in ocean mixing / transfers, climate models might need to resolve those processes in detail.
- We do need small scale boundary currents and overflows even more than eddies. There are no parameterizations available for those processes. Regionally varying – or even adaptive – model grids will be a necessary ingredient.

4) Recommendations were also given for evaluations of reanalyses results in terms of their usefulness for CLIVAR.

- CLIVAR should assess the robustness of processes diagnosed from reanalysis results by comparing them in different reanalyses or WGOMD forward runs.
- In this respect, it is very important to have comparisons performed between reanalysis efforts as part of reanalysis evaluation efforts.
- For this purpose, metrics for model evaluations should be defined, and should continue to be discussed and agreed on with WGOMD and GODAE.
- Rather than just compared to each other, reanalyses need to be compared relative to independent data (e.g., time series data, floats, current meters) and against information of climate indices available from other sources (including atmospheric reanalyses).
- The information emerging from various reanalysis evaluation and intercomparison efforts must be put together and must be carefully evaluated (statistics, Taylor diagram). This requires strong leadership, scientific insight and needs to be a part of CLIVAR's R&D (jointly with WGOMS).
- Analyzing O-F (observation – forecast) and constrained – unconstrained model runs should be part of any evaluation project. In particular having different models will help quantify errors, but do we agree on the methodology? (leadership needed)
- Document what we do right and what the problems are (information for future users).

5) Not discussed (due to time constraints) but deemed very important for decade-50 year long reanalyses and their applications is sea ice, its effect on surface forcing and on the local freshwater budgets.

Reanalyses are essential for understanding the carbon cycle in the ocean. CLIVAR – and WCRP for that matter – should gear up with IGBP to approach the reanalysis issue jointly and to make maximum use of the data obtained from the repeat-hydrography and carbon program.

Working Group 2

Surface Fluxes from ocean, ice, and atmospheric reanalyses.

Chairs: William Large and Robert Weller

This working group addressed several issues and problems related to surface fluxes, their estimates from data and NMC centers, and their impact on ocean models. The following set of questions was posed at the outset of the working group discussion:

- The physics of air-sea exchange: We have known for decades that the penetration of solar radiation is a key process governing SST, which requires separating this component from the Net Heat Flux. Also, the latent heat and freshwater evaporation are not independent, but coupled and both depend on wind estimates. Ocean reanalyses provide estimates of surface fluxes. But they are not a substitute for understanding the physical processes involved and the errors present in atmospheric or coupled ocean-atmosphere models.

- Diagnosing the error characteristics of flux fields used for forcing: surface flux uncertainty varies radically with time and space scale. Ocean inventories tell us that the global, decadal net heat and water fluxes are very nearly zero, (i.e., +- a few W/m2 in the case of heat). At the other extreme, one can only guess what the instantaneous stress is over a particular square meter of ocean. Even over a 10km square region, the hourly stress probably can't be estimated to within a factor of 2. How can a Reanalysis system handle this sort of error behavior?
- Developing minimum error ocean forcing fields: A concern of ocean reanalysis (and for that matter ocean modeling in general) can be the accuracy of the ocean model rather than of the surface forcing if minimum error surface fluxes would exist. Would "minimum error" be unique and generally applicable to all models and resolution?
- Space/time resolution required for the forcing fields: What are the target space/time resolution of the flux fields sought for use in ocean reanalyses? What space/time resolution flux fields can now be produced with what level of uncertainty? What needs to be done to develop the required forcing fields?
- Problems associated with high latitude sea-ice and snow: What are the challenges to be faced in developing forcing fields for high latitudes and in the presence of sea ice and snow? What is being done to address these challenges
- What is the role of atmospheric reanalysis fluxes, which will not be linked strongly with ocean reanalysis fluxes as long as an atmospheric scheme can dump all the heat, momentum and freshwater it wants into the ocean without affecting its bottom boundary condition, i.e. the specified SST? What is the relationship between the shortcomings of these fluxes and the need for assimilation cloud observations? Can in-situ flux observations be used to detect and correct biases in atmospheric reanalysis fluxes?
- What is the quality of global run-off databases and their impact on ocean reanalysis?

Recommendations that emerged during the working group discussion can be summarized as follows:

I SPACE/TIME RESOLUTION REQUIRED FOR THE FORCING FIELDS FOR OCEANIC REANALYSES: The actual time resolution of the surface fluxes and flux-related variables in the atmospheric reanalyses (~ 100 km and 3-6 hours) does not account for many energetically active processes in the atmospheric boundary layer:

- cold/warm air outbreaks in the deep convection regions and western boundary currents,
- cold/warm skins in the tropics associated with the convective clouds,
- convective precipitation

Field experiments and alternative high-resolution data sources: processes on the scales < 6 hours in time and < 100 km in space can add to the synoptic variance from 5 to 30 percents and change the mean flux by up to 10-15 W/m*m. Although mesoscale variability is very important for the adequate representation of sea-air interaction on these time scales, the extent to that it can affect the model solutions at very high resolution (e.g. WBC, LS convection, upwelling, tropical patterns) is unknown.

II WAYS TO GO IN OCEANIC REANALYSES:

- To simulate these effects by model numerics and parameterizations with no attribution to the surface fluxes.
- To develop high resolution forcing functions with actual spatial resolution of better than T513 for the derivatives and better than 0.5 degree for parameterizations.

HR forcing function can be developed for a time 1 to 4 years by operational centers with the use of operational models and high resolution satellite observations (first of all winds and radiation fields). These products can be further used for sensitivity experiments with oceanic GCMs at high resolution.

1. Wind stress is very important and matters at various instances in the computation of surface fluxes. Attention should therefore being paid to the wind stress product that is being used, and maximum use of available scatterometer wind stress fields should be made in ocean reanalysis efforts (either as forcing fields and/or as constraints in the optimization procedure).

2. It is strongly suggested not to go straight from NWP products to reanalysis. Instead, for NWP provided surface flux fields adjustment/correction needs to be applied. To do this properly it is recommended to work closely with flux groups. They have the best knowledge about required corrections and can also feed back to NWP groups for future improvements. It is suggested that recommendations are being developed under GSOP efforts with respect to available surface flux products with minimum error characteristics.

3. There is a new real-time, global sea surface temperature (RTG SST) field available that should be used and RTG should be extended back in time to allow atmospheric reanalysis efforts to produce better surface forcing fields (see contribution from D. Chelton below).

4. Some of the ocean reanalysis efforts produce an estimate of surface forcing fields that are required to bring the underlaying ocean model into consistency with ocean data. Typically those fluxes are being estimated as changes relative to a first guess NWP product, such as NCEP. The testing of those reanalysis increments is an important requirement for existing ocean reanalysis efforts if one where to learn from them about errors in either the atmospheric flux products or the ocean model itself. For that purpose target reanalysis comparison studies should be conducted in specific regions where accurate surface flux measurements exist. The WGSF at their recent meeting stressed the need for routine model/in situ/satellite inter-comparisons of surface fluxes at selected sites. GSOP should define a standard CLIVAR reference flux data set that can and should be used by any group producing surface flux fields as a test data set.

5. Run off is an important forcing field of the coastal oceans. However, information form gauged rivers is not sufficient. Instead information about large scale E_P over continents is required to construct best possible run off data sets. Reanalysis efforts should work closely with groups producing such run of data sets.

6. Temporal discontinuities in the atmospheric observing network does pose discontinuities in the quality of NWP surface flux products. Those discontinuities are known to exist in 1978, 1987, and in the 90's. Unique remedies for those deficiencies are not known.

Working Group 3

Ocean Observing Requirements for CLIVAR.

Chairs: Mike McPhaden and Victor Zlotnicki

This working group started from the following statements made during the recent CLIVAR assessment which concluded

"...that CLIVAR had failed to meet the challenge...[to] facilitate management of data... to ensure that its observing systems were well integrated with those of other programs and that its data policy was clearly articulated."

"It was suggested that CLIVAR identify one or two cross-cutting themes...to become the focus of data management activities (e.g. ocean reanalysis...)."

"The SSG asked GSOP to develop a preliminary list of data requirements for ocean reanalysis as an outcome of the November workshop."

To address those issues, the working group discussed in detail:

The present status and future plans for in situ observations in support of CLIVAR/GOOS/GCOS (availability, timeliness, quality of data, obvious gaps). [McPhaden]

Present status and future plans for satellite observations in support of CLIVAR/GOOS/GCOS (availability, timeliness, quality of data, obvious gaps). [Zlotnicki]

Data requirements for reanalysis, now-casting, and prediction. [Carton]

Role for data assembly centers in supporting reanalysis, now-casting and prediction efforts (access to real-time and historic data, QC, archiving). [Garcia].

Summary and Recommendation from the discussion can be summarized as follows:

- DATA STREAM: CLIVAR has done little about its data stream. However, GSOP has to address this issue, and has to assure that CLIVAR DACs have all information required to optimally prepare data sets for reanalysis efforts, whether collected under the CLIVAR banner or otherwise.
- CLIVAR-RELEVANT data: A large diversity of data sets exist that need to be used in CLIVAR research and that need to be organized in terms of their QC and data stream. CLIVAR needs to make sure that these CLIVAR-relevant data sets (not collected as part of CLIVAR) are tracked and documented so that reanalysis efforts can easily locate and use them.
- REANALYSIS REQUIREMENTS: CLIVAR should confirm the data requirements of the various reanalysis efforts. As a guiding principle, data assembly should focus on specific variables (e.g., surface fluxes, temperature, salinity, velocity, ocean color, tracers), rather than the platforms or sensors that measured them. Details are specified in OceanObs 99. CLIVAR through GSOP and DACs should provide a catalogue of what data is available, their time/space resolution, level of QC, metadata requirements, etc.
- QUALITY CONTROL and DATA ASSEMBLY: are essential ingredients common to all successful reanalysis. Much duplication of effort seems to exist at present. CLIVAR in collaboration with GODAE should play a role in a) coordinating a common set of QC standards, b) coordinating the actual work, so all benefit from each other's efforts, and c) coordinating standards and methods of making the data available. A group of experts/practitioners should collate this information and provide it to CLIVAR GSOP.

- DATA POLICY: CLIVAR must finalize its data policy, and GSOP should ensure that it occurs. At present, data policy is still in draft form. The principle of free and open access, with no proprietary period, and 'with minimal delay' from collection or production should apply to data and to reanalysis products. The definition of 'minimal delay' is dataset specific, and was still being debated after the meeting. [Note: In April 2005, CLIVAR published its data policy in CLIVAR Exchanges].
- TIME SPAN: CLIVAR should assemble a high quality ocean reanalysis data set beginning in 1948 as input for seasonal, decadal, and global change multidecadal reanalyses. 1948 coincides with the start of the NCEP atmospheric reanalysis. High-resolution reanalyses of the satellite era can draw on a subset of this longer data set from 1992 onward.
- NEW RELEASES: Both data sets (1948-present, and 1992-present) should include as much data as possible and should be regularly updated (more frequently than every 4 yrs, as currently done for the World Ocean Atlas and Dataset due to the human-intensive editing and QC necessary for the older datasets).
- PARTNERS: CLIVAR should partner with existing data processing efforts to ensure a data set available for CLIVAR reanalysis: Many activities already underway provide a starting point (ENACT, GRHSST, GODAE, Argo, etc). CLIVAR should not duplicate these efforts but attempt to coordinate. Exact architecture needs to be worked out under GSOP leadership.
- GAPS IN SATELLITE DATA: Underlying much of the in-situ work is an implicit assumption that certain satellite data streams are here to stay. The continuity of global satellite measurements is not assured, as each mission's budget and technical development are unique. Two current examples. High-accuracy sea surface topography: a possible gap between the Jason altimetric mission and its follow-on. Surface wind vectors: the abandonment of scatterometry in the US in favor of polarized passive radiometry, even though the accuracy and sensitivity of the latter are still a matter of research. GSOP can help here by providing advocacy on behalf of a large group of scientists.
- SYSTEMATIC DIFFERENCES IN SATELLITE DATA: Whenever a long time series from either in situ or satellite observing systems is built from several instruments or platforms, systematic differences due to instrumentation are guaranteed to occur. A classic example for in-situ measurements is that of sea surface temperature from buckets, engine-intake, etc. More recently, combining data from the altimeters on TOPEX/POSEIDON, Jason, and the ERS or the Envisat missions has proven to be problematic because of the systematic differences between them. The solutions to creating climate quality time series from disparate records are specific to each measurement type. However, to ensure data sets of high quality for climate research, two criteria must be met: a) an overlap in the time series of two consecutive sensor/mission pairs, as is routinely done by the Defense Meteorological Satellite Program or the NOAA-n series of US satellites, and b) the availability of some type of 'benchmark' measurement available across the time series. For example, the global tide gage set provided such a benchmark for altimetry, even though each individual tide gage is not especially accurate or commensurate with the altimeter footprint.

Working Group 4: Assimilation techniques, uncertainties, biases and estimation errors

Chairs: Andrew Bennett and Anthony Weaver

Working group 4 addressed various theoretical and practical issues related to ocean data assimilation for reanalysis. The following topics were addressed during the discussion and recommendations drawn from them follows.

1) Resolution and configuration:

For climate reanalysis, should the emphasis be on high resolution or sophisticated assimilation method? Do reanalysis need to be global and/or coupled? Are regional reanalyses useful?

Recommendation:

- CLIVAR needs reanalysis and assimilation for different problems, related to GOALS, DEC-CEN and ACC. For the time being, separate reanalysis streams are needed for separate applications. In any case, it will be useful to pursue approaches that admit a multiplicity of scales, since problems that should be addressed do reach over various space and time scales.

2) Assimilation techniques

Various assimilation techniques are currently in use, including:

Multivariate OI or 3D-Var
Kalman filters (extended, ensemble and variants)
4D Variational / RTS (Kalman) smoothers

Critical issues include: terminology, significance testing, cycling, and model error.

Most (quasi-) operational data assimilation schemes used for initializing ocean models or the ocean component of seasonal forecasting models are either based on sequential filter approaches or on 4D-variational smoothers, the latter applied only on a short time window. Such schemes make limited or no use of future information in estimating past states (i.e., they are essentially filters not smoothers), can produce jumps in the state after the analysis step, and generally assume prefect model dynamics and surface fluxes. They can lock-in to spurious nonlinear (Riccati) modes in cycling applications.

The following question comes to mind in the context of CLIVAR reanalysis efforts:

Are these methods appropriate for reanalysis?

Are there theoretical and practical hurdles preventing us from performing an ocean reanalysis with an RTS smoother or a long time-window weak-constraint 4D variational method?

How can we reconcile the problem of non-linear error growth (and hence the loss of model predictability) with the desire to use long assimilation windows in a climate reanalysis? Is there an optimal assimilation window width?

Recommendations:

- Each assimilation and reanalysis effort should explain in detail its terminology, to avoid confusion between the different communities that in principle try to solve similar problems.
- Each reanalysis effort needs to be evaluated in detail a posteriori. It is strongly recommended to use at least a simple □2-statistic as a standard diagnostic tool to test significance and consistency. Valuable detailed information about the optimality of the assimilation system can be obtained by examining regional statistics of the innovation vector, observation residuals and analysis increments.
- For ocean reanalysis, the assimilation window should be long enough to allow for controls to be influenced by observations. Using long data and assimilation windows, on the other hand, require appropriate control variables, such as surface forcing fields, internal model mixing parameters or explicit model error terms.
- Regardless of approach, each reanalysis effort needs to check if “jumps” occur between analysis cycles and if they are a problem. Equally important, one should analyze them in detail to identify problems in the assimilation approach or the observational data base. Practical solutions to avoid “jumps” should be considered such as the use of Incremental Analysis Updating (introducing the analysis increment gradually via a forcing term) or other temporal smoothing procedures.
- It is equally important to understand the character of model error (systematic and random components) and to parameterize it appropriately in the assimilation system. The assumed noise structures are hypotheses about the errors in the model forcing fields and dynamical errors.

3) Modelling and estimating background state error covariances

An accurate representation of the model (background) state error covariances is the basis for a statistical data assimilation system. It has of course long been accepted that the error covariances are critical for selecting the solution of the reanalysis problem out of the manifold of possible solutions. In an OI or 3D-Var scheme, these covariances are specified. In dynamically constrained schemes, this covariance is explicitly or implicitly generated by the optimization algorithm. The generation is explicit in a Kalman filter or RTS smoother algorithm. The generation is implicit in a variational method (the forward and adjoint equations together constitute second moment equations).

Nevertheless, much background covariance structure must be hypothesized. Specifically, background (prior) error covariances are required for

- Initial states
- Boundary values (surface, open, bottom, lateral)
- Dynamical errors
- Parameter errors

Recommendations:

- As a way forward in this difficult problem, it is recommended to continue using OI/3D-Var covariances as a standard prior error description, while exploring more complex schemes for their generation.
- Much theoretical, observational and archival study of the statistics of these various errors is required. It is not always obvious that errors are reasonably described as random. The details will depend on the variables and their space or time scales.
- Scientific approaches for specifying (determining) covariances (functional forms or tabular values) are not yet operational but are much in the R&D realm. Significantly more experience is required not only to estimate error covariances but also to use them in the reanalysis context. Particular attention is needed to

develop computationally efficient algorithms for handling and manipulating error covariance functions and their inverses, especially during long reanalyses.

- In terms of CLIVAR reanalysis requirements, every reanalysis effort serving CLIVAR should assure that dynamical errors respect conservation laws. This may be achieved by stipulating that each dynamical error is the divergence of an erroneously parameterized flux.

4) Detecting and correcting model bias

Most assimilation systems are designed to correct random errors only. In practice, however, systematic errors in the model, surface forcing fields or observations can be substantial. Systematic errors can lead to many problems in assimilation systems, such as spurious climate variability in response to changes in the observing system, non-physical circulations, and poor use of observations. A non-zero time-mean error (bias) in the observation residuals or assimilation increments is usually evidence of systematic error. However, it is also known that random processes can lead to long-period variations which again could look like non-zero time-mean differences when evaluated over a finite period. While detecting a model bias in the form of a time-mean offset is possible, identifying its cause is often not so easy.

Weak-constraint 4D assimilation methods provide a framework for correcting systematic model error by allowing model forcing variables to be included in the control vector. For example, some existing reanalysis systems attribute model error entirely to the surface forcing fields, while others are less discriminate and account for fully 3D model forcing error terms. Weak-constraint reanalysis approaches have the potential to shed more light on the causes and possible remedies of known model bias. However, results from these approaches must be interpreted with care since large corrections may be produced for certain control variables because of incorrectly specified background error covariances or to compensate for errors in other variables that are not explicitly controlled in the assimilation process. Careful parameterization of model error and its associated background covariance are therefore key aspects to this problem.

Recommendation:

- A general recommendation is to monitor assimilation statistics carefully in order to identify regions or variables which display persistent error patterns.

5) Estimating observation error

The observation error is usually defined as the sum of measurement (instrumental) errors and the so-called representativeness errors. The latter arise from insufficient resolution in the model and will be reduced in high-resolution model runs (a low resolution model cannot resolve “eddies”), but may also arise from hydrodynamical approximations (hydrostatic balance, shallow Boussinesq fluid). We can assume (hope) that estimates of measurement error are supplied by the observers. Altimetry, which is dominated by highly structured and deterministic tidal error, presents special problems. However, for low resolution (i.e., non-eddy resolving) ocean models, the observation error will be dominated by representativeness errors in the absence of consistent signal preprocessing.

How can we get reliable estimates of representativeness error? It is often assumed that observation errors are unbiased and uncorrelated. These assumptions are usually made for practical reasons but are known to be false in many cases (e.g., altimetry again, while densely distributed in situ observations will have strongly correlated representativeness error in relatively low resolution ocean models). Certain observation errors can be reduced by an appropriate choice of vertical coordinates in the model. Correlated observation error can be reduced by thinning or “superobbing” the data prior to assimilation.

Recommendation:

- The community should be spending more effort on developing better observation error models, particularly for the representativeness component. This effort is especially important for low resolution models for which representativeness error can dwarf measurement error.

6) Estimating uncertainties in synthesis

Theoretical estimates of posterior (analysis) error covariances can be obtained as a by-product of deterministic statistical analysis methods such as Kalman filter and variational. But are these estimates reliable given our generally crude assumptions about the observation error covariances and, especially, the background error covariances from which these estimates are derived? Only a few alternative methods could be used to derive more reliable estimates of uncertainties in analysis none of which might be the ultimate solution.

But what is the required accuracy for CLIVAR reanalysis products and which reanalysis product can meet those requirements? An attempt to answer to those questions can already be made now before formal uncertainty estimates are practical. For that purpose, renanalyses from a variety of systems that use different models and assimilation schemes should be compared against each other. This may be the most practical way forward. Comparison efforts should also include checks against data withheld from the assimilation, which is possibly the most reliable test of a product. Solutions also need to be tested against their sensitivity to prior information (initial conditions and prescribed error information). Different estimators (maximum likelihood, different pdfs, maximum entropy, etc.) could also be considered.

Recommendation:

- In terms of the evaluation of CLIVAR reanalysis products, several approaches should be considered:
    - Independent checks (forecasts, withholding data)
    - Multi-model, multi-system approach
    - Sensitivities of individual systems to internal (poorly known) parameters.

7) Salinity

In sequential assimilation approaches some issues appeared in the assimilation of temperature profiles without equivalent salinity coverage. In addition, salinity data do exist, but with varying degree of quality. The question was posed: is the QC of old CTD data satisfactory? Moreover, should – in fact could - we agree on a possible approach to constrain salinity from temperature data?

Recommendations:

- An effort should be made to reassess the quality of salinity measurements or reassure the users.
- In terms of constraining salinity from temperature data, one might use either a climatological T-S relationship or choose not to alter the T-S relationship already in the model. When assimilating observed salinity one might then use salinity information with T as a depth coordinate, which then complements the choice of not altering the T-S relationship when assimilating temperature data. This approach would enable T-S relationships of water masses to be correctly captured even in regions that do not exhibit tight T-S relations over large areas. These approaches to handling T-S constraints could be developed into rigorous formulations within the structure of the background error covariance matrix.

5) Workshop Outcomes and Challenges:

CLIVAR ocean reanalysis efforts need to address research needs over seasonal-to-interannual, decadal-to-centennial, and even millennial time scales. Example applications of ocean reanalyses products and capabilities include:

1) Studies of sea level change
2) Input for the 5thIPCC assessment.
3) Investigations of the oceans role in CO2 sequestration
4) Characterizing and understanding important climate processes and dynamics
5) Initial conditions and boundary conditions for higher-resolution approaches intended to elucidate regional impacts.
6) Initializing coupled models for seasonal to interannual and for decadal and centennial forecasting.
7) Observing System Experiments (OSE) required for designing ocean elements of the climate observing system

There are quite different needs and requirements across this spectrum of applications, implying that several assimilation activities need to co-exist for some time to serve different purposes. In general terms climate quality ocean reanalyses must address the CLIVAR goals of: (1) describing the dynamics of climate change in the ocean (plus coupling with other elements of the climate system); (2) initialization of seasonal-to-interannual forecast systems; and (3) initialization of decadal-to-centennial (and longer) predictions and projections.

While there are many seasonal-to-interannual-related activities institutionalized, there is not yet a corresponding set of activities that will provide needed climate-quality hindcasts/reanalyses as well as initializations for decadal and longer models and anthropogenic time-scale projection problems. CLIVAR, through GSOP actions, first should test (this testing should include determining uncertainties in an ensemble framework) existing reanalysis results in terms of their usefulness critical areas and then decide on a well-defined strategy to fill in any gaps and work with funders to support required efforts. This needs to be done in close collaboration with WGOMD, GODAE and the basin panels (model-model; model-data; prediction, residuals)

Areas of focus that will be addressed initially include:

- In contrast to seasonal-to-interannual ocean analysis efforts, which require only recent and real-time data and information (and generally less stringent data quality), assembling suitable data streams of acceptably quality-controlled data becomes a large issue for decadal reanalyses efforts. There seems to be a well organized data stream for seasonal-to-interannual efforts that is partially used by other ocean reanalyses efforts. The data stream for climate reanalysis needs to be better organized between CLIVAR/ GSOP and GODAE to assure sufficiently long data streams of high quality. Every effort is required to avoid duplication of action.

- Surface heat, momentum, and freshwater flux (plus run off and ice volume advection) uncertainties remain a large issue. Reanalyses efforts need to work with WGOMD and the WCRP Working Group on Surface Fluxes (WGSF) on identifying the best surface flux products and standards to utilize in ocean reanalyses efforts. Such an evaluation should include satellite vector wind stress and SST. The flux community could benefit more from ocean reanalyses. For that purpose, each reanalysis effort (atmosphere and/or ocean) should provide a well-defined comparison of their estimated surface fluxes against a CLIVAR standard surface flux reference data set. This will help to establish a process for better characterizing air-sea interactions.
- Evaluating the ocean reanalysis products requires a serious entrainment and participation of the science community. GSOP will need to spend considerable energy in strengthening the linkages between reanalysis groups and users. GSOP will help foster closer links between global reanalysis centers and CLIVAR research activities through the CLIVAR basin Panels. These Panels should also participate in the definition of required metrics. Challenges will always remain in estimating the impact of observing system changes on regional and global results.

There are many challenges that will remain over the foreseeable future and need attention. Among those is the question of what is required for a good initialization of coupled model runs for seasonal-to-interannual forecasts and longer-term model predictions (e.g. decadal) and projections (i.e. future years based on assumed forcings). While ocean-only dynamically consistent reanalysis will be able to provide a good description of the ocean over the past, it might actually be necessary to perform data assimilation in coupled ocean-atmosphere models to improve forecasting skills. Nurturing coupled data assimilation capabilities is a long-term strategy for GSOP and CLIVAR.

CLIVAR Ocean Reanalysis Actions Underway:

- Working group on data quality requirements for reanalyses and ocean data system.
- Working group on intercomparison of reanalyses (in partnership with GODAE, WGOMD and CLIVAR panels). This will be done in a pilot intercomparison process during 2006.
- Preparation of recommendations for model standards and surface fluxes that should be used by reanalysis efforts. To be done in close link to CLIVAR-WGOMD and Flux WG.
- Coordination between WCRP and IGPP synthesis efforts to assure synergy and interconnect between both efforts.

References

WCRP, 2000: Final Report of the Joint WCRP/SCOR Working Group on Air-Sea Fluxes (SCOR Working Group 110): Intercomparison and Validation of Ocean–Atmosphere Energy Flux Fields. WCRP-112, WMO Tech. Doc. 1036, 306 pp.

WCRP, 2001: Proceedings of the Workshop on Intercomparison and Validation of Ocean–Atmosphere Flux Fields. WCRP-115, WMO Tech. Doc. 1083, 362 pp.

Special Issue on WCRR/SCOR Workshop on Flux Fields. JOURNAL OF CLIMATE 16 (4): FEB 2003. 18 Articles. The interface or air-sea flux component of the TOGA coupled ocean-atmosphere response experiment and its impact on subsequent air-sea interaction studies.

Weller RA, Bradley F, Lukas R. JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY, 21 (2): 223-257 FEB 2004

Curry, J. A., and 18 coauthors, 2004: SEAFLUX. Bull. Am. Met. Soc., 85, 409-424.

Houze, R. A., et al., 2004: Uncertainties in oceanic radar rain maps at Kwajalein and implications for satellite validation. J. Appl. Meteorol., 43,1114-1132.

Appendix A

Scientific Steering Team:

David Anderson (ECMWF)
Prof. Awaji (Japan)
John Gould (SIO)
Simon Josey (SOC)
Ants Leetmaa (GFDL)
Pierre-Yves LeTraon (CLS)
Jens Schroeter (AWI)
Detlef Stammer (SIO, chair)
Anne-Marie Tregiur (Ifremer)
Kevin Trenberth (NCAR)
Gerrit Burgers (KNMI)
Robert Weller (WHOI)
Andreas Schiller (CSIRO, AU)

ex-officio: Ed Harrison (OOPC)

Appendix B:

Present Status of Ocean Data Assimilation

The following reanalysis and/or assimilation efforts were summarized during the afternoon of the first day's plenary session of the workshop:

1) HYCOM (C. Thacker)

The goal of the Global ocean prediction with the Hybrid Coordinate Ocean Model (HYCOM, US-GODAE) multi-institution partnership is to develop and apply eddy-resolving, real-time global and basin-scale prediction systems using HYCOM and to transition these systems to the U.S. Navy and NOAA. A Hybrid Ocean Modeling Environment (HOME) will be developed and several ocean data assimilation systems will be implemented and utilized. The first operational assimilation system will be a multivariate optimum interpolation (MVOI), with subsequent evaluations of the Reduced Order Information Filter (ROIF) and Singular Evolutive Extended Filter (SEEK). Atlantic and global configurations of the system will be used for varied applications. Products will be evaluated primarily by comparison to independent observations. An important set of users will be the coastal ocean community that is also expected to evaluate products. Research directions and issues include correction of mean biases (e.g. SSH), parameterizations (e.g. sea ice), grid resolutions, ocean observing systems assimilated (SST, profiles, drifters), and product distribution.

2) ENACT (Mike Davey; Anthony Weaver)

ENACT is the ENhanced ocean data Assimilation and Climate predicTion (ENACT) project. It is a European multi-partner project supported by the European Commission, from Jan. 2002 – Dec. 2004. The main project objective is to improve global ocean analyses with application to seasonal/ interannual prediction using coupled models. ENACT is primarily an EU project to develop and inter-compare global ocean analysis systems using OI-type, 3D-Var, 4D-Var, and ensemble Kalman filter assimilation methods. The ocean models used include HOPE-E, HOPE-C, UM, OPA. Multi-model multi-method multi-decadal ocean analyses have been produced, and sets of associated seasonal to multi-annual range CGCM forecasts have been made. The project has now formally ended: a detailed report of the results and some datasets are available at

http://www.ecmwf.int/research/EU_projects/ENACT/index.html and at http://www.hadobs.org

Several observational datasets were produced in ENACT for use in global ocean analyses:

(a) Surface fluxes based on the ERA40 atmospheric reanalysis 1957-2001. Daily fluxes and daily climatology, with precipitation corrected.

(b) Sea level anomalies from satellite altimetry, based on T/P, Jason, ERS (1992-2004) and Geosat (Oct. 86-Jan. 89) data. Mean dynamic topography.

(c) In situ temperature and salinity data with uniform quality control, 1957-2004.

As summarised in Table 1, a number of ocean analyses have been produced. The analyses have a common experimental design, and all use the data products listed above. Archived output from the analyses includes monthly-mean u, v, w, T, S on a common 3d grid (1 by 1 latitude-longitude, 'Levitus' levels), and work is underway to make these datasets available for research. (See the websites above, and http://www.nerc-essc.ac.uk/godiva/ .) The ocean analyses are being processed to produce summary maps and verification statistics for a range of variables and indices.

It is very relevant to CLIVAR to note that notable advances have been made in the gathering and processing of the observational data required for ocean analysis, and advanced assimilation schemes have been implemented in several global OGCMs. This lays the framework for future multi-model multi-decadal ocean analysis work. The ocean analyses already produced in ENACT provide a substantial database for further exploration of ocean climate and variability, including estimates of uncertainty.

Table 1 - Ocean analyses produced in ENACT

centre	stream	Data	scheme	OGCM
CERFACS	S1	T, TS	3D-Var, 4D-Var	OPA
	S2	T, TS	3D-Var	
	Sa	TS	"	
LODYC	Sa	A	4D-Var	OPA

INGV	S1	T	OI	
	S2	T, TS	“	
	Sa	A	“	
NERSC	Sa	A	EnKF	OPA
ECMWF	S1	T, TS	OI	HOPE-E
	S2	T, TS	“	
	Sa	TSA	“	
KNMI	S1	TSA	EnKF	MPI-OM
MPIM	Sa	A	3D-Var	MPI-OM
Met Office	S1	TS	OI	GloSea
	S2	TS	“	(UM)
	Sa	TSA	“	
	1956-2001	TS	“	ObjA

S1 indicates stream1 (1987-2001); S2 is stream 2 (1962-2001); Sa is satellite stream (1993-2001). T denotes assimilation of in situ temperature data, S salinity, A altimeter (sea level). OI denotes a type of optimal interpolation assimilation scheme, EnKF denotes ensemble Kalman filter scheme, ObjA denotes a gridded objective analysis produced with no dynamical ocean model. For each model there is also a control analysis for which no ocean in situ or sea level data were assimilated.

ENACT formally finished at the end of 2004. One of the important achievements of ENACT is the development of a common experimental framework (data-sets, diagnostics,...). One question remains: will this infrastructure be exploited in the post-ENACT period? Some partners are using the ENACT ocean analysis framework for the EC project ENSEMBLES (http://www.ensembles-eu.metoffice.com/), and in operational applications. Resources are an issue, e.g., to continue with system developments, to develop the post-ENACT ocean analysis web site.

3) ECCO (Ichiro Fukumori, Carl Wunsch)

The consortium for Estimating the Circulation and Climate of the Ocean (ECCO), funded by the National Oceanographic Partnership Program (NOPP) for the period 1999-2004, is a partnership between the Scripps Institution of Oceanography (SIO), the Jet Propulsion Laboratory (JPL), and the Massachusetts Institute of Technology (MIT) whose objective is to provide the best-possible, dynamically consistent estimate of ocean circulation for applications in climate research and forecasting. Existing ECCO syntheses include:

- an 80S-80N, 1992-2002, adjoint-method optimization on a 1-deg, 23-level grid, and
- a 74S-74N, 1993-present, approximate Kalman filter and smoother analysis on a 1-deg, 46-level grid with enhanced meridional resolution (0.3-deg grid) in the tropics.

The consortium’s activities and progress are documented at http://www.ecco-group.org/.

With support from the Global Ocean Data Assimilation Experiment (GODAE), the ECCO estimation technology is becoming quasi-operational, it is being transferred to other centers, the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Space Flight Center (GSFC), and the National Centers for Environmental Prediction (NCEP), and it is being applied to longer estimation periods (1950-present) and to seasonal-to-interannual prediction. A separate effort, ECCO II, which aims to dramatically improve the resolution and accuracy of rigorous ocean state estimation, has also been proposed (http://ecco.jpl.nasa.gov/cube_sphere/)

ECCO Plans for CLIVAR Support include: ECCO contributions to CLIVAR are focused towards providing sustained global synthesis capability in near real time and in delayed (high-quality) modes. The approaches build upon ECCO technology, an approximate Kalman filter and smoother for the near real time analysis and the adjoint method for the high-quality mode. The adjoint method adjusts the model’s initial conditions, surface forcing, open boundaries, and empirical model parameters in order to fit the data to within specified error bars. The aim is to obtain estimates that satisfy the model’s time-evolution equations, with no temporal discontinuities, and in which the error field has been propagated using the same model as the state vector.

Input Data at present include:

- Forcing data: NCEP and ECMWF reanalyses, COADS fluxes, and scatterometer winds.

- In situ data: from XBT, ARGO centers, NODC and WOCE DACs, drifter, tide gauge, etc.
- Altimetry: ECCO uses its own altimetry product (absolute and time-varying) derived from data available through NASA PODAACs, including sea surface height anomalies from ERS-1 and 2.
- SST: Reynolds and TMI SST product are currently used.

Assimilation products and dissemination

With support from GODAE, ECCO is committed to maintaining the analysis capability, updating it at convenient intervals, and adding any new data that appear to carry new information. ECCO results are being distributed on the projects data servers: http://www.ecco-group.org/data_server.html.

4) GFDL (Leetmaa, Rosati)

The Upper Ocean Assimilation Systems of GFDL/NCEP/SODA focuses on global ocean data assimilation, with an emphasis on the upper ocean. The GFDL effort is based on a quasi-global MOM4 model with 3D-VAR of XBT and SSH data, from 1993 to the present.

The main goals of Ocean Data Assimilation at GFDL are:

- To develop and improve assimilation methodologies to integrate diverse data streams for initialization of seasonal-to-decadal climate forecasts.
- High-resolution, decadal time scale global ocean analyses of ocean temp, salinity and flow fields, to support scientific research.
- Infrastructure to facilitate access to observation and assimilation products.
- Climate time scale sensitivity analysis of ocean circulation

GFDL has set perspectives for its ocean data assimilation efforts, where the process of bringing new datasets into the ocean analyses has been greatly simplified by the GODAE server. Besides, by having a unified data structure and metadata would facilitate sharing of ODA tools between the involved parties. This would also ease the transition to an operational setting.

In relation to Argo, in order to use this dataset in ODA, it is first necessary to analyze how a large scale signal ca be mapped from sparse measurements with low signal to noise ratio (mainly due to mesoscale variability). Also, how much data is required to initialize?

The OM3 Model has a horizontal resolution of 1o with enhanced 1/3o in tropics, with 50 vertical levels (uniform 10m down to 210m). It is set on a Tripolar grid, with bipolar Arctic starting north of 65o.Barotropic Mode: Explicit free surface with fresh water flux affecting surface height, and it has a Staggered scheme: no time splitting mode, conservative of volume and tracer.

Parameterizations include:

1) Tracer Advection: third order Sweby scheme
2) Neutral Physics: GM skewsion and neutral diffusion
3) Horiz. Friction: Anisotropic friction
4) Penetrative SW Radiation: with prescribed Chlorophyll based on SeaWIFS climatology
5) Vertical Friction & Diffusion: KPP mixed layer, Bryan-Lewis background

The3D-variational method has been used in operational S/I prediction for over a decade. A minimum variance estimate using a constant prior covariance matrix, which remains unchanged in time, with a stationary filter.

Two new classes of methods have been developed recently:

- 4D-variational-A minimum variance estimate by minimizing a distance between model trajectory and observation, using adjoint to derive the gradient under model's constraint, using a linear filter.
- Ensemble filtering, which accounts for the nonlinear time evolution of the covariance matrix

In order to evaluate these methods, it is essential that each are developed and tested in the same model framework using the same observations.

The use of the 4D-Variational Ocean Data Assimilation has followed a continuing development of MOM4/OM3's adjoint method, using automatic differentiation tools (TAF, Giering) in collaboration with MIT, JPL, Harvard. Its current status is as follow:

1) Tangent Linear Model of OM3 nearly complete (GFDL)
2) Adjoint of prototype model (Harvard)
3) Communications for parallel computers (JPL)

The use and development of the above method has been motivated because it is easy to maintain a shared trunk which continuously incorporates the new/modified subroutines/functions to ensure the convergence of efforts from all parties, to test potential issues in 4D-Var/sensitivity study experiments (e.g. the adjoint tactics in Massively Parallel Processing), and to locate the problem once experiment results are showing flaws. In order to test deliverables for this method, four test sessions, based on the MOM4 syntax and structure, have been performed: a tangent linear test, a adjoint test, a gradient test, and a Minimization test.

5) U Maryland (J. Carton)

The SODA ocean model is built on the POP (http://www.acl.lanl.gov/climate/models/pop/current_release/UsersGuide.pdf) 1.4 ocean numerics with diagnostic free surface and a 0.25x0.4 degree horizontal grid with displaced North Pole and 40 vertical levels. Mixing schemes include KPP and nonlinear horizontal mixing. We expect to transition to the recently released POP2 code to exploit several improvements including partial filled bottom cells and NetCDF output tools. The new POP2.0 formulation does allow anisotropic horizontal viscosity, which has certain advantages as well (Large et al., 2001). River inflow is based on climatological data from the Global Rivers Data Center (GRDC). Bottom topography has been obtained from the 1/30 degree GTOPO30 with modifications for certain passages provided by Julie McLean. Under the Arctic ice surface salinity is relaxed to the monthly Polar science center Hydrographic Climatology 2.1 (Steele et al., 2001) in order to account for seasonal melting/freezing. Monthly polar sea ice coverage is based on satellite estimates of ice concentrations (Parkinson, 2001) for the period 1979-pres edited by John Weatherly of ERDC-CRREL.

The current assimilation method approach is based on a computationally efficient multivariate sequential estimation, a development of the approach described in Carton et al. (2000a,b). This approach has been augmented to allow for an empirically-based bias-correction model (Chepurin et al., 2004). Analysis of forecast minus observation statistics is used to specify the (bias-corrected) forecast error covariances in a reasonable. This preliminary analysis allows us to introduce a number of features of the observed ocean including high vertical correlations within the mixed layer, geostrophic relationships, latitudinal and flow-dependence, and rather steady relationships between temperature and salinity forecast errors.

Input Data

Forcing data: two reanalyses have been produced to date, SODA1.0, 1948-present, based on NCEP/NCAR daily reanalysis winds and SODA1.2 based on ECMWF ERA40 winds (1958-2001). The disadvantage of the NCEP/NCAR wind product is the presence of bias, particularly the weakness of the equatorial winds. We address bias in the stress by adding a steady spatially dependent term to each stress component to correct for time-mean bias and multiplying by a steady spatially dependent term to properly scale the stress variance. Both of these terms are determined by comparison with Quickscat scatterometer wind stress during the years of overlap. However, bias in the NCEP/NCAR reanalysis winds remains a lingering issue. Surface heat boundary conditions are provided by a bulk formula for heat flux (which is reduced under polar ice), while precipitation is provided by the Global Precipitation Climatology Project.

The basic subsurface temperature and salinity data sets consist of approximately profiles, of which two-thirds have been obtained from the World Ocean Database 2001 (Boyer et al., 2002) and are extended by operational temperature profile observations from the National Oceanographic Data Center\NOAA temperature archive, including observations from the TAO/Triton mooring thermistor array and ARGO drifters. The profile data is concentrated along commercial shipping lanes. Mixed layer temperature observations are available from the COADS surface marine observation set (Diaz et al., 2002). Satellite altimeter sea level from GEOSAT, ERS/1-2, TOPEX/POSEIDON and JASON is used beginning in the mid-1980s. Data checking for this analysis includes checks for duplicate reports and errors in the recorded position and time of observations, for static stability, for deviation from climatology, and checks on the relationship between temperature and salinity. Substantial quality control is already in the WOD2001. Our additional quality control (including buddy-checking, examination of forecast-minus-observation differences, and vertical stability) eliminates roughly 5% of the profiles.

Assimilation Products and Dissemination

Reanalysis fields are mapped onto a uniform 0.5ox0.5ox5-dyx40-level in NetCDF format. They will be distributed through our OpenDAP (formerly DODS) server dods.atmos.umd.edu and shortly through our LAS server. We are also distributing a revised version of our original reanalysis (beta23) through the same mechanisms.

Internal Metrics and Intercomparison plans

An ongoing series of comparisons with independent observations (for example, station time series and moored velocity) are being conducted, as well as comparisons with alternative reanalysis products. We also collect a complete set of observation-minus-forecast statistics to monitor bias in the forecast. From time to time these comparisons will be made available through our website, http://www.atmos.umd.edu/~ocean. Targeted Users and envisioned external metrics SODA reanalysis is directed toward the climate research community although it has proven to be of interest to other communities as well such as biological and chemical oceanographers. Links with application centers or service providers Aspects of this research have been funded by the National

Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and most notably, by the National Science Foundation.

Prototype Systems

An original prototype system was developed in the mid-1990s (Carton et al., 2000a). The 23rd revision of this original reanalysis (beta23) as recently been released.

References

Boyer, T.P., C. Stephens, J.I. Antonov, M.E. Conkright, , L.A. Locarnini , T.D. O'Brien, H.E. Garcia, 2002: World Ocean Atlas 2001, Volume 2: Salinity. S. Levitus, Ed., NOAA Atlas NESDIS 49, U.S. Government Printing Office, Wash. D.C., 165 pp..

Carton, J.A., G. Chepurin, X. Cao, and B.S. Giese, 2000a: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995, Part 1: methodology, J. Phys. Oceanogr., 30, 294-309.

Carton, J.A., G. Chepurin, and X. Cao, 2000b: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995 Part 2: results, J. Phys. Oceanogr., 30, 311-326.

Chepurin, G.A., J.A. Carton, and D. Dee, 2004: Forecast model bias correction in ocean data assimilation, Mon. Wea. Rev., submitted.

Large, W.G., G. Danabasoglu, JC McWilliams, PR Gent, and FO Bryan, Equatorial circulation of a global ocean climate model with anisotropic horizontal viscosity, J. Phys. Oceanogr., 31, 518-536.

Parkinson, C.L., 2002: Trends in the length of the southern Ocean sea-ice season, 1979-99, Annals of Glaciology 34, 435-440.

Steele, M., R. Morley, and W. Ermold, PHC, 2001: A global ocean hydrography with a high quality Arctic Ocean, J. Climate, 14, 2079-2087.

6) NCEP (D. Behringer)

The global ocean data assimilation system (GODAS) at NCEP was developed using the Geophysical Fluid Dynamics Laboratory's Modular Ocean Model version 3 (MOM.v3) and a three-dimensional variational data assimilation scheme, with analysis of temperature and salinity, with error covariance varying geographically and temporally. The datasets assimilated are Temperature profiles from XBTs, profiling floats (Argo), moorings (TAO), and synthetic salinity fields constructed from temperature and local Levitus T-S climatology, operational since September 2003. It has a Quasi-global grid, with 40 vertical levels.

It includes the KPP boundary layer mixing scheme, with free surface. The forcing fields are Wind stress, heat flux, E-P from Reanalysis 2 (R2), and surface salinity relaxed to Levitus monthly SSS climatology. The assimilation method used is the 3D VAR.

The atmospheric component of the coupled model is the current version of the NCEP Global Forecast System model (GFS03). It has been operational since August 2004. It adopts a spectral truncation of 62 waves (T62) in the horizontal (equivalent to nearly a 200 Km grid) and a finite differencing in the vertical with 64 sigma layers. The atmospheric and oceanic components are directly coupled without any flux adjustment.

There are still some issues to be solved for GODAS, e.g. changes in the observational suite over time and model bias, the need of improved salinity fields, and ocean currents, particularly in the western tropical Pacific, and issues related to assimilation of altimetric fields.

7) MEXT (Toshiyuki Awaji)

The aim of our study is to construct an innovative coupled data assimilation system capable of offering greater information content and forecast potential for seasonal to inter-annual (S-I) phenomena and thereby providing a higher-quality comprehensive dataset on the Earth Simulator than do models or data alone. In fact, such a dataset would be very useful for investigations of the seasonal to interannual (S-I) climate change and the associated hydrological cycle because it is dynamically consistent and the best fit between coupled climate dynamics and the many available observations.

(1) We have already performed a coupled reanalysis experiment to define seasonally-varying states with the coupled model called CFES (T42L24+1x1degL36) by using, for example, WOA data for the ocean and NCEP's "BUFR" data for the atmosphere.

The control variables are a variety of bulk parameters, which control the coupling among the atmosphere, ocean, and land surface, and the ocean initial state. Our reanalysis experiment has successfully reproduced many features of both the mean state and seasonal change in the coupled field.

(2) Further, the sensitivity experiments have clarified that our 4D-VAR coupled system has the ability to trace some climate phenomena such as precipitation back to the source regions.

(3) Using the oceanic component of our CDA system, we have performed an ocean reanalysis experiment to define a global ocean state in 1990s. The assimilated elements in this experiment are water temperature, salinity data, and sea surface height anomaly data. The obtained reanalysis dataset shows good dynamical consistency with previous knowledge of water mass distributions, surface flux fields, part of which was published in Masuda et al. (2003;GRL), and time-evolution of important climate events (e.g., the root mean square difference value between the observed time-evolution of Niño3 SST and the assimilated one is 0.8K during 1990-2000, while the difference is 1.6K for the simulation case.) These much improved results of the ocean state provide an attractive aspect for climate study and thereby significant contribution to various scientific researches of climate.

8) BlueLink ReAnalysis I (A. Schiller)

BlueLink reanalysis efforts have an initial focus on period 1992 to present, although decades prior to 1992 might be included in future reanalyses. The results from first reanalysis are expected to be made available via DODS and internet in the second quarter of 2005.

The products generated by the analysis:

- daily averages of T, S, u, v, eta, w_eta, surface heat and freshwater fluxes(eta is surface height)
- hourly averages of T, S, u, v, eta, w_eta, surface heat and freshwater fluxes, u*u, v*v, u*T, v*T, u*S, v*S, eta*u, eta*v, eta*eta, at selected locations (moorings, sections) in the Pacific, Indian and Southern Ocean, including the Indonesian Throughflow
- data sets in accordance with GODAE metrics (intercomparison project): products sub-sampled on (1/8)o grid, 12 vertical levels; Classes 1, 2 (3, 4 later).

Relevance to CLIVAR:

The reanalysis effort described above is the first one in a series of planned efforts over the next few years to be conducted by BoM and CSIRO. It is anticipated that in future experiments the period of the reanalysis will be increased to capture longer timescales and more climate-relevant signals. The data sets used for assimilation will be increased and improved (based on a more rigorous and automated QC). The data assimilation system will be improved (applying Kalman Filter techniques)

The aims of BlueLink reanalysis efforts are:

- To perform Ocean Reanalysis over last decade (1992-2004) with focus on Indian Ocean Asian-Australian region Part of Southern Ocean.
- To provide boundary conditions for nested models.
- To provide physical fields for biogeochemical models

Also, it aims to evaluate the strength/weaknesses of ocean monitoring and forecasting systems in Indian Ocean & Asian-Australian Region (part of GODAE Intercomparison Project). The timeframe for the project is to perform (first) hindcast run from October 2004 to May 2005, and have evaluation period in April 2005 to March 2006:

The high-resolution regional SST used in the analysis will consist of the archive of all Australian AVHRR data, at ~4km resolution, 1-, 3-, 6-, 10- and 15-day composite images for October 1993 – June 2003, in a geographical box between 80oE-190oE, 10oN-65oS.

The regional sea level dataset are gridded fields of sea level (0.2ox0.2o at 4-day intervals) from October 1992 to August 2002 using delayed-mode quality altimetric sea level data from the ERS-1, ERS-2, Topex/Poseidon and Jason-1 altimeters, and most Australian tide gauges. Daily-updated images of ocean surface temperature, sea level and currents – available through CSIRO CMR website at http://www.marine.csiro.au/remotesensing/oceancurrents/

The first reanalysis in a series of planned hindcasts with focus on Asian-Australian Oceans will be led by CSIRO Marine Research and Australian Bureau of Meteorology. The initial focus is on period 1992 to present, although decades prior to 1992 might be included in future reanalyses. Results from first reanalysis are expected to be made available via DODS and Internet in the second quarter of 2005.

The products generated by the reanalysis efforts are expected to be daily averages of T, S, u, v, eta, w_eta, surface heat and freshwater fluxes hourly averages of T, S, u, v, eta, w_eta, surface heat and freshwater fluxes, u*u, v*v, u*T, v*T, u*S, v*S, eta*u, eta*v, eta*eta at selected locations (moorings, sections) in the Pacific, Indian and Southern Oceans, including the Indonesian Throughflow. They will follow the GODAE Metrics, and will be used in the Intercomparsion Project for Indian, Austral-Asian & part of Southern Oceans.

9) Mercator (Eric Greiner)

The objective is to provide an oceanic large-scale reanalysis of the North Atlantic (70°N-20°S) for the years 1992-2002 that is:

- eddy permitting for mesoscale studies and embedding of area limited models
- close enough to data to give a good context for specific cruise campaigns
- homogeneous enough to allow the analysis of climate time series
- continuous enough to use model outputs as bio-geochemical dynamic inputs
- using ECMWF ERA-40 reanalysis

This means in particular that the "best analysis" is not really the goal, because the inhomogeneity in the observing system (in situ) would reduce the confidence on trend and long-term variability. Consistency with accuracy is the goal. Outlines of the protocol of the reanalysis will be exposed. The following performances will be detailed:

- SLA err < 5cm (analysis) - 8cm (forecast)
- SST err < 0.7°C Sal err < 0.3psu
- Temp err < 0.7°C (a) - 1.5°C (f)
- good balance analysis/forecast
- no shocks but gravity waves
- good circulation, no bad region
- still biases up to 10cm/0.7°C

Biases of the system (ERA-40, MSSH, EOFs) and lack of observability (salinity) are major concerns.

10) ECMWF (Magdalena Balmaseda)

The Systems Summary presentation (D. Anderson) reviewed why and how data assimilation is carried out, including its relevance in forecasting. Specific issues discussed include multi-method approaches, systematic model errors, multivariate schemes, and data impact studies. For monthly to climate predictions, data assimilation provides initial conditions for ocean-atmosphere forecasts and corrects for errors in the model. Adequate error metrics are especially important. Since there is no unique purpose in data assimilation applications, there may be no best method. Ensemble of ocean states, multi-model and multi-method approaches are useful and feasible. For operations, an issue is to determine if advanced methods are worthwhile. The ENhance ocean data Assimilation and ClimaTe (ENACT) is a multi-institution project to improve ocean data assimilation systems, produce global ocean analyses over multi-decadal periods and quantify enhancements through retrospective forecasts. Research questions addressed include data usage and impacts, utilization of different models and data assimilation schemes, systematic errors, and measures of success. MERSEA aims to develop operational high-resolution global and regional ocean analyses. MERSEA produces a 0.25 deg. analysis as part of a seasonal forecast system based on the OPA ocean model. Such European concerted collaborations (also DEMETER, DUACS, ENSEMBLES, etc) with multi-model, multi-analyses and multi data-assimilation schemes have merit, and U.S. collaborations should be useful. The system examples illustrated show that ocean data assimilation improves the coupled forecasts, adequate ensemble generations and representation of model errors are essential (use of stochastic forcing and bias correction), and data impact studies (denial of either TAO, XBT or ARGO) are needed. General research directions and issues in ocean data assimilation systems include: systematic errors and bias corrections; multivariate error covariances; coupled-models and multi-models; data availability, impacts and sufficiency; wide range of resolutions, scales and processes; and multiple applications (coastal, biogeochemical, CO2, waves, sea-ice, etc.).

11) UKMO (Bruce Ingleby)

Quality Control and Reanalysis for ENACT

The Met Office ocean quality control system was completely rewritten in 2002/03 and now forms a robust and effective automated system for both historical and real-time data. The system has been used to process data from 1958 to the present, these have been distributed to all the partners in the EC Framework 5 ENACT project (ENhanced ocean data Assimilation and Climate predicTion). All types of temperature-salinity profiles - bathythermographs, CTDs, moored buoys and ARGO floats - are processed. The primary data source was the World Ocean Database 2001, but from about 1990 onwards it was supplemented from other sources. The automated ship track check is an important part of the system. Use of a time evolving background in the quality control gives an advantage over using climatology, particularly in the Tropical Pacific. Each month an OI-type analysis was performed and 0.9 times the anomaly from climatology was added to the next month's climatology – this gave the background for the next round of QC and analysis. From use so far, most decisions in the ENACT-QC processing seem reasonable (below about 1000 m the salinity checks are too lax). 4-5% of the ship-based temperature values are rejected and about 10% of the salinity values; some of the rejections come from the track check. 1-2% of the TAO/TRITON and Argo temperature values are rejected. There are particular difficulties in performing QC in areas of large gradient, such as the Gulf Stream and to a lesser extent the tropical thermocline. A paper on the QC system and some results from it has recently been submitted to the Journal of Marine Systems. The processed observations and the objective analyses will be made available, free of charge, to other researchers. The analyses have been used by Allison (pers. comm.) to calculate a time-series of ocean heat content. The time-series shows reasonable consistency with that of Levitus et al (2000), which extends up to 1995 – since then it shows a faster increase of OHC, although further work is necessary to confirm this. Some further development and reprocessing of historical data will be performed as part of the EC Framework VI ENSEMBLES project. In the short-term this will include redressing the double-correction of some XBT data since 1995 (this and some problems with the track check show the importance of clear well-documented meta-data). Improvements to background error estimates are also high priority. We are currently assimilating the ENACT-QC observations into an ocean model and will be performing seasonal hindcasts using a version of the HadCM3 coupled model. Fluxes from ERA-40 and SSTs from NCEP (OI version 2) are used in the reanalyses. Both temperature and salinity are being assimilated – using a version of the Troccolli and Haines scheme to try to preserve temperature-salinity relationships. From 1992 onwards a separate assimilation including altimeter sea surface height anomalies is planned. Ensemble Kalman Filter and 3D- and 4D-Var analysis systems are being tested at other centers as part of ENACT. Comparison with these systems will help to guide future ocean data assimilation development at the Met Office. The ENACT-QC database is being used or is planned to be used by other groups within the Met Office Hadley Centre – see below.

Climate Reanalysis: Chris Gordon

The Hadley Centre is developing plans to carry out an ocean reanalysis using the FOAM system that is used operational for ocean prediction. This will include regionally embedded high-resolution models (e.g. 1/9 deg in the North Atlantic) and will make use of the ENACT-QC dataset described above. The reanalysis with this operational system will be compared with that produced from the seasonal and climate modeling systems.

Decadal Prediction: Doug Smith

A decadal climate prediction system has been developed at the Met Office Hadley Centre. Initial conditions in the ocean are created by relaxing HadCM3 to monthly 3D analyses of temperature and salinity anomalies. These are created by statistical interpolation (using covariances derived from a model climate simulation) of subsurface temperature and salinity data which have been quality controlled by procedures developed for the ENACT project. Initial conditions in the atmosphere are created by relaxing to ECMWF reanalyses. Hindcast experiments covering the period 1979 to 2001 show significant skill at predicting surface temperature both globally and in many regions throughout the ten years of the integrations. Future plans include sampling model uncertainties in addition to uncertainties in the initial conditions, and assessing the impact of improved subsurface ocean data coverage provided by the ARGO project.

Data Applications: Simon Tett

The Hadley Centre is planning to produce a sub-surface temperature and salinity objective analysis on constant density surfaces. The eventual aim of this work is to produce a times-series of global ocean heat-content with uncertainty estimates. We plan to use Ruth Curry's Hydrobase toolkit and to collaborate with Ruth to do this. The input data for this project will be the quality controlled observations produced by the ENACT project. The resulting timeseries will be compared with coupled model simulations and ocean data assimilation experiments using the same input data. We plan to start the project in the spring of 2005.

12) Historical Data Archiving (Hernan Garcia)

Our experience is building scientifically quality-controlled ocean profile-plankton databases for the world ocean as exemplified by "World Ocean Database 2001" (WOD01). These databases are frequently used as a source for reanalysis studies. We work with historical data, "real-time", "near real-time" reported over the GTS and collated via the Global Temperature-Salinity Profile Project (GTSPP) (and delayed mode versions of these data), and modern data submitted via CD-ROM, the Internet.

The various "systems" of present-day ocean data management work but need improvement. Problems with real-time, delayed mode, and historical data include:

(a) Many profiles are not properly identified (e.g., is a profile an XBT, or a drifting thermistor chain T profile?;

(b) Numerous "near duplicates"- e.g., same T profile but different years, months, days, or same metadata but slightly different T profile values;

(c) Multiple submissions of the "same" data from different sources; (d) Incorrect metadata, e.g., bad dates, locations, instrument I.D.s;(e) XBT profiles extending deeper than maximum rated depth etc. It is time-consuming, labor-intensive work to identify and correct these problems.

The existing ocean data delivery systems can be improved by (a) Identifying and fixing metadata problems in near-real-time etc.; (b) Identifying data quality problems by using the data to generate scientific products. These are labor-intensive tasks. Simply running data through automatic checking programs does not catch many of the problems. We inform GTSPP groups of our findings and work with them to find solutions. This way all users benefit.

The flow of delayed-mode data by DACs to users and data centers needs to be made faster, e.g., the community cannot wait three years for delayed-mode (quality-controlled) data to become available. Statistical checks can be done by anyone. In addition, as new data become available the statistical checks need to be redone and perhaps new statistical checks applied. The real value of a DAC is to identify random and systematic problems, in the measurements and in the flow of data. Everyone makes mistakes, all must actively work to maintain the integrity of the data flow and databases. DACs can also serve a useful role in these activities.

Requirements for a DAC: A DAC must make data available on-line. Another DAC function should be to use the DAC data in making products. This will likely result in the identification of additional problems with the data. However, this function should not interfere with the basic DAC function of making data available. This is potentially a contentious issue since DACs may be viewed as being in competition with their user community. Experience has shown that it is inevitable that problems will be discovered with data and future users will want to further process historical data. Also, new improved processing techniques may be developed after a DAC has "closed'. Therefore: A DAC must completely document how they process data and make this information available to all users. Data need to have complete metadata available for DAC data and their database so present and future users know how data were processed.

Advantages of a DAC: DAC staff may (and in fact should) have expertise and experience difficult to duplicate at a data center function, e.g., TAO array data. Thus, data management should be co-located with the group deploying the instruments and ideally with a research group that uses the data. However, a DAC must above all make data available internationally, freely, and without restriction.

Ocean data management is under funded and understaffed at most data centers, DACs, and in general. Funding sources can pay now and produce higher quality database for community, use or pay later with potential permanent loss of more data as time goes by.

Data Sets of Oceanic Surface Fluxes

Statement prepared for the WCRP Working Group on Observations and Assimilation

Dr. Elizabeth C. Kent,

Constructing datasets of surface fluxes is an area in which there is much to be gained from an approach integrating in situ observations with satellite retrievals and model output or reanalysis. None of the three sources (in situ, satellite, model) can yet be used to generate global high quality surface flux products on their own.

It should be noted that although there may be pragmatic reasons for focusing this particular proposal on the 'satellite-era' that there is much work to be done for the 'pre-satellite-era'.

Direct turbulent flux measurements are rare and fluxes are usually calculated using parameterizations from the basic meteorological variables, which are all 'essential climate variables' in the GCOS Implementation Plan. In situ radiation measurements are more common and are an important verification/validation/calibration source for satellite fields of surface radiation. In situ precipitation measurement is problematic, particularly at sea. Satellites give various estimates of precipitation but calibration is a serious issue.

For surface turbulent heat flux estimates over then ocean we therefore require high quality fields of basic meteorological variables (air temperature, sea surface temperature, surface humidity, wind speed and direction and surface pressure) from which to calculate heat exchange using 'bulk formulae'. [Note that the exchange coefficients, especially at high and low wind speeds, contain uncertainty]. Traditionally, co-located observations of air temperature, sea surface temperature, surface humidity, wind speed and direction and surface pressure have been used. However if fields of sufficient resolution (as yet undefined) are available then it should be possible to relax the requirement for co-location. Of the required variables for turbulent flux calculation, the air temperature, surface humidity and (less importantly for surface fluxes) surface pressure are not retrieved from satellites with good accuracy. It is therefore particularly important for surface flux calculation that air temperature and humidity are obtained with good accuracy from in situ data. There are different issues for different variables. For example, satellites do not give good estimates of marine surface air temperature. Ship measurements of air temperature from the Voluntary Observing Ships (VOS) collated in the International Comprehensive Ocean-Atmosphere Dataset (ICOADS) have known biases due to solar radiative heating. These VOS biases can be detected in the NCEP1 Reanalysis, but could be corrected in the VOS data before assimilation.

For those ocean surface variables that are obtainable from satellites with good accuracy (e.g. winds and SST) the overlap between in situ and satellite observations of the same variables is valuable in improving understanding of both the in situ observations and satellite retrievals. The satellite information is particularly valuable in providing information in regions that are poorly sampled in the in situ record. The value of in situ data in extending the period of record to many decades should not be overlooked.

Ocean surface radiation and precipitation are variables that are estimated from parameters reported by ships (precipitation estimates from the present weather code and radiation from a combination of cloud cover and meteorological variables) and are retrievable from satellites. Comparison of the indirect methods used by the ships with the satellite estimates has the potential to provide improved ship-based estimates of ocean surface radiation and precipitation in the pre-satellite era. Absolute values of precipitation in particular will be hard to determine.

Reanalyses are an important resource but those currently available have well-documented problems with their surface flux fields. Surface based reanalyses with a goal of producing good surface fluxes would be welcomed. It should be noted that if we "assimilate all remotely sensed and in situ data into a coupled, comprehensive earth system model" then we will have no independent data for validation.

The WGSF at their recent meeting stressed the need for routine model/in situ/satellite intercomparisons of surface fluxes at selected sites. This is proposed by the SURFA project which aims to routinely compare surface fluxes from a range of atmospheric models with in situ estimates but which has progressed slowly.

The WGSF also has an interest in ocean biogeochemical fluxes, it is not clear whether these data are included in the proposal.

SST-Induced Small-Scale Variability in the Wind Stress Curl Field

Dudley B. Chelton, Oregon State University

Surface wind stress observations from the QuikSCAT scatterometer available since July 1999 have revealed previously unknown persistent small-scale features in the wind stress curl field. These become apparent when high-pass filtering the 4-year average curl field to isolate features with wavelength scales shorter than 30o of longitude by 10o of latitude (top left figure below). This small-scale variability is mostly attributable to air-sea interaction over SST fronts (Chelton et al., 2004). The magnitudes of these perturbations have a dynamic range as large as that of the large-scale curl field that drives the gyre circulations. Because of their persistence, these small-scale features in the curl field likely have important feedback effects on the ocean, at least locally.

The SST-induced small-scale features are present in the surface wind fields of the NCEP operational forecast model as well, but are significantly smaller in amplitude and smoother spatially (Chelton et al., 2004). These features are even weaker and smoother in the coarser resolution NCEP reanalysis surface wind fields (top right figure below). One factor contributing to the underestimate of the effects of SST on surface winds is inadequacies in the SST boundary condition. For the eastern tropical Pacific region, this accounts for about half of the underestimation of ocean-atmosphere coupling (Chelton, 2005).

The boundary condition for the NCEP reanalysis model after 1981 consists of the Reynolds SST fields. From

comparisons with satellite microwave AMSR observations, the resolution of the Reynolds SST fields is very coarse, as shown, for example, by the 3-day average (11-13 June 2002) SST over the Gulf Stream in the bottom row of figures below. The accuracies of NCEP reanalyses of surface wind fields could be improved by improving the resolution of the SST boundary condition. This could be done retrospectively to 1981 by reanalyzing the AVHRR data using shorter correlation scales in the Reynolds objective analysis system, analogous to what has been done in the Real-Time Global (RTG) SST fields produced by NOAA since February 2001 (third panel in bottom row of figures). In the longer term, the resolution of Reynolds and RTG SST fields could be further improved through assimilation of the AMSR data.

References

Chelton, D. B. 2005: The impact of SST specification on ECMWF surface wind stress fields in the eastern tropical Pacific. J. Climate, in press.

Chelton, D. B., M. G. Schlax, M. H. Freilich and R. F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean

winds. Science, 303,

Appenix C:

Workshop Agenda

CLIVAR Workshop on Ocean Reanalysis

November 8 -10, 2004 at NCAR (Boulder)

September 3, 2004

November 8 (Monday)

08:30 Opening:

Welcome and objectives of workshop (Stammer)

Welcome by NCAR Director Tim Killeen

Logistics, etc. (Trenberth)

- Morning Session: The requirements for ocean reanalysis:
- Overview talks. (45 min. each)

09:00 Ocean synthesis requirements, benefits and strategies for CLIVAR; Speaker: C. Wunsch.

09:45 Status of atmospheric reanalyses (ECMWF (ERA-40), NCEP, GMAO, SURFA); Speaker: S. Schubert.

10:30 COFFEE BREAK

11:00 Status of surface fluxes estimates; Speaker: Chris Fairall.

11:45 GODAE support for CLIVAR; Speaker: N. Smith.

12:30 –13:30 LUNCH BREAK

- Afternoon Session: Summary of ongoing reanalysis activities and historical data archiving in the ocean (20 min. each):

13:30 HYCOM (C. Thacker)

13:50 ENACT (Mike Davy; A.T. Weaver)

14:10 ECCO (Ichiro Fukumori, Carl Wunsch)

14:30 GFDL (Leetmaa, Rosati)

14:50 U Maryland (J. Carton)

15:10 NCEP (D. Behringer)

15:30 COFFEE BREAK

16:00 MEXT (Toshiyuki Awaji)

16:20 BlueLink (A. Schiller)

16:40 GMAO (M. Rienecker; canceled)

17:00 Mercator (Eric Greiner)

17:20 ECMWF (Magdalena Balmaseda)

17:40 UKMO (Bruce Ingleby)

18:00 Historical Data Archiving (Hernan Garcia)

6:30 – 8:30 pm Meeting Reception at NCAR

Tuesday November 9

08:30 – 18:30 WORKING GROUPS

Two working groups will meet in parallel at a time. Working Group discussions will be summarized during the plenary morning session of day 3 and will form the basis for subsequent activities within GSOP. Respective groups could continue to function as GSOP expert groups.

08:30 – 12:30 WORKING GROUPS 1 & 2

13:30 – 18:30	WORKING GROUPS 3 & 4

10:00 –10:30	COFFEE BREAK
12:30 – 01:30	LUNCH
15:30 – 16:00	COFFEE BREAK
18:30	Adjourn for the day

Working Group Descriptions:

Working Group 1:
Ocean (and ice) variability and processes as seen in prognostic simulations and reanalyses.
Chairs : A.-M. Treguier and I. Fukumori
Discuss capability to estimate variability relevant to climate with both prognostic models and ocean reanalysis, to identify open questions and suggests strategies to improve future ocean reanalysis efforts. Suggested topics of discussion include:

1) Model biases.
2) Changes in the ocean circulation and T/S properties.
3) Seasonal to interannual variations of heat transport and heat content.
4) Seasonal and interannual variations of freshwater and sea level.
5) Other climate-relevant considerations
6) Perspectives for better representation of variability and processes in reanalysis.
7) What has and will be learned from

Working Group 2:
Surface fluxes from ocean, ice and atmospheric reanalyses.
Chairs: B. Weller and B. Large
Assess interest on the questions already posed and eliminate any that fail to draw sufficient interest. Take additional issues from the floor. Prioritize the questions, so that the high-priority ones are discussed first.

For each of the following questions a “facilitator” will give a brief 10+-5 min “position” or lead statement. The facilitator will then moderate the subsequent discussion and invite relevant presentation from the floor.

1) The physics of air-sea exchange: J. Carton
2) Diagnosing the error characteristics of the forcing fields: TBD
3) Developing minimum error ocean forcing fields: R. Weller
4) Space/time resolution required for the forcing fields: S. Gulev
5) Problems encountered at high latitudes: M. Holland
6) Atmospheric reanalysis fluxes: D. Chelton
7) Continental Runoff : K. Trenberth

Working Group 3:
Ocean observing requirements for CLIVAR:
Chairs: M. McPhaden and Victor Zlotnicky
Discussion topics include:

1) Present status and future plans for in situ observations in support of CLIVAR/GOOS/GCOS (availability, timeliness, quality of data, obvious gaps). [McPhaden]
2) Present status and future plans for satellite observations in support of CLIVAR/GOOS/GCOS (availability, timeliness, quality of data, obvious gaps). [Zlotnicki]
3) Data requirements for reanalysis, nowcasting, and prediction. [Carton]
4) Role for data assembly centers in supporting reanalysis, nowcasting and prediction efforts (access to real-time and historic data, QC, archiving).

Working Group 4:
Uncertainties, biases, estimation errors and assimilation techniques
Chairs: A. Bennett and A.T. Weaver
This working group will address theoretical and practical issues in ocean data assimilation for reanalysis. Topics

and questions for discussion are indicated below. WG4 participants may contribute to the discussion through brief presentations.

1) Resolution and configuration.
2) Assimilation techniques: filtering vs smoothing, strong constraints vs. weak constraints.
3) Modelling and estimating background state error covariances.
4) Detecting and correcting model bias.
5) Estimating observation errors.
6) Estimating uncertainties in syntheses.

Wednesday November 10:

8:30 -13:00pm Plenary Discussions

8:30 Summary of Working Groups:

- Working Group 1: A.-M. Treguir, I. Fukumori
- Working Group 2: B. Weller and B. Large
- Working Group 3: M. McPhaden and V. Zlotnicky

10:30 – 11:00 COFFEE BREAK

11:00 Challenges for the future: M. Rienecker and D. Anderson

Discussion topics included:

1) Who will provide reanalyses for CLIVAR?
2) How can we improve coupled forecasts through reanalysis efforts?
3) What is required for good initializations of coupled runs?
4) Coupled reanalysis approaches
5) Required observing and data delivery systems
6) Human resource and infrastructure needs.
7) Computational and infrastructure requirements

12:30 Closing session:

Summary of Workshop Outcomes

Discussion of future activities and action items

13:00 pm End of Workshop

Appendix D:

List of Ocean Reanalysis Workshop Attendees

Anderson, David
ECMWF
Shinfield Park
Reading, Berks RG2 9AX
United Kingdom
sta@ecmwf.int

Anderson, Jeffrey
NOAA/GFDL & NCAR
P.O. Box 3000
Boulder, CO 80307, U.S.A.
jla@ucar.edu

Arkin, Phillip
Deputy Director
Earth System Science Interdisciplinary Center
University of Maryland
2207 Computer & Space Sciences Bldg.
College Park, MD 20742-2465, USA
parkin@essic.umd.edu

Awaji, MTosyiyuki
Faculty of Science
Kyoto University
Sakyo-ku, Kyoto 606-01 -
Japan
awaji@kugi.kyoto-u.ac.jp

Balmaseda, Magdalena
ECMWF
Shinfield Park
Reading, Berks RG2 9AX
United Kingdom
neh@ecmwf.int

Barnier, Bernard
Institut de Mécanique de Grenoble
Lab. Des Ecoulements
CNRS-UJF-INPG
BP 53, 38041 Grenoble cedex
France
Bernard.Barnier@hmg.inpg.fr

Behringer, David
NOAA / NWS / NMC
World Weather Building Room 807
5200 Auth Road
Camp Springs MD 20746-4303, U.S.A.
David.Behringer@noaa.gov

Bennett, Andrew
College of Oceanic and Amostpheric Sciences
104 Ocean Admin Building
Oregon State University
Corvallis, OR 97331-5503, U.S.A.
bennett@coas.oregonstate.edu

Boening, Claus
Institut fuer Meereskunde
Theorie und Modellierung
Duesternbrooker Weg 20
Germany
cboening@ifm-geomar.de

Brassington, Gary
Ocean & Marine Forecasting
Bureau of Meteorology
PO Box 1289K
Melbourne, Australia
g.brassington@bom.gov.au

Bryan, Frank
Oceanography Section
National Center for Atmospheric Research
PO Box 3000
Boulder CO 80307-3000, U.S.A.
bryan@ucar.edu

Burgers, Gerrit
Oceanographic Research
Royal Netherland Meteorological Institute KNMI
PO Box 201, 3730 AE de Bilt
The Netherlands
Gerrit.Burgers@knmi.nl

Carton, James
Dept. of Meteorology
University of Maryland
Lee Bldg. Rm 2100
College park MD 20742, USA
carton@atmos.umd.edu

Casey, Kenneth S
NOAA/NESDIS
National Oceanographic Data Center
1315 East-West Highway
Silver Spring MD 20910 - U.S.A.
kenneth.casey@noaa.gov

Chelton, Dudley
Oregon State University - COAS
Corvallis, Oregon 97331, U.S.A.
chelton@coas.oregonstate.edu

Church, John
CSIRO Marine Research
GPO Box 1538
Hobart, Tasmania 7001
Australia
john.church@csiro.au

Cummings, James
Marine Mateorology Divison Code 7533
Naval Research Laboratory
Monterey, California 93943, U.S.A
cummings@nrlmry.navy.mil
Curry, Judy
Georgia Institute of Technology
221 Bobby Dodd Way
Atlanta GA 30332-0340, U.S.A.
curryja@eas.gatech.edu

Desaubies, Yves
IFREMER / Centre de Brest
BP 70, F-29280 Plouzané
France
yves.desaubies@ifremer.fr

Donlon, Craig
Met Office
Beagle second floor
Fitzroy Road
Exeter EX1 3PB
United Kingdom
craig.donlon@metoffice.com

Fairall, Chris
NOAA/ETL
325 Broadway
Boulder -,m CO 80305, U.S.A.
Chris.Fairall@noaa.gov

Fu, Lee-Lueng
Jet Propulsion Laboratory
California Institute of Technology
MS 300-323
4800 Oak Grove Drive
Pasadena CA, U.S.A.
llf@pacific.jpl.nasa.gov

Fukasawa, Masao
Ocean Research Dept.
JAMSTEC
2-15 Natsushima, Yokosuka
Kanagawa 237-0061
Japan
fksw@jamstec.go.jp

Fukumori, Ichiro
Jet Propulsion Laboratory
California Institute of Technology
MS 300-323
4800 Oak Grove Drive
Pasadena CA , U.S.A.
Ichiro.Fukumori@jpl.nasa.gov

Garcia, Hernan
NOAA
1315 East-West Highway
Silver Spring MD 20910, U.S.A.
hernan.garcia@noaa.gov

Gleckler, Peter
Program for Climate Model Diagnosis and Intercomparison
Lawrence Livermore National Laboratory
PO Box 808
Livermore, CA 94550, U.S.A.
gleckler@pcmdi.llnl.gov

Gould, W John
Scripps Institution of Oceanography
UCSD Mail code 0230
9500 Gilman Drive
La Jolla, CA 92093-0230 , U.S.A.
wjg@ucsd.edu

Grenier, Eric
GIP Mercator Ocean
Parc Technolgique du Canal
8-10 rue Hermès
31520 Ramonville St Agne
France
egreiner@mercator-ocean.fr

Gulev, Sergei
PP Shirshov Institute of Oceanology
Russian Academy of Sciences
36 Nakhimovsky Ave
117218 Moscow
Russian Federation
gul@passat.sail.msk.ru

Haines, Keith
ESSC - Reading University
PO Box 238, 3 Earley Gate
Whiteknights, Reading RG6 6AL
United Kingdom
kh@mail.nerc-essc.ac.uk

Harrison, Ed
NOAA/PMEL
7600 Sandy Point Way NE
Seattle WA 90125, U.S.A.
D.E.Harrison@noaa.gov

Hill, Katy
International CLIVAR Project Office
National Oceanography Centre
Southampton SO14 3ZH
United Kingdom
klh@soc.soton.ac.uk

Holland, Marika
Oceanography Section
National Center for Atmospheric Research
PO Box 3000
Boulder CO 80307-3000
U.S.A.
mholland@ucar.edu

Huang, Bohua
COLA / IGES
4041 Powder Mill Road #302
Calverton, MD 20705-3106, U.S.A.
huangb@cola.iges.org

Ingleby, Bruce
Met Office
Fitzroy Road
Exeter EX1 3PB
United Kingdom
bruce.ingleby@metoffice.com

Itsweire, E
Division of Ocean Sciences
National Science Foundation
4201 Wilson Blvd., Rm 725
Arlington, VA 22230, U.S.A.
eitsweir@nsf.gov

Ji, Ming
NOAA
Office of Global Programs
1100 Wayne Avenue, suite 1225
Silver Spring, MD 20910, U.S.A.
ming.ji@noaa.gov

Johnson, M
NOAA
Office of Global Programs
1100 Wayne Avenue, suite 1225
Silver Spring, MD 20910, U.S.A.
Mike.Johnson@noaa.gov

Josey, Simon
James Rennell Division
National Oceanography Centre
Southampton SO14 3ZH
United Kingdom
Simon.A.Josey@soc.soton.ac.uk

Kalnay, Eugenia
Dept. of Meteorology
University of Maryland
3431 Computer and Space Sciences Bldg.
College Park, MD 20742-2425, U.S.A.
ekalnay@atmos.umd.edu

Kamachi Masafumi
Meterological Research Institute
1-1 Nagamine
Tsukuba, Ibaraki 305-0052
Japan
mkamachi@mri-jma.go.jp

Koehl, Armin
Institut fuer Meereskunde
Universitat Kiel
Dusternbrooker Weg 20
24105 Kiel, Germany
koehl@ifm.uni-hamburg.de

Large, William
Oceanography Section
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307, U.S.A.
wily@ucar.edu

Lee, Tong
Jet Propulsion Laboratory
California Institute of Technology
MS 300-323, 4800 Oak Grove Drive
Pasadena CA - U.S.A.
tlee@pacific.jpl.nasa.gov

Leetma, Ants
NOAA
Climate Predition Centre
5200 Auth Road
Camp Springs MD 20746-4303, U.S.A.
Ants.Leetmaa@noaa.gov

Legler, David
US CLIVAR Office
Suite 250
1717 Pennsylvania Avenue NW
Washington DC 20006 , U.S.A.
legler@usclivar.org

Lindstrom, Eric
NASA Headquarters
Code YS - Room 5032
300 E Street SW
Washington DC 20546, U.S.A.
eric.j.lindstrom@nasa.gov

Masina, Simona
INGV
Via Gobetti 101
40129 Bologna, Italy
masina@bo.ingv.it

Masuda, Shuhei
Frontier Research System for Global Change
Global Environment Modeling Research
Program
3173-25 Showa-cho, Kanazawa-ku
Yokohama, 236-0001, Japan
smasuda@mri-jma.go.jp

Kazuhiko Masuda
Meteorological Research Institute
1-1 Nagamine
Tsukuba-shi, Ibaraki, 305-0052
JAPAN
masuda@mri-jma.go.jp

McPhaden, Michael
NOAA / PMEL
7600 Sand Point Way NE,Bldg. #3
Seattle WA 98115, U.S.A.
michael.j.mcphaden@noaa.gov

Menemenlis, Dimitris
Jet Propulsion Laboratory
California Institute of Technology
MS 300-323
4800 Oak Grove Drive
Pasadena CA, U.S.A.
menemenlis@jpl.nasa.gov

Oke, Peter
CSIRO Marine Research
GPO Box 1538
Hobart, Tas 7001, Australia
peter.oke@csiro.au

Penduff, Thierry
Laboratoire des Ecoulements Geophysiques et Industriels
BP53, 38041, Grenoble Cedex 9
France
Thierry.Penduff@hmg.inpg.fr

Qu, Tangdong
IPRC
University of Hawaii
1680 East-West Road
Honolulu, HI 96822, U.S.A.
tangdong@soest.hawaii.edu

Richards, Kelvin
IPRC
University of Hawaii
1680 East West Road
Honolulu, HI 96822, USA
rkelvin@hawaii.edu

Roemmich, D
Scripps Institution of Oceanography
UCSD Mail code 0230
9500 Gilman Drive
La Jolla, CA 92093-0230, U.S.A.
droemmich@ucsd.edu

Rosati, Anthony
NOAA Geophysics Fluid Dynamics
Princeton University
PO Box 308
Princeton NJ 08540, U.S.A.
Tony.Rosati@noaa.gov

Sabine, Christopher
NOAA/ PMEL
7600 Sand Point Way NE,
Bldg. #3
Seattle WA 98115, U.S.A.
chris.sabine@noaa.gov

Schiller, Andreas
CSIRO Marine Research
GPO Box 1538
Hobart, Tas 7001, Australia
Andreas.Schiller@csiro.au

Sloyan, Bernardette
Physical Oceanography
Woods Hole Oceanographic Institution
Mailstop 21
Woods Hole MA 02543, U.S.A.
bsloyan@whoi.edu

Smith, Neville
Bureau of Meteorology Research
PO Box 1289K
150 Londsdale Street
Melbourne VIC 3001, Australia
nrs@bom.gov.au

Smith, Shawn
COAPS
Florida State University
2035 E Dirac Drive
RM Johnson Bldg. Suite 200
Tallahassee, FL 32306-2840, U.S.A.
smith@coaps.fsu.edu

Speer, Kevin
Florida State University - Oceanography
Call Street
Tallahassee, FL 32306-2840, U.S.A.
kspeer@ocean.fsu.edu

Stammer, Detlef
Institut fuer Meereskunde
University of Hamburg
Troplowitzstr. 7/11
22529 Hamburg, Germany
stammer@ifm.uni-hamburg.de

Sugiura, Nozomi
Frontier Research System for Global Change
3173-25 Showaq-machi, Kanazawa-ku
Yokohama city, Kanazawa
Yokohama 236-0001, Japan
nsugiura@jamstec.go.jp

Thacker, Carlisle
AOML
4301 Rickenbacker Causeway
Miami FL 33149 , U.S.A.
thacker@aoml.noaa.gov

Treguier, A-M
CNRS
LPO, IFREMER
BP 70, F-29280 Plouzané
France
Anne.Marie.Treguier@ifremer.fr

Trenberth, Kevin
Climate Analysis Section
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307 , U.S.A
trenbert@ncar.ucar.edu

Tribbia, Joseph
Climate and Global Dynamics
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307, U.S.A
tribbia@ucar.edu

van Leeuwen, Peter J
Institute for Marine and Atmospheric Research
Utrecht University
PO Box 80005
3508 TA Utrecht, The Netherlands
leeuwen@phys.uu.nl

Weaver, Anthony
Global Change and Climate Modelling
CERFACS
42 Avenue Guspard Coriolis
31057 Toulouse cedex, France
weaver@cerfacs.fr

Weller, Robert
Woods Hole oceanographic Institution
Clark 204A MS 29
38 Water Street,
Woods Hole, MA 02543 -1541, U.S.A.
rweller@whoi.edu

Wilson, Stan
NESDIS, NOAA
SSMC-1 Room 8212
1335 East West Highway
Silver Spring, MD 20910, USA
Stan.Wilson@noaa.gov

Wittenburg, Andrew
NOAA
Forrestal Campus
US Route 1 , PO Box 308
Princeton, NJ 08452, U.S.A.
Andrew.Wittenberg@noaa.gov

Wijffels, Susan
CSIRO Marine Research
GPO Box 1538
Hobart, Tasmania 7001
Australia
Susan.Wijffels@csiro.au

Worley, Steven
NCAR
PO Box 3000
Boulder CO 80307, U.S.A.
worley@ucar.edu

Yu, Lisan
Woods Hole oceanographic Institution
Clark 204A MS 29
38 Water Street,
Woods Hole, MA 02543 -1541, U.S.A.
lyu@whoi.edu

Zaron, Ed
104 Ocean Admin Bldg
Oregon State Univesity
Corvallis OR 97331, U.S.A.
ezaron@coas.oregonstate.edu

Zeng, Xubin
Dept. of Atmospheric Sciences
The University of Arizona
PO Box 210081
Tucson AZ 85721-0081, U.S.A.
zeng@atmo.arizona.edu

Zlotnicki, Victor
Jet Propulsion Laboratory
California Institute of Technology
MS 300-323
4800 Oak Grove Drive
Pasadena CA, U.S.A
vz@pacific.jpl.nasa.gov

International CLIVAR Project Office
National Oceanography Centre
Empress Dock
Southampton, SO14 3ZH, United Kingdom

email: icpo@noc.soton.ac.uk
tel: (0) 2380 596777
fax: (0) 2380 596204