Meeting report

OOPC-GODAE Meeting on OSSEs/OSEs

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UNESCO/IOC – Paris, France

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Participants of OSSE/OSE meeting in Paris (from left)
Front row: S. Matsumoto, Y. Fujii, K. Wilmer-Becker, P-Y Le Traon, S. Guinehut, T. Lee, E. Dombrowsky
Middle row: E. Bayler, M. Martin, D. Lea, A. Weaver, G. Larnicol, M. Balmaseda, P. Brasseur
Top row: F. Hernandez, A. Fischer, J. Cummings, P. Oke, B. Molinari

Presentations from the meeting are available from the GODAE website http://www.godae.org/OSSE-presentations.html.

November 2007

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I. Background

Global operational oceanography depends upon reliable near-real time access to ocean data - a sustained ocean observing system. The plan for the global ocean observing system being implemented at present (GCOS-92) was developed primarily by the global ocean climate research community. The plan was based on what was known about the ocean at the end of the 1990s, on the technology that was proven and in prospect at that time, and was expected to serve as wide a range of ocean needs as possible.

Because the ocean has been poorly sampled in the past over most of its volume, a key aspect of the plan is that new information about ocean variability, ocean predictability and the roles of the ocean in the full suite of societal benefit areas would be incorporated in subsequent versions of the plan for the sustained global ocean observing system.

In recent years the system has begun to produce data from regions of the ocean that have been very poorly observed previously, and there has been much analysis of the historical and modern ocean data sets. We are piecing together our first nearly synoptic looks at the upper kilometre of the ocean and building a data record that, if continued and properly exploited, will revolutionize our knowledge of the ocean and its roles in the earth system.

There has also been much progress over the past decade in the development of information systems that depend upon ocean observations. Global and regional ocean state estimation has become routine and ocean data assimilation has become essential for ocean and climate analysis and forecast systems. Evolution of the observing system plan depends upon making the best possible use of these capabilities, even as they are developing.

Global ocean state estimation systems are a powerful means to assess the impact of the observing system, to identify gaps and to improve the efficiency/effectiveness of the observing system. Observing System Experiments (OSE) or Observing System Simulation Experiment (OSSE) are particularly useful tools which have been applied to high-resolution ocean forecasting (the current primary focus of GODAE), seasonal-to-interannual prediction, and climate analysis and reanalysis.

An Observing System Experiment (OSE) determines the impact of specific observations on ocean analyses and forecasts by systematically including and/or excluding such observing system data in an ocean data assimilation system. This way the quality and effectiveness of the ocean observing system and the data assimilation system can be evaluated and improved.

An Observing System Simulation Experiment (OSSE) mostly uses synthetic observational data as a surrogate for real observations. These synthetic observations are produced through a *nature run* – a long term, high-resolution forecast – that imitates the true ocean state. The OSSE is a method to determine what impact a future/proposed observing system may have on ocean forecasts and analyses by assimilating the synthetic observation in a data assimilation system. As such experiments are relatively cheap, this determines a useful investment when expanding or developing a new observing system.

One of the aims of GODAE is to formulate more specific requirements for observations on the basis of improved understanding of data utility and to deliver a series of recommendations for an improved design of the global ocean observing system.

II. Executive Summary

The GODAE-OOPC Meeting on Observing System Simulation Experiments (OSSE) and Observing System Evaluation (OSE) was the first meeting dedicated to the subject of observing system evaluation using the GODAE model systems. The group agreed that there is a clear need to devote more efforts to OSE/OSSE studies to analyse the impact of the global ocean observing system and to improve its design. The incremental costs of such work are very small compared to costs of the observing system and the likely value of the outcomes.

A general conclusion from the work presented is that the addition of observing data improved the overall results/skill of the GODAE systems - the oceans are generally undersampled, and any degradation of the observing system will result in a degradation of forecast skill. When data had a negative or neutral impact this was useful in diagnosing where future improvements in the model and data assimilation system should be targeted. A composite observing system (of satellite and *in situ* elements) is needed because the different data sources provide complementary information which can be used in the GODAE systems, and also to respond to the many requirements for ocean information and the different questions that can be posed. Long-term data continuity is not only useful for climate research, but for developing the statistics required by the shorter-term forecast systems.

Specific requirements for the observing system have been identified:

a) GODAE systems and their applications require high resolution altimetry. There is a need to maintain continuity of the high-accuracy Jason altimetry and maintain continuity with altimeters on at least two and preferably three complementary, high-inclination satellites.

b) The global in-situ observing system needs to be sustained. In particular it needs to be ensured that Argo global coverage is maintained over the next 10 years. Argo data are critical for constraining T&S fields in GODAE systems.

c) The development of SST high resolution data and products need to be continued.

The group also identified longer-term issues and opportunities, including the broader adoption of NWP techniques on data impact, preparation for new data types including sea surface salinity, and the preparation for coupled data assimilation systems.

Building some harmonized frameworks (based on the GODAE intercomparison metrics) for the comparison of OSE results from different models has and will be important to identify the robustness of the results, and to help identify differences between the models to target improvements. Improvement in the assimilation techniques for different types of data, in the basic model skill, and in the coordination of these efforts needs to continue and therefore a working group (led by P. Oke) was formed to explore these questions, identify some common work, and present results at the final GODAE Symposium in November 2008.

International cooperation is essential in building a critical mass of shared expertise in this field. This group is proposing to continue its international collaboration beyond the end of GODAE through regular meetings and workshops.

III. Meeting organisation

Meeting structure
The meeting consisted of a variety of invited talks from presenters coming from international institutions and observing system agencies. All presentations were given in plenary followed by an open discussion on the final day. The meeting started at 14:00 on Monday, 5 November 2007 at the IOC in Paris and finished Wednesday, 7 November 2007 at lunchtime. The arrangement of the meeting to run over 3 days (1 full and 2 half days) allowed ample time for open discussion.

Meeting sessions

1. Introduction
2. General multi-purpose methods
3. Altimetry
4. Argo (T/S) and other in-situ observing systems

Meeting report
This report contains the summaries provided by the presenters, on the main results of their research (section 2 – 4) arranged in the same order as the agenda (see meeting programme in Appendix A). Section 5 summarises the outcome of the open discussion on the final day and the main recommendations extracted from the rapporteur reports.

Meeting convenors and organisers:
Pierre-Yves Le Tran, GODAE Co-chair, Ifremer, France
Ed Harrison, NOAA, US
Albert Fischer, IOC, France (local host)
Kirsten Wilmer-Becker, GODAE coordinator, Met Office, UK

IV. Full Meeting Report

Albert Fischer, the meeting host, welcomed everyone and informed the group that this meeting had attracted interest in-house, so that a few IOC secretariat members would participate (see attendance list).

1. Introduction

1.1 GODAE status and objectives

- Pierre-Yves Le Traon (Ifremer, France)

Pierre-Yves Le Traon gave a short summary of the current status of GODAE and highlighted the objectives for this meeting. A good set of recommendations for the design of the global ocean observing system was one anticipated outcome of GODAE, which is drawing to a close at the end of 2008 and this meeting is expected to contribute to this demand. He highlighted the importance of finding sound arguments to sustain the observing system as satellite and in-situ observations are vital major components for the current ocean forecasting systems.
The objectives for this specific meeting are to show the impact of satellite and *in situ* observations on analyses and forecasts in particular assimilation/forecast systems and to define a framework for future activities in OSSE/OSE experiments in GODAE. Further objectives are:

- Review work done on impact studies, OSEs and OSSEs over the past years
- Identify robust and common features
- Understand differences in assimilation systems
- Provide good examples of the contribution of observing systems
- Provide preliminary recommendations on observing system design
- Define and agree on activities to be carried out before the GODAE final symposium
- Develop new ideas on the way to assess and design the ocean observing systems and propose new experiments to be carried out in the coming years

1.2 The global *in situ* and satellite observing system and issues

- presented by Albert Fischer (IOC), Paris

Albert Fischer reminded the participants of the role of the Ocean Observations Panel for Climate (OOPC), one of the co-sponsors of the meeting. The current recommendations for the observing system both satellite and *in situ* had been formulated essentially through expert judgement. The *in situ* system is about 60% complete: some highlights include the achievement of 3000 floats in the Argo profiling float network, and maintenance over two years of a network of about 1250 surface drifters. Fischer introduced the OOPC ‘State of the Ocean’ web site (http://ioc.unesco.org/oopc/) which is a tool for communicating about the ocean climate and our ability to measure it. Remaining challenges include full global coverage for *in situ* elements, as well as continuity of key satellite ocean observations.
He invited the meeting participants to consider their work as a contribution to developing the arguments to respond to this challenge, and expressed the hope that this meeting was just a first step in developing quantitative observing system evaluation tools.

1.3 Status of XBT recommendations made to the Ocean Obs 99 Meeting

(R.L. Molinari (University of Miami), Gustavo Goni, Molly Baringer, Claudia Schmid, Sylvia Garzoli (NOAA)

– presented by Bob Molinari

Prior to the OceanObs’99 conference an *ad hoc* group of scientists met to develop plans for the future of global XBT sampling. Operational recommendations included discontinuation of low-density sampling, once Argo and satellite observations proved capable of resolving important ocean climate signals. This recommendation is being implemented. In addition high density and frequently sampled transects were to be fully implemented. The majority of high-density lines are being occupied; logistical problems have prevented full implementation of the frequently repeated lines. Data management recommendations for both real-time and delayed-mode quality control review of profiles are being implemented at many of the international XBT Data Assembly Centers.

1.4 OSSE/OSE at NOAA

- Eric Bayler (NOAA/ NESDIS /STAR)

NOAA's leadership views Observing System Evaluations (OSEs) and Observing System Simulation Experiments (OSSEs) as powerful and relatively inexpensive ways of assessing the impact of potential new observations, for determining the impact of losing current observing systems, and for refining and redirecting current observing practices. NOAA critically requires ocean OSE/OSSE development and implementation for satellite and *in situ* data integration, as well as optimization of the U.S. Integrated Ocean Observing System (US IOOS), the U.S. contribution to the Global Ocean Observing System (GOOS). NOAA leadership's budgetary guidance is that NOAA should carry out an OSSE as part of the preparation for certain observation system deployments, and as a way of redefining the overall observing strategy to fill critical mission needs. Further, with the advent of new forecast techniques, including high-resolution models, OSSEs would provide an excellent way of fine-tuning the observing system to the forecast needs. With OSE/OSSEs a specific focus for NOAA ocean data assimilation and being an area where NOAA ocean modeling has minimal exposure/development, it is crucial for NOAA to establish participation at the ground floor of national and international efforts.

2. General multi-purpose methods

2.1 Methods for computing analysis and forecast sensitivity to observations: examples from NWP

- Anthony Weaver (CERFACS, France)

Developing cost-effective methods to monitor the impact of observations in assimilation-forecast systems is an active area of research in NWP. Modern data assimilation methods are derived from statistical linear estimation theory. For these methods, the *information matrix* provides the appropriate diagnostic for quantifying the influence of individual observations on analyses.

The information matrix contains the partial derivatives (*sensitivities)* of the components of the analysis vector (in observation space) with respect to the components of the observation vector. It can be written as the product of the adjoint of the gain matrix and the adjoint of the observation operator. A large sensitivity indicates an influential observation.

This could be valuable information about an anomalous event, or could also point to a problem with the data quality or assimilation method (e.g., an incorrect specification of the background- or observation-error covariances).

Computing the information matrix requires the inversion of a large matrix: assimilation methods formulated in model space require the inversion of the analysis-error covariance matrix, whereas those formulated in observation space require the inversion of the innovation covariance matrix.

Practical methods have been developed in NWP to estimate aspects of the information matrix such as the self-sensitivities (the diagonal) or the information content (the trace). Methods to compute forecast-error sensitivity to observations require, in addition to the adjoint of the gain matrix, the adjoint of a linearized version of the forecast model. Forecast error is defined *a priori* via an objective function; e.g., the energy of the difference between the model forecast and a verifying analysis. Different objective functions will lead to different sensitivities. Adjoint forecast sensitivity techniques should be viewed as complementary to traditional OSEs. The adjoint techniques provide a cost-effective tool for assessing the sensitivity of a given measure of forecast error with respect to *all* of the individual observations used in the analysis. OSEs, on the other hand, provide more detailed forecast information for *a posteriori* diagnostics and are more appropriate for assessing forecast sensitivity over periods when the linear assumption underlying adjoint techniques breaks down.

2.2 Review of OSSE/OSE performed at Mercator-Ocean

– Eric Dombrowsky (Mercator-Ocean, France)

Eric Dombrowsky presented two impact studies performed at Mercator in the context of the potential degradation of altimeter coverage or even loss of this observing capacity in the future years. The first one is an OSSE in the North Atlantic at eddy permitting resolution to evaluate the potential impact of surface velocities (from SAR, or optical flow methods from SST and/or ocean colour). There was a slight positive impact of the assimilation of these velocities in addition to altimetry, the impact being mainly limited by the observational errors and coverage. In any case, the assimilation of this observed velocity would not compensate the absence of altimeter data. The second one is a 6-month OSE in 2004-2005 at eddy resolving resolution in the North Atlantic. The experiment demonstrated the importance of multiple altimeter coverage, with clear improvement when increasing the number of satellites up to 3 (Jason-1, Envisat and GFO), and even some positive impact with a 4th altimeter (T/P). Clear evidence of rapid total loss of predictive skill for the mesoscale without altimeter data is shown.

2.3 Observing System experiments with ECMWF operational analysis (ORA-S3)

(M. Balmaseda, D. Anderson, A. Vidard)

– *presented by Magdalena Balmaseda (ECMWF, UK)*

The impact of Argo and altimeter data on the new ECMWF ocean analysis system during the period 2001-2006 has been assessed by conducting a set of observing system experiments (OSE). The experiments evaluate the information content of Argo temperature and salinity data, and its synergy with the altimeter data. The impact of each observing system is gauged by its influence on the ocean state and its impact on skill of the seasonal forecasts.
Results show that the salinity information from Argo has a large effect on the ocean analysis. The assimilation of salinity information also improves the temperature analysis, especially in the Western Equatorial Pacific. The assimilation of altimeter derived sea level anomalies improves the fit to subsurface temperature.
The impact of the different observing systems on the seasonal forecasts of SST is measured by conducting a set of ensemble forecasts (5 ensemble members), initialized 4 months apart for the period 2001-2006. Results show that both Argo and altimeter information improves the forecast skill, and the best skill is obtained when all the observing systems are in place. Argo has larger influence in the Indian Ocean and Western Pacific, while the influence of altimeter is larger in the Eastern Pacific and Tropical Atlantic.
The Equatorial Atlantic is the region where the skill remains quite poor, probably because the errors in the initialization and/or the model preclude the successful use of all the available information.
The observing system experiments are also used to assess the robustness of recent climate signals, such as the post-2003 deceleration of global warming and steric height rise.

2.4 OSSE-OSE activities with Multivariate Ocean Variational Estimation (MOVE) System I: Application of singular vector analysis to the Kuroshio large meander

- Yosuke Fujii, (JMA/MRI, Japan)

Singular vector analysis is applied to the formation of the Kuroshio large meander south of Japan. The analysis reveals that an anticyclonic eddy approaching the Kuroshio southeast of Kyushu (southwestern part of Japan) from east activates the baroclinic instability, and generates an anticyclonic eddy in the deep layer (deeper than 1500m). This eddy interacts with a small meander of the Kuroshio in the upper layer, and promotes its growth into a large meander. This result implies the importance of observing around southeast of Kyushu and the deep layer south of Japan.

2.5 Objective Array Design: Application to the Tropical Indian Ocean

- *Pavel Sakov and Peter Oke (CSIRO, Australia)*

Peter Oke described a simple, versatile, computationally efficient ensemble-based method for objectively designing an observation array. The method seeks to compute the observation array that minimises the analysis error variance, according to Kalman Filter theory. The versatility of the method is demonstrated through a series of applications to the Tropical Indian Ocean (TIO) using both model-based and observation-based ensembles. The most challenging part of these OSSEs is defining the metrics; that is, what we seek to observe or monitor. These types of OSSEs are most appropriate for designing observing systems for process oriented studies.

2.6 Impact of Argo, SST and altimeter data on an eddy-resolving ocean reanalysis

- *Peter R Oke and Andreas Schiller (CSIRO, Australia)*

Peter Oke presented a series of Observing System Experiments (OSEs), where components of the Global Ocean Observing System (GOOS) are systematically withheld from a data assimilating ocean reanalysis. The relative importance of Argo temperature (T) and salinity (S) profiles, sea-surface temperature (SST) and altimetric sea-level anomalies (SLA) were assessed for constraining upper-ocean T and S properties and mesoscale variability of SLA in an eddy resolving ocean reanalysis in the Australian region. Each OSE is assessed by comparing modelled fields with assimilated and withheld observations. Each observation type brings complementary information to the GOOS. While there is some redundancy for representing broad-scale circulation, mesoscale circulation requires all observation types to be assimilated.

2.7 Optimal design of observing systems: review of methods based on assimilative systems

- Pierre Brasseur (CNRS, Grenoble, France)

The expected functionality of an assimilative model is to perform multivariate 4D dynamical interpolation of physical fields in space and time, with appropriate error estimates. As a result, the assimilation systems provide an ideal framework to conduct observing system optimal design and impact studies. Using the SEEK filter in mid-latitude and tropical Atlantic circulation models at eddy-permitting resolution, OSSEs have been conducted to determine the optimal orbit period for the future AltiKa altimetric mission. The results suggest that a repeat cycle of 35-days is a good space-time sampling compromise for a mission; however, some of the diagnosed quantities (e.g. heat transport, EKE variability) may be system-dependent. The Taylor diagram (Taylor, JGR, 2001) is shown to be a very useful technique to compare different satellite scenarios or constellations, and to summarize OSSE results in statistical terms. New assimilation diagnostics initially developed in the NWP context (e.g. degrees of freedom for system, or degrees of freedom for noise) are proposed to quantify the sensitivity to observations more accurately, and to objectively diagnose the impact of different data types in multi-component observing systems.

2.8 Assessment of Observations Impact using a Variational Assimilation Adjoint System

– James Cummings, Naval Research Laboratory

Jim Cummings described an adjoint-based procedure for assessing the impact of any or all observations used in an ocean data assimilation and forecast system. Observation impact is calculated using adjoint sensitivity gradients and actual model-data differences to estimate the impact of each observation on forecast error at different forecast periods. The method is computationally inexpensive and allows impacts to be partitioned for any set of observations: by instrument type, observed variable, geographic region, vertical level, or individual reporting platform. It is not necessary to add or remove observations from the assimilation to estimate their impact on the forecast. The procedure can be routinely applied in an operational analysis/forecast system to perform predictability/data impact studies, as well as a diagnostic tool to monitor the assimilation and quality control of the observations.

2.9 What do we gain by having an additional SeaWinds-like scatterometer?
– Tong Lee *(NASA Jet Propulsion Laboratory, California Institute of Technology)*

Wind stress measurements obtained from the tandem mission (Apr.-Oct. 2003) are used to evaluate the impact of having two QuikSCAT-like scatterometers on ocean model simulation. The tandem mission allows 90% of the world ocean to be measured twice daily (as opposed to daily by one). With only one scatterometer, the wind stress does not resolve diurnal variability. This causes insufficient vertical mixing and thus much warmer and fresher surface waters in mid- to high-latitude oceans (than with twice-daily wind). One scatterometer also causes aliasing of diurnal wind into the time mean, which affects time-mean coastal circulations and SST. The implication to data assimilation is discussed in terms of correct attribution of error sources (i.e., wind vs. buoyancy forcings).

3. Altimetry

3.1 Review of the impact studies done in the frame of the SSALTO/DUACS centre
– Larnicol *et al.* (CLS)

The objective of the presentation was to review the impact studies done in the frame of the SSALTO/DUACS centre.

Satellite altimetry has made a unique contribution to observing and understanding ocean variability. It is also a key observing system for operational oceanography. In this context, the SSALTO/DUACS centre has led numerous impact studies (OSSE and OSE) in order to define the main characteristics of an altimeter missions in the context of existing or future satellite configurations as well as to monitor the state of this observing system. All these studies are based on mapping methodology (optimal interpolation) which is complementary to modelling/assimilation techniques. The main message and results are the following ones:

First, the robustness of the results depends on how the error covariances of the observations (white noise, correlated error, etc…) are taken into account. Secondly, a good consistency has been obtained between the OSSE and OSE studies done in the past to document the choice the different satellite configuration (for instance for T/P tandem mission, Le Traon and Dibarboure (2004, 2002). Consequently, it seems important to continue to assess and to forecast the accuracy and the complementarity between future altimeters (AltiKa, Cryosat2, sentinel 3, Jason 3, etc.).

Despite strong improvement from one to two satellite altimeters are observed two satellites are necessary to observe the main mesoscale structure (Ducet etal, 2000, Le Traon and Dibarboure, 1999). However, three or four satellites are clearly needed to obtain an accurate description of the mesoscale signal (Pascual *et al.*, 2005, 2006). Moreover, in the context of operational applications, the accuracy and availability of the altimeter data is degraded (problem of orbit error, geophysical correction, data delivery). In this case, it was shown that four satellites in real time give same results than two satellites configuration in delayed time (Pascual et al. 2007). For climate change studies as monitoring of the mean sea level trend, it is necessary to ensure overlapping of the accurate mission (Jason).

3.2 The impact of assimilating sea surface height data from one, two and three altimeters on the surface currents in the 1/9˚ North Atlantic FOAM system
– Matt Martin (Met Office)

A number of integrations of the 1/9˚ resolution North Atlantic FOAM system were run for a four month period from 1st December 2005 to 31st March 2006, the last three months of which were used for assessment. The runs include one in which no altimeter data was assimilated, a run in which only Jason altimeter data were assimilated, a run in which both Jason and Envisat data were assimilated, and one in which data from all three satellites were assimilated. All of these runs included assimilation of the other temperature and salinity data sources. The output of these integrations was assessed by comparing the SSH of the model to the data, and also by comparing the surface currents to independent data from surface drifters. A single satellite altimeter significantly improved the results compared with no altimeter data, and errors were further reduced when data from both the second and third altimeters were assimilated.

3.3 Observations bias correction in altimeter ocean data assimilation in FOAM comparing two MDT's

\- *Daniel Lea and John Siddorn (Met Office)*

Dan Lea presented results which compare the original FOAM MDT (mean dynamic topography) to a new MDT developed by R. Bingham which is derived from GRACE gravity observations and drifter data. Diagnostics including observation minus background statistics showed that the Bingham MDT produces superior results compared to the original FOAM MDT. Experiments were also run with an online observation bias correction scheme which aimed to correct the errors in the MDTs. The results from both MDTs converged to an optimal MDT which produced more accurate results than either of the non-bias corrected experiments.

4. Argo (T and/or S) and *in situ* observing system

4.1 Contributions and complementarities of Argo and Altimeter data

- *Stephanie Guinehut (CLS)*

Results from an observing system simulation experiment of an idealized 3°x3° Argo array, using a mapping method, has first shown that due to high noise-to-signal ratio, it is only possible to resolve the temperature and salinity fields at wavelengths larger than 12° and a period of 2 months with a good accuracy. An additional study (still using an OSSE and a mapping method) has shown that it is possible to combine accurate but sparse *in situ* data with high-resolution satellite altimeter and SST measurements to estimate 3-D temperature fields at high temporal and spatial resolution and thus improve the representation of the large-scale and low-frequency fields. The combination of the two data sets (*in-situ* and remote-sensing) is instrumental in reducing the aliasing due to the mesoscale variability and in adjusting the analyzed fields to the sparse *in situ* measurements.
Finally, in applying the combination method to the actual observing system, it can be shown, that more than 40% of the temperature signal can be reconstructed at depth from remote-sensing data and a simple statistical method. The complementary use of *in-situ* measurements further improves the estimation by 10 – 20%. The main impact of SST measurements is observed in the first 200 m of depth. By contrast, impact of altimeter measurements is very similar at all depths in the mid-high latitude regions and it is reduced in tropical regions as depth increases. Results obtained for the salinity fields show the essential role played by the *in situ* measurements since the correlation between the altimeter surface measurements with salinity at depth are much lower than the ones between altimeter and subsurface temperature.

4.2 Argo and other profile data assimilation on z and density levels in FOAM

- *Daniel Lea and John Siddorn (Met Office)*

A 5-year assimilation experiment in FOAM with Argo data was shown to be substantially more realistic, compared to Levitus and observation values, than an experiment excluding it. Density level assimilation was also explored. This system is in an early stage of development so the results are still slightly worse than z-level assimilation. The system does have the potential to make better use of sparse data and OSSE/OSEs are planned to investigate this.

4.3 OSSE/OSE activities with Multivariate Ocean Variational Estimation (MOVE) System. II: Impacts of salinity and TAO/TRITON

- *Satoshi Matsumoto (MRI/JMA)*

The Multivariate Ocean Variational Estimation (MOVE) System is the ocean data assimilation system developed at MRI. Correcting model salinity fields using observation data improves near-surface temperature fields in the equatorial Pacific and the current fields in the North Pacific subarctic gyre in MOVE System. Assimilating TS profiles observed by Argo floats has relatively large impact in the Indian Ocean. Assimilating subsurface T and S observed by TAO/TRITON is also essential for reproducing accurate variability of the thermocline in the equatorial Pacific. The impact of TAO/TRITON on the NINO3.4 forecast is not deterministic, that is, a different ensemble member has a qualitatively different time evolution of difference between the cases with and without TAO/TRITON, and the spread of ensemble members becomes larger in the case with TAO/TRITON.

4.4 Design of surface drifting buoys deployments using eddy-resolving reanalyses

(Presented by Peter Oke (CSIRO)) - Gary Brassington and Nicholas Summons (BMRC)

Ensemble Lagrangian drifter trajectories are derived from an eddy-resolving ocean reanalysis to optimise the deployment strategy of surface drifting buoys for the East Australian Current (EAC). The deployment was constrained to be performed from two Volunteer Observing Ships that occupy the PX30 line and traverses the EAC reducing the design to selecting the longitude. Critical design criteria include: (a) low probability of convergence into the coast, (b) high probability of observing the EAC and (c) high probability of a long deployment period. The BLUElink ocean reanalysis provided three dimensional daily average velocities at 1/10 degree resolution. The Lagrangian model was developed and calibrated against historical observations during the reanalysis period. The analysis guided the deployment location of 8 drifting buoys between Feb-March 2007 with a 100% success rate of initial deployment. Experiment design, results and future plans are reviewed.

One pair from the experiment was deployed on an anticyclonic eddy which was forming and interacting with the core EAC. The pair of drifters remained on the eddy for a total of 8 orbits of the eddy showing long-lived stable surface flow. During this period the newly formed eddy came under the influence of an offshore deep anticyclonic eddy and separated from the EAC and merged. The merger occurred with minimal shear and Argo profiles suggest the eddy superimposed onto the offshore eddy over the top 150m. We conclude that this was a stratified merger of a deep old anticyclonic eddy and a more buoyant newly formed eddy with examples to be found in recent Quasi-geostrophic simulations. Deep, large anticyclones have been observed to persist in the Tasman Sea for 1-2 years while new buoyant anticyclones are generated from the EAC each summer season. This type of vortex merger may occur frequently and have a significant influence on the circulation in the region. We show how this merger was represented in OceanMAPS, the Bureau's operational ocean prediction system and discuss the implications and observing system requirements.

5. Recommendations

5.1 Rapporteurs

In order to capture the main issues of the meeting the assigned rapporteurs (see list below) provided short summaries of the meeting session outcomes. Most issues raised are covered by the individual session (see the website for information on the programme), but may also cut across all presentations/issues.

Item/session	Rapporteurs
Methodologies and issues	Jim Cummings, Pierre Brasseur

Altimetry and satellite observing system	Eric Dombrowsky, Peter Oke
Argo and *in situ* observing system	Magdalena Balmaseda, Bob Molinari, Albert Fischer
Requirements for high resolution ocean forecasting vs. ocean state estimation	Tony Lee, Matthew Martin

5.2 Summary

5.2.1 Summary of presentations and key results

The presentations made by the different GODAE groups showed a number of OSE/OSSE results obtained using mostly data denial approaches to test, assess and intercompare different types of variables individually or in combination with others: altimetry, SST, SSS, temperature and salinity vertical profiles (from ARGO), surface velocities (SAR, optical flow), and satellite winds. Most often impacts of the observing systems are diagnosed in terms of ocean analyses, but other metrics are also considered, such as seasonal forecast skill, climate variability, trends of Meridional Overturning Circulation (MOC), or sea-level changes.

The data denial experiments consistently show that best results are obtained when all data types are assimilated. This outcome indicates a good degree of complementary among existing elements of the observing systems. A general finding is that any degradation in the observing systems yields a degraded result in the performance of the assimilation system. However, it was recognized that conclusions obtained by the GODAE groups using present methodologies are model and data assimilation method dependent, and that the relative value of one data type compared to another depends on the question asked.

An ensemble-based method for objectively designing moored observational arrays was discussed. A series of examples of application to the Tropical Indian Ocean indicate the versatility of the method, but information on practical limitations of array deployment must be considered in order to obtain robust results. A process study at regional scales was presented on the meandering of the Kuroshio south of Honshu. The method generates sensitivity maps that are useful in providing guidance for the deployment of targeted observing systems, with possibly adaptive sampling strategies for predicting the onset of the Kuroshio meander.

Several presentations were focused on new methods that have been implemented by the NWP community to more objectively diagnose the value of information assimilated into operational systems. The first of these, the influence matrix, represents the influence of the Kalman gain in the observation space and can be used to diagnose the analysis sensitivity with respect to the data. A similar method, the Degrees of Freedom for Signal (DFS) corresponding to the trace of the influence matrix, characterizes how the assimilation system uses the observations to pull the signal from the background. Finally, an adjoint-based procedure was presented and shown to be directly applicable in assessing observation impact on ocean predictions at different forecast ranges.

One of the many advantages of the new methods is that data impacts can be partitioned by instrument type, observed variable, vertical level, or geographic region. There is no need to selectively add or remove data from the system. Consequently, the new methods are computationally much less expensive than more traditional data denial approaches and can easily be implemented as part of an operational ocean data assimilation suite. In this regard, data impact studies will be routine, providing almost instantaneous results when new instruments or observing systems are deployed. Further, diagnostics of “non beneficial” impact in all of the methods should be considered as an indication that something is wrong in the assimilation system (prior error statistics, quality control, model bias), or perhaps that something has occurred in the observing system (sensor drift, calibration issues) if many groups assimilating the same data obtain a similar “non-beneficial” result.

The systematic implementation of these new diagnostic methods into operational ocean forecasting systems will be very valuable to evaluate the relative merit of the different elements of the existing GOOS, or to optimally design new components of the future system. However, the validity of the linearity assumptions behind these methods should be investigated carefully in the oceanographic context. In addition, definition of the cost function used in the adjoint method is critical. It must represent the impact of all observing systems assimilated otherwise multiple cost functions, at additional computational expense, will have to be employed.

Several presentations addressing different systems and focussing on different regions highlighted the requirement of using altimetry to represent the meso-scale and intermediate-scale ocean circulation. It was stated that at least two altimeters are necessary, but that 3 - 4 are recommended to adequately capture the meso-scale circulation. An additional altimeter in orbit would also ensure continuity of climate data record as well as meso-scale ocean forecasting. Studies to evaluate the impact of several altimeters have been presented and preliminary experiments indicate that a fourth altimeter improves results.

Meso-scale features need satellite and *in situ* information. There is a consensus about the overall complementary nature of different observing systems; both for high-resolution ocean forecasts and climate ODA (e.g., altimeters, Argo, SST, tropical moored arrays, etc.) so the sustainability of the observing system is crucial and any discontinuation of an observing system should be carefully assessed. Assimilation of high-resolution sea surface temperature (SST) was identified as a necessity for short-range ocean forecasting. SST data have large contribution in the surface layer and are especially important in coastal regions where altimeter and Argo coverage are poor. Surface drifting buoys are of high value for system evaluations.

An enhanced investment in more OSE/OSSE studies is required to better analyse the impact of the global observing system and to improve its design. The relative impact of observations on ocean forecasts needs to be further quantified. Particular focus needs to be given to Argo, SST and altimetry, in particular the requirement for several altimeters. Use of altimeter data closer to the coast and in shallow seas needs to be addressed and complementarities with coastal tide gauge data to be investigated. Also the cause for negative impact to skill needs to be understood to further improve the model and assimilation systems.

International collaboration is essential when conducting OSSEs/OSEs, and regular meetings and workshops will need to be organised as part of post-GODAE activities.

GODAE groups should continue to work with groups working on climate reanalyses (*Appendix C-1*), which face many of the same issues. These include the integration of the changing observing system with time, highlighting the importance of XBTs as a 50+ year continuous record *(Appendix C-2),* and highlighting the issues around developing a continuous high quality (reprocessed) data base of historical observations. Further points are to define the observing requirements for decadal forecasting, start the development of coupled data assimilation systems, linking with atmospheric systems, and addressing emerging requirements for surface fluxes, and identifying ocean regions where vertical projections of ocean surface satellite data are ineffective, and therefore where in situ sensors should be increased in density.

5.2.2 New requirements

The impact of salinity data collected from ARGO floats was shown to be very significant in experiments conducted by several groups (e.g. reanalyzes), provided that the data are properly assimilated by the corresponding system. The need for further salinity data was raised during the discussion, and the general opinion was that this information was mostly useful when both temperature and salinity data are measured simultaneously at the same location. An exception to this is the measurement of sea surface salinity from space, which is expected to complement the measurement of sea surface temperature from space and provide improved constraints on ocean models at the surface.

Concerning altimeter data, the need for improved timeliness of the data was identified as crucial for the real-time GODAE systems, and this question should not be disconnected from the design issues of multi-satellite constellations. Delivery of poorer quality data with less latency vs. better quality data with more latency and their impact on the initialization of real-time ocean forecasting systems has to be investigated.

It is recognized that requirements for non-traditional data such as deep measurements (below 2000 m, with appropriate accuracy) or biogeochemical measurements (chlorophyll, oxygen) were not discussed in detail during the workshop and should deserve more attention in the future. In addition, no results were reported about the impact of sea-ice observations and ocean color data.

5.2.3 Short term and long term issues

The experiments achieved so far within the GODAE community have not been conducted in proper coordination between the participants. However, the need to intercompare results more rigorously and to assess the impact of observations in the different GODAE systems more consistently was identified as a possible line of collaborative work for the future.

An OSE intercomparison exercise between the MERCATOR, HYCOM, FOAM, BLUElink and possibly other systems using data denial methods was mentioned as a good opportunity to be achieved during a targeted period in spring 2008 when an additional GODAE model intercomparison study will be conducted. A working plan will be developed to define the details of the experimental setup, data denial protocol, and metrics to be used for the OSE intercomparison. A working group is being established (P. Oke, J. Cummings, M. Martin, E. Dombrowsky, to be completed) to prepare the plan (*Appendix C-3*) and ensure that the results will be finalized before the GODAE symposium in November 2008.

Although the methods presented in the workshop are still at an early stage of development, the variety of results discussed demonstrate a wealth of expertise gained by the GODAE community during recent years concerning both conceptual and practical aspects of observing system experiments. Based on their established assimilation capacity, the GODAE groups in place today will be in a position to provide objective guidance for the deployment of new components of the global ocean observing systems. Therefore, in the longer term, the GODAE participants should get organized at the international level to provide consistent and educated responses to agencies and organizations in charge of a sustained global ocean observing system useful for ocean monitoring and forecasting at short-term to seasonal (and perhaps even longer) time scales. This activity will require harmonized protocols for observation impact assessment, tools for routine production of appropriate diagnostics using NWP-derived methods, common sets of metrics for intercomparison of results, and objective methodologies to elaborate recommendations to be delivered to agencies and organizations. A working group (J. Cummings, P. Brasseur, M. Balmaseda, and A. Weaver) will be in charge of writing a white paper on these issues for presentation at the final GODAE symposium, in liaison with the working group on OSE intercomparisons (P. Oke).

In the longer term consideration is given to an evaluation strategy for identifying observing system requirements for different, possibly specific user-driven applications (*Appendix C-4).*

Appendix

A. Programme

Monday, 5 November 2007

13:45 *Speakers to transfer their talks onto conference room laptop*

14:00 Welcome - Pierre-Yves Le Traon (Ifremer)

14:05 **Session 1 - Introduction**

14:05 Pierre Yves Le Traon (Ifremer), Ed Harrison (NOAA) and Albert Fischer (IOC) - GODAE Status and workshop objectives

14:25 Albert Fischer, Ed Harrsion and Pierre-Yves Le Tran - The global *in situ* observing system, the satellite observing system and issues

14:50 Robert Molinari (University of Miami/CIMAS) - Status of the 1999 XBT Recommendations Made to the Ocean Obs99 Meeting

15:10 Eric Bayler (NOAA) - NOAA perspective/expectations

15:30 *Coffee/tea break & opportunity for personal discussion*

16:00 **Session 2 - General multi-purpose and methods**

16:00 Anthony Weaver (CERFACS) - Methods for computing analysis and forecasting sensitivity to observations: examples from NWP

16:30 Eric Dombrowsky (Mercator-Ocean) - Review of OSSE/OSE performed at Mercator-Ocean

17:00 Magdalena Balmaseda (ECMWF) - OSE's in the ECMWF operational ocean analysis: Impact on the ocean mean state, seasonal forecasts and climate variability

17:30 Yosuke Fujii (JMA/MRI) - OSSE/OSE activities with Multivariate Ocean Variational Estimation (MOVE) System.
I: Application of singular vector analysis to the Kuroshio large meander

18:00 **End of Day 1**

18:30 *Reception, Miollis Bar (-1 level)*

Tuesday, 6 November 2007

8:30	**Session 2 - General multi-purpose and methods (continued)**
8:30	Pavel Sakov and Peter Oke (CSIRO) - Objective Array Design: Application to the tropical Indian Ocean
9:00	Peter Oke and Andreas Schiller - Impact of Argo, SST and altimeter data on an eddy-resolving ocean reanalysis
9:30	Pierre Brasseur (CNRS) - Optimal design of observing systems: review of methods based on assimilative systems
10:00	Jim Cummings (NRL) - Assessment of Observation Impact Using a Variational Assimilation Adjoint System
10:30	*Coffee/tea break & opportunity for personal discussion*
11:00	Tony Lee (JPL) - What do we gain having an additional SeaWinds-like scatterometer?

11:30	**Session 3 - Altimetry**
11:30	Gilles Larnicol (CLS) - Impact studies on the altimeter observing system: review of the work done by the SSALTO/DUACS center
12:00	Matt Martin (Met Office) - The impact of assimilating sea surface height data from one, two and three altimeters on the surface currents in the 1/9° North Atlantic FOAM system
12:30	*Lunch - Speakers to transfer their talks onto conference room laptop*
13:30	Daniel Lea and John Siddorn (Met Office) - Observations bias correction in altimeter ocean data assimilation in FOAM comparing two MDT's
14:00	Discussion

14:30	**Session 4 - Argo (T and/or S) and *in situ* observing system**
14:30	Stephanie Guinehut (CLS) - Contributions of the ARGO array and complementarities with the altimeter observing system
15:00	Daniel Lea and John Siddorn (Met Office) - ARGO and other profile data assimilation on z and density levels in FOAM
15:30	*Coffee/tea break & opportunity for personal discussion*
16:00	Satoshi Matsumoto (MRI/JMA) - OSSE/OSE activities with Multivariate Ocean Variational Estimation (MOVE) System. II: Impacts of salinity and TAO/TRITON
16:30	Gary Brassington and Nicholas Summons (BMRC) - Design of surface drifting buoys deployments using eddy-resolving reanalyses (presented by Peter Oke

(CSIRO))

17:00	**Meeting with rapporteurs to prepare for the Synthesis of results, recommendations and work plan for 2008**
18:00	**End of Day 2**
19:30	*Dinner*

Wednesday, 7 November

9:00	**Session 6 - Synthesis of results, missing studies, recommendations and work plan for 2008**
9:00	Open discussion - summary by session (presentations by rapporteurs); outline of future work and other issues
10:30	*Coffee/tea break & opportunity for personal discussion*
11:00	Open discussion (continued)
12:30	**Close**

B. Details of recommendations and issues

B.1 Issue regards climate reanalysis:

⇒ OSEs can help to assess robustness of climate signals (sensitivity to changes in observing system)

- Climate reanalysis and changes in the observing system
  - Anchoring XBT's
  - Efficient Bias algorithms
  - Retrospective use of Argo data?
- Define observing system needed for decadal forecasting
  - Methods to answer this question (OSSEs, statistical.….) see also *Appendix C-4*
- Coupled DA? The ocean community should provide requirements on the atmospheric surface fluxes?
  - Errors, frequency, spatial scales
  - How much information is needed for retrospective reanalysis (100yr reconstructions)
  - Atmospheric indices? How good can it be?
- Role of XBTs should be re-addressed *(see also Appendix C-2)*
- Regions where vertical projection of satellite data is ineffective need to be identified and more heavily instrumented with in situ sensors

B.2 Requirements for XBTs / moorings

- ⇒ Potential time dependence of the XBT fall rate equation needs to be addressed
- ⇒ XBTs should be given unique identifiers
- ⇒ All XBTs should be placed on the GTS within 24 hours
- ⇒ TAO/PIRATA
  - Additional salinity sensors are needed on moorings

B.3 OSE Working Group – proposed collaborative work:

It has been decided to set up a working group, led by Peter Oke that will define and coordinate work within GODAE on OSEs leading to the final GODAE Symposium in November 2008, presenting a white paper. The work of this group will include

- ⇒ Develop working plan to define details of experimental setup, data denial protocol and metrics
- ⇒ Before the final GODAE Symposium, each group should consider:
  - comparing operational skill and delayed-mode (reanalysis) skill
  - performing OSEs to assess the impact of number of altimeters
  - performing OSEs (data denial) to assess forecast skill for the period that corresponds to the NH Spring 2008 inter-comparisons
  - for OSEs comparing to surface drifting buoy-derived velocities statistically using Taylor diagrams
- ⇒ (Systematically evaluate impact of observing systems on ocean forecast) Need to develop a common simple metrics first
- ⇒ Investigate the cause for degradation and determine potential strategy for improvement
- ⇒ Assess the merit of applying OSEs/OSSEs to specific user-driven applications (e.g., search and rescue, oil spill)

B.4 Evaluation strategy for identifying observing system requirements.

Different applications may include:

- ⇒ Mixed layer variability /military operations
- ⇒ Eddy development and evolution / search and rescue / paid environmental response
- ⇒ Ocean climate / seasonal forecasting

C. Attendance list

(Alphabetical order)

Name	Affiliation
Magdalena Balmaseda	ECMWF, UK
Eric Bayler	NESDIS/NOAA, USA
Mike Bell	Met Office, UK
Pierre Brasseur	CNRS, France
Jim Cummings	NRL, USA
Eric Dombrowsky	Mercator-Ocean, France
Albert Fischer	IOC, France
Yosike Fujii	MRI-JMA, Japan
Stephanie Guinehut	CLS, France
Gilles Larnicol	CLS, France
Daniel Lea	Met Office, UK
Tony Lee	JPL, NASA, USA
Matt Martin	Met Office, UK
Satoshi Masumoto	MRI-JMA, Japan
Bob Molinari	NOAA, USA
Peter Oke	CSIRO, Australia
Pierre-Yves Le Traon	Ifremer, France
Anthony Weaver	CERFACS, France
Kirsten Wilmer-Becker	Met Office, UK
Guests from IOC:	
Keith Alverson	IOC, France
Candyce Clark	IOC, France
Tom Gross	IOC, France

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