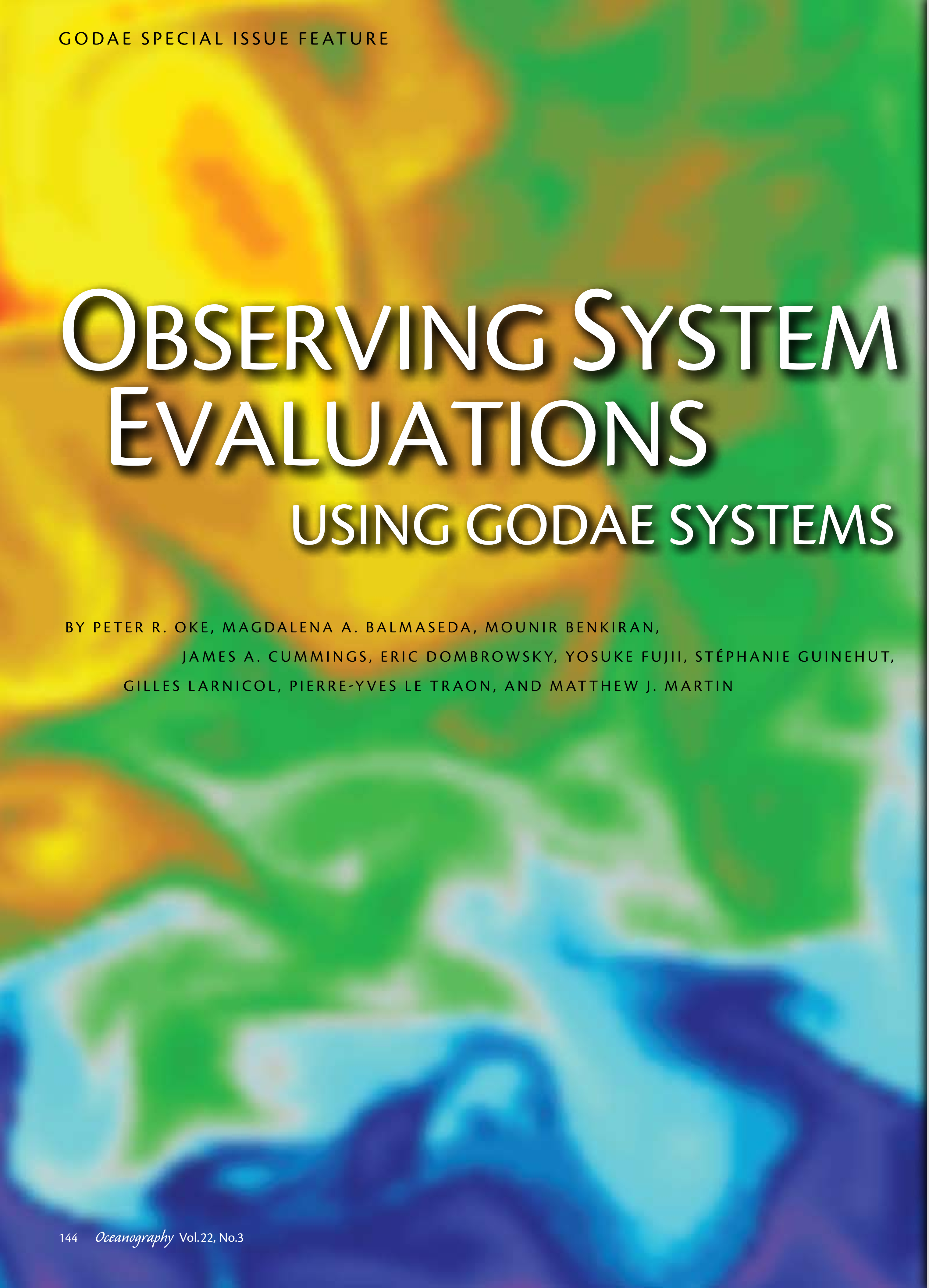
GODAE SPECIAL ISSUE FEATURE



OBSERVING SYSTEM EVALUATIONS USING GODAE SYSTEMS

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ABSTRACT. Global ocean forecast systems, developed under the Global Ocean Data Assimilation Experiment (GODAE), are a powerful means of assessing the impact of different components of the Global Ocean Observing System (GOOS). Using a range of analysis tools and approaches, GODAE systems are useful for quantifying the impact of different observation types on the quality of analyses and forecasts. This assessment includes both existing and future observation platforms. Many important conclusions can be drawn from these studies. It is clear that altimeter data are extremely important for constraining mesoscale variability in ocean forecast systems. The number of altimeters is also important. For example, near-real-time applications need data from four altimeters to achieve skill that is similar to systems using data from two altimeters in delayed mode. Another important result is that sea surface temperature is the only observation parameter that adequately monitors ocean properties in coastal regions and shallow seas. Assimilation of Argo data provides a significant, measurable improvement to GODAE systems, and is the only observation platform that provides global-scale information for constraining salinity. The complementary nature of different components of GOOS is now clear and the emergence of new assimilation techniques for observing system evaluation provides the GODAE community with a practical path toward routine GOOS monitoring.

INTRODUCTION

The development and application of data assimilation techniques for Earth systems have led to the growing use of models and assimilation tools for the assessment and design of atmospheric and oceanic observing systems. The development of operational ocean forecast systems is a key initiative of the Global Ocean Data Assimilation Experiment (GODAE). All GODAE systems are underpinned by the Global Ocean Observing System (GOOS; www.ioc-goos.org), which is comprised of satellite altimetry; satellite sea surface temperature (SST) programs, delivered through the GODAE High-Resolution SST effort (GHRSST; www.ghrsst-pp.org); and in situ measurements from the Argo Program, tropical moored buoy arrays, surface drifting buoys, expendable bathythermographs (XBTs), and tide-gauge networks. Each of these observation programs is expensive and requires a significant international effort to implement and maintain, including data processing and dissemination. Although many GOOS components are primarily intended for climate applications, their application to operational ocean forecast systems is important. In this paper, we present results from analyses that seek to assess the benefits of different observation types and arrays to realistic ocean forecast and reanalysis systems, such as Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs).

The OSEs described here generally involve the systematic denial, or withholding, of different observation types from a data assimilating model in order to assess the degradation in quality of a forecast or analysis when that observation type is not used. Importantly, the impact of each observation type may strongly depend on the details of the model into which they are assimilated, the method of assimilation, and the errors assumed at the assimilation step. We therefore present results from a range of different models and applications in an attempt to identify the conclusions that are common to a number of different systems.

OSSEs typically involve some sort of twin experiment where "synthetic observations," usually extracted from a model, are assimilated into an alternative model or into the same model but with different input parameters. Similarly, ensemble-based techniques and adjoint-based methods do not necessarily use real observations, but instead interrogate model physics and model sensitivities to identify regions in which small perturbations are quickly amplified. It is assumed that additional observations in regions of high sensitivity are likely to better constrain a data-assimilating model. These types of analyses, though idealized, may be used to assess the impact of some hypothetical array of observations that may not exist yet. Thus, these methods can be used to contribute to the design of future observing systems, quantifying their possible impacts and limitations.

The inaugural Ocean Observing Panel for Climate (OOPC)-GODAE meeting on OSSEs and OSEs was held at UNESCO/IOC in Paris, France, in November 2007 (www.godae.org/OSSE-OSE.html). It was the first international meeting dedicated to the subject of observing system evaluation using GODAE systems. Many of the ideas and results presented in this paper are based on presentations from the OOPC-GODAE OSSE/OSE meeting.

OBSERVING SYSTEM EXPERIMENTS

Determining GOOS requirements for operational oceanography is the primary goal of the studies described in this section. Collectively, we seek to assess the importance of different observation types for meeting the needs of a variety of operational oceanographic applications. These include the following range of applications:

- Ssalto/Duacs, a system that processes data from all altimeter missions to provide a consistent and homogeneous catalogue of products for both near-real-time applications and offline studies
- Short-range prediction (e.g., BLUElink>, Mercator, US Naval Research Lab, UK Met Office)
- Seasonal prediction (e.g., European Centre for Medium-Range Weather Forecasting [ECMWF])

How Many Altimeters are Needed?

Satellite altimetry is one of the core observation types that underpin GOOS. During the altimeter period (1992 to present), the number of altimeters has varied from one to four. Several groups have performed OSEs to assess the impact of the number of satellite altimeters on the accuracy of an analysis or forecast system, including the Ssalto/Duacs analysis system, Mercator, and the UK Met Office forecast system.

Using the Ssalto/Duacs system, Ducet et al. (2000) and Pascual et al. (2006, 2007) demonstrated the benefits of merging data from four altimeter missions to produce high-resolution global and regional maps of sea level anomalies (SLA). Figure 1a shows the root-mean-square (RMS) SLA variability when data from four altimeters are mapped, and Figure 1b shows the RMS difference between maps produced using data from a classical configuration of two altimeters (Jason-1+ERS2/Envisat) and the scenario merging data from four altimeters. These RMS differences can reach 10 cm. This figure represents a significant percentage of the signal variance and corresponds to a loss of up to 400 cm^2 s^{-2} for eddy kinetic energy (EKE). This loss is consistent with previous studies (Ducet et al., 2000; Le Traon and Dibarboure, 2002; Brachet et al., 2004) that have found that at mid and high latitudes, EKE can be significantly underestimated when data from only two altimeters are mapped because of the poor representation of high-frequency and high-wavenumber signals.

A similar story has ensued from studies using GODAE-type forecast systems such as the Mercator forecast system (Brasseur et al., 2005) and the UK Met Office forecast system (Martin et al., 2007). Both of these studies focused on the North Atlantic Ocean using high-resolution (5–12 km) operational systems. Both systems assimilated along-track altimeter data, SST, and in situ profiles in studies conducted over several months. Altimeter data are systematically withheld from both the Mercator Océan and UK Met Office systems for OSEs designed to assess the systems' performance when data from zero to four (three, for the UK system) altimeters are assimilated. Using data from Jason-1 as a measure of the true ocean, the Mercator OSEs indicate that the skill of that system using zero, one, and two altimeters degrades by 50%, 15%, and 5%, respectively, relative to the OSE that assimilates data from three altimeters. These OSEs also demonstrate a moderate improvement when data from four altimeters are assimilated. The OSEs using the UK Met Office system are evaluated against data from independent drifting buoys, and produce correlation coefficients between the forecast and drifter-derived near-surface velocity of about 0.16, 0.26, and 0.30 when data from zero, one, and three altimeters, respectively, are assimilated. These results indicate

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that for both the Mercator Océan and UK Met Office systems, the addition of the first altimeter has the greatest impact on forecast skill—and there are diminishing returns from each additional altimeter. However, we note that the benefits of additional altimeters are likely to be at short spacial and temporal scales that are better resolved with denser observational arrays. These small mesoscale features are important for many of the applications that GODAE seeks to address (e.g., search and rescue, oil spill mitigation).

The difference in the quality and coverage of near-real-time (NRT) and delayed-time (DT) altimeter data can be significant and is as important as the number of altimeters. These differences impact the accuracy of analysis products that use altimeter data because of the different orbit errors, data latency, and the use of asymmetrical observation windows that necessarily favor "old" data for NRT systems. The impact of these differences on analysis and forecast systems has been quantified by Pascual et al. (2008) for the Ssalto/Duacs analysis system and through a series of OSEs using the Mercator forecast system.

An evaluation of the accuracy of SLA maps using the Ssalto/Duacs analysis system against independent in situ data demonstrates the degradation of NRT maps compared to DT maps (Table 1; Pascual et al., 2008). That is, four altimeters in NRT are needed to obtain the same performance as two altimeters in DT. The statistics in Table 1 show comparisons between near-surface velocities derived from drifting buoys and SLA maps. Some of the discrepancies between SLA tide gauge data and SLA maps are probably due to the

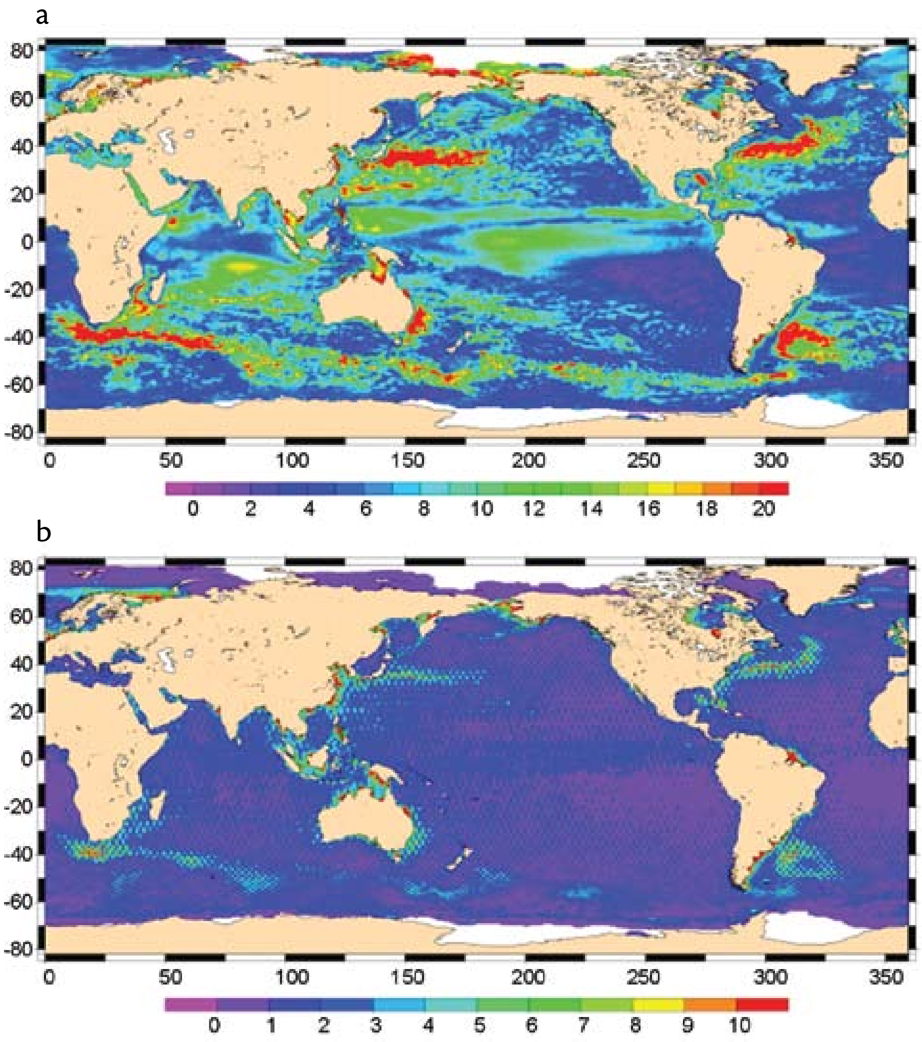

Figure 1. (a) Root mean square (RMS) of sea level anomaly (SLA) estimated with data from four altimeters (Jason-1 + TOPEX/Poseidon interleaved + ERS-2/Envisat + Geosat Follow-on). (b) RMS difference between mapped SLA using data from four and two altimeters (Jason-1 + ERS-2/Envisat). *Adapted from Pascual et al. (2006)*

Table 1. RMS difference between drifter- and altimeter-derived velocities (U and V; in areas with RMS variability > 20 cm s^{-1} and at latitudes greater than 10° from the equator) and tide-gauge and mapped altimetry-based sea level anomaly (SLA) using the new delayed-time (and the old delayed-time in parentheses) and the near-real-time system for the period October 2002–August 2003 (Pascual et al., 2008).

Variable	Delayed-Time		Near-Real-Time	
	2 missions	4 missions	2 missions	4 missions
U (cm s^{-1})	11.23	10.72	12.06	11.30
V (cm s^{-1})	10.70	9.97	11.63	10.69
Aviso SLA (cm)	4.26 (4.72)	3.94 (4.27)	4.82	4.42

mapping procedure in addition to the errors in the altimeter data and to the number of altimeters used.

The OSEs using the Mercator system, described here, are conducted in a real-time context. That is, they produce nowcasts under realistic conditions, excluding missing data due to latency of data availability. They produce seven-day forecasts that are initialized with each nowcast (using NRT data and surface fluxes) and also hindcasts (using DT data and surface fluxes). Table 2 summarizes their results, showing that if only SST and in situ temperature/salinity (T/S) are assimilated (i.e., no altimetry), the sea-level error (i.e., difference from Jason-1) is large (up to ~ 13 cm RMS). Table 2 also shows that with one altimeter, the situation improves for the hindcast (~ 8.5 cm), but the sea-level error is still large for the forecast (~ 10 cm RMS). Note also that to obtain error levels equivalent to the hindcast with only one altimeter, data from all four altimeters are needed for the initialization of each seven-day forecast under realistic conditions, and data from at least two altimeters are required for the nowcast.

What Is the Impact of Different Data Types?

Using the BLUElink> forecast system, Oke and Schiller (2007) performed a series of OSEs to compare the relative impact of Argo, SST, and SLA observations on an eddy-resolving ocean reanalysis. In their OSEs, Oke and Schiller systematically withheld altimeter, Argo, and SST observations. A qualitative assessment of the OSEs is presented in Figure 2. Their experiments highlighted the complementary nature of the different observation types. For example, satellite SST observations are the only observation type considered that have the potential to constrain circulation in shallow seas and over wide continental shelves. Altimetry is the only observation type that even comes close to constraining mesoscale ocean circulation, and Argo observations are the only observation type that constrains subsurface temperature and salinity. These results indicate that while there is some redundancy for representing broad-scale circulation, all observation types are required for constraining mesoscale circulation models.

Several OSE studies have been conducted using different versions of the ECMWF seasonal forecast system (e.g., Vidard et al., 2007; Balmaseda et al., 2007). Most notably, these studies show that the assimilation of Argo data results in improvements to seasonal SST forecasts and salinity analyses for most tropical areas. Additionally, Balmaseda and Anderson (2009) demonstrate, using a series of OSEs, that Argo, altimeter, and mooring observations all contribute to the skill of seasonal SST forecasts (Figure 3). Specifically, Figure 3 shows the percentage reduction in the mean absolute error of one- to seven-month SST forecasts, averaged over the period 2001–2006. Figure 3 demonstrates that assimilation of Argo observations is particularly beneficial to SST forecasts in the eastern tropical Pacific (NINO4), altimeter data are particularly beneficial to the central Pacific and the north subtropical Atlantic (NINO3 and NSTRATL), and mooring data have a significant positive impact on forecast skill across the entire tropical Pacific (NINO3 and NINO4). The positive impacts of Argo and mooring data on the forecast skill of SST in seasonal forecasts are also confirmed in the Japan Meteorological Agency's system (Fujii et al., 2008b).

All GODAE systems assimilate Argo data, which is the only means of constraining these systems' global temperature and salinity fields. Several studies have been conducted to assess the impact of Argo data in GODAE and related systems (e.g., Guinehut et al., 2004; Oke and Schiller, 2007; Balmaseda and Anderson, 2009). All of these studies conclude that, without Argo data, GODAE systems are not sufficiently constrained.

Table 2. RMS of the difference between Jason-1 observations and seven-day forecasts, nowcasts (real-time analysis), and hindcasts (best analysis) for several OSEs using the Mercator system, where altimeter data from 0, 1, 2, 3, and 4 satellites are assimilated in addition to in situ temperature/salinity (T/S) profiles and SST. GFO = Geosat Follow-on. T/P = TOPEX/Poseidon.

SLA RMS difference	No altimetry	Jason-1 only	Jason-1 + Envisat	Jason-1 + Envisat + GFO	Jason-1 + Envisat + GFO + T/P
7-day forecast	-	10.27	9.67	8.95	8.62
Nowcast	-	9.15	8.36	7.50	7.08
Hindcast	12.94	8.38	7.07	6.18	5.63

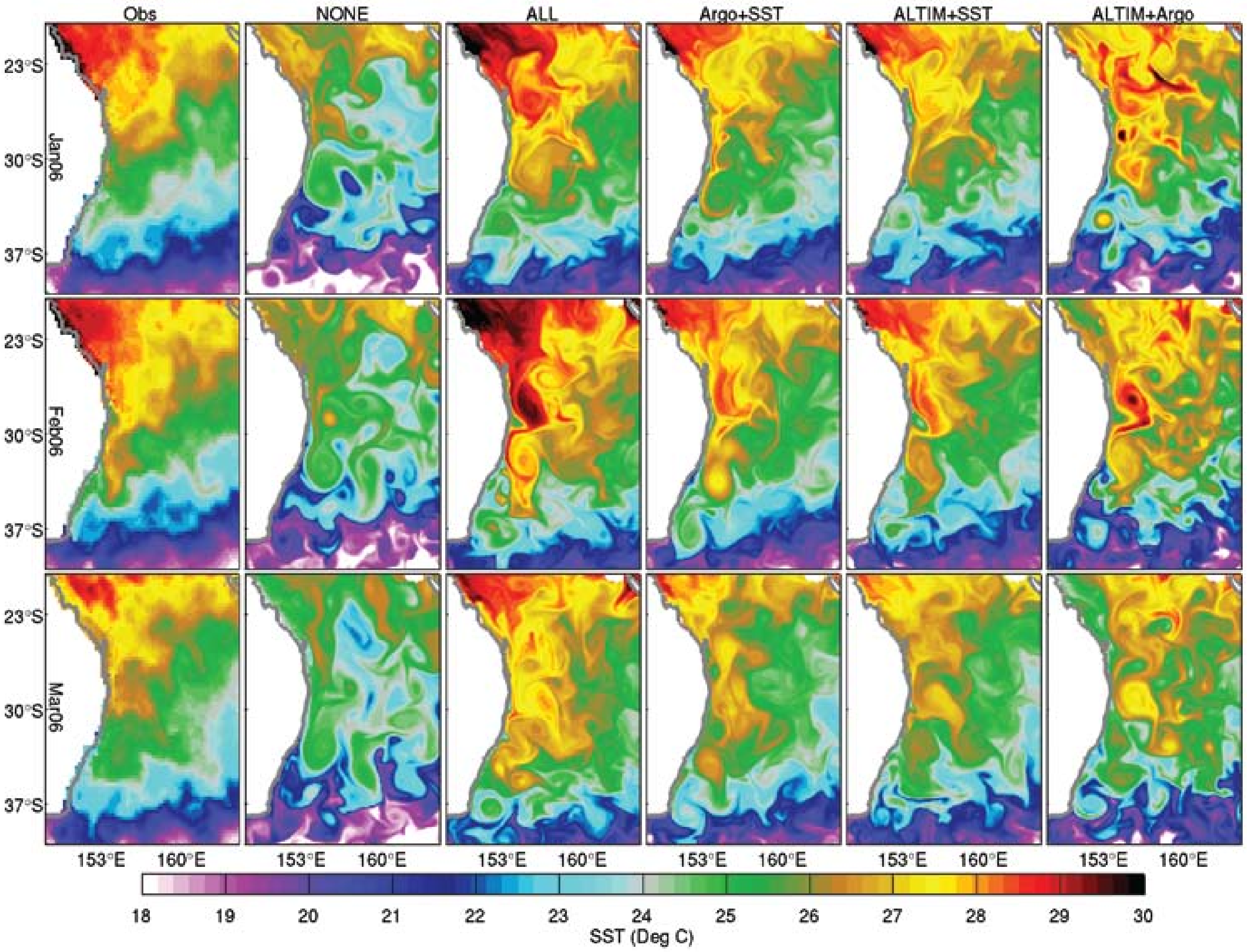

Figure 2. Observed sea surface temperature (SST) from (column 1) Advanced Very High Resolution Radiometer (AVHRR) + Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and (columns 2–6) modeled SST off Eastern Australia for OSEs, as labeled in the titles (NONE indicates no assimilation, ALL indicates Argo+SST+ALTIM, etc.), for different dates, as labeled in the first column, using the BLUElink> reanalysis system (Oke and Schiller, 2007).

OBSERVING SYSTEM SIMULATION EXPERIMENTS

Evaluating New Data Types

The potential impact of the assimilation of remotely sensed sea surface salinity (SSS) observations from the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission or the National Aeronautics and Space Agency's planned Aquarius satellite on the forecast skill of the Mercator system has been assessed by Tranchant et al. (2008) through a series of OSSEs. They conclude that the level of observation error will have a critical impact on the value of this new observation type to GODAE systems. This assessment is consistent with the conclusions of Brassington and Divakaran (2009), who evaluated the theoretical impact of SSS observations on an ensemble-based data assimilation system.

More recently, a series of twin experiments has been performed using Mercator systems, simulating surface velocity measurements in a manner that mimics that of synthetic aperture radar (SAR) data in coastal regions (Chapron et al., 2005) or optical flow methods applied to SST or ocean color data (Vigan et al., 2000) in addition to more conventional observations (altimeter, T/S profiles, and SST). Their goal was to

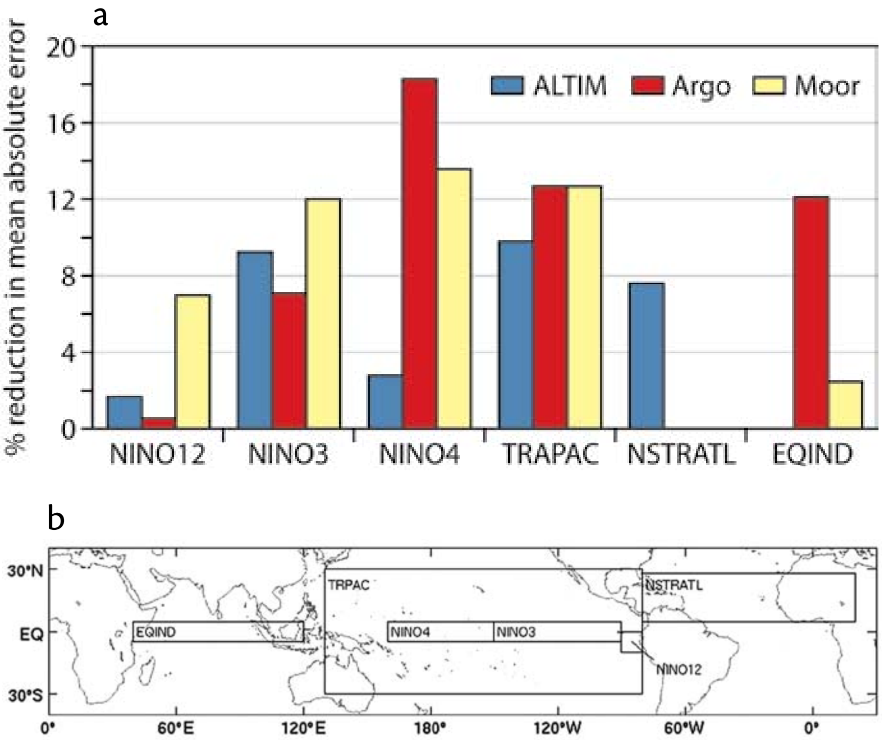

Figure 3. (a) Percentage reduction in the mean absolute error of one- to seven-month SST forecasts for the period 2001–2006. ALTIM, Argo, and Moor refer to the difference between the mean absolute error when altimeter, Argo, and mooring data are withheld, respectively. Results are presented for the regions denoted in (b).

evaluate the potential of these innovative observations in the perspective of an eventual degradation of the altimeter coverage in the near future. They conclude that ocean prediction systems could benefit from space-based velocity measurements—provided that observation errors remain below 7 cm s^{-1}, and provided they are used to complement satellite altimetry. Importantly, this study notes that the impact of these surface velocity measurements should not be expected to compensate for a total loss of altimeter capacity.

Designing Observing Systems

Several different techniques have been used together with GODAE systems to contribute to the design of ocean observation programs. These techniques include OSSEs that assess specific pre-determined design options (e.g., Guinehut et al., 2002) and techniques that objectively generate "optimal" observation arrays. The latter includes Kalman filter techniques (e.g., Ballabrera-Poy et al., 2007), ensemble approaches (e.g., Sakov and Oke, 2008), and adjoint and representer-based methods (e.g., Vecchi and Harrison, 2007; Fujii et al., 2008a; Le Henaff et al., 2009).

Examples of traditional OSSEs designed to assess the suitability of the Argo array for monitoring large-scale variability include those of Guinehut et al. (2002) and Schiller et al. (2004). Guinehut et al. (2002) show that the broad-scale variability in the North Atlantic is well reproduced by combining data from altimetry and a 3°-10-day Argo array. Similarly, Schiller et al. (2004) considered the design requirements of the Argo Program in the Indian Ocean. They concluded that five-day profiling may be needed in the Indian Ocean to properly resolve intraseasonal variability.

An example of an adjoint-based method for observing system design is the study described by Fujii et al. (2008a). They use the Multivariate Ocean Variational Estimation system to investigate the types of perturbations that influence the large meanders in the Kuroshio Current. Specifically, they show that the leading singular vector represents a growing perturbation that leads to further development of the large meander. Figure 4a shows the perturbation to vertical velocity and pressure at 820-m depth at initial time. The anticyclonic anomaly positioned at 133°E, 31°N causes cold advection across the Kuroshio Current and downwelling to the north. This results in the development of an anticyclonic circulation in the deep layers, and induces baroclinic instability. The corresponding anomalies to sea surface height (SSH) that coincide with these developments are summarized in Figure 4b–d, showing the development of a large meander about two months after the initial perturbation. This analysis indicates that to properly predict the Kuroshio meander, a forecast model must be well constrained by data assimilation around 133°E, 31°N and particularly at depths of 1000 to 1500 m. Thus, additional observations in that region are likely to benefit the forecast of the variability of the Kuroshio Current.

EMERGING TECHNIQUES

The GODAE community continues to work toward evaluation of GOOS to answer some of today's major challenges in ocean observing and forecasting: (1) where do we need improved observation coverage for ocean prediction, (2) what instruments and measurement variables are the most important, and (3) what are the accuracy requirements of the observations? Unfortunately, the computational and human resources required to routinely perform the types of OSEs and OSSEs referred to above can be very large. Drawing on the experience and directions of the numerical weather prediction (NWP) community, a new suite of observation evaluation techniques is emerging that will allow routine evaluation of GOOS (see Rabier et al., 2008). These new methods are designed to quantify the information content and impact of any and all observations used in the assimilation. It is no longer necessary to selectively add or remove observations or observing systems from the assimilation when assessing observation impacts as in conventional OSEs, which can change the analysis constraints on the remaining data and alter the outcome of the assimilation and subsequent forecast. The new diagnostics are predicated on the fact that all observations do not have equal value in reducing forecast error because of what is measured, where and when the measurements are taken, and the accuracy of the measurements themselves.

Analysis sensitivity is a potentially powerful way to quantify the impact of each individual observation on an analysis (Cardinali et al., 2004). Similarly, an adjoint technique can quantify the sensitivity of a forecast to assimilated observations (Langland and Baker, 2004). For comparison, analysis sensitivity could be routinely performed using any assimilation system after each assimilation step. By contrast, the adjoint technique requires the adjoint to the assimilation and forecast model. Although the analysis sensitivity quantifies the impact of each observation on an analysis, the adjoint technique also quantifies the impact of each observation on a forecast. However, the adjoint technique requires a linear assumption that is probably most appropriate for short-term (days) forecast problems, but may not be valid for longer-term (months) forecast problems, such as seasonal prediction using a coupled ocean-atmosphere model. Work is underway in the NWP community to extend the adjoint method into nonlinear forecast ranges. These types of analyses can help identify low-influence and high-influence observations, and can be partitioned for any data subset—instrument type, observed variable, geographic region, vertical level, or individual reporting platform—thereby making the diagnostic directly relevant to GOOS data providers.

CONCLUSIONS

One of the purposes of this paper is to identify the important results from a series of OSEs and OSSEs performed by different research teams for a range of different applications. One recurring result from different OSEs includes the apparent complementary nature of different observation types (e.g., Guinehut et al., 2004; Larnicol et al., 2006; Oke and Schiller, 2007; Balmaseda and Anderson, 2009). This analysis means that none of the GOOS observation types is redundant. Each different observation type brings unique contributions to GOOS and all

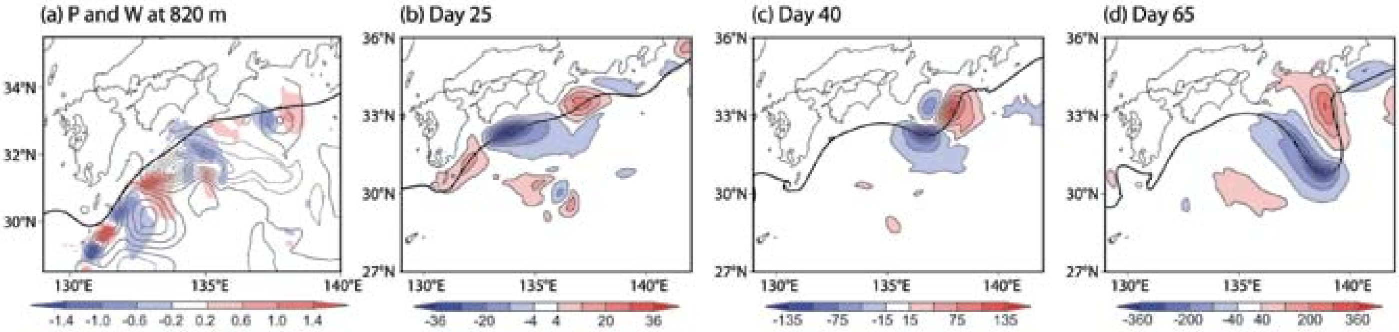

Figure 4. (a) Perturbation fields for pressure (contour; dotted lines are negative) and vertical velocity (shading; positive is downward) at 820-m depth. (b–d) Sea surface height anomalies (scales are different for each panel) that result from the perturbations represented in panel (a) at Day 0. Thick lines show the Kuroshio Current axis in the background state. *Adapted from Fujii et al. (2008a)*

observation types should be routinely assimilated by forecast and analysis products, and more importantly, maintained by the international community.

Another result common to many studies is the need to assimilate altimeter data to represent mesoscale variability (e.g., Pascual et al., 2006, 2007, 2008; Oke and Schiller, 2007). It has also been demonstrated that for NRT applications, data from four altimeters are needed to obtain errors that are comparable to systems using two altimeters in delayed mode (e.g., Pascual et al., 2008). This outcome is a result of differences in the quality and coverage of NRT data compared to DT data, and has important implications for operational systems that use altimeter data in NRT. Possibly, future wide-swath altimeter missions will go some way toward solving this problem, with more complete global coverage and shorter repeat cycles.

> “EACH DIFFERENT OBSERVATION TYPE BRINGS UNIQUE CONTRIBUTIONS TO GOOS AND ALL OBSERVATION TYPES SHOULD BE ROUTINELY ASSIMILATED BY FORECAST AND ANALYSIS PRODUCTS, AND MORE IMPORTANTLY, MAINTAINED BY THE INTERNATIONAL COMMUNITY.”

Several studies have demonstrated the critical importance of Argo observations, including several OSEs and OSSEs based on analysis systems, and OSEs based on both short-range and seasonal prediction systems. Several of these studies specifically noted that Argo is the only observation platform that provides global-scale information for constraining salinity. Without Argo data, temperature and salinity fields from global modeling and data assimilation systems are not sufficiently constrained and show large errors and drifts. Use of Argo data provides major improvements to all GODAE and related systems.

All GODAE systems considered in this paper include SST observations as an essential core data set. Indeed, one could argue that in many coastal regions and shallow seas, SST is the only observation type that adequately monitors ocean properties. The consistent uptake of SST observations is a credit to the GHRSST program that provides high-level quality-controlled SST data in NRT.

The versatility of OSSEs and variational data assimilation techniques is also demonstrated in this paper, which shows that insight can be gained into observing strategies for resolving specific processes. The impact of new observation types, such as surface salinity or surface velocity, is also assessed, with promising results.

We note that many groups from the NWP community routinely provide statistics on data impacts, in some cases, every day for every assimilation cycle. The methods discussed in this paper (OSE and OSSEs) are very expensive, and as a result are not applied routinely. They are also of limited value. For example, they will not automatically identify the impacts of changes in the Argo array as the total number of Argo floats fluctuates and their spatial distribution changes. OSEs and OSSEs are also typically performed with a “frozen” version of the analysis/forecast system, and by the time results are analyzed and conclusions drawn, the systems have often been upgraded. By contrast, as the NWP community has demonstrated, the routine application of computationally efficient methods can readily be applied to operational systems in NRT (e.g., Rabier et al., 2008) and can potentially support the maintenance and development of GOOS on an ongoing basis.

During the new sustained phase of GODAE, so-called GODAE OceanView, more efforts should be given to OSE and OSSE studies, and to the performance of observing system evaluation in NRT using the emerging techniques described above. Development of international coordination and cooperation on these topics is essential. They are needed to provide consistent and educated responses to space and in situ agencies and organizations in charge of the sustained global and regional ocean observing systems. A joint GODAE OceanView/OOPC Observing System Evaluation Task Team has been proposed with these objectives in mind.

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