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GODAE
The Global Ocean Data Assimilation Experiment

OVERVIEW

During 1996 and 1997, Neville Smith and Michel Lefèbvre developed the Global Ocean Data Assimilation Experiment (GODAE) concept (Smith and Lefèbvre, 1997). Its central idea was to conduct a 10-year international demonstration of the feasibility and utility of real-time, global ocean forecasting. The principal objectives, outlined in the GODAE Strategic Plan (IGST, 2000), were to:

1. apply state-of-the-art ocean models and assimilation methods for short-range open-ocean forecasts, for boundary conditions to extend predictability of coastal and regional subsystems, and for initial conditions of climate forecast models
2. provide global ocean analyses for developing improved understanding of the ocean and improved assessments of the predictability of ocean systems, and to serve as a basis for improving the design and effectiveness of the global ocean observing system

These broad objectives deliberately struck a balance between practical goals (e.g., forecasts and information for subsystems) and strategic objectives (science and evolution of the observing system).

GODAE implementation was led by the International GODAE Steering Team (IGST), which consisted of selected experts from operational and research institutes in Australia, Canada, China, France, Norway, Japan, the United Kingdom, and the United States. IGST was supported by a Patrons group representing the agencies with a stake in the outcome of GODAE. (See Box 1 for a full list of the members of these groups.)

The timetable for GODAE implementation, originally outlined in IGST (2000), was followed quite closely. Its main stages were

1998–2000: conceptual development
2000–2003: prototype development
2004–2008: main demonstration and consolidation phase

The end of GODAE was marked by a final symposium held in Nice, France, in November 2008 at which over 300 participants reviewed and critically examined key achievements of the last 10 years and discussed the future of operational ocean analysis and forecasting.

The aim of this special issue of *Oceanography* is to provide accessible summaries of the achievements and outcomes from GODAE and to set them into context. In this introductory paper, we outline the foundations on which GODAE was built, describe some of the key factors in building a collaborative international partnership, and discuss some of the challenges encountered en route. We emphasize the importance of observational data for GODAE and use the description of GODAE's functional components (Figure 1) to explain the content of and relationships between the papers in this issue and to summarize GODAE's overall achievements. The concluding summary includes an outline of the drivers and plans for future international coordination of research and development.

BOX 1: GODAE MEMBERS (STATUS: DECEMBER 2008)

International GODAE Steering Team

Members

Toshiyuki Awaji .... University of Kyoto, Japan
Pierre Brasseur .... CNRS/LEGI, France
Gary Brassington .... Bureau of Meteorology, Australia
Mike Bell (co-chair) .... Met Office, UK
Eric Chassignet .... Florida State University, COAPS, USA
James Cummings .... NRL/FNMOC, USA
Fraser Davidson .... Fisheries and Oceans, Canada
Pierre de Mey .... LEGOS, France
Eric Dombrowsky .... Mercator Océan, France
Craig Donlon .... ESA, The Netherlands
Nicolas Gruber .... ETHZ, Switzerland
Keith Haines .... ESSC, UK
Ed Harrison .... PMEL/NOAA, USA
Harley Hurlburt .... NRL-Stennis, USA
Masafumi Kamachi .... MRI /JMA, Japan
Tony Lee .... JPL/NASA, USA
Pierre-Yves Le Traon (co-chair) .... Ifremer, France
Andreas Schiller .... CSIRO, Australia
Matt Martin .... Met Office, UK
Kirsten Wilmer-Becker .... Met Office, UK
Jiang Zhu .... IAP/CAS, China

Expert Scientists (Regular Guests at IGST Meetings)

Frederique Blanc .... CLS, France
Fabrice Hernandez .... Mercator Océan, France
Laurence Crosnier .... Mercator Océan, France

Former Members

Pierre Bahurel .... Mercator Océan, France
Mike Carron .... US Naval Oceanographic Office, Stennis, USA
Geir Evensen .... NERSC, Norway
Ichiro Fukumori .... JPL/NASA, USA
Adrian Hines .... Met Office, UK
Hiroshi Kawamura .... Tohoku University, Japan
John Kindle .... NRL, USA
David Legler .... FSU, USA
Christian Le Provost .... CNRS/LEGOS, France
Yutaka Michida .... JODC, USA
Fumio Mitsudera .... IPTC/FRSGC, Honolulu, USA
Robert Molinari .... AOML/NOAA, USA
Patrick Monfray .... CNRS/IMBER, France
Gilles Reverdin .... CNRS/LEGOS, France
Michele Rienecker .... GMAO/NASA, USA
John Siddorn .... Met Office, UK
Neville Smith (former chair) .... Bureau of Meteorology, Australia
Detlef Stammer .... University of Hamburg, ZMAW, Germany
Keith Thompson .... Dalhousie University, Canada

Former Expert Scientists

Peter Dexter .... Bureau of Meteorology/JCOMM, Australia
Steve Hankin .... PMEL/NOAA, USA

GODAE Patrons' Group

Members

Stan Wilson (chair) .... NOAA, USA
Pierre Bahurel .... Mercator Océan, France
Mark Drinkwater .... ESA, The Netherlands
Scott Harper .... ONR/US Navy, USA
Eric Lindstrom .... NASA, USA
Francois Parisot .... EUMETSAT, Germany
Neville Smith .... Bureau of Meteorology, Australia
Eric Thouvenot .... CNES, France

Former Members

Jean-Claude Andre (former co-chair) .... CERFACS, France
Mel Briscoe .... ONR/US Navy, USA
Howard Cattle .... Met Office, UK
Philippe Courtier .... CNES, France
Masahiro Endo .... JAMSTEC, Japan
Yukio Haruyama .... NASDA, Japan
Masataka Hishida .... JAMSTEC, Japan
Hitoshi Hotta .... JAMSTEC, Japan
Chu Ishida .... NASDA, Japan
Masaki Ichihashi .... NASDA, Japan
Pinto Renato .... CCR, Brazil
Alain Ratier .... EUMETSAT, Germany
Takatoshi Takizawa .... JAMSTEC, Japan

THE FOUNDATIONS OF GODAE

The central idea of GODAE—to demonstrate the feasibility and utility of real-time, global ocean forecasting—was based on the experiences of the meteorological community in the First Global Atmospheric Research Program Global Experiment, known as FGGE (Bengtsson, 1981). FGGE set out to demonstrate that global weather prediction was feasible and practical. To accomplish their goal, FGGE participants assembled, for one year, a network for collecting remote and in situ observations capable of initializing models. FGGE was remarkably successful in showing that global numerical weather prediction was practical and of real benefit and impact, and added impetus to the development of measurements from geostationary satellites.

GODAE's scientific foundations were laid in the 1980s by the Tropical Ocean Global Atmosphere (TOGA) experiment and in the 1990s by the World Ocean Circulation Experiment (WOCE). In particular, WOCE championed altimeter measurements, extended the TOGA observing system globally through the ship-of-opportunity program and other initiatives, and promoted new technologies such as surface drifters and subsurface floats.

Toward the end of the 1990s, a number of factors converged to make GODAE feasible (IGST, 2000). Remote and in situ observing systems had developed sufficiently to make global, real-time observation possible. Supercomputer facilities sufficient for eddy-resolving global ocean model simulations were finally becoming available, and scientific capabilities were being developed to model the global ocean and assimilate data at fine spatial and temporal scales. There was also genuine enthusiasm within the community, particularly the remote-sensing community, to promote and implement integrated global observing systems.

GODAE was driven by the need to demonstrate the utility of ocean forecasting. Parallels with numerical weather prediction were used to argue that the full benefits of observations would only be realized through integration with numerical ocean prediction systems. The desire to exploit the full potential of ocean observing systems to support the case for sustained funding of their components gave a particular sense of urgency to seize the opportunity for GODAE. Improved understanding of the actual and potential benefits to society and how to realize them has been one of the major outcomes of GODAE activities.

KEY FACTORS IN BUILDING COLLABORATION AND DIFFICULTIES ENCOUNTERED

The inclusive and pragmatic but ambitious approach proposed for GODAE quickly gained and then retained over a 10-year period the commitment of key groups and individuals who would be crucial to its success.

The concept of a GODAE "Common," shared by and accessible to all the teams contributing to the goals and objectives of GODAE, emerged during IGST's first meeting, stimulated by the realization that it was in everyone's interest to accelerate collective progress. This collaborative atmosphere resulted in an open data policy, which enabled sharing of observation products and intercomparison of model analyses and forecasts. It also encouraged sharing of expertise and experience in the development of models, diagnosis of errors, demonstrations of utility, and the role of intermediate service providers. Furthermore, it stimulated collaborations between the operational and research communities that have had far-reaching consequences in the development of consortia such as the French Mercator Océan consortium, the Australian BLUElink>, the UK's National Centre for Ocean Forecasting, the Estimating the Circulation and Climate of the Ocean (ECCO) and HYbrid Coordinate Ocean Model (HYCOM) consortia funded by the US National Oceanographic Partnership Program (NOPP), and European consortia such as MERSEA and MyOcean. GODAE also consistently supported development of worldwide expertise. For example, the GODAE Summer School in 2004 and First Symposium in 2002 provided some excellent review articles and summaries that were very helpful introductions to newcomers to the field, and the Second Symposium in 2004 enabled a very

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valuable exchange of information, experience, and views on the development of oceanographic services.

GODAE was conceived and implemented as a finite-period "experiment" with a clear set of objectives. In early discussions with the satellite community, the importance of setting a schedule and sticking to it was strongly emphasized. Although GODAE did slip around 12–18 months behind its original schedule, the final conference was held in 2008, as originally scheduled. In parallel with this pragmatic approach, calculated risks were taken to explore ambitious options such as modern Web technologies for data dissemination and ensemble techniques for the calculation of error covariances.

The birth of Argo, which made GODAE plausible as an experiment, and the inspiring rationale and vision for GODAE, immediately generated a sense of purpose and tangible excitement among the individuals leading the development of ocean forecasting systems. It was the sustained energy and determination of this group that was instrumental in making GODAE viable and, we believe, a success. GODAE shared something with the US National Oceanic and Atmospheric Administration's (NOAA's) TOGA program in that most of those involved were (originally) young scientists with great passion for the field and keenness to "make a difference." The mix of youth and enthusiasm with the experience and wisdom accrued through WOCE proved a vital ingredient.

A GODAE Patrons Group, representing the agencies with a stake in the outcome of GODAE, was established

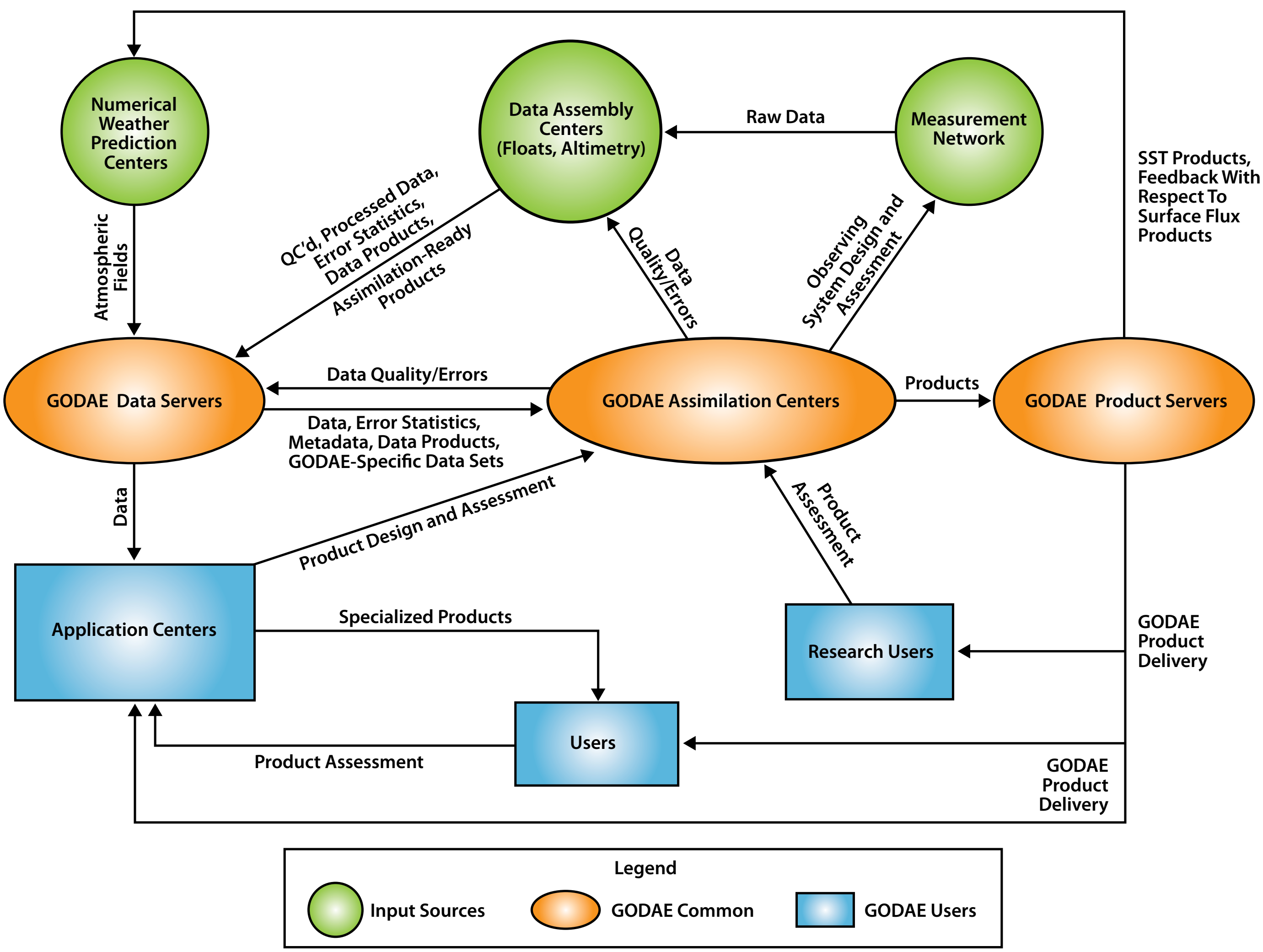

Figure 1. Diagram of the functional components of GODAE.

to coordinate and facilitate support for GODAE and its Project Office and to provide a stakeholder forum for consultation. The commitment of the GODAE Patrons to the initial vision and their investment in and sustained support for GODAE activities has been essential to the success of the experiment. At the core of this support throughout GODAE has been the satellite community, particularly the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), NOAA, Centre National d'Études Spatiales (CNES), the National Aeronautics and Space Administration (NASA), the National Space Development Agency of Japan (NASDA, now the Japan Aerospace Exploration Agency, JAXA), and the European Space Agency (ESA). A key step in gaining their initial support was made in February 1997 when the Committee on Earth Observation Satellites (CEOS) Strategic Implementation Team for an Integrated Global Observing Strategy (IGOS) endorsed GODAE.

There were a number of interconnected challenges that made it harder for GODAE to succeed than may have been foreseen and that will also be issues for future coordination. Engaging the interest of downstream users and securing funding for Argo and altimetry were harder than anticipated. These issues were exacerbated by the fact that it took longer than expected to develop good-quality assimilation systems and forecasts. Furthermore, the available resources for GODAE did not always match ambition. Many national teams' resources were limited or delayed and most IGST members were unable to fit their IGST commitments into their day jobs. There was a heavy reliance on a few key people (e.g., Christian le Provost, who died in 2004, Neville Smith, and Michele Rienecker) whose contributions could not be replaced when they left the team. Proactive coordination from the Project Office started late. The major achievements of GODAE are all the more remarkable for being made in spite of these challenges.

ON THE IMPORTANCE OF OBSERVATIONAL DATA

The dependence of GODAE on ocean data streams was recognized from the start, but also constituted a significant risk. IGST believed altimetry was crucial, both in high-precision, low-resolution and low-precision, high-resolution modes, the latter for resolving and initializing eddies.

Although GODAE contributed to the success of altimetry, the greater debt is in the reverse direction. The strength of the altimeter community, and the strength of advocacy for missions, has been an exemplar for the rest of the community, and GODAE has been able to take advantage of this success. It was envisaged that by the end of GODAE its partners would be able to demonstrate, on their own if necessary, that altimeter missions delivered tangible benefits to the community far greater in value than the investment required to sustain the missions. While such a demonstration on the part of GODAE itself has proven to be more challenging than anticipated, it appears that significant progress is being made—on the part of GODAE in concert with climate community interests in global sea level rise—in making the case for Jason-3, the next satellite in the Jason series of high-precision altimeter missions.

When the first "gap analysis" was done for GODAE, the glaring weakness was in securing in situ profiles of the ocean. Profiling floats developed during WOCE, combined with ship-based techniques, appeared to offer some potential, but at that time it was just that—potential. During 1997, proposals emerged to exploit float technology for a global profiling network. At IGST's first meeting in January 1998, there was little hesitation in providing strong support for these proposals though there was considerable debate about urgency and timing. Ultimately, it was agreed that GODAE would, in partnership with the Climate Variability and Predictability (CLIVAR) program, convene a meeting to launch a global profiling float initiative. At that meeting, held in Tokyo in July 1998, participants agreed to form a science team under the leadership of Dean Roemmich, and Argo was born.

In many ways Argo has become the flagship of ocean observing systems. From the start, the attraction of the approach was self-evident and, in the Science Team, it had all the ingredients needed to be successful. The governance model was similar to GODAE in that it was semi-autonomous and self-sufficient. Attracting the needed investment has, as expected, been an ongoing challenge, but through the strength of the science plan (Argo Science Team, 1998), the tireless work of a number of individuals, and the enormous strength of the Science Team, Argo has mostly exceeded the expectations that were agreed on at the meeting in 1998. Argo is providing data that are unparalleled in terms of quality and extent, particularly in relation to salinity. IGST is proud of the little push it provided to initiate the project, but the credit for success lies with the project itself.

The second pilot project spawned by GODAE was not envisaged in the original plans. Indeed, in the original concepts and plans, it was simply assumed that sea surface temperature (SST) was sampled with sufficient accuracy and resolution to satisfy even the most demanding ocean prediction model. Midway through the first phase of GODAE, however, it became evident that existing SST products lacked the quality and accuracy at the spatial and temporal resolutions demanded by GODAE. It was also evident that the needs of numerical weather prediction, upon which GODAE strongly depended, were not being satisfied, and that the uncertainty in climate products was perhaps larger than originally thought. Unlike altimetry, there appeared to be a surfeit of data, much of it from operational satellites, but at that time the community was not organized in a way that could bring these data together. The Global High-Resolution SST (GHRSST) Pilot Project was agreed on in 2000 on the basis of a prospectus released by GODAE and an initial meeting in Italy in November 2000 (Smith, 2001). From those modest beginnings, GHRSST has grown into a flagship project, revolutionizing the way SST products are developed (Donlon et al., this issue).

GODAE was active in a number of other data areas, particularly in promoting composite integrated data holdings, such as in the Coriolis project (Pouliquen, 2006). Indeed, GODAE had a critical influence in promoting real-time delivery of data and leadership for a number of initiatives that have assisted in consolidating data sets into a form that is more readily accessible and usable.

A BRIEF OVERVIEW OF THE PAPERS

Figure 1 shows the data flow diagram of GODAE's functional components, which was developed in the GODAE Strategic Plan (IGST, 2000). It captures the main sources of inputs required by GODAE, data and product servers, assimilation centers, users of the outputs, and many of the interactions required to ensure or enhance the quality of the systems and their outputs. It provides a suitable structure with which to explain the relationships between the papers in this issue and GODAE as a whole and the content of each paper.

"GODAE HAS GIVEN A MAJOR BOOST TO THE ESTABLISHMENT AND IMPROVEMENT OF OPERATIONAL OCEAN PREDICTION SERVICES IN A NUMBER OF COUNTRIES."

The measurement network and data assembly and processing centers provide the main inputs to the assimilation centers (top right of Figure 1). Clark et al. provide a concise overview of the in situ and satellite components of the current global observing system and discuss the continuing work required to sustain it.

Roemmich et al. describe the realization of the network of 3000 Argo floats freely reporting temperature and salinity profiles to 2000-m depth in a timely fashion, a feat that has transformed the in situ profiler network. Donlon et al. describe how the GHRSST project has resulted in a coordinated network of centers disseminating SST data in real time in a common format to agreed-upon standards from a wide range of microwave and infrared instruments on polar orbiting and geostationary satellites. Le Traon et al. summarize the substantial achievements during GODAE in the assembly and processing of observational data and the joint use of in situ and satellite data. Several assimilation centers have also developed useful tools for monitoring the input data on which their systems rely.

Blower et al. describe the progress in the capabilities of data and product servers (see middle row of Figure 1). They provide an overview of the underpinning concepts and technologies that enable the GODAE data to be discovered, visualized, downloaded, intercompared, and analyzed all over the world.

Progress within the assimilation centers (the central item in Figure 1) is described in a number of papers. The tables and descriptions in Dombrowsky et al. provide a useful overview of the present modeling and assimilation components of the major systems involved in GODAE. Most centers now operate systems with 1/10° or finer horizontal grid spacing; have a global capability; make use of community ocean models (e.g., HYCOM, Modular Ocean Model 4 [MOM4], or Nucleus for European Modelling of the Ocean [NEMO]); and assimilate in situ profile data, altimeter data, and some form of surface temperature data. Cummings et al. provide some insight into the data assimilation schemes used in the various systems, in particular describing (without recourse to equations) how each system represents the covariances of the errors in its forecasts. They also illustrate the performance of the assimilation systems. Hurlburt et al. demonstrate the skill of the high-resolution systems in forecasting sea surface height out to about a month ahead, sea surface currents, sea surface temperature, and baroclinic coastally trapped waves. Their Figure 5, comparing the statistics of forecasts of surface height for one of the systems with those of persistence for various regions, is a particularly interesting demonstration of forecast skill.

Product assessments and interactions with research users (lower right region of Figure 1) have been key activities, particularly in the last few years of GODAE. Hernandez et al. describe the procedures developed during GODAE to intercompare forecasts produced by different centers, and they illustrate the insights these intercomparisons can give into the way these systems perform. Lee et al. provide some examples of how systems developed for ocean state estimation have been used for climate research and how intercomparisons of results from the systems are being used to assess the consistency and uncertainty of the state estimates.

Three GODAE task teams were set up during 2006 and 2007. Oke et al. summarize results gathered by the observing system evaluation task team and outline the exciting prospects for future work. Their Figure 2, illustrating the complementarity of SST, altimeter, and profile data for mesoscale prediction, and Table 2, which presents statistics on the dependence of the accuracy of seven-day forecasts, real-time analyses, and delayed-mode analyses on the availability of altimeter data, are particularly noteworthy illustrations and demonstrations of capability. De Mey et al. summarize the wide-ranging investigations discussed by the task team on the applications of GODAE for coastal modeling. Finally, Brasseur et al. outline a number of categories of potential ecological and biogeochemical applications and discuss the challenges they pose to the fidelity of physical models and assimilation schemes and to measurement technologies.

The lower left-hand part of Figure 1 depicts the information flows to application centers (also known as downstream services) and users. Development of relevant enabling links was the focus of the Second GODAE Symposium in 2004 (see http://www.godae.org/modules/documents/documents/Symposium-II-report.pdf). Hackett et al. describe the use of GODAE outputs in monitoring and predicting marine pollution (e.g., oil spills) and the main conclusions from a number of case studies. Davidson et al. summarize demonstrations of the value of GODAE forecasts for safety and effectiveness of operations at sea. Jacobs et al. provide examples of the wide variety of information and tactical decision aids generated using GODAE products to assist naval operations. Finally, two papers illustrate the value of ocean monitoring and prediction for weather prediction. Goni et al. summarize the current operational use of upper ocean heat content information to forecast the intensity of tropical cyclones, and they describe current research in this area. Balmaseda et al. summarize the advances over the last decade in ocean initialization of coupled forecast systems and their impact on ocean state estimates and seasonal forecasts.

CONCLUDING SUMMARY

In summary, GODAE has given a major boost to the establishment and improvement of operational ocean prediction services in a number of countries. The

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papers in this volume provide an informative overview of the substantial capabilities that have been developed over the last 10 years for the robust, real-time collection and processing of measurements, and the generation and dissemination of analyses and forecasts. They demonstrate that forecasting of open ocean mesoscale phenomena is feasible in many regions. The papers also show that the forecasts are useful for a number of applications (e.g., heat content for tropical cyclones), although for other applications, the level of forecast skill achieved so far is limiting (e.g., use of surface currents for open ocean oil spill forecasting), and, as a result, a high level of expertise is required to make use of them.

GODAE members are eager and determined to further improve the scientific and technical quality of their analyses and forecasts, to strengthen their links with the users of their forecasts as part of providing operational services to them, and to build appropriate collaborations with other expert communities to improve capabilities for coastal, ecosystem, and coupled atmosphere-ocean monitoring and prediction. With the pressing societal need to monitor and adapt to climate changes, the many scientific and technological challenges to maintain, enhance, and exploit the global ocean observing system are more important than ever before. A new group, "GODAE OceanView," has been formed to establish a long-term international program for ocean analysis and forecasting, enabling the collaborations started by GODAE to contribute to these goals.

More detailed information about GODAE can be obtained from the Symposium Proceedings Web page (http://www.godae.org/documents.htm?parent=271) or the GODAE Web site (www.godae.org).

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