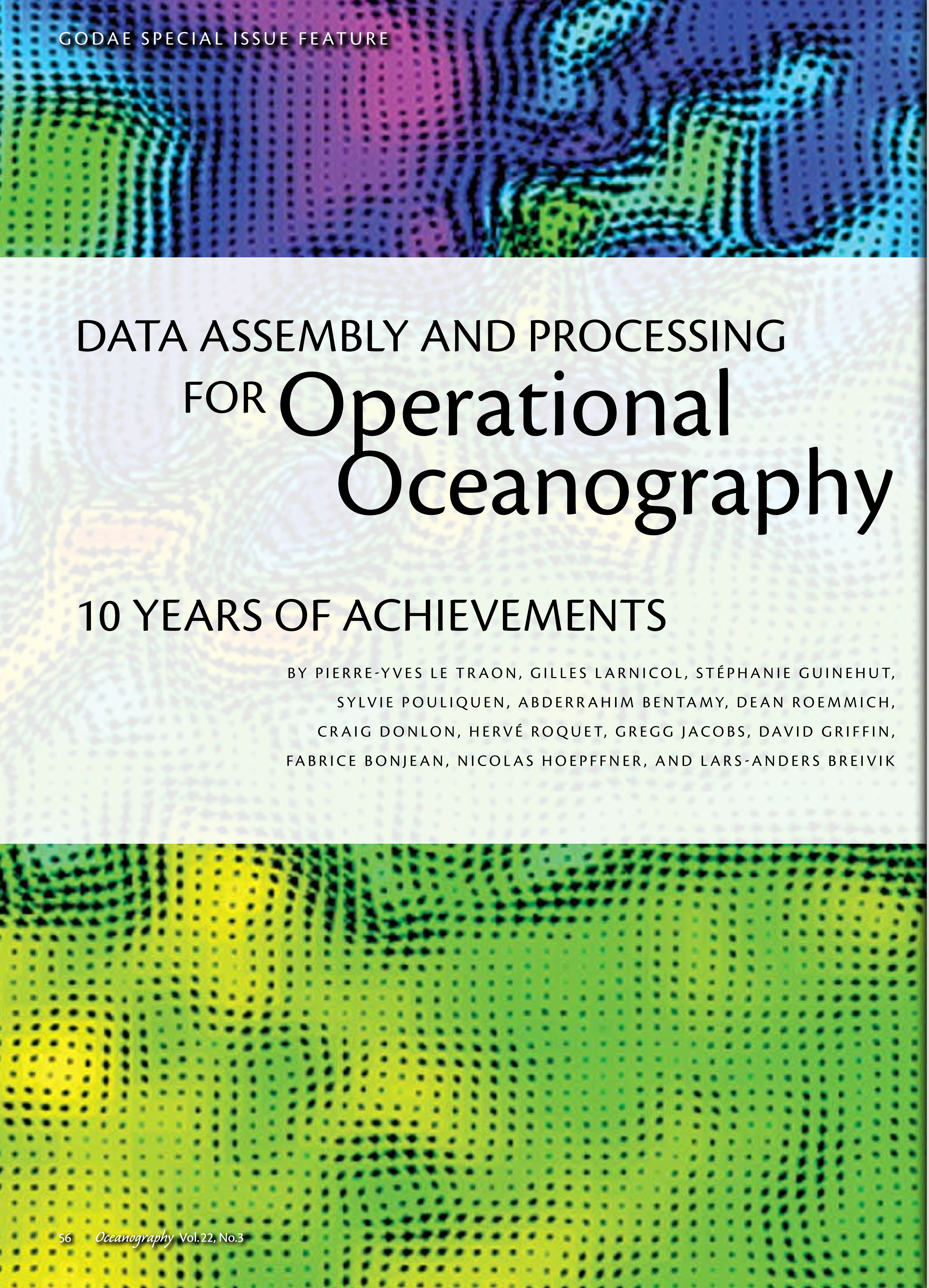

DATA ASSEMBLY AND PROCESSING FOR Operational Oceanography

10 YEARS OF ACHIEVEMENTS

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ABSTRACT. Data assembly and processing centers are essential elements of the operational oceanography infrastructure. They provide data and products needed by modeling and data assimilation systems; they also provide products directly usable for applications. This paper discusses the role and functions of the data centers for operational oceanography. It describes some of the main data assembly centers (Argo and in situ data, altimetry, sea surface temperature) developed during the Global Ocean Data Assimilation Experiment. An overview of other data centers (wind and fluxes, ocean color, sea ice) is also given. Much progress has been achieved over the past 10 years to validate, intercalibrate, and merge altimeter data from multiple satellites. Accuracy and timeliness of products have been improved, and new products have been developed. The same is true for sea surface temperature data through the Global High-Resolution Sea Surface Temperature Pilot Project. A breakthrough in processing, quality control, and assembly for in situ data has also been achieved through the development of the real-time and delayed-mode Argo data system. In situ and remote-sensing data are now systematically and jointly used to calibrate, validate, and monitor over the long term the quality and consistency of the global ocean observing system. Main results are illustrated. There is also a review of the development and use of products that merge in situ and remote-sensing data. Future issues and main prospects are discussed in the conclusion.

INTRODUCTION

Operational oceanography critically depends on the near-real-time availability of high-quality in situ and satellite data with sufficiently dense spatial and temporal sampling. The first requirement for obtaining these data is an adequate global ocean observing system. An initial design for a permanent, global, real-time observing system was proposed at the OceanObs 1999 conference and endorsed by the Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS), and Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). Specific Global Ocean Data Assimilation Experiment (GODAE) requirements were presented in the GODAE strategic plan (GODAE, 2001) and in Le Traon et al. (2001). They are refined and detailed in Clark et al. (2009) and Oke et al. (2009). There has been major progress over the past 10 years in implementing the initial system. The main challenge today is to complete the initial design and to ensure its long-term sustainability. A data processing, validation, and dissemination infrastructure must also be set up to ensure delivery of high-quality data sets and data products in a timely fashion that meets the requirements of modeling and data assimilation centers and other metocean applications. This paper focuses on data processing issues. Improvements in data and product serving capabilities are reviewed by Blower et al. (2009).

DATA PROCESSING ISSUES FOR OPERATIONAL OCEANOGRAPHY

Data processing centers or thematic assembly centers are an essential component of the global operational oceanography infrastructure. The quantity, quality, and availability of data sets and data products directly impact the quality of ocean analyses and forecasts and associated services. Products derived from the data themselves are also used directly for applications (e.g., in the case of a parameter observed from space at high resolution). More effective data assembly, more timely data delivery, improvements in data quality, better characterization of data errors, and development of new or high-level data products are among the key data processing needs for operational oceanography.

Operational oceanography needs two types of data. First are the near-real-time data required for daily and weekly forecasting activities. Second are delayed-mode data that are subject to greater quality control; these data are particularly valuable for reanalysis work and to assist seasonal forecasting and climate monitoring and prediction where long-term stability is essential. The usefulness of these data implies having clearly defined quality control procedures and validation processes with error characterization, as well as reprocessing capabilities for reanalysis purposes.

The role of data processing centers is to provide modeling and data assimilation centers with the real-time and delayed-mode data sets required for validation and data assimilation. This includes uncertainty estimates that are critical to effective use of data in modeling and data assimilation systems. High-level data products are also needed for applications and research (e.g., a merged altimeter surface current product for marine safety or offshore applications) and are essential to the long-term monitoring of the state of the ocean (e.g., to derive climate indices on the state of the ocean). They are also useful to validate data assimilation systems (e.g., statistical versus dynamical interpolation) and complement products derived through modeling and data assimilation systems. Data processing centers should monitor the performance of the observing system (e.g., data availability, possible degradation of performance, and/or sampling). They must establish strong relationships with data assimilation centers and intermediate or end users. Links with data assimilation centers are needed, in particular, to organize feedback (1) on the quality control performed at the level of data assimilation centers (e.g., comparing an observation with a model forecast), (2) on the impact of data sets and data products in the assimilation systems, and (3) on new or future requirements.

MAIN ACHIEVEMENTS OVER THE LAST 10 YEARS

Over the past 10 years, ocean data processing centers have been considerably enhanced in order to meet the needs of operational oceanography applications. We review here the main achievements. The review is far from being exhaustive; rather, we focus on a few examples of data centers that were deeply involved in GODAE and that developed strong interfaces with modeling and assimilation centers.

Argo: A Breakthrough in Data Management and Data Processing

During the past decade, Argo has revolutionized the distribution of ocean data within the research and operational communities (Roemmich et al., 2009). Argo led to a new paradigm for oceanography with all data and products freely and widely available in real time. The data management issue for Argo was to set up an information system able to provide a single entry point to data processed in national centers, applying commonly defined quality-control procedures at all steps of data processing. Two data streams have been identified (see Figure 1): first, a real-time data stream where data are free from gross errors and may be corrected in real time when the correction is known, and second, a data stream that operates in a delayed mode, where data profiles have been subjected to detailed scrutiny by oceanographic experts. There is, however, only one database where the "best" version of every Argo profile is kept. Two main actors were identified in Argo data management:

- DACs (Data Assembly Centers) receive the data via satellite transmission, and decode and quality control the data according to a set of 19 real-time automatic tests agreed upon within Argo. Erroneous data are flagged, if possible corrected, and then passed to the two global data centers and on to the Global Telecommunications System (GTS). The GTS data stream does not

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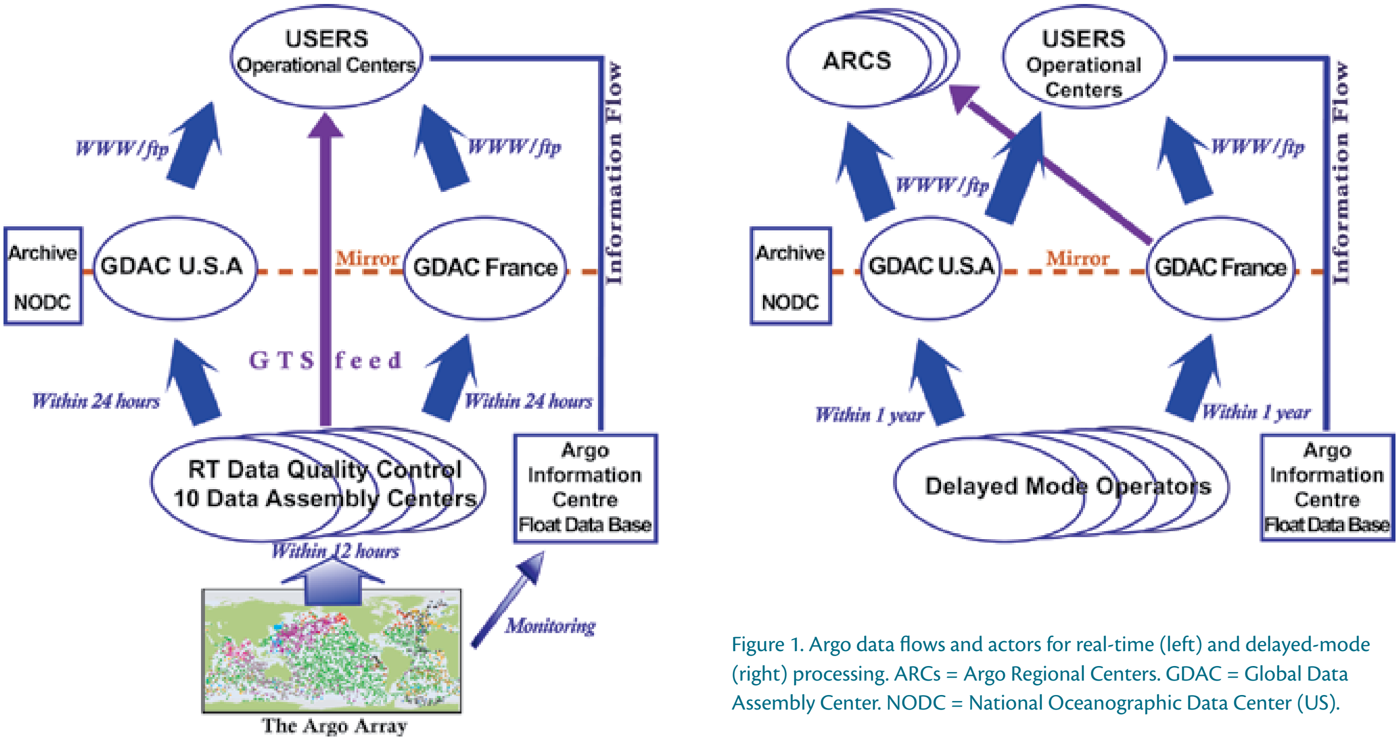

Figure 1. Argo data flows and actors for real-time (left) and delayed-mode (right) processing. ARCs = Argo Regional Centers. GDAC = Global Data Assembly Center. NODC = National Oceanographic Data Center (US).

include quality flags, and bad data and blacklisted data are not transmitted on GTS.

- GDACs (Global Data Assembly Centers), located at Coriolis in France and at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in the United States, are in charge of collecting the processed Argo data from the 11 DACs and providing users with unique access to the best versions of Argo profiles. Data are available in a common netCDF format and can be downloaded by file transfer protocol (FTP) or through a World Wide Web interface. The two GDACs synchronize their databases every day.

This architecture has proven that it is efficient, robust, able to serve both operational and research communities, and sustainable in the long term as relying on professional data centers. Other international programs, such as Global Oceanographic Surface Underway Data (GOSUD) and OceanSITES (Deep Ocean Eulerian observatories), which have both DACs and GDACs and have extended the Argo netCDF format to handle their data, have adopted this model.

Another primary objective of Argo's data management system is to provide climate-quality (delayed-mode) data through combined use of statistical tools and strong involvement of scientific experts in the quality-control process. The central task is estimation of the slow (multiyear) drift in salinity due to biofouling or other causes. Fortunately, the accuracy and stability of Argo salinity sensors exceeded original expectations, with most instruments showing no detectable drift for the first several years of deployment. The first step in delayed-mode processing is comparison of a sequence of Argo profiles from each instrument with nearby high-quality data (Wong et al., 2003; Owens and Wong, 2009). The high-quality data set used for this comparison comes primarily from research vessel cruises; it is supplemented with the more plentiful data sets of previously verified float profiles. Scientific judgment and regional expertise come into play whenever the research vessel data provide ambiguous or possibly outdated information, and if the nearby float data tell a different story. In addition to a salinity adjustment, the quality-control process includes additional tests, some still under development, for identification of systematic and random errors. These tests are carried out in Argo Regional Centers (ARCs) (see Figure 1). The tests include: (1) comparison of Argo data with climatological means and variability,

(2) comparison of satellite altimetric height with steric height from sequences of Argo profiles (see section on Joint Use of In Situ and Remote-Sensing Data), and (3) comparison of nearby floats ("buddies") of differing type, origin, or age to reveal systematic differences. All of these tests become more useful and accurate as the Argo data set grows and its statistics are better known.

Coriolis: An In Situ Data Thematic Assembly Center for Operational Oceanography

In situ data access is not always easy, in particular, to meet near-real-time needs of operational forecasting systems. It has improved in past years with the setting up of GDACs for major observation programs (see previous section). However, further work is needed to integrate the different data streams into a coherent data set directly accessible to operational users. In Europe, Coriolis has set up an in situ data thematic assembly center that integrates into a single data set data that is drawn from international networks (Argo, GOSUD, OceanSITES, Data Buoy Cooperation Panel [DBCP], and Global Temperature–Salinity Profile Program [GTSPP]) and from European regional data collections (EuroGOOS Regional Operational Oceanographic systems). It provides two main products: a real-time product for forecasting activities, and a delayed-mode product (updated on a yearly basis) for reanalysis and climate research activities. Over 10 years, the amount of data processed by Coriolis has increased tenfold (Figure 2). To be able to provide such products, Coriolis developed and implemented additional quality-control procedures that look at the data as a whole and can identify suspicious measurements not detected by automatic tests, or profiles and time series that are not consistent with their neighbors. Since 2005, Coriolis has also been producing global ocean weekly temperature and salinity fields from the Coriolis database using objective analysis. Statistical methods also permit detection of outliers in a data set by exploiting mapping error residuals (Gaillard et al., 2009). An alert system has been set up that detects the profiles for which the error is larger than a threshold. An operator scrutinizes outliers, discerning the difference between an erroneous profile and an oceanographic feature such as an eddy or a front. Coriolis is also setting up complementary validation activities for Argo data (see previous section).

Altimetry

Fifteen years after the launch of ERS-1 and TOPEX/Poseidon (T/P) and 10 years after the beginning of GODAE, satellite altimetry has become one of the most essential tools for ocean research and operational oceanography. The T/P and Jason-1 Science Working Team and later on the Ocean Surface Topography Science Team played a fundamental role in allowing scientific and operational users to exchange, share, and propose recommendations and mission evolutions. Major breakthroughs were achieved in several domains, such as sensor accuracy, orbit precision, geophysical corrections, and reference surfaces. They significantly improved the accuracy and consistency of each altimeter mission.

The two main multimission altimeter-data centers developed during GODAE are Ssalto/Duacs and NAVOCEANO (respectively, Segment Sol multimissions

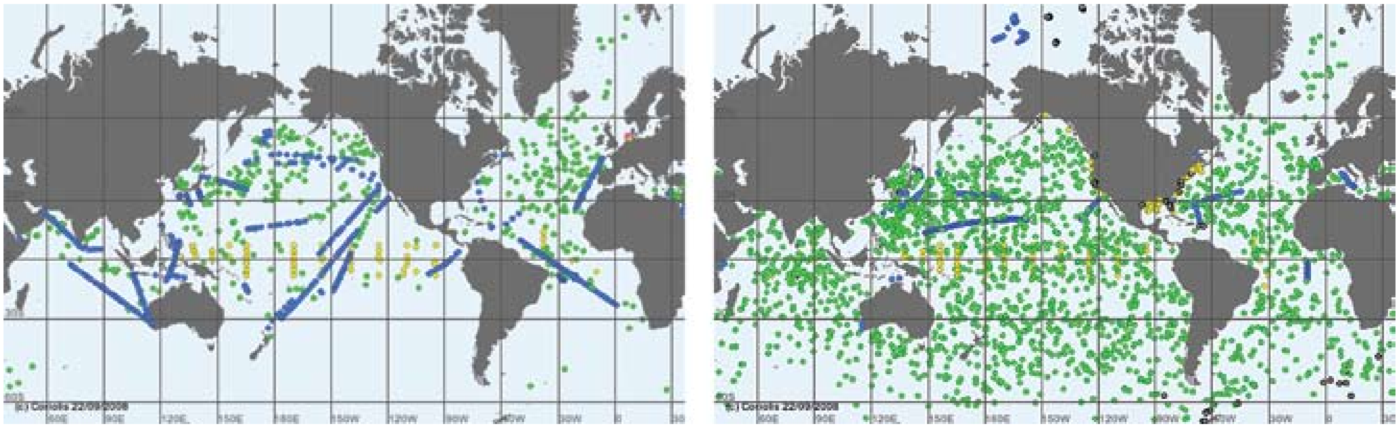

Figure 2. 10 days of profile data from the Coriolis database in September 2002 (left) and September 2008 (right). XBTs = blue. Argo = green. Moorings = yellow.

d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter Combination System and the Naval Oceanographic Office). The multimission processing of altimeter data developed by CLS as part of the Duacs European project started at the same time as GODAE (1997). The system was integrated into the Centre National d'Études Spatiales (CNES) multimission ground segment Ssalto in 2001. It aims to provide directly usable, high-quality, near-real-time and delayed-mode (for reanalyses and research users) altimeter products to the main operational oceanography and climate centers in Europe and worldwide. All products are described and available through the Aviso (Archiving, Validation and Interpretation of Satellite Oceanographic data) portal (http://www.aviso.oceanobs.com/). During the last decade, the system has been continuously upgraded. Main processing steps are product homogenization, data editing, orbit error correction, reduction of long wavelength errors, and production of tracks and maps of sea level anomalies. Major progress has been made in higher-level processing issues such as orbit error reduction (e.g., Le Traon and Ogor, 1998), intercalibration, and merging of altimeter missions (e.g., Le Traon et al., 1998; Ducet et al., 2000). Le Traon et al. (1998) refined the merging methodology, which is based on optimal interpolation, by taking into account explicitly long-wavelength errors in the mapping procedure. Ducet et al. (2000) derived for the first time global, high-resolution maps from T/P and ERS data, allowing a good description of mesoscale variability (Figure 3). Since 2001 and the launch of several altimeter missions (Geosat Follow-on [GFO], Jason-1, Envisat), the method was upgraded to analyze more than two missions (e.g., Pascual et al., 2006). During this decade, the merging method also evolved (e.g., improved signal and error covariance), taking into account improvements in Level 2 data processing (e.g., reduction of orbit error, better estimation of inverse barometer correction, better management of high frequency signal aliasing). The Ssalto/Duacs weekly production also moved to daily production in 2007 to improve timeliness of data sets and products. A new real-time product was also developed for specific real-time mesoscale applications.

Mean dynamic topography (MDT) is an essential reference surface for altimetry. Added to sea level anomalies, it provides absolute sea level and ocean circulation (Figure 3). After a preliminary MDT computed in 2003, a new MDT, called RIO-05, was computed in 2005. It is based on the combination of Gravity Recovery And Climate Experiment (GRACE) data, drifting buoy velocities, in situ temperature and salinity profiles, and altimeter measurements. The methodology is detailed in Rio et al. (2005). MDT was tested and is now used by several GODAE modeling and forecasting centers. It has a positive impact on forecast skill. An updated version based on the use of data from the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission will be prepared in 2010. This new version will provide MDT with unprecedented accuracy.

Every day, the NAVOCEANO system reprocesses all altimeter data received there within the past 14 days. Daily processing is necessary to provide information on ocean mesoscale features to numerical prediction systems that

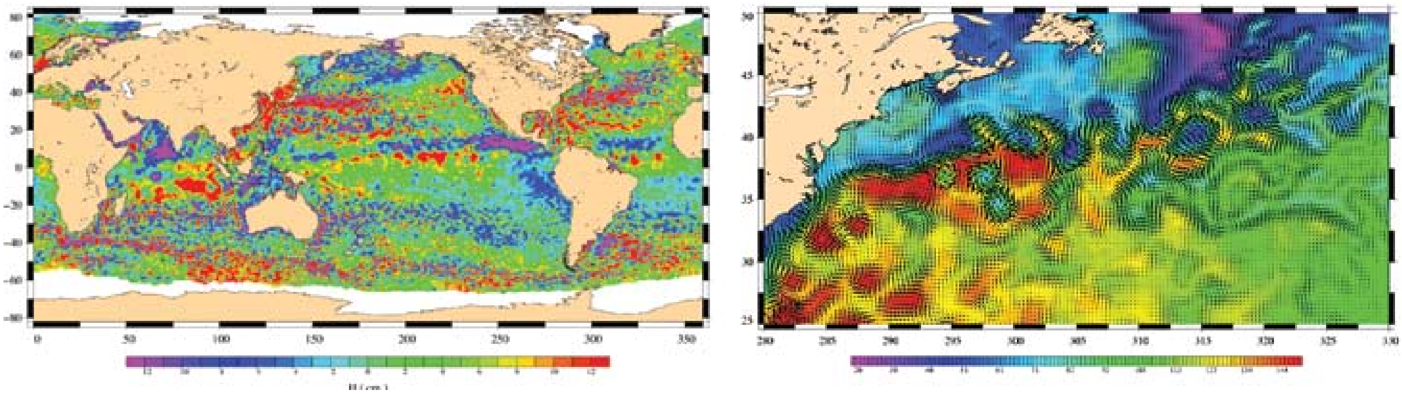

Figure 3. Global Maps of Sea Level Anomalies (MSLA) product (left) and absolute topography and currents in the Gulf Stream (right).

run daily. The reprocessing is necessary to capture data that may have been delayed and data that include more accurate orbit solutions and corrections. Geophysical corrections to altimeter-observed sea surface height (SSH) are quality controlled, and SSH anomaly maps are produced from all available satellites (Jason-1, Jason-2, GFO, and Envisat) using a consistent mean over the time period 1992 to 2007. Orbit solution errors are estimated for each full revolution of satellite data, and an initial estimate of synoptic, large-scale SSH from the most accurate orbit solution data sets (Jason-1 and Jason-2) is used to prevent the process from removing seasonal steric variability. The altimeter data are provided to the ocean data quality control system at NAVOCEANO, which quality controls all incoming data (both remote and in situ) relative to model forecasts, climatologies, and nearby observations for consistency and expected deviations.

> “OPERATIONAL OCEANOGRAPHY CRITICALLY DEPENDS ON THE NEAR-REAL-TIME AVAILABILITY OF HIGH-QUALITY IN SITU AND SATELLITE DATA WITH A SUFFICIENTLY DENSE SPATIAL AND TEMPORAL SAMPLING.”

Sea Surface Temperature

During the past 10 years, a concerted effort to understand satellite and in situ SST observations has taken place, leading to a revolution in the way we approach the provision of SST data to the user community. New passive microwave and high-accuracy infrared radiometers were flown for the first time, and the scene was set for new and exciting infrared and microwave imaging instruments over the following 10 years. GODAE, recognizing the importance of high-resolution SST data sets for ocean forecasting, initiated the GODAE High Resolution SST Pilot Project (GHRSST-PP) to capitalize on these developments and develop a set of dedicated products and services. A full description of the GHRSST-PP is provided in Donlon et al. (2009a,b) and in Donlon et al. (2009b). Main SST data processing issues are summarized here.

SST Infrared and Microwave Sensors

Infrared radiometers such as the Advanced Very High Resolution Radiometer (AVHRR) onboard operational meteorological polar orbiting satellites offer good horizontal resolution (1 km) and potentially global coverage, with the important exception of cloudy areas. However, their accuracy (0.4–0.5 K derived from the difference between collocated satellite and buoy measurements) is limited by the radiometric quality of the AVHRR instrument and correction for atmospheric effects. Geostationary satellites (e.g., USA's Geostationary Operational Environmental Satellites [GOES] and Europe's Meteosat Second Generation [MSG] series) are carrying radiometers with infrared window channels similar to the AVHRR instrument. Their horizontal resolution is coarser (3–5 km), but their great contribution comes from their high temporal sampling. Pre-operational demonstrators for advanced measurement of SST suitable for climate studies include the Advanced Along Track Scanning Radiometer (AATSR) series of instruments that have improved onboard calibration, and make use of dual views at nadir and 55° incidence angle. The along-track scanning measurement provides improved atmospheric correction leading to accuracy better than 0.2 K (O'Carroll et al., 2008). The main drawback of these instruments is their limited coverage, due to a much narrower swath than the AVHRR instruments. Several microwave radiometers have also been developed and flown over the last 10 years (e.g., Advanced Microwave Scanning Radiometer—EOS [AMSR], TRMM Microwave Imager [TMI]). The horizontal resolution of these products is around 25 km, and their accuracy is around 0.6–0.7 K. The great advantage of microwave measurements compared to infrared measurements is that SST can be retrieved even through nonprecipitating clouds, which is very beneficial in terms of geographical coverage.

Key Developments in Level 1 and 2 SST Data Processing

There have been key developments in data processing of SST data sets over the last 10 years. As a result, new or improved products are now available. Main achievements are:

- Improved radiative transfer schemes

that are used to derive retrieval algorithms by correcting for atmospheric attenuation (Merchant et al., 2006)

- Development and successful application of the dual view "along-track-scanning" technique to improve atmospheric correction (Smith et al., 2001; Noyes et al., 2006)
- Study of sea surface temperature diurnal evolution (Gentemann et al., 2003; Merchant et al., 2008)
- Derivation of uncertainty estimates based on the statistical analysis and combination of near contemporaneous in situ and satellite observations
- Improvements in flagging cloud- and aerosol-contaminated data
- Improvements in data delivery and timeliness
- Better understanding of SST in the marginal ice zone
- Stabilization of good calibration for passive microwave SST observations through improved algorithm development and knowledge of instrument characteristics
- Better understanding of microwave-derived SST in high-wind-speed regimes and better rain flagging
- Development of AATSR as a reference sensor for all other satellite SST data sets for reducing the impact of atmospheric aerosols in single-view infrared data sets (see Figure 4)

Levels 3 and 4 Data Processing

Several new high-resolution SST products have been produced in the framework of the GHRSST Pilot Project. As part of the Marine Environment and Security for the European Area (MERSEA) project (European contribution to GODAE, see Dombrowsky et al., 2009), the Ocean Data analYsis System for merSEA (ODYSSEA) was set up to produce global, high-resolution SST fields required by the various ocean models and downstream services. These fields are produced daily on a 0.1° grid. They are estimated by an optimal interpolation method merging SST satellite measurements from both infrared and microwave sensors. The processing scheme is broken down into two main steps. The first step is collecting and preprocessing all available GHRSST Level-2 preprocessed (L2P) products. Preprocessing consists mainly of screening and quality control of observations retrieved from each single data set and constructing a coherent, merged multisensor set of the most relevant and accurate observations (Level 3). Merging of these observations requires a method for bias estimate and correction (relative to a chosen reference, currently AATSR). Finally, the gap-free SST foundation field is computed from the merged set of selected observations using an objective analysis method. The performances and properties of the MERSEA analysis are estimated and monitored both daily and on a long-term basis through a set of evaluation tools (see http://www.mersea.eu.org/Satellite/sst_validation.html). Similarly, an operational Level 4 processing system at the Met Office, which is called Operational SST and Sea Ice analysis (OSTIA) and which provides boundary conditions for operational ocean and numerical weather forecasting systems, uses AATSR as a reference sensor together with in situ observations of SST and provides a 6.5-km global

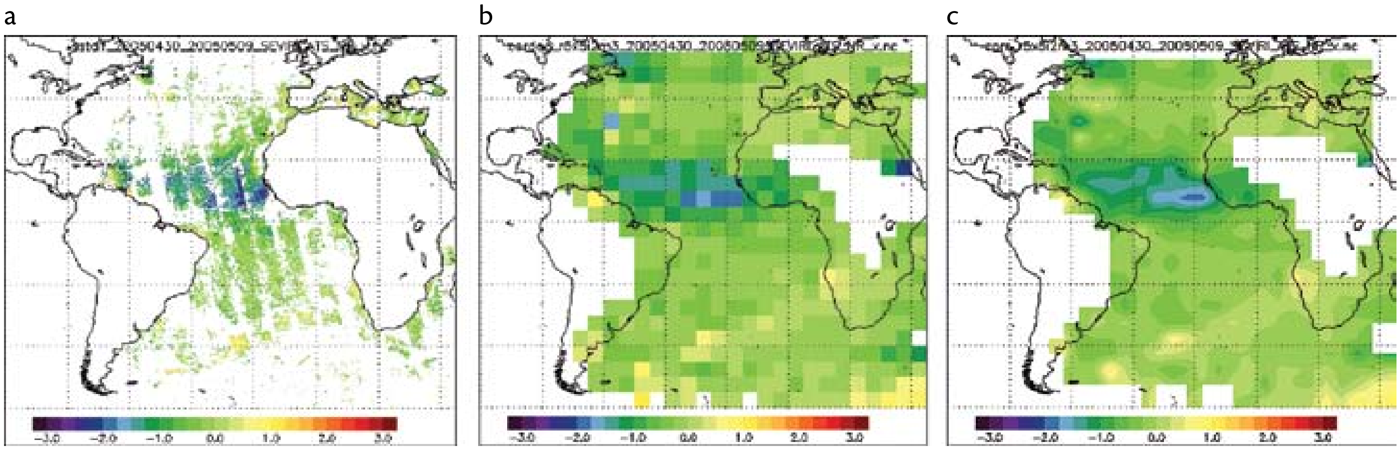

Figure 4. (a) Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) minus Advanced Along Track Scanning Radiometer (AATSR) sea surface temperature over a 10-day period showing the impact of Saharan dust (blue areas). (b) Analysis of the differences shown in (a) on a 5° grid. (c) Time-space interpolation of the results with fine-resolution correction for each day.

analysis every day (Stark et al., 2007). Outputs are available at http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html. Other new global SST analyses have been developed in the United States, Japan, and Australia in the context of the GHRSST Pilot Project, and existing global SST analyses have benefited from the new satellite SST data sources made available through it (e.g., Reynolds et al., 2007).

Other Data Sets and Products

Main GODAE efforts were focused on altimeter, SST, and in situ data needed and used by most GODAE global data assimilation systems. Advances were also made for other data sets and products that are critical for specific applications (e.g., sea ice) or will become more and more important for operational systems (e.g., ocean color, high-resolution winds), and/or for reanalysis activities (satellite winds and fluxes).

High-Resolution Winds

To enhance the spatial and temporal resolutions of surface wind, several attempts have been made to merge the remotely sensed data with the operational numerical weather prediction (NWP) wind analyses over the global ocean. As part of MERSEA, six-hourly gridded wind speed, zonal component, meridional component, and wind stress, and the corresponding components at global scale, were prepared, merging European Centre for Medium-Range Weather Forecasts (ECMWF) analyses with remote-sensing data. The longitudinal and latitudinal spatial resolution of the resulting wind fields is 0.25°. The remotely sensed wind observations are derived from near-real-time measurements performed by the Seawinds scatterometer onboard the QuikSCAT satellite and by the three Special Sensor Microwave Imagers (SSM/Is) onboard Defense Meteorological Satellites Program (DMSP) satellites. ECMWF analyses are interpolated in space and time over each satellite swath occurring within three hours from the synoptic time. The differences are evaluated at each scatterometer and radiometer wind cell of about 0.25° resolution. The former are calculated using an objective method to estimate global wind fields, retaining first ECMWF-QuikSCAT wind differences in swath regions; in the temporal and/or spatial QuikSCAT unsampled areas, available and valid observed differences between ECMWF and SSM/I are used. More details about data and processing methods can be found in Bentamy et al. (2007).

Sea Ice

Passive microwave (PM) data from the SSM/I instrument is still the backbone of operational sea ice observations. Daily Arctic and Antarctic analyses of ice concentration are delivered in near-real time from operational centers such as the National Centers for Environmental Prediction (NCEP; http://polar.ncep.noaa.gov/seaice) and the Ocean and Sea Ice Satellite Application Facility (OSI SAF; http://saf.met.no). These types of data sets are today assimilated in operational ocean model systems. Improved resolution and more detailed ice edge estimates are obtained by using scatterometer data (e.g., QuikSCAT) and new PM data from AMSR-E. Ice drift information based on successive satellite passes from these instruments is also assimilated in ocean/ice models.

The most important sources of high-resolution sea ice information are the national ice services, which provide manual analyses using synthetic aperture radar (SAR) data and images from optical and infrared instruments. The analyses are mainly designed for navigation, but they are increasingly used in local ice-ocean modeling (examples at http://www.polarview.org).

Sea ice data are also required for ocean reanalysis. PM data are available back to 1979 (e.g., http://nsidc.org) and today are also the most important data source for this purpose. However, long time series of satellite data now also exist for other instruments such as the scatterometer and SAR. In reprocessing and reanalysis, a lot of care is needed to ensure climate-consistent products. Both for re-analysis and for data assimilation, quantified knowledge of the uncertainty and errors in sea ice analyses is very important.

Although ice coverage and ice motion are well observed, there is still lack of regular information about the variation in ice volume. The expected ice thickness measurements from the advanced altimeter on Cryosat-II will be very much welcomed when launched in 2009.

Ocean Color

GODAE systems were focused on the analysis and forecasting of the ocean's physical state, but they are now evolving toward biogeochemistry and ecosystems. Thus, ocean color is now of central importance. Over the last decade, applications of satellite-derived ocean color data have been considerably extended to various disciplines, making important contributions to biogeochemistry, physical oceanography, ecosystem assessment, fisheries oceanography, and coastal management (IOCCG, 2008).

> “OVER THE PAST 10 YEARS, CAPABILITIES OF DATA ASSEMBLY AND PROCESSING CENTERS HAVE DRAMATICALLY IMPROVED.”

The MERSEA project has contributed significantly to an international effort to provide an accurate and consistent stream of ocean color data at a resolution and format compatible with the operational forecasting of the marine environment at global and regional scales (http://mersea.jrc.ec.europa.eu/). The assembled database consists of surface chlorophyll concentrations and diffuse attenuation coefficients, which are commonly used as indices of phytoplankton biomass and water transparency, respectively. A strong validation exercise (Mélin et al., 2007) and refinement of regional algorithms (Volpe et al., 2007) guarantee that this data set meets requirements for both scientific research and operations. The longest currently operating ocean color sensor (Sea-viewing Wide Field-of-view Sensor, or SeaWiFS) was launched in 1997. Additional overlapping missions, such as the USA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Europe's MEdium Resolution Imaging Spectrometer (MERIS), have the advantage of increasing the spatial coverage of the global ocean, otherwise limited to single observations due to sunglint effects or cloud cover. A combination of three ocean-color satellites can improve daily ocean coverage by 50% compared to a single sensor (Gregg and Woodward, 1998). All of these instruments grant access to unprecedented views of marine systems. Another challenge, however, is to optimize the information available by combining data from individual ocean color radiance (OCR) sensors with different viewing geometries, resolution, and radiometric characteristics (Pottier et al., 2006; Mélin and Zibordi, 2007; IOCCG, 2007). The availability of merged data sets through, for example, the European Space Agency (ESA) GlobColour initiative (http://www.globcolour.info/), allows users to exploit a unique, quality-consistent time series of ocean color observations, without being concerned about the performance of individual instruments.

Joint Use of In Situ and Remote-Sensing Data: Validation

The comparison of in situ and satellite data is needed to validate the satellite data. It is also useful for checking the consistency between different data sets before they are assimilated into an ocean model (e.g., Guinehut et al., 2006). The stability of different altimeter missions is, for example, commonly assessed by comparing altimeter SSH measurements with those from arrays of independent tide gauges (Mitchum, 2000). Other examples include validation of altimeter velocity products with drifter data (e.g., Bonjean and Lagerloef, 2002; Pascual et al., 2009), systematic validation of satellite SST with in situ SST from drifting buoys, and use of dedicated ship-mounted radiometers to quantify the accuracy of satellite SST (Donlon et al., 2008). Comparison of in situ and satellite data can also provide an indication of the quality of in situ data. Delayed-mode Argo quality control is a challenging task as it requires high-quality conductivity-temperature-depth (CTD) measurements in the float vicinity (see early section on Argo). Guinehut et al. (2009) proposed a complementary approach based on analysis of the consistency between Argo and satellite altimeter data. The method compares collocated sea level anomalies (SLA) from altimeter measurements and dynamic height anomalies (DHA) calculated from Argo temperature and salinity profiles for each Argo float time series. By exploiting the correlation that exists between the two data sets and a priori statistical information on their differences, altimeter measurements can be used to extract random or systematic errors in the Argo float time series.

Joint Use of In Situ and Remote-Sensing Data: Merged Products

Over the past 10 years, several GODAE groups have developed products that merge in situ and satellite data through statistical methods. They have been used both to validate data assimilation systems and to serve applications.

Mercator Océan and CLS Global Observation Ocean Products

Mercator Océan and CLS have set up an observation-based component to complement the Mercator Océan data assimilation systems (Larnicol et al., 2006). It provides three-dimensional thermohaline fields (ARMOR-3D) and surface currents fields (Surcouf) at high temporal and spatial resolution obtained from a combination of in situ and remote-sensing observations. From the ARMOR-3D temperature fields, statistics over the years 1993 to 2003 indicate that about 40% of the temperature variance at depth can be deduced from altimeter and SST data, and a simple linear regression method. The combination with in situ temperature profiles then improves the reconstruction of the fields by 25%. Additionally, these results show that optimal combination of in situ and remote-sensing observations is instrumental in reducing aliasing due to mesoscale variability (see also Oke et al., 2009). A validation experiment of the Surcouf surface-current products demonstrated that comparisons to independent drifting buoy velocities show an overall good consistency with an error of less than 40% (respectively 50%) of the buoy velocity variance in the zonal (respectively meridional) direction. As expected, higher errors are obtained in the meridional direction as well as in the equatorial band.

> “AS THE GLOBAL OCEAN OBSERVING SYSTEM EVOLVES, DATA PROCESSING SYSTEMS MUST ALSO BE READY TO INCORPORATE THE NEW DATA SETS AND DEVELOP QUALITY CONTROL, VALIDATION, AND HIGH-LEVEL PRODUCTS.”

NAVOCEANO and MODAS

Up until 2008, the main products provided by NAVOCEANO were based on analysis of incoming data. This analysis was done by the Modular Ocean Data Assimilation System (MODAS), which used an optimal interpolation of altimeter SSH and AVHRR SST, then used covariances of subsurface temperature and height to the temperature at depth based on historical data in order to construct a three-dimensional volume of temperature (Fox et al., 2002). Any in situ profile observations were then used with the three-dimensional temperature volume as a first estimate in another optimal interpolation step. In 2008, that system was discontinued, and it has been replaced solely by numerical model predictions using observations in a multivariate optimal interpolation with the model forecast from the prior run as a first estimate. This methodology is used in the present global operational circulation prediction system running at 1/8°, which is providing forecasts of the ocean environment. The physical model is being replaced now by the HYbrid Coordinate Ocean Model (HYCOM) system funded by the US National Oceanographic Partnership Program (NOPP; Chassignet et al., 2009; Hurlburt et al., 2009). This system assimilates on a daily basis data processed and quality controlled within the operational center, including available satellite altimeter observations, sea surface temperature, drifting and fixed buoy, Argo, ship of opportunity expendable bathythermograph (XBT), and other in situ observations.

BLUElink> Altimeter and SST Merged Products

Merged altimeter and SST products have been developed as part of GODAE Australia efforts (see http://www.marine.csiro.au/remotesensing/oceancurrents/) to complement modeling and data assimilation products. As illustrated hereafter, they proved to be quite useful for applications. In June 2007, two groups of observers (one scientific, one from industry) noticed that particularly strong currents were occurring on the continental slope near Ningaloo Reef, Western Australia. Long periods of clear skies gave the opportunity to view the motion of the water at high resolution (2 km) by animating High Resolution Picture Transmission (HRPT) AVHRR thermal imagery. The general clockwise circulation of the eddy was resolved by multimission altimetry, but the details of the submesoscale features believed to be associated with the peak velocities were not. In May 2008, industry attention was again focused on current flows over the continental shelf near Ningaloo Reef (Figure 5). Coincidentally, a Surface Velocity Program (SVP) drifter transited the area of interest, providing valuable ground-truth data that were clearly consistent with the SST imagery, but not with some of the routinely generated altimetry maps, which were suffering with only two altimeters (Jason-1 and Envisat) in use. The Maximum Cross Correlation (MCC) method estimates velocities by comparing pairs of thermal images (Bowen et al., 2002). Suitably filtered, these scattered velocity estimates can be used as a gradient constraint when mapping coastal and altimetric sea level observations. Doing this step brought the geostrophic velocity into agreement with the drifter. More work is required on the filtering step, however, before we include this technique in an automatic system. Maps like Figure 5 are very popular with a wide range of mariners all around Australia. Among those grateful for a detailed map of the very high velocities of the East Australian Current was a group rowing across the Tasman Sea from New Zealand in late 2007.

NOPP Ocean Surface Current Analyses Real-time (OSCAR)

The OSCAR project (http://www.oscar.noaa.gov) was initially established in response to a US NOPP call for proposals in 2001 to develop new operational applications for satellite sea level and vector wind measurements. The project became operational in 2002 for the tropical Pacific. The approach to computing the surface currents from satellite SSH and wind observations is a straightforward combination of quasi-steady geostrophic and wind-driven dynamics (Bonjean and Lagerloef, 2002). The geostrophic term is computed from the gradient of surface topography fields. Wind-driven velocity components are computed from an Ekman/Stommel formulation with variable viscosity, and the OSCAR model also includes a minor thermal wind adjustment using satellite SST data. With this model, 1° x 1° degree Eulerian vector fields have been generated every five days over the global ocean. A higher-resolution calculated field with a 1/3° resolution was released in October 2008. The tropical Pacific field was evaluated with more sparsely sampled SVP drifters, moored current meters, and acoustic Doppler current profiler (ADCP) transects (Johnson et al., 2007). Major improvements have been implemented, such as integration in the processing system of the Ssalto/Duacs altimeter product, extension of the calculation to the global ocean, and development of a quasi-real-time analysis. OSCAR surface currents are routinely validated globally with surface drifter data, and satellite-derived currents are also systematically compared to mooring data. These analyses have contributed significantly to understanding the role of surface transports in the genesis of the 1997/98 and the 2002/03 El Niños. In addition to the El Niño-related applications, OSCAR analyses have supported a wide range of studies, such as the role of salt transport in tropical freshwater, the influence of tropical instability waves on

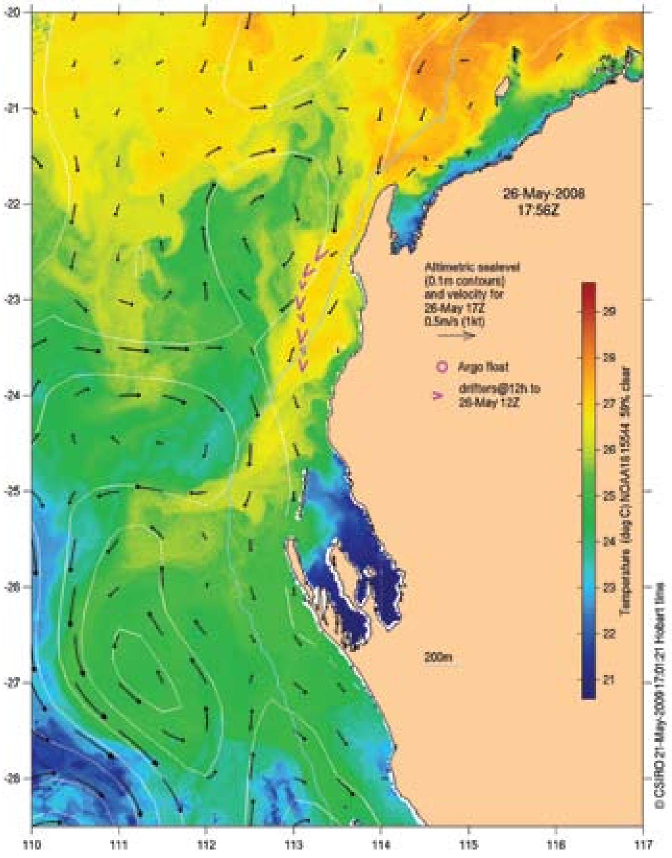

Figure 5. The northwest corner of Australia showing a cyclonic (cold-core) feature west of Ningaloo Reef (22°S). The magenta arrowheads show the path of a Surface Velocity Program drifter overlain on a single-pass image of sea surface temperature (SST). Black arrows show the velocity field derived by the routine mapping of sea level on a day of no obvious disagreement with SST.

phytoplankton blooms in the Pacific, and the mixed-layer temperature balance. OSCAR analyses have also been used to assess the surface current field from oceanic data assimilation systems.

CONCLUSIONS AND PROSPECTS

Over the past 10 years, capabilities of data assembly and processing centers have dramatically improved. New or improved data sets and products needed by the modeling and data assimilation systems and for applications have been developed. Accuracy and timeliness of products have also been improved. In situ and remote-sensing data are now jointly used to calibrate, validate, and analyze consistency of these data, and to derive merged products that provide information that complements modeling and data assimilation products. It is expected that series of advances in data processing will impact operational oceanography and its applications. Continuous improvements are needed so that data sets and products evolve according to the requirements of modeling and data assimilation systems. For example, more effort is needed for ocean color data processing and merging. Specific efforts should also be devoted to coastal areas where high temporal and spatial resolution products are needed, and specific data processing algorithms must be applied. As the global ocean observing system evolves, data processing systems must also be ready to incorporate the new data sets and develop quality control, validation, and high-level products. This holds, for example, with the development of biogeochemical in situ sensors (e.g., oxygen, Chl *a*) on Argo floats or gliders. New satellite missions for sea surface salinity (SMOS, Aquarius) and gravity (GOCE), and very-high-resolution altimetry (Surface Water Ocean Topography [SWOT]) will require innovative data processing techniques. There is also a need to improve the data assembly of key data sets such as velocity data (drifters, ADCPs, Argo floats) and to compare and merge them with satellite information (altimetry and scatterometry, but also surface currents derived from SST and ocean color data). New theoretical frameworks (e.g., Lapeyre and Klein, 2006) should also allow us to better exploit the high-resolution information in satellite observations (e.g., Isern-Fontanet et al., 2006).

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