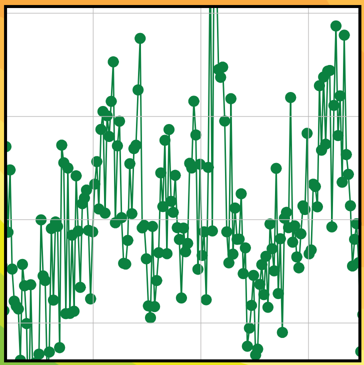
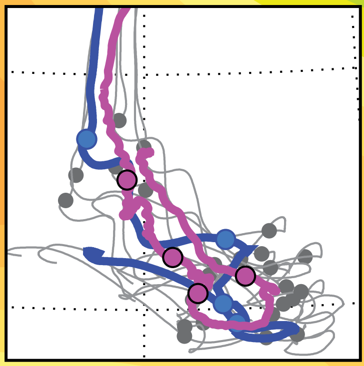
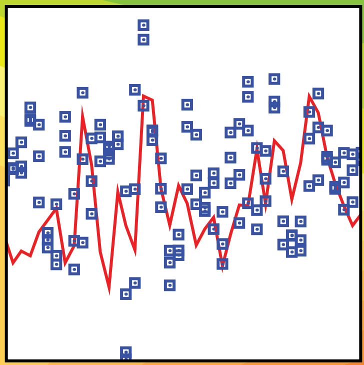
GODAE Systems in Operation







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ABSTRACT. During the last 15 years, operational oceanography systems have been developed in several countries around the world. These developments have been fostered primarily by the Global Ocean Data Assimilation Experiment (GODAE), which coordinated these activities, encouraged partnerships, and facilitated constructive competition. This multinational coordination has been very beneficial for the development of operational oceanography. Today, several systems provide routine, real-time ocean analysis, forecast, and reanalysis products. These systems are based on (1) state-of-the-art Ocean General Circulation Model configurations, either global or regional (basin-scale), with resolutions that range from coarse to eddy-resolving, and (2) data assimilation techniques ranging from analysis correction to advanced three- or four-dimensional variational schemes. These systems assimilate altimeter sea level anomalies, sea surface temperature data, and in situ profiles of temperature and salinity, including Argo data. Some systems have implemented downscaling capacities, which consist of embedding higher-resolution local systems in global and basin-scale models (through open boundary exchange of data), especially in coastal regions, where small scale-phenomena are important, and also increasing the spatial resolution for these regional/coastal systems to be able to resolve smaller scales (so-called downscaling). Others have implemented coupling with the atmosphere and/or sea ice. This paper provides a short review of these operational GODAE systems.

INTRODUCTION

The development of global and regional ocean data assimilation systems began in the 1990s. Several factors came together to make this development possible: (1) advances in numerical ocean modeling that led to development of Ocean General Circulation Model (OGCM) codes had by then been successfully implemented and scientifically validated in realistic configurations, had high coding and documentation standards, and were computationally efficient; (2) assimilation schemes were developed for the ocean and successfully demonstrated in realistic applications, with algorithmic simplifications allowing their implementation on existing computers; (3) supercomputing facilities were emerging, enabling implementation of realistic eddy-resolving ocean data assimilation systems at basin scale; and (4) global observing systems were developing, with real-time data delivery mechanisms, including satellite altimetry that allowed a continuous, quasi-synoptic picture of the global ocean eddy field. Finally, this development has been fueled by users' demands from navies and meteorological agencies for applications such as underwater acoustics, object drift monitoring, hurricane forecasting, and seasonal and climate prediction, and from the downstream commercial sector such as the oil industry.

This movement started at approximately the same time in Europe and the United States in the early 1990s. In the United States, the Naval Research Laboratory (NRL) implemented a 1/4° global NRL Layered Ocean Model (NLOM) system in 1997 (Hurlburt et al., 2008). In Europe, the Met Office implemented the Forecasting Ocean Assimilation Model (FOAM) system (Bell et al., 2000) in 1997 (global, 1°), and the French Navy implemented the Système Opérationnel d'Analyse et de Prédiction (SOAP) system (Giraud et al., 1997) in 1993 in the Azores current region (12.5 km horizontal resolution), then extended it to the northeastern Atlantic (at 1/10°) in 1998. A number of other countries have now developed real-time ocean prediction capacities, including Italy and Norway in Europe, Japan, Australia, China, and Canada. Today, a dozen systems routinely operate in the nine countries that participated in the Global Ocean Data Assimilation Experiment (GODAE); they range from regional high-resolution systems that include tides to global eddy-resolving systems that provide estimates of the ocean state updated regularly (from daily to monthly), and they provide forecasts from a few days to one month ahead.

SYSTEMS OVERVIEW

Today, eight different systems cover the world ocean. Three of these global systems are eddy-resolving, three are eddy-permitting, and the other two are of lower resolution. Several groups have also implemented regional systems covering an ocean basin to serve national/regional needs or to simulate specific phenomena such as the El Niño Southern Oscillation (ENSO). Tables 1 and 2 present their main model and assimilation character-istics, respectively. Table 3 gives some information about operational setups, and Table 4 gives URLs to access more

Table 1. GODAE systems: Main characteristics of ocean models

System	OGCM	Domain	Horizontal Resolution	Vertical Sampling	Atmospheric Forcing
BLUElink>	MOM4	Global	1° global 1/10° around Australia	47 z-levels	GASP 3-hourly
C-NOOFS	NEMO	Canadian Atlantic	1/4°	50 z-levels	EC/GEM hourly
ECCO-GODAE	MIT	Global	1° global (JPL+MIT) 1° x 0.3° tropics (JPL only)	46 z-levels (JPL) 23 z-levels (MIT)	NCEP (JPL + MIT) + COADS (JPL only)
FOAM	NEMO	Global	1/4°	50 z-levels	UKMO 6-hourly
		North Atl. + Med. + Indian	1/12°		
HYCOM/NCODA	HYCOM	Global	1/12°	32 hybrid layers	NOGAPS 3-hourly
Mercator	NEMO	Global	1/4°	50 z-levels	ECMWF daily
		North Atl. + Med.	1/12°		
MFS	NEMO	Mediterranean	1/16°	71 z-levels	ECMWF 6-hourly
MOVE/MRI.COM	MRI.COM	Global	1°	54 sigma-z hybrid levels	JMA 6-hourly
		North Pacific	1/2°		
		Western North Pacific	1/10°		
NLOM/NCOM	NLOM	Global	1/32°	7 layers	NOGAPS
	NCOM	Global	1/8°	40 sigma or z levels	
NMEFC	IAP/CAS	Tropical Pacific (30°S–30°N)	2° x 1°	14 z-levels	NCEP + clim
RTOFS	HYCOM	North and Tropical Atlantic (> 25°S)	4–18 km	26 hybrid layers	NCEP 3-hourly
TOPAZ	HYCOM	Atlantic and Arctic	11–16 km	22 hybrid layers	ECMWF 6-hourly

information and image products from the GODAE systems presented in this paper. The reader can refer to Hurlburt et al. (2009) and Cummings et al. (2009) in this issue for more details about some of the model configurations and assimilation systems used by GODAE teams.

SYSTEMS PRESENTATION

BLUElink> OceanMAPS

The BLUElink> Ocean Model, Analysis and Prediction System version 1.0b (Brassington et al., 2007) is Australia's first-generation

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Table 2. GODAE systems: Main assimilation characteristics

System	Assimilation Scheme	SST	SSH	Other
BLUElink>	Ensemble OI BODAS	AMSR-E	Along-track Jason + Envisat	T/S profiles
C-NOOFS	None	None	None	None
ECCO-GODAE	Kalman filter/ smoother (JPL) and adjoint (MIT)	Satellite + in situ	Along-track TOPEX, Jason (JPL + MIT), ERS, Envisat; tide gauges (MIT only)	Argo, XBT, CDT, TAO (JMP + MIT) QuikSCAT, SSM/I, SSS (MIT only)
FOAM	Analysis correction scheme + IAU	GHRSST (AMSR-E, AVHRR, AATSR)	Along-track Jason + Envisat + GFO from Ssalto/Duacs	T/S profiles, ice concentration
HYCOM/NCODA	Multivariate, OI + IAU, NCODA	Satellite + in situ	Along-track Jason + Envisat + GFO from NAVO ADFC	T/S profiles, ice concentration
Mercator	SEEK filter, SAM2	RTG SST	Along-track Jason + Envisat + GFO from Ssalto/Duacs	T/S profiles from Coriolis
MFS	3DVAR with vertical EOFs, nudging (SST)	AVHRR maps from CNR/ISAC	Along-track Jason + Envisat + GFO from Ssalto/Duacs	T/S profiles
MOVE/MRI.COM	3DVAR with vertical EOFs + IAU	MGDSST	Along-track Jason + Envisat	T/S profiles
NLOM/NCOM	OI + IAU/MODAS, NCODA, nudging	MODAS SST	NLOM: Along-track Jason + Envisat + GFO from NAVO ADFC	MODAS synthetic 3D T/S, NCODA T/S profiles (NCOM)
NMEFC	3DVAR OVALS	Reynolds SST	Along-track Jason from PO.DAAC SSHA	T/S profiles from Coriolis and CADC/NMDIS
RTOFS	3DVAR with vertical 1D cov	GOES AVHRR + in situ	Along-track Jason + Envisat	T/S profiles
TOPAZ	Ensemble Kalman filter 100 members	Reynolds SST	SLA MAPS from Jason + Envisat + GFO from Ssalto/Duacs	T/S profiles, ice concentration + drift

ocean forecasting system; it has been operational at the Bureau of Meteorology since August 2007. OceanMAPS features a global ocean model based on Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 4 (MOM4) OGCM version p0d (Griffies et al., 2004) with 0.1° x 0.1° resolution in the Asian-Australian region (90°E–180°E, 75°S–16°N). The BLUElink> Ocean Data Assimilation System (BODAS; see Oke et al., 2008) is used to perform a multivariate, ensemble optimal interpolation analysis nine days (symmetric analysis) and five days (asymmetric analysis) behind real time. The ocean model is forced by three-hourly average surface fluxes from the Bureau of Meteorology's operational global numerical weather prediction system (Seaman et al., 1995). A 15-year ocean reanalysis was performed using BODAS and MOM4p0d with historical observations to serve as a useful data archive of past ocean states as well as to test the performance of the analysis system (Oke et al., 2008; Schiller et al., 2008). The operational system produces a seven-day forecast twice per week.

Specific maritime applications include defense, search and rescue, port management, offshore oil and gas operations, marine park management, fisheries management, and ecotourism, as well as a number of recreational activities such as ocean-going yacht racing and beach swimming. The system also supports nested coupled regional systems for tropical cyclone and coastal ocean forecasting.

C-NOOFS

Fisheries and Oceans Canada (DFO) developed the Canada-Newfoundland Operational Oceanography Forecast System (C-NOOFS), which covers Canadian Atlantic waters and routinely provides daily six-day forecasts of ocean state. Currently, the system is run in a best-effort pre-operational mode without assimilation. A Singular Evolutive Extended Kalman (SEEK) filter (Pham et al., 1998) assimilation system is being developed with deployment planned for 2010. At present, the system is routinely nested (one-way) in the Mercator global system (see below) from which C-NOOFS is initialized once a week. The impact of observation is taken into account through initial and boundary data.

The system is implemented in Canadian Atlantic waters (26.69°N–83.68°N, 103.12°W–27.23°W), currently on the same grid (1/4°, 50 z-levels) as the Mercator global system and using the same Nucleus for European Modelling of the Ocean (NEMO) OGCM (see Madec, 2008) with a filtered free-surface approximation. Tidal forcing is also included.

The wind forcing field is computed from 10-m hourly wind fields provided by the Canadian 33-km resolution atmospheric forecast Global Environmental Multiscale (GEM) system from Environment Canada. Climatological heat and freshwater fluxes are used. C-NOOFS' long-term goal is to run at Environment Canada's Canadian Meteorological Center in a coupled operational Ocean-Atmosphere-Ice environmental forecast system. Present users include the Canadian Coast Guard and national defense operations.

ECCO-GODAE

The US Estimating the Circulation and Climate of the Ocean (ECCO)-GODAE systems that routinely produce global ocean data assimilation products

Table 3. GODAE systems: Main characteristics for routine setup

System	Forecast Range	Update Frequency	Hindcast Length
BLUElink>	7 days	Twice weekly	11 days
C-NOOFS	6 days	Daily	none
ECCO-GODAE	None	Up to every 10 days	
FOAM	5 days	Daily	1 day
HYCOM/NCODA	7 days	Daily	5 days
Mercator	14 days (weekly)	Weekly (global)	2 weeks (weekly)
	7 days (daily)	Daily (N Atl + Med)	
MFS	10 days	Daily	2 weeks
MOVE/MRI.COM	30 days	Every 5 days	10 days
NLOM/NCOM	4 & 30 days/4 days	Daily & weekly/daily	5 days
NMEFC	None	Monthly	
RTOFS	5 days	Daily	
TOPAZ	10 days	Weekly	1 week

include a near-real-time system based on Kalman filter/smoother assimilation (e.g., Fukumori, 2002) that runs at the Jet Propulsion Laboratory (hereafter called ECCO-JPL), and a delayed-mode estimation system based on the adjoint method (e.g., Wunsch and Heimbach, 2007) that runs at the Massachusetts Institute of Technology (MIT). Both systems use the MIT OGCM. ECCO products are primarily geared toward scientific applications for physical oceanography and climate research (e.g., Lee and Fukumori, 2003; Stammer et al., 2003; Wunsch et al., 2009). ECCO-GODAE products (along with those from other ECCO projects) are served by the Distributed Ocean Data System (DODS) and the Live Access Server (LAS). The products are characterized by their physical consistency (satisfying model equations exactly). This consistency allows the closure of property budgets (e.g., heat conservation) and greatly facilitates investigation of various processes controlling the evolution of the oceanic state, as well as oceanographic and climate research. ECCO products and tools have also been widely used for research in other areas, such as initialization of seasonal-to-interannual prediction, constraining regional analysis systems, geodesy, and biogeochemistry (references on various subjects can be found on the ECCO Web site—see Table 4). Different aspects

Table 4. GODAE systems: Web sites (accessed May 20, 2009)

System	Web Sites
BLUElink>	Technical description: http://www.bom.gov.au/oceanography/forecasts/technical_specification.pdf
	Viewing: http://www.bom.gov.au/oceanography/forecasts
C-NOOFS	Technical description: http://www.c-noofs.gc.ca/php/technical_e.php
	Viewing service: http://www.c-noofs.gc.ca/php/home_e.php
ECCO-GODAE	General and data servers: http://ecco-group.org/index.htm
	Additional data server: http://ecco.jpl.nasa.gov/external
FOAM	General: http://www.ncof.co.uk/Deep-Ocean-Modelling.html
HYCOM/NCODA	General: http://www.hycom.org/
	Viewing service: http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html
Mercator	General: http://www.mercator-ocean.fr/html/mod_actu/public/welcome_en.php3
	Viewing: http://bulletin.mercator-ocean.fr/html/welcome_en.jsp
MFS	General: http://gnoo.bo.ingv.it/mfs/
	Viewing service: http://gnoo.bo.ingv.it/mfs/Forecast/bulletin.htm?link=F
MOVE/MRI.COM	General: http://www.mri-jma.go.jp/Dep/oc/oc.html
	Viewing service (in Japanese): http://www.data.kishou.go.jp/kaiyou/db/index.html
NLOM/NCOM	Viewing service: NLOM: http://www7320.nrlssc.navy.mil/global_nlom32/skill.html
	Viewing service: NCOM: http://www7320.nrlssc.navy.mil/global_ncom/
NMEFC	General (in Chinese): http://www.nmefc.gov.cn
RTOFS	General: http://polar.ncep.noaa.gov/ofs/
	Viewing service: http://polar.ncep.noaa.gov/ofs/viewer.shtml?
TOPAZ	General: http://topaz.nersc.no
	Viewing service: http://topaz.nersc.no/Knut/

of ECCO products relevant to specific applications have been validated in a number of studies.

FOAM

The UK FOAM (Forecasting Ocean Assimilation Model) system run at the UK Met Office produces daily analyses and five-day forecasts of ocean and sea-ice variables. FOAM has full operational support including 24/7 operator coverage, on-call arrangements for response to problems by scientific staff, backup procedures, and use of resilient systems. The FOAM system currently uses the NEMO OGCM and Louvain-la-Neuve sea-Ice Model (LIM) version 2 (see Fichefet and Morales Maqueda, 1997). Various configurations are run, including a global 1/4° configuration on an Orca tripolar grid (Madec and Imbard, 1996), developed in collaboration with Mercator Océan, and nested 1/12° regional configurations of the North Atlantic, Mediterranean Sea, and Indian Ocean. These models are forced using six-hourly surface fluxes from the Met Office operational numerical weather prediction system.

An analysis correction assimilation scheme (see Cummings et al., 2009) is used together with schemes to correct for model and observation biases. Details of its implementation can be found in Martin et al. (2007).

The primary user of FOAM is the Royal Navy. Other users include ship routing and cable repair commercial outfits, the Met Office as input to the northwestern European model developed by the Proudman Oceanographic Laboratory (POL) for downscaling to coastal and shelf sea systems, and the Met Office for seasonal forecasting.

HYCOM/NCODA

The US Naval Oceanographic Office (NAVOCEANO) operates a 1/12° global ocean prediction system using the HYbrid Coordinate Ocean Model (HYCOM; see Bleck, 2002). This pre-operational system has been running in near-real time since December 2006, and in real time since February 2007 (Hurlburt et al., 2008; Chassignet et al., 2009). A one-year assimilative hindcast spanning June 2007–May 2008 was run to assess system performance and to compare with the NRL Coastal Ocean Model (NCOM)/NLOM system (Metzger et al., 2008). This hindcast was spun up to real time and is the basis for the system currently in use. The daily run consists of a five-day hindcast (which assimilates observations that have been received late) and a five-day forecast.

The model configuration is a global implementation of HYCOM 2.2 coupled to a thermodynamic ice model on a 1/12° Mercator grid from 72°S matching a bipolar grid for the Arctic north of 47°N with 32 hybrid layers in the vertical.

The system uses the three-dimensional multivariate optimum interpolation Navy Coupled Ocean Data Assimilation (NCODA; Cummings, 2005) system. Details of the implementation of NCODA in HYCOM can be found in Cummings et al. (2009). The model is forced during integration using Navy Operational Global Atmospheric Prediction System (NOGAPS) outputs including wind stress, wind speed, heat flux (using bulk formulae), and precipitation.

Users include NAVOCEANO, the research community, and private companies that use the nowcasts and forecasts to provide ocean state estimation that is critically important to cruising, shipping, fishing, and workboats fleets. Within the research community, the biggest users are coastal modeling groups that download the global HYCOM outputs as boundary conditions for even higher-resolution regional and coastal models. For an overview of the system and its applications, see Chassignet et al. (2009) and Hurlburt et al. (2008, 2009).

Mercator Océan

The French Mercator Océan operates a 1/4° global system with enhanced resolution (1/12°) in the tropical and North Atlantic (north of 20°S) and the Mediterranean Sea. The system uses the NEMO OGCM on an Orca tripolar grid and the LIM prognostic sea ice. Its assimilation system is based on the SEEK filter with fixed base (computed once from an ensemble) and an adaptive

"THE DEVELOPMENT OF GLOBAL AND REGIONAL OCEAN DATA ASSIMILATION SYSTEMS BEGAN IN THE 1990s."

scheme for the variance (Tranchant et al., 2008). Atmospheric forcing is applied by computing interactive fluxes (bulk formulae) of heat, momentum, and freshwater from European Center for Medium-Range Weather Forecasts (ECMWF) operational atmospheric products, applying a precipitation correction using US National Aeronautics and Space Administration (NASA) Global Precipitation Analysis (GPCP) data with a method derived from Troccoli and Kallberg (2004). River runoffs are computed from Dai and Trenberth (2003) climatology. The products are weekly updates of two-week forecasts for global ocean physics (including sea ice), and daily updates of one-week forecasts in the tropical and North Atlantic, and in the Mediterranean Sea.

Users include the French Navy and the research community. Mercator also is used in commercial applications, seasonal forecasting, oil-spill and drifting-object prediction, and downscaling to regional and coastal systems.

MFS

The Italian Group of Operational Oceanography has developed and maintains an ocean forecast system for the Mediterranean Sea (MFS) at the Istituto Nazionale di Geofisica e Vulcanologia as part of the Mediterranean Operational Oceanography Network. The first MFS system began providing weekly forecasts in 2000 (Pinardi et al., 2003). It was upgraded in 2005 to deliver daily 10-day forecasts. Assimilation is performed weekly with a 14-day hindcast (which assimilates observations that are received late). A biogeochemistry forecast is produced weekly, coupling offline with an ecosystem model operated by the Osservatorio Geofisico Sperimentale in Trieste, Italy.

At present, MFS is running a system based on NEMO implemented in the Mediterranean on a 1/16° grid with 72 unevenly spaced vertical levels (Tonani et al., 2008). The data assimilation system is a three-dimensional variational (3DVAR) scheme (Dobricic and Pinardi, 2008) that is nested into the Mercator system at the open boundaries of an Atlantic box west of the Strait of Gibraltar.

Forecast current fields have been used in support of search and rescue operations in collaboration with the Italian Coast Guard through a trajectory model. An MFS-MEDSLICK coupled system is operationally used for oil spill forecasting in support of Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea activities.

MOVE/MRI.COM

The Japanese Meteorological Research Institute (MRI) developed the Multivariate Ocean Variational Estimation (MOVE/MRI.COM) system, which has been operated by the Japan Meteorological Agency for nowcasting and forecasting since March 2008. There are three implementations: global (MOVE/MRI.COM-G), North Pacific (-NP), and western North Pacific (-WNP) systems (Usui et al., 2006) with a multivariate 3DVAR (Fujii and Kamachi, 2003a,b) and a preconditioned descent scheme (POpULar; Fujii, 2005). The global system application initializes seasonal-to-interannual forecasting, while North Pacific and western North Pacific system applications are ocean forecasting, sea surface temperature prediction, and oil spill forecasting. Reanalyses have also been conducted for climate analysis.

NLOM/NCOM

In addition to the pre-operational global HYCOM/NCODA system presented above, NAVOCEANO is running an operational two-model global ocean prediction system. The first model is NLOM, with simplified physics representation on the vertical, but with very high horizontal resolution. This system is designed to provide one-month forecasts of surface currents, including eddies and high-resolution processes on the one hand, and estimates of sea surface height (SSH) and sea surface temperature (SST) through the assimilation of altimeter SSH on the other. Its outputs, in addition to other observations, are used as described below to constrain NCOM, a full OGCM with high vertical resolution that includes more complexity in the physics representation but features lower horizontal resolution. NCOM is designed to provide boundary data for coastal systems worldwide.

NLOM is a layered model system (Wallcraft et al., 2003) featuring six Lagrangian layers capped by a mixed layer (seventh layer) implemented on a global 1/32° grid, and forced by daily outputs of NOGAPS. NLOM has run operationally at NAVOCEANO since September 2001, first with 1/16° horizontal resolution (Smedstad et al., 2003), and then at 1/32° since March 2006 (Shriver et al., 2007). NLOM was the first global ocean forecasting system to assimilate real-time altimeter data.

The NLOM assimilation of altimeter data is performed using an optimal interpolation (OI) deviation SSH analysis with the model SSH field as the first guess. A statistical inference technique updates all layers of the model based on the analyzed SSH deviations (Hurlburt et al., 1990), and a geostrophic update for the velocity field is calculated outside the equatorial region. An incremental updating scheme is used to assimilate the data.

Global NCOM (Barron et al., 2006) is a free-surface ocean model that allows its 40 vertical levels to consist of sigma coordinates for the upper layers and z-levels below. A stretched spherical grid south of 32°N with 14-km spacing transitions to an Arctic basin on a 5-km rotated bipolar grid with singularities over land in Siberia and Canada. Global NCOM has been providing daily forecasts in real time since November 2001 and became operational in March 2006. The current NCOM system (third generation), provides five-day forecasts, uses NCODA (Cummings, 2005) to assimilate in situ observations into a background of synthetic profiles, and includes a coupled ice model (Polar Ice Prediction System 3.0; Van Woert et al., 2004) for the Arctic.

The assimilation in NCOM is based on a three-dimensional interpolation system, including sophisticated vertical inference of surface parameters, called the Modular Ocean Data Assimilation System (MODAS; see Fox et al., 2002), which combines SSH coming from NLOM, SST from MODAS-2D (Barron and Kara, 2006), and historical correlations of SSH/SST/T/S to produce three-dimensional estimates of temperature (T) and salinity (S). These three-dimensional T and S estimates are assimilated into NCOM using a nudging technique. In the latest version, an NCODA analysis of in situ observations, using the three-dimensional T and S estimates as a first guess, is assimilated into NCOM. Surface heat and salinity fluxes are adjusted by the data-model differences times a flux rate. A more detailed description of the MODAS/NCOM assimilation system can be found in Rhodes et al. (2002) and Barron et al. (2007).

NMEFC

The National Marine Environment Forecast Centre of China (NMEFC) of the State Oceanographic Administration has implemented an operational ocean analysis system to estimate temperature and salinity fields in the tropical Pacific Ocean. This system was launched in 2008 to provide monthly real-time monitoring of ENSO events that have a large impact on Chinese climate variability.

This system is based on an OGCM developed by the Institute of Atmospheric Physics (IAP), Chinese Academy of Science (Zhang and Endoh, 1992), and implements primitive equations under hydrostatic and Boussinesq approximation in the tropical Pacific (30°S–30°N, 69°W–121°E) at 2° x 1° horizontal resolution, with eastern and western boundaries following realistic coastlines and no-slip and no-flux conditions applied to them. Relaxation of T and S (60 days time scale) to Levitus (1982) climatology is applied at the open boundaries (north and south). There are 14 levels on the vertical, with 10 levels in the upper 240 m, and flat bottom topography.

Observations are assimilated using a 3DVAR scheme called the Ocean Variational AnaLysis System (OVALS). The assimilation time window is 30 days. Control variables are temperature and salinity, which are both adjusted using nonlinear T/S relations as balance constraints for the assimilation of altimeter data as described by Zhu and Yan (2006). To reduce the memory size of the assimilation, vertical and horizontal background error correlations are solved separately (Yan et al., 2004).

The model is forced during integration using wind stress computed from the US National Centers for Environmental Prediction (NCEP) wind speed retrieved from the NCEP Web site, blended with Hellerman and Rosenstein (1983).

RTOFS

NCEP has implemented a prediction system in the North Atlantic called the Real-Time Ocean Forecast System (RTOFS). Operated on a routine daily basis to provide five-day forecasts of ocean state, RTOFS is designed to provide seamless boundary and initial conditions to more regional systems and to biogeochemical systems. RTOFS started to run in near-real time in 2005 (Chassignet et al., 2009).

This system is based on HYCOM, including body tides (eight constituents), implemented in the North Atlantic from ~ 20°S to ~ 70°N on a curvilinear coordinate grid whose horizontal resolution ranges from 18 km in the eastern North Atlantic to 4 km in the Gulf of Mexico, and with 26 hybrid coordinates on the vertical (21 isopycnal and five z-levels near the surface).

The assimilation system is an in-house 2DVAR scheme with one-dimensional vertical modes. The horizontal 2DVAR assumes a Gaussian isotropic, inhomogeneous covariance matrix using recursive filtering (Purser et al., 2003a,b), while the vertical covariance matrix is constructed from coarser-resolution simulations and implements the lifting/lowering of the main pycnocline for assimilation of altimeter SSH.

The model is forced using three-hour NCEP (Global Data Assimilation System/Global Forecast System [GDAS/GFS]) model outputs. The open boundaries are relaxed to climatology. Rivers' freshwater fluxes are prescribed from a blend of observations (USGS data) and climatology (Global River Discharge [RivDIS]).

The primary RTOFS user is the US National Oceanic and Atmospheric Administration (NOAA), and one of its major applications is the provision of initial conditions for a coupled ocean-atmosphere model based on HYCOM and the Hurricane Weather Research and Forecasting (HWRF) model for more accurate monitoring and prediction of hurricanes.

TOPAZ

Towards an Operational Prediction system for the North Atlantic European coastal Zones (TOPAZ; Bertino and Lisæter, 2008), developed at the Nansen Environmental and Remote Sensing Center in Norway, has been operating continuously since January 2003. In March 2008, the Norwegian Meteorological Institute (met.no) began exploiting the TOPAZ system in its operational suite.

TOPAZ uses the HYCOM model and the Ensemble Kalman Filter (EnKF; see Evensen, 2006) and covers the North Atlantic and Arctic configuration with 11-km to 16-km horizontal resolution and 22 hybrid vertical layers. HYCOM is coupled to an Elastic Viscous Plastic dynamic and thermodynamic sea-ice model. The system is forced by operational forecasts and analyses from ECMWF. EnKF runs 100 members with model errors in the wind and heat forcing terms; the same ensemble is used for all observations assimilated.

> "THE TRANSITION TO OPERATIONAL SERVICES REQUIRES THAT THESE OBSERVING SYSTEMS AND THE CORRESPONDING REAL-TIME PROCESSING AND DELIVERY SERVICES BE MAINTAINED IN THE LONG TERM."

TOPAZ serves ocean and sea-ice forecasts to the public, to environmental agencies, and to private users such as the offshore oil and gas industry, in particular, through acoustic tomography in the Fram Strait, iceberg modeling in the Barents Sea (Keghouche et al., 2009), ecosystem modeling in the Norwegian Sea, and eddy forecasting in the Gulf of Mexico (Counillon and Bertino, 2009).

SOME EXAMPLES OF SYSTEM PERFORMANCE EVALUATION

One of the major GODAE assets is the definition and implementation of performance metrics (Le Provost, 2002), which are used routinely to assess product quality and accuracy and system performance (i.e., accuracy of the forecast), and to measure progress made when updating the systems. We present here a brief performance overview for some of the systems. Hernandez et al. (2009) give a more exhaustive presentation of this system assessment and product validation methodology.

Innovation, defined as the difference between the observation and the model's first-guess forecast of the observed variable at the observation's location, is used to monitor a system's ability to simulate the real ocean as observed. Figure 1 shows the innovation root mean square (RMS) for altimeter sea level anomaly (SLA) observations. Jason-1 SLA RMS error with the Mercator system (top panel) is between 8 cm and 9 cm for the global ocean, and around 4 cm for the Niño 4 region in the tropical Pacific (5°S–5°N, 160°W–150°E). We see that this RMS error is stable, remaining below the RMS of the altimeter SLA shown in black at top. However, the performance (not shown) is lower in regions of high energy such as the western boundary currents, where the mesoscale activity is highly energetic and resolved by neither the model nor the observation systems. The bottom panel shows similar results obtained with the MFS system for the Mediterranean Sea. Here again, the SLA RMS error remains stable with values around 4 cm during the whole period, which is smaller than the RMS of the observations (not shown), which varies

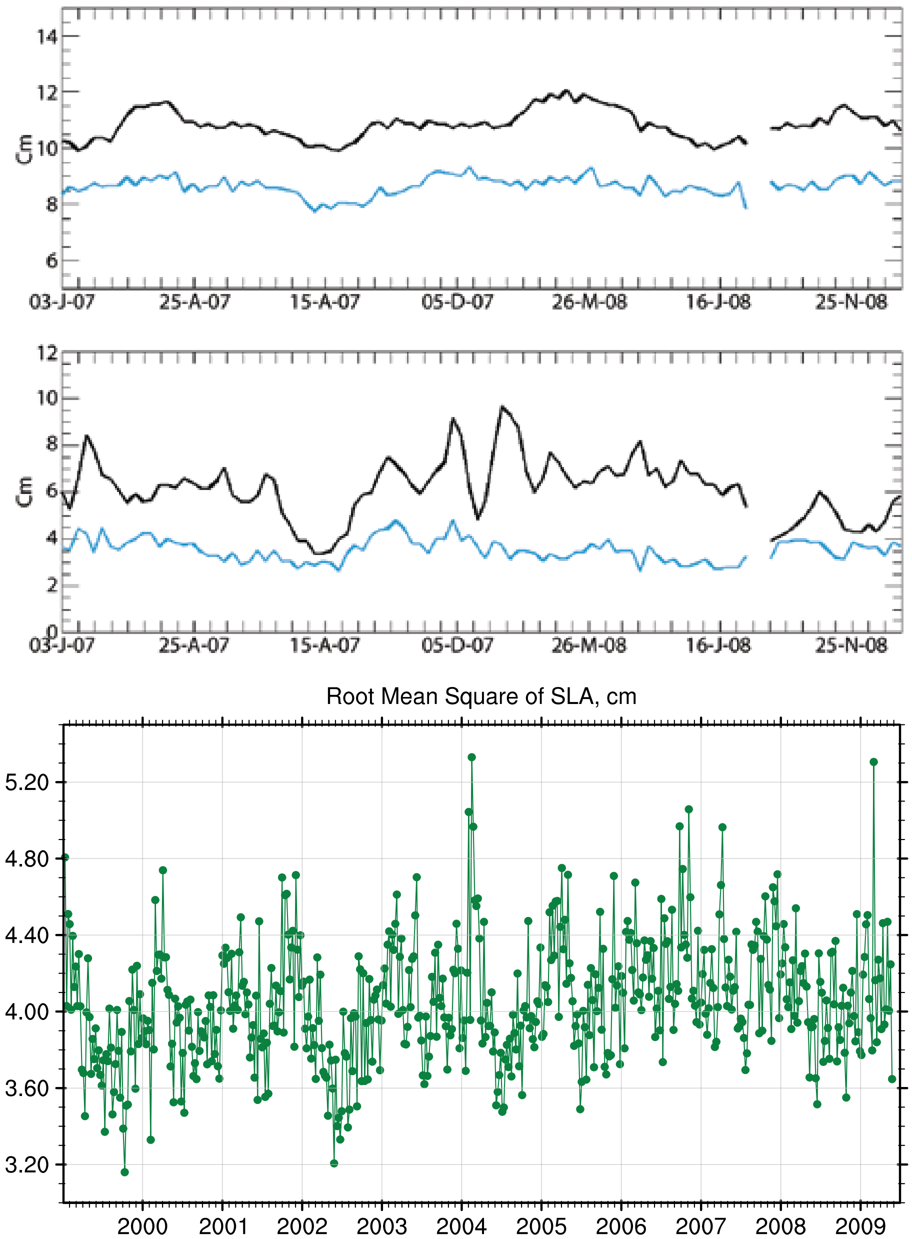

Figure 1. Root Mean Square (RMS) error of sea level anomaly (SLA) in centimeters for the Mercator system computed over the global ocean (top, blue line), the Niño 4 box in the tropical Pacific (middle, blue line) for 2007–2008, and the MFS (Mediterranean ocean Forecast System) system computed over the Mediterranean Sea from August 2004 to October 2008. For the top and middle panels, the solid black curve shows the RMS error of observed SLA.

between 5 cm and 17 cm with an average of about 8 cm in this area.

Figure 2 shows innovation statistics at depth for the in situ profiles of temperature and salinity obtained with the FOAM system over a one-year period. We see here that, thanks to the assimilation of observations, and unlike simulations without assimilation, no bias develops in the system except near the surface where some limited bias is observed. RMS error is maximum in the upper ocean with values up to 1.3°C and 0.3 PSU at about 100 m. The RMS error decreases with depth and is lower than 0.5°C below 1000 m, and 0.1 PSU below 700 m. This illustrates the ability of the FOAM system to remain close to the observed values for a one-year period. We see also that results obtained with the regional eddy-resolving system are better than those obtained with the global eddy-permitting system in this area. However, the improvement with increased resolution is not very large, suggesting that the observing system is not dense enough (especially the in situ network) to properly constrain, through use of data assimilation methods, the eddy field that develops in the eddy-resolving model configuration.

The innovation statistics shown here illustrate the ability of system outputs to remain close to the observed values of SLA, SST (not shown), and T/S profiles for multiyear periods, thanks to multivariate assimilation of surface and subsurface observations. This correlation would not have been the case without the combined multivariate assimilation of surface remotely sensed observations and in situ profiles (see Oke et al., 2009, for the relative impact of observation types through assimilation).

The skill of systems is also assessed through analysis of parameters that are not directly assimilated. This analysis can be done using independent observations (data not assimilated), or through derived quantities. Figure 3 shows a comparison of Kuroshio transport obtained with the MOVE/MRI.COM system south of Japan (Affiliated Surveys of the Kuroshio off Cape Ashizuri [ASUKA] line). Transport observation is calculated using a regression method with satellite altimetry and in situ data (Imawaki et al., 2001). The volume transport average (around 40 Sverdrups) and its simulated variability are close to the ones derived from observations. Some peak values are due to strong mesoscale eddies.

Various teams undertake additional validation efforts for specific applications. For example, Figure 4 shows that the composite seasonal variations of zonal wind, SSH, and SST in the equatorial Indian Ocean estimated by the ECCO-JPL product (upper panels) are fairly similar to the observational counterparts (lower panels) in terms of the magnitude and phase of the annual and semi-annual signals. This consistency inspires confidence for use of the ECCO product to study the seasonal variability of the tropical Indian Ocean (Halkides and Lee, 2009).

The assessment can also be based on the analysis of products of these systems that are used to serve the specific needs of each area. Figure 5 shows an example of such applications with the use of currents from the TOPAZ system in the Barents Sea as forcing fields for iceberg trajectory modeling from Keghouche et al. (2009). This figure shows the ability of the TOPAZ system to forecast the location of an iceberg after two months of drift, and to indicate the uncertainty of the forecast using ensembles.

CONCLUSIONS

The initial GODAE goal was to have global high-resolution (a few kilometers) advanced ocean modeling and assimilation systems fully assessed, operating in real time, and providing forecast services to users. Much progress toward this goal has been made

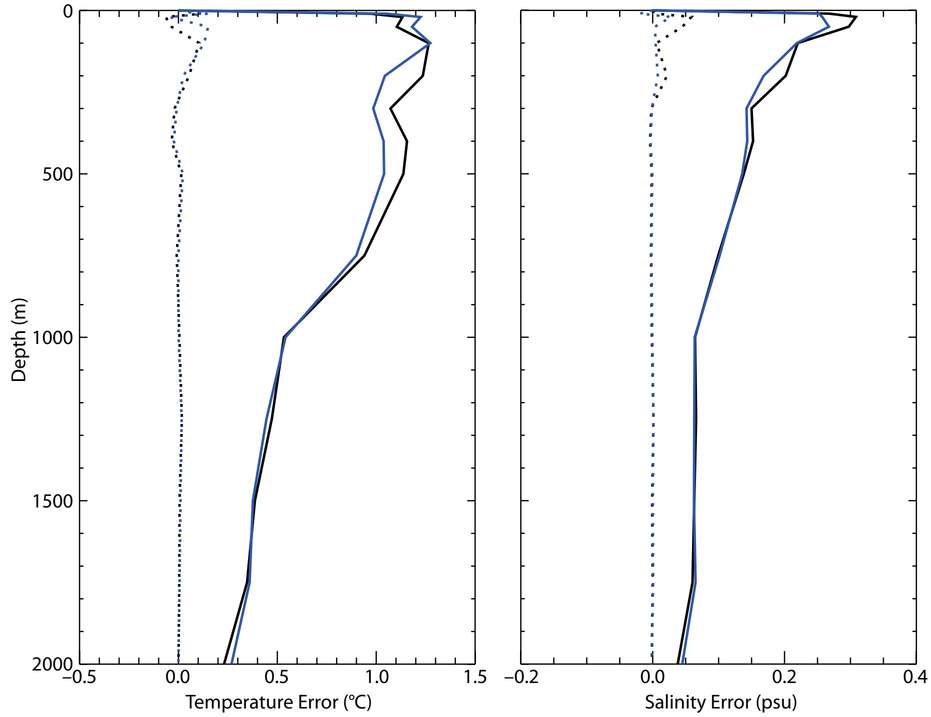

Figure 2. In situ profile innovation statistics for FOAM (Forecast Ocean Assimilation Model) global 1/4° (black) and regional 1/12° (blue) models in the North Atlantic computed over one year (from April 1, 2005, to March 31, 2006). Dark lines = RMS error. Dotted lines = bias (left is temperature, right is salinity).

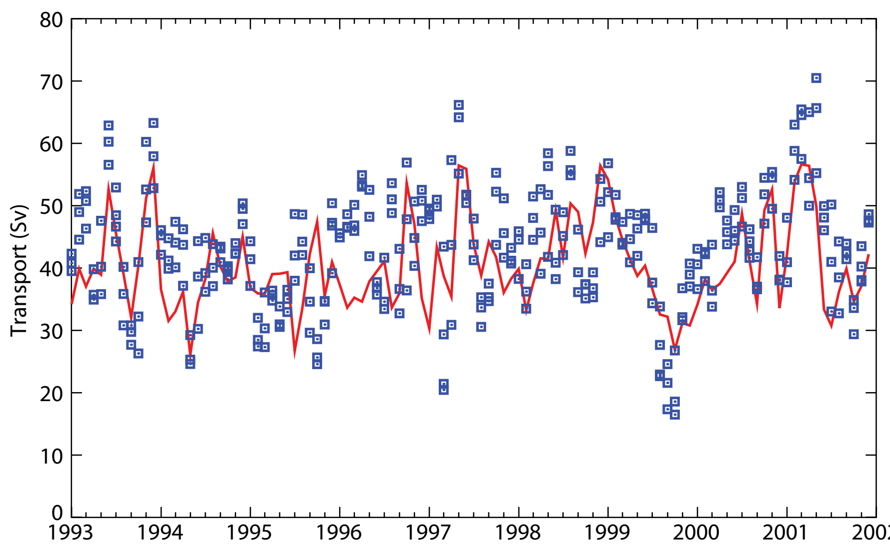

Figure 3. Comparison of the Kuroshio transport time series south of Japan. Red = MOVE/MRI.COM (Meteorological Research Institute Multivariate Ocean Variational Estimation). Square = observation.

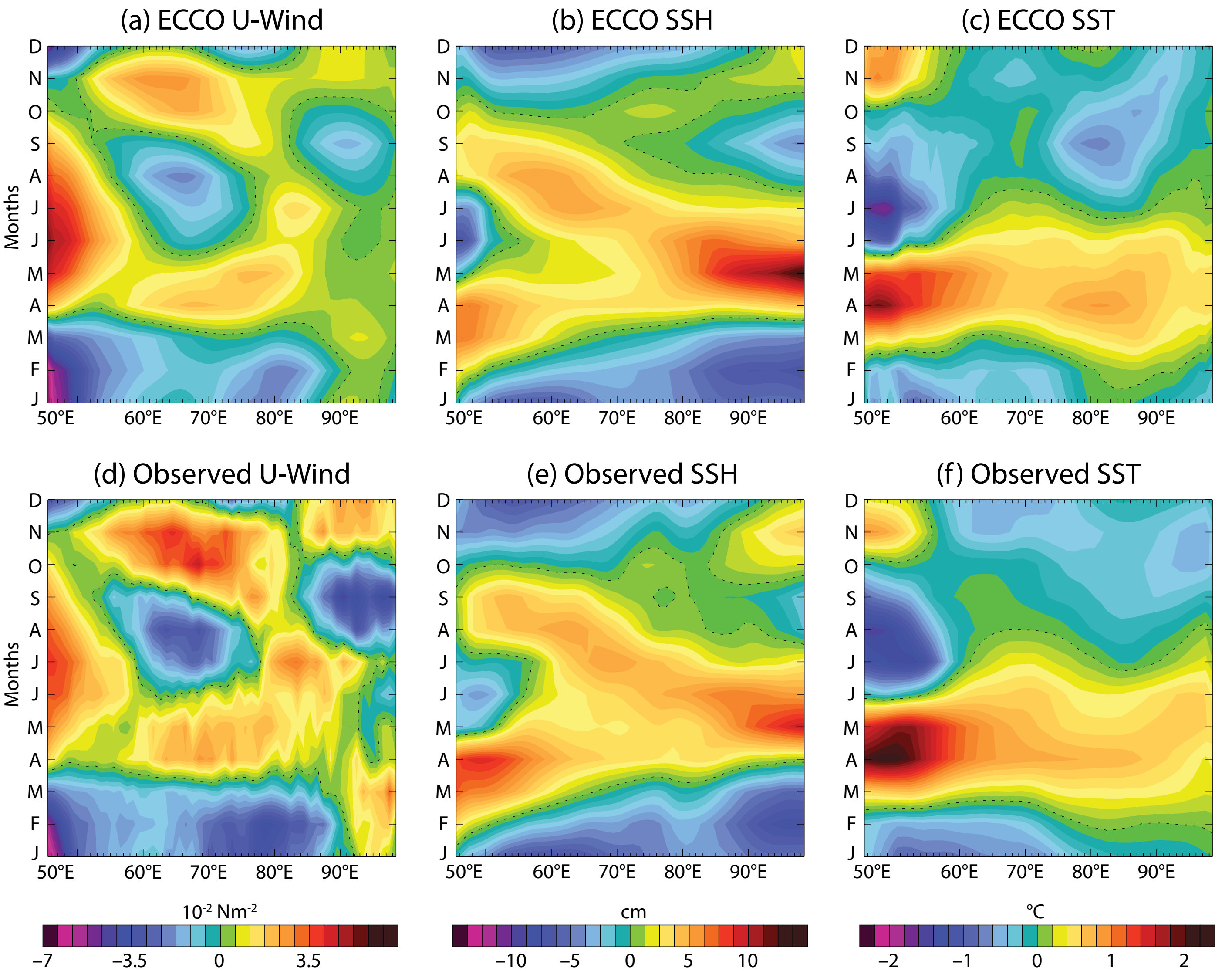

Figure 4. Comparison of seasonal variations of zonal wind stress, sea surface height (SSH), and sea surface temperature (SST) averaged across the equatorial Indian Ocean (0.5°S–0.5°N) between estimates from the ECCO-JPL (Estimating the Circulation and Climate of the Ocean-Jet Propulsion Laboratory) product and satellite observation for the period 2000–2006. *After Halkides and Lee (2009)*

during the 10-year GODAE period: today, several monitoring and forecasting systems have been developed and are operating in countries that have participated in GODAE. This advance has been possible because some nations developed operational oceanography systems, and because of their commitment to participate in this international experiment. The result of these national initiatives is availability of a real service capacity based on the systems discussed in this paper, and the implementation of mechanisms for their sustained development and operations—all the systems presented in this paper are still operating after the end of GODAE. Though this is close to the GODAE target for technical capacity, there is still some work to do, including not only R&D and engineering efforts but also international coordination to transition from the GODAE feasibility demonstration to fully operational implementation of services. In particular, the accuracy of the ocean estimates will have to be improved to reach most users' requirements, and systems will have to be extended to other fields such as ecosystem and coastal ocean research to respond to societal needs. This augmentation will lead to transitioning from the approach pushed

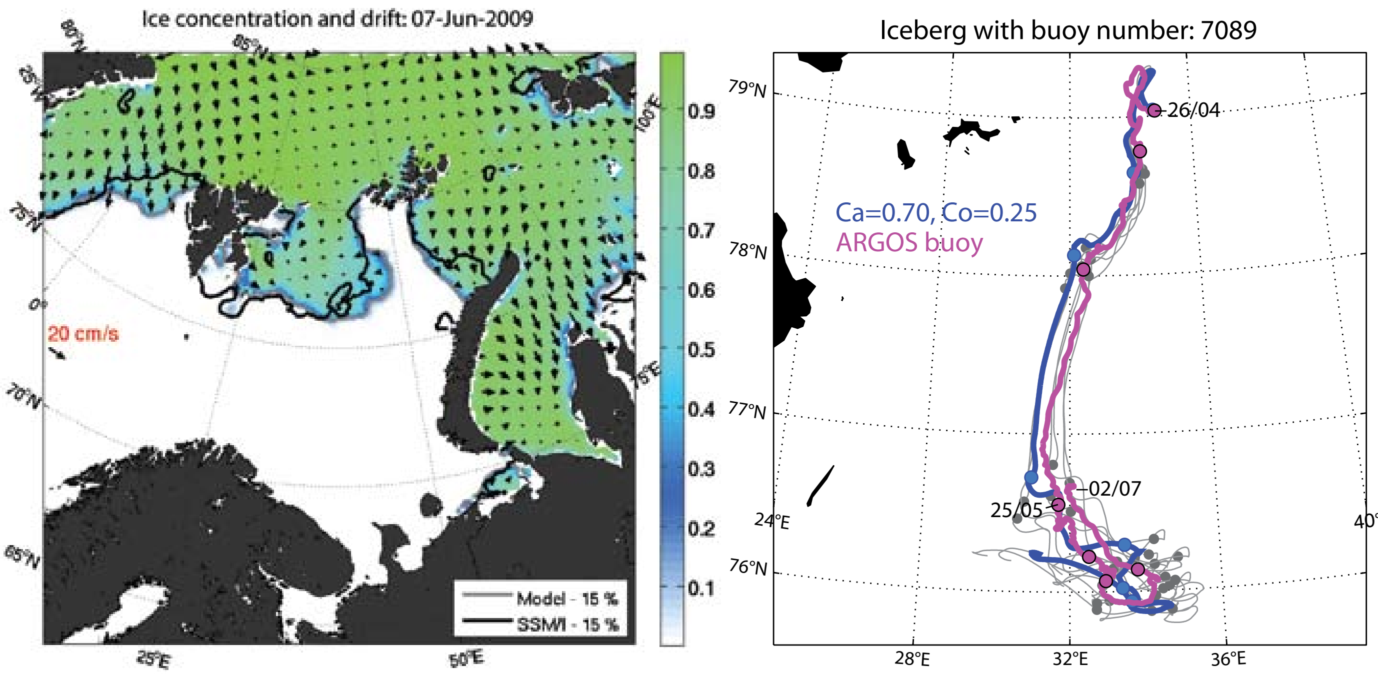

Figure 5. (a) Sea-ice concentration and drift at assimilation +5 days compared to ice edge from SSM/I (black line). (b) Application of TOPAZ (Towards an Operation Prediction system for the North Atlantic European coastal Zones) in the Barents Sea: ensemble simulation of an iceberg trajectory during two months (from Keghouche et al., 2009, © 2009, American Meteorological Society). The magenta line is hourly observations from the Ice Data Acquisition Program; the dots mark every 10 days along the trajectory. The blue and gray lines are, respectively, the best member and the rest of the ensemble. The average error of the best member is 15 km and the ensemble spread is of similar amplitude.

by technology and science, which has been one driver for GODAE, based on opportunities in terms of capacity (e.g., science, computing, observations), to a new approach for which new developments will be driven by users' needs. Finally, the building of this capacity has been possible because of the parallel development of observing systems, such as radar satellite altimeters and the Argo array, and observation centers that provide quality observations in real time on a routine basis. The transition to operational services requires that these observing systems and the corresponding real-time processing and delivery services be maintained in the long term.

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