Continental Shelf Research 63 (2013) S159–S176

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Multiscale forecasting in the western North Atlantic: Sensitivity of model forecast skill to glider data assimilation

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ARTICLE INFO

Article history:
Received 29 April 2011
Received in revised form
15 September 2012
Accepted 26 September 2012
Available online 11 October 2012

Keywords:
Glider data assimilation
Multiscale real-time forecasting
Observing simulation experiment (OSE)
Western North Atlantic
Mid-Atlantic Bight

ABSTRACT

A recently implemented real-time ocean prediction system for the western North Atlantic based on the physical circulation model component of the Harvard Ocean Prediction System (HOPS) was used during an observation simulation experiment (OSE) in November 2009. The modeling system was built to capture the mesoscale dynamics of the Gulf Stream (GS), its meanders and rings, and its interaction with the shelf circulation. To accomplish this, the multiscale velocity-based feature models for the GS region are melded with the water-mass-based feature model for the Gulf of Maine and shelf climatology across the shelf/slope front for synoptic initialization. The feature-based initialization scheme was utilized for 4 short-term forecasts of varying lengths during the first two weeks of November 2009 in an ensemble mode with other forecasts to guide glider control.

A reanalysis was then carried out by sequentially assimilating the data from three gliders (RU05, RU21 and RU23) for the two-week period. This two-week-long reanalysis framework was used to (i) study model sensitivity to SST and glider data assimilation; and (ii) analyze the impact of assimilation in space and time with patchy glider data. The temporal decay of salinity assimilation is found to be different than that of temperature. The spatial footprint of assimilated temperature appears to be more defined than that of salinity. A strategy for assimilating temperature and salinity in an SST-glider phased manner is then offered. The reanalysis results point to a number of new research directions for future sensitivity and quantitative studies in modeling and data assimilation.

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1. Introduction

Ocean observing has advanced in the last decade from a ship-based expeditionary science to a distributed and observatory-based approach. This transition, which has been occurring over last decade (Glenn and Schofield, 2003, 2009), reflects the maturation of a wide range of observation platforms, data assimilative numerical models, and improved global communications (Schofield et al., 2012). The expanding suite of observational assets include remote sensing (satellite: Halpern, 2000, aircraft: Lomax et al., 2005, HF Radar: Crombie, 1955; Barrick, 1972; Barrick et al., 1977), fixed location assets (moorings: Hayes et al., 1991, Weller et al., 2000, seafloor cables: Schofield et al., 2002, Kunze et al., 2006), and Lagrangian platforms (AUVs: Blackwell et al., 2008, gliders: Sherman et al., 2001, Eriksen et al., 2001, Webb et al., 2001, drifters: Niiler et al., 2003, floats: Davis et al., 1992, Gould et al., 2004). As the number of deployed platforms increases there is a growing need to aggregate the data and coordinate the sampling among the individual systems in order to create a system-of-systems. This will require the development of coherent software networks that allow a distributed group of sensors and/or scientists to operate as a group.

The integration of software systems is currently under development. For example, the U.S. National Science Foundation's Ocean Observatory Initiative (OOI, http://www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/) has focused a significant effort on developing a sophisticated cyberinfrastructure (CI) that binds the physical observatory, computation, storage and network infrastructure into a coherent system-of-systems. This CI is also being designed to provide a web-based social network, enabled by real-time visualization and access to numerical models, to provide the foundation for adaptive sampling science. The OOI cyber-development has chosen to utilize a spiral design strategy, allowing the oceanographic community to provide input during the construction phase with the strategy of utilizing existing ocean observing networks. For this effort, the OOI utilized an existing

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0278-4343/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.csr.2012.09.013

ocean observing network in the Mid-Atlantic Bight (MAB) as part of the National Oceanographic and Atmospheric Administration's (NOAA) Integrated Ocean Observing System (IOOS) in November 2009. The goal was to use this network to conduct an observation simulation experiment (OSE). The objective was to use the oceanographic testbed to support field operations of ships and mobile platforms aggregate data from fixed platforms, shore-based radars, and satellites; and offer these data streams to data-assimilative forecast models. Additional goals were to use multi-model forecasts to guide glider missions and coordinate satellite observing, and to demonstrate the ability to conduct two-way interactions between the sensor web and predictive models. While previous studies have focused on the phytoplankton dynamics during spring and/or spring transition (Ryan et al., 1999a, 1999b, 2001), this field effort was conducted to collect data on the status of the Mid-Atlantic shelf in early winter, when the winter phytoplankton bloom occurs (Schofield et al., 2010).

This paper uses data collected during the OSE to investigate the forecast sensitivity to glider data assimilation. One goal of this study is to understand and develop a protocol for future similar test experiments based on a careful reanalysis during the OSE period. An interesting new result from the assimilation analysis is the apparent difference of spatial and temporal scales of impact between temperature and salinity. These behavioral differences might lead to future areas of research in modeling and assimilation.

This paper is organized as follows. The methodology is presented in Section 2 and the analysis of the real-time forecasts made during the OSE period is presented in Section 3. A reanalysis based on systematic glider data assimilation is presented in Section 4, followed by a summary and discussion in Section 5.

2. Approach and methods

A distributed community of ocean scientists provided the CI team with regional surface datasets, a surface current mapping network, a constellation of fixed and taskable satellites, a fleet of autonomous Slocum gliders, a multi-vehicle network of autonomous underwater vehicles, and five different data-assimilative forecast ocean models that tested the OOI software. An overview of the OSE effort is described by Schofield et al. (2010). The OSE was a multi-institutional, multi-investigator effort. Various OSE groups coordinated satellites, multiple gliders, and an AUV during the OSE period of October 26 through November 17, 2009. A data and model portal was assembled (http://ourocean.jpl.nasa.gov/CI) (Wang et al., in this issue) for multi-model ensemble forecasting and glider guidance decision-making efforts.

2.1. Regional data streams

A large suite of satellites were used during this study. The satellites provided multiple passes of sea surface temperature and ocean color observations. The data was downloaded and processed at both the NASA Jet Propulsion Lab and the Rutgers Coastal Ocean Observation Lab. Data was processed in near real-time (hours) and posted to the data portal.

The surface currents on the MAB are measured by an extensive network of high frequency CODAR networks array. The CODAR network consists of twelve 5 MHz systems located along the northeast of the United States. The HF Radar uses the Doppler Shift of a radio signal backscattered off the ocean surface to measure the component of the flow in the direction of the antenna. The network provides surface current estimates to a depth of 2.4 m (Stewart and Joy, 1974).

2.2. Gliders

Slocum gliders are an autonomous underwater scientific platform (Webb et al., 2001) manufactured by the Teledyne-Webb Research Corporation. They are 1.8-m long, torpedo-shaped, buoyancy-driven vehicles with wings that enable them to maneuver through the ocean at a forward speed of 20–30 cm s^{-1} in a sawtooth-shaped gliding trajectory. Each Slocum glider has a payload bay that houses a SeaBird conductivity–temperature–depth sensor and includes space for a range of additional sensors. The glider acquires its global positioning system (GPS) location every time it surfaces, which is programmable and was set to call-in every 3 h for the purposes of this study. By dead reckoning along a compass bearing while flying underwater, estimates of depth averaged current can be calculated based on the difference between the glider's expected surfacing location and the actual new GPS position. Depth averaged current measurements obtained in this manner have been validated against stationary Acoustic Doppler Current Profiler data (Glenn and Schofield, 2003).

During this experiment, four Webb gliders were deployed by Rutgers University and the University of Delaware. The gliders were deployed prior to the start of the experiment on Nov 1 2009 and operated for two weeks. During that period the gliders traversed 1673 km underwater collecting 23,332 vertical profiles. The data collected were analyzed for various process studies including phytoplankton productivity (Schofield et al., 2012) and sediment re-suspension during fall storms (Miles et al., in this issue).

2.3. Numerical model

One of the five numerical models employed during the OSE is the SMAST-HOPS (School for Marine Science and Technology—Harvard Ocean Prediction System) real-time forecast system, which has been operational since March 9, 2009, providing a 7-day ocean forecast for the large-scale Gulf Stream region from Cape Hatteras to 55°W, including the Gulf of Maine and the Mid-Atlantic shelf region. The other four models were: (i) the New York Harbor Ocean Prediction System (NYHOPS) for MARACOOS (Bhushan et al., 2009; Georgas and Blumberg, 2009); (ii) the regional ocean modeling system for MARACOOS (Wilkin et al., 2005); (iii) the regional ocean modeling system from USGS (Warner et al., 2008); and (iv) the MIT multidisciplinary simulation, estimation and assimilation system (MSEAS) (Lam et al., 2009; Haley and Lermusiaux, 2010). The SMAST-HOPS operational system (described by Schmidt and Gangopadhyay, 2012, in this issue, SG12 henceforth; Brown et al., 2007a, b; Robinson et al., 2001) regularly assimilates satellite SST and, when available, MARACOOS glider-measured 4-D water properties to produce weekly 3-D nowcast and forecast MARACOOS regional temperature maps (see http://www.smast.umassd.edu/modeling/RTF/index.php). Four forecasts were provided during the OSE period, assimilating all available data from SST and the four gliders.

The horizontal structure of the SMAST-HOPS operational model domain consists of 131 × 83 grid points with 15 km resolution, extending from 30.5°N to 47.93°N in the meridional and from 80.54°W to 54.23°W in the zonal direction. The vertical structure of the model is resolved by 16 levels that are distributed according to a topography-following "double sigma" transformation described by Lozano et al. (1996) and Sloan (1996). The open boundary conditions for tracers and velocity are based on Orlanski (1976); and the horizontal subgridscale processes are parameterized using a set of scale-selective Shapiro filters: 4-1-1 (fourth order, one time, every time step) for velocity and tracers, a 2-2-1 for vorticity and 2-1-1 for streamfunction. The time step