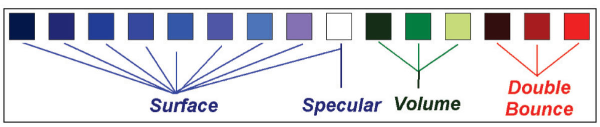
(a) Classification map



(b) Color-coded class label

FIGURE 5
(a) Final classification map of the San Francisco image into 15 classes. (b) The color-coded class label indicates scattering mechanisms.

and to rapid detection and deployment in disaster management, e.g., the detection of landslide associated with earthquake and forest fires.

Acknowledgment: DARPA has funded us through a terrain characterization study using a FOPEN (foliage penetration) UHF (233-445 MHz) polarimetric SAR. A FOPEN terrain characterization software package has been developed based on this automated classification technique and is being integrated into a FOPEN Terrain Workstation.

[Sponsored by ONR and DARPA]

References

[1] J.S. Lee, M.R. Grunes, E. Pottier, and L. Ferro-Famil, "Unsupervised Terrain Classification Preserving Scattering Characteristics," *IEEE Trans. Geoscience Remote Sens.* **42**(4), 722-731 (2004).

[2] A. Freeman and S.L. Durden, "A Three-Component Scattering Model for Polarimetric SAR Data," *IEEE Trans. Geoscience Remote Sens.* **36**(3), 963-973 (1998).

★

Comparing Ocean Prediction System Skill Using Ocean Color

H.E. Hurlburt,[1] J.F. Shriver,[1] O.M. Smedstad,[2] A.J. Wallcraft,[1] R.A. Arnone,[1] C.N. Barron,[1] E.P. Chassignet,[3] P.M. Flynn,[1] D.-S. Ko,[1] R.C. Rhodes,[1] and L.F. Smedstad[1]
[1] *Oceanography Division*
[2] *Planning Systems Inc.*
[3] *University of Miami*

Introduction: This article illustrates the value of SeaWiFS ocean color imagery in assessing the ability of five different ocean prediction systems to map the "ocean weather." Nowcast results are presented from three global systems in the northwestern Arabian Sea and from all systems in the Gulf of Mexico. Ocean weather includes warm and cold eddies, the oceanic analog of atmospheric highs and lows, and the meandering pathways of ocean currents and fronts. Ocean color imagery is a unique independent data set that is very effective in differentiating the relative skill of the different systems and in helping to diagnose specific strengths and weaknesses of the systems. Ocean color from the SeaWiFS satellite (operated by Orbital Sciences Corp.) was collected and processed at NRL using an extension of NASA algorithms.[1] Improved coupled ocean-atmosphere algorithms for coastal waters were used to uncouple the spectral color signature into the near-surface chlorophyll concentrations. These images provide unique tracers of both circulation and biological activity. Daily chlorophyll images were generated by a 7-day latest pixel composite to remove clouds and retain ocean features. The chlorophyll features are clearly associated with the location of ocean circulation features, whereas their absolute concentration is associated with the biological response. Features marked by both chlorophyll-rich and chlorophyll-poor water proved useful in comparing the ocean prediction systems. In addition, the study clearly illustrates that biological responses of the surface waters are strongly linked to physical events and processes.

Ocean Prediction Systems Compared: The five ocean prediction systems are based on three ocean models. (1) The NRL Layered Ocean Model (NLOM) has seven Lagrangian layers in the vertical (layer thickness varies in space and time), including the mixed layer. It is relatively inexpensive computationally and thus is presently run with high horizontal resolution globally (excluding the Arctic and most shallow water). Two of the systems are based on this model with 1/16° and 1/32° (~7 km and ~3.5 km mid-latitude) resolution. (2) The Navy Coastal Ocean Model (also developed at NRL) uses 40 levels in the vertical, which are at fixed depths in deep water and terrain following at depths <137 m. Two systems presented here are based on NCOM. The first uses a 1/8° fully global configuration (15-16 km midlatitude resolution)[2] and the second uses a regional 1/24° Intra-Americas Sea (Caribbean, Bahamas, Gulf of Mexico) configuration nested in the global NCOM. (3) The HYbrid Coordinate Ocean Model (HYCOM) has a generalized vertical coordinate, which is typically Lagrangian isopycnic in the stratified ocean, fixed depth in the unstratified mixed layer, and terrain-following in shallow water. It makes a dynamically smooth space-time varying transition between the coordinate types via the layered continuity equation. It has been developed under the National Ocean Partnership Program as a next-generation community ocean model, with contributions from researchers at several different institutions, including NRL. Here HYCOM is used in a 1/12° Atlantic configuration (~7 km midlatitude resolution) with 26 hybrid layers in the vertical.

All of the prediction systems assimilate sea surface height (SSH) from satellite altimetry and sea surface temperature (SST) from satellite infrared radiometry. The 1/16° global NLOM system[3] (1/16° NLOM) was the world's first real-time global prediction system of the ocean weather (October 2000), and in September 2001 it became the first operational system (run at the Naval Oceanographic Office). It is slated for replacement by the 1/32° global NLOM system[4] (1/32° NLOM) in early 2005. The 1/16° and 1/32° NLOM systems are the only ocean prediction systems here that assimilate altimeter track data using the model as a first guess. All of the NCOM systems assimilate SSH indirectly via synthetic temperature and salinity profiles. In this manner, the 1/8° global NCOM system assimilates the SSH analysis from 1/16° NLOM (1/8° NCOMa) or 1/32° NLOM (1/8° NCOMb). In that sense, global NLOM and global NCOM are components of the same ocean prediction system.[5] The high horizontal resolution of NLOM is used to assimilate altimeter data and to make 30-day forecasts of the ocean weather, while NCOM extends coverage to the Arctic and shallow water and adds the capability to make 5-day forecasts of the ocean mixed layer and upper ocean with high vertical resolution and to provide boundary conditions for nested models. The 1/24° Intra-Americas Sea (IAS) NCOM (1/24° NCOM) is nested in 1/8° NCOM and assimilates model-independent SSH analyses, as does the present version of the 1/12° Atlantic HYCOM prediction system (1/12° HYCOM). The surface observations provided by satellite have a strong correlation to the subsurface ocean structure, and each system represents this correlation differently. A 1/12° global HYCOM system with improved data assimilation is planned as a replacement for the present NLOM/NCOM system in 2007.

Comparison in the NW Arabian Sea: Satellite altimetry provides the key available data type (SSH) that allows a data-assimilative, eddy-resolving ocean model to accurately map the ocean weather. This is illustrated in Fig. 6 for the northwestern Arabian Sea and the Gulf of Oman. Table 1 provides a quantitative comparison of eddy center position errors in the global ocean predictions in relation to eddy center locations in the ocean color. Every clearly defined eddy center in the ocean color (Fig. 6(a)) was used in Table 1 (listed in order of decreasing size in the table and plotted by number on Fig. 6(a)). Comparison of 1/32° NLOM (with assimilation of SSH from three altimeters) and 1/32° NLOMn (no assimilation of altimeter data, atmospheric forcing only) demonstrates the effectiveness of the altimeter data assimilation. Assimilation of the altimeter data is essential because the eddies are generally nondeterministic due to flow instabilities. The table also indicates the value-added of high horizontal resolution in depicting eddies. The 1/8° NCOMa,b systems generally depict only the larger eddies, e.g., the prominent column of 4 alternating counterclockwise and clockwise eddies extending southward from the coast of Iran in the SeaWiFS ocean color imagery and all of the data-assimilative ocean prediction systems (Fig. 6).

Comparisons in the Gulf of Mexico: In Fig. 7, SSH contours from six ocean predictions are overlaid on ocean color. Chlorophyll-poor water, advected into the Gulf of Mexico from the Caribbean, depicts the Loop Current and shed eddies as dark areas. A bright high chlorophyll plume emanating from the Mississippi River outlines the eastern edge of the Loop Current and a semidetached eddy. SSH from two altimeters, GFO and JASON-1, were used for the ocean prediction system results depicted here. The 1/12° HYCOM system and the two NLOM systems have realistic northward penetration of the Loop Current and a semidetached eddy in accord with the ocean color. However, the eddy in 1/16° NLOM is extremely weak. The 1/24° IAS NCOM system and 1/8° NCOMb (with assimilation of 1/32° NLOM SSH) both depict a robust eddy, while 1/8° NCOMa

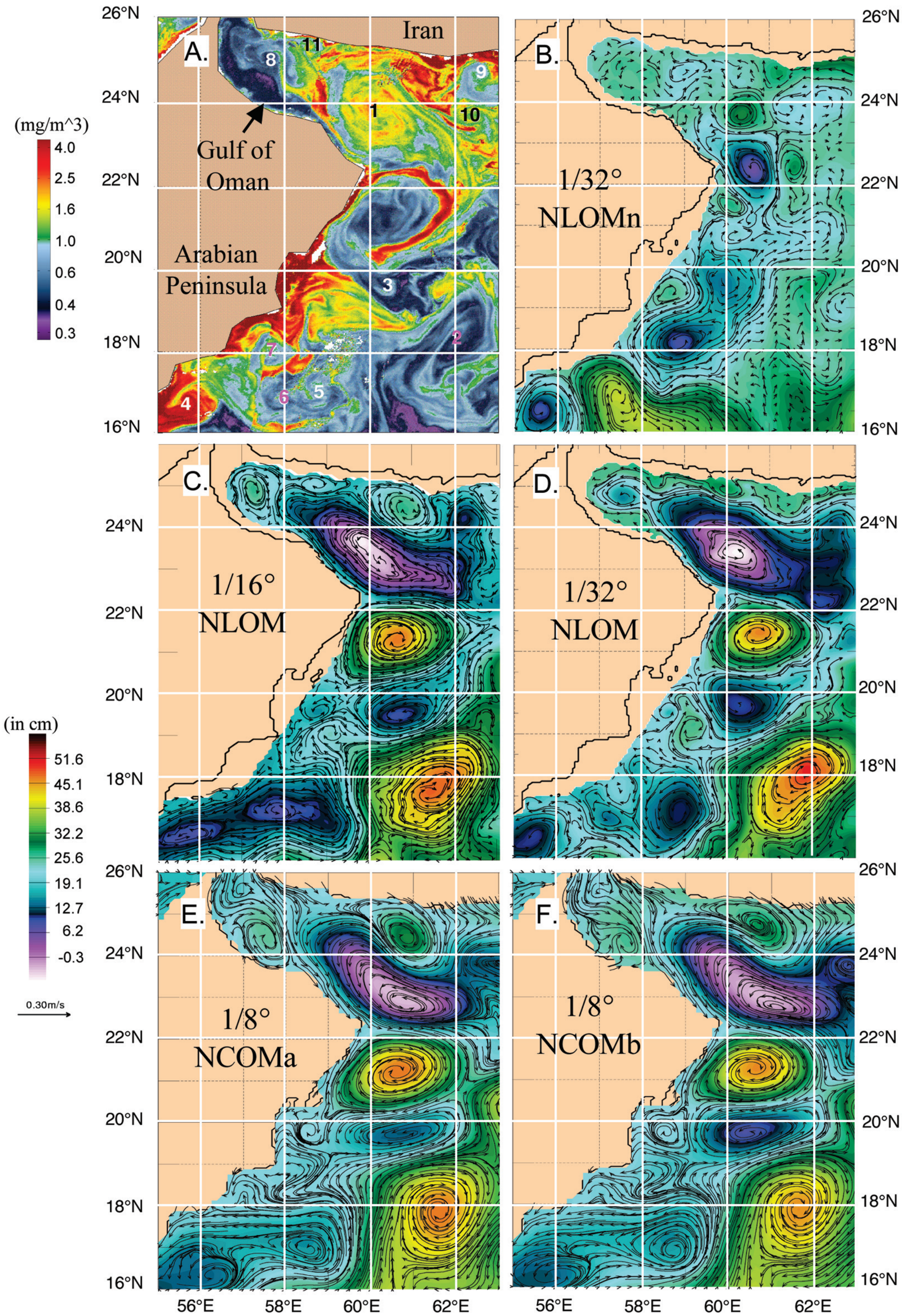


FIGURE 6
A comparison of (a) chlorophyll concentration from SeaWiFS (2-6 October 2002 latest cloud-free pixel composite with most data from 6 October) with 6 October 2002 from (b) 1/32° NLOMn with no assimilation of ocean data (atmospheric forcing only) and (c-f) nowcast results from the data-assimilative ocean prediction systems. (b-f) show surface layer currents overlaid on sea surface height (SSH). The color of the numbers plotted on (a) was varied for visual clarity only.

Table 1 — Eddy Center Position Errors in Ocean Prediction Systems Compared to Ocean Color

Ocean color eddy ID #	1/32° NLOM	1/16° NLOM	1/8° NCOMb	1/8° NCOMa	1/32° NLOMn
	Eddy center position error in km				
1	42	28	151	120	NP
2	27	100	58	70	NP
3	12	43	8	37	42
4	42	35	74	81	35
5	17	*	20	27	NP
6	79	50	NP	NP	NP
7	49	NP	NP	NP	NP
8	39	NP	NP	NP	NP
9	NP	32	NP	NP	NP
10	15	56	46	82	44
11	37	34	NP	NP	NP
Number of the ocean color eddies depicted					
11	10	8	6	6	3
Times had most accurate position					
	5	4.5	1	0	0.5

NP: eddy not present.

* : In 1/16° NLOM, eddies 5 and 6 are fused into one elongated eddy, with the center 50 km from eddy 6 and 97 km from eddy 5.

Notes:

The eddy ID numbers are plotted on Fig. 1(a). Eddies are listed in order of decreasing size as depicted by the ocean color. Eddy position measurement error is 10-15 km in both the ocean color and the models.

1/32° NLOM: 1/32° NLOM system with assimilation of altimeter track data from ERS-2, GFO, and JASON-1 altimeters.

1/16° NLOM: Operational 1/16° NLOM system with assimilation of real-time altimeter data from the ERS-2 and GFO altimeters (JASON-1 not in the operational data stream at that time).

1/8° NCOMb: 1/8° NCOM system with assimilation of 1/32° NLOM SSH.

1/8° NCOMa: 1/8° NCOM system with assimilation of 1/16° NLOM SSH.

Assimilation of 1/32° NLOM SSH vs 1/16° NLOM SSH improved the eddy center position accuracy for 5 of the 6 eddies 1/8° NCOMb,a depicted. With one exception 1/8° NCOMb,a only include the larger eddies depicted in the ocean color.

1/32° NLOMn: 1/32° NLOM with no assimilation of ocean data, only atmospheric forcing.

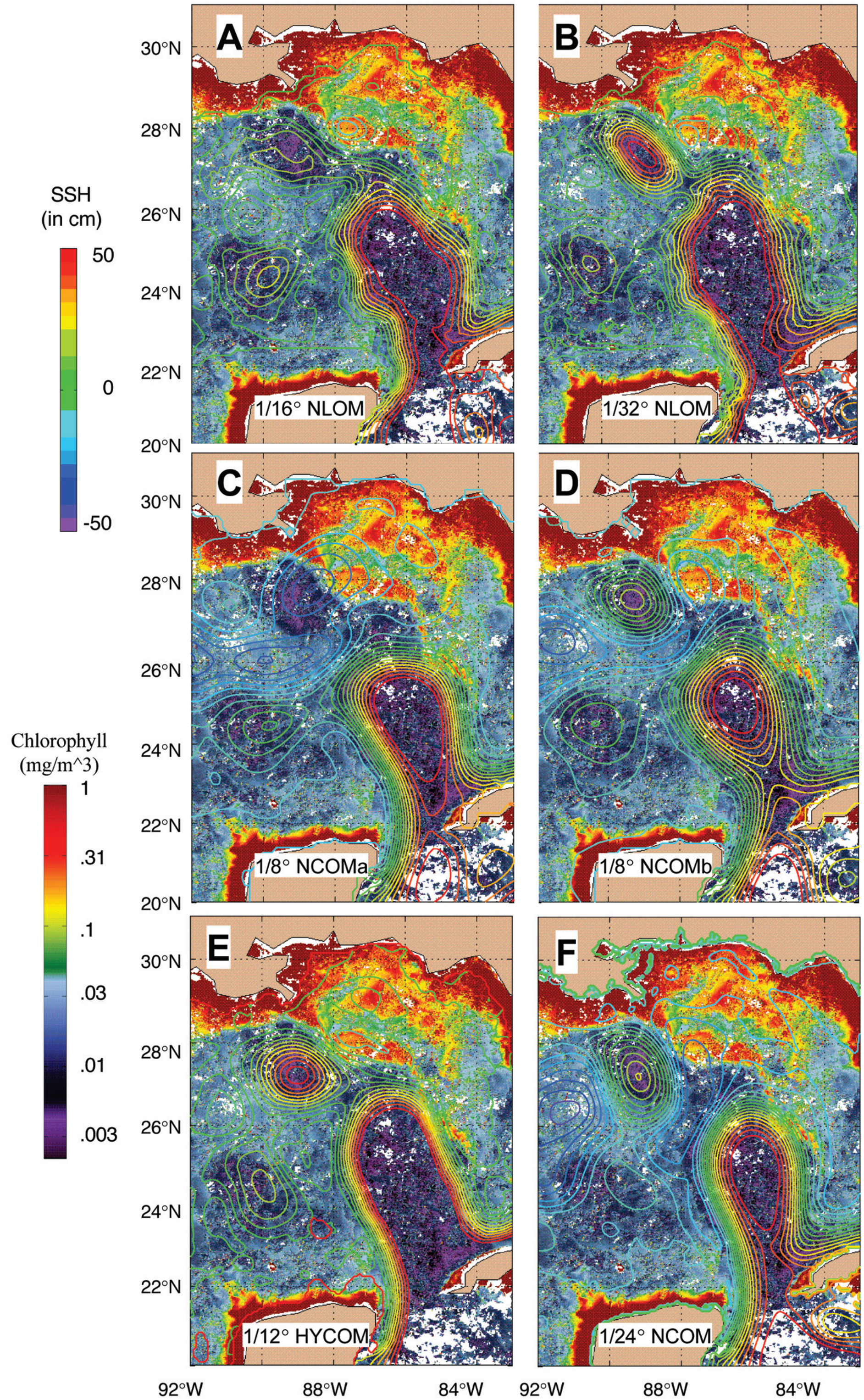


FIGURE 7
Nowcast SSH from 6 ocean prediction systems or their variants on 28 August 2003 overlaid on ocean color imagery from SeaWiFS. Both the SeaWiFS imagery and the SSH contours are colored prismatically from low (violet) to high (red). The SeaWiFS chlorophyll concentration is the latest cloud-free pixel composite over 22-28 August 2003. SSH from the GFO and JASON-1 altimeters are used for assimilation. SSH contour interval is 5 cm, and contours >50 cm are omitted.

(with assimilation of 1/16° NLOM SSH) shows none. Because none of the NCOM systems have sufficient northward penetration of the Loop Current, the Loop Current eddy is fully detached in 1/8° NCOMb and 1/24° NCOM.

Since the data assimilation method is identical for 1/16° and 1/32° NLOM, and it uses the model forecast as the first guess for the altimeter data assimilation, it is obvious that the ocean model is an integral component of the data assimilation. Hence, model simulation skill (without ocean data assimilation) is an important factor in both the data assimilation phase (for dynamical interpolation skill) and the forecasting phase of ocean prediction. Loop Current penetration is sensitive to the inflow transport from the Caribbean and to having a strongly surface-trapped inflow jet hugging the western boundary (evidenced by tightly packed SSH contours hugging the western boundary at the inflow in the HYCOM and NLOM systems). These are also requirements for strong baroclinic flow instabilities within the Gulf of Mexico, which are responsible for observed contortions of the Loop Current and associated eddies. Lack of a robust semidetached eddy in 1/16° NLOM is due to spurious westward bottom inflow into the Gulf of Mexico through the Florida Strait (not present in 1/32° NLOM). By following the geostrophic contours of the bottom topography, this results in a spurious westward current below the semidetached eddy location. Since bottom currents can advect upper ocean currents,[6] there is excessively rapid westward advection of any eddy that begins to form in this location, severely damaging the dynamical interpolation skill of the model in this case. Similar comparisons in the Gulf of Mexico for other Loop Current and eddy configurations can be seen on the HYCOM and NLOM web pages (listed below), including some with severe contortions.

Impact: Finding independent data sets that are effective in evaluating and comparing the skill of ocean prediction systems is essential in developing a state-of-the-art ocean prediction capability for the Navy. Ocean color is an independent data set that is particularly effective in assessing the ability of ocean prediction systems to map the "ocean weather." The strong correlation between the ocean dynamic field (SSH) and the ocean color imagery also suggests the possibility to use the ocean color imagery within the assimilation process to better predict the ocean circulation. NRL is participating in the multinational Global Ocean Data Assimilation Experiment (GODAE), which is designed to help justify a permanent global ocean-observing system by demonstrating useful real-time global ocean products with a customer base, a major step forward in transitioning oceanography into an operational science. NRL is also participating in the GODAE-related European Marine Environment and Security for the European Area (MERSEA) multinational ocean prediction system intercomparison project. Real-time and archived results from all of the ocean prediction systems compared here can be seen on the web:

1/12° Atlantic HYCOM at http://hycom.rsmas.miami.edu
1/8° global NCOM at http://www.ocean.nrlssc.navy.mil/global_ncom
1/16° and 1/32° global NLOM at http://www.ocean.nrlssc.navy.mil/global_nlom
1/24° IAS NCOM at http://www7320.nrlssc.navy.mil/IASNFS_WWW

[Sponsored by ONR, SPAWAR, NOPP, and HPCMO]

References

[1] R.A. Arnone and A.R. Parsons, "Real-time Use of Ocean Color Remote Sensing for Coastal Monitoring," chapter 14 in *Remote Sensing of Aquatic Coastal Environments*, ed. R.L. Miller, C.E. Del Castillo, and B.A. McKee, (Kluwer Academic Publishers, Netherlands, 2004).
[2] C.N. Barron, A.B. Kara, H.E. Hurlburt, C. Rowley, and L.F. Smedstad, "Sea Surface Height Predictions from the Global Navy Coastal Ocean Model (NCOM) During 1998-2001," *J. Atmos. Oceanic Technol.*, in press, (2004).
[3] O.M. Smedstad, H.E. Hurlburt, E.J. Metzger, R.C. Rhodes, J.F. Shriver, A.J. Wallcraft, and A.B.Kara, "An Operational Eddy Resolving 1/16° Global Ocean Nowcast/Forecast System," *J. Mar. Sys.* **40-41**, 341-361 (2003).
[4] J.F. Shriver, H.E. Hurlburt, O.M. Smedstad, A.J. Wallcraft, and R.C. Rhodes, "1/32° Real-time Global Ocean Prediction and Value-added Over 1/16° Resolution," *J. Mar. Sys.*, submitted (2004).
[5] R.C. Rhodes, H.E. Hurlburt, A.J. Wallcraft, C.N. Barron, P.J. Martin, E.J. Metzger, J.F. Shriver, D.S. Ko, O.M. Smedstad, S.L. Cross, and A.B. Kara, "Navy Real-time Global Modeling Systems," *Oceanography* **15**(1), 29-43 (2002).
[6] H.E. Hurlburt and J.D. Thompson, "A Numerical Study of Loop Current Intrusions and Eddy Shedding," *J. Phys. Oceanogr.* **10**, 1611-1651 (1980).

★