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Underwater Glider Observations and the Representation of Western Boundary Currents in Numerical Models

By Robert E. Todd and Lea Locke-Wynn

Western boundary currents are important oceanic components of Earth's climate system. In the subtropics, the Gulf Stream, Kuroshio, East Australian Current, Agulhas Current, and Brazil Current contribute to poleward heat transport. Low-latitude western boundary currents, such as the Somali Current, Mindanao Current, and New Guinea Coastal Undercurrent, are key connections between the subtropical gyres and equatorial current systems. Western boundary currents are generally narrow ($O(100)$ km wide) with strong currents ($O(1)$ m s^{-1}) and large property gradients, making them a challenge to both observe and simulate.

Autonomous underwater gliders (Rudnick, 2016) that cross strong subsurface gradients (i.e., fronts) associated with western boundary currents provide high-resolution observations that strongly impact numerical simulations of those currents. Such simulations are not well constrained by other assimilated observations that either do not capture the subsurface structures of the fronts (e.g., satellite observations) or have coarser spatial resolution. Rudnick et al. (2015) and Schönau et al. (2015) previously provided evidence

that assimilation of glider observations led to improved state estimates of the Loop Current and Mindanao Current, respectively. We demonstrate the impact of real-time glider observations on an operational forecast model's representation of the Gulf Stream.

Spray underwater gliders (Sherman et al., 2001; Rudnick et al., 2016) are currently surveying across the Gulf Stream between Florida and New England (Todd, 2017). Gliders are advected downstream as they cross the Gulf Stream and are navigated upstream in more quiescent waters on the flanks of the boundary current. Due to inherent Gulf Stream variability, gliders are generally unable to occupy repeat transects. Figure 1 illustrates how these glider observations fill a 1,500-km-long gap between sustained measurements of the Gulf Stream's subsurface structure in the Florida Strait (e.g., Baringer and Larsen, 2001) and those southeast of New York and New Jersey (e.g., Flagg et al., 2006; Molinari, 2011). With float density decreasing dramatically within the Gulf Stream and on its shoreward side, the Argo program cannot (and is not intended to) thoroughly sample the Gulf Stream along the continental margin; gliders can ably fill this role.

Spray gliders in the Gulf Stream typically measure temperature, salinity, absolute velocity (Todd et al., 2017), chlorophyll *a* fluorescence, and acoustic backscatter. Resolution between profiles is a function of profiling depth, with profiles to 1,000 m separated by approximately 5 km in cross-stream distance and 5.5 hours in time (see Todd, 2017, for examples of cross-Gulf Stream transects). Real-time observations are returned via the Iridium satellite network with temperature and salinity measurements distributed via the Integrated Ocean Observing System (IOOS) Glider Data Assembly Center (DAC) and Global Telecommunications System (GTS) and by email to the US Naval Oceanographic Office (NAVOCEANO) for operational usage.

NAVOCEANO produces daily four-day forecasts for a US East Coast domain using the regional Navy Coastal Ocean Model (NCOM US East) that assimilate all available observations in the region, including Spray glider data, using the Navy Coupled Ocean Data Assimilation (NCODA) system. Assimilation of subsurface observations collected by gliders results in substantial shifts in the location of the Gulf Stream front between successive forecasts (e.g., Figure 2). In November 2015, inclusion of glider observations collected on November 12 shifted the simulated location at which the Gulf Stream separates from the continental margin near Cape Hatteras, North Carolina, (as indicated by the 15°C isotherm intersecting the 200 m isobath) southwestward by approximately 15 km (Figure 2a,c). Southwest of Cape Hatteras, inclusion of glider observations collected on

March 7, 2017, shifted a meander crest (again indicated by the 15°C isotherm) southwestward by roughly 70 km (Figure 2b,d). For both time periods, simulated temperature profiles better agree with observations following assimilation of additional observations (Figure 2e,f).

Autonomous underwater glider surveys fill a critical gap in sustained subsurface monitoring of the Gulf Stream along the US East Coast. Spray glider observations have demonstrated impact on

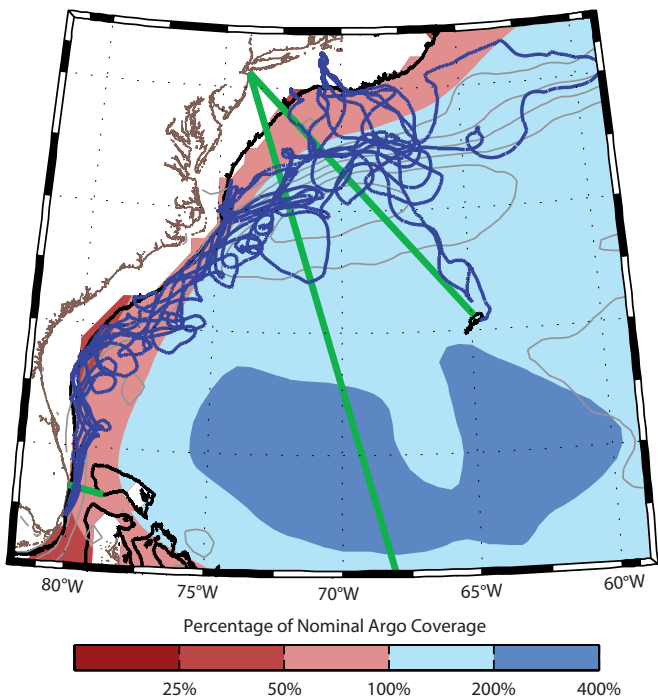


FIGURE 1. Gulf Stream observations along the US East Coast. Tightly spaced mean sea surface height contours (gray) denote the mean position of the Gulf Stream. The percentage of nominal Argo coverage (one float per $3^\circ \times 3^\circ$ box) during 2008–2014 is shaded in reds and blues (courtesy of P.E. Robbins, WHOI). Green lines indicate the locations of sustained subsurface observations in the Florida Strait, along the AX10 XBT line (a high-density repeat XBT transect run by NOAA), and along the M/V *Oleander* line (see <http://po.msfc.sunysb.edu/Oleander> for more information). Blue lines indicate trajectories of 11 Spray glider missions completed through May 2017. The 200 m isobath (black) denotes the edge of the continental shelf.

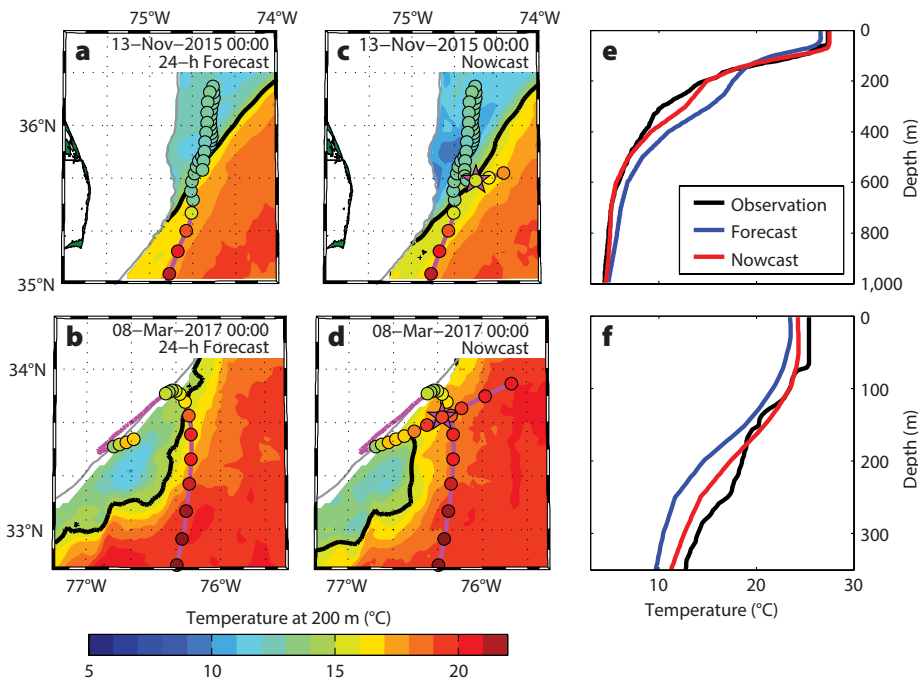


FIGURE 2. Impacts of real-time Gulf Stream glider observations on NAVOCEANO's operational simulations for (top) November 13, 2015, and (bottom) March 8, 2017. (a,b) Temperature at 200 m (color shading) from the forecast runs 24 hours before the indicated dates. (c,d) Nowcast temperature at 200 m (color shading) for the same dates. In (a–d), real-time glider observations of temperature at 200 m that were available for assimilation are shown by the colored markers along the gliders' magenta trajectories (earliest observations shown at the southern boundary are from November 3, 2015, and March 2, 2017, respectively), the 15°C isotherm is black, and the 200 m isobath is gray. (e,f) Temperature profiles at the locations indicated by the magenta stars in (c,d). Midpoints of glider profiles (black) were sampled at (e) 10:24 on November 12, 2015, and (f) 07:40 on March 7, 2017. Pre- and post-assimilation simulated profiles (blue and red) are from the model runs shown in (a–d).

NAVOCEANO's operational modeling of the Gulf Stream. Previous and ongoing surveys with gliders in western boundary currents globally (e.g., Davis et al., 2012; Rainville et al., 2013; Rudnick et al., 2013, 2015; Schaeffer and Roughan, 2015; Schönau et al., 2015; Todd et al., 2016; Krug et al., 2017; Schönau and Rudnick, 2017; Todd, 2017) promise to provide key observational constraints for a variety of numerical modeling efforts.

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