UNDERWATER GLIDER OBSERVATIONS AND THE REPRESENTATION OF WESTERN BOUNDARY CURRENTS IN NUMERICAL MODELS

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Western boundary currents are important oceanic components of the 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 structure 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 1500-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 1000 m separated by approximately 5 km in cross-stream distance and 5.5 hours in time (see Todd, 2017, for example 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 Naval Oceanographic Office (NAVOCEANO) for operational usage.

NAVOCEANO produces daily 4-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 causes 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 12 November shifted the simulated location at which the Gulf Stream separates from the continental margin near Cape Hatteras, NC (as indicated by the 15 °C isotherm intersecting the 200-m isobath) southwestward by approximately 15 km (Figures 2a and 2c). Southwest of Cape Hatteras, inclusion of glider observations collected on 7 March 2017 shifted a meander crest (again indicated by the 15 °C isotherm) southwestward by roughly 70 km (Figures 2b and 2d). For both time periods, simulated temperature profiles better agree with observations following assimilation of additional observations (Figures 2e and 2f).

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 NAVOCEANO's operational modelling 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 modelling efforts.

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136 FIGURES:

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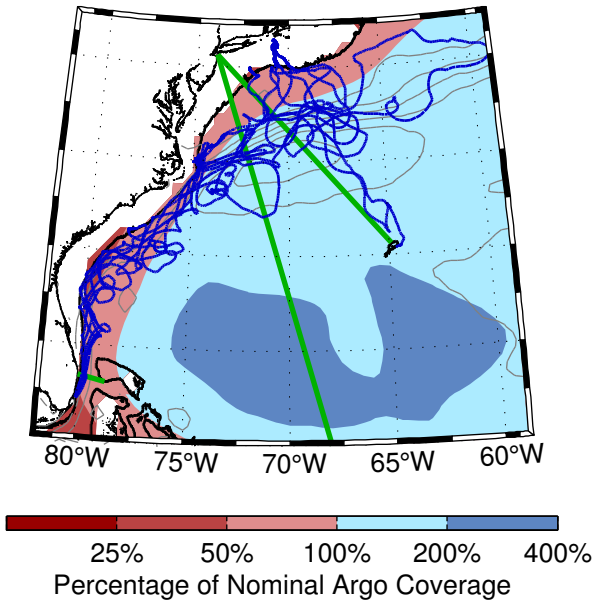

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140 Figure 1: Gulf Stream observations along the US East Coast. Tightly spaced mean sea surface
141 height contours (grey) denote the mean position of the Gulf Stream. The percentage of
142 nominal Argo coverage (one float per 3°×3° box) during 2008-2014 is shaded (courtesy of
143 P.E. Robbins, WHOI). Green lines indicate the locations of sustained subsurface observations
144 in the Florida Strait, along the AX10 XBT line, and along the M/V *Oleander* line. Blue lines
145 indicate trajectories of ten Spray glider missions completed through January 2017. The 200-
146 m isobath (black) denotes the edge of the continental shelf.

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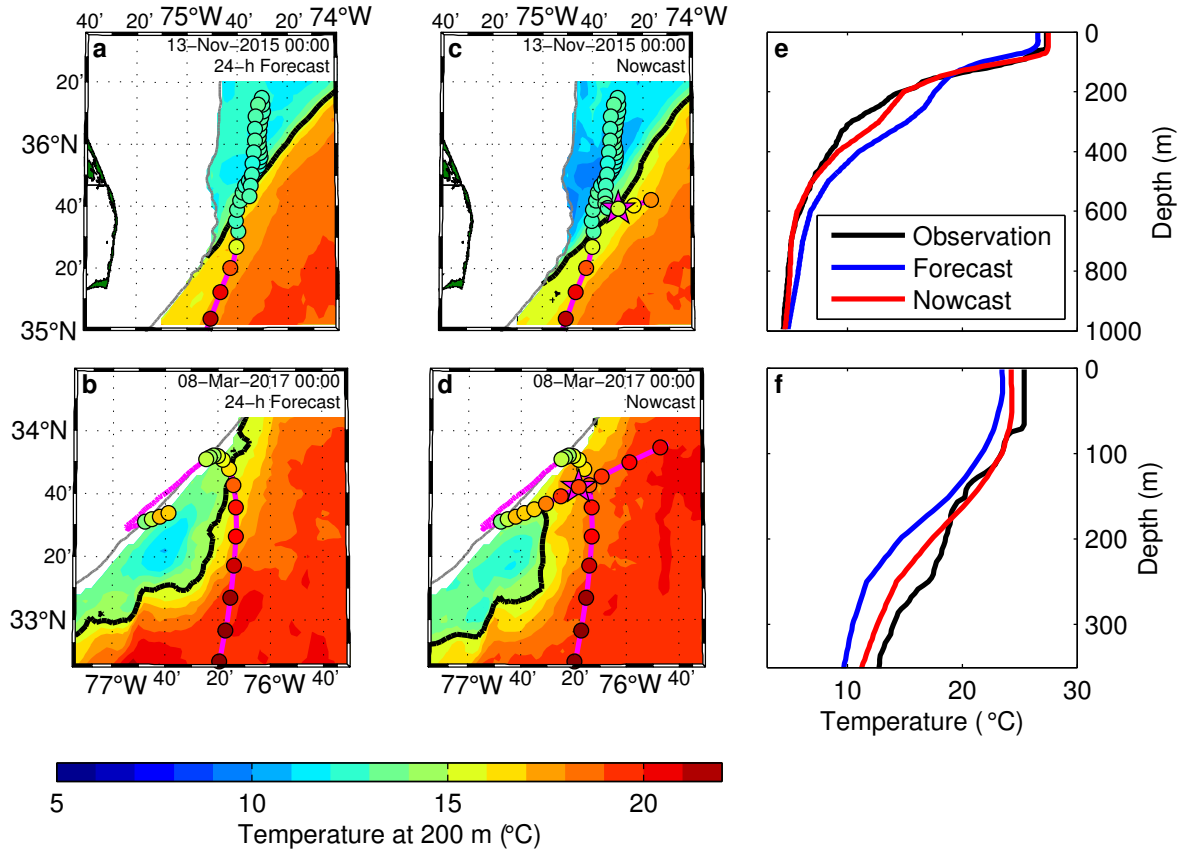

Figure 2: Impacts of real-time Gulf Stream glider observations on NAVOCEANO's operational simulations for (top) 13 November 2015 and (bottom) 8 March 2017. (a,b) Temperature at 200 m (color shading) from the forecast runs 24 hours before the indicated dates. (c,d) Nowcast temperature at 200 m (color 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 3 November 2015 and 2 March 2017, respectively); the 15 °C isotherm is black, and the 200-m isobath is grey. (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 12 November 2015 and (f) 07:40 on 7 March 2017, pre- and post-assimilation simulated profiles (blue and red) are from the same model runs shown in (a-d).