

ON THE POTENTIAL FOR SUSTAINED GULF STREAM MONITORING WITH AUTONOMOUS UNDERWATER GLIDERS

Robert E. Todd⁽¹⁾

⁽¹⁾ Woods Hole Oceanographic Institution, 266 Woods Hole Rd., MS#21, Woods Hole, MA, USA 02543, Email: rtodd@whoi.edu

ABSTRACT

The Gulf Stream is a key part of the climate system, but its subsurface structure and variability along the U.S. East Coast are not captured sufficiently by existing long-term observations. The potential for sustained Gulf Stream monitoring with autonomous underwater gliders is demonstrated. Initial results include investigation of cross-Gulf Stream potential vorticity, identification of two mechanisms by which energy is converted to smaller scales as the Gulf Stream flows over shallow bathymetry, and impacts on operational numerical models. Sustained, long-term monitoring of the Gulf Stream using gliders offers the opportunity to construct a variety of climatological products. Glider-based monitoring of the Gulf Stream serves as a model for autonomous sampling in other western boundary currents as a complement to the basin-scale coverage of the Argo program.

1. MOTIVATION

The Gulf Stream is one of the most important oceanic components of the Earth's climate system. Flowing along the U.S. East Coast and into the North Atlantic, the Gulf Stream is a major part of the Atlantic Meridional Overturning Circulation (AMOC) that is responsible for transferring heat from the equator to higher latitudes and for sequestering atmospheric carbon dioxide in the deep ocean. Despite its significance to the Earth's climate and its location just offshore of the U.S. East Coast, there exists a significant gap in our understanding of the subsurface properties of the Gulf Stream. Basic descriptions of the temporal and along-stream variability in Gulf Stream structure along the U.S. East Coast are lacking.

This gap is largely driven by a lack of spatially-broad, long-duration, high-resolution measurements in the Gulf Stream, which have been difficult to obtain. Sustained subsurface measurements of the Gulf Stream are currently only collected along three transects (Figure 1, green)—across the Florida Strait (e.g., Baringer and Larsen, 2001; Shoosmith et al., 2005), along the AX10 XBT line from New York to Puerto Rico (Goni et al., 2010; Molinari, 2011), and along the M/V *Oleander* line between New Jersey and Bermuda (e.g., Flagg et al., 2006). In the roughly 1500 kilometers between the Florida Strait and the AX10 line, the Gulf Stream triples its volume transport, separates from the continental margin to flow into the open North Atlantic, and develops a variety of large scale meanders. Argo sampling density decreases dramatically within the Gulf Stream and on its shoreward side (Figure 1) and so cannot thoroughly sample the Gulf Stream and, in particular, its variability along the continental margin. Even at its target float density of one float per $3^\circ \times 3^\circ$ box, Argo would only have approximately five floats within the Gulf Stream between Florida and New England. Remote sensing of sea surface temperature and sea surface height by satellites provides regular measurements of the surface characteristics of the Gulf Stream throughout its course, but fails to capture the subsurface structure of the current. Autonomous underwater gliders (Rudnick et al., 2004; Rudnick 2016) are now being used to fill the gap in subsurface Gulf Stream observations (Todd et al., 2016, 2017; Todd 2017; see below).

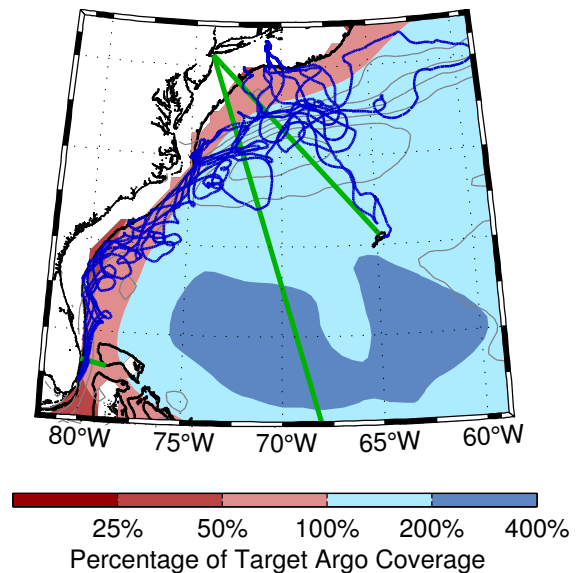


Figure 1: Observations of the Gulf Stream along the U.S. East Coast. Tightly spaced mean sea surface height contours (grey) denote the mean position of the Gulf Stream. Shading indicates the percentage of target Argo coverage (one float per $3^\circ \times 3^\circ$ box) during 2008-2014 courtesy of P.E. Robbins (WHOI). Green lines indicate the locations of sustained subsurface observations in the Florida Strait, along the AX10 XBT line, and along the M/V *Oleander* line. Blue lines indicate trajectories of 10 Spray glider missions. The edge of the continental shelf is denoted by the 200-m isobath (black).

2. SPRAY GLIDER OPERATIONS IN THE GULF STREAM

Spray underwater gliders (Sherman et al., 2001, Rudnick et al., 2016a) first surveyed across the Gulf Stream downstream of Cape Hatteras from 2004 to 2009 (see Todd et al., 2016). Since 2015, Spray gliders have been surveying the Gulf Stream along the entirety of the U.S. East Coast between Miami, FL and New England (see Todd, 2017). Figure 1 shows the trajectories of 10 Spray glider missions completed through January 2017.

The $O(1) \text{ m s}^{-1}$ depth averaged velocities in the Gulf Stream place constraints on the sampling that is possible using gliders that move through the water at approximately 0.25 m s^{-1} . Spray gliders operate successfully in such high current conditions due to automatic current crossing navigation, an ability to dive as deep as 1000 m, and months-long endurance afforded by lithium primary batteries. While within the Gulf Stream, gliders are commanded to steer perpendicular to observed depth averaged currents; the resulting glider trajectories are typically oriented $25^\circ\text{-}40^\circ$ to the left or right of the flow (Todd et al., 2016). In more quiescent waters on either side of the Gulf Stream, gliders can be navigated upstream resulting in loops on the flanks of the boundary current (e.g., Figure 1). Due to the inherent variability of the Gulf Stream flow, gliders are generally unable to occupy repeat transects.

Spray gliders in the Gulf Stream are typically equipped to collect measurements of temperature, salinity, absolute velocity (Todd et al., 2017), chlorophyll a fluorescence, and acoustic backscatter (e.g., Figure 2). Horizontal resolution between profiles is a function of profiling depth with profiles to 1000 m separated by approximately 5 km in cross-stream distance (e.g., tick marks in Figure 2). Realtime observations are returned via Iridium satellite with temperature and salinity measurements distributed via the Global Telecommunications System (GTS) and email for operational usage. After recovery of gliders, post-processed data are made publically available and citeable through <https://doi.org/10.21238/S8SPRAY2675>.

3. RESULTS TO DATE

3.1. Potential Vorticity Structure

A useful dynamical quantity in the ocean is the potential vorticity (Ertel, 1942). Since gliders surveying across the Gulf Stream return concurrent, high-resolution measurements of both hydrography and velocity, it is possible to estimate potential vorticity structure in the Gulf Stream from glider observations. Todd et al. (2016) used cross-Gulf Stream potential vorticity distributions from early Spray glider missions to contrast mean Gulf Stream structure with that of the Loop Current and to investigate stability of the western boundary current. In particular, Todd et al.'s (2016) analysis demonstrated how the mean and instantaneous structure of the Gulf Stream make it susceptible to barotropic, baroclinic, and overturning instabilities.

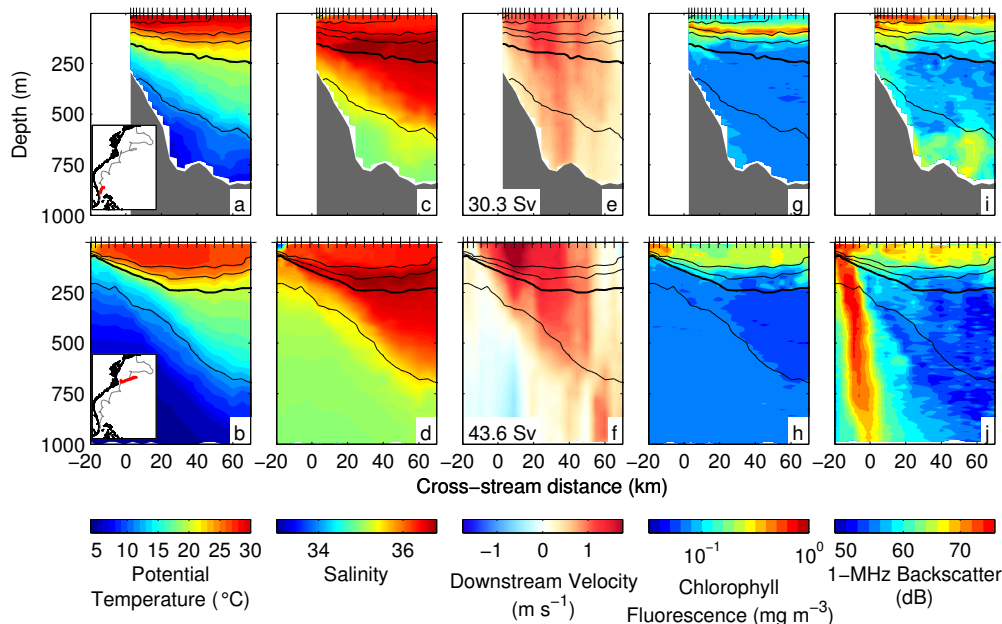
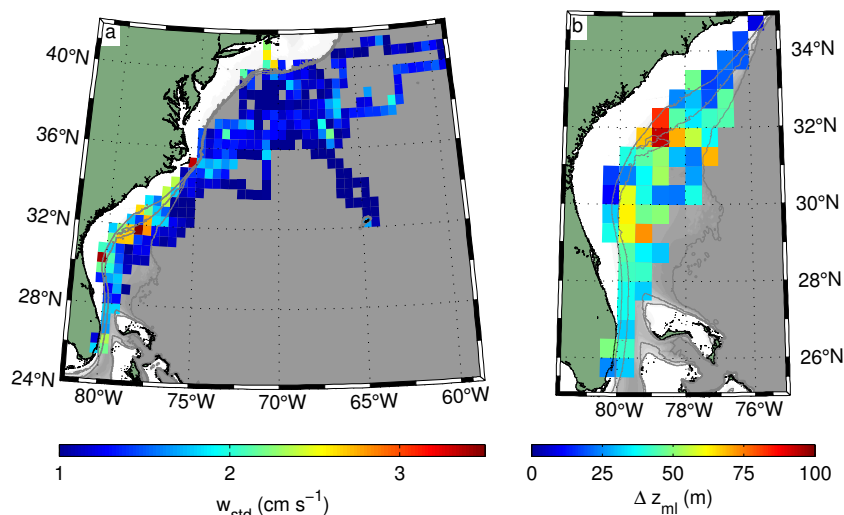


Figure 2: Example Spray glider observations across the Gulf Stream from mission 15A065. Potential temperature (a-b), salinity (c-d), downstream velocity (e-f), chlorophyll a fluorescence (g-h), and 1-MHz acoustic backscatter (i-j) are shown near the Florida Strait (top) and just downstream of Cape Hatteras (bottom). The inset map in each temperature panel shows the location of the transect (red) along the glider's complete trajectory for the mission (grey). Tick marks on the upper axes denote the locations of individual profiles. Downstream (positive only) volume transport through each transect is given in panels e-f. Adapted from Todd (2017).

Figure 3: Averages in $0.5^\circ \times 0.5^\circ$ boxes of (a) standard deviation of vertical velocity w_{std} , a measure of high-frequency internal wave amplitude, and (b) bottom mixed layer thickness Δz_{ml} from Spray glider observations. Both internal wave amplitudes and bottom mixed layer thicknesses are elevated in the vicinity of the Charleston Bump, a topographic feature near 31.5°N , 79°W . Adapted from Todd (2017).



3.2. Internal Lee Waves And Thick Bottom Mixed Layers

Upstream (southwest) of Cape Hatteras, the Gulf Stream flows over the Blake Plateau. With water depths less than 1000 m, flows near the seafloor can be $O(1)$ m s^{-1} . Todd (2017) shows that Gulf Stream flow over the topographic features of the Blake Plateau, and the Charleston Bump near 31.5°N , 79°W in particular, results in generation of internal lee waves with frequencies near the local buoyancy frequency and in formation of bottom mixed layers with thicknesses in excess of 100 m. From multiple glider missions passing through the region, the spatial distribution of both the internal lee waves and the bottom mixed layers is observed (Figure 3). Generation of internal lee waves and formation of bottom mixed layers both remove energy from the Gulf Stream flow.

3.3. Impact Of Realtime Observations On Operational Numerical Models

The availability of realtime observations of temperature and salinity profiles within the Gulf Stream can significantly improve representation of the Gulf Stream in operational models. For example, Figure 4 shows how the location at which the Gulf Stream separates from the continental margin in the Regional Navy Coastal Ocean Model (RNCOM), as indicated by the 15°C isotherm intersecting the 200-m isobath, shifts southwestward by approximately 15 km following assimilation of additional glider profiles within the Gulf Stream front. Simulated water column structure is in markedly better agreement with observations throughout the upper 1000 m following assimilation. Ongoing Gulf Stream observations are expected to have similar impacts in any models that assimilate them and their use for such purposes is encouraged.

4. POTENTIAL CLIMATOLOGIES

As of January 2017, a total of 22 Spray glider missions in the Gulf Stream have been funded and 10 have been completed, returning approximately 6000 profiles and more than 60 cross-Gulf Stream transects. This growing

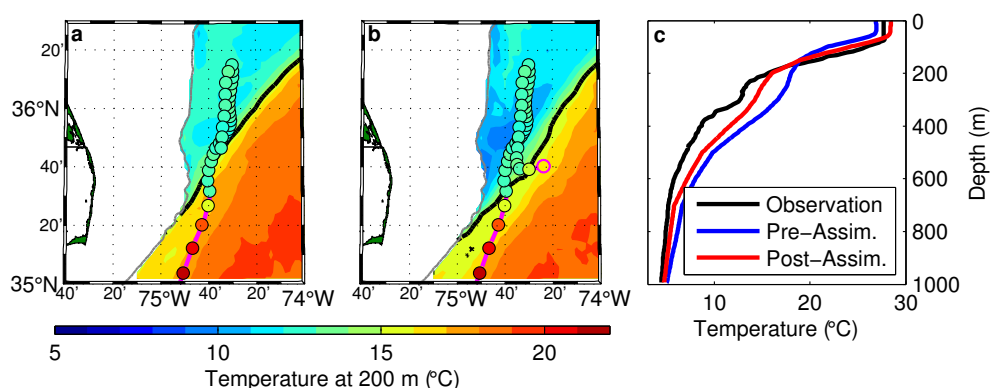


Figure 4: Effects of assimilating realtime observations from a glider mission into RNCOM during November 2015. (a) Forecast temperature at 200 m for 13 November 00:00 from the 12 November 00:00 model run. (b) Nowcast temperature at 200 m for 13 November 00:00. Glider observations of temperature at 200 m from 3 November through each assimilation period are shown by the colored markers along the glider's trajectory. The 15°C isotherm is drawn black, and the 200-m isobath is drawn grey. (c) Temperature profiles at the location indicated by the magenta circle in (b); glider observations (black) are from 12 November 16:01, pre- and post-assimilation simulated profiles (blue and red) are for 13 November 00:00.

observational dataset offers the potential for constructing a detailed climatology of the Gulf Stream along the U.S. East Coast. Such a climatology would complement basin-scale climatologies such as those derived from Argo observations (e.g., Roemmich and Gilson, 2009). Detailed regional climatologies can be used to study the effects of interannual climate variability, to place other regional measurements in context, or to validate regional circulation models (Rudnick et al., 2016b)

Figure 5 shows examples of the sorts of climatological products that will be possible. By averaging individual observations in geographic boxes, spatial maps of Gulf Stream properties can be produced. For example, Figures 5a and 5b show averages of temperature and salinity at 200 m as well as depth averaged and surface velocity estimates in $0.5^\circ \times 0.5^\circ$ boxes. Though temporally sparse sampling at some locations leads to transient features appearing in these averages, a picture emerges of the mean Gulf Stream flowing along a prominent temperature and salinity front with $O(1)$ m s^{-1} velocities in the upper kilometer and stronger surface currents. For a meandering jet like the Gulf Stream, these geographic averages are smeared, resulting in smaller property gradients. Constructing averages in streamwise (or natural) coordinates eliminates such smoothing (e.g., Figures 5c-5f; Todd et al., 2016).

5. SUMMARY AND OUTLOOK

Routine autonomous underwater glider surveys of the Gulf Stream can fill a critical gap in sustained subsurface monitoring of this key ocean current. Though Gulf Stream speeds are much faster than the speed of gliders through the water, the ability of gliders to cross the current has been well-established. Observations collected by underwater gliders have immediate impact on operational numerical modelling, allow for near-term scientific analysis, and offer the promise of constructing high-resolution climatologies of Gulf Stream properties along the U.S. East Coast.

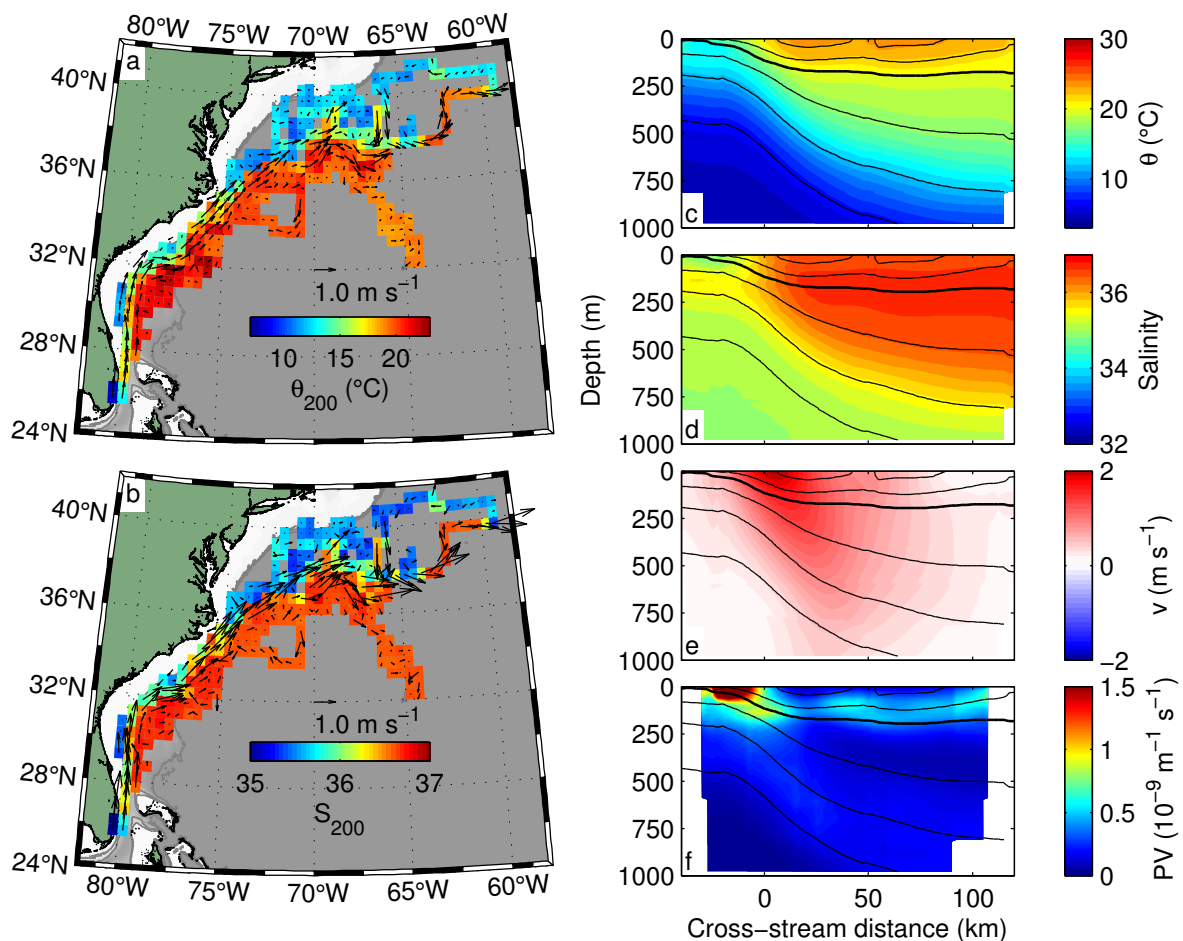


Figure 5: Average Gulf Stream properties from Spray glider observations. Averages in $0.5^\circ \times 0.5^\circ$ boxes of (a) vertically averaged currents and potential temperature at 200 m and (b) salinity at 200 m and surface currents are from ten Spray glider missions to date; adapted from Todd (2017). Mean cross-stream transects of (c) potential temperature, (d) salinity, (e) downstream velocity, and (f) total Ertel potential vorticity are from four Spray glider missions through 2009; adapted from Todd et al., (2016). Black contours in (c-f) indicate mean potential density with a 0.5 kg m^{-3} contour interval and the 26.0 kg m^{-3} isopycnal bold.

Sustained monitoring of the Gulf Stream and other boundary currents is a key goal of the Global Ocean Observing System (GOOS). The OceanGliders Boundary Ocean Observing Network (BOON) is an effort to build global coordination of glider-based regional boundary current observing networks. Together with previous and ongoing work in the Kuroshio (Rainville et al., 2013; Rudnick et al., 2013), Mindanao (Schönau et al., 2015), and Solomon Sea (Davis et al., 2012), the Gulf Stream surveys that are currently underway represent initial steps toward sustained, high-resolution sampling with autonomous underwater gliders in western boundary currents.

REFERENCES

- Baringer, M.O. and J.C. Larsen. 2001. Sixteen years of Florida Current transport at 27°N. *Geophysical Research Letters*. 28(16):3179-3182, <http://doi.org/10.1029/2001GL013246>.
- Davis, R. E., W.S. Kessler, and J.T. Sherman. 2012. Gliders Measure Western Boundary Current Transport from the South Pacific to the Equator. *Journal of Physical Oceanography*. 42(11):2001-2013, <http://dx.doi.org/10.1175/JPO-D-12-022.1>.
- Ertel, H. 1942. Ein neuer hydrodynamischer Wirbelsatz. *Meteorologische Zeitschrift*. 59(9):277-282.
- Flagg, C.N., M. Dunn, D.-P. Wang, H.T. Rossby, and R.L. Benway. 2006. A study of the currents of the outer shelf and upper slope from a decade of shipboard ADCP observations in the Middle Atlantic Bight. *Journal of Geophysical Research*. 111, <http://dx.doi.org/10.1029/2005JC003116>.
- Goni, G., Roemmich, D., Molinari, R., Meyers, G., Sun, C., Boyer, T., Baringer, M., Gouretski, V., DiNezio, P., Reseghetti, F., Vissa, G., Swart, S., Keeley, R., Garzoli, S., Rossby, T., Maes, C. and Reverdin, G., (2010). "The Ship of Opportunity Program" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2)*, Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, <http://dx.doi.org/10.5270/OceanObs09.cwp.35>.
- Molinari, R.L. 2011. Information from low-density expendable bathythermograph transects: North Atlantic mean temperature structure and quasi-decadal variability. *Progress in Oceanography*. 88(1-4):131-149, <http://dx.doi.org/10.1016/j.pocean.2010.12.013>.
- Rainville, L., C.M. Lee, D.L. Rudnick, and K.-C. Yang. 2013. Propagation of internal tides generated near Luzon Strait: Observations from autonomous gliders. *Journal of Geophysical Research*. 118(9):4125-4138, <http://dx.doi.org/10.1002/jgrc.20293>.
- Roemmich, D. and J. Gilson. 2009. The 2004-2009 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. *Progress in Oceanography*. 82(2):81-100, <http://doi.org/10.1016/j.pocean.2009.03.004>.
- Rudnick, D.L., R.E. Davis, C.C. Eriksen, D.M. Fratantoni, and M.J. Perry. 2004. Underwater gliders for ocean research. *Marine Technology Society Journal*. 38:73-84.
- Rudnick, D. L., T.M.S. Johnston, and J.T. Sherman. 2013. High-frequency internal waves near the Luzon Strait observed by underwater gliders. *Journal of Geophysical Research: Oceans*, 118(2):774-784, <http://dx.doi.org/10.1002/jgrc.20083>
- Rudnick, D.L. 2016. Ocean research enabled by underwater gliders. *Annual Reviews of Marine Science*. 8:519-541, <http://dx.doi.org/10.1146/annurev-marine-122414-033913>.
- Rudnick, D.L., R.E. Davis, and J.T. Sherman. 2016a. Spray underwater glider operations. *Journal of Atmospheric and Oceanic Technology*. 33:1113-1122, <https://doi.org/10.1175/jtech-d-15-0252.1>.
- Rudnick, D.L., K.D. Zaba, R.E. Todd, and R.E. Davis. 2016b. A climatology of the California Current System from a network of underwater gliders. *Progress in Oceanography*. Under review.
- Schönau, M. C., D. L. Rudnick, I. Cerovecki, G. Gopalakrishnan, B. D. Cornuelle, J. L. McClean, and B. Qiu. 2015. The Mindanao Current: Mean structure and connectivity. *Oceanography*, 28:34-45.; <http://dx.doi.org/10.5670/oceanog.2015.79>
- Sherman, J.T., R.E. Davis, W.B. Owens, and J. Valdes. 2001. The autonomous underwater glider "Spray". *IEEE Journal of Oceanic Engineering*. 26(4):437-446, <http://doi.org/10.1109/48.972076>.
- Shoosmith, D.R., M.O. Baringer, and W.E. Johns. 2005. A continuous record of Florida Current temperature transport at 27°N. *Geophysical Research Letters*. 32:L23603, <http://doi.org/10.1029/2005GL024075>.
- Todd, R.E., W.B. Owens, and D.L. Rudnick. 2016. Potential vorticity structure in the North Atlantic western boundary current from underwater glider observations. *Journal of Physical Oceanography*. 46(1):327-348, <http://doi.org/10.1175/JPO-D-15-0112.1>.
- Todd, R.E., D.L. Rudnick, J.T. Sherman, W.B. Owens, and L. George. 2017. Absolute velocity measurements from autonomous underwater gliders equipped with Doppler current profilers. *Journal of Atmospheric and Oceanic Technology*. 34(2):309-333, <http://doi.org/10.1175/JTECH-D-16-0156.1>.
- Todd, R.E. 2017. High-frequency internal waves and thick bottom mixed layers observed by gliders in the Gulf Stream. *Geophysical Research Letters*. Under review.