Gliders monitor western boundary current transport in the Solomon Sea

William S. Kessler[1], Russ E. Davis[2], Uwe Send[2]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle WA
[2] CIMEC, Scripps Institution of Oceanography, San Diego, California

Table of Contents

1. Project Summary 2
2. Scientific and Observing System Accomplishments 3
3. Outreach and Education 8
4. Publications and Reports 9
   4.1. Publications by Principal Investigators 9

1. Project Summary

The Solomon Sea glider project is developing cost-effective methods for sustained measurement of the characteristics of strong western boundary currents that are most important to climate dynamics; these characteristics are integrated measures of the transport of mass, heat, salt and potential vorticity between different regions in the general circulation. Although this project studies the Solomon Sea western boundary currents - important for their role in the evolution of ENSO (El Niño/Southern Oscillation) - the results have broader technological implications for monitoring coastal currents in other remote regions. This report focuses on the work of Kessler at PMEL, complementing the separate report on the same project by the Scripps collaborators Davis and Send. The Project Summary is very similar to theirs, while the specific accomplishments at PMEL are described below in sections 2-4.

To describe climate, long observation records are required. The speed and small scales of boundary currents, as well as the near-shore environment with extensive local fishing, challenge conventional moored techniques, and ship cost precludes regular use of research vessels. Our approach is to use autonomous underwater gliders that are launched from small boats near shore, small subsurface moorings outside the current itself and bottom mounted pressure gauges with inverted echo sounders. Beginning with a 2007 pilot glider-crossing of the Solomon Sea we have improved glider technology and operational methods while completing 57 Solomon Sea crossings. No gliders have been lost during the life of this project. The operational cost of a coast-to-coast glider section is now reduced to the equivalent of one day's ship time. Beginning in 2011 we developed a simple end-point approach with moorings and PIES, suitable for the rugged bathymetry and remote logistics, to complement the glider sections with high time-resolution data. These were deployed in 2012 and the first data were retrieved by small boats in 2013, and again in 2014. New developments continue as we seek ways to enable expanded global boundary current observations within limited budgets.
Our techniques to observe western boundary currents are tested during regular observations of transport through the Solomon Sea. This flow carries water from the subtropical South Pacific to the equator and is a central, and largely unmeasured, element of the tropical Pacific circulation.

Our interest in this remote current is its impact on predicting air-sea interaction in the equatorial zone, most notably on ENSO and related decadal climate variations. ENSO is the clearest example of the ocean's role in climate and its effect on predicting climate variability that strongly impacts human activity. Potentially predictable impacts include: precipitation-drought patterns that modulate agriculture, wildland fires and the water supply, particularly in the western and southern US; the global frequency and regional distribution of tropical storms that impact public safety, property loss and emergency response; the frequency and typical strength of cold-season storms, particularly along the Pacific coast from the US to South America where rain and coastal flooding are key; and ocean ecosystem variation along the west coast that dramatically impacts fishing, its regulation and conservation.

Today's models of ENSO, which focus on equatorial dynamics, provide useful prediction skill a few months in advance. Extending prediction range to years is a goal that requires including influences from the extratropics. Transport through the Solomon Sea is the primary source for the Equatorial Undercurrent (EUC) which, as it upwells along the equator, modulates sea-surface temperature and air-sea interaction that affects the global atmosphere. The widely speculated effect of the EUC's source on climate predictability has not been proven. Our scientific goal is to provide time series of this source's transport with which its importance to prediction can be assessed by researchers and by developers of operational prediction methods.

2. Scientific and Observing System Accomplishments

2.a Scientific results

A first paper (Davis, Kessler and Sherman 2012) presented an analysis of transport through the Solomon Sea based on glider observations through 2010. The major findings, summarized here as background to the current findings below, were

- Equatorward transport above 700 m varies between 0 and 25 Sv on seasonal time scales. The single El Niño in the record brought strong equatorward flow while two La Niñas reduced transport near to zero. These fluctuations were larger than expected from model simulations, especially for these moderate events, raising questions about our understanding of subtropical-equatorial exchange during ENSO.
- Mean equatorward flow peaks near 250 m depth where the potential density near 25.5 matches the EUC's. Transport variability is dominated by two modes describing two independent layers separated by a transition zone centered near 150 m depth and spanning 50 to 250-m depth.
- The upper-layer mode is well-correlated with ENSO. Deeper flow enters the Solomon Sea from the west (Coral Sea coast of Australia; Kessler and Cravatte 2013b) and follows the western boundary as it moves equatorward. Surprisingly, upper layer flow into the Solomon Sea and its variability are focused near mid-basin in a jet marked by high salinity indicating a subtropical origin (Kessler and Cravatte 2013b).

These early results covered a single ENSO cycle; we now have processed data through 2013 (more than twice the length of the earlier data and including two complete ENSO cycles) and a second paper is in preparation. The results described above are largely confirmed, and additional findings are:

- With more than six years of data, the annual cycle of transport - unresolved by the shorter time series of the 2012 paper - is now clear. The ability to define the annual cycle means that we can correspondingly define anomalies from it, namely interannual variability that can be related to ENSO. The annual maximum is in July and minimum in February (Fig. 1a), with an amplitude of about ±8 Sv, roughly as large as the ENSO amplitude for the two events observed (Fig. 1b).

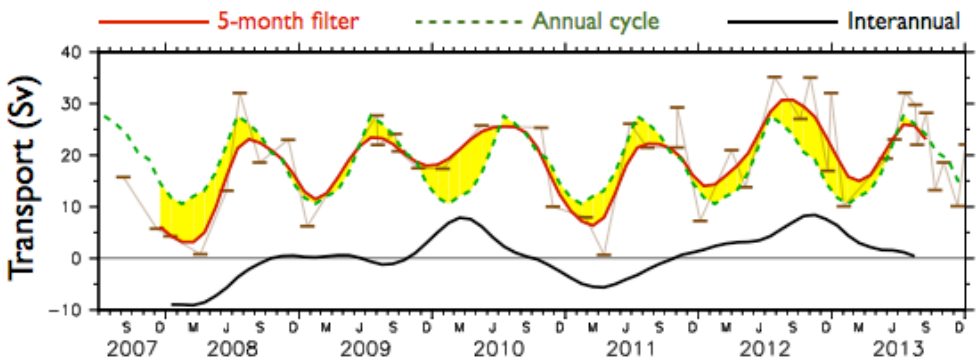

Fig. 1a. Time series of coast-to-coast transport. Brown dashes: Raw mission-by-mission values. Red line: 5-month triangle filtered time series. Green dashed line: Fit annual cycle. Yellow shading: Difference between red and green lines is the estimated interannual variability. Black line: Interannual anomalies as a time series.

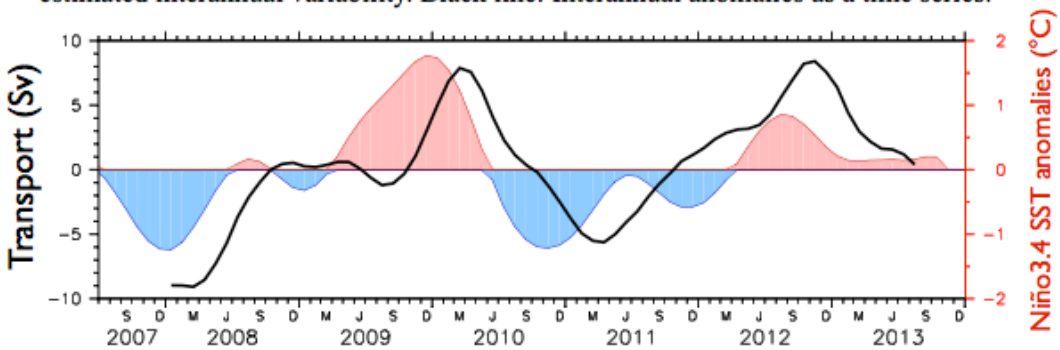

Fig. 1b. Interannual variability of Solomon Sea transport (black line, same as black line in Fig. 1a), compared to a measure of the ENSO cycle (color shading shows SST in the east-central equatorial Pacific, with pink for warm anomalies, blue for cool, scale at right.

- Both annual and ENSO transport variability occurs primarily in the shallow mid-basin jet, with relatively little signal in the deeper near-coastal western boundary current (WBC; Fig. 2).
- Solomon Sea transport lags ENSO indices by several months (3 to 5 months for the two positive and two negative interannual peaks in our record; Fig. 1b). This suggests that the Solomon Sea variations are a lagged response to central Pacific winds perhaps consistent with classic "delayed oscillator" ideas. The lag also implies that the Solomon Sea is not a short-term predictor of ENSO, but the magnitude of the transport fluctuations shows that this is a major part of the recharge and discharge of mass on the equator that characterizes ENSO's role in the climate system of the Pacific.

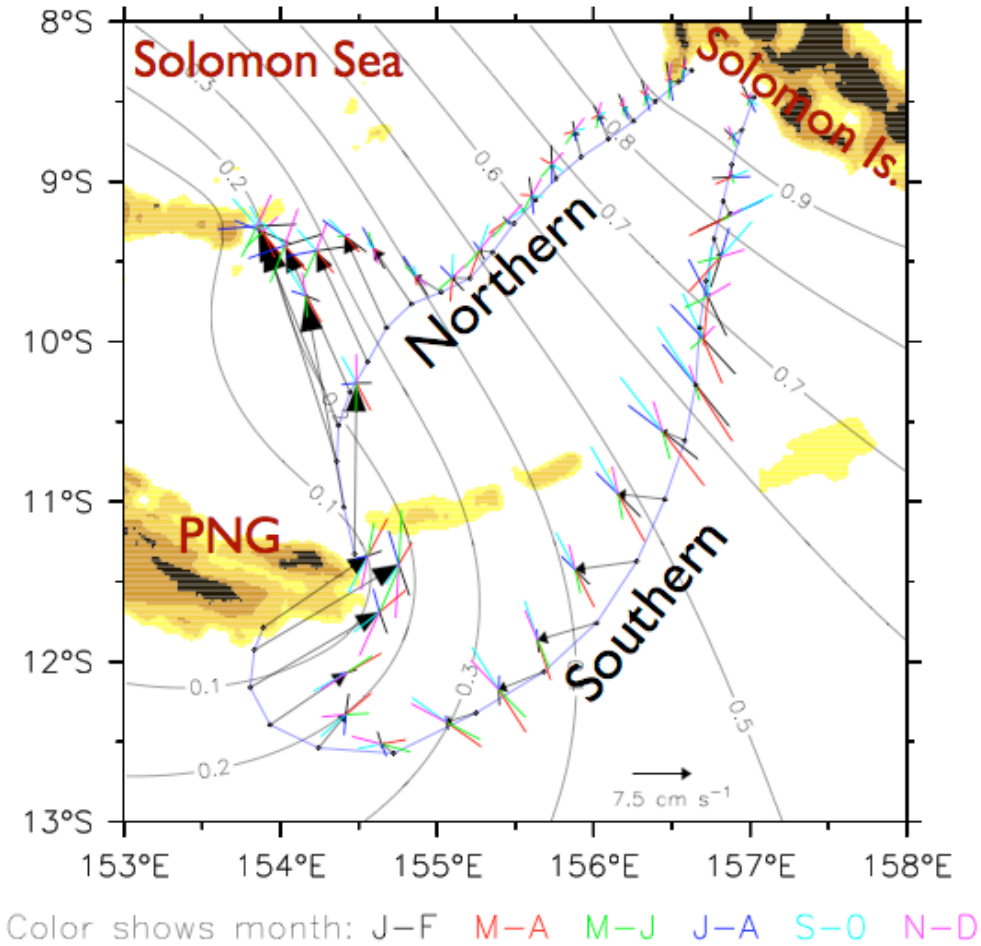

Fig. 2. Vectors of the mean vertically-integrated current (black, scale at bottom) for the glider data averaged onto two typical section lines. On the southern section, the large transport close to the PNG coast and bending around the tip of the islands is the western boundary current, about 80 km wide. A second inflow in mid-basin contributes, and the two have joined by the time they cross the northern section.

The black contours show fractional distance across the basin. Black shading shows land, brown-yellow shading shows bathymetry at 100, 500, 1000m depths.

The colored stick vectors show the average annual cycle on the same scale, where the color indicates the month (key at bottom). Total flow in any month is the sum of the black mean vector plus the colored stick for that month. The western boundary current has relatively small annual variance, but the mid-basin inflow is largest in September-October (light blue), reversing or near-zero during the opposite season.

- The deep WBC and shallow mid-basin jet merge soon after their arrival in the Solomon Sea, resulting in a combined current flowing north that has similar velocity and water property profiles as are observed in the exit straits at the north end of the Solomon Sea (Fig. 3).
- Heat transport variability through the Solomon is a significant element of the total heat content variability of the equatorial region. The Solomon Sea contribution is about 40% as large as the total rate of temperature change across the entire equatorial Pacific, comparable to the change due to air-sea fluxes. The glider time series allows quantifying and monitoring this

surprisingly large element of the tropical heat balance. Most of the heat flux variability results from transport changes rather than variability of the incoming water temperature.

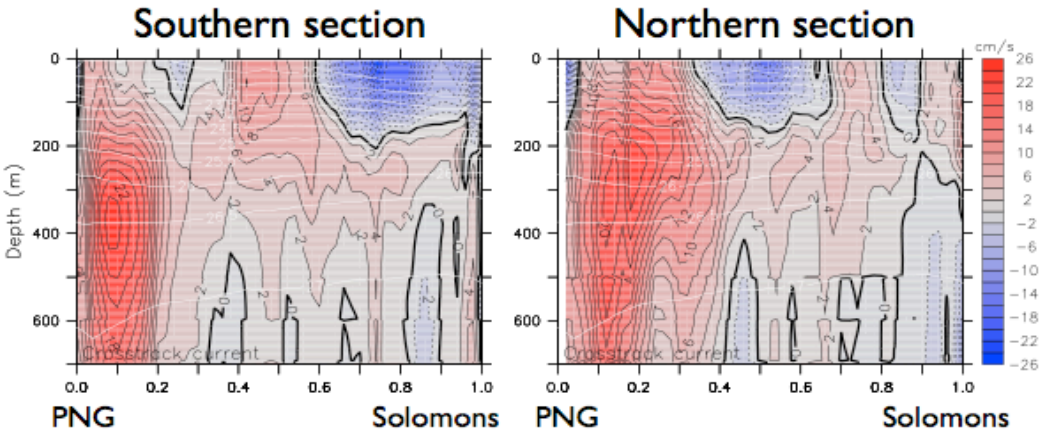

Fig. 3. Vertical sections of mean crosstrack current on the two transects of Fig. 2. Red shading indicates equatorward flow, blue poleward. The horizontal axis is fractional distance from Papua New Guinea on the left to the Solomon Islands on the right. On the southern section, two separate inflows are seen: a subsurface narrow western boundary current, and a shallow mid-basin current. On the northern section the two currents have largely joined.

Some of these findings have been published. Kessler and Cravatte (2013a) used historical XBT data and satellite sea surface height to diagnose the shallow flow that provides the ENSO signal measured by the gliders entering the Solomon Sea. Piecing together a time series extending back to 1985, this study showed that ENSO transport variability is due to coherent wind changes over the western half of the basin, propagating west to the Coral and Solomon Seas. Most of the ENSO signal is found as variations of thermocline depth, consistent with the shallow mode emphasized by the gliders.

Kessler and Cravatte (2013b) used these glider data and nearby Argo float data to show that the mid-basin shallow jet into the Solomon Sea had its origin near the Tasman Front northeast of New Zealand, while the deeper western boundary current originated in the subtropical eastern Pacific. Both jets are characterized by high salinity at their cores, but the two pathways cross each other (at different depths) in the Coral Sea before joining irrevocably at the mouth of the Solomon Sea.

2.b Technical developments

Near the end of FY 2013 we began launching gliders with enhanced buoyancy control. This allows deeper dives (to 1000m instead of the previous 700m), and increased speed about 20%. In a typical 4-month mission the gliders can now make two round-trips (four transects) across the Solomon Sea instead of the previous one (with some extra sampling). The increased speed also makes our crossings of the fast currents more consistent. In FY 2014 all gliders deployed had this improvement.

Also beginning in late 2013, we have trained Solomon Islanders to deploy and recover gliders without requiring us to travel. We still need to travel to prepare, build and test the gliders for

launch, and to dismantle recovered gliders, dispose of batteries, etc, but this allows spacing out deployments more evenly through the year. The travel schedule is now about one trip every five months, each preparing two gliders. We launch one and leave the other for locals to deploy later.

The combination of improved buoyancy and locally-done deployments results in an average of about five deployments per year, each making two round-trips across the Solomon Sea. For somewhat reduced travel costs (about 2.5 rather than 3 trips/year), we get more and better spaced transects.

Deliverable: "[In FY 2014 we will conduct] four-six glider cruises across the Solomon Sea with reports of depth-average velocity above 1000 m, and profiles of temperature and salinity across the SS [will be made] available as data files and graphical descriptions on spray.ucsd.edu ."

Five gliders were launched in FY 2014, completing nine complete coast-to-coast sections (another is underway). One glider deployed in September 2014 is in the water now. We had two failures during this year: One glider was badly attacked by a shark early in its mission but limped home and will be redeployed after minor repairs. A second had an electrical fault after completing one round-trip. It dropped its emergency weight and drifted on the surface to Woodlark Is., Papua New Guinea, where we recovered it (see photo in next section). This one also is in good condition and will be redeployed. No gliders have been lost during the life of this project. The nine transects completed in FY 2014 is three short of our goal of monthly sections, but the section distribution is fairly even during the year so the data should still resolve the annual cycle well.

While our scientific goal requires decadal time series, the data are of immediate use to researchers, local policy makers, and maritime activity. Realtime glider data are plotted at spray.ucsd.edu and can be downloaded with an available password; additional connections are invited. Realtime temperature and salinity data are posted on the Global Telecommunications System for use by the operational prediction centers and others. Delayed-mode data are archived locally and can be downloaded (with a password). IOOS is establishing archival and regular distribution of all glider data.

2.c Field operations by Kessler in 2014:

As the funding for this element of the glider project is entirely to support the PI's travel to the region for the field operations, these trips and their purpose is listed. The two trips made by the PI in FY 2014 were:

Mar 2014: **Gizo, Solomon Islands**:

- Build two gliders, deploy one, prepare second for local deployment.
- Briefed Solomon Islands Meteorological Service (Honiara).
- Classroom lecture at the University of the South Pacific Honiara campus.
- Lecture to Honiara Rotary Club.

Sep 2014: **Alotau, Papua New Guinea**:

- Recover, dismantle ,ship home the glider that drifted on to the Woodlark Island reef.
- Lecture to PNG Fisheries Authority staff.
- Meet Milne Bay Province officials per EEZ clearance agreement.
- Supported travel by a UPNG faculty member to accompany the operation for training and education, and to assist in the operation and boat charter negotiations.

Gizo, Solomon Islands:

- Build two gliders, deploy one, prepare second for local deployment.
- Lecture to Solomon Islands Meteorological Service staff (Honiara).

3. Outreach and Education

Development of the ocean observing system is a fascinating technological accomplishment of surprising public interest.

Photo shows the PI explaining the glider's operation to local staff of the PNG Fisheries Authority during dismantling in Alotau, Papua New Guinea (photo by Chalapan Kaluwin).

Our operations occur near coasts, populations, and economic activity (fishing), making them conspicuous to the local people and sensitive for the governments of Papua New Guinea and the Solomon Islands. PI Kessler meets regularly with provincial and tribal leaders encouraging them

to accept gliders in fishing areas. A side benefit is visible beneficial representation of the United States in regions where Americans are not often seen. Relations with the governments require ongoing maintenance. Both governments are wary of foreign researchers, and insist that the findings be shared (beyond sending copies of data and published articles) and that their people receive some benefit, typically by contributing to their educational systems and by training local personnel. To this end, Kessler regularly lectures at schools, colleges and churches throughout both countries and meets with stakeholders, local government officials, and the Solomon Islands Meteorological Service where he lectures to their personnel on results from the project. He also maintains a close connection with students and faculty at the University of Papua New Guinea (UPNG), involving them in our science and technology, which provides us very helpful contacts for field work. These contacts enabled recovery of the glider that had drifted onto the reef at Woodlark Island, Papua New Guinea. The visit to recover and dismantle the glider is depicted in the above photo.

4. Publications and Reports

4.1. Publications by Principal Investigators

Published in FY 2014 (Kessler-authored pubs only):

Kessler, W.S. and S. Cravatte, 2013a: ENSO and short-term variability of the South Equatorial Current entering the Coral Sea. *J. Phys. Oceanogr.*, **43**, 956-969.

Kessler, W.S. and S. Cravatte, 2013b: Mean circulation of the Coral Sea. *J. Geophys. Res.-Oceans*, **118**, 1-26, doi:10.1002/2013JC009117.

Gourdeau, L., J. Verron, A. Melet, W.S. Kessler, F. Marin, and B. Djath, 2014: Exploring the mesoscale activity in the Solomon Sea: A complementary approach with a numerical model and altimetric data. *J. Geophys. Res.*, **119**(4), doi: 10.1002/2013JC009614, 2290–2311.

Hristova, H.G., W.S. Kessler, J.C. McWilliams, and M.J. Molemaker, 2014: Mesoscale variability and its seasonality in the Solomon and Coral Seas. *J. Geophys. Res.*, **119**(7), doi: 10.1002/2013JC009741, 4669–4687.

McGregor, S., P. Spence, F.U. Schwartzkopf, M.H. England, A. Santoso, W.S. Kessler, A. Timmermann, and C.W. Böning, 2014: ENSO-driven interhemispheric Pacific mass transports. *J. Geophys. Res.*, **119**(9), doi: 10.1002/2014JC010286, 6221–6237.

In Press:

Ganachaud, A., S. Cravatte, A. Melet, A. Schiller, N. Holbrook, B. Sloyan, M. Widlansky, M. Bowen, J. Verron, P. Wiles, K. Ridgway, P. Sutton, J. Sprintall, C. Steinberg, G. Brassington, W. Cai, R. Davis, F. Gasparin, L. Gourdeau, T. Hasegawa, W. Kessler, C. Maes, K. Takahashi, K. Richards, and U. Send, 2014: The Southwest Pacific Ocean and Climate Experiment (SPICE). *J. Geophys. Res.*, doi: 10.1002/2013JC009678.

Manuscripts submitted, in review:

Hu, D., L. Wu, W. Cai, A. Sen Gupta, B. Qiu, A. Gordon, X. Lin, Z. Chen, S. Hu, G. Wang, T. Qu, and W.S. Kessler, 2014: Pacific western boundary currents and their roles in climate. *Nature Geosci*.