Gliders monitor western boundary current transport in the Solomon Sea

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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. 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 identical to theirs, while the specific accomplishments at PMEL are described below in sections 2-4.

To describe climate, long observation records are required. The strength of boundary currents challenges conventional moored approaches 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 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 50 Solomon Sea crossings. A single glider was lost as the operational cost of a section was reduced to the equivalent of one day's ship time. During 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 implemented in 2012 and the first data were retrieved by small boats in 2013. 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 ocean circulation. Our interest in this remote current is its impact on predicting air-sea interaction in the equatorial zone, most notably on El Niño – Southern Oscillation (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.

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, can be downloaded with an available password, and are delivered regularly to US agencies/programs (e.g US Navy for operational forecasts/planning and research); additional connections are invited. Delayed-mode data are archived locally and can be downloaded (with a password). IOOS is establishing archival and regular distribution of all glider data. Mooring/PIES data from the Solomon Sea will be gathered only for a 2-year demonstration period. Nonetheless, once processed they will be made available to modelers, SPICE collaborators, and any other researchers interested in them. In a sustained operation, this could become a routine product to complement the glider data. There are now no known operational users for delayed-mode Solomon Sea data.

2. Scientific and Observing System Accomplishments

Scientific results

Davis, Kessler and Sherman (2012) presented an analysis of transport through the Solomon Sea based on glider observations through 2010. The major findings were

- Equatorward transport above 700 m varies between 0 and 25 Sv on seasonal time scales. Transport variations are correlated with the ENSO cycle as measured by SST indices like Niño 3.4 or the Southern Oscillation Index. 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 EUC-source waters at 250 m are in the lower layer, but this layer's variability is the weaker so both modes contribute comparably to EUC source variability.

- 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 2014) 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 2013). However, the origin of the lower-layer variability remains unknown.

These results, which need confirmation through more than one ENSO cycle, show that transport of the EUC's Solomon Sea source has comparable variability from two origins: a shallow mode that varies with ENSO and a deeper mode whose driver is unknown. However, it is the deeper mode that feeds the EUC.

Kessler and Cravatte (2013) 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 in variations of thermocline depth, consistent with the shallow mode emphasized by the gliders. A simple index of westward transport based on satellite altimetry was developed that will allow ongoing near-real-time monitoring of this incoming signal for comparison with the glider observations.

Operational activity

Deliverable: "[In FY 2013 we will conduct] six glider cruises across the Solomon Sea with reports of depth-average velocity above 700 m, and profiles of temperature and salinity across the SS [will be made] available as data files and graphical descriptions on spray.ucsd.edu ." The five glider deployments completed is one short of this, but the 12 sections made matches the expectation from 6 cruises. This required three trans-Pacific trips, for two people, yet the total cost per section (vehicle and instrument preparation, shipping and travel, and field operations) was less than $20K. There were no operational mishaps and the data quality is good. Data from all cruises finished before September 2013 has been quality controlled, corrected for flight dynamics changes, and is available for distribution.

The complete glider record is depicted in Figure 1 as a time series of directly measured transport and relative geostrophic transport from glider-measured density. Our archive now includes 24 cruises and 50 sections covering 35,000 km (near a global circumference). One glider was lost and another needed rescue recovery.

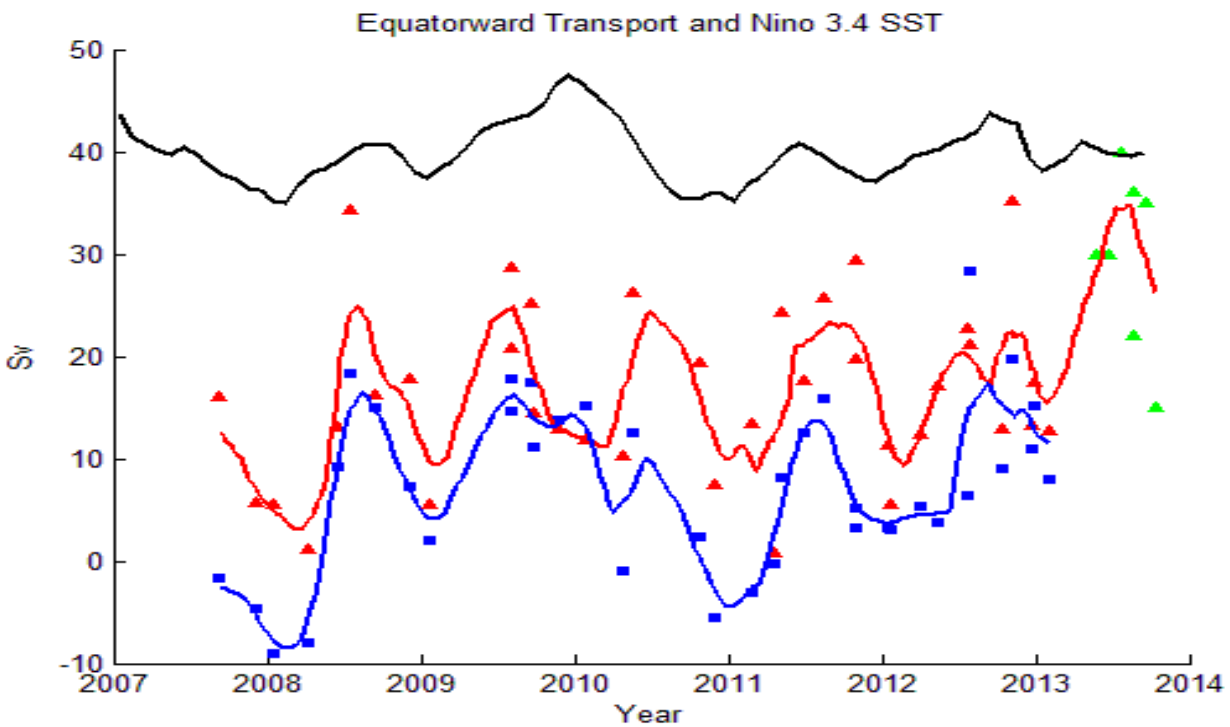

Figure 1. *Equatorward Solomon Sea transport above 700 m from: (red) absolute velocity from glider motion; (blue) geostrophic relative flow referenced to 700 m from glider profiles. Symbols are transports from single cross-basin sections; green triangles are realtime data without QC. Solid lines are outputs of a 3-month running mean filters applied to the interpolated series. The black line is the Nino 3.4 monthly anomaly from its seasonal cycle (arbitrarily scaling).*

Deliverable: "Operation of moorings and PIES across the Solomon Sea and analyses of acoustically downloaded data." Two PIES were deployed across the Solomon Sea in February 2012 and two simple moorings added in July 2012. In May 2013, Kessler used local boats to visit the PIES/mooring locations and acoustically download most of their data. Technical problems with a modem on one PIES led to data gaps which we can close after instrument recovery. The moorings allow the calculation of geostrophic transports (as a function of depth to 500m) through the Solomon Sea relative to 320m; the PIES measure the pressure gradient fluctuations at 320m. Only the mean pressure difference at 320m is unknown. The mean vertical profile of the transport looks very similar between the 10 months of mooring data and 2½ years of glider data (figure 2, left), thus we adjusted the mean PIES pressure gradient to bring the two profiles into approximate agreement. The resulting total transport for 0-500m is shown in figure 2 (right) in black, with the total glider transports superimposed as red circles. Joint analysis of the glider and mooring/PIES data is in progress and will be presented at the AGU/ASLO Ocean Sciences Meeting in February 2014.

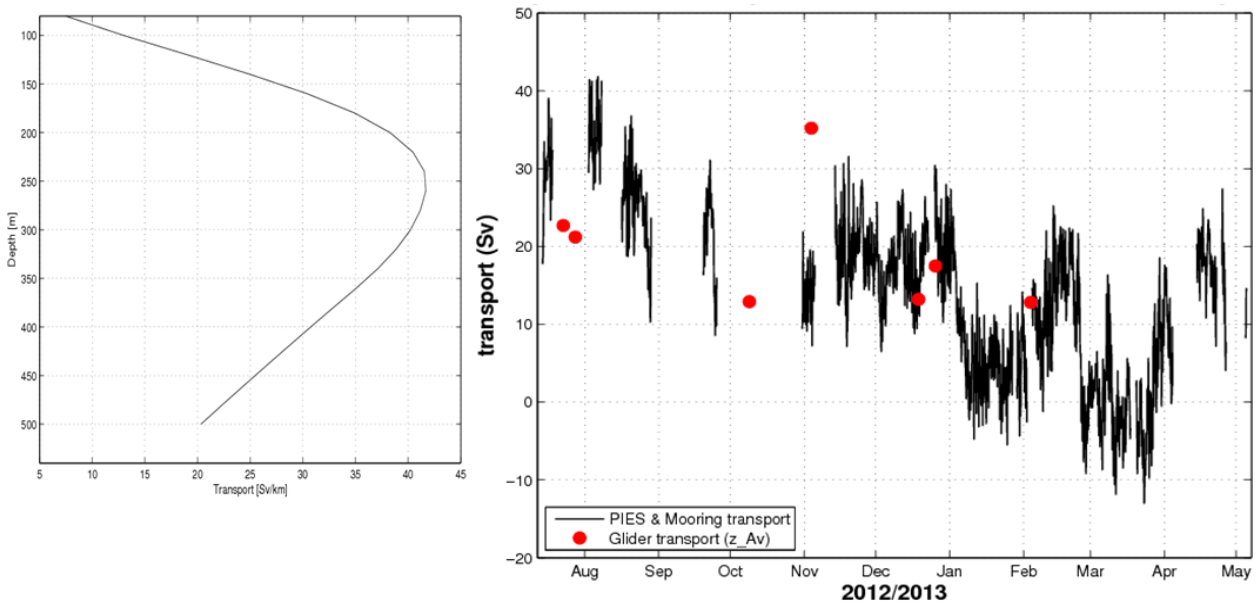

Figure 2. *Mean profile of transport through the Solomon Sea from mooring/PIES data (left). Timeseries of 0-500m transport from moorings/PIES in black and 0-700m from gliders in red (right).*

Figs. 1 and 2 show remarkably rapid variation of basin-wide transport. Glider transport from depth-average velocity and relative geostrophic flow both show several examples of transport changes of O(15 Sv) over a month or two. Similarly, the mooring/PIES data show several 10 to 15 Sv changes over 10-20 days. These changes are noise to the seasonal variability of interest. Correlation of the two independent glider measurements and the changes in the mooring/PIESs data argue that this noise is, in fact, ocean variability not instrumental.

The 2009 El Niño is evident in both glider series but is clearest in the geostrophic relative transport because this is dominated by the upper layer that is well correlated with ENSO. Transport to the EUC occurs in the lower layer and the O(10) Sv difference between the absolute and relative-geostrophic transports reflects a flow of O(4 cm/s) at the relative flow's reference level, which is in the lower layer. This is why direct velocity measurements are important in the Solomon Sea boundary current.

When filtered, both glider series show a clear seasonal cycle that was not detected in the first 2½ years of record. This shows how extending record length not only raises the precision of measurements but can disclose new processes. As our record approaches a decade in length, we can begin to see how the quasi-annual variability is modulated by ENSO and as the record grows longer we will be able to examine what is now just a hint of slower variability. Proponents of a subtropical influence on equatorial air-sea interaction expect it to be on decadal periods.

Technical developments

Deliverable: "Technology modifications of SS gliders to improve data quality and reduce the cost of maintaining the transport time series. A technical report of our technical improvements is planned for FY14." Maintaining the glider time series of trans-basin sections roughly every month has depended on technical and methodological advances in two general areas: (a) minimizing cost by training Solomon Islanders to deploy and recover gliders in our absence and (b) improving glider performance to get more data from a cruise and avoid failures requiring expensive recoveries. New techniques (including tests that the glider carries out itself) were developed to enable locals to check-out gliders before deployment. This allows us to deploy six gliders a year with only three trans-Pacific trips. Reliability improvements used post-cruise forensics to target modifications to eliminate systemic weak points. The most important was adding a small pump to remove gas from the hydraulic system to avoid vapor-lock of the buoyancy pump. This is key to "remote" preparation for launches and "delayed" deployments

Major glider improvements introduced this year were:

- "Delayed" deployments provide a way to start multiple missions at minimum effort in order to improve control of the mission schedule and control cost. Two gliders are deployed simultaneously and one begins its mission immediately. The other goes into "sleep" mode for a month or more before beginning its mission. A "sleeping" glider rests at depth using little energy and occasionally surfaces for communication. No drag-producing biofouling has been observed from resting at depth.
- The Spray buoyancy system was modified to pump 100 cc more oil for buoyancy. This raises velocity 20% and increases operating depth from 700 to 1000 m. The small speed increase greatly reduces the time to transit adverse currents that otherwise might nearly halt progress. Greater operating depth gives more time in weak currents and reduces the rate at which biofouling adds vehicle drag. Extra pumping increases energy use and reduces duration, but duration was already determined by biofouling and simulations suggest that added performance in adverse currents will actually increase range.
- As a result of extra buoyancy control, since May 2013 all cruises are being scheduled for two round-trips (four transits) across the Solomon Sea. The first two of these cruises are complete after making four sections each. This promises to nearly halve the cost to complete a section.

The technical developments for the mooring/glider complement are being validated now with the first data in hand. We took care to design this component to be cost-effective by using small hardware that can be handled by local boats, can remain in the water for 2 years (moorings) and 4 years (PIES), and carry acoustic modems for data retrieval from small boats. We are in the process of assessing the quality of the data. The richness of the information provided in the time domain is demonstrated by Figure 2. First indications suggest that this is a feasible, low-cost approach for the integrated mass transports in this and other western boundary current regions.

Another development area was the glider data system. Stated FY13 and FY14 goals were:

- to improve the data system to process delayed mode data more quickly with lower human effort, to document the system while making it transportable to other operators, and
- to develop products for dissemination that will allow others to integrate our results into their research and prediction studies.

We have adopted the initial quality control procedures developed by Rudnick and used in CORC California Current work. We built a system based on wide-spread MatLab to support the special analyses needed for accurate transport measurements, including the novel techniques to estimate glider-speed as vehicle drag changes. This is operational and is speeding delayed-mode processing. Its regular use is still leading to improvements through code revision.

Data management

Product dissemination will need the faster data processing now available. Developing useful indices of Solomon Sea transport will require describing its climate impacts and subtropical influences to equatorial air-sea interaction. Simple plots like Figs. 1 and 2 are not adequate and research is required to develop more useful products. This is still planned for FY14.

The glider data flow begins with satellite reports received at Scripps, added to a realtime archive on three local servers and delivered to requesting operational and research users. Plots of profiles and velocities are made publically available at spray.ucsd.edu and the data can be downloaded from sushi.ucsd.edu with an available password. Soon the IOOS Glider Data Assembly Center will distribute these data over the Global Telecommunications System (GTS), make them publically available and archive them centrally. More complete data is collected when a glider is recovered. This is archived on sushi.ucsd.edu , backed up to three local servers and quality controlled. The complete glider data set is re-archived approximately monthly. Quality controlled delayed-mode data can be downloaded (with available password) from sushi.ucsd.edu. At this writing (20 October), the most recent observation recovered from the delayed-mode online archive was taken 16 September 2013 and had not been quality controlled.

Field operations by Kessler in 2013:

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. A third trip was made by two engineers in October 2012, but the PI could not go on that due to a family conflict. The two trips made by the PI for this project during FY 2013 were:

May 2013: **Misima, Papua New Guinea:** Download PIES data.
Supported local travel by a UPNG faculty member to accompany the operation for training and education (and to assist in the operation and boat charter negotiations).
Visited Alotau, PNG (capital of Milne Bay Province) to meet provincial government officials per EEZ clearance agreement.
Lectures and school visits as described in the next section.
Gizo, Solomon Islands: Download PIES data. Recover/Deploy two gliders

Sep 2013: **Gizo:** Recover/Deploy 2 gliders
Lectures and school visits as described in the next section.

3. Outreach and Education

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

Fig. 2. Villagers on Ponam Island, Manus Province, Papua New Guinea examine a Spray glider recovered in their waters. Maintaining diplomacy and cooperation with local residents through education is time-consuming but rewarding. (Photo by W.S. Kessler).

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, PIES and moorings 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. An example of this benefit occurred during the recovery of a sick glider north of Manus Island. Our UPNG contacts explained that we needed to visit the island to request permission from the local chief, and help make these arrangements. The resulting visit is depicted in Figure 2.

During negotiations to place the PIES moorings in PNG and Solomons water, we agreed to construct and provide tide tables from the PIES data, in these regions where such data is previously unknown. These tables are being calculated from data downloaded in May 2013 (about 15 months of data) and are nearly complete. They will be provided to the Solomon Islands Meteorological Service and the University of PNG, and updated as we obtain longer time series.

During FY 2013, the following lectures and visits were made:
* Lecture to regional high school assembly (400 students) in Alotau, PNG (May 2013)
* Lecture at 7th-day Adventist church in Misima, PNG (May 2013)
* Meetings with students and faculty at UPNG, Port Moresby, PNG (May 2013)
* Lecture at Rotary Club, Honiara, Solomon Islands (Sep 2013)
* Two school lectures in Gizo, Solomon Islands (Sep 2013)
* Lecture at United Church of Christ, Mbabanga Island, Solomon Islands (Sep 2013)

4. Publications and Reports

4.1. Publications by Principal Investigators

Published in FY 2013 (Kessler-authored pubs only):

Davis, R.E., W.S. Kessler and J.T Sherman, 2012: Gliders measure western boundary current transport from the South Pacific to the equator. *J. Phys. Oceanogr.*, **42**, 2001-2013.

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

Ganachaud, A., M. Bowen, G. Brassington, W. Cai, S. Cravatte, R. Davis, L. Gourdeau, T. Hasegawa, K. Hill, N. Holbrook, W. Kessler , C. Maes, A. Melet, B. Qiu, K. Ridgway, D. Roemmich, A. Schiller, U. Send, B. Sloyan, J. Sprintall, C. Steinberg, P. Sutton, J. Verron, M. Widlansky and P. Wiles, 2013: Southwest Pacific Ocean circulation and climate experiment (SPICE), *CLIVAR Exchanges*, **18**(61), 16-23.

In Press:

Kessler, W.S. and S. Cravatte, 2014: Mean circulation of the Coral Sea. *J. Geophys. Res.*, Accepted, in press.

Manuscripts in preparation (both of these are for a Special Section of J. Geophys. Res.-Oceans on the southwest Pacific):

Ganachaud, A., M. Bowen, G. Brassington, W. Cai, S. Cravatte, R. Davis, F. Gasparin, L., Gourdeau, T. Hasegawa, N. Holbrook, W. Kessler, C. Maes, A. Melet, K., Richards, K. Ridgway, U. Send, A. Schiller, B. Sloyan, J. Sprintall, C., Steinberg, J. Verron, M. Widlansky, P. Wiles, 2014: Ocean circulation of the Southwest Pacific: New insights from the Southwest Pacific Ocean and Climate Experiment (SPICE). In preparation.

Hristova, H., W.S. Kessler, J.C. McWilliams and J. Molemaker, 2014: Eddy distribution in the Coral and Solomon Seas. In preparation.

4.2. Other Relevant Publications