Measuring the Flow Through the Kerama Gap

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BACKGROUND

The principal flows in and out of the East China Sea (ECS) are through channels penetrating the Ryukyu Ridge (Figure 1). Since ~20 Sv of Kuroshio mean flow enters and exits through two of these channels, they are especially well known: the East Taiwan Channel (sill depth 775 m) at the ridge's southwestern end, and the Tokara Strait (sill depth 690 m) near its northeastern end [*Choi et al.,* 2002]. But the deepest channel connecting the ECS to the surrounding ocean is near the ridge mid-point; it is the Kerama Gap, about 50 km wide with sill depth 1050 m [*Choi et al.,* 2002]—see Figure 1.

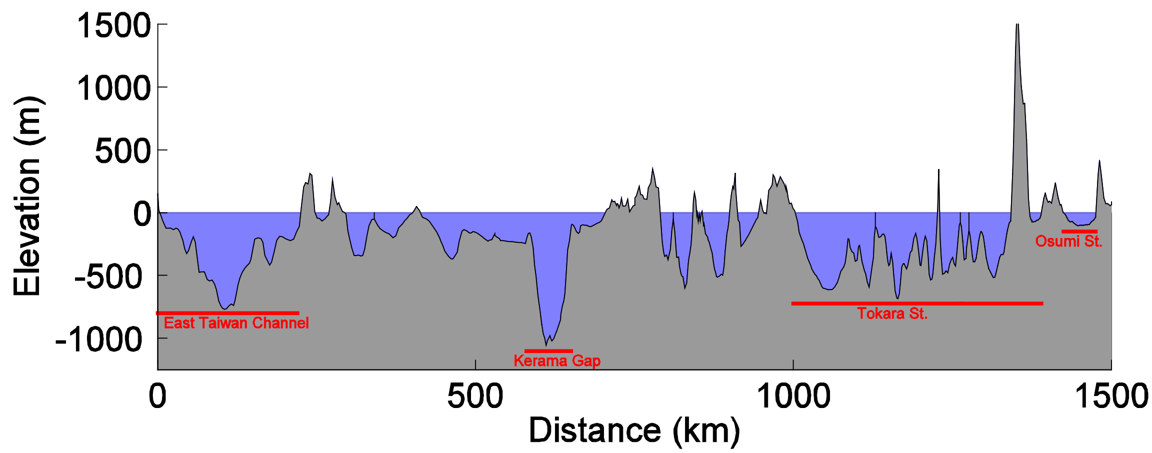

Figure 1. The Ryukyu ridgeline, from Taiwan (on the left) to Kyushu, Japan (on the right). The Kerama Gap at Distance = 600 km from Taiwan has sill depth > 1000 m, and is the deepest channel connecting the Pacific Ocean with the East China Sea. The island of Okinawa is at Distance = 700-800 km, just to the right (i.e., northeast) of the Kerama Gap.

From previous studies, little is reliably known about the flow through the Kerama Gap. Mean-flow estimates from measurements and models range from 0.9 Sv out of the ECS to 7.2 Sv into it. Knowledge of the flow variability is even more uncertain, but there is evidence of transport variations with magnitude a few Sverdrups, caused by impingement of Philippine Sea eddies from the east, at intervals of a few months [*Andres et al*., 2008a].

Our main purpose in this project is to make a reliable determination of the varying flow through the Kerama Gap.

LONG-TERM GOAL

To measure and understand the time-varying structure and transport of flow between the Pacific Ocean and the ECS through the Kerama Gap, on scales from a few hours to more than a year.

OBJECTIVES

On time scales ranging from two days to two years, our main objectives are to measure the variable flow through the Kerama Gap and to test the following three hypotheses:

(1) increase in transport through the Kerama Gap is associated with (a) an increase in ECS-Kuroshio transport across the PN-line, north of Okinawa, and (b) a decrease in Ryukyu Current transport east of Okinawa about two months earlier;

(2) the arrival of anticyclonic (cyclonic) eddies at the eastern side of the Kerama Gap is associated with an increase (decrease) of transport through the Gap;

(3) variations in wind stress over the local region cause variation in the flow through the Kerama Gap.

APPROACH

Our plan was to deploy for two years, in conjunction with our Japanese colleague, Dr. Hirohiko Nakamura of Kagoshima University, an array of Current-and-Pressure-sensor-equipped Inverted Echo Sounder (CPIES) instruments and current-meter (CM) moorings across the Kerama Gap. At the sea floor, the CPIES measures acoustic echo time (τ) from the sea surface, pressure (P) and horizontal current velocity $\vec{u}$. A cross-section of the Kerama Gap showing instruments positions is shown in Figure 2.

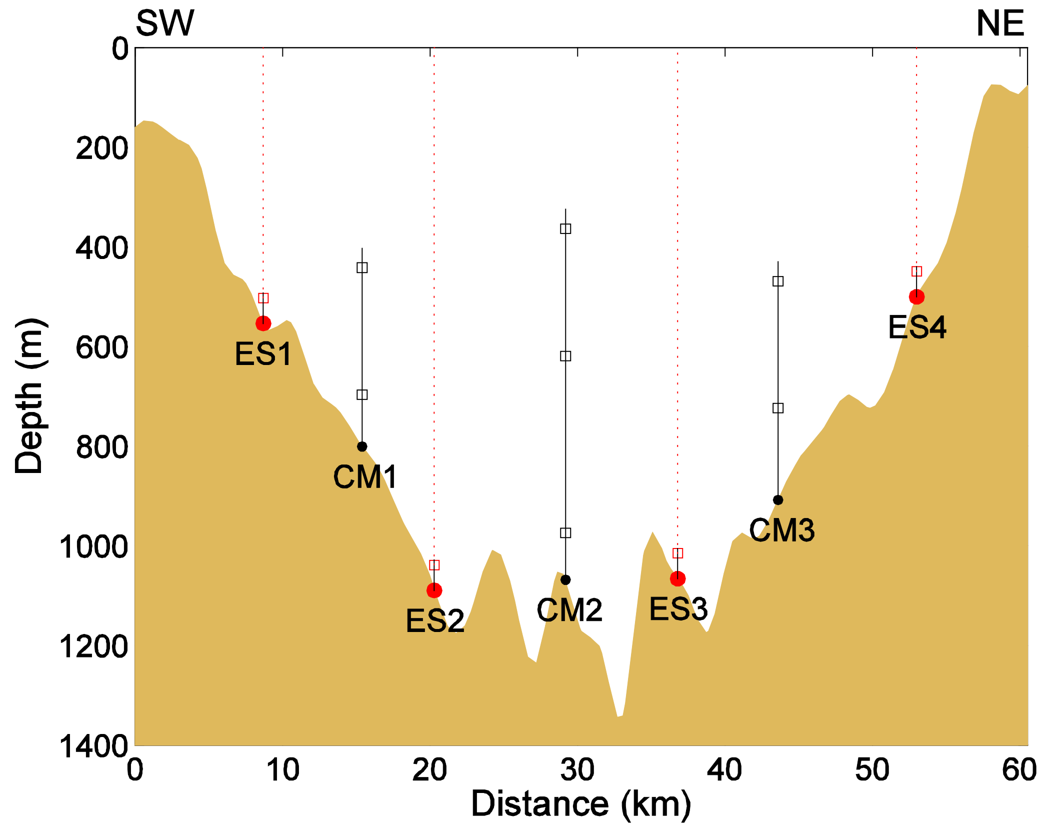

Figure 2. Cross-section diagram of the Kerama Gap array. Four CPIESs are shown as solid red dots (open red squares immediately above represent the current sensors 50 m above the sea floor). Seven CMs on three moorings are shown as black open squares. Topography is from measurements taken on the June 2009 cruise. Note: this section across the Kerama Gap is slightly northwest of the sill, hence the maximum depth at the section is greater than the sill depth (1050 m).

WORK COMPLETED

Together with Dr. Nakamura and his team, we conducted, from the Japanese Training Vessel *Kagoshima-maru*, three cruises to the Kerama Gap region at one-year intervals, one each in 2009, 2010 and 2011. On the first cruise, in June 2009, we successfully deployed our array of CPIES and CM moorings (Figures 2 & 3) and obtained hydrographic profiles at each site.

In spring 2010, the shallowest current meter (365-m depth on the central CM mooring), together with its floatation, was found by a fisherman near the Tokara Strait drifting on the surface. It appeared to have been severed from the mooring either by trawling or by fish-bite. This occurred on February 9, 2010, but thanks to the Japanese fisherman who retrieved the instrument, we obtained good data up to this time of severance.

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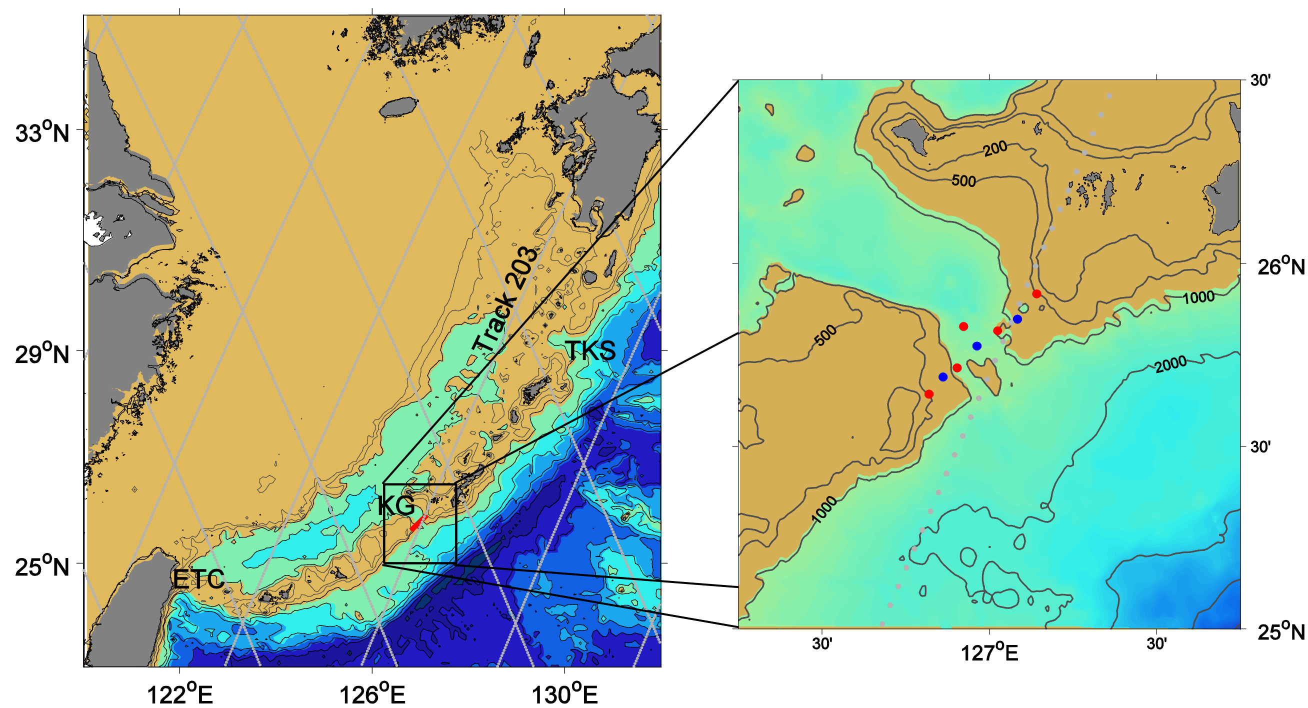

Figure 3. Left panel: East China Sea (ECS) region; ETC = East Taiwan Channel, KG = Kerama Gap, TKS = Tokara Strait; Jason-1 altimetry tracks shown as gray lines; red bar shows position of the deployed array. Right panel: Enlargement of Kerama Gap region showing the deployed array: red dots are CPIES moorings, blue dots are CM moorings. The array is along a line across the Kerama Gap, except that one CPIES instrument near the center of the Gap is about 10 km northwest of this line. Depth contours are at 200, 500, 1000, 2000, 3000 and 4000 m.

On our second cruise, in June 2010, we recovered and redeployed the CM moorings and collected additional hydrographic profiles. The final cruise was in June 2011, when we recovered all the CPIES and CM moorings from the Kerama Gap and again took hydrographic profiles at each site. The CPIESs from the deep (~1,000 m depth) region of the Gap had all suffered leaks from apparent fish-bites on the 50-m electrical cables connecting the current-sensors to the main instruments. As a result, the data from these CPIESs are essentially unusable. Fortunately, the two shallow (~500 m depth) CPIESs were undamaged and obtained good data throughout the two-year deployment period, and we have good data from all the instruments on the CM moorings.

Figure 4 shows good correlation of the difference in acoustic echo times (τ) measured by the two shallow CPIES instruments (one on either side of the Kerama Gap) with sea-level difference measured across the Gap by the Jason-2 altimeter (on a nearby track, see Fig. 1). The combined (τ, P, $\vec{u}$) data set from the two shallow CPIES instruments will be used to infer transport in the top 500 m, using the Gravest Empirical Mode (GEM) technique (see Results, Section a). The >500 m transport will be obtained from the CM instruments. Adding these two we will obtain the full (surface-to-bottom) time-varying transport through the Kerama Gap during our two-year deployment period.

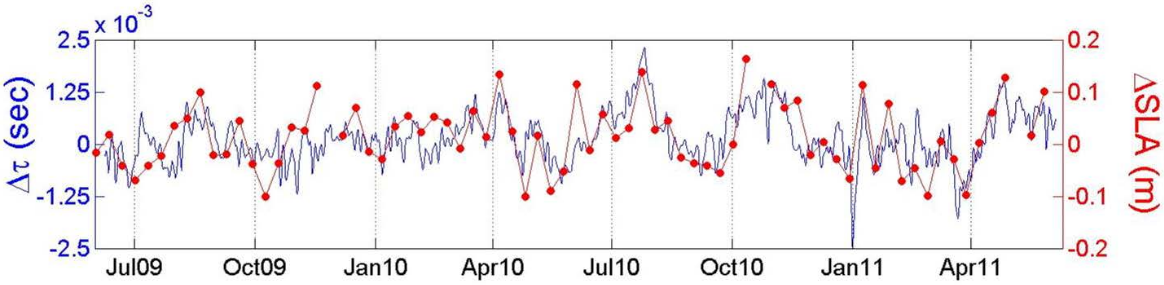

Figure 4. $\tau_{ES1} - \tau_{ES4}$ ***(blue) from CPIES measurements and sea-level-anomaly difference (red) across the Kerama Gap measured by the Jason-2 altimeter.***

If, as we expect, this transport time series is strongly correlated with the altimeter record shown in Figure 4, we will be able to use the altimeter record going back to 1992 to infer longer-term (~decadal) variations of the Kerama Gap transport.

RESULTS

(a) Gravest Empirical Modes (GEMs)

We have assembled data from historical hydrocasts in the region and from CTD casts taken on our three cruises to the Kerama Gap, a total of 147 Profiles (see Fig. 5 for site locations). After calculating and removing the seasonal signals from these data at pressure levels less than 200 dbar, we computed sound-speed profiles and hence 0-500 dbar acoustic echo times τ_{500}. At each pressure level we then spline-fitted temperature T as a function of τ_{500} and plotted the resulting GEM field for temperature (Fig. 6, left). We similarly obtained the GEM field for specific volume anomaly δ (Fig. 6, right). Using these GEM fields, we can infer profiles of T and δ from τ_{500} measured by the two shallow CPIESs, and in combination with the CPIES measurements of P and $\vec{u}$ we can then determine 0-500 dbar absolute transports between these two instruments.

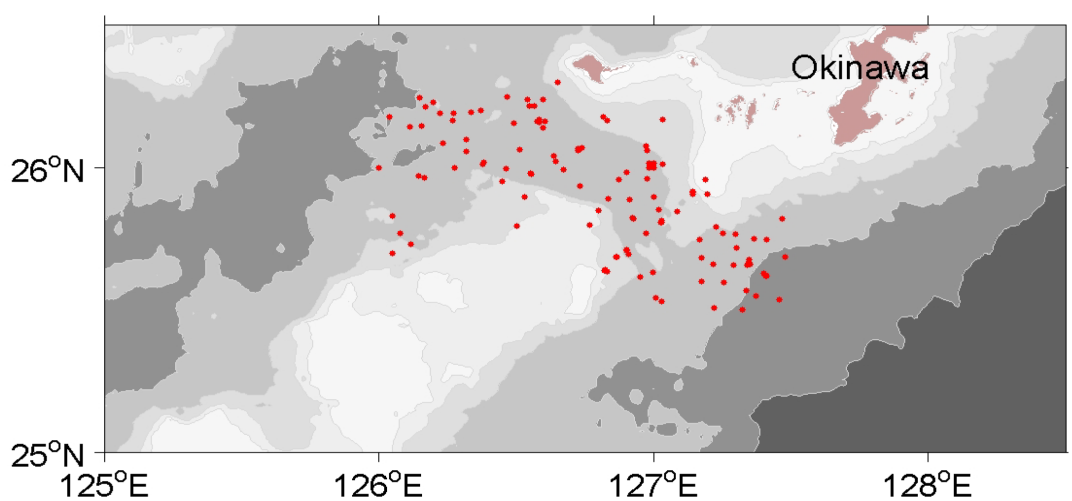

Figure 5. Site locations of hydrocast data used in computing Gravest Empricial Modes (GEMs) for the Kerama Gap region.

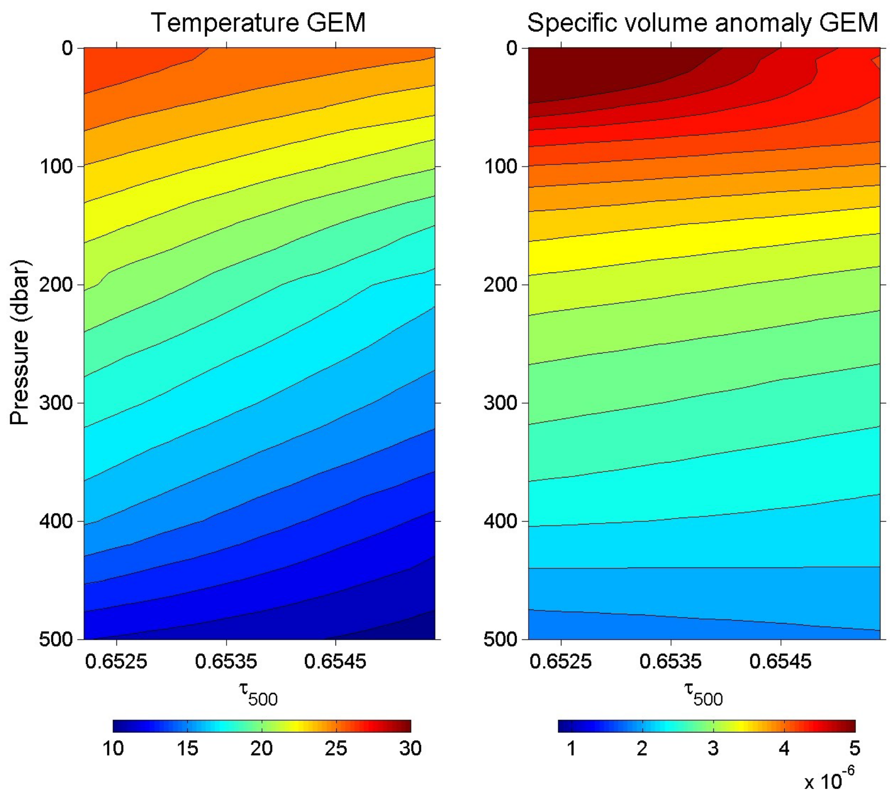

Figure 6. Temperature T (left) and specific-volume-anomaly δ (right) GEM fields computed from hydrocasts in the Kerama Gap region. Contours are shown at intervals of 1°C (left) and 2×10^{-7} m^{-3}/kg (right). These fields allow us to determine T and δ profiles from measurements of τ_{500}.

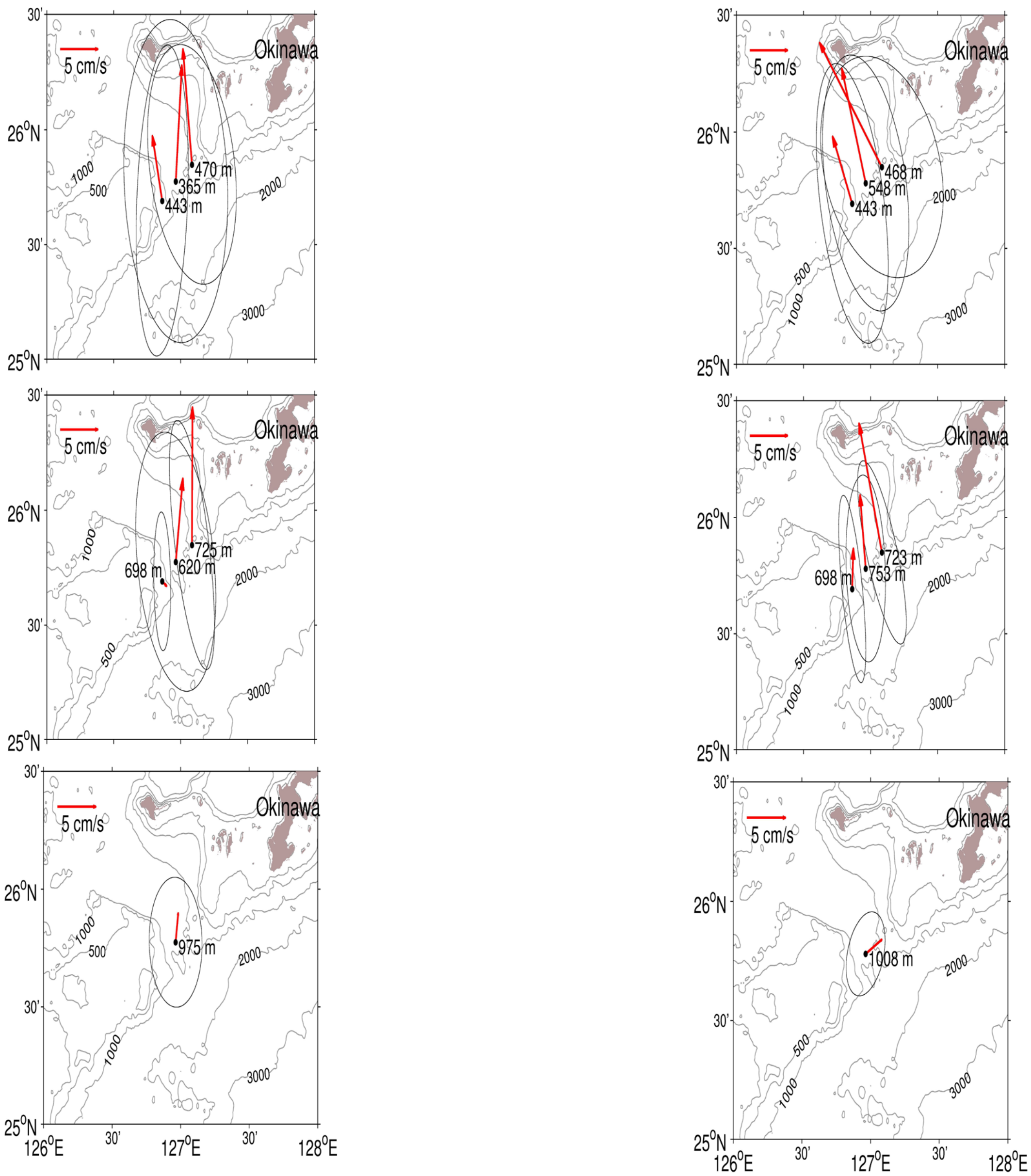

Figure 7. Mean currents and standard-deviation ellipses measured at upper, middle and deep levels by the three CM moorings during Year 1 (left panel) and Year 2 (right panel). Mean flows are generally northward (i.e., into the ECS) and variability is comparable to or stronger than the mean in each case. Year 1 is June 2009 – June 2010. Year 2 is June 2010 – June 2011. Values are based on the full year for each current meter, except that the Year 1 CM2 record at 365 m depth was cut short: June 2009 – February 2010 (see text).

(b) Other Results and Continuing Work

For each of the two years of deployment, means and standard-deviation ellipses of currents measured on moorings CM 1-3 are shown in Figure 7. Clearly the mean currents are generally northward (i.e., into the ECS) and are stronger toward the eastern side of the Kerama Gap. Variability is comparable to or stronger than the mean in each case.

Combining these deep current-meter-measured velocities with the < 500 m volume transport determined from the CPIES data (see Results, Section a), we will obtain a two-year time series of full-water-column transport through the Kerama Gap. We will then use satellite-measured SSH and SST data to investigate the relationship of variations in this transport to eddies arriving from the Philippine Sea to the east. We will also study the possible relationship of the transport to wind-stress over the local region.

We plan to compare our transport time series with three simultaneous time series of SSH difference (ΔSSH) obtained with the Jason-2 satellite altimeter: (1) ΔSSH across the Kuroshio in the ECS north of Okinawa, related to ECS-Kuroshio transport [*Andres et al*. 2008a], (2) ΔSSH across the Ryukyu Current east of Okinawa, related to Ryukyu Current transport [*Zhu et al.* 2004], and (3) ΔSSH across the Kerama Gap itself. We anticipate (from Fig. 4) that there will be significant correlation between our measured Kerama Gap transport and the Kerama Gap ΔSSH; if this is indeed so, we will be able to extend our time series of Kerama Gap transport to the time period from 1992 to the present.

A numerical model has shown that volume transport through the Kerama Gap increases two years after the formation of the Kuroshio Large Meander south of Japan (E. Douglass, personal communication). Since 1992, a single Large Meander formed in 2004-2005 and we will see if this was associated with anomalous Kerama Gap transport, as implied by the model result.

It has been shown that Kuroshio transport in the ECS is correlated with the Pacific Decadal Oscillation (PDO) index [*Andres et al*., 2009]. We will use our extended time series to investigate whether there is a similar PDO-related component in flow through the Kerama Gap.

IMPACT/APPLICATIONS

Because flows through the Kerama Gap add to or subtract from the measured Kuroshio flow in the ECS north of Okinawa [*Andres et al*., 2008a], the results from this study should lead to advances in our understanding of western-boundary-current dynamics.

RELATED PROJECTS

The University of Rhode Island was supported by ONR to deploy an array of IESs in the Okinawa Trough near the PN-line in a project titled, "Variability of the Kuroshio in the East China Sea, and its Relationship to the Ryukyu Current." These instruments recorded the main part of the Kuroshio transport in the ECS. The array was deployed in December 2002 and recovered in November 2004, thus providing spatiotemporal structure of the Kuroshio for a two-year time period. The results of the study are to be found in *Andres et al*. [2008a,b] and *Andres et al*. [2009].

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