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 the Kerama Gap, near the ridge mid-point. It is about 50 km wide with sill depth 1050 m [*Choi et al.,* 2002]—see Figure 1.

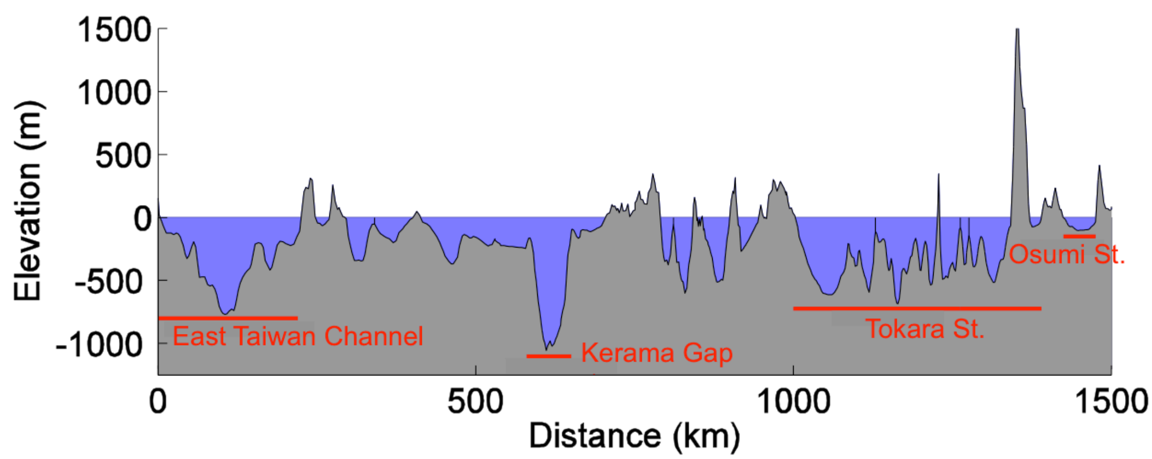

Figure 1. The Ryukyu ridgeline, from Taiwan (on the left) to Kyushu, Japan (on the right). The Kerama Gap at Distance = 600 km from Taiwan has sill depth > 1000 m, and is the deepest channel connecting the Pacific Ocean with the East China Sea. The island of Okinawa is at Distance = 700-800 km, just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

Previous studies have provided little information 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 mean and time-varying flow through the Kerama Gap.

LONG-TERM GOAL

To measure and understand the time-varying 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 temperature (T), and horizontal current velocity $\vec{u}$ 50 m above the sea bed. A cross-section of the Kerama Gap showing instrument positions is shown in Figure 2.

WORK COMPLETED

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

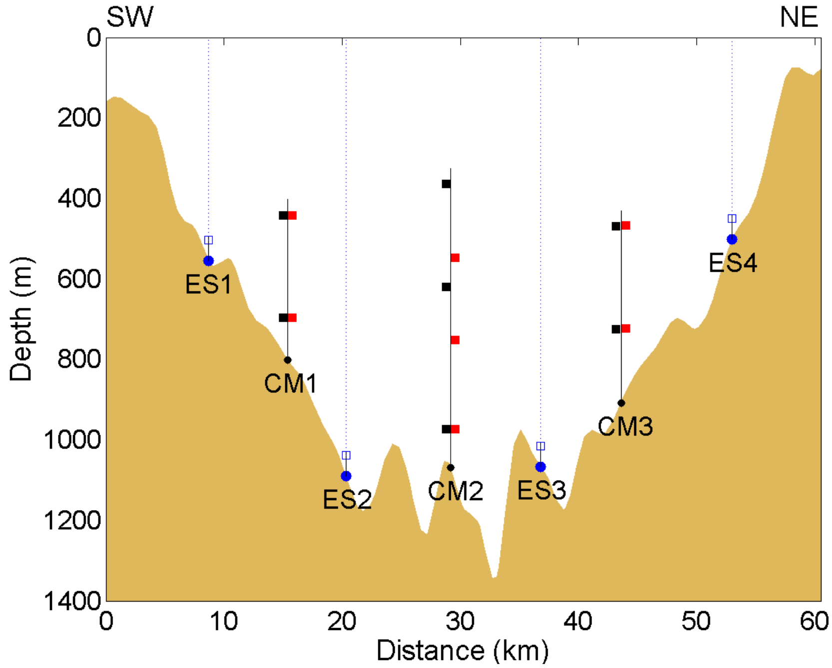

Figure 2. Cross-section diagram of the main Kerama Gap array. Four CPIESs are shown as solid blue dots (open blue squares immediately above represent the current sensors 50 m above the seafloor). Seven CMs on three moorings are shown as solid black (Year 1) and red (Year 2) squares. Topography is from 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).

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.

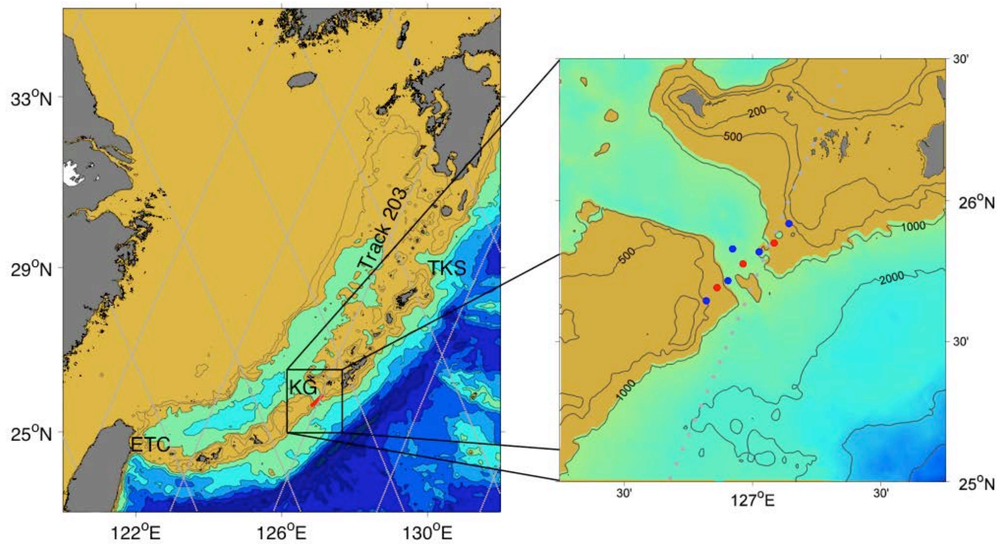

Figure 3. Left panel: East China Sea (ECS) region; ETC = East Taiwan Channel, KG = Kerama Gap, TKS = Tokara Strait; Jason-1 altimetry tracks shown as gray lines; red bar shows position of the deployed array. Right panel: Enlargement of Kerama Gap region showing the deployed array: blue dots are CPIES moorings, red dots are CM moorings. The array is along a line across the Kerama Gap (see Fig. 2), except that one CPIES instrument near the center of the Gap is about 7.4 km northwest of this line. Depth contours are at 200, 500, 1000, 2000, 3000 and 4000 m; dotted gray line is the Jason-1 altimetry track.

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 (or eel-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. The CM moorings adequately sampled the deep (depth >500 m) flow, but data from the two shallow CPIESs were essential for determining the upper-layer (depth < 500 m) transport; so it is indeed fortunate that these two instruments were undamaged and provided excellent records.

Dr. Jae-Hun Park, a Principal Investigator on this project, began work at the Korea Institute of Ocean Science and Technology in 2011. He is still actively engaged with the Kerama Gap study and has visited the University of Rhode Island several times this year. Early in 2012 a post-doctoral fellow, Dr. Hanna Na, from Seoul National University, came to work with us on this project (and others) and has spearheaded the completion of a comprehensive data report [*Liu et al*., 2012].

RESULTS

(a) Gravest Empirical Modes (GEMs)

We have improved our GEM calculations using data from historical hydrocasts in the region, from CTD casts taken on our three cruises to the Kerama Gap, and from Argo floats – a total of 167 Profiles (see Fig. 4 for site locations). After calculating and removing the seasonal signals from these data at pressure levels less than 250 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. 5, left). We similarly obtained the GEM field for specific volume anomaly δ (Fig. 5, 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.

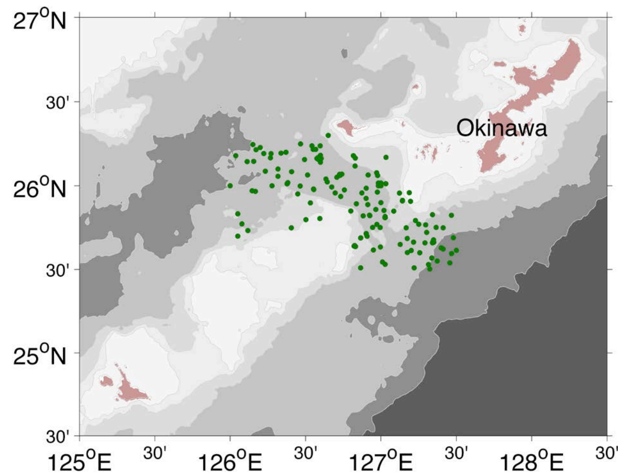

Figure 4. Site locations of hydrocast data used in computing Gravest Empirical Modes (GEMs) for the Kerama Gap region.

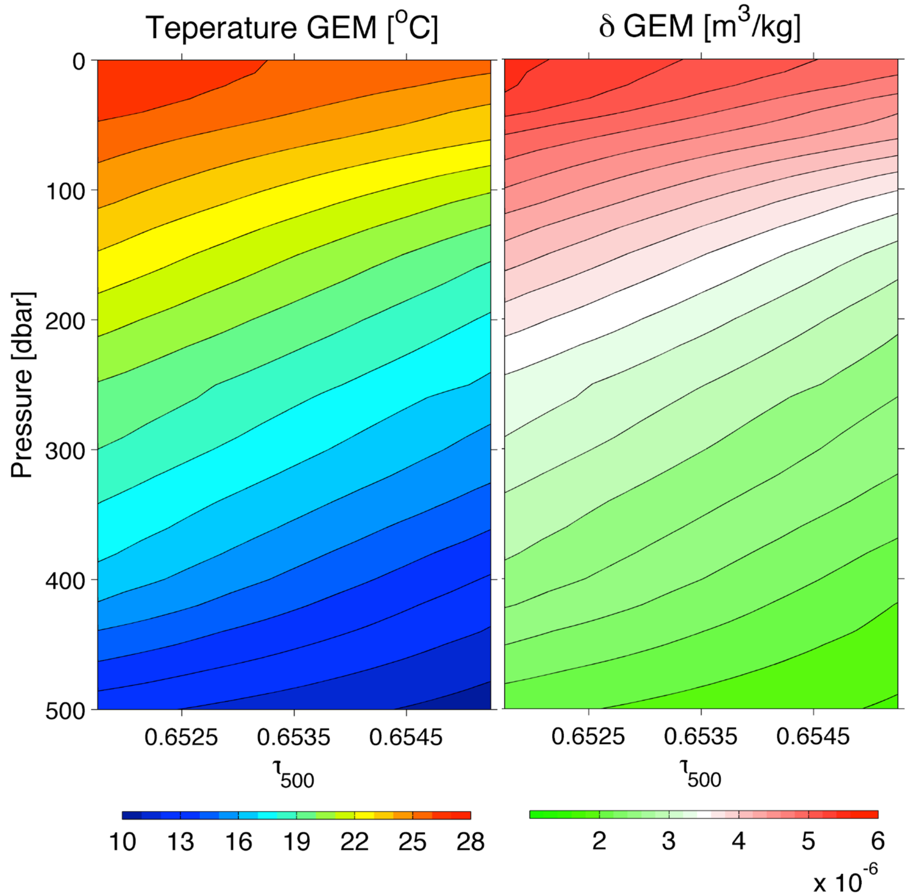

Figure 5. Temperature T (left) and specific-volume-anomaly δ (right) GEM fields computed from hydrocasts in the Kerama Gap region. Contours are shown at intervals of 1°C (left) and 2×10^{-7} m^{-3}/kg (right). These fields allow us to determine T and δ profiles from measurements of τ_{500}.

(b) Main Results

Figure 6 shows means and standard-deviation ellipses of currents measured on moorings CM 1-3. 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 obtain the two-year time series of transports (above and below 500m, and total) through the Kerama Gap shown in Figure 7.

We have compared the total transport time series to that of sea level difference (SLD) across the Kerama Gap measured by satellite altimeter, and have found the highest correlation (0.81) to occur for gridded altimeter data with SLD taken between the two points shown in the top left panel of Figure 8. This comparison gives a linear relationship (total transport = 0.60 Sv/cm + 2.32 Sv) allowing us to infer, from the SLD record, the time varying transport through the Kerama Gap during the past twenty years (Figure 9). Basic transport statistics for the two- and twenty-year records are given in Table 1.

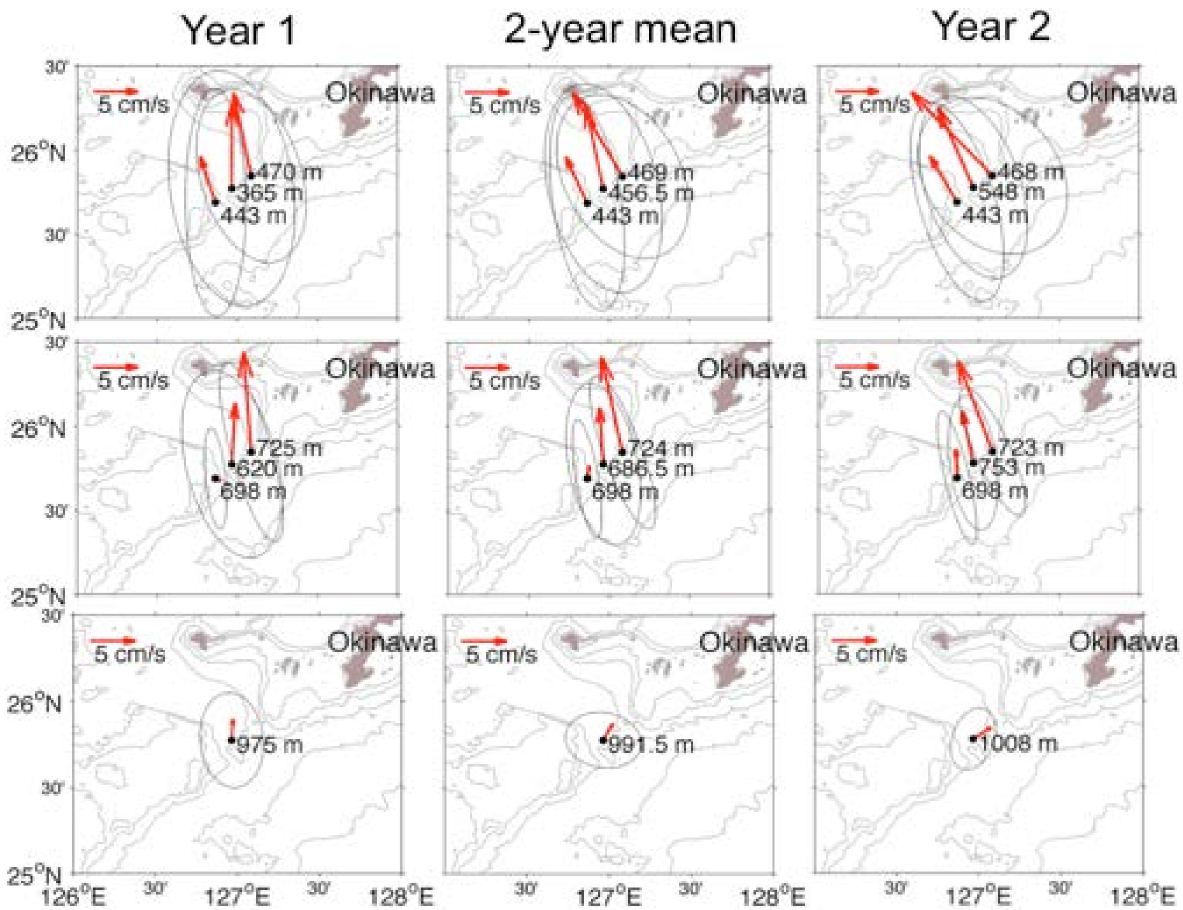

Figure 6. Mean currents and standard-deviation ellipses measured at upper, middle and deep levels by the three CM moorings. Left column is for Year 1 only. Right column is for Year 2 only. Center column is for the overall two-year deployment period (the indicated depths are the average of the Year 1 and 2 depths). Mean flows are generally northward (i.e., into the ECS) and variability is comparable to or stronger than the mean in each case. Note that the CM2 record at 365 m depth was missing from February to June 2010 (see text).

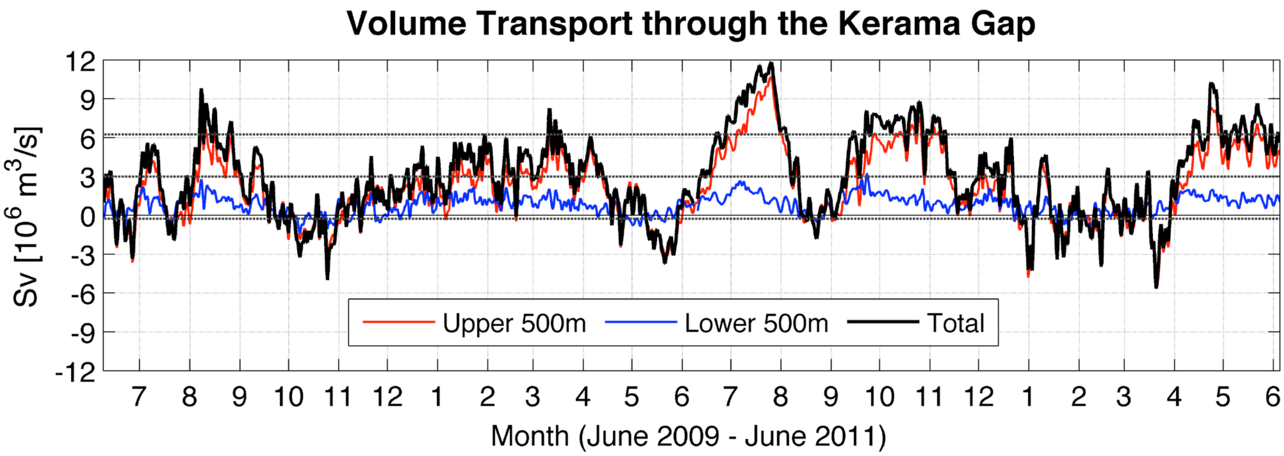

Figure 7. Two-year time series of Kerama Gap transports: upper 500 m layer (red), lower layer (blue), and total (black).

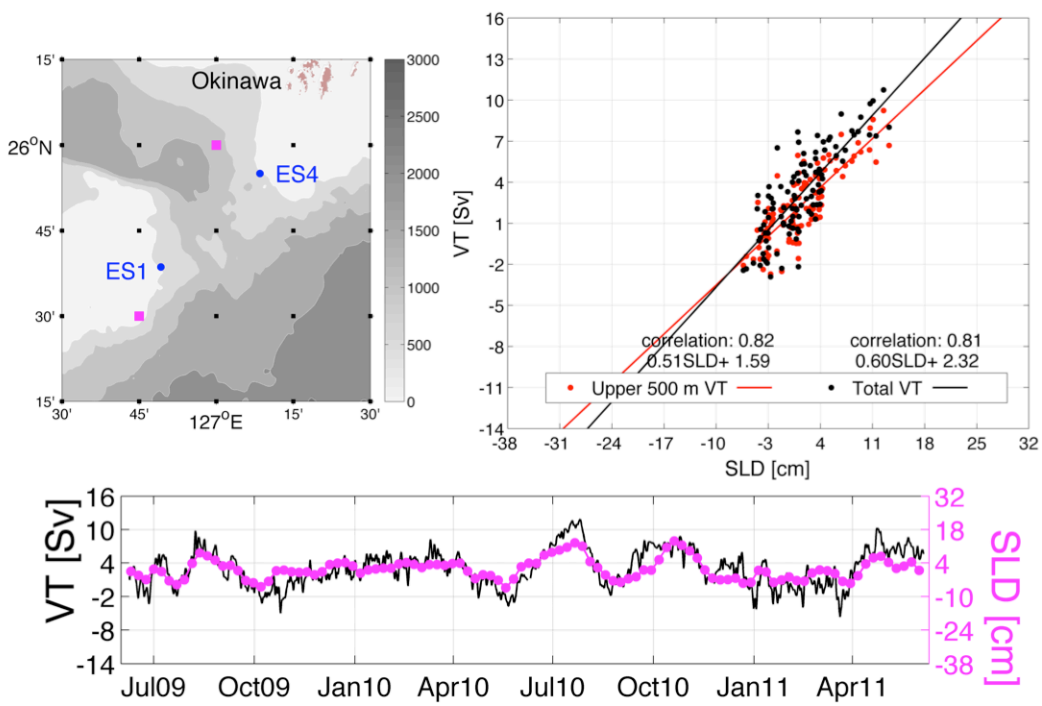

Figure 8. Comparison of measured Kerama Gap transport with sea level difference (SLD) across the Gap obtained from weekly gridded (1/4°) satellite-altimeter data. Left top panel: blue dots show sites of ES1 and ES4 CPIES moorings, pink dots show the pair of grid points giving highest correlation (0.81) of SLD with measured total Kerama Gap transport. Right top panel: linear regressions of upper 500m (red) and total (black) transports with SLD. Lower panel: two-year time series of total Kerama Gap transport (black) and SLD (pink).

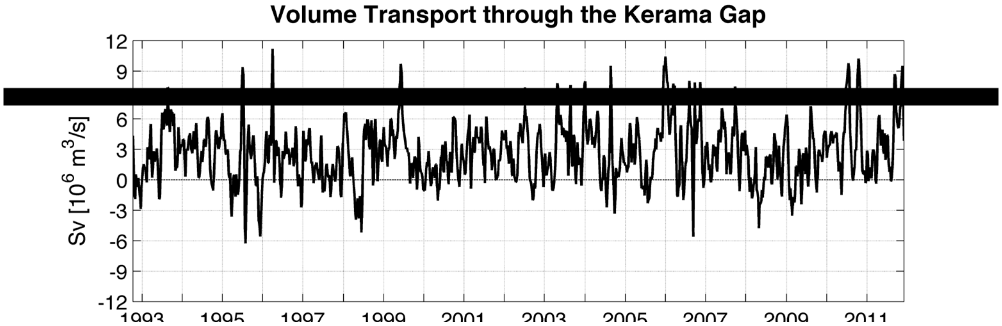

Figure 9. Extended (20-year) Kerama Gap transport time series (Oct. 1992–Dec. 2011).

Table 1. Transport (Sv) statistics for 20- and 2-year time series. (Note: in the first row, "std", "max" and "min" are for the 20-year period.)

Transport regime	20-year mean	2-year mean	Year 1 mean	Year 2 mean	std	max	min
Total (20-year)	2.48	3.17	2.77	3.57	2.70	11.19	–6.26
Total (2-year)		2.99	2.15	3.84	3.25	11.83	–5.65
Upper 500 m		2.19	1.49	2.88	2.76	10.67	–5.66
Lower 500 m		0.80	0.66	0.95	0.73	3.25	–1.39

To begin our investigation of the relationship between Kerama Gap transport and eddies (Objective 2), we have averaged the sea surface height (SSH) and sea level anomaly (SLA) fields separately for those times, during our two-year deployment, when the measured transport was more than one standard deviation above (Figure 10a,c) or below (b,d) the mean. The resulting maps (Figure 10) show high transport into the ECS is associated with the presence of a cyclonic eddy south of the Kerama Gap, and low transport with an anticyclonic eddy there.

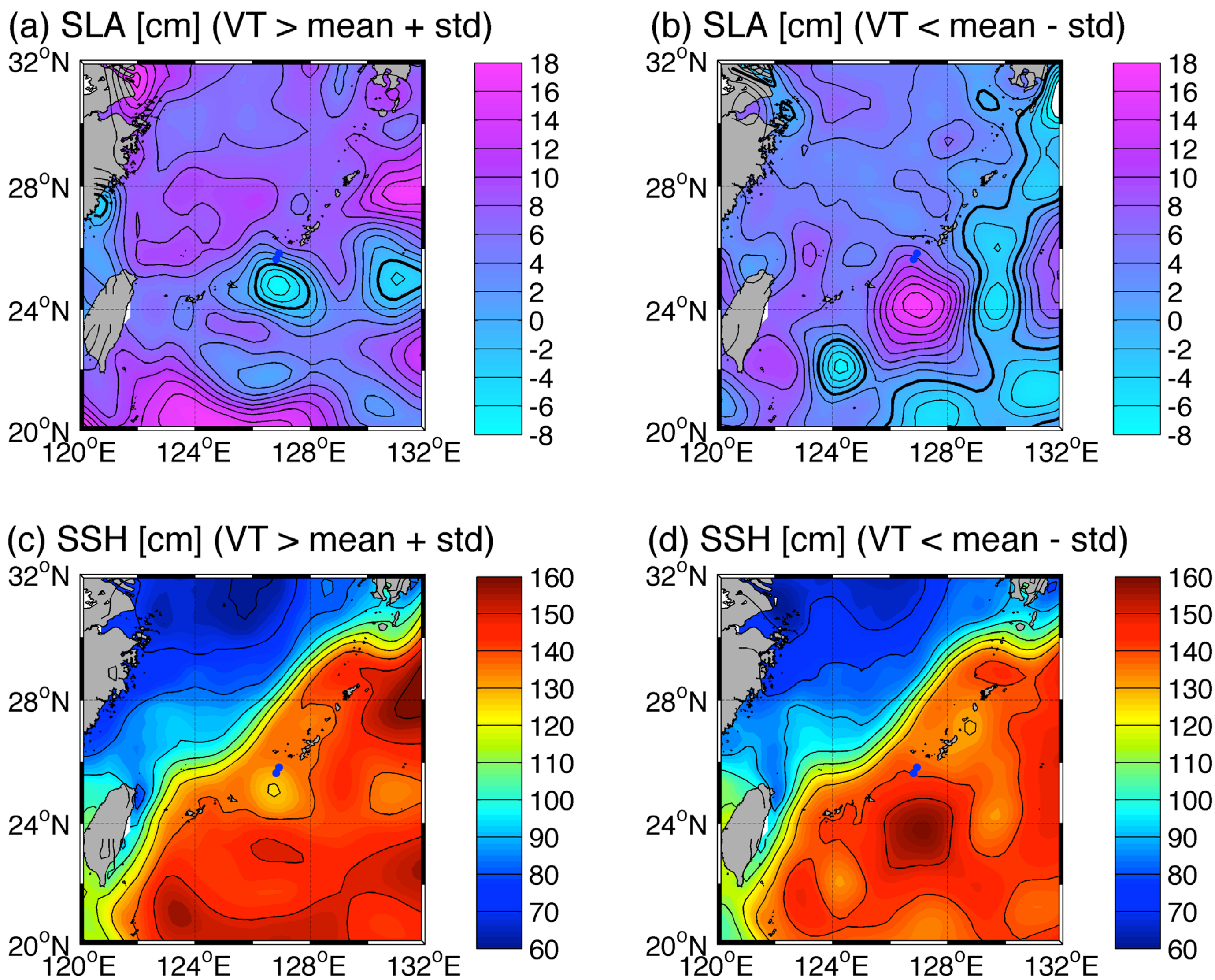

Figure 10. Satellite-altimeter-derived average sea level anomaly (upper panels, a & b) and sea surface height (lower panels, c & d) for two subsets of the period June 2009 – June 2011: times for which Kerama Gap transport > 6.24 Sv (left panels, a & c), and < -0.26 Sv (right panels, b & d). Bold contour lines in (a) and (b) represent zero SLA. Blue dots in the near-middle of the maps denote locations of ES1 and ES4 in 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. They will also give us insight into the flushing of deep (> 800 m) waters in the ECS for which the Kerama Gap is the only connection with the open ocean.

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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