Variability of the Kuroshio in the East China Sea, and its Relationship to the Ryukyu Current

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LONG-TERM GOALS

To characterize and understand (with our Korean and Japanese colleagues) the dynamics of the time varying structure and transport of the Western Boundary Current (WBC) system at 26°–28°N in the northwest Pacific Ocean, in particular the Kuroshio in the East China Sea (ECS), and the Ryukyu Current.

OBJECTIVES

On time scales ranging from two days to two years, our main objectives are the following:

(1) To observe the WBC variations near Okinawa on all relevant timescales, and, with ancillary information on wind forcing and arrival of offshore eddies, address a comprehensive set of hypotheses that have been proposed to account for the WBC structure and variability:

- that the combined WBC mean transport balances the average Sverdrup transport;
- that the phasing of the annual cycle in transport is lagged in a predictable manner from the seasonally varying Sverdrup transport, by the propagation of wind-generated Rossby waves from offshore;
- that variability in how the Kuroshio bifurcates upstream (off Taiwan) governs the proportion of transport that enters either the ECS Kuroshio or the Ryukyu Current;
- that eddies arriving at this WBC system from the ocean interior affect the upstream bifurcation and—as a result—the strength of these two currents.

(2) To measure the characteristic periods and phase speeds of Kuroshio meanders in the ECS and relate them to the strength of the transport.

(3) To investigate the relationships between the transports of the ECS Kuroshio, the Ryukyu Current and the Tsushima Current.

APPROACH

We deployed an array of inverted echo sounder (IES) instruments (with additional sensors) in the Okinawa Trough from December 2002 through November 2004. The resulting data enable us to determine the time-varying current and temperature structure in the region, over this two-year time period. From the measurements of a similar array south of Okinawa and satellite-altimeter data, Japanese scientists, led by Dr. Hiroshi Ichikawa, at the Japan Agency for Marine-Earth Science and Technology, Institute of Observational Research for Global Change (JAMSTEC) have determined the varying Ryukyu Current transport during the same time period. Also (with NICOP support) scientists, led by Dr. Kyung-Il Chang from Seoul National University (SNU) and the Korea Ocean Research & Development Institute (KORDI), deployed ADCPs on the continental shelf near our array, to measure the flow over the outer shelf (see the Report on this study titled, "Kuroshio Variability on the Shelf of the East China Sea").

In addition, SNU scientists, led by Dr. Kuh Kim, are continuously measuring the Tsushima Current transport with a cable across the Korea/Tsushima Strait. They will work with us in studying the relationship of this transport to variations in the ECS Kuroshio.

Besides the principal investigators, there are two University of Rhode Island people engaged in this work, Dr. Jae-Hun Park (Marine Research Scientist) and Magdalena Andres (Graduate Student), as described below.

To determine temperature and specific-volume-anomaly profiles from the IES measurements, we use the Gravest Empirical Mode (GEM) technique (Meinen and Watts, 2000) similar to that which has been successfully applied to the Kuroshio 700 km further downstream (Book et al., 2002).

Satellite altimeter data will be used to track eddies arriving in the region from the ocean interior.

WORK COMPLETED

Under ONR (DURIP) support, we first modified our IES design to incorporate the Aanderaa 3820R current measuring head. Then, after successful field testing, we constructed 12 CPIES instruments (current-and-pressure-sensor-equipped IESs). In December 2002, six of these, together with five PIES instruments (pressure-sensor-equipped IESs) belonging to NRL, were deployed in two lines north of Okinawa, each line being near and parallel to the PN-line (along which the Nagasaki Marine Observatory, Japan Meteorological Agency takes hydrographic sections once every three months). This deployment was carried out in conjunction with Dr. Hiroshi Ichikawa and his associates from JAMSTEC on their ship, *R/V Yokosuka*. In November 2004, all eleven instruments were successfully recovered, again in conjunction with Dr. Ichikawa, from the Kagoshima University vessel, *T/V Kagoshima-maru*. With the following exceptions, the acoustic echo time (τ), bottom pressure (*pb*), and bottom-current (***ub***) data records are all of excellent quality and complete. (1) The *pb* records of the two shallowest instruments show a few pressure "jumps," probably because the instruments were dragged by bottom-fishing gear. The westernmost CPIES (C1) was moved twice, leaving the instrument about 1 m deeper after the first incident and another 5 m deeper after the second. The easternmost PIES (P5) was moved once about 1 m deeper. (2) The ***ub*** data from the current sensor on the easternmost CPIES (C6) were intermittent from April 2004 until the end of the record. (3) The ***ub*** record on the neighboring CPIES (C5) terminated after about two weeks. Also about 1/3 of the *pb* record from this instrument is missing (though the τ record is complete). These problems on C5 appear to have been caused by a faulty o-ring seal on the current-sensor connector.

Magdalena Andres, a doctoral student supported by this grant, completed computations of suitable GEMs based on historical hydrographic data from the region; she also completed the basic processing of all the data from the CPIES and PIES instruments, including error correction, calibration, pressure-drift and pressure-jump removal, time interpolation and low-pass filtering. This work is described and the results are shown in a data report (Andres et al., 2005).

Dr. Jae-Hun Park (under partial support from this grant) led an investigation of the cause of relatively large errors in ECS GEM fields at 100-200 m depth. This revealed that second-mode internal tides, while weak in the area southeast of the Ryukyu Islands, are strong in the Okinawa Trough (being generated at the continental shelf break during ebb tides) and are responsible for the depth band of high error there (Park et al., 2005, 2006). Nevertheless, since we will be using our IES data to study ECS dynamics with longer periods than the tides, the GEM fields will provide accurate representations of these dynamics throughout the water column.

RESULTS

The scientific analysis of our CPIES/PIES data set (in conjunction with the SNU ADCP data set) from the ECS will become Magdalena Andres's doctoral dissertation. Because the ADCP data from the shelf were of limited spatial and temporal coverage (see RELATED PROJECTS section below), spatial and temporal extrapolations of those data were necessary. Various extrapolation techniques were developed and applied, and the results were in good agreement with one another (< 1 Sv rms). We have prepared a manuscript describing the variations in Kuroshio flow determined from the CPIES+ADCP array and it will be submitted for publication when it has been read and approved by all the authors (M. Andres, M. Wimbush, D.R. Watts and W.J. Teague in the U.S., K-I. Chang in Korea, and H. Ichikawa in Japan).

Figure 1 displays the mean velocity cross-section for the 23-month observational period. It shows a double core of positive (northeastward) flow: a surface maximum, 8 km offshore from the shelf break (170 m depth; distance=0), and a maximum at 170 m depth, 50 km from the shelf break. There are two regions of mean negative flow: a deep countercurrent over the continental slope beneath the Kuroshio surface maximum and a recirculation offshore which extends throughout the water column.

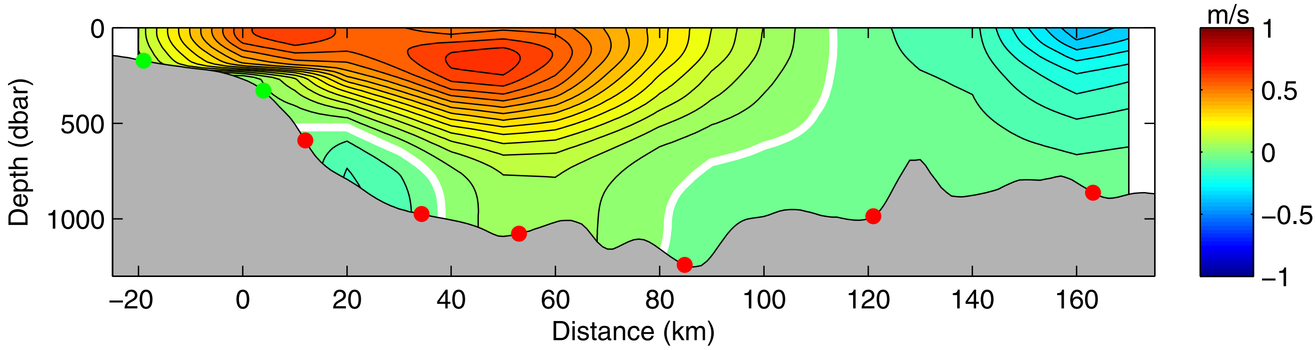

Figure 1. The 23-month mean cross-section of absolute velocity across the PN-line in the ECS shows positive Kuroshio flow with a double core; also negative flow in two areas, one beneath the Kuroshio, the other seaward of it. Zero contour shown in white; contour interval 0.05 m/s.

Figure 2 shows absolute-transport time series for the positive- and (both) negative-flow regions, together with the absolute net transport. The mean, maximum and minimum net absolute transports are 18.1, 28.9 and 3.8 Sv, respectively. Seasonal averages show transports in winter and summer about 2 Sv stronger than those in spring and fall.

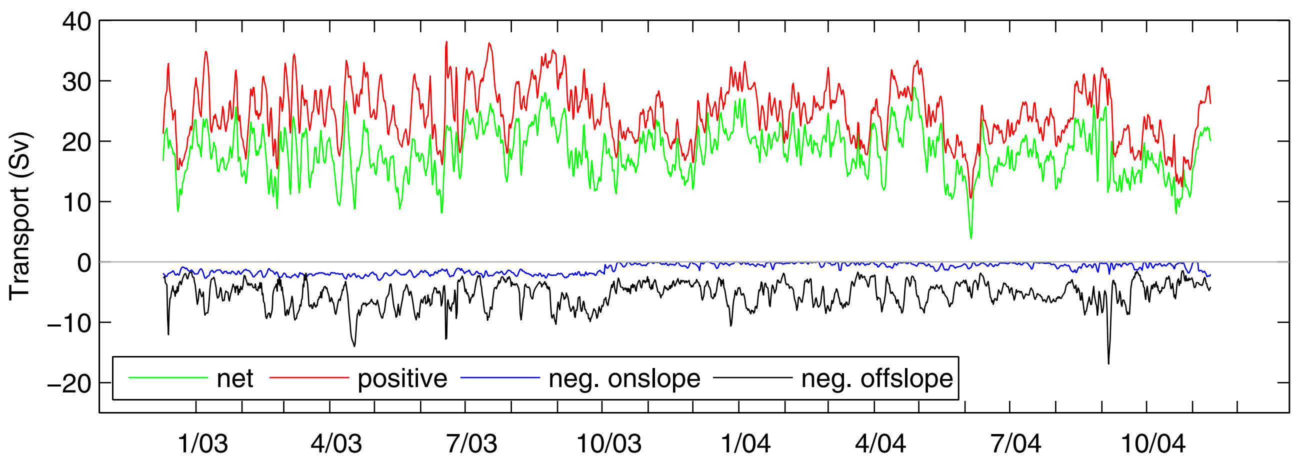

Figure 2. 23-month times series of absolute transports across the PN-line in the ECS for positive flow (red; mean=24.6 Sv), negative countercurrent flow beneath the Kuroshio core (blue; mean=−1.1 Sv), negative recirculation flow seaward of the Kuroshio (black; mean=−5.3 Sv), and net flow (green; mean=18.1 Sv).

The spectrum of absolute net transport, shown as the green line in Figure 3, has significant peaks at periods of 64, 15 and 11 days. The 11-day peak is related to meanders of the Kuroshio position; 11 days is the dominant meander period in the region (James et al., 1999). The 15-day peak is likely related to 15-day variability in Kuroshio inflow to the ECS (Johns et al., 2001). The cause of the 64-day peak is presently unknown.

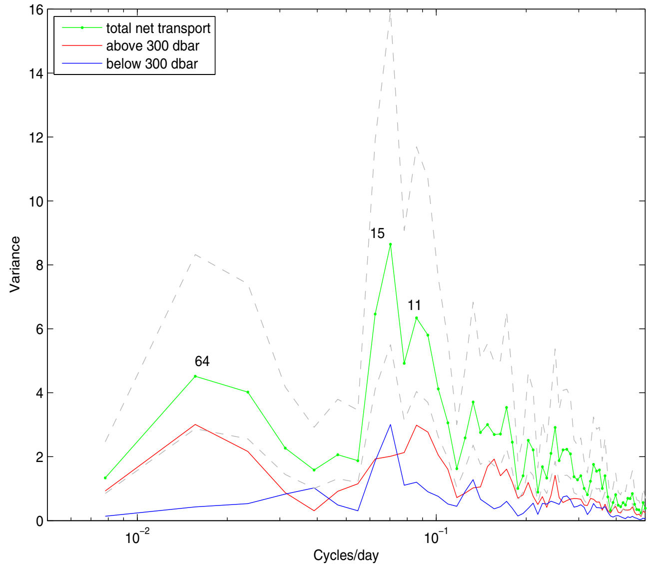

Figure 3. Variance-preserving spectra of absolute net transports above 300 dbar (red), below 300 dbar (blue) and total (green). The total transport spectrum, whose 90% confidence limits are displayed as dashed lines, shows significant peaks at periods of 64, 15 and 11 days, with contributions predominantly from the upper, lower, and upper layer, respectively .

IMPACT/APPLICATIONS

The results from this study should lead to advances in our understanding of WBC dynamics, in particular the dynamics associated with spatiotemporal variability of meanders and bifurcations. This knowledge should be applicable to the Kuroshio at other latitudes, and also to other WBCs.

RELATED PROJECTS

(1) The Korea Ocean Research and Development Institute (KORDI) and Seoul National University (SNU) were supported by ONR/NICOP to deploy ADCPs on the outer continental shelf near the PN-line in a project titled "Kuroshio Variability on the Shelf in the East China Sea." These instruments recorded the part of the Kuroshio transport which flows over the shelf. Dr. Kyung-Il Chang of SNU (previously at KORDI) made three deployments of the ADCPs at two sites during 2003-04. Dr. Chang was able to obtain a one-year 179-275 m current record from the deeper site and a six-month 34-146 m current record from the shallower site.

(2) The JAMSTEC "Kuroshio Observation Project" (KOP) focuses on understanding the barotropic and baroclinic components of the WBC on either side of Okinawa, in the Ryukyu Island Chain. The JAMSTEC array was on the southern side of Okinawa, under the Ryukyu Current. Our array was on the northern side in the ECS Kuroshio. The JAMSTEC group experienced difficulties in recovering some of the instruments in their array, but has successfully computed time series of Ryukyu Current transport by combining their *in situ* measurements with satellite-altimeter data.

(3) Dr. Kuh Kim of SNU has calibrated the voltage measured on a cable across the Korea/Tsushima Strait and was thus able to measure the time varying Tsushima Current transport while our array was

deployed. Drs. Kuh Kim and Kyung-Il Chang will work jointly with us in using these data to study the relationship between the ECS Kuroshio and the Tsushima Current transport.

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PUBLICATIONS

Park, J-H., M. Andres, P.J. Martin, M. Wimbush and D.R. Watts, 2006. Second-mode internal tides in the East China Sea from historical hydrocasts and a model. *Geophysical Research Letters*, **33**(5), doi:10.1029/2005GL024732 [published].