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 several 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 (JAMSTEC) Institute of Observational Research for Global Change, 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 at two sites on the continental shelf near our array, to measure the flow over the outer shelf.

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 variations in this transport to variations in the ECS-Kuroshio.

Besides the principal investigators, there are three University of Rhode Island people currently engaged in this work, Dr. Jae-Hun Park (Marine Research Scientist), Magdalena Andres and Joseph Kuehl (doctoral graduate students), 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).

In addition, we use satellite altimeter data to track eddies arriving in the region from the ocean interior and to determine sea level anomaly difference (Δsla) across the ECS-Kuroshio.

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, 40 km apart, 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 (p_b), and bottom-current ($\boldsymbol{u}_b$) data records are all of excellent quality and complete: (1) the p_b records of the two shallowest instruments show a few pressure "jumps," probably because the instruments were dragged by bottom-fishing gear; (2) the $\boldsymbol{u}_b$ data from the current sensor on the easternmost CPIES (C6) were intermittent from April 2004 until the end of the record; (3) the $\boldsymbol{u}_b$ and p_b records on the neighboring CPIES (C5) are incomplete because of a faulty o-ring seal on the current-sensor connector.

Magdalena Andres, a doctoral student, 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). From the processed data sets, we have obtained 23-month absolute transport time series , and, in addition, a time series of the detailed velocity structure for the last 13 of these months (when we had concurrent ADCP data measuring velocity on the shelf and slope). These results were presented in May, 2007, at the 14th PAMS/JECSS meeting in Hiroshima, Japan (Andres et al., 2007) and have been submitted for publication in the Journal of Geophysical Research.

Dr. Jae-Hun Park 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.

Our study is concerned with the relationships of Ryukyu Current and ECS-Kuroshio transports. So we felt it necessary to respond to a recent paper (Nagano et al., 2007) which gave (we believe) wrong determinations of the Ryukyu Current flow field in the region near our ECS array, because of an inappropriate reference level used in the inverse-method calculation. In collaboration with Dr. Xiaohua Zhu at the Second Institute of Oceanography in China, we have written a "Comment" paper showing how a better choice of reference level produces more realistic Ryukyu Current flow fields. Our paper has been reviewed and accepted for publication (Zhu et al., 2007).

Joseph Kuehl, a second doctoral student, is investigating the nonlinear dynamics of the Kuroshio just south of the ECS, as it crosses the Luzon Strait. In a laboratory rotating tank, he has built a simulation of the gap-leaping behavior of a western boundary current in order to understand and predict the formation and cutting-off of the Loop Current which forms intermittently from the Kuroshio in the South China Sea. This process may affect the flow of the Kuroshio downstream in the ECS.

RESULTS

The scientific analysis of our CPIES/PIES data set (in conjunction with the ADCP data set) from the ECS will become Magdalena Andres's doctoral dissertation which she plans to complete in 2008. In addition to determining the ECS-Kuroshio transport for the 23-month instrument deployment time, she has used it to obtain an empirical relationship between this transport and sea-level difference across the ECS-Kuroshio measured by the Jason-1 satellite altimeter. This enables comparison of ~12 years of ECS-Kuroshio transport with a similar time series of Ryukyu Current transport southeast of Okinawa determined by Zhu et al. (2004).

Figure 1 displays the 12-year transport time series of the ECS-Kuroshio, together with that of the Ryukyu Current from Zhu et al. (2004). To generate these, satellite altimeter data were 5-point boxcar filtered, resulting in 40-day lowpassed transport. The Ryukyu Current has a smaller mean transport than the ECS-Kuroshio (5.4 Sv vs. 18.7 Sv), but significantly more variability (standard deviation = 4.0 Sv vs 1.9 Sv). The maximum ECS-Kurohsio transport is in 1997 (24.3 Sv) and the minimum is in 2000 (13.1 Sv).

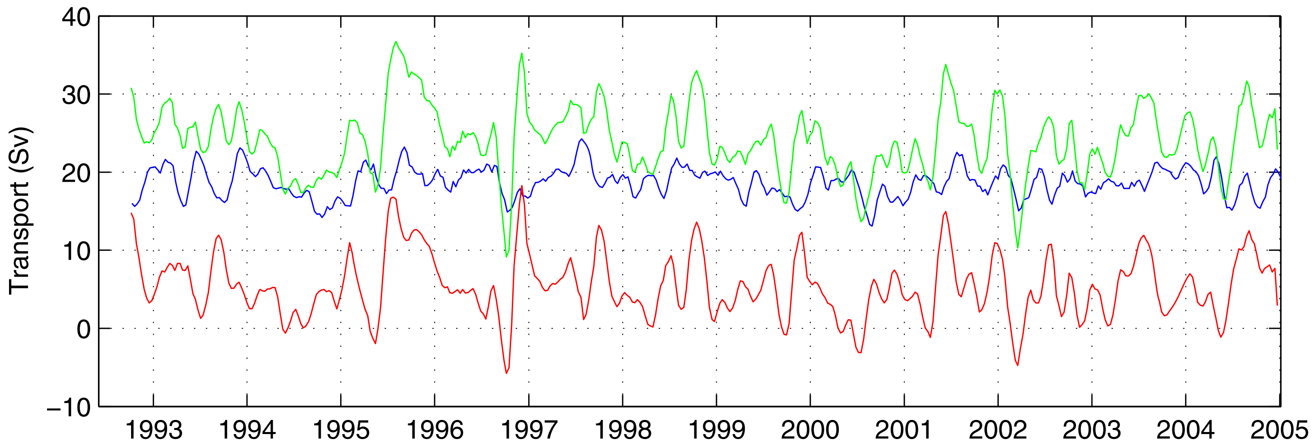

Figure 1. 12-year record of net absolute transport in the ECS near the PN-line (blue), in the Ryukyu Current southeast of Okinawa (red), and combined transport (green).
[Time series lasting from end of 1992 until 2005 showing transport in Sverdrups of the Ryukyu Current, ECS-Kuroshio and the two currents combined.]

There is no significant correlation at zero lag. Correlation magnitude between the lowpassed transports is maximum when the ECS-Kuroshio transport lags that of the Ryukyu Current by 60 days (Figure 2). The two currents are then positively correlated (correlation coefficient = 0.40 with 95% confidence limits at 0.32 and 0.48).

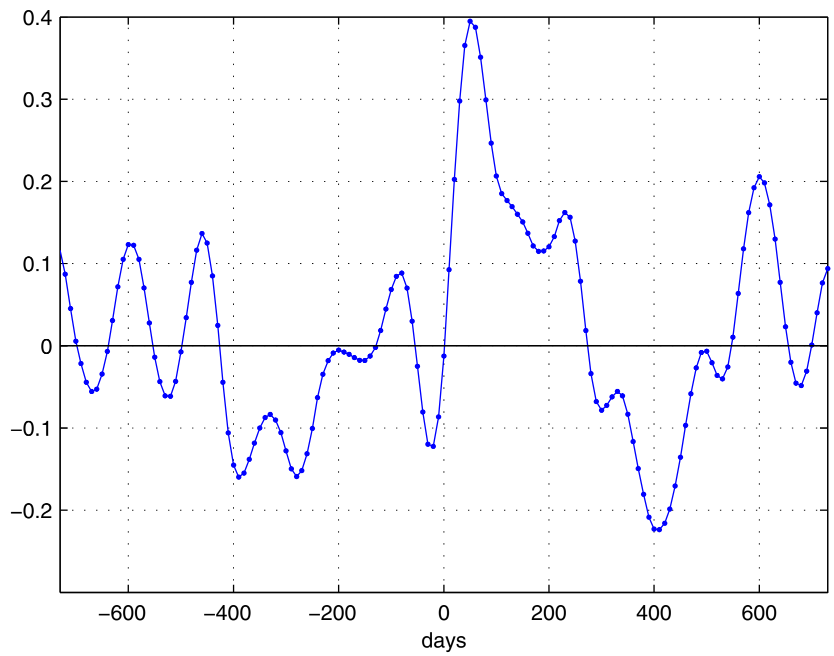

Figure 2. Cross-correlation of Ryukyu Current and ECS-Kuroshio transports as a function of time lag. Positive lag indicates ECS-Kuroshio lagging Ryukyu Current.
[A plot of the cross-correlation of Ryukyu Current and ECS-Kuroshio transports as a function of time lag. Maximum cross-correlation is seen to occur for ECS-Kuroshio lagging Ryukyu Current transport by 60 days.]

The spectrum of the 23-month net absolute transport of the ECS-Kuroshio 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 but a complex empirical orthogonal function (CEOF) analysis of the CPIES/PIES travel time data shows that the first CEOF accouts for more than 80% of the variance occurring in the band between 50 and 70 days. This CEOF has northwestward (i.e., on-slope) phase propagation, and increases in amplitude in that direction (Figure 3). The phase speed of this 60-day wave is about 4 cm/s and the wavelength is about 200 km.

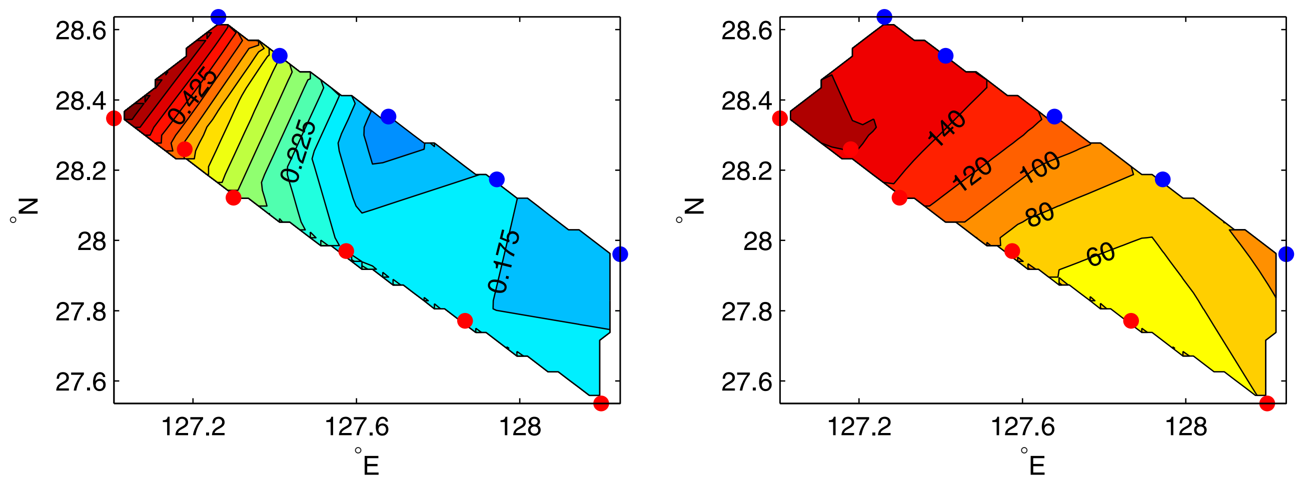

Figure 3. Maps of the maginitude (left panel) and phase (right panel) of the 1st CEOF of the 50- to 70-day bandpassed net absolute transport. Blue and red dots show the locations of the PIES and CPIES instruments, respectively.
[Maps of instrument array with corners at 127.26ºE, 28.64ºN; 128.25ºE, 27.96ºN; 128.20ºE, 27.54ºE and 127.01ºE, 28.34ºN overlain with contours of (1) the magnitude of the 1st CEOF which ranges from about 0.18 near the southeastern edge to about 0.48 near the northwestern edge and (2) the phase of first CEOF which ranges from about 70º at the southeastern edge to about 150º at northwestern edge.]

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 thirteen-month 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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