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^{O}–28^{O}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 sounders (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 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 during this period, scientists (with NICOP support) from Seoul National University (SNU) and the Korea Ocean Research & Development Institute (KORDI) deployed ADCP's on the continental shelf near our array, to measure the flow over the outer shelf.

In addition, SNU scientists 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.

To determine temperature and specific-volume-anomaly profiles from the inverted-echo-sounder 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 inverted echo sounder design to incorporate the Aanderaa 3820R current measuring head. Then, after successful field testing, we constructed 12 CPIES instruments (current-and-pressure-sensor-equipped inverted echo sounders). In December 2002, six of these, together with five PIES instruments (pressure-sensor-equipped inverted echo sounders) 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 (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. 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 $\boldsymbol{u}_b$ data from the current sensor on the easternmost CPIES (C6) was intermittent from April 2004 until the end of the record. (3) The $\boldsymbol{u}_b$ record on the neighboring CPIES (C5) terminated after about two weeks. Also about 1/3 of the p_b record from this instrument is missing (though the τ record is complete). These problems on CPIES5 appear to have been caused by a faulty o-ring seal on the current-sensor connector.

During 2005, Magdalena Andres, a doctoral student supported on this grant, completed computations of suitable GEM's based on historical hydrographic data from the region. She has also completed the basic processing of all the data from the CPIES and PIES instruments. This includes error correction, calibration, pressure-drift and pressure-jump removal, time interpolation and lowpass filtering. This work is described and the results shown in a data report (Andres et al., 2005).

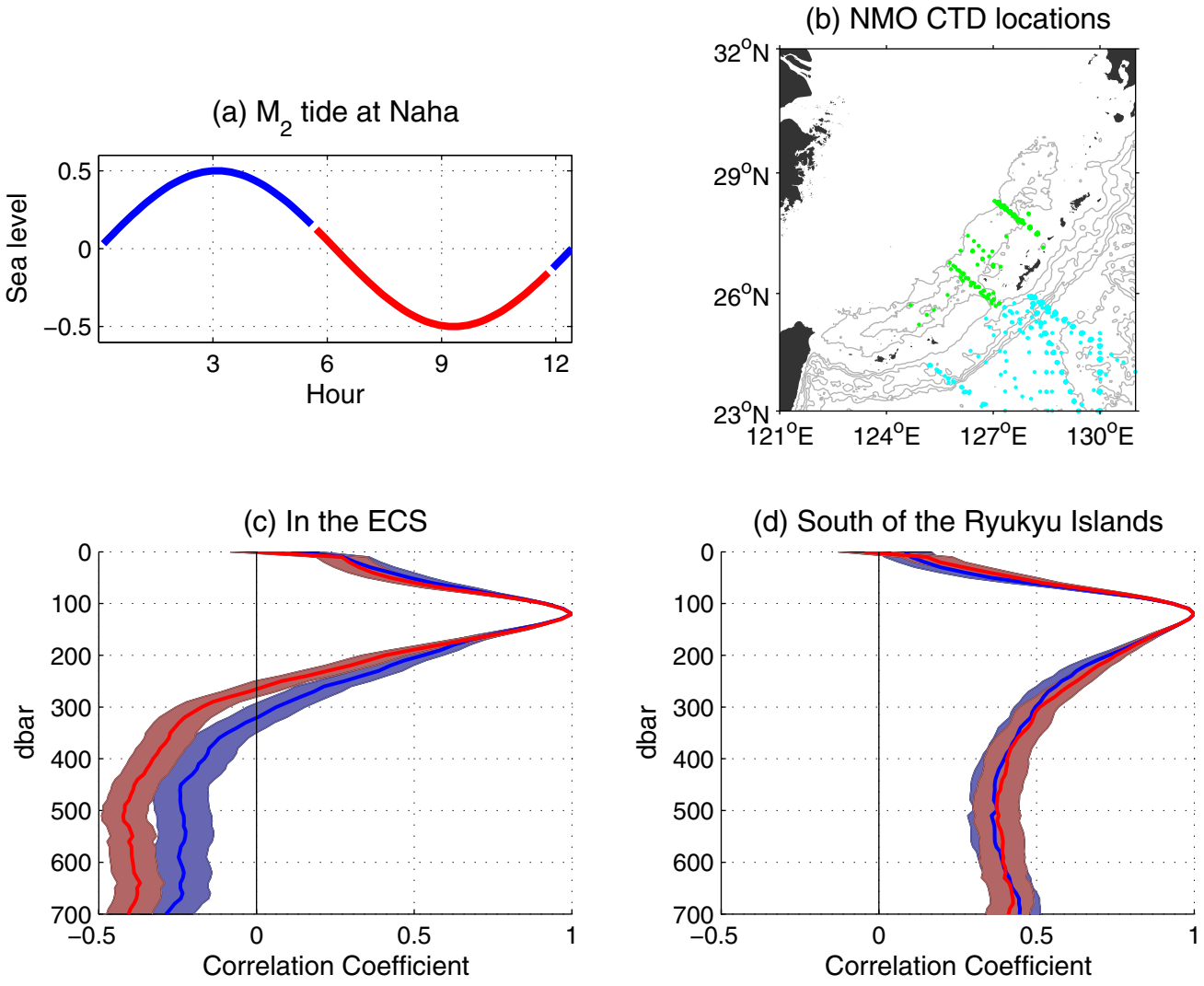

Figure 1. For times (a) of flood (blue) and ebb (red) tides at Naha, Okinawa, hydrostations (b) in the ECS (green) and southeast of the Ryukyu Islands (turquoise) show very different correlation profiles of temperature at 120 dbar with temperatures at other pressure levels. For the ECS data (c), the correlation changes sign, becoming negative at pressure levels deeper than 300 dbar with the ebb-tide negative correlation significantly higher (at the 90% confidence level) than the flood-tide negative correlation. For the data from the other side of the Ryukyu Islands (d), the correlation is positive at all levels and is the same for ebb- and flood-tide periods.

RESULTS

During 2005, we investigated (under the leadership of Dr. Jae-Hun Park) the cause of relatively large errors in ECS GEM error fields at 100-200 m depth, by first separating the hydrocasts, according to the time when they were taken, into tidal "flood" or "ebb" tide periods, and then calculating, at each pressure level, the correlation of the measured temperature with that at 120 dbar (in the large-GEM-error band). This revealed (Figure 1) 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). Nevertheless, since we will be using our ECS inverted-echo-sounder data principally to study dynamics with longer periods than the tides, it is apparent that the GEM fields will provide accurate representations of these dynamics throughout the water column.

Having successfully passed her comprehensive examinations in August, Magdalena Andres will now work intensively on the scientific analysis of our CPIES/PIES data set. The resulting work will become her doctoral dissertation.

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 WBC's.

RELATED PROJECTS

(1) The Korea Ocean Research and Development Institute (KORDI) was 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 KORDI made three deployments of the ADCP's at two sites during 2003-04. Dr. Chang, now at Seoul National University (SNU), 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. We anticipate a strong correlation between Kuroshio axis position (determined from the PIES data) with Kuroshio transport over the shelf (determined from the ADCP data). Since the dominant meander period in this region is 11 days (James et al., 1999), 6-12 months of ADCP measurements during the CPIES array deployment should be very adequate to establish that this is so and enable us to determine the relationship of Kuroshio shelf transport to axis position. This will allow us to infer Kuroshio shelf transport during those intervals (in our two-year array deployment time) when the ADCPs were not deployed.

(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, 2005. Second-mode internal tides in the East China Sea from historical hydrocasts and model. The Indonesia Ocean Forum 2005 and 13th PAMS/JECS workshop, Bali, Indonesia, Proceedings, 77-78 & CD-ROM. [published]. [An extended version of this article is being prepared for journal publication.]