Mass, heat and salt transports in the western North Pacific

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A time series of volume transport of the Kuroshio current south of Japan was obtained from the TOPEX/POSEIDON altimeter data, using a high correlation between the transport and sea level difference across the Kuroshio.
This monitoring of volume transport will be continued for the Jason-1 mission by using in-situ oceanographic data as well. A data assimilation system will be developed to obtain a four-dimensional representation of a dynamically consistent, evolving ocean circulation for the western North Pacific.

Jason-1 science plan

Using TOPEX/POSEIDON (T/P) altimeter data, the following results have been obtained. A time series of volume transport of the Kuroshio current south of Japan was obtained from the T/P altimeter data, using a very high correlation between the transport and sea level difference across the Kuroshio has been found by the combined use of moored current meter data and repeated hydrographic data obtained on a line crossing the Kuroshio.
Anomalies of sea surface dynamic topography (SSDT) derived from T/P altimeter data compared well with those from in-situ oceanographic data obtained for the western North Pacific during the mission. Statistical space-time scales of those anomalies were estimated in order to be used for an optimum interpolation, which is embedded in the data assimilation system. Variability of the circulation in the subarctic North Pacific was investigated using altimeter data and wind data. The data shows that SSDT variations can be approximated by the time-dependent wind-driven circulation. By combining in-situ oceanographic data with the T/P altimeter data, distribution of the mean SSDT for the North Pacific was estimated.

During the Jason-1 mission period, we are going to carry out the following studies for the western North Pacific. The studies mentioned above will be continued using the altimeter data from missions of T/P, ERS-1/2 (European Remote Sensing satellite) and Jason-1, which will be combined with in-situ oceanographic data. The monitoring of volume and heat transports of the Kuroshio current south of Japan will be continued for the Jason-1 mission using inverted echo sounder (IES) data and repeated hydrographic data, as well as altimeter data.
The surface flow field of the Kuroshio will be described in detail by combined use of the altimeter data and acoustic Doppler current profiler (ADCP) data. The surface flow field for the entire North Pacific will be mapped using altimeter data and expendable bathythermograph (XBT) data and will be widely distributed to the operational community three times a month. Through these studies, we intend to better understand the circulation of the western North Pacific, especially its role in transports of mass, heat and salt.

In the following sections, we highlight recent results of studies about the Kuroshio south of Japan and flow field of the western North Pacific.

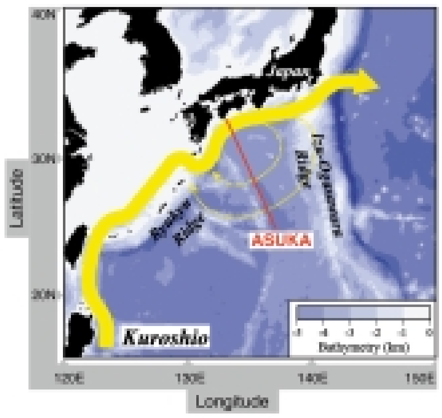

Figure 1: ASUKA observational line (red line) across the Kuroshio south of Japan, superimposed on the bathymetry. Moored current meter measurements, repeated hydrographic surveys and other measurements were carried out on the line from October 1993 to November 1995. This line was purposely located along a track of the TOPEX/POSEIDON altimeter. Schematic flow patterns of the Kuroshio and its recirculation south of Japan are also shown.

The Kuroshio south of Japan

Oceanographic observations along a line crossing the Kuroshio and Kuroshio recirculation south of Japan were carried out by the Affiliated Surveys of the Kuroshio off Cape Ashizuri (ASUKA) Group. Figure 1 shows the observation line, which was chosen to coincide with a subsatellite track of T/P. During October 1993 to November 1995, they maintained nine moorings equipped with 33 current meters [Imawaki et al., 2001]. During that period, they carried out repeated hydrographic measurements in order to estimate upper layer velocities which cannot be adequately measured by the moored instruments. From those moored current meter data and repeated hydrographic data, geostrophic velocities observed at a nominal depth of 700 m are estimated.
The estimated absolute volume transport (as the sum of those geostrophic velocities) of the Kuroshio for the upper 1000 m is found to have a very high correlation (0.90) with the SSDT difference across the Kuroshio.
This relationship and T/P altimeter data calibrated with the in situ data provide us, for the first time, with the long time series of the Kuroshio transport.

Figure 2 shows the results for seven years (1992-1999) from the T/P mission [Imawaki et al., 2001].
The transport of the eastward flowing Kuroshio (figure 2a) fluctuates much between 33 and 88 Sv ($Sv = 10^6\ m^3/sec$) with a seven-year mean of 57 Sv. Part of the transport is associated with the transport of the stationary local anticyclonic warm eddy located on the offshore side of the Kuroshio (see figure 1). The throughflow transport of the Kuroshio is calculated as the difference of transport between the eastward flowing Kuroshio and this westward flowing Kuroshio recirculation. The transport of the Kuroshio recirculation is estimated in a similar way using altimeter data and the relationship between the transport and SSDT difference obtained for the Kuroshio recirculation region; here the transport is estimated between the offshore edge of the Kuroshio and 26°N latitude. The result is shown in figure 2b. The seven-year mean of the transport is estimated to be 42 Sv, which is reduced considerably from that for the eastward flowing Kuroshio of 57 Sv. The variability is also reduced considerably compared with the eastward flowing Kuroshio; the standard deviation is reduced from 11 Sv to 9 Sv.

The seasonal signal of the Kuroshio throughflow transport is estimated from this seven-year record and is shown in figure 3 [Uchida and Imawaki, 2001]. For comparison, the seasonal signal of the transport of western boundary current expected from the interior wind-driven (Sverdrup) transport at 30°N is estimated from the surface wind field data of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis. The seasonal signal of the Kuroshio throughflow transport is small compared with this theoretical transport. There may be some evident seasonality, however, with low through-flow transport in September, and high transport in December. This tendency is similar to the theoretical transport.
The reason for this low in the observed seasonal signal is discussed by Isobe and Imawaki [2001], showing that the Izu-Ogasawara Ridge filters the seasonal signal which propagates westward from the interior.

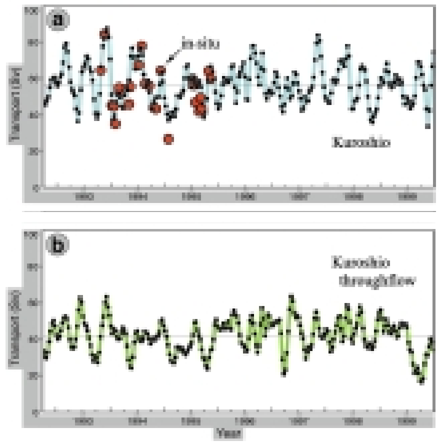

Figure 2: Time series of the Kuroshio transport (solid line with dots; in Sv) south of Japan during 1992-1999, estimated from TOPEX/POSEIDON altimeter data using the relationship between the transport and sea-surface height difference. A Gaussian 3-point filter with weights (0.25:0.5:0.25) has been used. Panel (a) is the transport of the eastward flowing Kuroshio. Also shown are transports (red dots) estimated from in-situ data. Panel (b) is the throughflow transport of the Kuroshio (see text for definition).

Sea-surface geostrophic velocities for the Kuroshio region obtained above compare well with surface velocities derived from drifting buoy trajectories, suggesting that the Kuroshio surface layer is essentially in geostrophic balance within the measurement error [Uchida et al., 1998]. This study also suggests that Eulerian mean velocities for the Kuroshio region estimated from drifting buoy data tend to be larger than actual means, because drifting buoys have tendency to sample preferentially in the high-velocity Kuroshio.

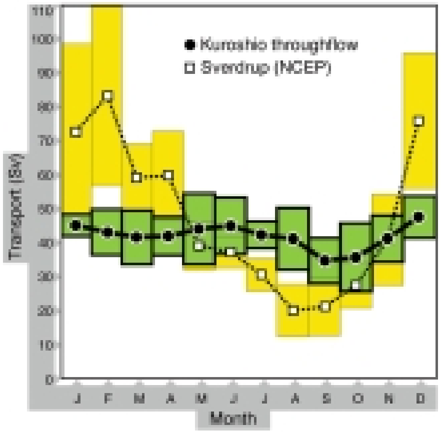

Figure 3: Seasonal variation of the Kuroshio throughflow transport (solid line with dots; in Sv) south of Japan, estimated from the seven-year record shown in figure 2b; boxes show monthly standard deviations.
Also shown is the seasonal variation of Sverdrup transport (doted line with squares) at 30°N of the North Pacific during the same period, estimated from the NCEP/NCAR reanalysis wind data.

The western North Pacific

A method has been developed to obtain the mean SSDT map of the North Pacific, using T/P altimeter data, hydrographic data including XBT, moored instrument data, and climatological mean temperature and salinity profiles [Kuragano and Shibata, 1997]. Accuracy of annual mean SSDT maps are estimated to be less than 2 cm in most areas and 2.5 cm for areas where oceanographic data is sparse. Geostrophic velocities based on this method compare well with surface currents analyzed from ship observations.

We are developing an ocean data assimilation system for the North Pacific, studying the impact of the T/P and Jason-1 altimeter data on the assimilation model, and carrying out an operational nowcasting of the oceanic state. Statistical space-time scales with anisotropy and inhomogeneity have been estimated with decorrelation scales from correlation functions of the T/P altimetric SSDT anomaly field. Using those scales we have developed an optimum interpolation method in three-dimensional space-time coordinates, and have obtained a more statistically accurate distribution of the variance of the SSDT anomaly [Kuragano and Kamachi, 2000]. The data assimilation system will be developed to obtain a four-dimensional representation of a dynamically consistent, evolving ocean circulation for the western North Pacific.

Variability of the circulation in the subarctic North Pacific is investigated by using T/P altimeter data and the European Centre for Medium-Range Weather Forecast (ECMWF) wind data for about two years [Isoguchi et al., 1997]. Empirical orthogonal functions of the SSDT anomaly are found to be related with several oscillations, including a basin-wide oscillation associated with spin-up and spin-down of the subarctic gyre, Oyashio current variations, basin-wide north-south oscillations associated with the Aleutian Low, and Sverdrup transport fluctuations estimated from the wind stress curl near 40°N. These results suggest that SSDT variations in the subarctic North Pacific can be approximated by time-dependent wind-driven circulation.

One of the successful results of the T/P mission is the improvement of global ocean tide models [Matsumoto et al., 1995; Matsumoto, 2000]. Although existing ocean tide models are much better than those developed before T/P data were available, they are still insufficient for some applications. Efforts to improve ocean tide model using T/P and Jason-1 data will be continued especially for marginal seas.

References

Imawaki S., H. Uchida, H. Ichikawa, M. Fukasawa, S. Umatani and the ASUKA Group, 2001: Satellite altimeter monitoring the Kuroshio transport south of Japan, *Geophys. Res. Lett.*, 28, 17-20.

Isobe A., S. Imawaki, 2001: Annual variation of the Kuroshio transport in a two-layer numerical model with a ridge, *J. Phys. Oceanogr.* (submitted).

Isoguchi O., H. Kawamura, T. Kono, 1997: A study on wind-driven circulation in the subarctic North Pacific using TOPEX/POSEIDON altimeter data. *J. Geophys. Res.*, 102, 12457-12468.

Kuragano T., M. Kamachi, 2000: Global statistical space-time scales of oceanic variability estimated form TOPEX/POSEIDON altimeter data, *J. Geophys. Res.*, 105, 955-974.

Kuragano T., A. Shibata, 1997: Sea surface dynamic height of the Pacific Ocean derived from TOPEX/POSEIDON altimeter data: Calculation method and accuracy, *J. Oceanogr.*, 53, 585-599.

Matsumoto K., 2000: Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: A global model and a regional model around Japan, *J. Oceanogr.*, 56, 567-581.

Matsumoto K., M. Ooe, T. Sato, J. Segawa, 1995: Ocean tide model obtained from TOPEX/POSEIDON altimetry data, *J. Geophys. Res.*, 100, 25319-25330.

Uchida H., S. Imawaki, 2001: Seven-year record of the Kuroshio transport south of Japan estimated from satellite altimeter data (in preparation).

Uchida H., S. Imawaki, J.H. Hu, 1998: Comparison of Kuroshio surface velocities derived from satellite altimeter and drifting buoy data. *J. Oceanogr.*, 54, 115-122.

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