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Identification of the Kuroshio Extension, its Bifurcation and Northern Branch from altimetry and hydrographic data during October 1992 - August 1999: Spatial and temporal variability

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Abstract. A methodology is proposed using altimter-derived upper layer thickness and baroclinic transport to identify the Kuroshio Extension, the Bifurcation Point and the Northern Branch, by combining TOPEX/POSEIDON altimeter and climatological data within a two-layer reduced gravity model. Results obtained from the Japanese coast to 175°W show that the location of the Bifurcation Point presents interannual variability that is related with upstream conditions. The longitude of the Bifurcation Point ranged from 147 to 160°E. Estimates of baroclinic transport at the Kuroshio Extension and its Northern Branch decrease steadily to the east trough the region of study from 35 to 11 and from 10 to 3 Sv, respectively.

1. Introduction

The Kuroshio Extension (KE) separates from the Japanese coast near 35°N becoming then a meandering eastward current. Kawai (1972) and Mizuno and White (1983) showed by different methods the presence of two quasi-stationary meanders with crests at 144°E (FC) and 150°E (Figure 1). The horizontal distribution of the mean dynamic height (Wyrtki, 1975 and Teague *et al.*, 1990), the mean sea surface height (Qiu *et al.*, 1991; Qiu, 1995, 2000) and the mean temperature at 300 m depth (Mizuno and White, 1983) show a widening and weakening of the current to the east of these meanders. These and other hydrodynamic modifications along its course are linked to the main bathymetric features encountered by the KE while flowing to the east, the Shatsky Rise (SR) and the Emperor Sea Mounts (ESM) (Bernstein and White, 1981; Levine and White, 1983; Roden *et al.*, 1982; Mizuno and White, 1983; Qiu *et al.*, 1991; and Qiu, 1995). The KE usually bifurcates between 150 and 165°E (Mizuno and White, 1983). The main current flows eastward and can be easily recognized until reaching the ESM, while its Northern Branch (NB) flows northeastward along the SR (Levine and White, 1983; Mizuno and White, 1983) approaching the subarctic front (Kawabe and Taira, 1998) (Figure 1). The KE and, east of the Bifurcation Point (BP), its NB represent the northern boundary of the warm water carried by the Subtropical Gyre. The variability in their position and water transport are important subjects which have a significant impact on the sea surface temperature and heat content anomalies, and thus on climate (Qiu, 2000). The Kuroshio Bifurcation Front, associated with the NB, was identified using hydrographic data along cross sections at 155, 165 and 175°E between 38 and 41°N (Roden *et al.*, 1982; Zhang and Hanawa, 1993; and Kawabe and Taira, 1998).

TOPEX/POSEIDON (T/P) altimeter data from October 1992 to August 1999 combined with climatological data within a two-layer reduced gravity model, previously validated with available hydrographic data, allowed us to clearly identify the KE, its NB, and BP from the Japanese coast to 175°W. The volume transport of the KE and its NB at different regions were also estimated.

2. Data

2.1 Hydrographic Data

CTD data obtained at the seasonal section carried out by the R.V. Kofu Maru along 144°E, usually from 34 to 42°N and every 20 miles (JMAa, 1992-1999) were used to identify the path of the KE at the first crest (FC) (Figure 1). The CTD data used to identify the KE downstream and its NB was obtained by the R.V. Ryofu Maru along 165°E from 30 to 45°N (Figure 1) (JMAb, 1998-1999). CTD data obtained by the R.V. Hakuho Maru (University of Tokyo) along 165°E on 1993 (Taira and Kawabe, 1994) were also included in the time series.

2.2 Altimeter Data

The T/P-derived sea height anomaly, $\eta'(x,y,t) = \eta(x,y,t) - \overline{\eta}(x,y)$, is the deviation of the sea surface height, η, referred to the mean sea surface height, $\overline{\eta}$, which is usually computed over a period of time of several years. The T/P altimeter measures the sea height anomaly along groundtracks, which are separated 3 degrees longitudinally (Figure 1), and approximately every 9.91 days. The data used in this work was

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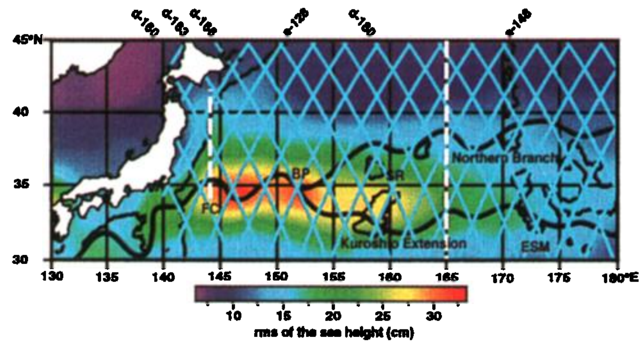

Figure 1. Schematic representation of the Kuroshio Extension, its Northern Branch, the first crest (FC) and Bifurcation Point (BP). The bottom bathymetry is represented by the 4000 m depth contour showing the two main topographic features, the Shatsky Rise (SR) and the Emperor Sea Mounts (ESM). Selected ascending and descending groundtracks of the TOPEX/POSEIDON altimeter (light blue), and the meridional lines at 144 and 165°E of CTD vertical sections (dashed white) are superimposed. The background scale shows the rms of the sea height obtained from the TOPEX/POSEIDON altimeter data for the study period.

processed with the standard altimetric corrections and the sea height anomaly values referred to the 1993-1998 mean and interpolated into a 9 km alongtrack grid (Cheney *et al.*, 1994).

3. Two-layer Model

The sea height anomaly combined with historical climatological data can be used to monitor the upper layer thickness, which in this study is defined to go from the sea surface to the depth of the 9°C isotherm. Assuming that the ocean in the region of study is vertically stratified, a two-layer reduced gravity approximation can be used to link the variations in sea level with the variations in upper layer thickness. The upper layer thickness, h_1, can be approximated by (Goni *et al.*, 1996):

$$h_1(x,y,t) = \bar{h}_1(x,y) + \frac{g(y)}{g'(x,y)}\left[\eta'(x,y,t) - B'(x,y)\right],$$

Where $\bar{h}_1$ is the mean upper layer thickness, g is the acceleration of gravity, g' is the reduced gravity, η' is the altimeter-derived sea height anomaly, and B' is the barotropic contribution to the sea height anomaly. B' can be estimated, for example, when simultaneous observations of sea height anomaly and thermocline depth are available (Goni *et al.*, 1996). Values of this parameter were estimated to be approximately 10% of the η' values in the region of study (Goni, 1999) and will be disregarded in this work. Steric effect on the sea height anomaly, included in this work within the baroclinic component, have a maximum amplitude of 5 cm in the region (Stammer, 1997).

Climatological temperature and salinity 1 x 1 degree data (Conkright *et al.*, 1998) are used in this work to compute the mean upper layer thickness and the mean reduced gravity fields. The mean reduced gravity, g', which provides a measure of the vertical stratification in the region, is estimated using the mean upper and lower layers densities:

$$g'(x,y) = \frac{\rho 2(x,y) - \rho 1(x,y)}{\rho 2(x,y)} g(y),$$

where $\rho 1$ and $\rho 2$ are the mean densities of the upper and lower layers, respectively.

The baroclinic transport, Scl, between two locations, xb and xc centered at (xa, ya), is found when the bottom layer is assumed to be at rest (Goni *et al.*, 1996):

$$Scl(xa,ya,t) = \frac{g'(xa,ya)}{2f(ya)} \Delta h_1^2(xa,ya,t),$$

where f is the Coriolis parameter ($\approx 10^{-4}$ s^{-1}), and $\Delta h_1^2(xa,ya,t)$ is the difference of the square of the upper layer thicknesses between the two locations.

4. Validation of the Model

The upper layer thickness and baroclinic transport were computed along the ascending T/P groundtrack a-128 using the methodology described above, and validated using the hydrographic data at 144°E. This groundtrack, crosses the 144°E meridian at 36° 09'N, near the mean location of the KE axis at the first crest (Figure 1).

The axis of a current such as the KE is considered as the location of its maximum surface velocity and transport. The location of the maximum estimate of transport on groundtrack a-128 is in good agreement with the altimeter derived 9°C at 500 m depth, which accurately reproduce the actual situation shown by the hydrographically-derived latitude of the 9°C isotherm (Figure 2). The rms of the difference between the altimeter-derived and the hydrographically-derived latitude of the 9°C isotherm at 500 m depth is 10 km. Moreover, variations of altimeter-estimates agree with the hydrographic observations. This result confirms that the altimeter-obtained upper layer thickness through the described method can be readily used to determine the depth of the 9°C isotherm, which at 500 m depth represents the location of the KE axis at the first crest.

T/P groundtracks d-180 and a-148 are chosen to validate the two-layer model at 165°E in the KE front and Kuroshio Bifurcation Front, respectively. These two groundtracks cross the 165°E meridian near the expected location of the KE and its NB, respectively (Figure 1). The maximum values of cross-track baroclinic transports related to the KE and its NB are in good agreement with the latitude where 9°C is at 450 and 250 m depth, respectively (not shown). The rms of the difference between the location of the altimeter-derived 9°C at 450 and 250 m depth at the two selected groundtracks and the hydrographicaly-derived 9°C at 450 and 250 m depths at 165°E, although sparse (7 observations for each isotherm) is near 15 km, and again, variations of altimeter-estimates

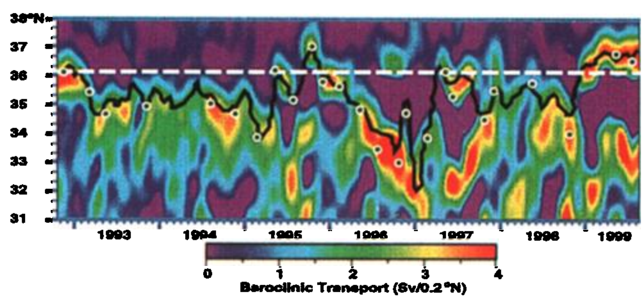

Figure 2: Time series of the baroclinic transport across groundtrack a-128 estimated every 0.2 degrees of latitude (color scale). The continuos black line indicates the location of the altimeter-derived 9°C isotherm at 500 m depth on the same groundtrack. The dots represent the latitude of the 9°C isotherm at 500 m depth from the hydrographic sections at 144°E. The horizontal dashed line at 36° 09'N represents the latitude where the a-128 and the 144°E meridian cross each other.

correspond with those of the hydrographic observations. As reported by Kawai (1972), indicative isotherms of the Kuroshio and KE at a fixed depth correspond to lower temperatures while going downstream. These results agree with our finding that in the first crest, near 144°E, the location of the axis is better represented by 9°C at 500 m depth, and near 165°E by 9°C at 450 m depth. Our results also show that the location of the KE axis is always better represented by 9°C at 450 m depth downstream of the first crest. The 9°C isotherm at 500 and 450 m is in the area of maximum isothermal slope associated with the KE at 144°E and 165°E in the vertical sections of temperature (Figure 3). Moreover, the 9°C isotherm at 250 m depth is still in the area of the maximum temperature gradient corresponding to the KE Front at 144°E. However, it is associated with a northern front, the Kuroshio Bifurcation Front, at 165°E.

5. Results

We constructed monthly fields of upper layer thickness to investigate the temporal and spatial variability of the KE and its NB. The main path of the KE was identified by the 9°C isotherm at 450 m depth, and the main path of its NB by the 9°C isotherm at 250 m depth. The mean location of the KE axis and its standard deviation from 142 to 175°W during the study period is 34°55'N and 0.87°, respectively (Figure 4). The minimum latitude of the path location (34°36'N) is located over the SR (155-165°E) where there are also maximum values of standard deviation (0.98°). The mean location of the NB from 155°E directs northward in the area of the SR increasing its latitude until the widest and deepest gap in the ESM area (Roden *et al.*, 1982) near 170°E, where it pass trough. Although in the individual monthly maps of upper layer thickness the meander structure of the KE is usually clear, the trough between the two quasi-stationary crests is obscure in the mean axis location (Figure 4), probably due to the wave-length variability depicted by the meanders.

The meridional distance between the 9°C isotherm at 450 m depth and the 9°C isotherm at 250 m depth from the coast of Japan to the east describes a sequence of maximums and minimums due to the meandered structure of the KE. We define the BP as the location where the meridional distance between 9°C at 450 and 250 m has a minimum value followed by a persistent increase of this distance to the east. Assuming that upstream of the BP, the location of the 9°C at 450 and 250 m are inside the KE front and that downstream of the bifurcation

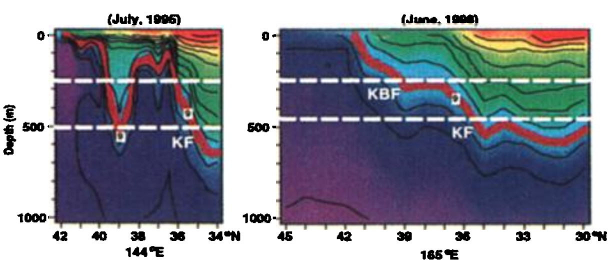

Figure 3: Vertical sections of temperature at 144°E and 165°E from CTD data obtained by the R.V. Kofu Maru on July, 1995 and the R.V. Ryofu Maru on June, 1998, respectively. The red line indicates the 9°C isotherm, which at 500 m (450 m) depth gives the location of the Kuroshio axis at the Kuroshio Front (KF) at 144°E (165°E). The 9°C isotherm at 250 m depth is associated with the Kuroshio Bifurcation Front (KBF) at 165°E. The temperature interval is 2°C.

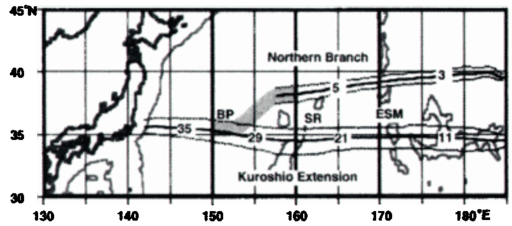

Figure 4: Mean position (continuous black line) and standard deviation (dotted black line) of the Kuroshio Extension and its Northern Branch during the period of study identified by the 9°C isotherm at 450 and 250 m depth, respectively. The gray line schematically represents the mean location of the bifurcation linking the Bifurcation Point (BP) and the Northern Branch. Numbers indicate the mean baroclinic transport at the different regions.

9°C at 450 is still inside the KE front but 9°C at 250 is inside the Kuroshio Bifurcation Front (Figure 3), this distance, derived from upper layer thickness maps, can provide the location of the BP. The time series of the altimeter derived longitude of the BP versus the latitude and volume transport of the KE at the first crest (a-128) reveals a link between these parameters. Results show that when the latitude of the KE at the first crest shifts northward (southward) the volume transport decreases (increases) and the longitude of the BP shift westward (eastward), (Figure 5).

The volume transport of the KE was computed for a region of 2 degrees of latitude centered at the maximum value of transport. Since the NB is centered near the latitude where 9°C is at 250 m depth, its volume transport was computed similarly to that of the KE but centered at the location of a transport maximum where 9°C was between 150 and 350 m depth. Results show that the mean volume transport of the KE decreases steadily to the east. According to the decreasing rate of transport we can distinguish 4 different regions: 1) upstream of 150°E, 2) between 150 and 160°E, the region where the Kuroshio bifurcation usually occurs, 3) between 160 and 170°E, and 4) downstream of 170°E, with a mean volume transport (standard deviation) during the whole period of 35 (10), 29 (8), 21 (6), and 11 (4) Sv, respectively (Figure 4). A distinctive peak in the volume transport of near or over 10 Sv was observed at the NB when the bifurcation occurs. In the last two regions the mean volume transport (standard deviation) of the NB is 5 (4) and 3 (2) Sv, respectively (Figure 4). Previous computations of transport in the Kuroshio system correspond mainly to the upstream region. Combining T/P and hydrographic data, Imawaki *et al.* (1997) estimated the volume transport of the Kuroshio south of Japan to a depth of 1000 m from 34 to 91 Sv, almost double of our estimations for the upper layer that goes from the surface to the depth of the 9°C isotherm.

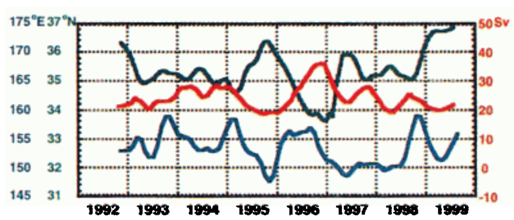

Figure 5: Time series of the monthly based latitude (green) and volume transport (red) of the KE at the first crest, and of the longitude of the BP (blue).

6. Discussion

Kawai (1972) statistically observed that the location of the KE axis at the first crest would be well represented by the 14°C isotherm at 200 m depth and by the 9°C isotherm at 400 m depth for a period from the mid 1950s to the late 1960s. For a larger area (130°E-175°W), and during the late 1970s, the 12°C isotherm at 300 m depth was consistently located at or near the center of the thermal front over the KE in all the seasons and used as indicative of the current path (Mizuno and White, 1983). Our finding that the KE axis at the first crest fits with the location of 9°C at 500 m depth (100 m deeper than the previous study) is probably related with differences between both study periods. Our identification of the NB by the location of 9°C at 250 m depth agrees with that of the 6-8°C isotherm at seasonal 300 m depth temperature maps used by Mizuno and White (1983), and with the central part of the bifurcation front in the temperature sections across the NB obtained by Zhang and Hanawa (1993).

The temporal variability of the KE along groundtrack a-128 (Figure 5) represents the variability of the first quasi-stationary meander (FC). Movements of the Kuroshio axis on a time-scale of a few months at the FC are clearly associated with variations of volume transport. An extreme southern position of the Kuroshio axis in 1996-1997 can be associated with the highest volume transport during the study period. In the descending groundtracks downstream of this first crest, the previous relationship was not clear in d-160, but very clear in alternative periods at d-163 and d-166. The mean longitude of the Kuroshio axis at a-128, d-160, d-163 and d-166 is 143, 146.3, 149 and 151.8°E, respectively. Therefore, the previous relationship would be very clear at crests, which in this region have a quasi-stationary location near 144 and 150°E, but not at troughs. Because the location of crests and troughs is more variable downstream, the rest of the descending groundtracks show this relation very clearly only during some periods. Northerly positions of the KE path (zonally averaged from the east of Japan to 180°) correspond to larger surface height difference across the current (Qiu *et al.*, 1991) and larger surface transports (Qiu, 1995, 2000) on interannual time-scales. This difference with our results reflects the distinct local dynamics existing in the area of the FC. The maximum surface height difference across the current, correlated with maximum transports, was observed in fall (Zlotnicki, 1991; Qiu *et al.*, 1991).

The rms values of the sea height range from 8 to 38 cm (Figure 1). The larger values in the KE, associated with the current meandering and variability, are located in the area of the two quasi-stationary meanders until the SR, with maximum values at their leading edges. The maximum near 153°E agrees with the mean location of the BP. Although the presence of the SR may have influence on the location of the BP, its variability and relation with upstream water transport and latitude of the axis also suggest hydrodinamical causes. However, changes in the decreasing rate of water transport at the KE near 160 and 170°E, the southward deflection of the KE axis near 160°E, and the location of the NB path are probably related with the topographic features.

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