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KUROSHIO PENETRATIONS INTO THE SOUTH CHINA SEA: MULTIPLE STATES, HYSTERESIS, AND PREDICTABILITY

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1. INTRODUCTION

The Kuroshio is a strong western boundary current in the North Pacific similar to the Gulf Stream. East of Luzon and Taiwan it is on average 140 km wide, its maximum velocity is 1-1.5 m/s, while the volume transport is between 28 and 43 Sv (Nitani, 1972; Guo and Wendong, 1988). The Kuroshio usually flows north past Luzon Strait, but at times part or all of it flows west through the strait into the South China Sea forming a loop current (Hu *et al.*, 2000). Perhaps, the first evidence of such Kuroshio bimodality was reported by Nitani (1972), who also suggested its possible seasonal origin.

Penetration of the loop current into the South China Sea is a very dramatic dynamical process. The maximum speed of the loop current may reach 1.4 m/s. As confirmed by the observations during the ASIAEX pilot survey conducted from the R/V Ocean Researcher I cruise 570 in April 14-25, 2000 (Gawarkiewicz, *pers. comm.*), the loop current impinging on the Chinese coast generates very strong currents near the shelfbreak. Li, L. *et al*. (1998) reported a closed current ring with speeds up to 1 m/s detached from the loop current. There is a very sharp density gradient at the intrusion's boundary located near 100 m depth, which supports strong internal waves of large amplitude (Liu *et al.*,1998). The water in the intrusion is much warmer and saltier than in the South China Sea, which significantly alters sound propagation characteristics.

Though connection between the Kuroshio intrusions and monsoon winds has been generally recognized, the details of this process are not clear (Hu *et al*., 2000). In particular, it is not known how regular is this process. Farris and Wimbush (1996) found a relationship between the loop current stage (derived from satellite infrared images) and the wind stress history: the Kuroshio penetrations occur when the time-integrated strength of the northeast monsoon exceeds a threshold value. Metzger and Hurlburt (2001) attempted to analyze the predictability of the Kuroshio intrusions based on results of numerical simulations. They found very low correlations between the intrusions and the transport of the current as well as the wind stress on the annual time scales. However, they noted “certain amount of intradecadal determinism when the Kuroshio intrusion is in one of two extreme modes, either deep penetration or very shallow penetration."

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Here we present a theory that may explain dynamics of the Kuroshio intrusions. A theoretical analysis of a single-layer depth-averaged model suggests that the flow inside the strait is governed by the balance between the beta effect and inertia: with the beta effect forcing the Kuroshio to intrude westward through the strait while the inertia allowing the current to leap across it. The model predicts the existence of multiple steady states (leaping and penetrating, corresponding to the large and small transport of the Kuroshio), hysteresis in evolution between them, explains the shape of the main intrusion, and formation of rings. We also present observational evidence (satellite and in situ), which supports our conclusions.

2. THEORETICAL MODEL

We consider an idealized problem of a western boundary current of Munk thickness $L_M=(A_L/\beta)^{1/3}$ flowing across a gap in a ridge using a single-layer depth-averaged approach (see sketch in Fig.1). The (steady) dynamics is governed by the planetary vorticity advection-diffusion equation for the stream function

$$J(\psi,\nabla^2\psi+\beta y)=A_L\nabla^4\psi\ . \qquad (1)$$

When the gap (of width $2a$) is narrow, $a \le 3.12 L_M$ viscous forces restrict penetration of the current through the gap. For larger gap width, the boundary current may leap across the gap due to inertia characterized by the Reynolds number Re (proportional to the total transport of the boundary current V), completely choking off water exchange between the two basins. For $a \ge 4.55\ L_M$ the flow may be in one of two regimes (penetrating or leaping) for the same parameters depending on previous evolution. The penetrating branch solutions become unsteady with eddies forming west of the gap between the two counter-flowing zonal jets. As the boundary current slowly accelerates, transition from the penetrating to leaping regime happens when the width of a zonal jet near the gap becomes comparable with a, implying the Reynolds number $Re_P \propto (a/L_M)^3$.

On the other hand as the boundary current slowly decelerates, the leaping regime persists while the meridional advection dominates the beta effect in a wiggle of the current core within the gap, implying that the leaping regime breaks at $Re_L \propto a/L_M$. Thus hysteresis occurs over the range of Reynolds numbers $Re_L < Re < Re_P$.

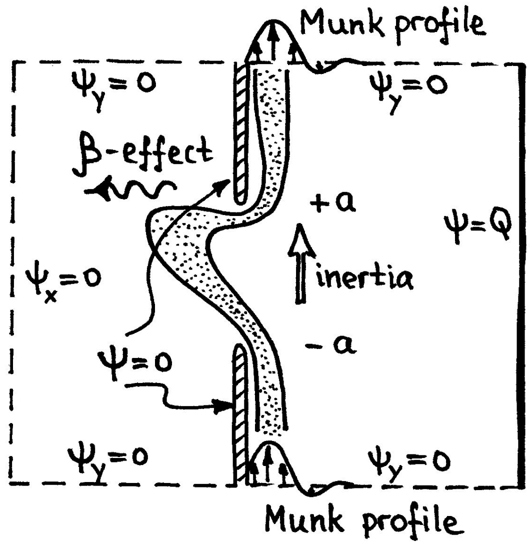

Figure 1. Sketch of the problem formulation. Dashed lines indicate open boundary conditions. The western boundary current is driven by prescribed difference *Q* in the stream function between the eastern boundary (solid) and the ridge (cross hatched). The Munk profile develops naturally for a parallel flow. The core of Kuroshio is shaded by dots.

The scaling arguments confirmed by numerical results (Sheremet, 2001) show that the crucial dynamical parameter is the inertial scale of the current determined by the balance between the inertia and the planetary beta effect,

$$L_{QP} = (Q/\beta)^{1/3}\,, \qquad (2)$$

where Q is the transport per unit depth. When it is comparable with the half width of the gap the hysteresis is possible.

For Luzon Strait the half-width is a =170 km, β = $2{\cdot}10^{11}$ $m^{-1}s^{-1}$. The average volume transport of the Kuroshio just east of the northern part of Luzon is estimated as V=$30{\cdot}10^{6}$ m^3s^{-1} from hydrographic sections, with the vertical distribution having an *e*-folding depth scale of H=250 m (Nitani, 1972). This gives Q=$1.2{\cdot}10^{5}$ m^2s^{-1}, and therefore L_{QP}=182 km according to (2). This means that normally the Kuroshio can leap across Luzon Strait ($L_{QP} \geq a$). However, during periods when its strength is substantially reduced, it may penetrate into the South China Sea. Thus multiple states and hysteresis are likely to occur.

Because of the possible hysteresis, in analyzing the observational data, it is important to correlate the Kuroshio penetrations not only with the parameters describing the present state of the current, but also to take into account its history. Otherwise simple correlation with the transport will not give a meaningful result.

Tang *et al*. (2002) and Liang *et al.* (2002) recently compiled the shipboard ADCP measurements in Luzon Strait collected over the period 1992-2002. The time-averaged flow field at 100m depth compares favorably with the prediction of our theoretical model: the shape of the main intrusion is represented quite accurately. There are also some common small-scale features such as the recirculation east of the southern tip of Taiwan, which is analogous to the front edge separation on a plate.

3. DECADAL TIME SCALES

Metzger and Hurlburt (2001) conducted a study of the Kuroshio penetrations using four realizations of Navy Ocean Layered Model (NLOM) with observed wind stress spanning the period from 1979 to 1997. They found significant variability on the decadal time scales and the evidence for bimodal behavior. They characterized the penetration by the measure of the Sea Surface Height (SSH) difference between the two areas inside the South China Sea west of Luzon Strait and Taiwan. They found that 1983-90 are characterized by low SSH difference corresponding to shallow Kuroshio penetrations, while 1994-97 are characterized by high SSH difference and hence deep Kuroshio penetrations. These periods also exhibit high interexperimental correlations and decadal determinism. 1979-82 and 1991-93 were found to be transition years between two extremes with moderate Kuroshio intrusion, low interexperimental correlations, and low determinism. Such behavior is consistent with the idea of hysteresis in evolution: near the two extreme states the system is more predictable, while close to the critical points small perturbations may lead to unpredictable regime shifts.

To put these results in a historical perspective we compare them with the Kuroshio Path Index (KPI), which is defined as the offshore distance of the Kuroshio axis (inferred from 16^{o}C isotherm at the 200-m depth) from the coast of Japan averaged from 132^{o} to 140^{o}E (Qiu and Miao, 2000). It is considered to be a good proxy for the Kuroshio transport and more generally speaking for the strength of the subtropical gyre in the North Pacific. The KPI reflects similar physical mechanism as one operating in Luzon Strait: when the flow is weaker it is pressed stronger to the western boundary by the beta effect. Plotted together (Fig.2) KPI and SSH difference characterizing Kuroshio intrusions reveal similar behavior on decadal time scales. Dots (upper half) denote the seasonal index values and the solid line indicates the annual average. The lower half of the plot shows the annually averaged data from the four numerical simulations of Metzger and Hurlburt (2001). The substantial geographic separation between Luzon Strait and Japan in combination with the apparent relationship between the KPI and Kuroshio intrusions on decadal time scales speak about the large scale nature of this process, essentially the scale of the subtropical gyre circulation in the North Pacific which is driven by wind stress curl.

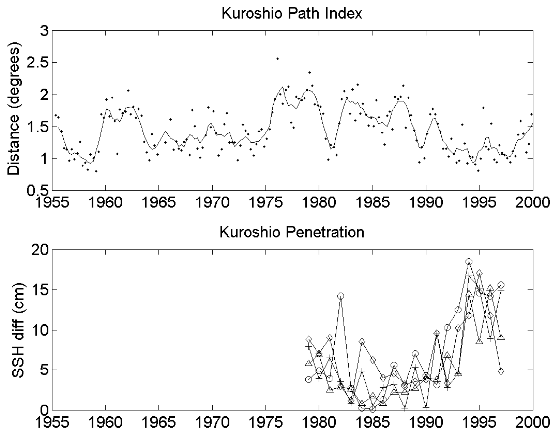

Figure 2. Comparison of the Kuroshio Path Index (observed offshore distance from Japan coast) with SSH difference in Luzon Strait (four NLOM numerical simulations).

4. SEASONAL TIME SCALES

To study seasonal time scales we analyzed the results from the experimental real-time North Pacific Ocean Nowcast/Forecast System provided by D.S. Ko (Stennis Space Center, *pers. comm.*; see www7320. nrlssc. navy. mil / npacnsf_www). This model assimilates the observed wind stress, satellite altimetry, and sea surface temperature data and extrapolates them below the surface using Levitus monthly climatology. According to the model the Kuroshio transport near Luzon Strait exhibits significant seasonal fluctuations sufficient to cause flow regime transitions. Instantaneous flow field snapshots allow to identify patterns with clear Kuroshio leaping or penetrating (Loop Current) states. The penetrating states are associated with the development of the anticyclonic gyre west of Taiwan mostly during winter months (November-February) following the minimum of the total Kuroshio transport west of Luzon (Fig. 3). We note that these fluctuations are not sinusoidal, the transport gradually decreases during the year and then rapidly increases in winter; therefore, a simple correlation of the intrusions with the transport value will not give meaningful interpretation. In agreement with the hysteresis idea one has to take into account the prior evolution.

The seasonal nature of the Kuroshio intrusions is also corroborated by our analysis of historical hydrographic data for 1966-2001 accumulated at the National Oceanic Data Center. Seasonal averages of the temperature field at 150 m depth (which is inside the core of the intrusion and below the seasonal mixed layer) show consistent warming in the area west of Taiwan during winter months (November-February). The monthly temperature averaged over all the data (1966-2001) in that area (1^{o} by 1^{o} square centered at 21^{o}N, 120^{o}E) varies from 17.5°C in April to 20.5°C in December. The signal is somewhat masked by the strong interannual variability with the standard deviation

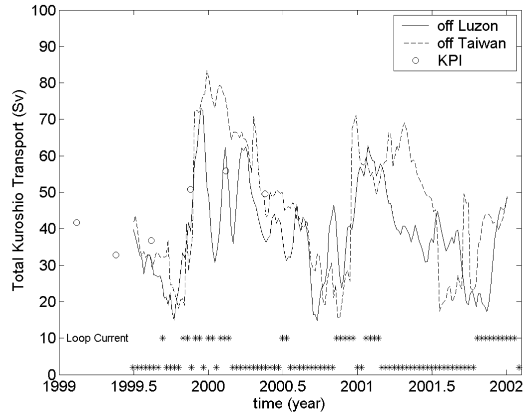

Figure 3. The Loop Current and transport fluctuations on seasonal time scales from the NPACNFS results. The Kuroshio transport is calculated by integrating the total depth-averaged flow offshore to the point of first meridional velocity reversal.

of 1.5°C. However, the warming should be contrasted with the fact that the Kuroshio core waters are generally cooler in winter. This is a clear indication that, despite of the general cooling, the Kuroshio tends to intrude through Luzon Strait during winter months and causes the warming in the anticyclonic gyre west of Taiwan.

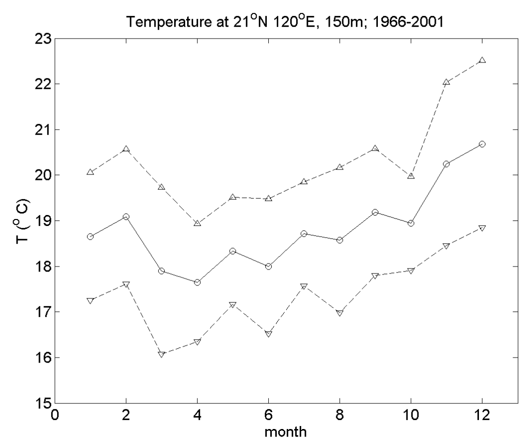

Figure 4. Monthly averaged temperature (solid) at a characteristic area west of Taiwan from hydrographic XBT and CTD observations at 150 m. Dashed lines indicate standard deviations.

The Kuroshio penetration into the South China Sea are recognized to be connected to the northeast monsoon which can be seen as stronger winds coming consistently towards about 225° beginning about September and lasting through about March. During the southeast monsoon, the winds are not as strong nor is the direction as steady. Farris and Wimbush (1996) found a relationship between the loop-current stage (derived from satellite infrared images) and the wind-stress history: the Kuroshio penetrations occur when the time-integrated strength of the northeast monsoon exceeds a threshold value. This is in qualitative agreement with the present theory in a sense that the penetrations occur when the Kuroshio is weakened by the monsoon blowing in the opposite direction.

Other possible source of the significant Kuroshio transport fluctuations on the seasonal and shorter time scales is the reflection of Rossby waves and baroclinic eddies from the western boundary. The signal of the seasonal enhancement of this process is clearly visible in the satellite altimetry data, in the hydrodgraphic data from the High Resolution XBT/XCTD survey network (HRX) (Gilson et al., 1998; Roemmich and Gilson, 2001). The direct moored velocity measurements at the PCM-1 array (Zhang *et al*., 2000) reveal also significant transport fluctuations with periods about 100 days, which are connected with the Kuroshio meandering.

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