Strait transports among the East Asian marginal seas

Chau-Ron Wu[1], Yi-Chia Hsin[2], and Tzu-Ling Chiang[1]

[1]*Department of Earth Sciences, National Taiwan Normal University*
[2]*Research Center for Environmental Changes, Academia Sinica*

ABSTRACT

Numerous models have been developed with different integration domains and resolutions to study Strait transports among the East Asian marginal seas. The annual average transport of the Taiwan Strait is 1.09 Sv (1 Sv=$10^6 m^3/s$), which is smaller than most published values based on shipboard Acoustic Doppler Current Profiler (sb-ADCP) observations. The result suggests that sb-ADCP observations are biased toward estimates in summer and fair weather since bad weather during the winter northeast monsoon often prevents seagoing observations. The Kuroshio extends from the coast to 123°E - 123.5°E between 22°N - 25°N with currents reaching a depth of 1000 m at some latitudes. The Kuroshio transports east of Taiwan are 28.4 ± 5.0 Sv and 32.7 ± 4.4 Sv with and without the contribution from the countercurrent, respectively. The annual mean Luzon Strait transport is estimated to be westward (-4.0 ± 5.1 Sv) along 120.75 °E. Past estimates from models and data suggested a three-layered Luzon Strait transport, having two inflows in upper and lower depths separated by a mid-depth outflow.

Over the upwelling region (from 122.25°E to 122.75°E in longitude, and from 25.1°N to 25.6°N in latitude), the average upwelling rate over the five-year period is 5.5 m/day in the upper 60 m. For the upwelling domain of 2800 km^2, the total upwelling transport is about 0.16 Sv. Previous observation-based estimates are comparable; the corresponding upwelling rate and upwelling transport are respectively 5.4 m/day and 0.2 Sv by Liu et al. (1992).

感言

KK 老師：您是精采人，成就精彩人生！ 朝榮敬上

敬愛的 KK 老師：您一生致力於海洋研究與教育。感謝您的付出！ 宜佳敬上

KK 老師是我碩士及博士的口試委員。老師一直都很風趣幽默、平易近人，但仍以最嚴謹地態度給予研究上的建議。敬愛的 KK 老師：謝謝您的指導，感謝您對海洋界的努力以及對海洋學子的付出！祝您順風～ 學生 紫綾敬上

NUMERICAL MODELS:

The Seas Around Taiwan (SAT) model is derived from the sigma-coordinate Princeton Ocean Model (POM; Blumberg and Mellor, 1987). The three-dimensional, free surface model solves the primitive equations for momentum, salt and heat. It includes a 2.5-level turbulence closure sub-model developed by Mellor and Yamada (1982), and the Smagorinsky (1963) formulation for horizontal mixing. The SAT model domain is from 110.5°E to 126°E and from 13.5°N to 28°N with realistic bathymetry (Figure 1). The horizontal grid size is 1/20°, and there are 26 sigma levels in the vertical. On open boundaries, the SAT model derives its boundary condition from a larger-scale East Asian Marginal Seas (EAMS) model.

The EAMS model is also based on the Princeton Ocean Model. The model covers a domain of 99 °E ~ 140 °E and 0° ~ 42 °N with a horizontal resolution of 1/8° × 1/8° and has 26 sigma levels in the vertical. On open boundaries, its lateral boundary conditions are one-way nested in a 1/4° × 1/4° North Pacific Ocean (NPO) model having an expanded domain of 99 °E ~ 71 °W and 30 °S ~ 65 °N. The daily outputs of NPO model are linearly interpolated in space and time to the open boundaries of EAMS model (Figure 2). The NPO model is initially spun up for 50 years. The initial spin-up is driven by monthly 2.5° × 2.5° NCEP-DOE 10-meter wind climatology derived from averaging all historical data month-by-month regardless of the year. Also, the monthly climatology of the Simple Ocean Data Assimilation (SODA) reanalysis products, similarly derived through averaging over all available years with 0.5° resolution, provide lateral boundary conditions for the NPO model.

RESULTS:

TAIWAN STRAIT

Model experiments suggested that the best simulation is achieved when the model is driven by the QSCAT wind forcing. The model also suggests that flow in the entire Taiwan Strait is to the southwest during periods of strong northeasterly wind. The modeled annual average transport is 1.09 Sv, which is smaller than most published values based on sb-ADCP observations. The result suggests that sb-ADCP observations are biased toward estimates in summer and fair weather since bad weather during the winter northeast monsoon often prevents seagoing observations.

A fine-resolution model is constructed to further study the spatial and temporal variations of the Taiwan Strait circulation. Because of the high resolution in model grids and forcing, the model achieves a previously unavailable level of agreement with most observations. On biweekly time scales surface-trapped current reversals often lead to Strait transport reversals if the northeasterly wind bursts in winter are sufficiently strong. On seasonal time scales the northward current is the strongest in summer since both summer monsoon and pressure gradient force are northward. Past studies have failed to reveal an anticyclonic eddy that develops on the northern flank of the Changyun Rise in winter. The winter appearance of the anticyclone suggested by our model is consistent with theoretical expectations (Taylor column). On interannual time scales a weakened northeast monsoon during El Niño reduces advection of the cold China Coastal Water from the north and enhances intrusion of warm water from the south, resulting in warming in the Taiwan Strait.

LUZON STRAIT

We use a high-resolution numerical model to examine the forcing mechanism responsible for the Kuroshio intrusion into the South China Sea (SCS). Model experiments demonstrate the importance of wind inside the SCS is superior to that outside the SCS. Especially, wind stress curl (WSC) off southwest Taiwan is chiefly responsible for the Kuroshio intrusion. Both WSC and intrusion present not only seasonal variation, but also intra-seasonal fluctuation. As negative WSC off southwest Taiwan becomes stronger, it contributes to an anticyclonic circulation. The enhanced anticyclonic circulation helps the development of the Kuroshio intrusion. The well consistency between WSC variability and intrusion suggests that WSC off southwest Taiwan is the ultimate driving force for the variation of the Kuroshio intrusion.

We update Luzon Strait transport (LST) using a fine resolution model. The annual mean LST is estimated to be westward (-4.0 ± 5.1 Sv) along 120.75 °E. We have conducted process of elimination experiments to assess the relative importance of inflow/outflow, wind stress and surface heat flux in regulating LST and its seasonality. The East Asian monsoon winds stand out as the predominant forcing. Discounting monsoon winds, sea level in the Sulu Sea is generally higher because it receives the Indonesian Throughflow before the SCS, which causes an inflow from the Sulu Sea to the SCS. On the other hand, the annual mean wind from the northeast invites outflow from the SCS to the Sulu Sea. Weighing the two competing factors together, we see the cessation of northeast monsoon as a condition favorable for the Luzon Strait outflow or the Mindoro Strait inflow.

An advanced artificial neural network classification algorithm is applied to multi-satellite geostrophic velocities to study the Kuroshio intrusion into the SCS. The Kuroshio intrusion may occur year round. However, intrusion is not the major characteristic of the region. Winter intrusion events are more frequent than summer events. Both stronger intrusion (related to wind speed) and weaker intrusion (related to the upstream Kuroshio) may occur during winter, but stronger intrusion is dominant. Kuroshio intrusion usually occurs when the PDO index is positive.

Rather than ENSO, the interannual variability is highly correlated to the PDO index. Tracing back to its source mechanism, in the warm phase of PDO, a southerly anomalous wind off the Philippines causes northward shift of the North Equatorial Current bifurcation latitude (NECBL). This leads to a weakened Kuroshio off Luzon, favoring the Kuroshio intrusion into the SCS. Since the influence of ENSO is not stationary, one should take PDO’s impact into account when performing the interannual variability study on the low-latitude western North Pacific.

There are two types of behaviors when westward-propagating eddies approach the Kuroshio. The eddy either crosses the current, or it is blocked and advected northward by the Kuroshio. Whether or not an eddy can pass through the Luzon Strait depends on (i) the Kuroshio strength and the PV-jump across it; and (ii) the curvature of the Kuroshio just north of the Luzon Island. Strong transports tend to produce a ‘leaping’ Kuroshio. Weaker transports tend to produce a ‘looping’ Kuroshio. Composite analyses also show that the blocking mode appears in spring-summer when the NEC shifts southward, while the westward-passage mode appears in fall-winter when the NEC shifts northward.

KUROSHIO AND UPWELLING

The Kuroshio variability east of Taiwan is presumably caused by complicated bathymetry, eddies, the upstream conditions, and instability in the Kuroshio. Although short-term current measurements have shed light on these processes, the observational data are limited in both spatial and temporal coverage. Variations of event-like features are not resolved in earlier modeling studies. For the first time, we have used a nested ocean model to resolve the key features in observations and to provide a better description of the transport variation. The Kuroshio consists of an inshore path and an offshore path. The inshore path is likely affected by the water entering the Kuroshio from the loop current south of Taiwan, but most transport of the Kuroshio is associated with the deeper offshore path. The Kuroshio extends from the coast to 123°E - 123.5°E with currents reaching a depth of 1000m. The Kuroshio transports east of Taiwan are 28.4 ± 5.0 Sv.

The upwelling at the southern East China Sea (ECS) Shelf draws much attention because the exchange between the Kuroshio Water and the ECS Shelf Water takes place in that region. Observations are gappy in time and space. Important issues remain, such as temporal variability and vertical distribution. Model results demonstrate upwelling exists all year-round below 150m. In upper depths, the Kuroshio migration regulates the upwelling. A seaward migration of the Kuroshio favors the upwelling formation, while upwelling disappears when the Kuroshio moved shoreward. Upwelling appears more frequently in summer than in winter. Collectively, the foregoing results provide a logical explanation that bridges gaps among sparse observations in the past. The migration is active only in the upper 150m; this explains the upwelling’s vulnerability above this depth and lack thereof below.

Observations indicate that off the northeastern coast of Taiwan the Kuroshio intrudes northward closer to the shelf of the ECS in winter. We demonstrate that this seasonal migration can be explained solely by the cooling of the near-surface layer of the Kuroshio near Taiwan. Cooling results in parabathic density gradient which combines with the cross-shelf topographic slope (JEBAR effect) to enable on-shelf movement of the Kuroshio in winter.

Observations off northeast Taiwan indicate a curious seasonal variability of upwelling. At deeper levels, 100m below the surface, upwelling is most intense in summer but weaker in winter. Nearer the surface, ~30m below the surface, the opposite is true and the upwelling is stronger in winter than in summer. Results from a high-resolution numerical model, together with observations and simple Ekman models, are used to explain the phenomenon. It is shown that the upwelling at deeper levels (~100m) is primarily induced by offshore (summer) and onshore (winter) migrations of the Kuroshio, while monsoonal change in the wind stress curl, positive in winter and negative in summer, is responsible for the reversal in the seasonal variation of the upwelling near the surface (~30m).

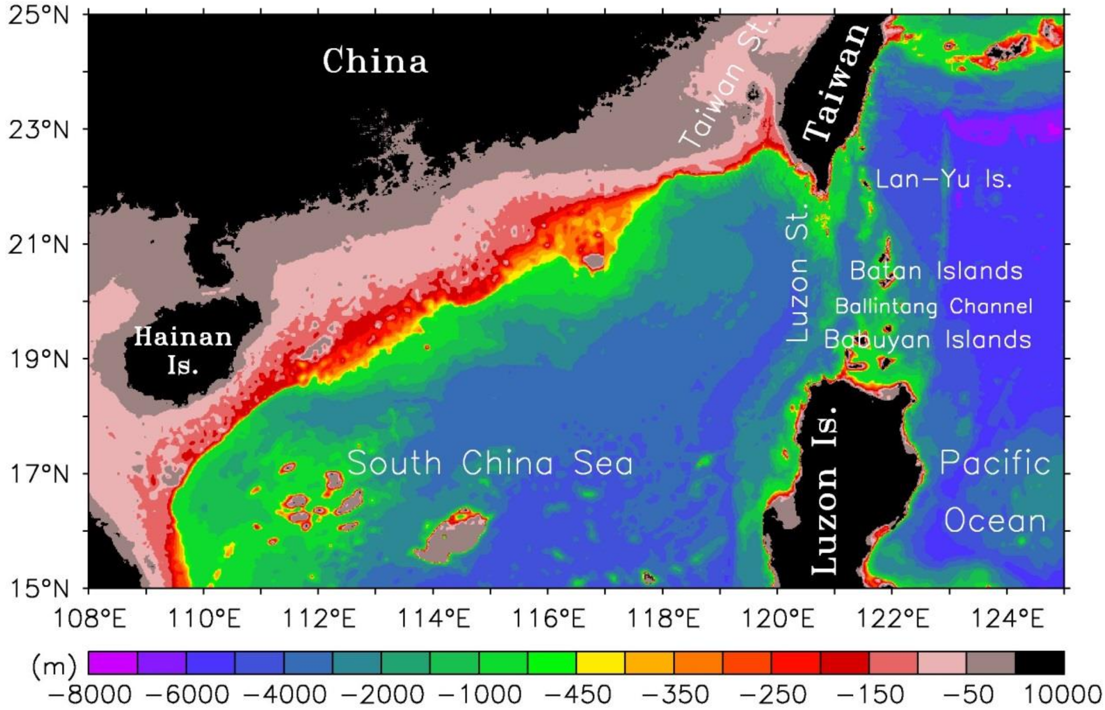

Figure 1. Bathymetry of the northern South China Sea.

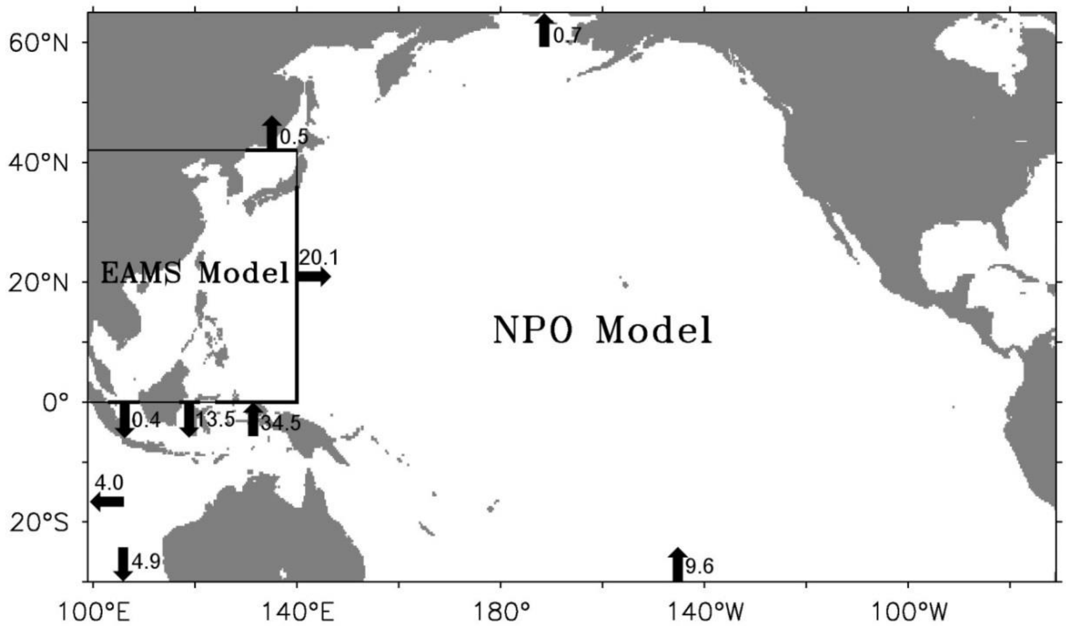

Figure 2. Nested East Asian Marginal Seas model (EAMS) domain within the North Pacific Ocean (NPO) model. The ten-year (1999 ~ 2008) mean volumetric fluxes in and out of open ocean boundaries are indicated by thick arrows and numbers (in Sv).