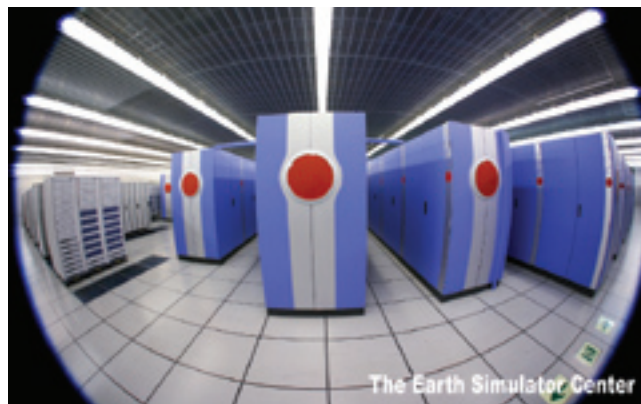


Earth Simulator's Virtual Ocean Brings New Insights

In March 2002, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) began operations of its high-speed supercomputer, the Earth Simulator. Scientists at the JAMSTEC Earth Simulator Center developed three general circulation models (GCMs) to study the climate system at unprecedented fine resolution: The Atmosphere, the Ocean, and the coupled Atmosphere-Ocean GCMs for the Earth Simulator, or AFES, OFES, and CFES. “We can now build the virtual atmosphere and ocean on the Earth Simulator. Information exchange between observations and simulations shall lead to better understandings of the weather and climate systems,” writes **Wataru Ohfuchi**, Group Leader for Atmospheric and Ocean Modeling, on the Earth Simulator website.

IPRC scientists have been participating with their partners at the Earth Simulator Center in the analysis of outputs from these high-resolution models. The following describes several findings from OFES, the ocean model.

Because of the Earth Simulator's ability to perform a nominal 40 trillion floating-point operations per second (Tflops), fewer ocean processes need to be parameterized in OFES than in existing global circulation models. The model's high resolution with a grid-spacing on the order of 0.1° and 54 vertical levels allows good representation of the western boundary currents and mesoscale eddies. The codes, based on the GFDL Modular Ocean Model 3, are optimized for massively parallel computations on the Earth Simulator. The



model, driven with observed atmospheric fields, provides a comprehensive three-dimensional view of the ocean that aids scientists in interpreting the extensive observations made during the last decades.

Alternating Zonal Jets

At the IPRC, associate researcher **Nikolai Maximenko** was among the first to use OFES output. He had noticed in satellite altimetry data unusual east-west jets that alternated their direction with latitude. Together with **Bohyun Bang**, now a research scientist at the University of Washington, and **Hideharu Sasaki**, a research scientist at the Earth Simulator Center, he decided to look at the climatological run of OFES, and, indeed, found these jets occurred in OFES, too. The finding was consistent with the earlier result by Nakano and Hasumi, who demonstrated the formation of zonally elongated structures in their model of the North Pacific. Furthermore, **Kelvin Richards**, team leader for IPRC Regional-Ocean Influences Research saw these jets also in the high-resolution POP model run on the Earth Simulator and in the OFES hindcast run forced by NCEP reanalysis winds. The presence of these time-varying alternating zonal jets is changing the long-held view of world ocean circulation (see *IPRC Climate*, Vol. 5, No. 1).

OFES, with its high horizontal resolution and many vertical levels, turned out to be ideal for analyzing these jets further, particularly their vertical structure. The model revealed that the jets extend deep into the ocean, although they are significantly more energetic at the surface than at one-km depth. The jets populate virtually every part of the world ocean and the marginal seas. Moreover, the jets are closely related to ocean eddies, and not just at the surface but also at depth.

Maximenko has continued to study these jets. He has found that, although alternating zonal jets are predicted by the theory of geophysical turbulence, the two most distinct classes of jets—seen in both observational and model data—seem to be of different origin.

The first class of jets is amazingly steady over a 10-year and longer period. Such jets all seem to be controlled by local processes at their eastern origins. Most of the jets are located in the eastern parts of oceans with unknown forcing mechanisms. Their kinematical structure reveals a new, interesting interaction between zonal jets and the surrounding large-scale flow. They are not advected by the geostrophic current, according to Maximenko, because they take the form of Rossby wake waves standing in the surrounding flow. He believes this is the mechanism that sets the orientation of such currents as the Azores Current and the Hawaiian Lee Countercurrent (HLCC). The warm eastward-flowing HLCC, for example, results from the blocking of

the tradewinds by the tall mountains of the Hawaiian Islands and is associated with positive and negative wind stress curl, according to an OFES simulation by **Hideharu Sasaki**, and **Masami Nonaka**. This air-sea interaction sustains the HLCC along its 4000-km path from west to east. The current, however, is oriented slightly northward, and Maximenko could demonstrate that the path's orientation is inconsistent with that expected from the prevailing wind direction. He suggests that the orientation results from the northward propagation of the HLCC as a Rossby wave that opposes its southward advection by the geostrophic flow. This is illustrated in Figure 1.

The second class of jets is found at mid-latitudes. This class appears as alternating jets only on snapshot maps of altimetry or model data. The jets behave like sets of linear Rossby waves with a nearly meridional wave vector and north-south wavelengths of about 500 km, propagating toward the equator at 0.45 cm/s phase speed with a

3.5-year local period. The origin of these jet-waves remains unknown and is under active investigation.

The Shifting Kuroshio Extension

The Kuroshio Extension (KE) is the swift, warm, eastward current formed when the Kuroshio separates from the Japanese coast. The jet impacts North Pacific climate considerably, carrying nearly 140 million cubic meters of warm water per second (140 Sv) eastward into the North Pacific. Above the jet lies the Pacific storm track. The KE is also a large carbon sink and a busy fishing region.

Satellite altimetry measurements have shown that the sea surface height (SSH) in the Kuroshio region has varied greatly over the last 10 years, indicative of both a shift in the current's latitude and strength. The mechanism that causes the KE to slowly shift in this manner is being debated. There are two views. One holds that the shift is due to a change in winds over the region, the other that it is due to internal ocean dynamics. Until OFES, the resolution of the ocean circulation models was too coarse to answer this question. But OFES now resolves the 100-km-wide KE front.

“The combination of high-resolution modeling that matches satellite observation resolutions allows new science to be done. Now the slow changes in the jets' intensity and the position of its front over time can be studied,” according to IPRC research team leader **Shang-Ping Xie**.

To resolve the debate, **Bunmei Taguchi**, an IPRC-sponsored University of Hawai'i graduate student until Spring 2006 and now scientist at the Earth Simulator Center (see p. 29), Xie,

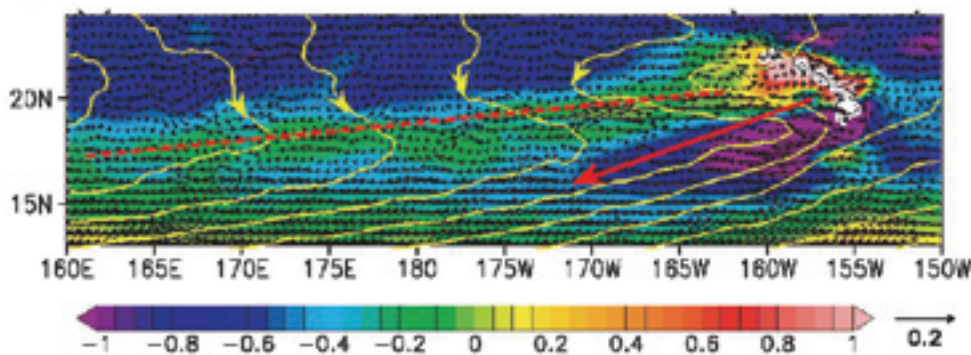


Figure 1. The Hawaiian Lee Countercurrent (HLCC)—the dashed red line—is induced by the wind stress curl in the lee of the tall islands and sustained by strong air-sea interaction along its entire 4000-km path. The figure, adapted from Sasaki and Nonaka (2006), shows the eastward OFES surface velocity vectors (black) in the area of larger QuikSCAT wind stress curl (colors). The yellow lines, representing the contours of mean surface dynamic topography plotted at 5 dyn. cm intervals, show the mean southward geostrophic flow. The northward tilt of the HLCC differs from the mean wind direction and suggests that the current system behaves like the crest of a Rossby wave standing in the geostrophic flow.

and Niklas Schneider at the IPRC partnered with Hideharu Sasaki and Masami Nonaka and Yoshikazu Sasai at the JAMSTEC Frontier Research Center for Global Change. To determine whether OFES captures past changes in this region, they studied an OFES hindcast of ocean conditions for the period of 1950 to 2003. The hindcast, conducted by Earth Simulator Center scientists, was driven with NCEP reanalysis daily mean winds for the 54-year period. This is the first multi-decadal hindcast that resolved fronts and eddies in the world ocean from the tropics to midlatitudes.

The OFES simulation matches remarkably well the 10 years of SSH anomaly maps compiled from TOPEX/Poseidon, JASON, and ERS-1/2 satellites (referred to as T/P in the figures). OFES, like the satellite data, shows the interannual variability of the jet concentrated in a narrow latitudinal band that broadens as it approaches the dateline (Figure 2). The meandering of the KE also stands out distinctly.

Figure 3 shows fluctuations in the jet’s latitude position and strength over time as reflected in an index. The model tracks the altimetry data very closely, with the initial south-

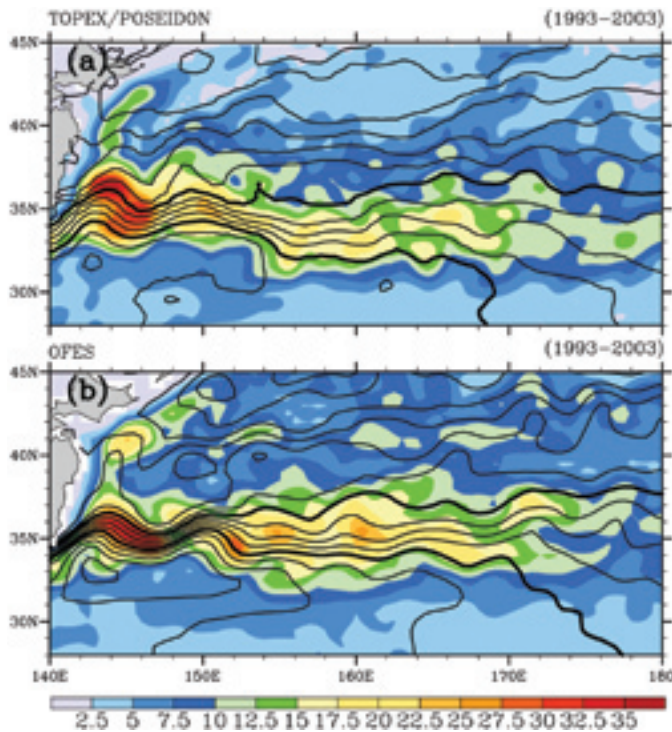


Figure 2. (a) Standard deviation of 12-month low-pass filtered SSH observed by satellite altimeters (shade) and the mean absolute sea level (contours at 10-cm intervals; the 60- and 100-cm contours thickened to delineate the KE frontal zone). (b) Same as (a) but for the OFES hindcast (the 30- and 70-cm contours for the mean SSH are thickened). Adapted from Taguchi et al., *J. Climate*, in press.

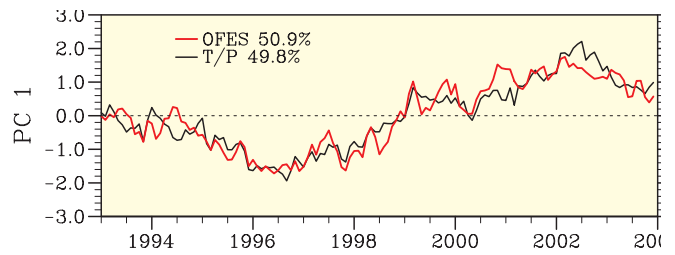


Figure 3. The first principal component of the zonal and monthly mean SSH anomalies (cm) for the period 1993 to 2003: the OFES hindcast (red) and satellite altimeter observations (black). Adapted from Taguchi et al., *J. Climate*, in press.

ward excursion of the KE during the early 90s and then the subsequent northward shift. To validate the OFES hindcast before the satellite altimeter era, the team compared monthly ocean temperature data from OFES with data compiled from expendable bathythermograph measurements gathered by Scripps Institution of Oceanography. Again, the temperature patterns follow each other fairly closely. In short, the OFES hindcast is realistic enough to explore what causes the KE to shift in latitude.

Taguchi and colleagues went on to compare the evolution of the KE latitude–strength index derived in OFES with projections made by the theory that holds the KE variations are due to changing winds (the linear Rossby wave theory). The comparison supports the view that the KE position-shift is due to a change in the wind—the northward shift of the current in the early 1980s follows four years on the heels of a wind shift associated with changes in the Aleutian Low (Figure 4). The north–south structure of the KE, however, is

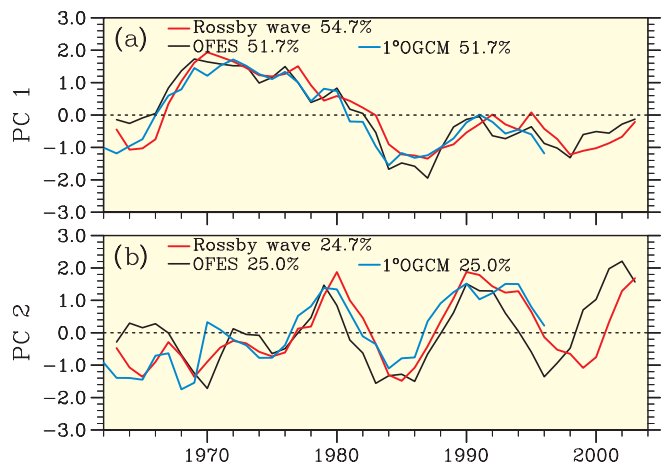


Figure 4. Meridional EOF modes of annual and zonal mean OFES SSH (black), SSH hindcasted with a linear Rossby wave model (red) and the 400-m-temperature simulated with an Ocean GCM (blue): (a) PC-1, and (b) PC-2. Adapted from Taguchi et al., *J. Climate*, in press.

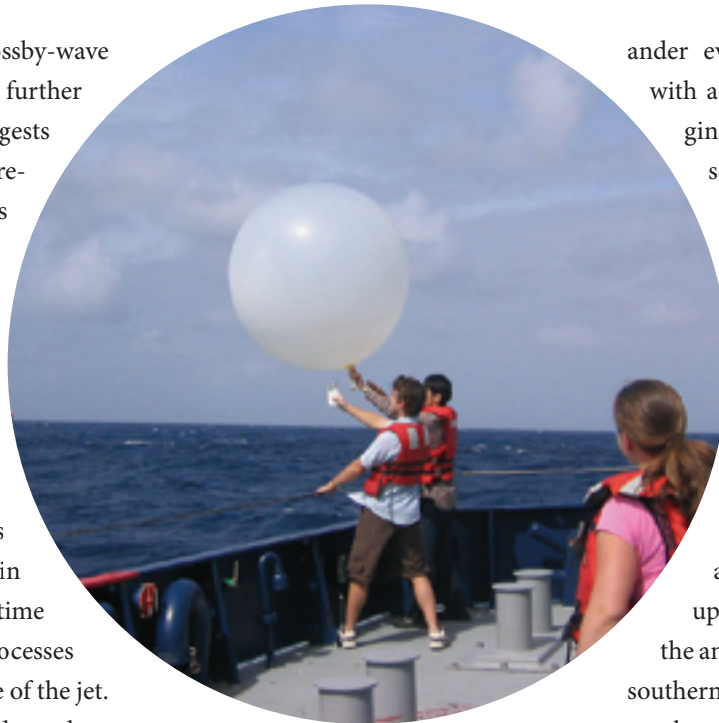
much narrower than the Rossby-wave theory would predict. A further analysis of OFES output suggests that this narrow structure results from internal dynamics of the KE, with subsurface variations exerting a strong influence. The wind-forced Rossby waves appear to act as pacemaker regulating the intrinsic variability of the jet.

In sum, the analyses show that wind shifts explain the variations in the jet over time and that nonlinear ocean processes organize the spatial structure of the jet. The next question now is, how does this oceanic front (as well as others) affect the atmosphere that lies above it and the storm track? Experiments at the Earth Simulator Center with the high-resolution AFES are already looking into this significant question.

Kuroshio's Shifting Pathways

The Kuroshio flows along the coast of Japan in one of three paths: a large meander, which moves offshore near Shikoku for up to 300 km and returns to the coast west of Izu ridge; a rather straight path along the shore past Kii peninsula and north to Miyake-Jima; and a small offshore excursion south of Hachijo-Jima. The location of the Kuroshio impacts Japan's coastal ocean and fishing industry.

Several theories have been put forward to explain the sudden switches in Kuroshio paths: lee Rossby waves, multiple steady states selected by upstream variations in the Kuroshio, and accumulation of potential vorticity in the recirculation of the Kuroshio. OFES with its near-global domain, eddy-resolving



Releasing a GPS sonde from the RV *Melville*, see p. 27 (photo courtesy Kohei Kai).

grid, and multi-year hindcast provides a unique opportunity to investigate the dynamics of the Kuroshio paths.

IPRC research team leader **Niklas Schneider, Bo Qiu** (University of Hawai'i) and **Hideharu Sasaki** (Earth Simulator Center) found that the 1950–2003 OFES hindcast produces variations in sea level, thermocline temperature, and ocean pressure that indicate vigorous variations in the Kuroshio path. They used a Complex Empirical Orthogonal Function to decompose sea level or geostrophic stream function anomalies; the leading mode accounts for 63% of the variance in this area and yields an index for the Kuroshio path. The index suggests the systematic evolution of two preferred paths, similar to the large observed meander and the straight path (Figure 5).

Using the evolution of the leading principal component, the team obtained a composite of the large me-

ander evolution (Figure 6). Starting with a straight path, a meander begins to form near Izu ridge. Over several years, this meander grows and moves upstream until the large meander is established. After a period of several years to a decade, the system collapses in a few months into a straight path again. This evolution is independent of upstream anomalies in the Kuroshio, and is associated with a build-up of low potential vorticity in the anticyclonic recirculation on the southern side of the Kuroshio. On the northern side, high potential vorticity is generated at small topographic features, a process that can only be simulated because of the high resolution of OFES. Lateral mixing in the OFES due to friction along the coast appears to

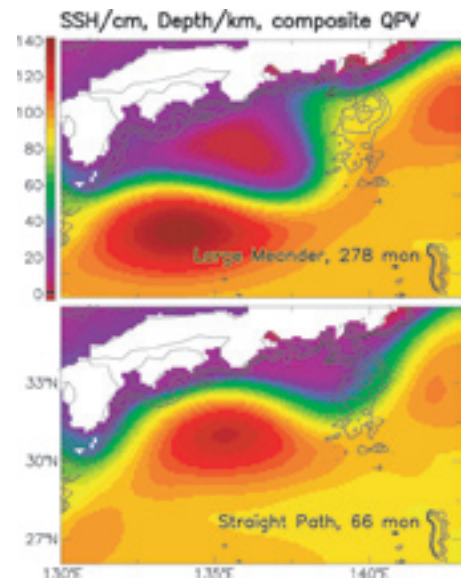


Figure 5. Sea level (in cm) composites for OFES's large meander and straight path, the preferred states in the principal component of the CEOF. Out of 648 months, the large meander occurs 278 months and the straight path only 66 months.

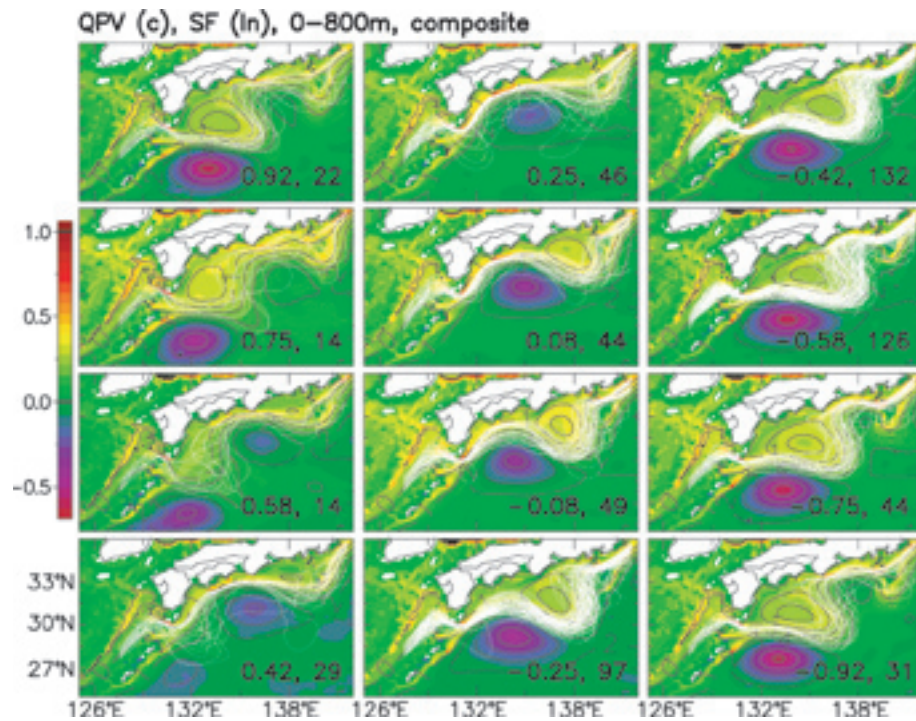


Figure 6. Composite evolution of the large meander based on the phase of the CEOF of quasi-geostrophic potential vorticity south of Japan. Contours denote stream function, colors denote quasi-geostrophic potential vorticity, and white lines the Kuroshio path for the months within the phase. The first number in the bottom right corner of each panel denotes the phase in units of π and decreases as time progresses; the second number denotes the number of months in the phase. Note the continuous buildup of the large meander and very fast collapse to a straight path.

be insufficient to mix these waters and to convert low potential vorticity water into the high potential vorticity water known to leave the coast of Japan in the Kuroshio Extension. Thus, in OFES, the low potential vorticity water accumulates until the system becomes unstable and forms the straight path again.

In these OFES simulations, a few features differ from observations. The large meander, for instance, detaches from the Japan coast already near Tokara Strait and returns to the coast just west of Izu Ridge. During its straight path, the Kuroshio departs at Kii pen-

insula to loop around the northern part of Izu Ridge. Furthermore, the preferred state in OFES is a large meander, the straight path occurring for only a fraction of the cycle.

These differences pose an exciting challenge to understand the model's physics and improve the simulation. Previous studies, which have used simplified, idealized models of the Kuroshio, detail many features that can affect the behavior of the Kuroshio. Schneider and his colleagues now intend to combine the insights gained from the OFES simulations with those from the simpler models to further investigate the observed evolutions of the different Kuroshio paths.

South China Sea May Impact Indo-Pacific Warm Pool

The Indonesian Throughflow transports water between the Pacific Ocean and the Indian Ocean through the Indonesian Archipelago. The region has unusually high sea surface temperature (SST). The interaction between atmosphere and ocean in the region significantly impacts climate, particularly the El Niño–Southern Oscillation. Research has shown that small changes in SST there may significantly change atmospheric convection and rainfall across the Indo–Pacific basin. The adjacent South China Sea, though, has been seen as a passive body of water and has received little attention in climate research.

IPRC Associate Researcher **Tangdong Qu** has been studying this region for some time and believes the South China Sea heat content and freshwater concentration vary in ways that very likely influence the climate not only of the Indonesian Seas but also the tropical Indian and Pacific oceans. Existing models, however, have not resolved the region well enough to explore this idea.

Analysis of the climatological run from OFES by **Yan Du** (IPRC post-doctoral fellow), **Qu**, **Hideharu Sasaki** (JAMSTEC Earth Simulator Center) and **Gary Meyers** (Australia's CSIRO) demonstrated that the high-resolution OFES represents the complex topography of the passages through the islands and the region's ocean bottom much more realistically than previous models. Qu, Du, and Sasaki, therefore, decided to examine the region's circulation, heat content, and freshwater flux in the 1950–2003 OFES hindcast.

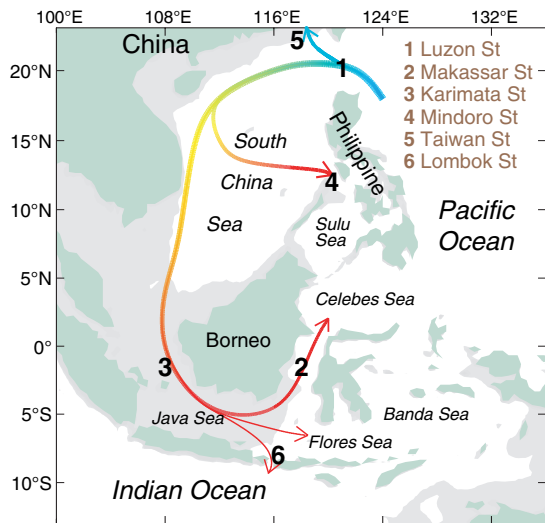


Figure 7. A schematic diagram showing the South China Sea through-flow adapted from Qu *et al.*, *GRL* 2006. Water entering the South China Sea through Luzon Strait is lower in temperature (blue) than water leaving it through Karimata, Mindoro, and Taiwan Strait (red).

OFES results show Pacific water entering the South China Sea through Luzon Strait. This water leaves the South China Sea through three straits: Karimata, Mindoro, and Taiwan, each transporting on average approximately 1.3 million cubic meters of water per second (Figure 7). Comparing the mean heat transported through Luzon Strait and the three exit straits, the team determined that the water in the exit straits is 1.8°C warmer than in the inflow through Luzon Strait. That means strong heat flux from the atmosphere warms the water while in the South China Sea.

The team estimated that between 0.1 to 0.2 Petawatts (the total heat flux transported by Earth's atmosphere and oceans away from the equator towards the poles is estimated at 4 Petawatts) leaves the South China Sea through Karimata and Mindoro straits. This large amount of heat transfer can be expected to have considerable effect on the heat and freshwater distributions in the Indonesian Seas, as well as the Indian and Pacific oceans. Even more important for long-term climate fluctuations is the finding that in OFES the outflow through Karimata and Mindoro straits varies greatly from year to year. In most years, the flow through the Karimata and Mindoro straits is stronger during El Niño years and weaker during La Niña years. Because volume and heat transport are nearly perfectly correlated ($r = 0.98$), the maximum heat transported out of the South China Sea through Karimata and Mindoro straits tends to occur during El Niño years—around four months before the mature phase of El Niño.

During El Niño years, the South China Sea receives more heat from the atmosphere than during La Niña years, according to the surface-heat-flux data from the NCEP re-analysis. This increase usually has less impact on the upper heat content of the SCS than the variations in the transport through Karimata and Mindoro. Since this transport is stronger during El Niño years, the South China Sea actually tends to lose more heat during El Niño years than in other years (Figure 8).

There are intriguing exceptions to this trend, though. During the two super El Niños of the last century, the 1982–83 and the 1997–98 El Niño, the surface heat flux into the South China Sea was stronger than the transport out of the sea, increasing the heat content of the South China Sea.

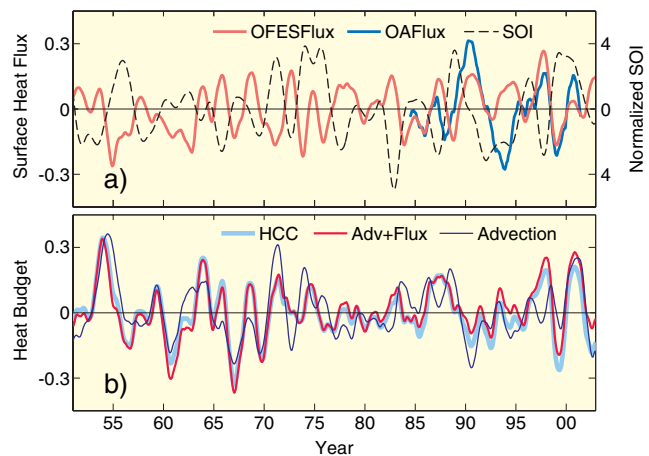


Figure 8. (a) OFES surface heat flux compared with the OAFflux surface heat flux and the Southern Oscillation Index (SOI), and (b) upper layer (0–432 m) heat content change (HCC) compared with heat advection and the sum of surface heat flux and heat advection averaged over the South China Sea. The 13-month mean filter has been applied twice to remove the mean seasonal cycle. Unit is 1014 W. Adapted from Qu *et al.*, *GRL* 2006.

What does all this mean? The year-to-year fluctuations in the South China Sea heat content should impact long-term climate variability. Based on the OFES results, Qu believes that the South China Sea is acting as a heat capacitor, storing and releasing heat and modulating conditions in the Indo-Pacific warm pool region. The sea should, therefore, impact the southeast Asian monsoon and El Niño and La Niña. He hopes that this OFES research with his partners at the Earth Simulator Center is putting the South China Sea on the map as worthy of attention from climate scientists.

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