

Research Highlights

The central theme of my research is large-scale ocean-atmosphere interaction or the ocean's role in climate. My research also touches on ocean and atmospheric circulation, providing solid footing for my studies of their coupled system. Geographically, my work covers all three major oceans of the Pacific, Atlantic, and Indian, and monsoons of Asia, Africa, and the Americas.

1. Climate formation.

Climate deviates strongly from solar radiation distribution at the top of the atmosphere (TOA). Despite a nearly symmetric TOA solar radiation, the Pacific and Atlantic ITCZ is displaced in the Northern Hemisphere, sustaining lush rainforests in Central America but turning the Pacific coast of Peru a dry desert. We were the first to suggest that ocean-atmosphere interaction, specifically wind-evaporation-sea surface temperature (WES) feedback, helps maintain the climatic asymmetry (Xie and Philander 1994). Subsequent studies, including some of mine, establish the WES feedback as a major mechanism for tropical ocean-atmosphere interaction, along with the Bjerknes feedback that makes ENSO. The former involves interaction in the north-south direction and favors an anti-symmetric pattern while the latter involves interaction in the east-west direction and creates an equatorial trapped pattern.

Another mystery of tropical climate is the annual cycle in the eastern equatorial Pacific and Atlantic that features a sea surface temperature (SST) maximum in March and a minimum in September despite little changes in TOA solar radiation on the equator. I developed the first theory for the equatorial annual cycle that is consistent with Todd Mitchell and Mike Wallace's observations, pointing to the ITCZ's northward displacement as the cause of the March-September difference on the equator (Xie 1994). The equatorial annual cycle is important for ENSO and its Atlantic and Indian Ocean counterparts, all showing a strong peak at the cold phase of the annual cycle.

There is much interest in the Pacific and Atlantic ITCZ as state-of-the-art general circulation models (GCMs) fail to place it north of the equator (de Szoeke and Xie 2008; Richter and Xie 2008). Besides WES, the interaction of SST and clouds, especially low clouds that keeps the tropical Southeast Pacific cool, is also important. This cloud-SST interaction is poorly understood and represented in GCMs, and is the focus of an international (US, UK, and Chile) field campaign this fall in the subtropical Southeast Pacific (VOCALS). At the International Pacific Research Center (IPRC), I led a team that developed the IPRC regional ocean-atmosphere model (iROAM) of the tropical East Pacific (Xie et al. 2007), run on Japan's Earth Simulator. The model keeps its ITCZ north of the equator and simulates a realistic annual cycle on the equator. We have tested model sensitivity to shallow convection in the atmospheric boundary layer and the Andes, a steep mountain range poorly represented in GCMs. The model will be used to support the VOCALS program in a NOAA-funded project.

2. Tropical Atlantic variability

WES feedback leads to the tropical Atlantic meridional mode (TAMM) as illustrated by Ping Chang's group at Texas AM. TAMM affects precipitation in northeast Brazil, a semi-arid region susceptible to rainfall variability. We developed the first fully dynamical model for TAMM (Xie 1999) and showed the effect of positive low cloud-SST feedback from observations. Built on our result that the WES mode is rather independent on basin size,

Kawamura in Japan, John Chiang of Berkeley and Dan Vimont of Wisconsin reported similar meridional modes in the Indian and Pacific Oceans. We noted a pan-Atlantic pattern featuring zonal bands of anomalies stacked in the meridional direction from Greenland to the South Atlantic (Xie and Tanimoto 1998), possibly driven by the North Atlantic Oscillation and mediated by WES in the tropics. John Chiang proposed this pan-Atlantic mode as a conceptual model to explain high correlation between Greenland ice core and Cariaco basin sediment core records. Indeed, a similar pattern emerges from water-hosing experiments with coupled GCMs that simulate the ice sheet/melt water discharges into the high-latitude North Atlantic (Timmermann et al. 2007), such as those during Heinrich events and the Younger Dryas.

The equatorial cold tongue of the Atlantic develops in June-September in response to the West African monsoon onset, and it displays pronounced interannual variability akin to ENSO. Analyzing new satellite and buoy observations, my former student discovered a weaker secondary development of the Atlantic cold tongue and a new Atlantic Niño mode centered on November-December (Okumura and Xie 2006). She was awarded the prestigious NOAA Global Change Postdoc Fellowship in 2006.

3. Tropical Indian Ocean

Unlike the Pacific and Atlantic, the equatorial thermocline is deep and flat in the Indian Ocean without prevailing easterly trades. For this reason, ocean dynamics was considered unimportant for climate variability in the tropical Indian Ocean (TIO), and indeed a slab ocean model is quite successful in simulating some aspects of ENSO-induced SST variability as demonstrated by Gabriel Lau and others. The La Niña-like, Indian Ocean dipole event in 1997 changed this perception. Contributing to the turning tide, our work documents the importance of ENSO-induced, ocean downwelling Rossby waves over the Southwest TIO (Xie et al. 2002), where the thermocline shallows as a result of the Ekman pumping between the southeast trades and equatorial westerlies. It takes a year for these ocean Rossby waves to cross the basin, enhancing predictability. Indeed in coupled GCMs, Southwest TIO SST is most predictable with the longest leads (Schott et al. 2008).

The TIO displays a robust basin-wide warming following El Niño. The TIO warming persists through summer long after El Niño itself has dissipated. We showed that WES-type ocean-atmosphere interaction within the basin, anchored by the Southwest TIO Rossby wave, is important for the long persistence of the TIO warming. We proposed a TIO capacitor mechanism: the TIO warming prolongs El Niño's climatic influence during the summer long after the latter is gone, like a discharging capacitor. This capacitor effect successfully explains mysterious climate anomalies in the Indo-western Pacific and East Asia that are more pronounced in the summer following the El Niño's dissipation than the one during El Niño development (Xie et al. 2009). Our earlier work has documented TIO's effects on ENSO development and the onset of the Indian summer monsoon.

4. Asian summer monsoon

The Asian summer monsoon is full of mysteries begging for dynamical answers. Contradictory to the often invoked explanation as a planetary sea breeze, the summer monsoon commences often abruptly and much later than the spring equinox, notably over India and the subtropical Northwest Pacific. We proposed a geostrophic monsoon hypothesis for the Indian monsoon (Xie and Saiki 1999): the thermal wind balance between the easterly shear and land-sea temperature gradient delays the onset until dynamical instabilities such as baroclinic

instability of the increasing meridional temperature gradient cause the abrupt onset of monsoon rain. Our recent atmospheric GCM experiment points to unsteady atmospheric adjustments, such as the gradual moistening of the mid-troposphere, as the cause of the delayed and abrupt onset of the Northwest Pacific summer monsoon.

Convection of the Asian summer monsoon is organized into a few well-defined centers. Based on recent observations by the Tropical Rain Measuring Mission (TRMM) satellite's precipitation radar (PR), we showed that all the monsoon convection centers are anchored by narrow mountain ranges of South Asia (Xie et al. 2006), features poorly represented in GCMs. Not surprisingly, models almost always misplace summer convection centers in their simulations of the Asian summer monsoon.

Monsoon variability may be divided into two types: forced directly by ENSO or indirectly through the TIO capacitor effect, and internal arising from land-atmosphere-ocean interaction over the Indo-western Pacific sector. Much of the efforts since 1980s has been devoted to the ENSO-forced variability, which accounts for a small fraction of total variance over the monsoon region. I believe that an improved dynamical understanding of the monsoon in the context of seasonal cycle is necessary to advance monsoon research and prediction. Toward this goal, we are investigating the summer Meiyu-Baiu rain band, the single most important climate phenomenon for the hundreds of million people in China, Korea and Japan. We ask the fundamental questions of why the rain band takes place where and when it is observed. We are making progress taking advantage of uniform reanalysis, high-resolution satellite observations and models.

5. Climate Change

Observed climate anomalies increasingly contain human-induced change as well as natural variability. Sorting out the emerging patterns of climate change amid natural variability is a great scientific opportunity and challenge with benefits to climate predictability. For example, the secular warming trend appears to have emerged from the noise of natural variability over TIO. In fact, the La Nina's induced basin-wide cooling is no longer observed in unfiltered SST anomalies. We have developed a framework to assess climate feedback at the sea surface based on an ocean heat balance, to answer questions of why the TIO warming is particularly pronounced and robust. Preliminary results are promising, revealing the increased atmospheric stability and relative humidity at the sea surface as important factors for regulating SST warming (Du and Xie 2008). We are currently applying this framework over the global ocean, shedding light on the hydrological cycle paradox Isaac Held and Brian Soden highlighted: global precipitation increases much more slowly than tropospheric moisture in a warming climate.

The increasing accuracy and coverage of paleoclimate observations now offer constraints for developing meaningful theories for climate events of the past. The water-hosing experiment pioneered by Suki Manabe and colleagues is a wonderful example for studying Heinrich events and the Younger Dryas. Our analysis of hosing runs by several coupled GCMs shows robust and consistent spatial patterns among the models (Timmermann et al. 2007). Using experimental approach with GCMs, we identified the tropical North Atlantic cooling in the hosing run as the key conduit for global teleconnection. We used a high-resolution regional coupled model, the first for paleoclimate modeling, to study how North Atlantic cooling affects the tropical Pacific across Central America, a narrow isthmus poorly resolved in global GCMs

(Xie et al. 2008). The high-resolution regional model results have aided interpretation of sediment core data off the Columbia coast.

6. Extratropical air-sea interaction

In the extratropics, SST is generally not high enough for atmospheric deep convection, and the ocean's influence is often considered to be limited to the atmospheric boundary layer (ABL). Internal variability of the extratropical atmosphere is high, making it difficult to detect ocean influences there. On the basin scale, negative correlation dominates between SST and wind speed with the latter driving the former changes. From satellite, we detected ubiquitous positive correlation between SST and wind (high winds over warm SST) near major ocean fronts, indicative of an unambiguous ocean influence on the atmosphere, as reviewed in a *BAMS* cover article (Xie 2004). The exact mechanisms for this positive correlation are still under investigation but the rapid change in atmospheric stability and horizontal thermal advection across the fronts are considered important.

SST gradients of ocean fronts maintain zones of enhanced baroclinicity in the ABL, on which midlatitude storms grow. Our model simulations show that large-scale ocean fronts intensify individual storms and storm tracks (defined as the maximum of eddy variance; Inatsu et al. 2003). In a cover article in *Nature* this year, we showed that the Gulf Stream's heating extends to the upper troposphere, affecting the local rainfall, storm track and the downstream development of stationary Rossby waves (Minobe et al. 2008).

To better understand ocean front-atmosphere interaction, we participated in four cruises (two in summer and two in winter) to the Kuroshio Extension east of Japan and obtained a total of 600 vertical soundings of the atmosphere, as part of the NSF-funded Kuroshio Extension System Study (KESS) program involving several institutions in the US and Japan. The Kuroshio Extension front strongly modulates weather variations (Tokinaga et al. 2006); in summer, sea fog forms with southerly cross-frontal winds while stratocumulus with elevated cloud base is observed under northerly winds. Surface turbulent heat flux is suppressed under southerly but intensified under northerly winds blowing across the ocean front. How ocean fronts affect the deeper atmosphere over the region is of great interest to the Japanese research community, which is pursuing funding for major field campaigns.

7. Satellite discoveries

Since the 1990s, a suite of satellite-borne microwave sensors co-orbited around Earth, enabling simultaneous observations of quantities important for air-sea interaction such as sea surface height (SSH), SST, surface wind velocity, cloud water path, and precipitation. Over the vast ocean, traditional climate data are limited by sparse ship observations and resolve horizontal scales of 1000 km or coarser. Microwave satellite observations see through clouds and produce global datasets at 25 km resolution, bringing about a revolution in observing air-sea interactions with a flurry of discoveries of short-scale (<1000 km in either horizontal direction) ocean-atmospheric phenomena. We were among the first to recognize the potential of multi-sensor synthesis and fortunate enough to have contributed to this revolution. Our observations uncovered two classes of new phenomena, near ocean fronts and forced by coastal orography, respectively.

Our analysis revealed surprisingly far-reaching effects of Hawaii to the west of the islands (Xie et al. 2001). The orographic blockage of the northeast trades by Hawaiian mountains triggers ocean-atmosphere interaction sustaining what *Science* magazine called the longest

island wake of the world. Our recent synthesis of satellite data and regional model simulations reveals interesting orographic-induced lee-cloud features near the islands (Yang et al. 2008). We have studied other orographic-induced wind jets and their influence on ocean circulation, SST and atmospheric convection elsewhere in the South China Sea (Xie et al. 2003) and off Central America (Xie et al. 2005). We have followed up these satellite studies with high-resolution model simulations.

Ocean dynamical changes affect SST most strongly in upwelling regions or near major currents such as the Kuroshio and Gulf Stream. Synthesis of microwave sensors enabled us to observe how the atmosphere co-varies with meanders of ocean fronts associated with dynamical instabilities of ocean currents. Ubiquitously we found high winds over warm meanders of ocean fronts and vice versa, convincing evidence for an ocean influence on the atmosphere (Xie 2004). We reported such positive SST-wind correlations around the world, on the Pacific equatorial front, in the Somali Current, South China Sea upwelling filaments, the Kuroshio and its extension, Gulf Stream, and Brazil-Mavinas Currents.

We mapped the first climatology of high-wind occurrence over the global ocean from satellite, a product of applied values. Frequent high-wind occurrence is found near coastal orography and in the warm meanders of the Gulf Stream and Antarctic Circumpolar Current (Sampe and Xie 2007).

8. Ocean circulation

I did my graduate study in a physical oceanography lab, where the North Pacific mode water was a major research topic. Mode waters are pockets of weak stratification in the thermocline and appear as a potential vorticity (PV) minimum. Working then on modeling ENSO and the Madden-Julian Oscillation (MJO), I was nevertheless fascinated by such anomalous stratification in the ocean. Nearly 10 years later when a graduate student of mine at Hokkaido finished a 40-year ocean GCM hindcast with the then newly available NCEP reanalysis, we went to study mode water formation. Our analysis shows that three major mode waters of the North Pacific each form by a different mechanism (Xie et al. 2000). The subtropical mode water, of the strongest PV signature among the three, forms where the southeastward geostrophic current intersects a mixed layer depth front south of the Kuroshio Extension. Traditional water mass analysis treats mode waters as a diagnostic tracer but our studies help cast them in a more dynamical role. For example, our hindcast shows that the lateral shifts of low-PV mode waters in response to wind changes are an important mechanism for subsurface temperature variability.

Our analysis of hydrographical observations shows that the horizontal overlapping of mode waters of different densities pushes up pycnoclines in the upper thermocline and creates a family of eastward subtropical countercurrents in the southern part ($\sim 25^{\circ}\text{N}$) of the North Pacific subtropical gyre where the Sverdrup theory predicts westward flow (Kobashi et al. 2006). This result supports a PV theory of Atsushi Kubokawa of Hokkaido University. Our recent satellite study reveals that the signature of mode waters extends into the atmosphere: a rain band forms along the subtropical countercurrent, with cyclonic wind curls at the surface.

Our ocean GCM hindcast showed that the Kuroshio Extension is where subsurface changes affect strongly SST variability in the deep winter mixed layer (Xie et al. 2000). We have extended this work recently by analyzing a multi-decadal, eddy-resolving hindcast with the Ocean GCM for the Earth Simulator (OFES). The simulated variability of the Kuroshio Extension (position and intensify changes) agrees remarkably well with both satellite altimeter

and XBT observations (Taguchi et al. 2007). This is the first time that slow variability of ocean inertial jets like the Kuroshio Extension has been shown to be controlled by basin-scale wind changes. A puzzle remains: while the temporal variations are determined by winds, dynamical mechanisms remain unknown for transforming broad-scale, wind-forced Rossby waves into meridionally narrow jet structures.

9. Reviews

I co-edited an AGU book on ocean-atmosphere interaction and its role in climate (Wang et al. 2004). I was part of an international CLIVAR team surveying the work on the role of tropical oceans in climate (Chang et al. 2006). I published several other review articles on a number of topics: ocean front-atmosphere interaction (Xie 2004); the history and modern advance of ITCZ research (Xie 2005); tropical Atlantic variability (Xie and Carton 2004); and tropical Indian Ocean variability (Schott et al. 2008).

Selected publications (available at http://iprc.soest.hawaii.edu/~xie/pub_list.html)

- Chang, P., T. Yamagata, P. Schopf, S. K. Behera, J.A. Carton, W. S. Kessler, G. Meyers, T. Qu, F.A. Schott, S. Shetye, and S.-P. Xie, 2006: Climate fluctuations of tropical coupled system—The role of ocean dynamics. *J. Climate*, **19**, 5122–5174.
- de Szoeké, S.P., and S.-P. Xie, 2008: The tropical eastern Pacific seasonal cycle: Assessment of errors and mechanisms in IPCC AR4 coupled ocean-atmosphere general circulation models. *J. Climate*, **21**, 2573–2590.
- Du, Y., and S.-P. Xie, 2008: Role of atmospheric adjustments in the tropical Indian Ocean warming during the 20th century in climate models. *Geophys. Res. Lett.*, **35**, L08712, doi:10.1029/2008GL033631.
- Inatsu, M., H. Mukougawa, and S.-P. Xie, 2003: Atmospheric response to zonal variations in mid-latitude SST: Transient and stationary eddies and their feedback. *J. Climate*, **16**, 3314–3329.
- Kobashi, F., H. Mitsudera and S.-P. Xie, 2006: Three subtropical fronts in the North Pacific: Observational evidence for mode water-induced subsurface frontogenesis. *J. Geophys. Res.-Oceans*, **111**, C09033, doi: 10.1029/2006JC003479.
- Minobe, S., A. Kuwano-Yoshida, N. Komori, S.-P. Xie, and R.J. Small, 2008: Influence of the Gulf Stream on the troposphere. *Nature*, **452**, 206–209.
- Richter, I. and S.-P. Xie, 2008: On the origin of equatorial Atlantic biases in coupled general circulation models. *Clim. Dyn.*, doi:10.1007/s00382-008-0364-z.
- Sampe, T., and S.-P. Xie, 2007: Mapping high sea winds from space: A global climatology. *Bull. Amer. Meteor. Soc.*, **88**, 1965–1978.
- Schott, F.A., S.-P. Xie, and J.P. McCreary, 2008: Indian Ocean circulation and climate variability. *Rev. Geophys.*, in press, doi:10.1029/2007RG000245.
- Taguchi, B., S.-P. Xie, N. Schneider, M. Nonaka, H. Sasaki, and Y. Sasai, 2007: Decadal variability of the Kuroshio Extension: Observations and an eddy-resolving model hindcast. *J. Climate*, **20**, 2357–2377.
- Timmermann, A., Y. Okumura, S.-I. An, A. Clement, B. Dong, E. Guilyardi, A. Hu, J. Jungclaus, U. Krebs, M. Renold, T.F. Stocker, R.J. Stouffer, R. Sutton, S.-P. Xie, J. Yin, 2007: The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *J. Climate*, **20**, 4899–4919.
- Tokinaga, H., Y. Tanimoto, M. Nonaka, B. Taguchi, T. Fukamachi, S.-P. Xie, H. Nakamura, T. Watanabe, and I. Yasuda, 2006: Atmospheric sounding over the winter Kuroshio Extension: Effect of surface stability on atmospheric boundary layer structure. *Geophys. Res. Lett.*, **33**, L04703, doi:10.1029/2005GL025102.
- Wang, C., S.-P. Xie, and J. A. Carton (eds.), 2004: *Earth Climate: The Ocean-Atmosphere Interaction*. Geophys. Monograph, **147**, pp. 414, AGU, Washington, D.C.
- Xie, S.-P., 1994: On the genesis of the equatorial annual cycle. *J. Climate*, **7**, 2008–2013.
- Xie, S.-P. and S.G.H. Philander, 1994: A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340–350.

- Xie, S.-P. and Y. Tanimoto, 1998: A pan-Atlantic decadal climate oscillation. *Geophys. Res. Lett.*, **25**, 2185-2188.
- Xie, S.-P., 1999: A dynamic ocean-atmosphere model of the tropical Atlantic decadal variability. *J. Climate*, **12**, 64-70.
- Xie, S.-P. and N. Saiki, 1999: Abrupt onset and slow seasonal evolution of summer monsoon in an idealized GCM simulation. *J. Meteor. Soc. Japan*, **77**, 949-968.
- Xie, S.-P., T. Kunitani, A. Kubokawa, M. Nonaka and S. Hosoda, 2000: Interdecadal thermocline variability in the North Pacific for 1958-1997: A GCM simulation. *J. Phys. Oceanogr.*, **30**, 2798-2813.
- Xie, S.-P., W.T. Liu, Q. Liu and M. Nonaka, 2001: Far-reaching effects of the Hawaiian Islands on the Pacific Ocean-atmosphere system. *Science*, **292**, 2057-2060.
- Xie, S.-P., H. Annamalai, F.A. Schott and J.P. McCreary, 2002: Structure and mechanisms of South Indian Ocean climate variability. *J. Climate*, **15**, 864-878.
- Xie, S.-P., Q. Xie, D.X. Wang and W.T. Liu, 2003: Summer upwelling in the South China Sea and its role in regional climate variations. *J. Geophys. Res.-Oceans*, **108**, 3261, doi: 10.1029/2003JC001867.
- Xie, S.-P., 2004: Satellite observations of cool ocean-atmosphere interaction. *Bull. Amer. Meteor. Soc.*, **85**, 195-208.
- Xie, S.-P. and J.A. Carton, 2004: Tropical Atlantic variability: Patterns, mechanisms, and impacts. In *Earth Climate: The Ocean-Atmosphere Interaction*, C. Wang, S.-P. Xie, and J.A. Carton (eds.), Geophys. Monograph, **147**, AGU, Washington D.C., 121-142. (http://iprc.soest.hawaii.edu/~xie/Xie_Carton.pdf)
- Xie, S.-P., 2005: The shape of continents, air-sea interaction, and the rising branch of the Hadley circulation. In *The Hadley Circulation: Past, Present and Future*, H. F. Diaz and R. S. Bradley (eds.), Kluwer Academic Publishers, Dordrecht, 121-152. (<http://iprc.soest.hawaii.edu/~xie/hadley4camera.pdf>)
- Xie, S.-P., H. Xu, W.S. Kessler, and M. Nonaka, 2005: Air-sea interaction over the eastern Pacific warm pool: Gap winds, thermocline dome, and atmospheric convection. *J. Climate*, **18**, 5-25.
- Xie, S.-P., H. Xu, N.H. Saji, Y. Wang, and W.T. Liu, 2006: Role of narrow mountains in large-scale organization of Asian monsoon convection. *J. Climate*, **19**, 3420-3429.
- Xie, S.-P., T. Miyama, Y. Wang, H. Xu, S.P. de Szoeke, R.J. Small, K.J. Richards, T. Mochizuki, and T. Awaji, 2007: A regional ocean-atmosphere model for eastern Pacific climate: Towards reducing tropical biases. *J. Climate*, **20**, 1504-1522.
- Xie, S.-P., Y. Okumura, T. Miyama, and A. Timmermann, 2008: Influences of Atlantic climate change on the tropical Pacific via the Central American Isthmus. *J. Climate*, in press.
- Xie, S.-P., K. Hu, J. Hafner, Y. Du, G. Huang, and H. Tokinaga, 2009: Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Nino. *J. Climate*, submitted.
- Yang, Y., S.-P. Xie, and J. Hafner, 2008: Cloud patterns lee of Hawaii Island: A synthesis of satellite observations and numerical simulation. *J. Geophys. Res.-Atmos.*, in press, doi:10.1029/2008JD009889.