# 30. OCEANIC PROCESSES INFLUENCING SST IN REGIONS RELATED TO THE ASIAN-AUSTRALIAN MONSOON SYSTEM

BO QIU
*Department of Oceanography, University of Hawaii*
*Hawaii, USA*
*E-mail: bo@soest.hawaii.edu*

YUKIO MASUMOTO
*Japan Agency for Marine-Earth Science and Technology*
*Yokohama, Japan*
*E-mail: masumoto@jamstec.go.jp*

Variability associated with the Asian-Australian monsoon system has been recognized in recent years as resulting from air-sea coupled processes. This points to the importance of ocean dynamics that controls the time-varying sea surface temperature (SST) signals. Aside from the surface heat flux forcing, many oceanic processes can produce changes in SST in the Asian-Australian monsoon regions: lateral advection by oceanic mean/eddy flows, enhanced tidal mixing in shallow seas, variability in the thermocline depth induced either locally or remotely (via wave-guides) in the Pacific and Indian Oceans, wind-induced coastal upwelling, and salinity stratification related to the monsoonal rainfall and river runoff. This article reviews some of these oceanic processes on the basis of our understanding achieved in recent years.

## 1. Introduction

The tropical western Pacific and eastern Indian Oceans (Fig. 1) are regions under direct monsoonal wind forcing of the Maritime Continent. In these regions, sea surface temperatures (SSTs) are highest within the global oceans and changes in the SST are relatively weak (Fig. 2). Despite their small amplitudes, the subtle SST variations have been found to result in significant changes in the vigour of the monsoon and the weather patterns across the Indo-Pacific basin (e.g., Ashok *et al.* 2001; Neale and Slingo 2003; McBride *et al.* 2003). Indeed, as noted recently by Webster (2006), there is a paradigm shift in viewing the monsoon as being driven simply by land-ocean heating differences, to an appreciation that ocean dynamics are important, and, more recently, to the realization that the monsoon is a thoroughly air-sea coupled system.

## 2. Western Pacific Ocean

In the western tropical Pacific, important oceanic pathways from subtropics to tropics involve low-latitude western boundary currents (WBCs). The physics of these WBCs is extremely complex, and present climate model resolutions are commonly too coarse, and

The Global Monsoon System: Research and Forecast (2nd Edition)
edited by Chih-Pei Chang et al.

parameterizations too crude, to give confidence in the results of numerical experiments involving advection and mixing in this region. For a better understanding of the long-term changes in the western tropical Pacific and its roles in controlling the regional surface ocean heat budget, it is crucial to obtain accurate analyses of the cross-gyre exchanges that occur in the region. Specifically, the North Equatorial Current (NEC) encounters the Philippine coast and splits into the Kuroshio and the Mindanao Current (e.g., Toole *et al.* 1990; see Fig. 1 and Fig. 3). Part of the equatorward-flowing Mindanao Current transport contributes to the Indonesian Throughflow (ITF), bringing northern hemisphere-origin water, commonly fresh in salinity, into the Indonesian Seas and the eastern Indian Ocean. The bifurcation of the NEC and partitioning of the Mindanao Current is affected by remote forcing from the interior of the Pacific, from the north along the western boundary, and by local monsoonal wind and buoyancy forcing (Qiu and Lukas 1996; Kim *et al.* 2004). Being a low-latitude WBC, the Mindanao Current variability is also directly impacted by the presence of the Mindanao Dome, whose changes are in part induced by the intrinsic, nonlinear ocean dynamics (Masumoto and Yamagata 1991; Tozuka *et al.* 2002).

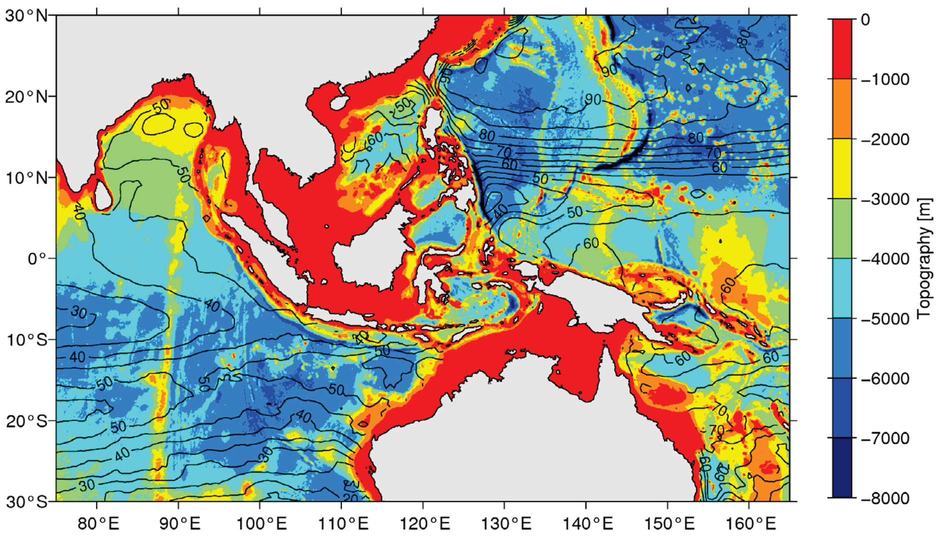


Figure 1. Regions of the western Pacific and eastern Indian Oceans under the influence of the Asian-Australian monsoons. Colored map shows the bathymetry based on Smith and Sandwell (1994) and black contours show the mean surface dynamic height (in cm) derived by Niiler *et al.* (2003).

A similar situation also exists in the tropical South Pacific where the westward-flowing South Equatorial Current splits upon reaching the Australian coast, into the northward-flowing North Queensland Current (NQC) and southward-flowing East Australian Current (Holbrook and Bindoff 1999; Kessler and Gourdeau 2007). The NQC connects to the New Guinea Coastal Current system which contributes ultimately to the water mass characteristics of the Pacific equatorial current systems and the ITF (e.g., Tsuchiya *et al.* 1989; Fukumori *et al.* 2004; Inoue and Welsh 1993; Talley and Sprintall 2005). The South Pacific circulation is

more directly connected to the Equator than the North Pacific circulation and its changes have been argued to influence and modulate the equatorial background state upon which El Niño-Southern Oscillation (ENSO) evolves (Tsuchiya *et al.* 1989; Goodman *et al.* 2005). As noted in other articles of this publication, changes in the ENSO phase can indirectly impact the Asian-Australian monsoon system.

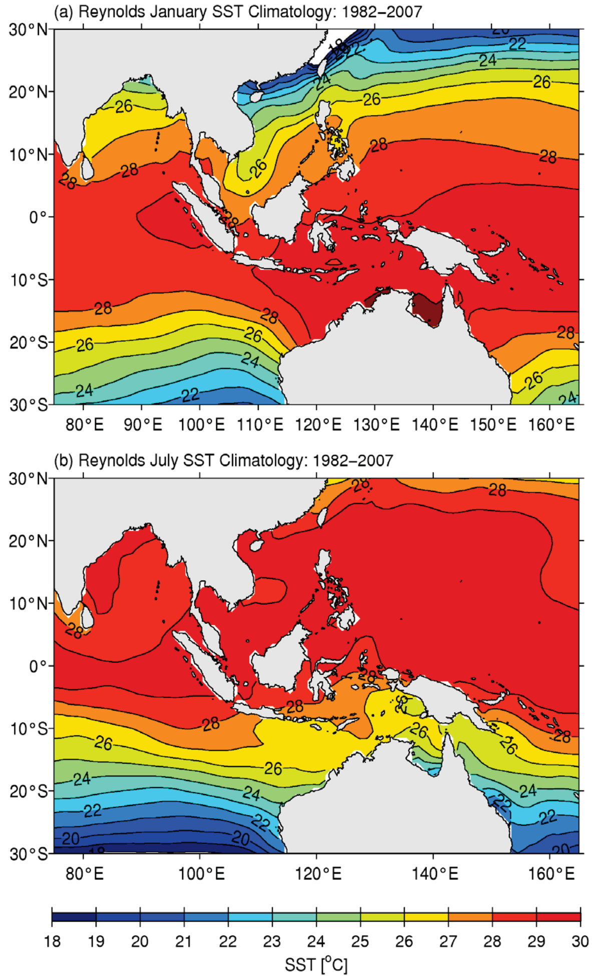


Figure 2. Climatological sea surface temperature distributions in (a) January, and (b) July. (based on Reynolds *et al.* 2002).

Compared to its counterpart in the northern hemisphere, ocean circulation in the tropical South Pacific is heavily affected by the complex regional topography. Presence of the Fiji Plateau, the Vanuatu and New Caledonia Archipelagos, the Solomon Island Chain, the Vitiaz and Solomon Straits and the St. Georges Channel induces narrow boundary currents and jets, providing an energy source for eddy-mean flow interaction, lateral mixing and water mass transformation (Webb 2000; Stanton *et al.* 2001; Gourdeau *et al.* 2008; Qiu *et al.* 2009). At

present, a multi-national program named "SPICE" (Southwest Pacific Ocean Circulation and Climate Experiment; Ganachaud *et al.* 2007) is underway under the auspices of the International Climate Variability and Predictability (CLIVAR) Pacific Panel. As the SPICE program covers both the oceanic and atmospheric (specifically, the South Pacific Convergence Zone) variability in the southwest Pacific region, the results from SPICE will likely contribute significantly to the scientific goals of Asian Monsoon Years (AMY) and Asian-Australian Monsoon Panel (AAMP).

The hydrological cycle in the tropical western Pacific and eastern Indian Oceans is characterized by intense convective precipitation. In these regions, high precipitation leads to salinity-stratified barrier layers, where the surface isohaline layer becomes shallower than the isotherm layer (Lukas and Lindstrom 1991; Sprintall and Tomczak 1992). Salinity stratification is important in such a case because it controls the development of the surface ocean mixed layer (e.g., the wind-induced kinetic energy tends to be trapped within a thin mixed layer and the entrainment cooling is commonly reduced when a barrier layer is present) and dictates the amount of oceanic heat available for the overlying atmosphere. The surface freshwater fluxes in the western Pacific and eastern Indian Oceans undergo substantial variations on seasonal and interannual timescales associated with ENSO and regional monsoon systems. Changes in the freshwater fluxes, as well as fluctuations in oceanic advection, result in an observed sea surface salinity variation with a standard deviation of 0.4~1.4 psu in the western tropical Pacific (Delcroix *et al.* 2005). What remains unclear is how this low-frequency change in sea surface salinity affects the regional mixed layer evolution and, ultimately, impacts the SST signals, upon which the atmospheric deep convection and heavy rainfall are sensitive.

A part of the convergent Mindanao and New Guinea western boundary currents in the western Pacific feeds the ITF westward through the Indonesian Seas, entering the eastern Indian Ocean between Australia and the Indonesian Archipelagos. Despite its significance to the regional and global climate, the mass, heat, and freshwater transports of the ITF are still poorly known, and their variability is high, albeit based on limited observations (Gordon 2005). Coupled and uncoupled general circulation model (GCM) studies, with the Indonesian Archipelagos open vs. closed, have indicated that the ITF affects both the Indian Ocean SST patterns and the Asian-Australian monsoon system (e.g., Wajsowicz 2002; Jochum and Potemra 2008). The ITF may also be involved in ENSO and Indian Ocean dipole (IOD) mode evolution, as they affect the variability of the heat budget of the western tropical Pacific and the eastern Indian Oceans on climate time scales. At present, a concerted, multi-national, *in situ* measurement program called “INSTANT” (International Nusantara Stratification and Transport) has just been completed (Gordon 2005) and the observational results are being quantified to clarify how regional SST changes are related to the oceanic advection, eddy mixing, and surface wind and buoyancy forcing.

A potentially important process that influences SST in the Maritime Continent is the South China Sea Throughflow (SCSTF), which involves inflow of cold, salty water through the Luzon Strait and outflow of warm, fresh water through other straits along the South China Sea (Qu *et al.* 2006). Preliminary model experiments also suggest that the SCSTF can reduce

the ITF heat transport by as much as 47% (Tozuka *et al.* 2007), thus having a potential impact on heat distribution in the Maritime Continent and its adjoining tropical Indian and Pacific Oceans.

## 3. Eastern Indian Ocean

In the Indian Ocean, the warm water pool is located in the eastern half of the basin (Fig. 2). Most of the SST variability in this region is more or less affected by atmosphere-ocean interactions, in which the Asian-Australian monsoons play important roles in developing energy and material fluxes between the two mediums and ocean circulation systems. Although the region is far apart from the western boundary current systems both in the Pacific and Indian Oceans, the currents in the eastern Indian Ocean are as complex as the western Pacific (Fig. 3), mainly due to the direct influences of such monsoonal wind forcing (see a comprehensive review by Schott and McCreary 2001; Schott *et al.* 2009; and references therein). The surface currents in the northern hemisphere including the Bay of Bengal are characterized by seasonally reversing monsoon currents, with northeastward (southwestward) flows during boreal summer (winter) (e.g., Cutler and Swallow 1984; Vinayachandran *et al.* 1999). Heat and mass transport responsible for the SST variability in this region are determined partly by the monsoon currents. While in the southern hemisphere, the ITF makes the circulation quite unique to this particular region (Tomczak and Godfrey 1994). The ITF brings warm western Pacific equatorial water masses into the southeastern Indian Ocean, thus creating a rather large meridional pressure gradient. This in turn drives eastward geostrophic currents south of the ITF latitude and they converge into the boundary area off western Australia to generate southward eastern boundary current known as the Leeuwin Current, which flows against the prevailing northward winds over the region (e.g., McCreary *et al.* 1986; Godfrey and Weaver 1991; Hirst and Godfrey 1993). Because of this unusual current system, the SST off the northwestern coast of Australia is warmer than those in similar locations in the different ocean basins, and strongly influences the Australian monsoon system.

Superimposed on these mean and seasonal circulations are strong eastward surface jets, often referred to as Wyrtki jets, along the equator twice a year during the monsoon transition seasons of April/May and October/November (Wyrtki 1973). This semiannual variability is associated with the thermocline variability via radiation of the equatorial Kelvin waves, which contribute to zonal mass and heat re-distribution within the equatorial band, thus affecting the SST variability (Han *et al.* 1999). Subsequent propagation of the Kelvin waves, along the coasts of Indonesia to the south and of Thailand and countries further north in the Bay of Bengal, produce upper-layer heat content anomalies in areas remote from the equatorial forcing region (Yu *et al.* 1991; Potemra *et al.* 1991). One interesting example can be found in a relatively small region off the southwestern coast of India, known as Laccadive High (Bruce *et al.* 1994), where the maximum SST develops during the boreal winter/spring associated with low salinity water intrusion from the Bay of Bengal, causing the barrier layer in the upper ocean to absorb more heat in the surface layer (Masson *et al.* 2005). It has been

shown by Masson *et al.* (2005) that such an SST anomaly, though small in magnitude, tends to create earlier onset of the Asian monsoon system.

The semiannual Kelvin waves associated with Wyrtki jets also propagate to the southeast along the southern coasts of Sumatra, Java, and the Lesser Sunda Islands (e.g., Clarke and Liu 1993; Yamagata *et al.* 1996). Part of this wave energy penetrates into the Indonesian Seas through the Lombok Strait, influencing the variability in the upper-layer conditions within the archipelago, and possibly affecting the SST (e.g., Sprintall *et al.* 2000; Ffield *et al.* 2000). In addition, recent observational and modeling studies reveal that the Kelvin wave propagation can also be seen on an intraseasonal time-scale, which is generated in the equatorial Indian Ocean by the atmospheric intraseasonal variations, including the Madden-Julian Oscillation (e.g., Qiu *et al.* 1999; Iskandar *et al.* 2005).

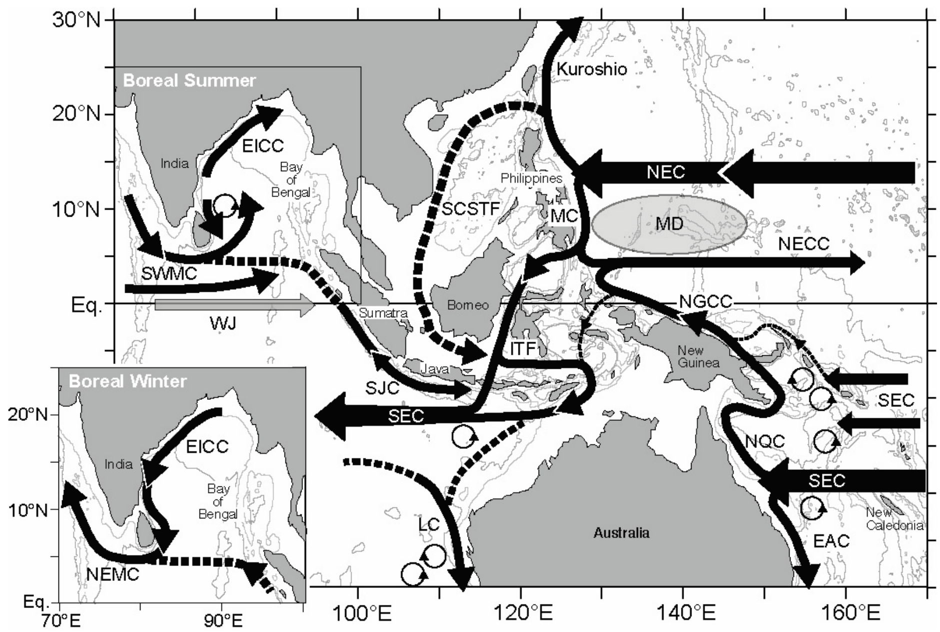


Figure 3. A schematic view of major surface current systems in the western tropical Pacific and eastern Indian Oceans, including those in the Maritime Continent. For the northern Indian Ocean, the currents in the boreal summer are indicated in the main figure, with a separate figure for the boreal winter currents. Current systems indicated by abbreviations are the North Equatorial Current (NEC), Mindanao Current (MC), North Equatorial Countercurrent (NECC), New Guinea Coastal Current (NGCC), South Equatorial Current (SEC), North Queensland Current (NQC), East Australian Current (EAC), Indonesian Throughflow (ITF), South China Sea Throughflow (SCSTF), South Java Current (SJC), Leeuwin Current (LC), East Indian Coastal Current (EICC), Southwest Monsoon Current (SWMC), and Northeast Monsoon Current (NEMC). Wyrtki jets (WJ) appear in April/May and September/October, while the Mindanao Dome (MD) develops during boreal winter.

Basin scale air-sea coupled climate modes in the tropics are another key phenomena directly affecting the SST variability in the Indian Ocean on interannual time-scales. With the standard statistical analyses to the SST variability, a basin-scale mono-pole structure is detected as the most dominant pattern of the interannual variability, which has strong

association with ENSO in the Pacific Ocean (e.g., Chambers *et al.* 1999; Lau and Nath 2003). In most cases the warming (cooling) of the Indian Ocean SST occurs a few months after the height of El Niño (La Niña) event in the tropical Pacific Ocean. Such SST variability generated mainly by atmospheric bridging over the Indo-Pacific sector causes an anomalous condition of Asian and Australian monsoons.

The IOD mode is another important phenomenon appearing over the eastern Indian Ocean warm pool region. IOD is normally characterized by anomalous cooling of SST in the southeastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean, and such conditions are often referred to as positive IOD events (Saji *et al.* 1999; Webster *et al.* 1999). Associated with these SST changes, the atmospheric convection that is normally situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over east Africa and severe droughts/forest fires over the Indonesian/Australian region. The name IOD represents the zonal dipole structures not only in the SST field but also in other various coupled ocean-atmosphere parameters such as outgoing longwave radiation (OLR) and sea surface height anomalies (e.g., Yamagata *et al.* 2002). The canonical positive IOD event starts around May with a small patch of the negative SST anomaly in the eastern tropical Indian Ocean along the southern coast of Sumatra and Java. Stronger than normal southeasterly surface wind anomaly is associated with these SST variations, and the easterly wind anomaly penetrates into the equatorial region, creating upwelling-favorable conditions in the upper ocean, thus developing the negative SST anomaly. The westward shift of the warm water region enhances the easterly winds along the equator, activating Bjerknes feedback mechanism over the Indian Ocean.

The negative IOD event, which is, in effect, the reversal of the positive IOD event, has the warmer SST, deeper thermocline, and stronger atmospheric convections over the eastern Indian Ocean. This negative event increases precipitation over Australia and Indonesia, while dryer conditions develop over the western Indian Ocean. It is thought that the IOD events provide interannual modulation to the background state that result in abnormal conditions in monsoon and other related variability (e.g., Ashok *et al.* 2001, 2004; Guan *et al.* 2003).

The tropical Southwest Indian Ocean (SWIO) has emerged recently as highly climatically relevant (e.g., Xie *et al.* 2002). Along the thermocline ridge in SWIO, ocean dynamics is shown to be important for interannual SST anomalies, which in turn affect local atmospheric convection, tropical cyclones, and the onset of the Indian summer monsoon. More recently, Du *et al.* (2009) show that the dynamically-induced SWIO warming induces a basin-wide wind pattern and helps prolong the basin-wide warming via wind-induced latent heat flux. The long-lasting basin-wide warming of the tropical Indian Ocean is not merely a passive response to El Niño but exerts marked influences on the summer monsoons over the Northwest Pacific and East Asia (Xie *et al.* 2009).

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