Review on observational studies of western tropical Pacific Ocean circulation and climate*

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Abstract

The Western Tropical Pacific Ocean (WTP) holds the largest area of warm water (>28℃) in the world ocean referred to as the Western Pacific Warm Pool (WPWP), which modulates the regional and global climate through strong atmospheric convection and its variability. The WTP is unique in terms of its complex 3-D ocean circulation system and intensive multiscale variability, making it crucial in the water and energy cycle of the global ocean. Great advances have been made in understanding the complexity of the WTP ocean circulation and associated climate impact by the international scientific community since the 1960s through field experiments. In this study we review the evolving insight to the 3-D structure and multi-scale variability of the ocean circulation in the WTP and their climatic impacts based on *in-situ* ocean observations in the past decades,

with emphasis on the achievements since 2000. The challenges and open questions remaining are reviewed as well as future plan for international study of the WTP ocean circulation and climate.
Keyword: western tropical Pacific, ocean circulation, climate, observation

1. Introduction

The Western Tropical Pacific (WTP) Ocean (23.5ºN -23.5ºS, 120ºE-160ºW), with surface temperature higher than 28℃, contains the largest area of warm water in the global ocean, namely the western Pacific warm pool (WPWP) fueling atmospheric convection and influencing tropical and global climate (Fig. 1; De Deckker, 2016). The WTP is the convergence region of currents from the North and South Pacific, forming the 'crossroads' of water masses (Fine et al., 1994; Lukas et al., 1996; Hu et al., 2015). The ocean circulation there is characterized as the origin and fate of several major tropical ocean currents in the WTP in the near-surface layer, including the North/South Equatorial Current (NEC/SEC) and New Guinea Coastal Current (NGCC), the Kuroshio (KC), the Mindanao Current (MC), the North Equatorial Countercurrent (NECC), and the Indonesian Throughflow (ITF), as well as a complicated subsurface current system beneath the upper ocean such as the Mindanao Undercurrent (MUC), Luzon Undercurrent (LUC), North Equatorial Undercurrent (NEUC), New Guinea Coastal Undercurrent (NGCUC), Gulf of Papua Current (SPICE Community, 2012), North Equatorial Subsurface Current (NESC), and the North and South Subsurface Countercurrents (Fig. 2; e.g., Wyrtki, 1961; Nitani, 1972; Tsuchiya, 1975; Church and Boland, 1983; Gordon, 1986; Hu and Cui, 1989; Hu et al., 1991, 2015; Qu et al., 1998; Wang et al., 1998, 2016b; Rowe et al., 2000; Yuan et al., 2014). The complex ocean circulation system and intensive multiscale air-sea interactions in the WTP make it unique and crucial in the multi-scale variability of the ocean environment, water mass exchanges, nutrient transports and climatic events.

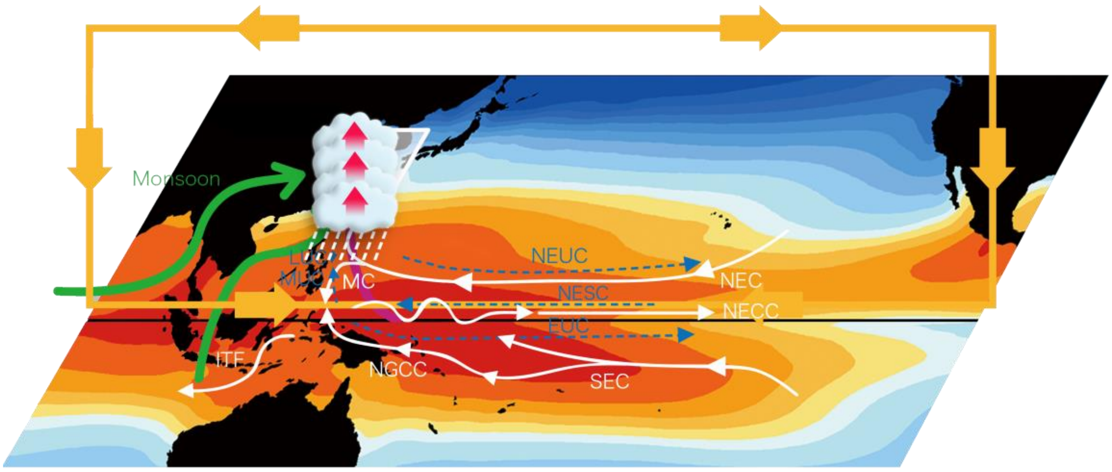

Figure 1. The Western Pacific warm pool and its climate impact (from Hu et al., 2011)

The WTP is central to the strongest signal in the interannual variation of the ocean-atmosphere system, namely the El Niño Southern Oscillation (ENSO). The zonal transport of seawater by ocean currents in the WTP plays a key role in shaping the air-sea feedback cycles governing ENSO (Picaut et al., 1997; An et al., 1999; Jin and An, 1999). Additionally, the meridional transport by geostrophic currents within the WTP is suggested to be a precursor for the long-lived El Niño-like pattern of Pacific climate variability, the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Zhang et al., 1997; Liu, 2012; Zhou et al., 2018). The air-sea interaction over the WTP is believed to have significant influence on intra-seasonal oscillations such as the westerly wind burst (WWB) and Madden-Julian Oscillation (MJO) by modulating the upper tropospheric humidity (Madden and Julian, 1994; Soden and Fu, 1995; Harrison and Vecchi, 1997; Seiki and Takayabu, 2007), and also influences the occurrence and development of tropical storms due to their close connection with equatorial waves, the MJO, and ENSO (Chan, 1985; Sobel and Maloney, 2000).

Observations are fundamental to advance our understanding of the ocean state and to identify key dynamics controlling the multi-scale variability, as well as to validate and improve model capacity in simulating oceanic processes crucial to the air-sea interaction and multi-scale variability. Great advances have been made over the past decades in our understanding of the structure and variability of ocean circulation and their interactions with the atmosphere in the WTP based on *in-situ* and remote sensing observations. In this paper, we review the progresses and achievements based on *in-situ* ocean observations in the WTP since the 1960s, with emphasis on those since 2000. The challenges remaining and future plans that target these gaps through international ocean observations and climate programs that contribute towards the themes of OceanObs'29 and the United Nations Decade of Ocean Science for Sustainable Development are also discussed.

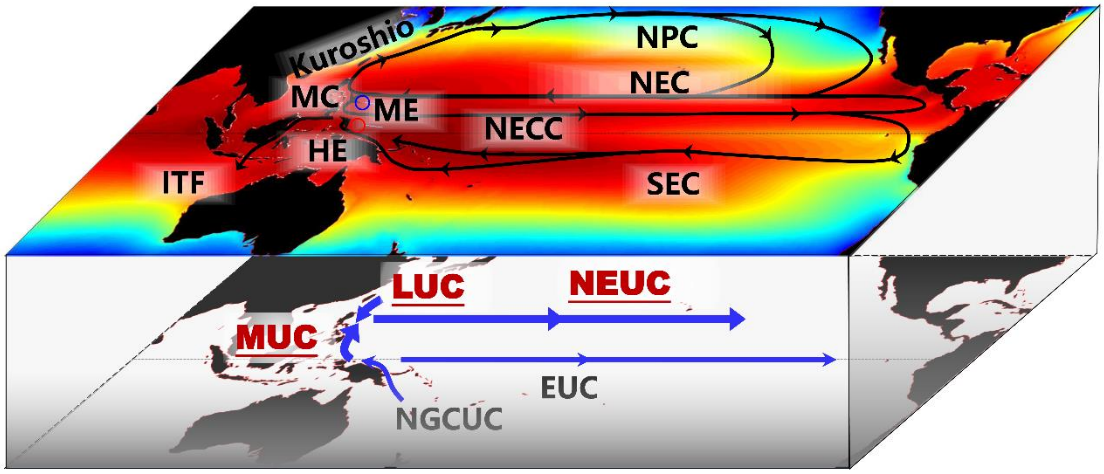

Figure 2. Sketch indicating surface and subsurface currents in the western tropical Pacific. North/South Equatorial Current (NEC/SEC), New Guinea Coastal Current (NGCC), Mindanao Current (MC), North Equatorial Countercurrent (NECC), Indonesian Throughflow (ITF), Mindanao Eddy (ME), Halmahera Eddy (HE), North Pacific Current (NPC), Mindanao Undercurrent (MUC), Luzon Undercurrent (LUC), North Equatorial Undercurrent (NEUC), New Guinea Coastal Undercurrent (NGCUC), and Equatorial Undercurrent (EUC).

2. Brief history of western Pacific Ocean circulation and climate investigation since 1960s

2.1 Cooperative Study of the Kuroshio and Adjacent Regions (CSK)

The international program Cooperative Study of the Kuroshio and Adjacent Regions (CSK) was launched between 1965-1979 under the auspices of the International Oceanographic Commission of UNESCO and the Indo-Pacific Fisheries Council of FAO (Food and Agriculture Organization). This program was first approved by a regional meeting in Manila, and incorporated participants from China, Japan, Korea, Philippines, Singapore, Thailand, the USA, the UK, the USSR, and Vietnam. This was the first large-scale field investigation program in the northwestern Pacific, covering the area east of Asia from the coast to 160ºE and from 4º S to 47ºN. During the CSK, the main ocean currents, such as the NEC, KC, MC and NECC, were studied (e.g., Masuzawa, 1968, 1969; Tsuchiya, 1968; Nitani, 1972; Stommel and Yoshida, 1972). Some essential research results were achieved. For example, Nitani (1972) applied Munk (1950) theory on the wind-driven circulation to the western Pacific and estimated the volume transports of the NEC, NECC, MC, and KC to be 55, 40, 25, and 30 Sverdrup (Sv: 10^6 m^3/s), respectively. The existence of the eastward flowing Subtropical Countercurrent (STCC) was first predicted by Yoshida and Kidokoro (1967) based on the calculation of the Sverdrup transport from the wind stress data, and then was confirmed by Uda and Hasunuma (1969) from direct current meter observations and geostrophic calculations.

As a part of CSK, the meridional 137ºE repeat hydrography section over 1ºS-34ºN was initiated in 1967 under the leadership of Dr. Jotaro Masuzawa. This section has been repeated by the Japan Meteorological Agency (JMA) biannually in winter since 1967 and in summer since 1972, for the past 50 years to date (see https://www.data.jma.go.jp/gmd/kaiyou/db/mar_env/results/OI/137E_OI_e.html). These data including conductivity-temperature-depth casts and water samples have been widely used to study seasonal to decadal and even longer-term changes of currents and water masses (e.g., Qiu and Joyce, 1992; Nan et al., 2015), biogeochemical (Akiyama, 1968) and biological properties (Kawarada et al., 1968), and marine pollution (Suzuoki and Shirakawa, 1979), and their connections with climate variability such as ENSO and PDO (e.g., Oka et al., 2018). Furthermore, the significant development of other observing platforms over the recent decades along the 137ºE section, such as satellites, Argo floats, and moorings, has enabled more study opportunities and enriched the scientific value of this section. The continuous extension (maintenance) of this section will contribute more to the study of variability on decadal and longer time scales (Oka et al., 2018). It is worth noting that the JMA also carried out other repeat hydrographic sections, including 147ºE and 165ºE sections (1987-present, over 5ºS-50ºN) (Kawabe and Taira, 1998; Sasano et al., 2015).

2.2 TOGA-WOCE Period

The Tropical Ocean and Global Atmosphere (TOGA: 1985-1994) was the first project under the World Climate Research Programme (WCRP). The failure to predict the 1982/83 El Niño resulted in the birth of TOGA in order to reveal the dynamical process of air–sea interaction in the equatorial Pacific Ocean related to El Niño event. Several projects associated with TOGA are worth mentioning. The first is the PRC/USA (People's Republic of China/United States of America) Program on Cooperative Investigation in the Equatorial Western Pacific Ocean, which was designed and initiated in early 1982 by a group (J. Fletcher, D. Halpern, D. Hu, and J. Huang) in Seattle, US, and co-chaired by J. Chao (PRC side) and B. Taft (USA side) (1985-1991). The second is the Chinese Academy of Sciences (CAS) Multi-Institutional Joint Program on Air-Sea Interaction in the Tropical Western Pacific Ocean initiated by C. Fu and D. Hu in 1983 and chaired by X. Zhou et al. (1986-1991). The third is the international Western Equatorial Pacific Ocean Circulation Study (WEPOCS) chaired by E. Lindstrom and R. Lukas (1985-1988). The fourth is the TOGA-COARE (Coupled Ocean-Atmosphere Response Experiment) chaired by R. Lukas and P. Webster (1992-1993). An especially important component of the TOGA-COARE field experiment was the IFA (Intensive Flux Array, at 156°E, 2°S) in the center of the warm pool. Among others, there were three Chinese Research Vessels (RVs) that participated in this work: RV Science-I, RV Practice III, and RV Xiangyanghong-V covering the IFA. At the end of the meeting held in Townsville, Australia, Dr. David Carlson, the director of the TOGA-COARE Operation Center, said that there would be no TOGA-COARE without China. The fifth project is the Japanese Cloud-Climate Study chaired by S. Asano (JACCS, 1991-2000). The implementation of JACCS advanced the application of satellite data to the cloud-climate study and led to better parameterizations of cloud and radiation processes used in general circulation models. Overall, the significant results of TOGA include: 1. The enormous amount of air-sea data collected that vastly increased our understanding of the role of the WPWP in global climate; 2. Discovery of a number of previously unknown subsurface countercurrents such as GBRUC, NGCUC, MUC, LUC, NEUC, and New Ireland Coastal Undercurrent (Church and Boland, 1983; Lindstrom et al., 1987; Hu and Cui, 1989; Hu et al., 1991; Butt and Lindstrom, 1994; Qu et al., 1998; Wang et al., 1998); 3. The predictive capability from the TAO/TRITON (Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network) moored array led to fundamental progress in our understanding of the physical processes responsible for ENSO, to the development of coupled ocean-atmosphere models for ENSO prediction (e.g. Hayes et al., 1991; McPhaden et al., 1998; Ando et al., 2017).

The World Ocean Circulation Experiment (WOCE: 1990-2002) was also a very important project of the WCRP, with the aim to obtain biological, chemical and physical data from the sea surface to the bottom of the global ocean, which were then used to validate and improve ocean models. Based on the resources and the collective effort from nearly 30 countries, WOCE acquired a tremendous and unprecedented in-situ data set of the global ocean during 1990-1998, more than all the data collected throughout history prior to that time, which have been essential for understanding the physical processes of the global ocean and facilitating the development of the global eddy-resolving ocean circulation models.

In order to describe the "state of the oceans", the WOCE Hydrographic Programme (WHP) conducted a comprehensive global hydrographic survey of top-to-bottom physical and chemical properties with unprecedented scope and quality during the 1990s. In the WHP, one zonal section (P4 (10°N)) and six meridional sections (P8 (130°E), P9 (137°E), S3 (140°E)，P10 (149°E), P11 (155°E), P13 (165°E)) were investigated with one-time surveys, 8 sections (the trans-basin zonal sections PR1, PR2, PR3 and PR4 and the shorter sections PR21, PR22, PR23 and PR24, Talley, 2007) east of the Philippines were conducted with repeat surveys, and moored current meter arrays (PCM-1 and PCM-15) were deployed east of Taiwan Island (Sep.1994-May 1996; Johns et al., 2001) and in Vitiaz Strait (1992-1993; Murray et al., 1995), respectively. The PCM-1 array with 11 current meters on 8 moorings across the KC from the coast near the northern end of Taiwan (Lee et al., 2001; Johns et al., 2001) was the first attempt to directly measure the KC and revealed seasonal changes (Zhang et al., 2001, 2002). Vitiaz Strait acts as a choke point for NGCC/NGCUC that carries water equatorward along the northeastern coast of New Guinea. The PCM-15 array was designed to extend the spatial and temporal resolution of earlier measurements in the strait that established the existence and strength of NGCC/NGCUC (Murray et al., 1995).

It is worth noting that the WHP first core Working Group held its meeting in 1988 at Institute of Oceanology, Chinese Academy of Sciences (IOCAS) and accepted IOCAS' suggestions to set up some short hydrographical sections (PR21-24) covering the western boundary currents (WBC) east of the Philippines. Importantly, at that meeting the mooring array (PCM-3), to be deployed off Mindanao Island, was designed to understand the MC system near the Mindanao Trench. Unfortunately, PCM-3 was not actually implemented until 2010, when the Northwestern Pacific Ocean Circulation and Climate Experiment program (NPOCE) deployed the array and obtained more than 4 years of continuous time series of velocity between 0-5500m through the National Natural Science Foundation of China (NSFC) Major Project (PI: Dunxin Hu, 2009-2012). With the PCM-3 data some scientific achievements were gained, for example, the measurements verified the existence of the MUC, and revealed the strong multi-time scale variability from intraseasonal, seasonal and interannual time scales (e.g., Zhang et al., 2014; Hu et al., 2016, 2018; Ren et al., 2018).

The WOCE era drove a revolution in oceanographic exploration and built up the foundation for the global ocean observing system (Gould, 2003). During the WOCE period, a global perspective for the time-varying nature of the world ocean from the top to the bottom, was realized.

2.3 CLIVAR Period (SPICE/NPOCE)

In order to continue the study of ocean circulation and climate after TOGA and WOCE, the Climate Variability and Predictability Programme (CLIVAR) was launched in 1995 as a core project of the WCRP. With a particular focus on the tropical Pacific Ocean, the TAO array was deployed in 1995 as an upgraded observing system of TOGA. Together with the TRITON array proposed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in 1996, these arrays continued ocean observing in the region after TOGA ended, and was known collectively as TAO-TRITON (Hayes et al., 1991; Ando et al., 2017). This work played an essential role in ENSO prediction in recent decades. Over time, there was a continuous decrease of the moored array data and a significant decrease of renewed support and experience. This led to the recent development of the Tropical Pacific Observing System for 2020 project (TPOS-2020) initiated in 2014 to carry and explore further direction for maintaining international observations in the tropical Pacific Ocean (http://tpos2020.org/).

After TAO-TRITON there were relatively few major international process-oriented projects conducted in the western Pacific until the establishment of the Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) and NPOCE, both endorsed by CLIVAR.

The SPICE program (2008-2015), chaired by Alexandre Ganachaud, played a significant role in understanding the southwest Pacific Ocean circulation and its climate effect with participants from France, Australia, New Zealand, USA, the Japan and Fiji Islands. It started with a workshop on “the Southwest Pacific Ocean Circulation and its relation with climate” held near Cairns, Australia, in 2005, and was endorsed by CLIVAR in 2008. These efforts on both short-term process studies and *in situ* oceanic observation and modeling over 7 years led to a refined description of the Southwest Pacific Ocean circulation variability. Repeated glider sections, moorings deployments, high-density repeated XBT lines and hydrographic surveys formed invaluable observations (e.g. Davis et al., 2012; Gasparin et al., 2012; Germineaud et al., 2016; Ganachaud et al., 2017; Ridgway et al., 2018; Alberty et al., 2019; Anutaliya et al., 2019; Kessler et al., 2019a). Major achievements of SPICE include: 1) A more refined description of the various branches of the ocean circulation system, of their variability and connections, including the discovery of the deep extension of the North Caledonian Jet (NCJ) and Gulf of Papua Current (GPC); 2) An unprecedented description of the Solomon Sea, of the water mixing and enrichment, of the variability of inflows and outflows toward the equator (Ganachaud et al., 2017; Alberty et al., 2019); 3) A much refined description and understanding of the EAC (East Australian Current) extension, of the Tasman Front (TF) and of the currents around New Zealand, and of their interplay; 4) An observation that equatorward spice anomalies are strongly damped in the low-latitude western boundary current system (Ganachaud et al., 2014). The observed data collected during the SPICE was compiled at http://spice.legos.obs-mip.fr/, and the data is open to public according to the CLIVAR data policy.

The NPOCE program (2010-present) was designed through a number of formal and informal discussions through a series of workshops starting in 2004, and finally endorsed by CLIVAR in 2010 as a joint international program, chaired by Dunxin Hu with participation by 19 institutions from 8 countries, including China, USA, Australia, Japan, Korea, Philippines, Indonesia, and Germany. It was aimed at understanding the dynamics of the northwestern Pacific (NWP) Ocean circulation and its role in climate with special reference to warm pool formation and maintenance (Hu et al., 2011). The observed data collected during the NPOCE project can be found at http://npoce.org.cn/dateAcc.aspx, and the data is open to public according to the CLIVAR data policy.

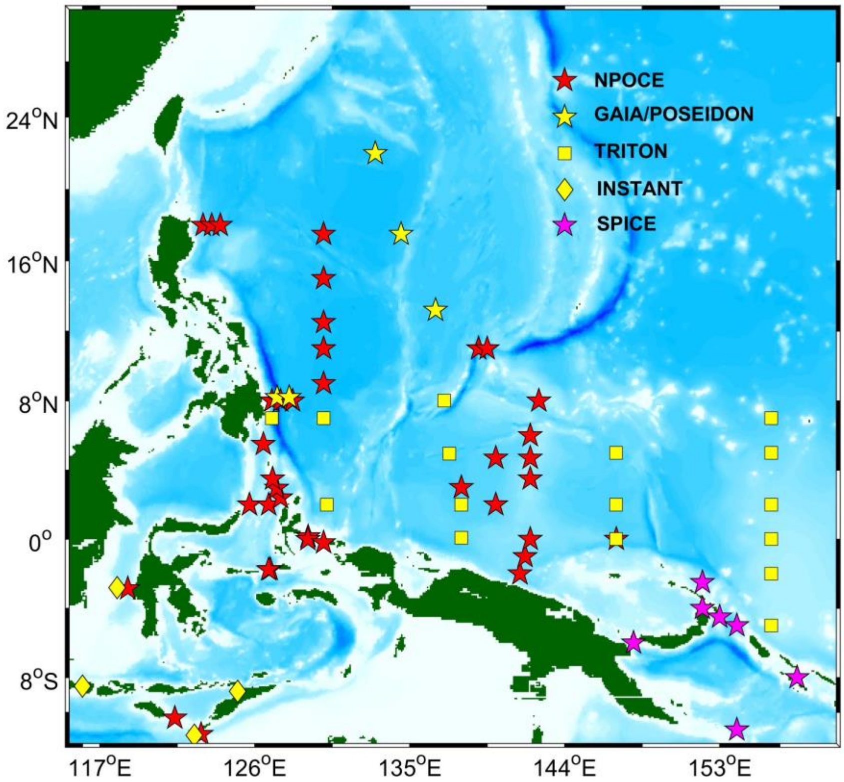

Figure 3. Mooring and buoy arrays during the NPOCE period. Red stars denote moorings deployed by IOCAS through NPOCE, yellow stars denote moorings deployed by KIOST through GAIA and Poseidon, yellow squares denote moorings and buoys deployed by JAMSTEC through TRITON, yellow diamonds denote moorings deployed through INSTANT, and purple stars denote moorings deployed through SPICE.

Since the inauguration of NPOCE, large-scale in-situ observations have been successfully carried out 9 times over the last ten years in the northwestern Pacific Ocean with forceful support from a number of Chinese national projects, such as two National Nature Science Foundation of China (NSFC) Major and Key Projects led by D. Hu (2009-2012; 2014-2018), four National Basic Research Program of China (973 Program) led by L. Wu (2007-2011), F. Wang (2012-2016), D. Yuan (2012-2016), and D. Chen (2013-2017), and Strategic Priority Research Program of Chinese Academy of Sciences (S. Sun, 2013-2017). Moreover, projects from NPOCE involved various countries provide stable support and contributions to NPOCE, such as GAIA (J. Lee, 2009-2019) and POSEIDON (D. Jeon, 2006-2014) from KIOST, Korea, INSTANT (A. Gordon, 2004-2006), ITF Gateway (A. Gordon, 2013-2015) and the Argo program (S. Riser, 1998-present, Riser et al., 2016) from the USA, TRITON (1999-present, Ando et al., 2017) from JAMSTEC, Japan, and SPICE (A. Ganachaud, 2008-2015) from France. Large-scale mooring arrays in the western Pacific have been built through international collaboration under the framework of NPOCE and other related programs (Fig. 3).

The most recent main contribution to the NWP observations from China is the establishment of the CAS Scientific Observing Network (CASSON, red stars in Fig. 3). Through about 5 years from 2010 a subsurface mooring array consisted of about 20 subsurface moorings was build up by China. Full-depth temperature, salinity, and ocean current data were acquired for more than 6 years (Wang et al., 2017b). To satisfy the demand of real-time reporting of subsurface data for ocean and climate predictions, the CAS developed a new real-time subsurface mooring (RTSM) and has updated 10 moorings to carry out real-time data transmission since 2017. Data down to 5000 m depths can be transmitted to the surface buoy through wireless acoustic communication, and then back to a shore-based laboratory through the Beidou satellite. The working period of the real-time data transmission capability can persist for more than 260 days on average over a 1-year cycle (Wang et al., 2020a). This real time transmission observing network is a revolutionary addition to the Chinese capability of deep ocean observations, providing a transition from intermittent or interrupted measurements to continuous monitoring.

To facilitate multi-discipline studies and collaborations in the western Pacific, NPOCE also initiated and held a series of conferences (three Open Science Symposia and one workshop) on western Pacific Ocean circulation and the climatic effects from a broader perspective, which attracted a total global attendance of more than 1000 attendees. These gatherings have become important academic conferences for the study of the tropical Pacific Ocean.

3. Scientific achievements of WTP ocean circulation and climate study over the last three decades

3.1 Ocean circulation in the WTP

3.1.1 3-D structure of the surface and subsurface currents

Driven by the basin-scale wind stress curl, the surface ocean circulation in the western Pacific is characterized by the intense western boundary currents, narrow zonal jets and the broad equatorial currents, which have been investigated by many previous studies. The NEC and SEC flow westward and bifurcate upon reaching the Philippine and Australian coasts, forming the KC, MC and the EAC, GPC feeding the NGCU/NGCC. In the southern hemisphere, the broad SEC divides in many zonal jets when encountering Islands and Archipelagos. When reaching the Australian coast, these zonal jets turn northward or southward, depending on their latitude and depth (e.g. Kessler and Cravatte, 2013a; Gasparin et al., 2014). The MC and NGCC, flow equatorward to coalesce at the western boundary and, in part feed the NECC (e.g., Lukas et al., 1996).

Below the surface circulation, several subsurface countercurrents (MUC, LUC, NEUC, NGCUC) have been discovered, based on limited hydrographic measurements and theoretical dynamic analyses (Fig. 2; Lindstrom et al., 1987; Hu and Cui, 1989; Hu et al., 1991; Qu et al., 1998; Wang et al., 1998; Wang and Hu, 1999). Recent intensive measurements from mooring arrays, Argo floats, and gliders have confirmed the existence of these subsurface undercurrents, and the MUC and LUC carry water from the southern and northern hemisphere, respectively, converge east of the Philippines, then flow eastward feeding the NEUC, and so playing an important role in the inter-hemisphere water exchanges (Fig. 4; e.g., Kuroda, 2000; Ueki et al., 2003; Davis et al., 2012; Hu et al., 2013; Zhang et al., 2014, 2017; Lien et al., 2015; Qiu et al., 2015; Schönau and Rudnick, 2015, 2017; Wang et al., 2015; Kessler et al., 2019a). Argo and shipboard ADCP measurements also indicate that these subthermocline currents exist across the tropical Pacific basin, which are apparent in the western and central Pacific, and weakened when approaching the eastern Pacific (e.g., Cravatte et al., 2012; Qiu et al., 2013a; Cravatte et al., 2017).

Recent investigations show that these subthermocline currents exist in connected zones where the baroclinic adjustment below the thermocline overcomes the barotropic forcing at the sea surface (Wang et al., 2015; Li and Gan, 2020). Their generation is thought to be related to meso-scale eddies (Qiu et al., 2013b) or coupled ocean-atmosphere processes (Kessler and Gourdeau, 2006; Taguchi et al., 2012). The tilted vertical structure of the NEC bifurcation is associated with the asymmetric wind forcing over the subtropical and tropical gyre (Guo et al., 2019), and the tilted vertical structure of the SEC bifurcation is governed by the vertical shear of the various zonal jets impinging on the Australian coast, and by the existence of the ITF transport (Kessler and Cravatte, 2013a).

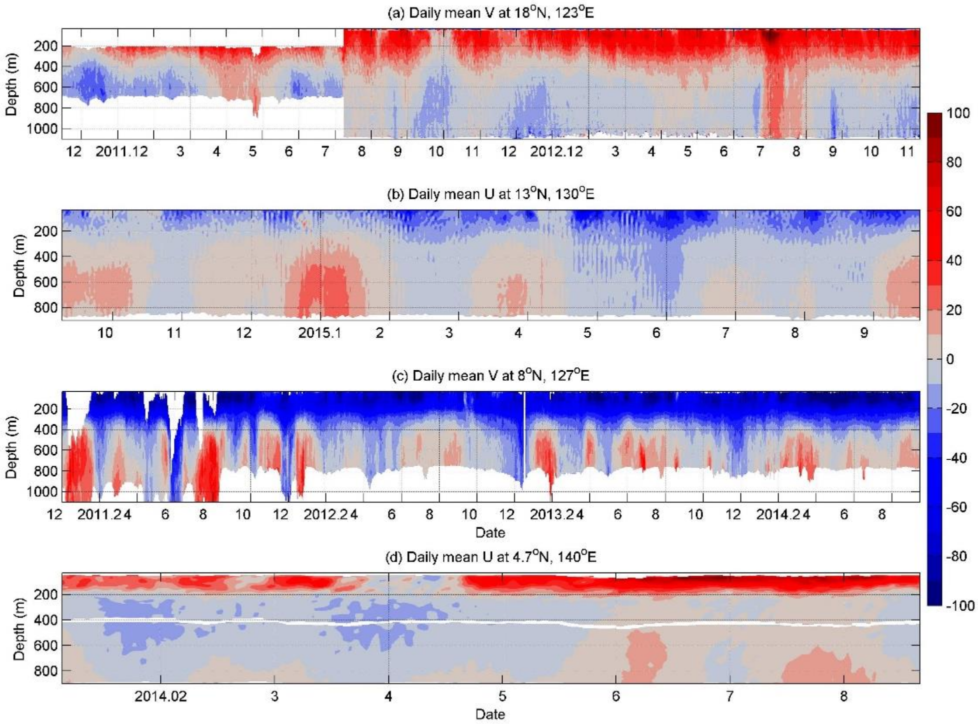

Figure 4. ADCP measurements of the subsurface undercurrents east of the Philippines (adapted after Hu et al., 2013; Zhang et al., 2014; Chen et al., 2015b; Hu et al., 2016; Wang et al., 2016b; Zhang et al., 2017)

A new sub-thermocline ocean current was discovered in the tropical Pacific Ocean during the NPOCE program, based on Argo profiles and ship-board Acoustic Doppler Current Profiler measurements (Yuan et al., 2014), which is named as the North Equatorial Subsurface Current (NESC). This current flows westward toward the entrance of the ITF below the NECC between 3°-7°N across the North Pacific basin, with a geostrophic transport exceeding 4.0 Sv in the western Pacific, and appears much stronger than the NEUC and other off-equatorial sub-thermocline zonal currents. The NESC had been indicated by sporadic historical measurements in the past (e.g. Hayes et al., 1983; Wyrtki and Kilonsky, 1984; Kessler, 2006; Qiu and Chen, 2010), but the existence was confirmed by the latest mooring ADCP data of NPOCE (Wang et al., 2016b). The dynamics of the sub-thermocline currents (NESC) are suggested to be a low-baroclinic mode response of the ocean circulation to wind-curl forcing (Li et al., 2020b), suggesting the importance of the bottom boundary conditions on the ocean circulation. The variations of the sub-thermocline currents in the western Pacific are associated with the westward and downward propagation of the Rossby waves (Yang et al., 2020). The sandwich structure of the Tropical Meridional Overturning Circulation (TMOC) between 0°-6°N characterized by northward surface current, southward thermocline current and northward subthermocline current was also suggested with subsurface moorings deployed at 142°E (Song et al., 2018a).

3.1.2 Intraseasonal to decadal variability of the surface and subsurface currents

Multi-scale variability of the ocean circulation in the western Pacific has been intensively studied with both observation and models, which has previously been summarized in two review papers (Ganachaud et al., 2014; Hu et al., 2015). Subsequently significant progress has been made through studies based on continuous mooring measurements, and pronounced variations of the currents have been detected from intraseasonal to interannual time scales. On intraseasonal time scales, energetic velocity fluctuations are observed both in the surface and subthermocline layer, which play efficient roles in the water exchange of the tropical Pacific (e.g., Wang et al., 2016a; Zhang et al., 2017; Hu et al., 2018; Lyu et al., 2018; Azminuddin et al., 2019). These intraseasonal variations are mainly associated with different types of meso-scale eddies caused by oceanic internal instability in this area, as well as the atmospheric Madden-Julian Oscillation (MJO) that is also known to contribute to intraseasonal variability (e.g., Chiang et al., 2015; Wang et al., 2016a, 2016b, 2017c; Zhang et al., 2017; Hu et al., 2018; Lyu et al., 2018; Azminuddin et al., 2019; Song et al., 2019a). Semiannual signals are also detected in the MUC, with further observations indicating surface wind forcing and the superimposition of the first and second baroclinic modes jointly give rise to enhanced subsurface semiannual variability (Wang et al., 2016c; Ren et al., 2018).

On seasonal time scales, moored observations have revealed that the dominant annual signal was the variability at depths above 300 m in the Mindanao Dome (Kashino et al., 2011), while the MC tends to be stronger in spring (boreal) and weaker in fall (Ren et al., 2018), consistent with previous studies based on synoptic shipboard measurements (Qu et al., 1998; Yaremchuk and Qu, 2004; Kashino et al., 2005). Seasonal variability of the NEC is latitude-dependent, with a seasonal phase delay that is mainly controlled by the local wind near the western boundary (Wang et al., 2019). Due to the westward propagating annual Rossby wave, the NEC/NECC axis shifts on seasonal time scales (Hsin and Qiu, 2012), inducing significant temperature anomalies in the thermocline (Hui et al., 2020). Both the NSCC and NESC strengthened when the NECC shifted to the south in boreal fall, likely due to the first-mode baroclinic Rossby wave response to basin-wide wind forcing (Song et al., 2018b). In terms of the meridional circulation, the TMOC is generally stronger in boreal winter and weaker in summer (Song et al. 2018a). In the Southwest Pacific, the subtropical gyre in the Coral Sea spins up during austral spring, producing larger transports at 10° S, with a maximum in November (Kessler and Gourdeau, 2007), while the lower latitude western boundary currents in the Solomon Sea are stronger in austral winter (Cravatte et al., 2011; Hristova and Kessler, 2012; Germineaud et al., 2016; Alberty et al., 2019).

On interannual time scales, moored velocity time series indicate that the Kuroshio strengthens when the NEC bifurcation moves southward (Chen et al., 2015b). The MC/MUC has depth-dependent interannual variability: stronger and lower-frequency variability dominates the upper-layer MC, while weaker and higher-frequency fluctuation controls the subsurface MUC (Hu et al., 2016). The STCC develops during the decaying phase of ENSO and weakens during La Niña, with strong easterlies during La Niña appearing to cause the NEC to expand further north (Azminuddin et al., 2019). The phase of the NESC is reversed in comparison with the NECC and exhibits a complex vertical structure (Song et al., 2018b; 2019a) in the zonal currents. In the Southwest Pacific, the transport entering into the Coral Sea is stronger after an El Niño (Kessler and Cravatte, 2013b). The transport entering into the Solomon Sea through its southern entrance also strengthens during El Niño (Anutaliya et al., 2019; Kessler et al., 2019a; Melet et al., 2010a, 2011), mainly in the top 250m. Only a weak ENSO signal is evident in EAC transport (Sprintall et al., 2020), and the interannual variability of regional circulation around New Caledonia is also weak (Cravatte et al., 2015).

On decadal timescales, the MC variations are closely associated with the strength of the NEC and largely controlled by off-equatorial wind forcing (Duan et al., 2019a). Multidecadal trends in the MC transport in models are weak and not robust due to discrepancies in the different wind datasets. Anomalous westerly winds in the western Pacific can dramatically enhance the MC in a nonlinear manner (Duan et al., 2019b). Repeated shipboard ADCP measurements suggest that the Pacific NEC intensified over the period 1993-2008 (Hu and Hu, 2012). Satellite altimetry and Argo float data reveal that the South Pacific subtropical gyre has accelerated since 1993 (Roemmich et al., 2007, Zhang and Qu, 2015), with repercussions to the main current variability (Holbrook et al., 2005, 2011; Cai, 2006; Hill et al., 2008). The acceleration is also observed in the global mean ocean circulation (Hu et al., 2020a). Enhanced warming is revealed to be associated with the intensification and/or synchronous poleward shift of global subtropical western boundary currents in conjunction with a systematic change in winds over both hemispheres (Wu et al., 2012).

3.1.3 Deep ocean circulation

The Pacific deep ocean stores enormous quantities of heat and carbon with long residence times, and therefore plays an important role in global climate change (e.g., Johnson et al., 2007). The general pathways of the lower and upper deep branches of the Pacific Meridional Overturning Circulation (the L-PMOC and U-PMOC, respectively) in the western Pacific have been sketched out over the past 20 years (Kawabe and Fujio, 2010; Siedler et al., 2004), and their intraseasonal-to-seasonal variations have been examined recently using CASSON mooring data (Ma et al., 2019; Wang et al., 2020b). Note that the deep branches of PMOC here are deep western boundary currents flowing from the Southwest to the North Pacific below 2000 m, differing from the TMOC which is located less than 1000 m of the tropical ocean. In the deep channel of the Yap-Mariana Junction, a chokepoint for the PMOC flowing into the western Pacific, L-PMOC and U-PMOC both showed broadly seasonal variations but with opposite phase. The L-PMOC flows northward below ~3800 m over December-May on the western side of the channel, and is accompanied by a weaker southward return flow on the eastern side. The U-PMOC flows southward at ~3000-3800 m depth over June-November on the eastern side (Wang et al., 2020b). At intraseasonal timescales, observed velocity and isotherm displacement over ~3000-4600 m showed intensified variability with depth, arising from topographic Rossby waves. Both the energetic surface eddy field that interacts with the rough topography and barotropic-baroclinic instability of the background PMOC are candidates to generate the observed the Rossby waves (Ma et al., 2019).

3.2 ITF and inter-basin climate interactions

3.2.1 ITF transport in different straits

The ITF is the tropical component of the Global Ocean Conveyor Belt that connects the western Pacific with the eastern Indian Ocean (Gordon, 1986) and plays an important role in climate variations and changes. Large scale observations of the ITF were carried out during the International Nusantara Stratification and Transport Program (INSTANT) program (2004-2006), with a number of moorings deployed in the main pathway of the Makassar Strait and the exit channels of Lombok, Ombai, and Timor Straits (Sprintall et al., 2011). Based on INSTANT measurements, the total ITF transport into the Indian Ocean is 15 Sv and the Makassar Strait transport (11.6 Sv) represents about ~80% of the total ITF derived mainly from the North Pacific waters (Sprintall et al., 2009; Gordon et al., 2010). A small transport (1.0-2.0 Sv) through the Karimata Strait carries heat and freshwater from the South China Sea (SCS) into the Indonesian seas (Fang et al., 2010; Gordon et al., 2012; Susanto et al., 2013).

During the NPOCE observation period, a large-scale moored array was deployed in the Indonesian seas (Fig. 5). The western Pacific water enters into the Indonesian seas mainly via Makassar Strait, Maluku Channel, Halmahera Sea, and the SCS. Recent transport estimates in the Makassar Strait consistently find 12.0-13.0 Sv (Gordon et al., 2019). About 1.0-1.3 Sv transport in the upper 300 m flows northward into the western Pacific Ocean through the Maluku Channel (Yuan et al., 2018), and 2.4-4.6 Sv South Pacific water enters the Indonesian seas through the Jailolo Strait of the Halmahera Sea (Li et al., 2020a). Both the Makassar transport and the upper Maluku transport are associated with the retroflection of the MC, which contributes about 11.0 Sv to the mean ITF. The total ITF transport through the eastern Indonesian seas (Halmahera Sea and the deep Banda Sea) is ~4.9-7.1 Sv, around 48-55% of the flow through the Makassar Strait. The transport of the South Pacific waters into the Indonesian seas may suggest the important role of the South Pacific overturning circulation in the Great Ocean Conveyor Belt, although accurate transport estimates of this pathway remain elusive.

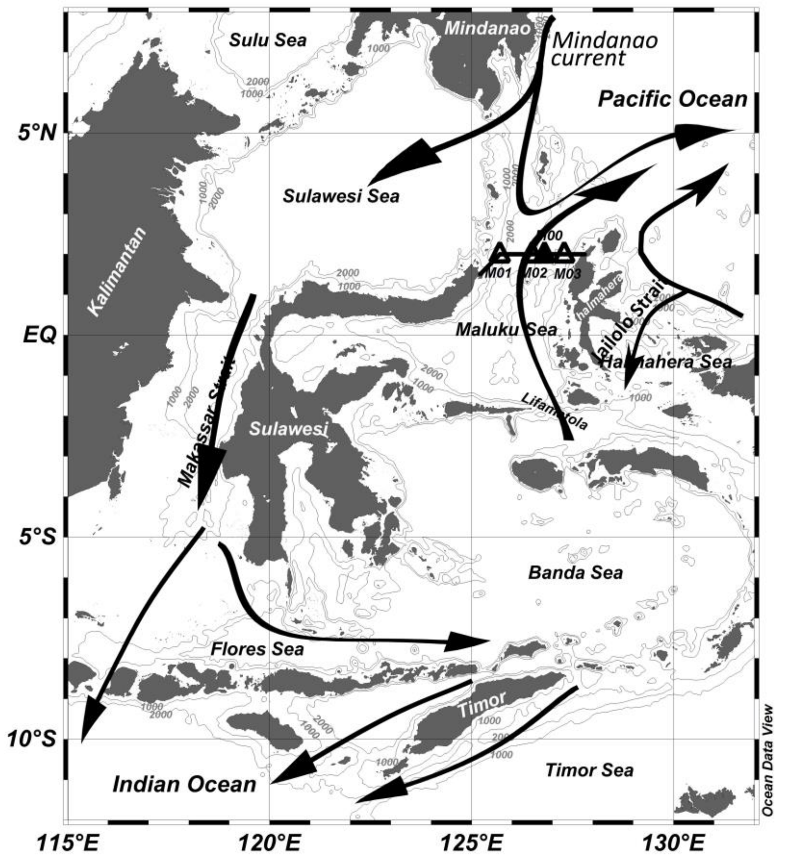

Figure 5. Schematic of the upper-ocean circulation of the Indonesian Seas. The triangles mark the positions of the 2012-2016 mooring positions.

3.2.2 Indo-Pacific climate interactions through the ITF

An overview of recent changes in the ITF and their effect on climate variability can be found in Sprintall et al. (2014, 2019), and a few highlights are elaborated on here. Observations suggest that the variability of the Maluku transport in the upper 300 m is regulated strongly by the nonlinear retroflection of the MC (Yuan et al., 2018). The northward flows below 200 m in the Makassar Strait are forced by the Indian Ocean Kelvin waves that modulate the ITF variability on intraseasonal and interannual time periods (Susanto et al., 2012; Pujiana et al., 2013, 2019; Napitu et al., 2015, 2019). Interannual Kelvin waves from the equatorial Indian Ocean propagate into the Indonesian seas along the Sumatra-Java island chain and influence the ITF interannual variability (Yuan et al., 2011, 2013; Liu et al., 2015). During the 2015-2016 strong El Niño events, these Indian Ocean Kelvin waves were found to reach the western Pacific, while the Rossby wave propagation from the Pacific was largely blocked by the Pacific western boundary currents (Hu et al., 2019b). On decadal and longer time scales, the variability of ITF transport is mainly associated with decadal climate modes in the tropical Pacific, such as the PDO (Zhuang et al., 2013). Recent studies suggest that the salinity effect associated with the PDO variability also considerably influences the interannual to decadal variability of the ITF transport, and acts to shape the decadal variability of salinity in the southeastern Indian Ocean (Hu et al., 2019a). These salinity changes represent an important mechanism for influencing the interannual to decadal variability of the ITF transport (Hu and Sprintall, 2016, 2017). About 36% of the interannual ITF transport is attributable to the salinity changes associated with ENSO-related freshwater anomalies (Hu and Sprintall, 2016). During the past two decades, enhanced freshwater input and intensified salinity have led to a significant strengthening of the ITF, giving rise to significant warming and freshening in the eastern Indian Ocean (Hu and Sprintall, 2017; Gruenberg and Gordon, 2018). Lee et al. (2019) also revealed that the longer-term variations of the ITF are associated with the variability and change in the Indo-Pacific climate and Maritime Continent water cycle. Tidal mixing within the Indonesian seas can also provide feedbacks to climate and influence the discharge-recharge processes of upper-ocean heat content, which can modulate the climate variability such as ENSO, the Indian Ocean Dipole (IOD), and the MJO in the inter-basin region (Koch-Larrouy et al., 2010; Sprintall et al., 2014). A comprehensive strategy is still needed for measuring the temporal and spatial scales of variability that govern the ITF as suggested by the white paper for OceanObs'19 (Sprintall et al., 2019).

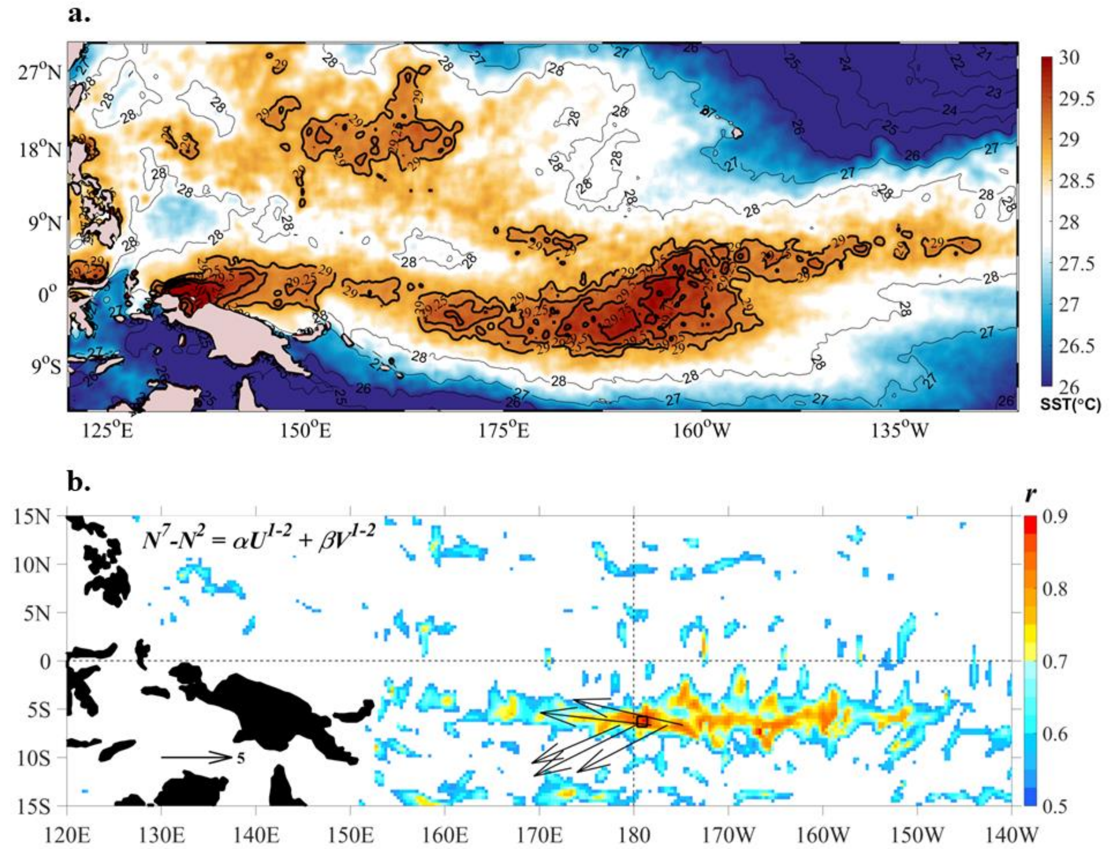

Figure 6. (a) SST during a WPWP Split event and (b) regression relationships between Niño 3.4 index and surface currents. Upper panel shows the SST averaged over August 10-December 10 of 1997 (color shading and contour lines), where the WPWP cores are highlighted in heavy black lines. Color shading in b: correlations (r) between annual time series of N^7-N^2 and regressed $\alpha U^{1\text{-}2}$+$\beta V^{1\text{-}2}$ that are significant at the 0.01 level. Vectors in b: regression coefficients (α, β). N^7 and N^2 denote the Niño 3.4 index in July and in February, respectively. ($U^{1\text{-}2}$, $V^{1\text{-}2}$) denote surface currents averaged from January to February. Adapted from Hu et al. (2017) and Wang et al. (2017a).

3.3 Western Pacific Ocean variability and its climatic impacts

3.3.1 Variability and oceanic processes in the WPWP and their relationship with ENSO

ENSO is the dominant mode of interannual variability in the tropical Pacific Ocean. The knowledge of the basic characteristics of the WPWP are fundamental to understanding the interaction between the warm pool and ENSO dynamics (Brown et al., 2012). While the SST structure in the WPWP is usually spatially homogeneous, a recent study suggests that the WPWP can occasionally split into two distinct parts known as the WPWP split phenomenon (Fig. 6a) that seems to intensify following El Niño events (Hu et al., 2017).

Interannual variability of WTP water masses was investigated in the context of spice anomalies that quantify density-compensated temperature and salinity changes along isopycnal surfaces (Li et al., 2012a). Prominent spice variations were determined from Argo float profiles in the thermocline of the Philippine Sea and attributed to cross-front advection by wind-forced anomalous currents. Such variations were observed over the entire Pacific basin and shown to propagate toward the equatorial Central Pacific, contributing to the recent Central-Pacific El Niño events during 2003–2012 (Li et al., 2012b). A similar analysis was performed in the tropical Indian Ocean, where spice anomalies were generated by the IOD and South Asian monsoon changes (Li and Wang, 2015). Recently, a dipole structure of mixed layer salinity anomalies in the tropical Pacific has been uncovered in response to El Niño and La Niña events, and the mixed layer salinity also demonstrates different patterns in the central Pacific El Niño compared with the more traditional eastern Pacific El Niño (Guan et al., 2019a, 2019b; Qi et al., 2019). The salinity of the South Pacific Tropical Water observed in Argo profiles also exhibits a dipole structure trend during 2004-2013. The dipole, originating from the subduction region of South Pacific Tropical Water, is attributed to the freshwater flux variability associated with the PDO (Zhang and Qu, 2014).

A heat center for the WPWP was defined, with the longitudinal variation of the WPWP heat center leading the Niño-3 index by 3–4 months (Hu and Hu, 2012). Zonal heat advection is revealed to be a key process in the SST variability of the WPWP on seasonal to interannual time scales (Guan et al., 2013; Guan and McPhaden, 2016). In the tropical Pacific Ocean, heat content variations dominate the sea surface height fluctuations on interannual and decadal time scales, whereas in the subtropical and polar regions, the deep ocean and salinity changes contribute significantly to the sea surface height signals (Zhang et al., 2012; Zhang and Qu, 2015).

The Solomon Sea is a key region connecting the south Pacific subtropics to the WPWP via low latitude western boundary currents (Kessler and Gourdeau 2007; Melet et al. 2010a, 2010b, 2011, 2013; Grenier et al., 2011; Hristova and Kessler, 2012; Qu et al., 2013; Zilberman et al., 2013; Djath et al. 2014; Grenier et al., 2014; Hristova et al., 2014). Variability of the heat transport from the Solomon Sea can modulate the heat budget of the warm pool, which is critical for the evolution of ENSO (Davis et al., 2012; Kessler and Cravatte, 2013b; Melet et al., 2013; Zilberman et al., 2013). Spice anomalies are dampened in the Southwest Pacific near the western boundary, although spice signals they can be transported to the equator via Pacific interior pathways and significantly affect ENSO events (Kolodziejczyk and Gaillard, 2012; Li et al., 2012b). A “hotspot” where surface current variability influences the short-lead time predictions of the July Niño 3.4 index has been found at the southern edge of the SEC and suggested to be useful for ENSO predictions (Fig. 6b, Wang et al., 2017a).

The WPWP was found to be freshening and warming during 1955–2003 (Cravatte et al., 2009). Under global warming, surface ocean temperatures are expected to warm fastest near the equator (Collins et al., 2010). The dominant cause of the observed increase in the intensity and size of the WPWP is greenhouse gas forcing (Weller et al., 2016), although natural fluctuations associated with the PDO are also significant (Gan and Wu, 2012). In response to greenhouse warming, the extreme El Niño (La Niña) events, which features a pronounced eastward extension (westward concentration) of the WPWP, will occur more frequently (Cai et al., 2014, 2015). However, due to the projected weakening influence from the tropical Atlantic to the equatorial Pacific (Jia et al., 2016, 2019) and the vigorous pantropical climate interactions (Cai et al., 2019), prediction of these future extreme ENSO events is likely to be more challenging.

3.3.2. Western Pacific Ocean variability and the Asian summer monsoon

The East Asian monsoon is the most important component of the global monsoon system. The South China Sea summer monsoon (SCSSM) onset is considered to be the start of the East Asian summer monsoon and a sign of the rainy season onset in eastern China, as well as being a good predictor of eastern China rainfall (Huang and Li, 1988; Wu et al., 2003). A number of factors can influence the SCSSM onset. Being a major heat source, the WPWP has a significant effect on Asian summer monsoon onset for instance, by influencing the western north Pacific subtropical high or by affecting the cyclones over the Bay of Bengal (e.g., Liang and Wu, 2002; Hung et al., 2006; Lin et al., 2013).

In contrast to SST, the upper ocean heat content (HC) is a much better indicator of oceanic variation, on account of its stability. HC not only remembers the influence of SST on the atmosphere, but also conveys the feedback of the atmospheric signals to SST (Yan et al., 2010). A significant correlation (-0.59) is found between the HC in the WPWP and the SCSSM (Fig. 7). Studies suggest that when the western Pacific HC anomaly in the preceding winter-spring is positive (negative), the SCSSM usually occurs earlier (later) than normal (Chen and Hu, 2003; Hu and Yu, 2008; Yu et al., 2011; Feng et al., 2013; Feng and Hu, 2014).

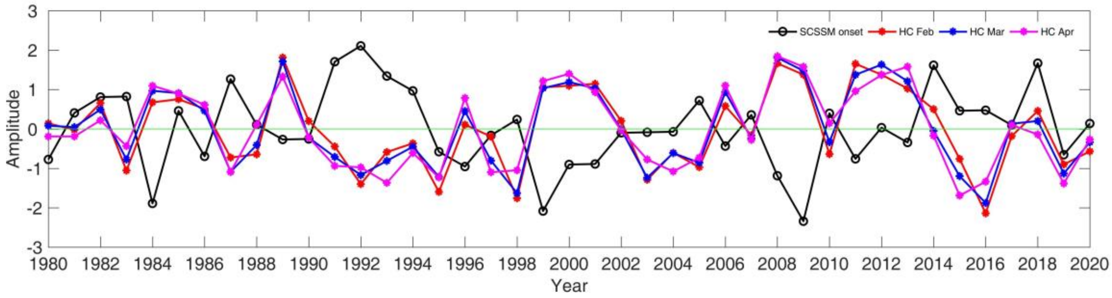

Figure 7. Time series of the SCSSM onset (black) and the heat content (HC) averaged in 0°–14°N, 130°–150°E during preceding February (red), March (blue) and April (purple). The correlation between the SCSSM onset and the HC in April is -0.59. (Adapted from Feng and Hu, 2014)

3.3.3 Typhoon-Ocean interaction

Based on the Chinese National Key Basic Research project "The mechanism of upper ocean response to and modulation on typhoons", a three-dimensional observational system for typhoon-ocean interaction was established (Zhou et al., 2019). The oceanic variables, including temperature, salinity, surface waves and oceanic currents in the upper ocean, are measured using mooring and buoy arrays (Fig. 8), along with Argo floats, and glider deployments. The atmospheric variables within a typhoon, including wind, temperature, pressure, humidity and rainfall, are obtained using rocket-deployed dropsondes.

The upper ocean undergoes great variation along tropical cyclone tracks (Fu et al., 2014; Sun et al., 2014; Wang et al., 2014, 2016; Pei et al., 2015; Lu et al., 2016; Liu et al., 2017; Yan et al., 2017). Conversely, the ocean can in turn modulate the genesis and development of tropical cyclones (Sun et al., 2016; Zheng et al., 2016). For the upper ocean thermal response to a typhoon, a hypothesis of "cold suction" effect that is caused by typhoon-induced upwelling was postulated, on the basis of the traditional view of the "heat pump" effect, which is caused by typhoon-induced mixing (Zhang et al., 2016, 2018, 2019). A relationship between typhoons, westerly wind burst (WWB), and El Niño was found: 69% of WWBs were closely associated with tropical cyclones; WWBs can drive El Niño by generating eastward equatorial surface currents and downwelling Kelvin waves (Lian et al., 2014, 2018; Chen et al., 2015b). Furthermore, an air-ocean-wave observing system or coupled prediction system can be evaluated, leading to improved operational typhoon forecasts (Lei et al., 2019). Moored ADCP current measurements indicate that the near-inertial kinetic energy has strong low-frequency variability due to tropical cyclones and strong wind events in the WTP (Hu et al., 2020b).

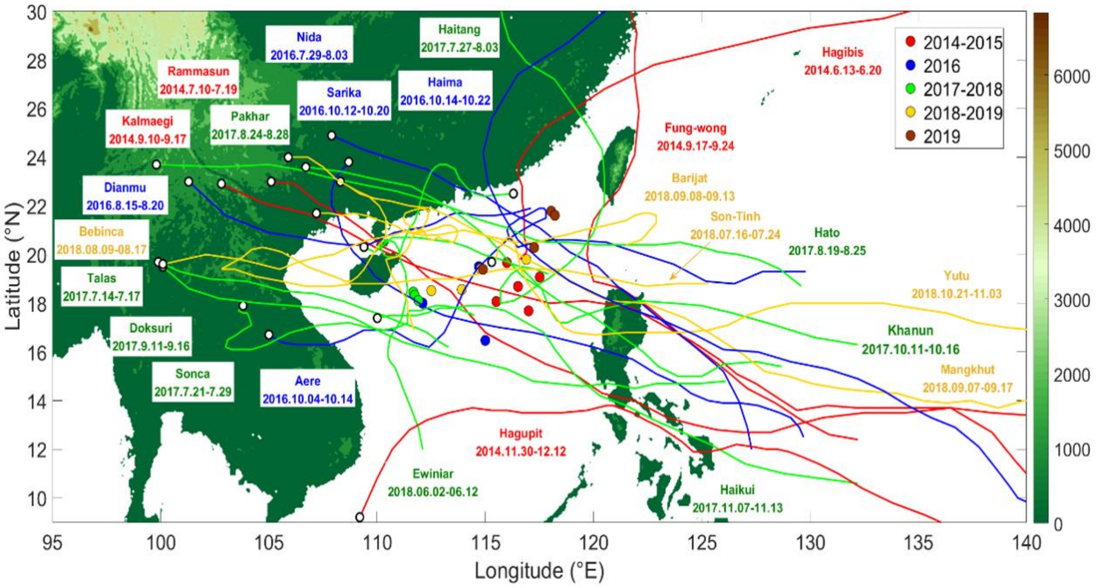

Figure 8. The positions of the moored observational stations (circle) and the tropical cyclone tracks (lines) that can be captured by the mooring array (adapted from Zhou et al. 2019).

4. Perspective

Tremendous progress has been made in the understanding of the structure and multi-scale variability of ocean circulation and its climatic impact in the WTP in the last half-century based on ocean observations from a series of international programs. However, our understanding of the western boundary current system in the WTP is still lacking as current observations are unable to resolve the structure and variability of these narrow/strong and highly variable boundary currents and eddies. There are important remaining problems that are unsolved, which obstruct our success in simulating and predicting some important climate events (Chen et al., 2018; Smith et al., 2019; Todd et al., 2019). The cold bias of SST in the equatorial oceans is still a common problem in the current state-of-the-art coupled General Circulation Models (CGCM). In addition, many processes in the WTP are undergoing significant changes under global warming scenarios, which also challenge CGCMs. Improved reliability of climate predictions and projections in the WTP requires a better understanding of ocean-atmosphere coupling. This critically depends on having a comprehensive ocean observing system of high-quality data. It would be more difficult and costly to extend this to the deep ocean but this is also critically needed.

Based on the significant achievements that NPOCE has made to date, the next step for NPOCE should be to continue to promote the observations and studies of ocean circulation and climate in the WTP in the coming years. First, to meet the needs for purpose of prediction of ocean environment in the WTP and its remote teleconnection impacts, the subsurface mooring real-time transmission network should be continued with a stronger effort to expand its scale with improved and innovative technology. Intensive and long term WTP observations aided by combining in-situ measurements, data from ocean-observing satellites, and taking advantage of the new generation technology are highly anticipated, along with the accompanying rapid delivery of data to both operational prediction agencies and research institutions. For NPOCE, the next step will be to expand its observation connecting the circulation features with the WTP: (1) southward with the south tropical Pacific to study the North-South Pacific exchanges through the tropical subsurface undercurrents that modulate the water mass properties from either side of the equator; and (2) westward with the ITF and potentially into the East Indian Ocean in order, for example, to better resolve the nature of the flow of the direct pathways of South Pacific contributions that might feed into the ITF. With respect to this aspect, NPOCE will also focus on a better understanding of the complexity of the physical and biogeochemical processes between the far western Pacific islands of Mindanao and New Guinea, areas characterized by strong dynamical nonlinearity. That is, NPOCE goals in the future will continue to improve our knowledge of the relationship between the inflows of the MC and NGCC, that originate from the NEC and SEC, respectively, and how these might partition into the NECC and ITF, through an integrated observation and model simulation efforts.

International collaborative efforts are also underway in the context of the TPOS2020 project (Chen et al., 2018; Kessler et al., 2019b; Smith et al., 2019; Song et al., 2019b). An enhanced array of surface and subsurface moorings will be deployed in the northwestern Pacific Ocean, to better understand air-sea interaction, intraseasonal variability, and to track monsoon and typhoon development over the northwestern Pacific Ocean. The recently renewed recognition of the dynamic, climate-relevant deep variations below 2000 m has led to a call for a ‘Deep Argo’ array (Johnson et al., 2015). Still, given the importance of this variability in understanding long-term changes in climate, more efforts should be encouraged to extend the observation to the deep ocean in the WTP so as to characterize its physical state, biogeochemistry, and ecosystems, and their changes. These efforts will contribute to “A transparent and accessible ocean” mentioned in the Roadmap of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030). Such a sustained effort would greatly enhance our understanding of the complex ocean-atmosphere coupled system in the region, and improve sub-seasonal predictions.

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