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Special Section:
Recent Progresses in Oceanography and Air-Sea Interactions in Southeast Asian Archipelago

Special Section:
Years of the Maritime Continent

Key Points:
- Development of two-way coupled regional climate models over the Maritime Continent is still in its infancy; mixed results from coupled models are observed
- Unresolved physical processes, inadequate model representations of the coupled system, and uncertainties in model configurations are main factors responsible for modeling biases
- Opportunities emerge for improving regional coupled modeling through advancing the representation of physics and dynamics in coupled models

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Coupled Ocean-Atmosphere Modeling Over the Maritime Continent: A Review

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Abstract The Maritime Continent (MC) plays a vitally important role in the Earth's climate system from both oceanic and atmospheric perspectives. While the critical role of ocean-atmosphere coupled dynamics over the MC has long been recognized, development of two-way coupled regional climate models for this region is still in its early stages. In this work, the authors review recent progress in two-way coupled ocean-atmosphere regional climate modeling. Development of coupled models and their applications in the MC are summarized. Model performances are discussed with a focus on regional oceanic and atmospheric characteristics. Through a critical review of modeling advances and limitations in simulating sea surface temperature, precipitation, and oceanic throughflows, the authors identify deficiencies of current models and discuss possible reasons. The review shows that model biases mainly stem from unresolved physical processes, inadequate model representations of the coupled system, and uncertainties in model configurations. The study reveals large-scale coupled modes of variability, local air-sea interactions, atmospheric dynamics, and oceanic processes play various roles in the observed modeling biases. Lastly, the authors offer suggestions on emerging opportunities for improving regional coupled modeling over the MC.

1. Introduction

The oceans and the atmosphere are the two large components in the Earth's hydroclimate system. The two are complexly linked to one another and have a significant impact on Earth's weather and climate. While the atmosphere drives the ocean through the input of momentum, heat, and moisture fluxes, the ocean regulates the weather and climate system through its supplies of moisture and heat to the atmosphere system. The most notable example is the tropical oceans where the dynamics is dominated by the strong coupling between the ocean and atmosphere. The first and most studied example is the tropical Pacific Ocean, where the El Niño–Southern Oscillation (ENSO) is the dominant ocean-atmosphere mode of variability, with the two oscillating phases of El Niño/La Niña.

ENSO is a coupled atmospheric-oceanic variation that redistributes heat and momentum over and in the equatorial Pacific. ENSO has been explained as an oscillatory mode of the coupled ocean-atmosphere system or a damped oscillating mode triggered by stochastic forcing that causes sea surface temperature (SST) growth or decay (C. Wang & Picaut, 2004). In all proposed theories, ENSO involves the positive ocean-atmosphere feedback of Bjerknes (1969). In addition, negative feedbacks of the ocean-atmosphere system are needed for the system to transfer between two oscillating phases of El Niño/La Niña. Based on the coupled ocean-atmosphere model of Zebiak and Cane (1987), several oscillator paradigms have been developed with emphases on the negative feedback of reflected Kelvin waves at the ocean western boundary (e.g., delayed oscillator (Battisti & Hirst, 1989; Suarez & Schopf, 1988)), a discharge-recharge oscillator due to Sverdrup transport (e.g., the recharge oscillator (Jin, 1997)), wind-forced Kelvin waves in the western Pacific and anomalous zonal advection (e.g., the western Pacific oscillator (e.g., Wang, 2001; Weisberg & Wang, 1997)), and the advective-reflective oscillator (Picaut et al., 1997).

A more recently discovered atmosphere-ocean coupled mode of variability is the Indian Ocean Dipole (IOD). Similar to ENSO, the IOD is also a coupled ocean-atmosphere phenomenon but in the equatorial Indian

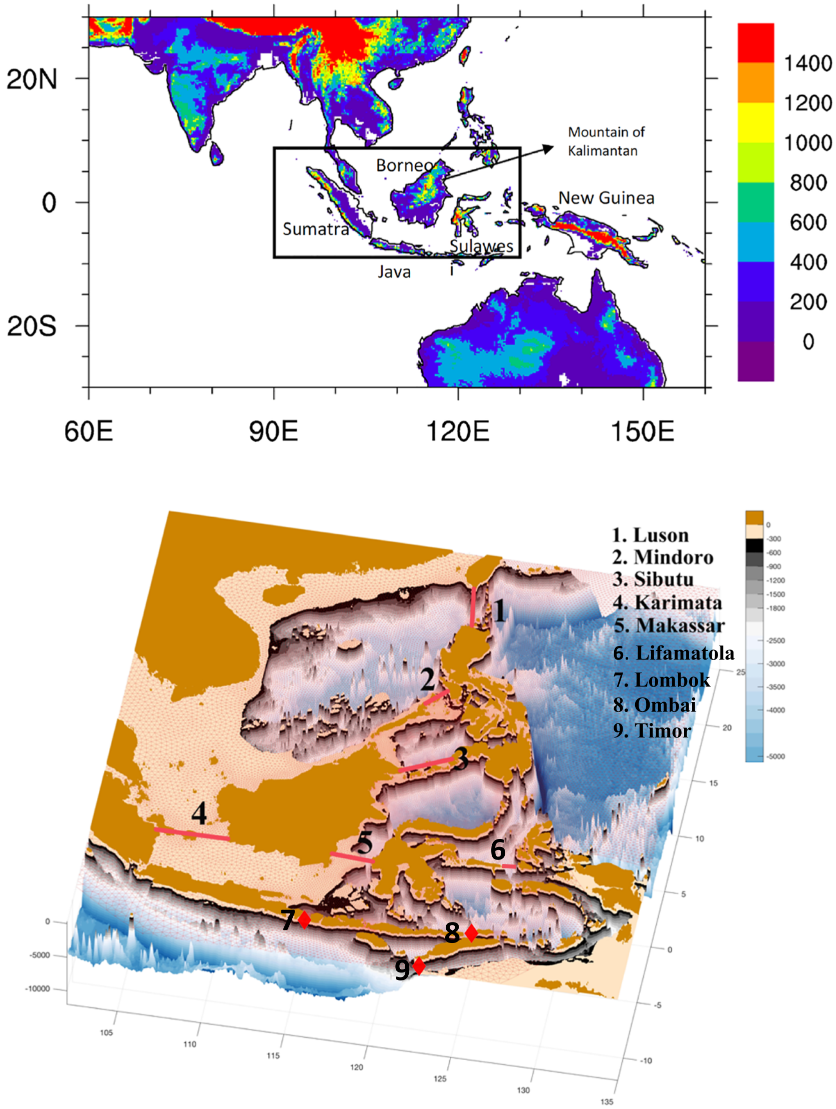

Figure 1. Topography (a; (Jiang & Li, 2018)*) and bathymetry of the maritime continent with the key straits (b).*

Ocean (e.g., Saji et al., 1999; Webster et al., 1999). Like ENSO, IOD involves an irregular oscillation of SST across the Indian Ocean and the change in water temperature gradients results in rising and descending moisture and air in preferred regions. A positive IOD is associated with unusual cooling of waters off the coasts of Sumatra and Java in the eastern Indian Ocean, warm SST anomalies and greater precipitation in the central and western equatorial Indian Ocean, as well as easterly wind stress anomalies along the equator. A negative IOD is associated with the opposite conditions. IOD events can either develop independently or coincide with ENSO (e.g., Webster et al., 1999; Xie et al., 2002; Ashok et al., 2004; Meyers et al., 2007; Yamagata et al., 2004). Similar to the development of ENSO, the growth and decay of IOD could involve positive Bjerknes feedback and negative atmosphere-ocean feedbacks (Li et al., 2003; McPhaden & Nagura, 2014; Schott et al., 2009; Yamagata et al., 2004; Wang et al., 2016). Propagation of baroclinic Kelvin and Rossby waves and their reflections at the western and eastern boundaries play an important role in the development and termination of the IOD events (Feng & Meyers, 2003; Masumoto & Meyers, 1998; Rao et al., 2002; J. Wang & Yuan, 2015; Xie et al., 2002; Yuan & Liu, 2009).

While ENSO and IOD dominate on interannual scales, a remarkable feature of atmosphere-ocean coupled mode on the intraseasonal scale is the Madden–Julian Oscillation (MJO) (Madden & Julian, 1971, 1972). MJO is characterized as an eastward traveling pattern of cloud and rainfall at 4–8 m/s across the equatorial Indian and western/central Pacific oceans, with an intraseasonal oscillation of 30–90 days (C. Zhang, 2005). In the equatorial Indian and western Pacific oceans, an active phase of MJO features an eastward, large-scale movement of strong deep convection and enhanced rainfall, while the suppressed phase is characterized with the weak convection and precipitation. As a strongly coupled mode, the MJO involves variations in cloudiness, rainfall, wind and SST; influences the timing and strength of monsoons; affects tropical cyclone numbers and strength; and modulates the diurnal cycle of precipitation (Klotzbach, 2014; Peatman et al., 2014; Taraphdar et al., 2018; Zhou & Neale, 2012).

Among the tropical bands in the Pacific and Indian Oceans, a particularly important role can be assigned to the tropical Maritime Continent (MC). This name refers to the region of South Asia and is approximately bounded by 90–140°E and 10°S to 10°N. It includes the archipelagos of Indonesia, the Malay Peninsula, New Guinea and the surrounding shallow seas connected by a multitude of straits. From a global point of view, the MC region has a very complex orography affecting and modifying the overlying Hadley Cell (Figure 1a). The MC, situated within the tropical Warm Pool and the ascending branch of the global Walker atmospheric circulation, plays a critical role in the Earth's climate system. It is a significant source of energy with a large input of heat and moisture fluxes for the global circulation and precipitation (Gianotti et al., 2012; Neale & Slingo, 2003; Ramage, 1968; Yamanaka et al., 2018). More specifically, the MC transfers coupled modes of variability, such as ENSO, from the Pacific Ocean to the Indian Ocean, both through atmospheric teleconnections (Alexander et al., 2002; Klein et al., 1999; Latif & Barnett, 1995; Lau & Nath, 2003; Wieners et al., 2019) and oceanic ones. From the oceanographic point of view, particularly important are the Indonesian Throughflow (ITF) (Gordon, 1986; Godfrey, 1996; Lee et al., 2002; Sprintall et al., 2014) and the South China Sea Throughflow (SCSTF) (Gordon et al., 2012; Liu et al., 2012; Qu et al., 2005, 2009; Tozuka et al., 2009; Wang, Liu, et al., 2006). The ITF major pathways include inflow paths through the Makassar Strait and Lifamatola passage and three outflow passages of Lombok, Ombai, and Timor, while the SCSTF enters through Luzon Strait and exits through the Mindoro and Karimata Straits (Figure 1b). ITF and SCSTF play important roles of the oceanic MC in transferring and mediating the coupled modes of variability associated with the IOD and ENSO. In turn, the ITF variability can be weakened by wind forcing associated with IOD, which is often coupled with ENSO but not always in phase with it (Cai et al., 2012; Meyers et al., 2007; Stuecker et al., 2017). Compensated effects have also been suggested between direct ENSO and positive IOD as forcing on the ITF (Feng et al., 2018; Liu et al., 2015; Yuan et al., 2013). The MC also has vitally important effects on the propagation of the MJO. The convective anomalies of MJO tend to weaken as the oscillation passes through the MC, which may be linked to a number of processes including a decrease in total surface moisture flux (Sobel et al., 2010), reduced low-level convergence by the topography (Inness & Slingo, 2006; C. Wu & Hsu, 2009), and an energy dissipation through the strong diurnal cycle around the MC (Neale & Slingo, 2003).

All the above examples show that the MC region is indeed unique for its location, connecting the Pacific and India Oceans, and for its extremely complex structure. Despite the significant effects of the MC on Earth's climate, currently no global model is able to provide sufficient resolution to resolve the orography/bathymetry complexity satisfactorily with accurate simulations of its circulation and properties distributions. Regional models are built to enhance regional detail through a more realistic representation of physics and dynamics by resolving finer scale topography, circulation pattern, thermostructure, and so forth (Feser et al., 2011; Giorgi, 2019). For the MC's complex structure and strongly coupled features, development and application of coupled ocean-atmosphere regional models are crucial to advance understanding of this system and its atmospheric and oceanic features and their coupled dynamics.

Furthermore, a very important reason for having two-way coupled regional atmosphere-ocean models is that they constitute the necessary foundation for regional climate modeling for understanding the present Earth's climate and to make projections of future climates under different anthropogenic forcing scenarios. This is, in fact, one of the most important recommendations made in the IPCC AR5 (2013) as the only tools adequate for climate projections in semienclosed basins, such as the Mediterranean Sea, or regions endowed with extreme geographic complexity such as the MC.

Two points must be clarified here. Following the common definition of the word, this review paper is first a review of the existing literature, specifically of ocean-atmosphere coupled models for the MC. It aims to provide a reference for scientists interested in two-way coupled regional modeling and an overall view of the

Table 1
Configuration of Coupled Models Over the MC

	Atmosphere model	Ocean model	Coupler	Grid resolution (atmosphere)	Grid resolution (ocean)	Coupled domain	Simulation period
Aldrian et al. (2005)	REMO	MPI-OM	OASIS3	50 km	20 km to unknown	19°S to 8°N 95–145°E	1979–1999
Wei et al. (2014) Xue et al. (2014)	RegCM3	FVCOM	OASIS3	60 km	7–50 km	20°S to 28°N 85–140°E	1970–1979
Li et al. (2014)	WRF	POM	OASIS3	15 km	10 km	0–30°N 100–135°E	26–29 Sept. 2009 21–24 Sept. 2008
Li et al. (2017)	WRF	NEMO	OASIS-MCT	0.75° and 0.25°	0.75° and 0.25°	30°S to 30°N 70–180°E	1989–2009
				(1/12)°	(1/12)°	20°S to 20°N 90–160°E	1989–1995
Thompson et al. (2018)	MetUM	NEMO	OASIS-MCT	4.5 km	4.5 km	92–117°E 15°S to 24°N	23–27 Jan. 2016 13–19 Oct. 2016

development of this special area of research in a region of extreme complexity such as the MC. The relevant scientific questions addressed will emerge along with discussions on model simulations, as well as their successes and deficiencies. For the interested reader, a complete, recent overview of the scientific issues related to the MC can be found in “Years of the Maritime Continent (July 2017-July 2019)” (www.jamstec.go.jp/ymc/docs/YMC_SciencePlan_v2.pdf). Second, the coupling in this review involves only the atmosphere and the ocean. Coupled dynamics with the land surface of the region is beyond the scope of the paper. The scientific and technical issues related to the coupling of the two fluids are complicated enough without adding another component, and hence further complexity, which would only obscure our understanding of the results.

2. Two-Way Coupled Atmosphere-Ocean Models Over the MC

The development of interactively coupled models (see review by Giorgi, 2019; Giorgi & Gutowski, 2015) emerged in the late 2000s due to rapid technological advancement and the increase in computational capability. Over the past two decades, a number of coupling modules have been developed. Examples include Earth System Modeling Framework (ESMF), the Model coupling Toolkit (MCT), and OASIS-MCT coupler, which is the latest version of the OASIS3 coupler interfaced with the MCT which offers a fully parallel implementation of coupling fields regridding and exchange (Valcke, Balaji, Craig, et al., 2012, Valcke, Craig, Coquart, 2012). In general, coupling data must be interpolated and transferred between the constituent models under several constraints such as conservation of physical properties, numerical stability, consistency with physical processes, and computational efficiency.

In the MC region, coupled models are typically configured with atmospheric and oceanic components that are integrated forward simultaneously with a coupler controlling the data transfer between them and coordinating/synchronizing the constituent models. Table 1 provides a summary of existing coupled modeling studies for the MC region, which will be discussed in the next sections in the context of the scientific questions addressed. Table 2 provides a summary and key references of the participating atmosphere and ocean models.

2.1. SST and Air-Sea Fluxes

SST and heat/moisture fluxes are the fundamental thermodynamic variables for the tropical climate (Lau & Nath, 1994). They directly couple the atmosphere and ocean and are responsible for positive/negative feedbacks between the two. Ocean-only models are deficient because momentum (wind stress) and air-sea fluxes are prescribed as surface boundary conditions for the ocean. Hence, the surface ocean circulation and SST distributions are passive responses and realistic as much as the surface boundary conditions are. Atmosphere-only models are equally deficient because the SST is also prescribed as the lower boundary

Table 2
Summary and Key References of the Participating Atmosphere and Ocean Models

Acronym	Description	Key references
REMO	The REgional MOdel (REMO) is based on the Europamodell, the former numerical weather prediction model of the German Weather Service. Further development of the model took place at the Max-Planck-Institute for Meteorology, now further developed further developed and maintained by the Climate Service Center Germany (GERICS).	Jacob and Podzun (1997) and Jacob et al. (2001)
RegCM3	Regional Climate Model Version 3 (RegCM3) is a three-dimensional, hydrostatic, compressible, primitive equation, σ-coordinate regional climate model. It is maintained in the Eltahir Research Group at MIT, as well as at the International Center for Theoretical Physics (ICTP).	Giorgi and Mearns (1999) and Pal et al. (2007)
WRF	The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications, maintained and distributed by the National Center for Atmospheric Research (NCAR).	Skamarock et al. (2008)
MetUM	UK Met Office Unified Model (MetUM) is a unified model that has been used at the Met Office for both low-resolution climate modeling and high-resolution operational numerical weather prediction (NWP).	Davies et al. (2005)
MPI-OM	The Max Planck Institute ocean model (MPIOM) is the ocean-sea ice component of the MPI-Earth System Model. MPIOM is a primitive equation model (C-Grid, z-coordinates, free surface) with the hydrostatic and Boussinesq assumptions made.	Marsland et al. (2003)
FVCOM	Finite Volume Community Ocean Model (FVCOM) is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model.	Chen et al. (2006)
POM	The Princeton Ocean Model (POM) is a community general numerical model for ocean circulation that can be used to simulate and predict oceanic currents, temperatures, salinities and other water properties.	Mellor (1998)
NEMO	Nucleus for European Modeling of the Ocean (NEMO) is a modeling framework for research activities and forecasting services in ocean and climate sciences, developed in a sustainable way by a European consortium.	Madec et al. (2017)

conditions for the atmospheric model, constituting a reservoir of heat and moisture that does not interactively respond to the overlying fluid.

In coupled models, both the SST and air-sea fluxes are the crucial metrics used for model evaluation and climate analysis. Examples of these evaluations are given in Figure 2. SST is sensitive to the exchange of air-sea surface fluxes. Aldrian et al. (2005) conducted stand-alone ocean model simulations driven by regional atmosphere model outputs, which are forced by different reanalysis products. All simulations tend to produce warm bias (Figure 2a). After the atmosphere-ocean model is two-way coupled, warm biases are effectively removed (Figure 2b). On the other hand, instead of producing warm biases of SST (Aldrian et al., 2005), Wei et al. (2014) showed an ocean-only model driven by underestimated net heat fluxes (from MIT General Circulation Model (MITgcm)) as prescribed surface forcing may cause not only a cold bias but also a significant cold drift of SST. This hypothesis is proven by using heat fluxes from the National Centers for Environmental Prediction (NCEP) to drive the ocean-only model, which eliminates the cold drift, thus also demonstrating the critical role of heat exchange at the air-sea interface (Figures 2c and 2d). Such a cold drift is also eliminated by using a coupled model (Figures 2c and 2d), as local air-sea feedbacks may play an important role in preventing SST drift through SST → evaporation (latent heat) feedback and SST → low-level clouds→ insolation feedback (Xue et al., 2014).

While coupled simulations may effectively reduce both warm bias and cold bias of SST, they are also sensitive to model grid resolution. Li et al. (2017) showed that cold bias that exists in the majority of the model domain in the low-resolution (e.g., (3/4)°) experiment can be considerably reduced and turned into a moderate SST warm bias with increased model resolution (e.g., (1/4)°). Interestingly, further increasing the horizontal resolution to (1/12)° increases the magnitude and extent of the warm bias (Figures 2e and 2f). Mixed results from coupled simulations are also seen in short-term events such as a cold surge or typhoon (Thompson et al., 2018). Predicted SST cooling using a coupled model is relatively weaker than in the ocean-only simulation and reanalysis data in the region southeast of Vietnam, while the SSTs simulated in the coupled model are improved in comparison to the ocean-only simulation in the southern SCS (Figures 2g and 2h).

The understanding and correct attribution of SST biases is often very difficult, and in many cases, a variety of reasons may be invoked. Atmosphere-ocean feedback processes relating the warm pool of the tropical Indian and the western Pacific Ocean, where the MC is located, occur on a wide range of spatiotemporal scales. These feedbacks range from large regional and basin scales affecting ENSO and IOD variabilities

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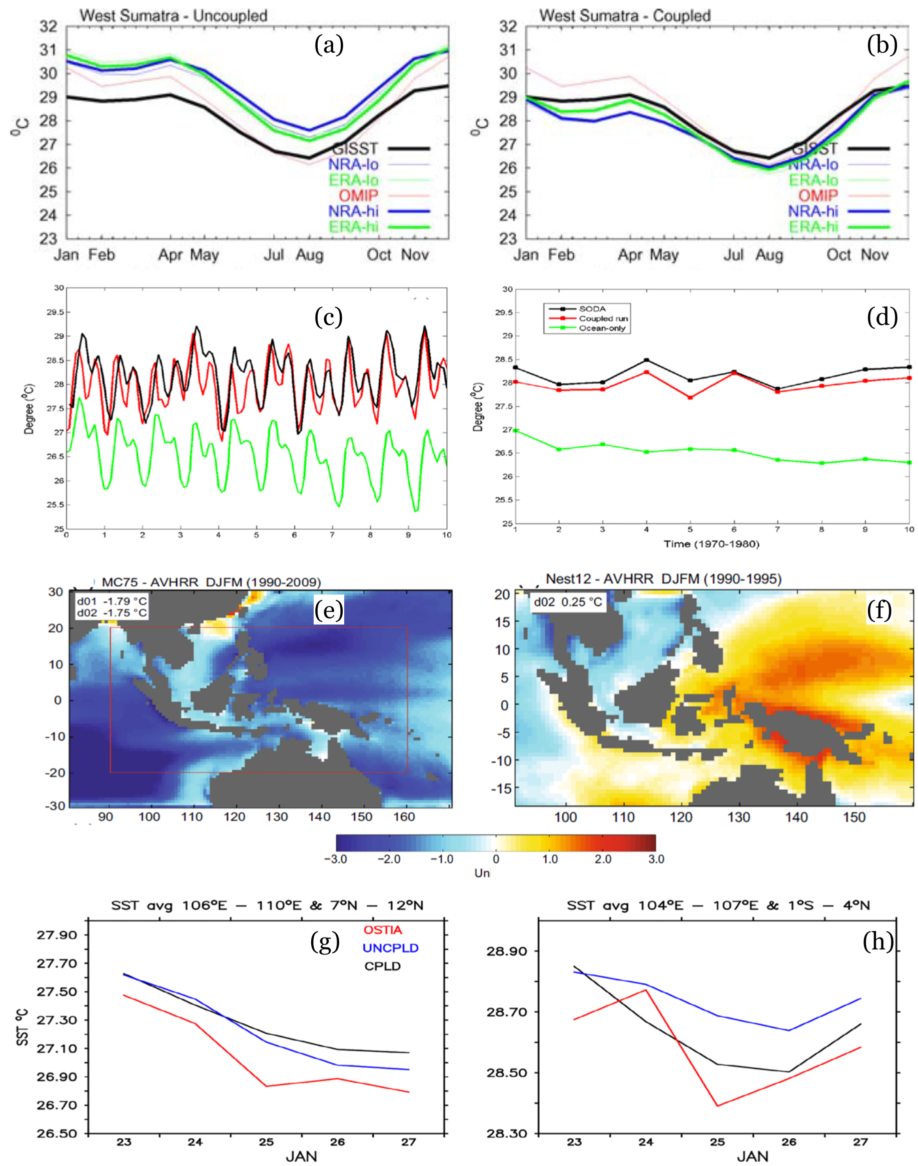

Figure 2. An example of coupled simulation (b) reduces a warm bias of uncoupled simulation (a) in comparison to GISST (Aldrian et al., 2005); an example of the coupled (red) simulation reduces the cold bias and cold drift of ocean-only (green) simulation in comparison to SODA SST (black) on monthly (c) and yearly (d) average (Wei et al., 2014); an example of SST biases sensitive to model grid resolution in coupled simulation. Cold bias relative to AVHRR at low resolution ((3/4)°) model (e) and warm bias at high-resolution ((1/12)°) model (f) (Y. Li et al., 2017); an example of coupled model showing mixed results over different regions. Underestimated SST cooling (warm bias) in the coupled simulation (black) compared to the ocean-only simulation (blue) and reanalysis data (red) in the region southeast of Vietnam (g), while the coupled SST is improved with respect to the ocean-only simulation in the southern SCS (h) (Thompson et al., 2018).

(Alexander et al., 2002; Lau et al., 2005; Wang, Wang et al., 2006; Xie et al., 2009), to intraseasonal Kelvin and Rossby wave modes that sustain MJO (Wang & Xie, 1998; Zhang, 2005) and to local negative feedbacks on a daily and weekly scale (Xue et al., 2014). Various feedbacks on tropical SST include cloud feedback mechanisms (Miller, 1997; Ramanathan & Collins, 1991), wind-evaporation feedback (Hartmann & Michelsen, 1993; Zhang et al., 1995), and ocean dynamics (Clement et al., 1996; Sun & Liu, 1996). MJO interacts with air-sea fluxes over the MC during its eastward propagation, which is modulated by ENSO and IOD events. The MJO signature increases over the MC warm pool during the development of the ENSO warm phase (Hendon et al., 2007; Kessler, 2001), and the intraseasonal air-sea heat flux variability

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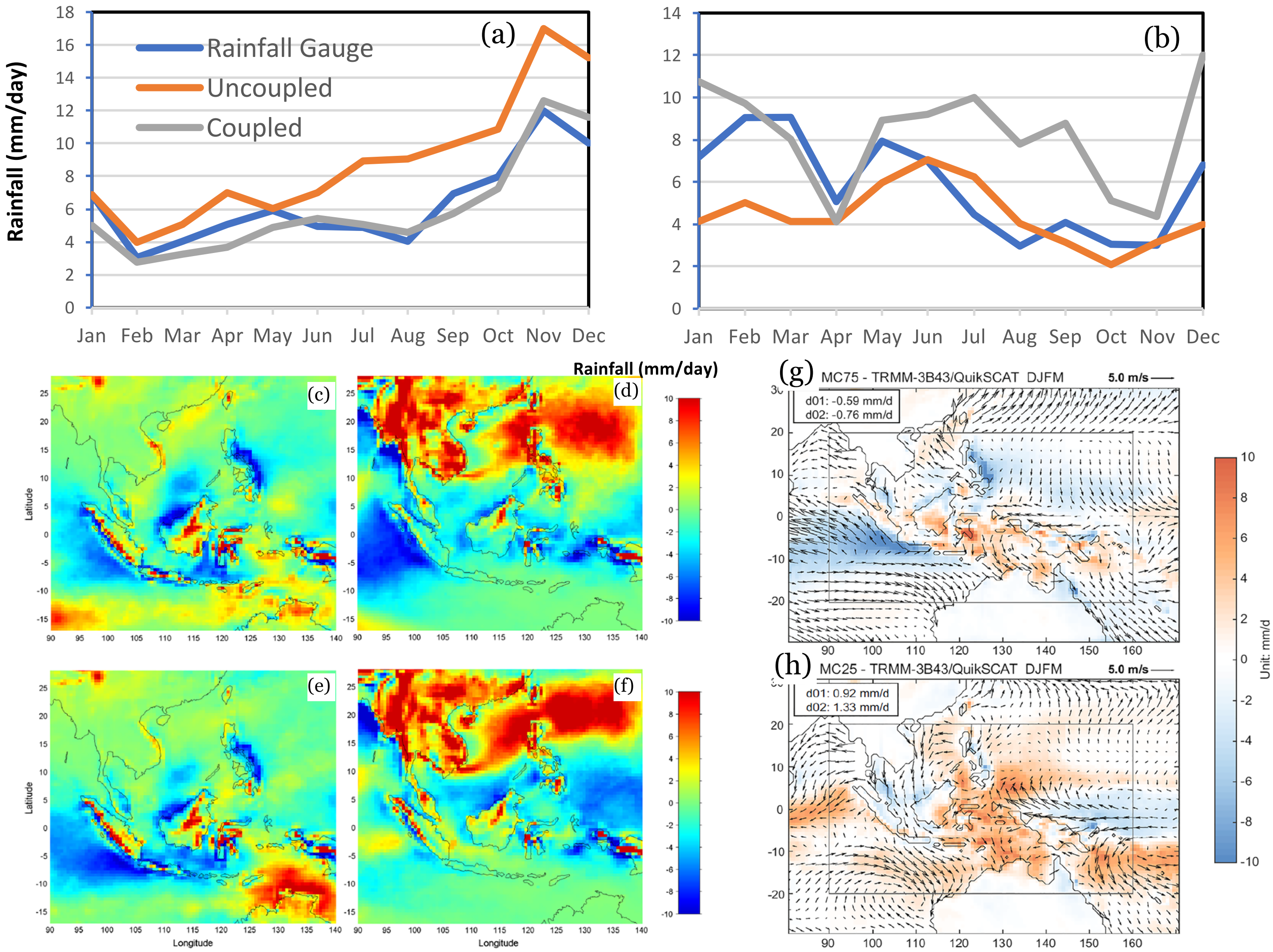

Figure 3. An example of coupled simulation reduces a rainfall bias of uncoupled simulation in SCS (a) but worsens the precipitation results over the Molucca Sea (b) (Aldrian et al., 2005); an example of the rainfall bias relative to observations for coupled simulation during wintertime (c) and summertime (d) and the same but for atmosphere-only simulation during wintertime (e) and summertime (f) (Wei et al., 2014); an example of precipitation and wind biases sensitive to model grid resolution in coupled simulation. Biases relative to TRMM/QuickSCAT observation in the low resolution ((3/4)°) model (g) and warm bias in the high-resolution ((1/4)°) model (h) (Y. Li et al., 2017).

due to MJO events may account for its 69–78% intraseasonal SST variability (Napitu et al., 2015). Many modeling studies suggested that MJO simulations are sensitive to model configurations (e.g., vertical resolution and cumulus parameterization), but a comprehensive understanding of fundamental dynamics of the MJO is still missing (Batstone & Hendon, 2005; Kapur & Zhang, 2012; Seo & Xue, 2005). Again, these contrasting results in different subregions of the coupled climate model are difficult to rationalize and are possibly due to multiple causes requiring very detailed sensitivity studies to different resolutions, boundary conditions, parameterizations, and so forth.

2.2. Precipitation

Unlike interactions between SST and air-sea heat fluxes, for which the coupling mostly produces noticeable improvements in the simulations, coupling effects on precipitation are controversial. This is partly because SST indeed affects precipitation but only indirectly through both dynamic and thermodynamic pathways. As a result, in some coupled simulations, the precipitation patterns are significantly improved; in others, they are almost unaffected. On the one hand, rainfall biases correlate with SSTs to a certain extent, which is evidenced in several coupled modeling studies over the MC. Weak pattern correlations can be found between the warm bias of SST (Figure 2f) and the overestimated precipitation (Figure 3h). A sensitivity experiment also shows that lowering the prescribed SST can effectively correct the rainfall overestimation (Aldrian et al., 2004). On the other hand, in all air-sea coupled simulations over the MC, model biases in precipitation relative to observational data are much more significant than the model difference between coupled and uncoupled simulations (e.g., Aldrian et al., 2005; Wei et al., 2014; Thompson et al., 2018). For example, both coupled and uncoupled models display similar and significant precipitation errors (Figures 3c–3f), which suggests that precipitation errors must be attributed to other factors rather than only air-sea coupling.

The challenge in rainfall simulation lies in the fact that many factors affect precipitation over the MC, and these processes are extremely complex, involving convection, cloud, and annual and seasonal large-scale atmosphere circulation, coastal breeze, and land topography. As one example, the rainfall complexities and their linkage to wind characteristics in coupled simulations are demonstrated by Aldrian et al. (2005). Their simulations over three seas (the West Sumatra, the Molucca Sea, and the southern part of the SCS), which represent the monsoonal, antimonsoonal, and semimonsoonal regions, show that while the coupled model reduced SST warm biases in all these regions, the model performances in rainfall simulation were very different. The coupled model effectively reduced the rainfall bias particularly for the Southern SCS (Figure 3a) but increased the precipitation error over the Molucca Sea (Figure 3b), and no significant impact was found in the West Sumatra region. As intense oceanic rainfalls are often found in areas with surface wind convergence, another example (Li et al., 2017) shows that overestimated easterlies over the equatorial Pacific can transport excessive moisture into the north and south hemisphere convergence zones and overestimate rainfall over these regions (Figure 3h).

Uncertainty is also related to model configuration. While the increased model resolution may turn dry biases into wet biases (Figures 3g and 3h) (Li et al., 2017), other studies report the benefit of a high-resolution coupled model in resolving precipitation extremes (Thompson et al., 2018). As precipitation extremes are often caused by energetic local convective activities, the impact of model resolution on simulating convective rainfall is vital as it is fundamental over the MC. Similar to the SST, the causes of the deteriorated precipitation simulation when increasing the horizontal resolution have not been fully understood.

The interactions of multiscale processes further complicate the rainfall simulation. The MC is characterized by a remarkable diurnal cycle of convection and precipitation, which is driven by a thermodynamical response to solar radiation and interfered with several key mesoscale processes (Yang & Slingo, 2001). Additionally, mountain-valley winds reinforce sea breezes to enhance precipitation over land, which can further be amplified by the cumulus merger processes (Qian, 2008). On intraseasonal timescales, the MJO modulates the diurnal cycle (Oh et al., 2012; Peatman et al., 2014; Sui & Lau, 1992; Sui et al., 1997; Suzuki, 2009; Tian et al., 2006) to complicate rainfall patterns. The active phase of the MJO may enhance precipitation over ocean but suppress precipitation over land (Oh et al., 2012; Rauniyar & Walsh, 2011). Again, all these complexities related to air-sea feedbacks, interactions between different spatiotemporal scales, and model configurations make it challenging to attribute the observed model errors.

2.3. Ocean Throughflows

The coupled dynamics affects not only the surface variability in the ocean but also the volume transport, particularly the throughflows, that is SCSTF and ITF. The former one brings cold, salty water from the western Pacific into SCS through the Luzon Strait and exits through the Mindoro and Karimata Straits (Gordon et al., 2012; Qu et al., 2005, 2009; Xu & Malanotte-Rizzoli, 2013; Zhou et al., 2008). The latter one constitutes the major pathway of warm, freshwater from the Pacific to enter the Indian Ocean through the Indonesian archipelago, transferring climate signals and affecting the energy budget of both oceans (Gordon et al., 2008, Gordon et al., 2010; Schiller et al., 2010). In particular, the ITF vertical structure and temporal variability are affected by the SCSTF (Fang et al., 2010; Gordon et al., 2012; Qu et al., 2009; Tozuka et al., 2007), as the SCSTF may create an upper-layer freshwater plug that spreads into the main channel (Makassar Strait) of the ITF (Gordon et al., 2012; G. Jiang et al., 2019; M. Li et al., 2019). This can lead to an anomalously large dynamic height that weakens the along-strait pressure gradient and thus the southward ITF transport in the upper layer (Gordon et al., 2012; Lee et al., 2019). Large observational programs such as the International Nusantara Stratification and Transport (INSTANT, Gordon et al., 2008; Sprintall et al., 2004), the

Monitoring the ITF (MITF, Gordon et al., 2012, 2019), the Transport, Internal Waves and Mixing in the Indonesian Throughflow regions (TIMIT, Wei et al., 2019), and the SCS-Indonesian Seas Transport/Exchange (SITE, Susanto et al., 2010; Wei et al., 2019) were developed to understand the importance of the ITF and SCSTF for the tropical climate.

The importance of the ITF in modulating the regional climate of the MC, and vice versa, has been extensively studied by linking the throughflows to the IOD-ENSO events (Feng et al., 2018; Liu et al., 2015; Yuan et al., 2011, 2013). The ITF injects warm and salty water into the eastern Indian Ocean and modifies the IOD strength (Gordon et al., 2003). On the other hand, the IOD variability can feed back to the MC and even the western Pacific by the oceanic bridge (e.g., Kelvin waves, Yuan et al., 2011 and 2013) and the atmospheric bridge (e.g., MJO eastward propagation, Napitu et al., 2015; Waliser et al., 1999; Zhang, 2005). The ocean-only model is obviously unable to include the atmospheric bridge feedback, and therefore, the simulated throughflow characteristics are only a response driven by the Pacific Ocean forcing.

The understanding of ITF modulation of climate leads to an expectation that two-way coupled models may be beneficial to the ITF simulation. J. Wei et al. (2014) demonstrated that the fully coupled models overall produced the best estimate of the volume transport of the ITF and its seasonal variability in the Makassar Strait, while the values from ocean-only simulations were all underestimated. Although the coupled model by Aldrian et al. (2005) was not specifically designed to explore this variability and the coupled domain was focused on the region where improvement in precipitation is required, their results show that the coupled model produces stronger variability and southward transport in the long-term simulation of the ITF. Neither of the studies reveals the underlying dynamics associated with the coupled and uncoupled model performances in simulating the ITF transport. All the other coupled model studies listed in Table 1 have not explored the ITF issue.

3. Uncertainty in Models

3.1. Atmosphere Modeling

Rainfall simulation is one of the essential characteristics in the regional model over the MC that begs improvement. Local convective activities are the fundamental rainfall-producing mechanism in this region, which are still not well resolved in models. This is particularly true for climate modeling, as model grid resolution is often coarse (tens of km) to accommodate decadal-scale simulations for the sake of affordable computational cost. Unless the regional model resolution can be sufficiently high (e.g., 3 km or less), the numerical schemes for parametrizing convection are essential. A number of regional climate models show varying patterns of rainfall bias. These include both the underestimation and overestimation of precipitation rates spatially across the MC on the seasonal or annual scale and often present an overestimation (underestimation) of low- (high-) intensity rainfall, as well as a mismatch of the rainfall peak on a diurnal scale (Chow et al., 2006; Gianotti et al., 2012; Y. Li et al., 2017). The results also indicate that the primary driver for the observed rainfall errors in the model is within the atmospheric component, and these errors are attributed to user choices of regional climate model configuration and, more fundamentally, the challenge in accurately resolving the convective rainfall process.

Several studies assess the impact of the atmosphere model configuration on model performance in rainfall simulation. Francisco et al. (2006) evaluated a set of simulations of monsoon seasons over the Philippine archipelago and surrounding oceans. Their study shows that model rainfall patterns are susceptible to the choices of lateral boundary fields (NCEP vs. ERA40) and the ocean surface flux scheme (BATS vs. Zeng). With ERA40 lateral forcing, the model consistently predicts higher amounts of precipitation in comparison to the simulation using NCEP. Similarly, with the BATS scheme, the model also predicts more significant amounts of precipitation in contrast to the simulation with the use of Zeng's scheme. Therefore, different combinations of model configurations (e.g., ERA40 + Zeng's scheme vs. NCEP+BATS) may provide similar simulation results of precipitation. "As a result, it is difficult to unambiguously establish which of the model configurations is best performing." (Francisco et al., 2006).

Similarly, Gianotti et al. (2012) find that the NCEP data set is much drier than ERA40 and causes a dry bias over ocean areas (Figure 4). They conclude that the NCEP data set is less suitable as lateral boundary conditions than the ERA40 data set. Moreover, different convection schemes influence model results

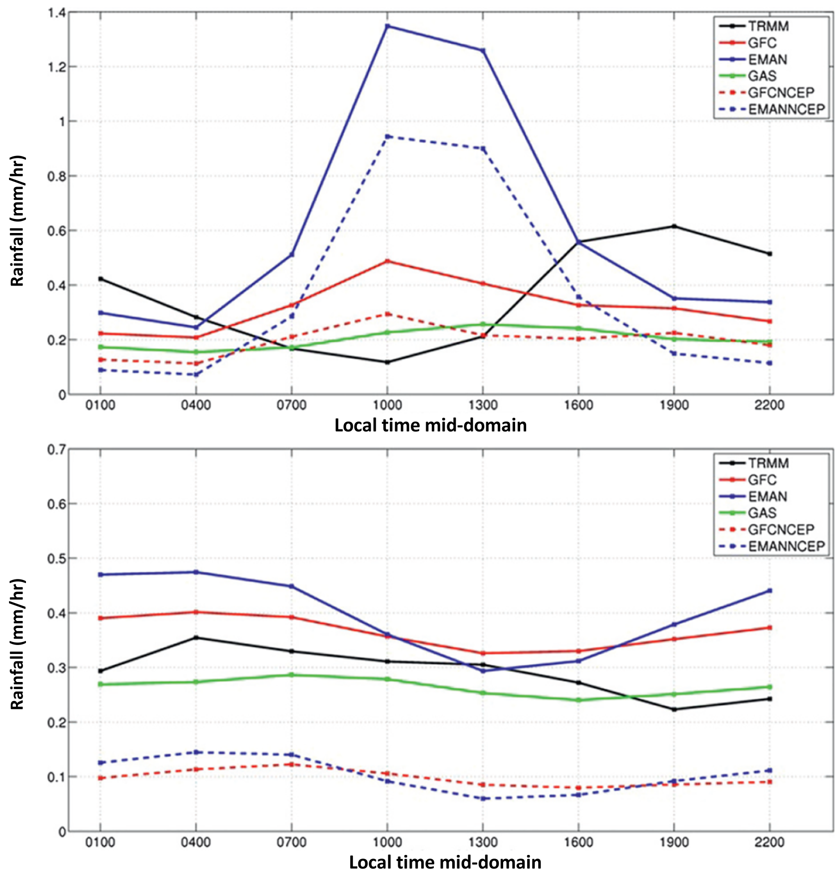

Figure 4. An example of average diurnal cycle of rainfall simulation over the period 1998–2001using different model configuration in comparison to TRMM over land (upper panel) and over ocean (lower panel). GFC: Grell scheme with Fritsch-Chappell; GAS: Grell scheme with Arakawa-Schubert; EMAN: Emanuel scheme; GFCNCEP: GFC with NCEP lateral forcing instead of ERA40; EMANNCEP: EMAN with NCEP forcing instead of ERA40. (Gianotti et al., 2012).

significantly over the tropical region (Davis et al., 2009; Zhou & Neale, 2012). Modeling exercises (Figure 4) over the MC also show that using the Grell scheme with the Fritsch-Chappell closure results in a dry bias over the land and a wet bias over the ocean, while the Grell scheme with the Arakawa-Schubert closure causes dry biases over both land and ocean. On the contrary, using the Emanuel scheme may present a significant wet bias over the entire model domain (Gianotti et al., 2012).

The fact that convective rainfall errors persist to varying degrees, regardless of the choice of model configuration, suggests a fundamental uncertainty in the representation of the convective process in the regional model simulation. Convection results in entrainment and detrainment of air into and out of convective plumes, yet such interactions are usually crudely parameterized with fractional convective entrainment/detrainment rates in most schemes (Y. Wang et al., 2007). Also, errors can stem from the uncertainty of how to activate the convective adjustment, which involves "establishing threshold criteria for triggering convection and creating sufficient environmental conditions to meet those criteria" (Gianotti et al., 2012).

Besides, the uncertainty of model results associated with model grid resolution, and the difficulty in addressing this issue, is significant. As shown in the previous section, model biases are grid resolution dependent (e.g., Y. Li et al., 2017). This suggests that when the model resolution is not sufficiently high to achieve the convergence of model results, resolution-induced uncertainty is observed. Although it may be related to the representation of convection in the model, the issue has yet to be examined more carefully. Similar model performance is also observed in uncoupled regional climate modeling; Im and Eltahir (2018) show that "a higher resolution (12 km vs. 27 km) has improved model performance in simulating the migrating

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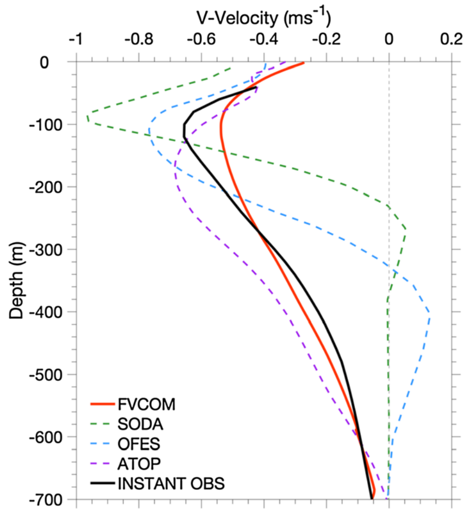

Figure 5. Time-averaged (2004–2012) vertical profile of V-component of INSTANT data (black solid line), FVCOM (red solid line), SODA (green dashed line), OFES (blue dashed line), and ATOP (purple dashed line) at the Makassar Strait. SODA and OFES are reanalysis data, ATOP is an ocean-only model, and FVCOM is the ocean component of a fully coupled model (FVCOM-RegCM).

patterns of rainfall in the vicinity of offshore along western Sumatra and northern Java, two regions characterized by sharp gradients and complex topography. … However, such improvement is not consistent across the whole domain". Similarly, many issues associated with the uncertainty of model configuration and unresolved dynamics are also seen in the ocean model component.

3.2. Ocean Modeling

ITF affects the ocean circulation, thermal structure, and air-sea exchange over the MC (Godfrey, 1996; Lee et al., 2002; Macdonald, 1993; Vranes et al., 2002) and is an essential characteristic that seeks improvement in the ocean modeling for this region. The variability of ITF is influenced by both Rossby and Kelvin waves generated by remote zonal winds, deep upwelling in the Pacific basin, sea level and pressure differences between the Pacific and Indian Ocean, and so forth. (Sprintall et al., 2014; Feng et al., 2018), all of which may introduce uncertainties to regional ocean model.

The Mindanao Current retroflection is another crucial factor affecting the ITF variability through the interaction between the Rossby waves and the western boundary currents. Theoretical analysis of the dynamics of the Mindanao Current flowing across a boundary gap was conducted by Arruda and Nof (2003), Yuan and Wang (2011), and Z. Wang and Yuan (2012). However, the in situ information about nonlinear reflection of the Rossby waves at the western boundary has not been readily available due to a lack of observation data. Recently, based on four consecutive years of mooring observations in the Indonesian Seas, Yuan et al. (2018) obtained for the first time the upper-ocean circulation in the Maluka Sea, the entrance of ITF, which provided solid evidence for the theoretical analysis in Yuan and Wang (2011) and Z. Wang and Yuan (2012). Unfortunately, very few ocean models or coupled models are able to simulate the Mindanao Current retroflection variability well, which may be a future topic of regional coupled model simulation at the ITF entrance.

Another example that indicates the uncertainty in model configurations is the fidelity of ocean reanalysis products, which are often used as lateral boundary conditions for regional ocean models. By comparing total ITF transport estimated from 14 ocean data assimilation products, Lee et al. (2010) find that although these products have overall consistency, results do show considerable variability among these reanalysis products. More importantly, all but one failed to resolve the strong semiannual signal of ITF. Unlike atmospheric modeling, there are no model studies on the MC that systematically investigate the impact of the model configuration on model performances and corresponding errors. Instead, most ocean models for the MC are validated through model-data comparisons, mainly against the data from the INSTANT program (Gordon et al., 2008; 2010). Although regional models showed their success to a certain extent, challenges remain in understanding how to improve the model accuracy in simulating ITF variability and correctly attribute errors to underlying dynamics, model resolution, and boundary forcing.

For example, the newly released MITF data (Gordon et al., 2019) demonstrated significant interannual variability of the Makassar Throughflow that was poorly resolved by the previous model simulations or reanalysis data set. The subsurface velocity maximum (V-max) is mispredicted with respect to amplitude or depth in many reanalysis data sets such as SODA, OFES, and ATOP. A recent model effort by Jiang et al. (2019) obtained a more realistic ITF profile by adopting a higher resolution with ~3 km within the Makassar Strait (Figure 5). This indicates that model resolution may play a critical role in model performance. The model resolution affects not only model results but also underlying dynamics. Early modeling work suggests that the ITF velocity profile is primarily controlled by the southward Karimata flow inhibiting the southward surface ITF (Tozuka et al., 2009; 2007). However, their work used a global ocean model, with a coarse resolution varying from 0.4° to 2°, which cannot resolve the Mindoro-Sibutu Strait (~40 km wide) and is scarcely enough to resolve the Makassar Strait (~200 km wide). On the other hand, based on the HYCOM reanalysis that has a higher resolution of (1/12.5)°, Gordon et al. (2012) proposed another mechanism for which the SCSTF brings fresher and more buoyant SCS water into the Sulawesi Sea through the Mindoro-Sibutu passage, building up a west-to-east pressure head toward the Pacific Ocean and thus inhibiting the surface Mindanao-Sulawesi inflow. By closing the Luzon, Karimata, and Mindoro-Sibutu Straits in an atmosphere-ocean coupled model with 3 km resolution in a set of sensitivity experiments, Jiang et al. (2019) suggested that the Karimata and Sibutu Straits affect the Makassar velocity profile only in the seasonal time scale. Thus, the interannual variability of the V-max depth likely originated from the upstream Mindanao Current. A similar vertical profile of the Mindanao Current was observed by Zhang et al. (2014) at the location of 8°N,127°E, which is likely carrying ENSO signals transferred from the North Equatorial Currents (NEC) and large-scale trade winds.

The vertical mixing (and its representation in models) is another important factor that regulates water mass transformation and transport within the ITF region (Ffield & Gordon, 1996; Koch-Larrouy et al., 2007; Robertson & Ffield, 2005). Large tidal mixing signatures were observed in the Indonesian seas, and "strong vertical mixing modifies the thermocline by transferring surface heat and freshwater to deeper layers before the upper water column is exported to the Indian Ocean" (Ffield & Gordon, 1996). Furthermore, the energy can be effectively transferred from barotropic tides to baroclinic tides with a mean magnitude that is ~20 times higher than averaged in the global ocean (Koch-Larrouy et al., 2007). Moreover, vicious internal tidal energy is well confined in this region due to the existence of multiple semienclosed seas (Koch-Larrouy et al., 2007). Vertical mixing associated with barotropic and baroclinic tides has often been parameterized or explicitly included in regional models in the MC region. Inclusion of tidal mixing may improve water mass characteristics (e.g., T-S diagram) in the different Indonesian seas and may result in increased transport through the Makassar Strait, thus resulting in different transport partitioning and change in net total ITF transport at the outflow passages (Schiller, 2004). Parameterization of vertical mixing also impacts the upper ocean thermal structure. Inclusion of nonbreaking wave-induced mixing may improve modeling of thermocline depth in the SCS, which improves the simulation in SST cooling and typhoon intensity through air-sea feedbacks (Li et al., 2014).

4. Conclusions and Recommendations

After having examined in the previous sections the successes and deficiencies of regional coupled models for the MC, we present here those that we believe are the most important issues which need further investigation.

For the atmospheric component, convective processes are essential dynamic features over the MC, and no regional climate model has adequately resolved them. In addition to allocating efforts to evaluating existing numerical schemes, there is a need to develop approaches suitable for the MC. Convective activity influences coupled dynamics not only through vertical transport of heat and moisture but also through the interaction of cloud-radiation and convection (Gianotti & Eltahir, 2014a, 2014b; Ramanathan & Collins, 1991; Tiedtke, 1988, Xue et al., 2014). Atmospheric motion affects cloud formation, rainfall, and associated atmospheric convection, thus creating convective-cloud-radiative feedback.

Furthermore, the parameterizations of fractional coverage of convective cloud and autoconversion of convective rainfall in large-scale regional climate models (i.e., the model grid size is much larger than the scale of a cumulus cloud) are still very crude. Efforts to better resolve the effects of subgrid variability in convective activity on convective cloud formation and autoconversion are recommended. Recent modeling work (Gianotti & Eltahir, 2014a, 2014b) shows some success in predicting subgrid variability of convective cloud and associated rainfall reduction using a combination of both the cloud liquid water (CLW) simulated in a climate model with climatological CLW and rainfall intensity estimated from observational data. However, more research is still needed.

From the oceanic point of view, ITF is connecting western Pacific and eastern Indian Oceans and therefore is directly impacted by Pacific circulations at its entrances and by the Indian Ocean at its exits. There have been many modeling studies on the ITF variability associated with the Pacific side. However, most of them emphasized on the impacts of the northwestern Pacific on the ITF transport (Gordon et al., 2012; Hirst & Godfrey, 1993; G. Jiang et al., 2019; Li et al., 2019; Qu et al., 2005; Wei et al., 2016). The northwestern Pacific circulations are crucial to the ITF transport; meanwhile Li et al. (2019) show that the lower layer ITF is instead controlled by the southwestern Pacific circulations, the South Equatorial Current (SEC). In addition, the lower layer of the Makassar Throughflow was previously deemed to be insignificant compared to the upper layer. Yet it increases significantly during 2016, reaching an equivalent amount to the upper layer. Jiang et al. (2019) suggest that the vertical profile of ITF at Makassar Strait can be modulated by the Mindanao Current and its retroflection. Therefore, improving the modeling strategy of resolving boundary currents of the western Pacific is vital for better resolving the ITF vertical structure and its variability. On the other hand, as the ITF exits into the Indian Ocean, its variability can be weakened by wind forcing associated with IOD. Compensated effects between IOD and ENSO on the ITF have been reported (Feng et al., 2018; Liu et al., 2015; Stuecker et al., 2017; Yuan et al., 2013). The roles of the ITF exit flows into the Indian Ocean and its feedbacks should also be further investigated.

Within the MC, both more extensive data sets and higher-resolution regional ocean models are crucial to resolve the Mindoro-Sibutu Strait (~40 km wide), the Makassar Strait entrance (~80 km), Lifamatola Passage (~36 km, up to 2,000 m deep), the ITF exit straits, Lombok Strait (~20 km), and Ombai Strait (~40 km). Not only the total transport of the throughflow but also their vertical structures are in need of better resolution. As the INSTANT-MITF data are extended to 2017 (Gordon et al., 2019), the new data reveal very different structures on the Makassar Throughflow profile, which changes significantly in response to the 15/16 summer El Niño. From the modeling point of view, the importance of fully resolving the narrow straits and the bathymetry of the oceanic MC cannot be emphasized enough. Recent studies suggest that the relative importance of the Mindoro-Sibutu pathway cannot be established for the upper layer circulation of the SCS and the ITF unless the model resolution is dramatically increased (Jiang et al. in press).

Apart from resolution issues, including freshwater exchange and tides in coupled models might be critical to achieving accurate simulations. Recent studies have shown that the freshwater exchange between atmosphere and ocean plays an important role (Gordon et al., 2012; Lee et al., 2019), which, however, has rarely been implemented in coupled models. As pointed out by Gordon et al. (2012), freshwater accumulation within the Sulawesi Sea, Makassar Strait, and the Java Sea might be crucial to influence ITF variability and maintain its subsurface V-max profile. Lee et al. (2019) further reveal the dominant contribution of local precipitation and runoff to boreal winter-spring freshening in the Java Sea. Such freshening is associated with an upstream decrease of sea level anomaly along the Makassar Strait, corresponding to a reduced along-strait pressure gradient that would weaken the ITF. On the other hand, most of the present regional models do not include tides, as they focused on the seasonal or interannual time scales. Modeling studies (Ffield & Gordon, 1996; Koch-Larrouy et al., 2007; Tranchant et al., 2016) show that tidal mixing is important in the straits and passages to accurately represent the throughflow variability, as well as the water properties.

A more accurate representation of the coupled dynamics in the model might also be necessary. One missing feedback mechanism in coupled models for the MC region is the momentum exchange induced by surface waves. The representation of the wave effect on the surface roughness and the resulting change in wind stress should be explicitly resolved in the coupled modeling, which in turn affects the oceanic and atmospheric simulation, including surface fluxes and vertical mixing calculations (Drennan et al., 2005; Edson et al., 2013; Shi & Bourassa, 2019). The wave-current-induced surface roughness and the near-surface wind change in the neutral log profile play a vital role in sea-state response to the wave-current-stress coupling, thus causes considerable changes in the latent and sensible heat fluxes (Shi & Bourassa, 2019). To that end, the three-way coupling of the wave, circulation, and atmospheric dynamics needs more attention.

The development of regional coupled climate models over the MC is still in its infancy. Current studies using two-way atmosphere-ocean coupled models focus more on model development and validation. We have identified critical physical mechanisms for this region and associated model biases/drifts. Our review shows that large-scale coupled modes of variability, local air-sea interactions, atmospheric/oceanic dynamics, and processes all contribute to the uncertainties observed in model simulations. We hope that this review will be not only useful to the community but will also stimulate further efforts in those areas we believe are the most important and least understood.

Conflicts of Interest

The authors declare no conflict of interest.

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