Seasonal Prediction of Boreal Winter Rainfall over the Western Maritime Continent during ENSO

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ABSTRACT

Since the beginning of the Association of Southeast Asian Nations Climate Outlook Forum (ASEANCOF) in 2013, the most difficult challenge has been the rainfall forecast in boreal winter. This is the Maritime Continent monsoon season during which rainfall reaches maximum in the annual cycle. This forecast difficulty arises in spite of the general notion that seasonal predictability of the Maritime Continent rainfall may be higher than most places because of the strong and robust influences of ENSO. The lower predictability is consistent with the lower correlation between ENSO and western Maritime Continent rainfall that reaches minimum during the boreal winter monsoon. Various theories have been proposed to explain this low correlation. In this paper, we review the research on ENSO–Maritime Continent rainfall relationship and show that the main cause of the forecast difficulty is the wind–terrain interaction involving the Sumatran and Malay Peninsula mountains, rather than the effect of sea surface temperature (SST). The wind–terrain interaction due to the low-level regional scale anomalous horizontal circulation offsets the anomalous Walker circulation during both El Niño and La Niña. The net result of these two opposing responses to ENSO is a lower local predictability. We propose to call this low-predictability region the WIMP (Western Indonesia–Malay Peninsula) region both for its geographical location and its special characteristic of causing difficulties for forecasters to make a confident forecast for the boreal winter. Our result suggests that climate models lack skills in forecasting rainfall in this region because their predictability depends strongly on SST.

Key words: seasonal forecast, Maritime Continent, ENSO, monsoon, rainfall, wind–terrain interaction

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1. Introduction

The Maritime Continent is a region that is strongly influenced by ENSO. However, the correlation between ENSO and monsoon rainfall over the region is highest in the boreal summer dry and boreal fall transitional seasons, and lowest in the boreal winter monsoon season (e.g., McBride and Nicholls, 1983; Ropelewski and Halpert, 1987). The correlation is low even though in boreal winter, the anomalous Walker circulation associated with ENSO events exhibits a robust pattern of large-scale upper-level convergence over the Maritime Continent during warm events and divergence during cold events. The low correlation may be associated with the typical low skills of climate models in the Maritime Continent area during boreal winter (Neal and Slingo, 2003; Chang et al., 2004b, 2016; Zhang et al., 2016a, b). There is also no clear consensus among climate change models on monsoon rainfall over the second half of the 21st century (Jourdain et al., 2013).

The possible causes of the low correlation during boreal winter have been suggested by several investigators. Hamada et al. (2002) attributed this relationship to the different monsoon onset dates during ENSO. They reported that the onsets are earlier in La Niña years and later in El Niño years. Haylock and McBride (2001) cal-
culated the spatial coherence of Indonesian rainfall anomalies among different stations and showed that over most of Indonesia, the rainfall varies coherently on an interannual timescale during the transition season, but not during the wet season. They reasoned that the “control” of ENSO on the rainfall across the region is therefore effective only during northern fall and that the wet season rainfall in Indonesia is inherently unpredictable. Hendon (2003) postulated that these coherence patterns result from the change of the feedback of ENSO on the sea surface temperature (SST) surrounding the Indonesian islands. The change is due to the seasonal reversal of the prevailing winds. This change leads to the enhancement of the equatorial Pacific SST gradient and Walker circulation from the dry season to the transition season and a rapid reduction in the SST gradient and Walker circulation during the wet season. Chang et al. (2004a, b, 2016) suggested that the key reason of the low correlation is related to the interaction between the anomalous circulation and the complex terrain in the region. They argued that the wind–terrain interaction is the main driving force for the Maritime Continent monsoon rainfall on all timescales from meso- and synoptic scale to the annual cycle to interannual variations. The purpose of this paper is to show that in the western part of the Maritime Continent, the terrain of Sumatra and Malay Peninsula mountains plays an especially important role, such that their interaction with the anomalous horizontal circulations during ENSO offsets the effects of the Walker circulation. The result is a lower predictability of boreal winter rainfall.

2. ASEAN Climate Outlook Forums

In late 2013, the Association of Southeast Asian Nations (ASEAN) working with World Meteorological Organization’s Regional Climate Outlook Forum program for Region V, which covers Southeast Asia, started the series of the ASEAN Climate Outlook Forum (ASEANCOF; http://asmc.asean.org/asmc_asean_cof_about/). The forum has been held twice a year to produce consensus climate outlooks for boreal winter and boreal summer seasons, respectively. The outlooks are derived by consensus from discussions of both climate model forecasts from major world centers and subject forecasts from experienced National Meteorological and Hydrological Service (NMHS) forecasters of individual member nations attending the forum. The results of all six boreal-winter outlooks (DJF, 2013/14 to 2018/19) produced at the time of the writing of this manuscript highlight the significant difficulty in forecasting the boreal winter rainfall in the western part of the Maritime Continent, particularly over a local region covering Sumatra, the Malay Peninsula, and western Borneo. The challenge in reaching a consensus rainfall forecast (ASEANCOF-1, -3, -5, -7, -9, and -11) is a key reason that this is the only local region to have the highest probability assigned to the middle tercile (near normal) in five of the six boreal winters (Table 1). It was not until the most recent consensus outlook (for DJF 2018/19) that one of the non-normal terciles, the “above normal” category, receives a probability that exceeds the near normal category.

The favoring of the near normal category in the first five DJF outlooks does not necessarily mean that the NMHS forecasters predicted a near normal rainfall season. Rather, it also reflects the lack of confidence resulting from the diverging results from different models. This is indicated in the remark in the ASEANCOF-9 Bulletin, which reviews the outlook of DJF 2017/18 produced in ASEANCOF-9: “For the regions where predictions favoured near-normal conditions but the season developed into above- or below normal-conditions, the near-normal predictions were considered low-confidence predictions due to the low probability attached to the middle tercile category.” This lack of confidence dominated the first three DJF outlooks [ASEANCOF-1 (ASEANCOF-1, 2013), -3 (ASEANCOF-3, 2014), and -5 (ASEANCOF-5, 2015)] for DJF 2013/14, 2014/15, and 2015/16

### Table 1. The probabilistic rainfall outlooks for boreal winter (DJF) produced from the six ASEANCOFs between 2013/14 and 2018/19 in terms of tercile categories of above normal (upper tercile), near normal (middle tercile), and below normal (lower tercile) in the western Indonesia and Malay Peninsula region, with Sumatra being the primary location. In ASEANCOF-1, -3, and -5, most of the region is in the probabilistic rainfall outlook regime of Sumatra, so one set of tercile probabilities can be used to represent the outlook of the region. In ASEANCOF-7, -9, and -11, some parts of the region outside of Sumatra contains tercile probabilities that are different from the primary (Sumatra) regime, so a second set of the probabilities is listed on the right side columns of this table.

| ASEANCOF | Boreal winter | Above normal | Near normal | Below normal | Above normal | Near normal | Below normal |
|---------|---------------|--------------|-------------|--------------|--------------|-------------|--------------|
| 1       | 2013/14       | 35           | 35          | 30           |              |             |              |
| 3       | 2014/15       | 30           | 50          | 20           |              |             |              |
| 5       | 2015/16       | 30           | 40          | 30           |              |             |              |
| 7       | 2016/17       | 20           | 40          | 40           | 40           | 40          | 20           |
| 9       | 2017/18       | 30           | 30          | 40           | 40           | 40          | 40           |
| 11      | 2018/19       | 50           | 30          | 20           | 40           | 40          | 20           |
even though in ASEANCOF-1 the distribution of probability shows 35% for both near normal and above normal for DJF 2013/14. This first ASEANCOF was held on 2–3 December 2013, after the DJF season has started. At that time, some NMHSs have already announced their official seasonal forecast for the season based on traditional empirical methods. The empirical forecasters did not know about the diverging climate model results at the time of their forecast, and an above normal forecast for western Maritime Continent was published before 1 December 2013. It would be very confusing if the official ASEANCOF outlook contradicts an official NMHS seasonal forecast made just a few days earlier. As a result, the ASEANCOF-1 participants agreed to change the consensus outlook from a 30/40/30 distribution to 35/35/30.

After the first three DJF seasons, the ASEANCOF consensus outlooks began to show probabilities of above or below normal tercile that matches or exceeds the normal tercile. This eliminated the concern that the model divergence and the resulting lack of confidence dominate the forecast of this region. Below we evaluate the skill of these recent three outlooks. Figure 2a shows the ASEANCOF-7 rainfall outlook for DJF 2016/17. Here the outlook (20/40/40) called for an equal chance of near normal and below normal. The following ASEANCOF-8 (2017) bulletin did not provide a graphic comparison of the outlook with observed rainfall. As a surrogate for the latter, we show in Fig. 2b the anomaly outgoing long-wave radiation (OLR) for DJF 2016/17 downloaded from the Asia–Pacific Climate Center (APCC), Busan, Korea. In the latter, low OLR, indicative of above normal rainfall anomaly, dominates over the entire Maritime Continent region, and this is especially conspicuous over Sumatra. Thus, the attempt to make a skillful forecast of the possibility of a deficit in rainfall did not do well, with the forecast turning out to be opposite from what happened.

Figure 3 compares the ASEANCOF-9 outlook for DJF 2017/18 with the observed rainfall anomaly published in ASEANCOF-10. The outlook probability of 30/40/30 (Fig. 3a) for most of the region was very different from the observed strong anomaly signals, both above and below normal (Fig. 3b). There was some good news in the small area over western Borneo, where a local probability regime of 20/40/40 shows skill as the observed rainfall shows a deficit. But overall the forecast was wrong.

The rainfall outlook for DJF 2018/19 produced in ASEANCOF-11 was the first time that the near normal tercile has a lower probability than a non-normal tercile. Figure 4a shows that in the primary region, the entire Sumatra was assigned a 50% probability of above normal, indicating a strong confidence that was not seen before. However, compared to the observed anomaly pattern published by ASEANCOF-12 (Fig. 4b), an outlook of near normal would have been better, and a below normal outlook would be even better. Hence, this high confidence forecast also turned out to be wrong. It is interesting that ASEANCOF-11 also assigned a 50% above normal probability for the Southeast Asian mainland to
the north of the region, which was clearly very successful. The skill showing in the secondary region of southern Malay Peninsula appears to be a “spill out” from the successful above normal forecast in the Southeast Asian mainland, rather than in a different regime as shown in Fig. 4a.

Therefore, the seasonal forecast for boreal winter rainfall in the western Maritime Continent remains a serious challenge in spite of an apparent increase in the confidence in the operational climate models by NMHS forecasters in the ASEANCOF program. This difficulty is not limited to the ASEANCOF consensus outlook. Zhang et al. (2016a, b) showed that the NCEP Climate Forecast System version 2 (CFSv2), which was not a part of the guidance models used by ASEANCOF, generally produced skillful rainfall forecast in both dry and wet seasons for eastern Maritime Continent but only in the dry season for western Maritime Continent (Fig. 5).

3. Roles of wind–terrain interaction

Instead of the seasonal march in other monsoon regions where the annual cycle of rainfall is synchronized with that of the monsoon winds, the annual cycle of rainfall in the Southeast Asia–Maritime Continent region is mainly driven by the interactions of the local terrain with the prevailing winds from the surrounding oceans (Chang et al., 2004a, 2005, 2016). Chang et al. (2004b) suggested that similar effects may give rise to local rainfall–ENSO relationships that vary among different sub-regions during boreal winter, when the region is affected by cold surges off the Asian continent from the north, Indian Ocean zonal wind anomalies from the west, and cross-equatorial flow from the south. These external influ-
ences from different directions each have their own dynamics and interannual variations that are usually not well correlated, so that one part inside the domain may have localized relationship with ENSO that is different from other parts. This view was confirmed by several recent analyses (e.g., Ma et al., 2018; Chen et al., 2019; Xu et al., 2019).

Using the 1979–2002 NOAA Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) rainfall and eastern Pacific SST, Chang et al. (2004b) showed that the low correlation between ENSO and Maritime Continent rainfall during boreal winter is limited to a western section of the Maritime Continent rather than across the full width of Indonesia (Fig. 6). Outside of this limited sub-region, the correlation is significant in most of the central part of the Maritime Continent and the southwestern oceanic area adjacent to the western coast of Sumatra. The low-correlation sub-region covers mainly Sumatra and Malay Peninsula (“SMP” in Fig. 6) and extends to Java and western Borneo coast. It coincides with the region in which the ASEANCOF has difficulty to produce skillful consensus outlooks for the boreal winter monsoon rainfall. This sub-region over western Indonesia and Malay Peninsula has been called different names (“SMP” by Chang et al., 2004b, “SMB” by Zhang et al., 2016a, “WMC” by Zhang et al., 2016b, and “the Sumatra, Malay Peninsula and western Sarawak/Kalimantan regions” by ASEANCOF). Here we
propose to use the name “WIMP” (Western Indonesia–Malay Peninsula) region for three considerations. It describes the geographic region of West Indonesia and Malay Peninsula; it can stand for “Weak Interacting Monsoon Precipitation” to describe the relationship (idea borrowed from the description of dark matter in theoretical physics) with ENSO; and it reflects the difficulties in reaching a consensus decision faced by operational forecasters.

Figure 7 shows that the correlation between rainfall in the WIMP region and the adjacent southwest oceanic area to the west (“SWO” in Fig. 6) and central Maritime Continent to the east (CMC in Fig. 6) are both weak, while the correlation between the non-adjacent SWO and CMC rainfall is significantly higher. This is an indication that the rainfall variations in the SWO and CMC region may be synchronized by the same driving mechanism. Since typically the planetary scale rainfall anomalies over the Maritime Continent regions are wet during La Niña and dry during El Niño, the composite of the anomalous 850-hPa winds from the 1979–2002 NCEP reanalysis with respect to the Niño3 SST (Fig. 8a) is compared with that with respect to the WIMP rainfall. Figures 8a and 8b show their Niño3 cold anomaly (cold minus warm) and WIMP wet anomaly (wet minus dry) composites, respectively. The main difference between Figs. 8a and 8b is the equatorial 850-hPa westerly wind, which in the cold anomaly (Fig. 8a) is stronger and extends over a large longitudinal span from Indian Ocean to central Maritime Continent. This is a manifestation of the anomalous Indian Ocean Walker cell during La Niña that is often enhanced by the Indian Ocean zonal SST gradient (Li et al., 2003), and the anomalous cyclonic circulation centered near Philippines, which is established and extends southwestward into the equatorial South China Sea during La Niña. This anomalous cyclonic circulation is the counterpart of the Philippine Sea anticyclone that develops in boreal fall of the El Niño developing phase (Zhang et al., 1996; Wang et al., 2000; Wang and Zhang, 2002; Li et al., 2016). The convergence with the anomalous easterly wind from the Pacific Walker cell implies strong rising motion and favors convection in the eastern and central parts of the Maritime Continent. On the other hand, in the WIMP wet anomaly (Fig. 8b), the equatorial westerlies from Indian Ocean is weaker and attenuates in the WIMP region, so the convergence with the low-level easterlies from the Pacific Walker cell occurs mainly in the WIMP region.
The difference between Figs. 8a and 8b may be viewed from two angles. The first is to consider La Niña events. If a La Niña is strong, then the westerlies associated with the Indian Ocean Walker cell and the extension of the Philippines circulation in the South China Sea will also be strong and penetrate further to the east, pushing the maximum convergence to central and eastern Maritime Continent rather than the WIMP area. The high correlation of the SWO and CMC rainfall shown in Fig. 6 results from the Indian Ocean westerlies encountering the Sumatra mountains, producing heavy rainfall on the windward side and a deficit of moisture on the lee side. Therefore, the WIMP area is even less likely to experience heavy rainfall. Both situations suggest that a strong La Niña condition is unfavorable for the WIMP area to have excess rainfall. Another angle is to consider the El Niño events, which may be examined by reversing the anomaly signs in Fig. 8 to those of the warm anomaly (warm minus cold). In this case, the circulation centered near the Philippines is anticyclonic and strengthens the equatorial easterlies in the South China Sea, which favors rainfall in the WIMP area as the anomalous easterly winds will encounter mountains in Sumatra and Malay Peninsula from the east (Fig. 8). In either scenario, the rainfall in the WIMP area tends to have an anomaly sign that is opposite to the rest of the Maritime Continent during strong Niño3 events. On the other hand, if the Niño3 anomalies are not strong, the development of the Philippines circulation (and possibly the Indian Ocean SST gradient) likely will be less pronounced. The opposite tendency of rainfall anomalies between WIMP and the other parts of the Maritime Continent may be less pronounced too. In such cases, it is conceivable that the rainfall in the WIMP area will be dominated by the planetary-scale Walker cells driven by ENSO, and the correlation pattern between rainfall and Niño3 may be more uni-
El Niño development phase

The importance of the effect of wind–terrain interactions associated with the Sumatra mountains has been confirmed in separate analyses of El Niño and La Niña events by Jiang and Li (2018). They used 1979–2012 data to show that in El Niño events, the effect of the anomalous anticyclone in the South China Sea is more prominent, and in La Niña events, the effect of the Indian Ocean westerlies is more prominent. The difference in importance of these two circulation systems in the opposite phases of ENSO actually points to the same information, namely, the rainfall produced from the lifting of moist air by the Sumatra mountains is the dominant effect of the observed rainfall anomalies in the WIMP region in both phases of ENSO.

Chang et al. (2004b) suggested that rainfall in the WIMP area may also be affected by an anomalous cross-equatorial flow that interacts with the East Asian winter monsoon. In the cold anomaly composite (Fig. 8a), the zonal wind direction between the equator and northern Australia is mostly westerly over 125°–140°E while it is mostly easterly in the WIMP wet anomaly composite (Fig. 8b). The mean 850-hPa wind field in this region during the boreal winter monsoon (Fig. 8c) has prevailing westerly winds that are the result of the cross-equatorial flow from the Northern Hemisphere. Thus, for cold events (La Niña), the anomalous circulation enhances the northern-winter mean cross-equatorial flow, while for the WIMP wet events, it opposes the cross-equatorial flow. In the latter case, the cross-equatorial monsoon wind is opposed upstream (north) of the equator, which will favor anomalous 850-hPa convergence and more rainfall in the WIMP region.

Lindzen and Nigam (1987) proposed that local SST anomalous warming can set up anomalous ascending motion by low-level moistening. Haylock and McBride (2001) and Hendon (2003) have suggested that the low correlation of rainfall in the Indonesian region with ENSO may be the result of the SST anomalies. Jiang and Li (2018) evaluated this possibility by examining the evolution of area-averaged vertical velocity and SST anomalies during the ENSO development phase. They found that the anomalous ascending motion that peaks in January starts before October, two months prior to the local warming of the SST (Fig. 9). Thus, the factor leading to anomalous rainfall in December already starts in October and November and is primarily due to the orographic lifting of the Sumatra mountains, and not due to the lo-

Fig. 9. Normalized area-averaged 850-hPa vertical \( \omega \) velocity \( \omega_{850} \) evolution (black solid line) and SSTA evolution in the western Maritime Continent region (black dotted line; 4°S–5°N, 100°–112°E) and in a broader equatorial Maritime Continent region defined by Hendon (2003) (black dashed line; 0–10°S, 95°–135°E) during El Niño year from July (0) to February (1) (from Jiang and Li, 2018).

Fig. 10. Schematic diagram of the low-level anomalous circulation over the WIMP area during (a) La Niña and (b) El Niño development phases. For La Niña, the circulation centered near Philippines is cyclonic and the equatorial anomalous westerlies are part of the lower branch of the planetary-scale Walker circulation that produces low-level convergence in the broad Maritime Continent area. However, the westerlies in the eastern Indian Ocean encounters the Sumatra mountains and produce dry descent in the WIMP region, resulting in decreased rainfall. For El Niño, the equatorial anomalous easterlies are part of the lower branch of the Walker circulation that produces low-level divergence over in the broad Maritime Continent area, while the easterlies associated with the Philippine Sea anticyclone encounters the Sumatra mountains from the west, producing moist ascent and increased rainfall in the WIMP region. The shading represents the topography (m).
cal SST warming.

4. Concluding remarks

The decrease of correlation between Maritime Continent rainfall and ENSO from the dry and transition seasons to the boreal winter wet season appears to be caused by the wind–terrain interaction in the WIMP region. The interaction is particularly strong on the sides of the steep mountains in Sumatra, which is a narrow island aligned approximately northwest–southeast and perpendicular to the prevailing wind. This interaction can be demonstrated by the schematic diagrams of the low-level anomalous circulations during ENSO in Fig. 10. During development phase of La Niña (Fig. 10a), the planetary-scale Walker circulation produces anomalous westerlies around the equator that generally leads to low-level convergence and anomalous rainfall in the Maritime Continent region, but the westerlies in the equatorial Indian Ocean encounters the Sumatra mountains causing more rainfall on the windward side and less on the lee side. Thus, the WIMP area tends to experience less rainfall. During the development phase of El Niño (Fig. 10b), the planetary-scale Walker circulation produces anomalous easterlies around the equator that leads to broad-scale low-level divergence and rainfall deficits in the region. But the circulation of the anomalous anticyclone near Philippines produces upward motion and more rainfall on the east side of the Sumatra mountains, or the WIMP region. Therefore, in both cases the local wind–terrain interaction due to the anomalous horizontal circulation offsets the effect of the planetary scale anomalous Walker circulation. The result is a less predictable rainfall anomaly in the WIMP region.

The low skill in seasonal forecast by climate models is likely the result of models not able to represent this offsetting mechanism adequately, which is at least partly due to the model resolutions that are inadequate to represent the complex terrain of the region. Most climate model predictions appear to be rooted in the linkage between SST and rainfall (Zhang et al., 2016a, b). In order to improve forecast for the WIMP area, climate models need to be freed from the over-dominance of this SST linkage and incorporate properly the local terrain effects that are very important for the Maritime Continent monsoon rainfall for all timescales.

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