The 2011 Great Flood in Thailand: Climate Diagnostics and Implications from Climate Change

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ABSTRACT

Severe flooding occurred in Thailand during the 2011 summer season, which resulted in more than 800 deaths and affected 13.6 million people. The unprecedented nature of this flood in the Chao Phraya River basin (CPRB) was examined and compared with historical flood years. Climate diagnostics were conducted to understand the meteorological conditions and climate forcing that led to the magnitude and duration of this flood. Neither the monsoon rainfall nor the tropical cyclone frequency anomalies alone was sufficient to cause the 2011 flooding event. Instead, a series of abnormal conditions collectively contributed to the intensity of the 2011 flood: anomalously high rainfall in the premonsoon season, especially during March; record-high soil moisture content throughout the year; elevated sea level height in the Gulf of Thailand, which constrained drainage; and other water management factors. In the context of climate change, the substantially increased premonsoon rainfall in CPRB after 1980 and the continual sea level rise in the river outlet have both played a role. The rainfall increase is associated with a strengthening of the premonsoon northeasterly winds that come from East Asia. Attribution analysis using phase 5 of the Coupled Model Intercomparison Project historical experiments pointed to anthropogenic greenhouse gases as the main external climate forcing leading to the rainfall increase. Together, these findings suggest increasing odds for potential flooding of similar intensity to that of the 2011 flood.

1. Introduction

The Chao Phraya River basin (CPRB) flows through densely populated areas in Thailand, including large areas of manufacturing industry in and around Bangkok (Fig. 1). The Chao Phraya River flows from the northern mountains of Thailand southward into the Gulf of Thailand. The lower CPRB and Bangkok cover a low-lying area, less than 2.5 m above mean sea level (MSL) and in some areas below mean sea level (Cooper 2014),

and terrain like this slows down the river substantially. Having an area of 162 800 km², CPRB covers approximately 30% of the country (Aon Benfield 2012), and its episodic floods have impacted agriculture, economics, and life in general to a great extent. The lower basin has undergone several large flooding events, including those in 1831, 1942, 1983, 1995, 1996, 2002, 2006, and 2011 (Aon Benfield 2012). The flood in 1995 was ranked the highest in terms of submerged area (444 000 km²), while the 2011 flood ranked ninth (97 000 km²; Gale and Saunders 2013). However, the 2011 flood lasted 158 days—longer than any other flood event in history and affecting the urban area. Damage and economic losses were unprecedented (Haraguchi and Lall 2014). As a result, the 2011 flood has been considered the worst in the last 50 years (Aon Benfield 2012; Rakwatin et al. 2013).

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FIG. 1. Map of Thailand and the CPRB (shaded area of terrain) with blue boxes highlighting northern Thailand or upper CPRB (indicated by “a”), central Thailand or lower CPRB (indicated by “b”), and the Gulf of Thailand (indicated by “c”). The red box marks the location of Bangkok.

Previous studies suggest that the 2011 flood was caused by heavy rainfall in the northern and central CPRB (Thai Meteorological Department 2011; Aon Benfield 2012; Komori et al. 2012; Gale and Saunders 2013; Rakwatin et al. 2013). The large rainfall amounts that accumulated from March to October were compounded by five tropical storms that affected Thailand from June through October (Thai Meteorological Department 2011). Gale and Saunders (2013) suggested that the above-normal summer monsoon rainfall in 2011 was related to anomalous low pressure and a moderately positive Southern Oscillation index (SOI), which is typically associated with La Niña. While the peak of the 2011 flood was not the highest, its duration was the longest in history (Koontanakulvong 2012). The extended period of flood is likely linked to high tides in the

Gulf of Thailand, which raised the river level to 2.6 m MSL (Rakwatin et al. 2013), together with land subsidence of Bangkok, which is sinking at a rate of $2\text{--}3\text{ cm yr}^{-1}$ (Aobpaet et al. 2009).

The lack of direct links of the 2011 flood with specific natural causes is concerning. For instance, van Oldenborgh et al. (2012) reported that the amount of rainfall in the CPRB was not unusual, and La Niña in 2011 did not have a prominent effect on the region. Gale and Saunders (2013) noted that there were substantially more tropical storms in 1995 than 2011 and yet the 1995 flood was not nearly as severe. Additionally, in 2011 the monsoon arrived on 6 May, which is about 7 days earlier than normal (Thai Meteorological Department 2011). This early onset is in contrast with the projected 15-day delay in monsoon onset in Southeast Asia for the twenty-first century (Ashfaq et al. 2009; Loo et al. 2015). As far as climate change is concerned, van Oldenborgh et al. (2012) did not find any role of climate change in the 2011 flood as a result of the lack of significant trend in the monsoon precipitation in Thailand. As will be discussed in this paper, the mere focus on monsoon season precipitation undermines the substantial effect of pre-monsoon precipitation on soil moisture and sea level. Therefore, the objectives of this study were to 1) explore the climatic causes of the 2011 severe flood in CPRB along with a comparison with historical flood years and 2) diagnose the climate conditions, trends, and their collective implication on future flood occurrence in the basin.

The paper is arranged as follows. Section 2 introduces the methodology. The outputs from our diagnostics are presented in the five parts of section 3: section 3a considers rainfall distribution and changes, section 3b evaluates the role of soil moisture and sea level, section 3c explores the impact of tropical cyclones, section 3d looks at weather and climate patterns, and section 3e conducts a model attribution analysis. Section 4 provides concluding remarks and a discussion of the implications on future flood occurrence in the CPRB.

2. Data and methods

a. Methodology

The conceptual framework to fulfill our objectives is to quantify the climatic factors involved in the imbalance of natural water supply and demand in the CPRB. Precipitation and tropical cyclones are the primary sources of water addition to the basin, while soil moisture content and sea level height determine the capacity of natural discharge. Different from previous studies, we included soil moisture content and sea level height in our analysis and considered them as important factors

for flooding in Thailand. To explore the role of climatic variations in the 2011 flood in CPRB, we conducted empirical analyses (e.g., linear regression and correlation) and analyzed climate model outputs. First, we examined atmospheric and surface conditions of 2011 and compared them with those of five historical flood years (1983, 1995, 1996, 2002, and 2006). Monthly distributions of rainfall, soil moisture content, and sea level height averaged over the upper and lower basins were analyzed. To assess the impacts of tropical cyclones on the precipitation and flooding in 2011, we analyzed tracks that potentially affect Thailand from either the Bay of Bengal or western North Pacific. In terms of climate dynamics, epoch differences of 850-mb wind field and sea surface temperature between 2011 and 1980–2013 were examined, both at regional and global domains. We also analyzed the springtime occurrence of rainstorms over CPRB using daily wind fields. Trends were computed for rainfall, soil moisture content, sea level height, and tropical cyclone frequency in order to assess the role of climate change on the 2011 flood. To attribute the role of climate change in the long-term rainfall variations, we analyzed simulation outputs forced with various external climate forcings, following previous studies (Cho et al. 2015; Wang et al. 2015) that have used similar models for attributing climate extreme events in South Asia.

b. Data sources

We analyzed four meteorological variables (precipitation, tropical cyclones, wind, and sea surface temperature) and two relevant factors (soil moisture and sea level height). Daily precipitation was obtained from two sources: the Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE; <http://www.chikyu.ac.jp/precip/>), version 1101, which covered the monsoon Asia region of 15°S–55°N, 60°–150°E for the period of 1951–2007; and the Tropical Rainfall Measuring Mission (TRMM; http://disc2.nascom.nasa.gov/dods/3B42_V7_daily) daily precipitation for the period 1998–2014. Since APHRODITE and TRMM produced agreeable rainfall analyses over monsoon Asia (Yatagai et al. 2012), both precipitation datasets were merged to create a longer, continuous dataset covering 1951–2014 with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The merger was done by subjecting the two datasets to least squares regression during their overlapping period. The regression function was then applied to the TRMM data to correct for the mean differences and systematic biases. We note that, although the APHRODITE and TRMM datasets have correlated trends, magnitude differences do exist and the correction method eliminated those differences.

We also analyzed monthly precipitation data from CRU time series (TS), version 3.21, to cross-check the precipitation trend obtained from APHRODITE and TRMM.

The 6-h-interval best-track records of tropical cyclones over the period of 1975–2014 were obtained from the Joint Typhoon Warning Center (JTWC; http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/) and UNISYS Weather (<http://weather.unisys.com>). Monthly soil moisture (assimilation) data with a spatial resolution of $0.5^\circ \times 0.5^\circ$ were obtained from the NOAA/OAR/ESRL Physical Sciences Division (PSD; <http://www.esrl.noaa.gov/psd/data/gridded/data.cpcsoil.html>). The dataset contains model-based water height equivalent (volume of water/soil surface area) over landmass (van den Dool et al. 2003; Fan and van den Dool 2004). The wind field of the period 1951–2014 was obtained from the NCEP–NCAR reanalyses at a spatial resolution of $2.5^\circ \times 2.5^\circ$ (Kalnay et al. 1996). Sea level height data came from the Oceans and Atmosphere Flagship of Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Arctic and Ecosystems (ACE) Cooperative Research Centre (CRC) as a combination of data from various satellites (http://www.cmar.csiro.au/sealevel/sl_data_cmar.html). The sea level data are monthly averages on a $1^\circ \times 1^\circ$ grid applied with an inverse barometer correction, seasonal (annual and semiannual) signal removal, and glacial isostatic adjustment (GIA) correction (Church et al. 2004). NOAA Extended Reconstructed SST, version 3b (ERSST.v3b), data with a resolution $2^\circ \times 2^\circ$ during the period of 1854–2014 were also used.

Finally, for the attribution analysis of external climate forcing, we analyzed precipitation outputs of 10 models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) historical single-forcing experiments, which were driven by (i) only greenhouse gas forcing (GHG), (ii) only aerosol forcing (AERO), (iii) only natural forcing including volcanic and solar forcing (NAT), and (iv) all of the forcings combined (ALL). These experiments were initialized from a long, stable preindustrial (1850) control run up to 2005. The specifics of these models are described in Table 1.

3. Results and discussion

a. Rainfall distribution and changes

We compared the monthly and accumulated rainfall in 2011 with that of the other flood years (1983, 1995, 1996, 2002, and 2006) for two study areas, defined as the upper CPRB (16.0°–20.6°N, 97.5°–101.5°E; indicated by “a” in Fig. 1) and the lower CPRB (13.5°–16.0°N, 98.5°–101.5°E; indicated by “b” in Fig. 1), the division of

TABLE 1. CMIP5 specifics as used in this study.

Acronym	Model name	Organization, country	Ensemble member size
CanESM2	Second Generation Canadian Earth System Model	Canadian Centre for Climate Modelling and Analysis, Canada	5
CCSM4	Community Climate System Model, version 4	National Center for Atmospheric Research, USA	3
CNRM-CM5	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France	6
GFDL CM3	Geophysical Fluid Dynamics Laboratory Climate Model, version 3	National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, USA	3
GFDL-ESM2	Geophysical Fluid Dynamics Laboratory Earth System Model, version 2	National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, USA	1
CSIRO Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation Mark 3.6.0	Commonwealth Scientific and Industrial Research Organisation/Queensland Climate Change Centre of Excellence, Australia	4
FGOALS	Flexible Global Ocean–Atmosphere–Land System Model	Institute of Atmospheric Physics, Chinese Academy of Sciences, China	1
GISS-E2	Goddard Institute for Space Studies Model E2	National Aeronautics and Space Administration Goddard Institute for Space Studies, USA	3
IPSL-CM5	L’Institut Pierre-Simon Laplace Coupled Model, version 5	L’Institut Pierre-Simon Laplace, France	3
NorESM1	Norwegian Earth System Model, version 1	Norwegian Climate Centre, Norway	1

which follows [Molle \(2007\)](#) and [Rakwatin et al. \(2013\)](#). [Figures 2a and 2b](#) illustrate the distribution of monthly rainfall averaged for the upper and lower CPRB, respectively, for these 6 flood years and the 63-yr average (1951–2013). Rainfall in 2011 was above the 63-yr average from January to July in the upper basin and until August in the lower basin. This excessive rainfall apparently occurred and accumulated before the flood started at the upper CPRB in late July. The usually dry month of March and the early monsoon season of May–July received significantly more rain than normal. According to the [Thai Meteorological Department \(2011\)](#), measured rainfall was higher than the 61-yr average (1951–2011) by $\sim 370\%$ in March and $\sim 110\%$ in June, consistent with (and therefore verifying) our analysis using gridded data merged from TRMM and APHRODITE.

It is worth noting that monsoon rainfall in 2011 after July was not unusual—it was only slightly above normal in the upper CPRB ([Fig. 2a](#)). In fact, rainfall was below normal in the lower CPRB after August ([Fig. 2b](#)). This is contrary to most other events in which heavy monsoon rains (July–October) caused the flooding ([Chokngamwong and Chiu 2008](#); [Thai Meteorological Department 2012](#)), such as the monsoon season flooding

in 1995 ([Gale and Saunders 2013](#)). In the lower CPRB, the highest amount of monsoon rainfall occurred in 1983, not 2011. In terms of annual accumulation of precipitation ([Figs. 2c,d](#)), the 2006 amount actually surpasses the 2011 amount and yet it did not cause any serious flooding. Thus, rainfall accumulation alone is not a universal indicator for flooding in the CPRB. Likewise, heavy monsoon rains emphasized by previous studies ([Thai Meteorological Department 2011](#); [Aon Benfield 2012](#); [Komori et al. 2012](#); [Gale and Saunders 2013](#); [Rakwatin et al. 2013](#)) could not be held as a primary cause for flooding. In the case of 2011, wintertime and premonsoon rainfall anomalies in the upper CPRB appear to be critical.

The role of climate change in the abnormal rainfall of 2011 was investigated by plotting the rainfall trends separately for the premonsoon (January–April) and monsoon (May–October) periods over 33 years (1980–2013). [Figures 3a and 3b](#) illustrate a significant increase in rainfall during the premonsoon season for both the upper (coefficient of determination $r^2 = 0.33$, $p < 0.01$) and lower ($r^2 = 0.32$, $p < 0.01$) CPRB. This trend coincides with the record rainfall received in the upper basin during the dry season of 2011. By comparison, the monsoon season rainfall exhibits a flat trend in the upper CPRB ([Fig. 3c](#)) and an insignificant upward trend in the

FIG. 2. (a),(b) The 63-yr average (1951–2013) monthly rainfall overlaid with the 6 flood years for the upper (top) and lower CPRB (bottom). (c),(d) Cumulative rainfall of each flood year and the 63-yr average for the upper (top) and lower CPRB (bottom). The above- and below-normal rainfall in 2011 is indicated by yellow- and blue-filled areas, respectively.

lower CPRB (Fig. 3d). This lack of trend in the monsoon rainfall led van Oldenborgh et al. (2012) to conclude that climate change was not involved in the 2011 floods. However, Fig. 3c does suggest that the monsoon rainfall variability has amplified in recent decades with a strong decadal signal, as was noted by Kripalani and Kulkarni (1997). According to the literature, such rainfall variability might be associated with the Indian Ocean dipole (Muangsong et al. 2014), SOI (Singhrattna et al. 2005), El Niño–Southern Oscillation (ENSO) (Singhrattna et al. 2005; Muangsong et al. 2014), or the Pacific quasi-decadal oscillation (Wang and Gillies 2013). More importantly, Fig. 3c indicates that the highest monsoon rainfall in the upper CPRB occurred in 1994, a nonflood year. This observation suggests that premonsoon rainfall plays a more important role in the 2011 flood than monsoon rainfall.

To understand the seasonal difference in the long-term change, we derived the monthly trend of rainfall for three different periods: 1951–2013, 1951–79 (an early era), and 1980–2013 (a recent era). The linear trend slopes of each month are plotted for the upper (Fig. 3e) and lower (Fig. 3f) CPRB. The results indicate that rainfall during the dry season (January–April and

December) has increased considerably in the recent era, with the most dramatic change in March (i.e., a month of record rainfall in 2011). Although interdecadal variation is apparent and might involve natural causes, in the following section we will show that anthropogenic causes do apply. During the monsoon months, rainfall in either basin does not reveal any robust trends, with the exception of the lower basin (Fig. 3f) in which the early monsoon (May–July) rainfall has increased. Increased rainfall in this region of Thailand coincides with the finding of Wang et al. (2013) that early monsoon rainfall in the vicinity of Myanmar has increased partly as a result of anthropogenic aerosols.

b. Role of soil moisture and sea level

Despite the abnormal rainfall, change in the water budget of a basin system also directly influences flood potential. Here, we analyzed soil moisture content anomalies as an indicator for infiltration capacity and runoff (Nijssen et al. 2001). As soil moisture increases in the premonsoon season, rainfall infiltration and percolation in the monsoon season could be low, causing the river basin runoff to move more easily and/or quickly (Nijssen et al. 2001). The situation could worsen when

FIG. 3. (a) Premonsoon (January–April) rainfall overlaid with the linear trend of the period 1980–2013 (red) and the 5-yr moving average (orange) for the upper CPRB. (b) As in (a), but for the lower CPRB. Linear trend slopes are highly significant with $r^2 = 0.33$ and 0.32 , $p < 0.01$, for the upper and lower CPRB, respectively. (c),(d) As in (a),(b), but for the monsoon season (May–October). (e),(f) Linear trend slopes of monthly rainfall for the periods of 1951–2013, 1951–79, and 1980–2013 in the upper and lower CPRB, respectively.

the basin receives high rainfall during and after the monsoon onset. Figures 4a and 4b show the monthly distribution of soil moisture indicating the low point in April and high point in September. In 2011, soil moisture started to exceed normal in March and stayed above normal until October, amounting to as much as 11 cm above the long-term mean—the highest among all flood years. This continual surplus in soil moisture stands out from other flood years during which soil moisture was uniformly lower than normal, with the exception of 2006 when soil moisture was near normal. Arguably, the abnormally high soil moisture content in 2011 so early in the season facilitated the release of discharge when large rainfall events occurred in subsequent months, increasing runoff in the CPRB (Komori et al. 2012). The importance of concurrent increases in soil moisture and rainfall during the premonsoon season to the flood magnitude is clearly illustrated. In further examination, historical trends of premonsoon soil moisture (January–April) are shown in Figs. 4c and 4d for both basins. Although 2011 had the highest soil moisture after 1990, there was not an apparent trend in the soil moisture content of the CPRB during the past 3–4 decades. This observation echoes the pan-evaporation

data in the CPRB showing a decrease throughout the years since 1970 (Tebakari et al. 2005; Limjirakan and Limsakul 2012), which may be related to the increase in rainfall. Therefore, interannual variability in rainfall and temperature may explain the above-normal soil moisture anomaly in 2011. This relationship will be further analyzed in the weather and climate pattern section next.

Sea level height can affect drainage of surplus water from CPRB to the Gulf of Thailand (Rakwatin et al. 2013). When sea level at the mouth of CPRB rises, water flowing from the river into the Gulf of Thailand slows. Trisirisatayawong et al. (2011) have measured a tidal increase of $0.6\text{--}0.8\text{ cm yr}^{-1}$ near the coast of Bangkok and the mouth of the Chao Praya River. Under these circumstances, Dutta (2011) projected Bangkok to be increasingly vulnerable to flood. Therefore, we analyzed sea level fluctuation and its seasonal patterns within the domain of $6.1^{\circ}\text{--}13.5^{\circ}\text{N}$ and $99^{\circ}\text{--}106^{\circ}\text{E}$, covering the Gulf of Thailand (Fig. 1c). Figure 5a shows monthly sea level height and the fact that 2011 was higher than the long-term average and all other flood years by a great margin, reaching 12.5 cm above normal in March and 5 cm above normal in July and August. By late October as floodwater reached the inner metropolitan area of

FIG. 4. Monthly distribution of soil moisture computed from the 1951–2014 average overlaid with 6 flood years for the (a) upper and (b) lower CPRB. The above-normal soil moisture content in 2011 is indicated by the yellow area. Premonsoon soil moisture for the (c) upper and (d) lower CPRB overlaid with the linear trend after 1980 (red) and the 5-yr moving average (orange).

Bangkok, sea level height was about 4 cm above average, thereby obstructing drainage from CPRB and possibly prolonging the flood. This effect of sea level on drainage can be illustrated by comparing with the shorter flood duration in 2006 (Gale and Saunders 2013), as the sea level was near normal and would not have

blocked the drainage as much as it did in 2011. The implication of this observation is important because, according to Fig. 5b, average sea level in the Gulf of Thailand has increased about 5 cm since 2003 and 8 cm since 1994. This trend is expected to continue under the warming climate.

FIG. 5. (a) Monthly distribution of sea level height in the Gulf of Thailand from the long-term (1993–2013) average and overlaid with 6 flood years. The anomaly of 2011 sea level height from normal is indicated by the yellow area. (b) Flood-period sea level height (July–December) overlaid with the linear trend. The linear trend slope was highly significant with $r^2 = 0.67$, $p < 0.01$.

Recall that in Figs. 3a and 3b we showed that the premonsoon rainfall in the CPRB underwent a pronounced increase since 1980. Incidentally, Lacombe et al. (2012) suggested that the projected rainfall increases would induce local sea level rise by 2050. In addition, sea level variation in the tropical Pacific Ocean is regulated by ENSO events (Chang et al. 2013), and this coincides with the presence of La Niña in 2011 with increased sea level in the western Pacific and Indian Ocean—an interannual feature that adds to the changing climate and sea level trends.

c. Impact of tropical cyclones

Thailand is more prone to tropical cyclone strikes after July. In 2011, there were six tropical storms that impacted Indochina, and these were suggested as a contributor to the flooding (Aon Benfield 2012; Gale and Saunders 2013). However, only one tropical storm reached Thailand before the flood period (i.e., before July), while the other five impacted Thailand during and after July (Nockten in July, Nesat and Haitang in September, Nalgae in October, and Washi in December) when the flood had already taken place. Thus, it is unlikely that tropical cyclones contributed much to the abnormal rainfall of the premonsoon season in any significant manner. As shown in Fig. 6, which depicts tropical cyclone tracks during the period of 1975–2014, mainland Southeast Asia undergoes frequent tropical cyclones coming from two sides: the Bay of Bengal and the western North Pacific. However, compared to other flood years, the timing and annual number of tropical cyclones in 2011 were not outstanding; in fact, the 2011 number (six cyclones) was lower than the average of 1975–2013 (seven cyclones). The fact that rainfall in the post-July period of 2011 was not outstanding (cf. Fig. 3) suggests that the tropical cyclones that impacted Thailand, as depicted in Fig. 6b, may not contribute sufficiently to the flooding. We also note that the annual tropical cyclone numbers in the western North Pacific (13.5°–20.6°N, 97°–115°E) and the northern Indian Ocean (13.5°–20.6°N, 90°–106°E) have not changed throughout the recent 40 years (analysis not shown). Therefore, we argue that the effect of tropical cyclones on the 2011 flood is minimal.

d. Weather and climate patterns

In this section, we analyze the climate anomalies in 2011 and associated trends in the context of atmospheric circulations. The abnormal rainfall during winter and premonsoon seasons in the upper CPRB is likely driven by patterns of circulation anomalies. In Fig. 7a we show the 6-hourly zonal u wind evolution at 850 mb as the time–longitude diagram for March each year, averaged

FIG. 6. Tropical cyclone tracks that could have affected Thailand from both the Bay of Bengal (blue) and western North Pacific (yellow) over the period 1975–2014 during (a) January–June and (b) July–December. Red lines indicate 2011 tropical cyclones.

over 13°–20°N across the CPRB from 95° to 110°E. Low-level zonal wind was analyzed in order to depict any change in the easterly flows that dominate the winter season (i.e., before the arrival of the monsoonal westerly winds). The month of March is shown here because it received the highest anomaly of rainfall in 2011. As shown in Fig. 7a, 2011 stands out as having the most pronounced easterly winds from the middle to end of March compared to all other years. This means that the relatively cool northeasterly monsoon that characterizes winter in the CPRB was much enhanced in 2011. This is further illustrated in Fig. 8a by the departure of 850-mb winds during January–April from the climatology (i.e., persistent increase in the northeasterly flows coming from East Asia). The strengthened northeasterly flows interact with the mountains in western CPRB, enhancing orographic lift and subsequent rainfall generation. The cooler air temperature in spring 2011 over the CPRB (not shown) also acted to reduce evaporation and increase soil moisture.

In Fig. 7b, we show the 6-hourly 250-mb meridional v winds in the same time–longitude cross sections as Fig. 7a to examine the activity of synoptic waves passing through the CPRB. Although a rather strong trough passed over the basin in mid-March 2011, which produced substantial frontal rainfall (not shown), neither the magnitude nor frequency of the synoptic waves is unprecedented. This result indicates that strong

low-level northeasterly wind played a crucial role in the increased precipitation of 2011 as it interacted with upper-level synoptic troughs and orography. Apparently, any long-term change in the circulation regimes affecting the CPRB is likely tied to the lower-tropospheric circulations more so than the upper level.

The large-scale circulation pattern and associated SST anomalies were examined in Fig. 8 for the period of January–April. At the regional domain (Fig. 8a), the enhanced winter monsoon manifested as northeasterly flows is accompanied by cold SST anomalies over the East Sea and the South China Sea, suggesting a strengthened East Asian winter monsoon. Meanwhile, in the Bay of Bengal the wind anomalies appear to be southwesterly accompanied by a local warming in the SST. The outcome of these two converging flows is that they collided near the western hills of the CPRB. When compared to the long-term change in the low-level wind and SST, depicted by the era difference between the years of 1951–79 and 1980–2013 (Fig. 8b), similar wind patterns appear: southwesterlies in the Bay of Bengal and (weak) northeasterlies along the East Asian coast. However, the SST near East Asia has increased persistently during the past three decades as a result of anthropogenic warming and a warming landmass (Luo et al. 2012; He and Zhou 2015).

By expanding our analysis to the global domain, it is found that the 2011 anomalies in the 850-mb winds and SST (Fig. 8c) exhibit a pattern generally consistent with the long-term change (Fig. 8d; i.e., era difference between 1997–2013 and 1980–96), although around East Asia the colder SST and stronger winter monsoon northeasterlies stood apart from the global pattern as a pronounced regional feature. One possible explanation is that the well-developed La Niña during 2011 may enhance East Asian winter monsoon; this echoes the observation by Cheung et al. (2012) that the cold event of ENSO (i.e., La Niña) tends to enhance the Siberian high and lower the temperatures in East Asia. This observation is also apparent in 2011 by the robust anticyclone anomaly over Siberia (Fig. 8c), in contrast to its absence in the long-term change (Fig. 8d). The discrepancy here suggests that the stronger East Asian winter monsoon during 2011 is likely affected by interannual variability rather than a long-term trend. On the other hand, the Indian Ocean warming and the anomalous southwesterlies over the Bay of Bengal are part of the long-term change, and these may incidentally enhance the 2011 situation by transporting moisture toward the CPRB from the increasingly warmer water of the Bay of Bengal (Wang et al. 2013). This feature contributed to the increase in the wintertime precipitation over the CPRB, as seen in Fig. 3, through

FIG. 7. (a) The 6-hourly u wind at 850 mb during 1–31 Mar for each year since 1985, averaged over 13° – 20° N across the CPRB from 95° to 110° E (the light-blue dashed contours represent -8 m s^{-1}). (b) As in (a), but for the v wind at 250 mb.

convergent upslope winds from the east and moist flows from the southwest, as shown in Fig. 8b.

e. Model attribution analysis

The next important question is the extent to which the post-1980 rainfall increase resulted from anthropogenic climate change. As an attribution analysis, premonsoon rainfall in the upper and lower CPRB as simulated by the CMIP5 ensembles are displayed in Figs. 9a and 9b with normalized scales. The ALL experiments produced the rainfall increase in both the upper and lower basins, though the increase in the upper CPRB is not significant. Only the GHG experiments reproduced the marked increase in rainfall after 1980, while the AERO and NAT experiments generated a flat trend. We therefore could reach a preliminary conclusion that anthropogenic

FIG. 8. The 850-mb wind (vectors) and SST anomalies (shading) computed from (a) 2011 and (b) epoch between the periods of 1997–2013 and 1980–96 for Southeast Asia in the premonsoon season [January–April (JFMA)]. (c),(d) As in (a),(b), but for the global domain.

GHG plays an important role in the increase of premonsoon rainfall, especially in the lower CPRB. Overall in the tropics, increased GHG would increase precipitation as the atmosphere holds more water; however, the precipitation processes in CPRB are manifold. Some implications are suggested: (i) an increase in radiative forcing, especially GHGs, can influence radiation balance on the surface, and, according to [Singhrattna et al. \(2005\)](#), there is a significant correlation between surface temperature in March–May and rainfall in August–September over Thailand, likely due to the increased land–ocean gradient; and (ii) rainfall in northern Thailand has been reported to fluctuate in association with global temperature increases ([Likasiri et al. 2014](#)). However, our analysis indicated a less direct dynamical process—that the slight decrease in temperature after 1980 (not shown) is related to the discernable strengthening of the cool northeasterly winds ([Fig. 8b](#)) associated with the global SST and low-level circulation changes, both of which are tied to the GHG-induced global warming (e.g., [Tokinaga et al. 2012](#)). The GHG-induced Pacific SST pattern (e.g., [Yeh et al. 2012](#)) that resembles La Niña’s structure shown in [Fig. 8d](#) also helps strengthen a 2011-like anomalous wind pattern.

4. Concluding remarks

The causes of the extreme floods in Thailand during 2011 were diagnosed in terms of the changes and variability in meteorological and surface conditions. The 2011 flood was different from most of the other flooding years in that it was driven by unusually high rainfall in the premonsoon (normally dry) season leading to unusually saturated soil moisture. Together with the lower basin’s drainage being constrained by the large increase in sea level height in the Gulf of Thailand, the flood became not only widespread but also prolonged. Putting these yearly anomalies in the context of climate change, the effects of the substantially increased rainfall during the premonsoon season and sea level rise in the Gulf of Thailand were evident. The rainfall increase in CPRB is coupled with a mild strengthening of northeasterly winds prevailing in the premonsoon season, a feature associated with the documented global SST and circulation changes at the interdecadal time scale. In 2011, the northeasterly winds were further enhanced by La Niña. Attribution analysis using the CMIP5 single-forcing experiments indicated that anthropogenic GHG played an important role in

FIG. 9. Premonsoon rainfall derived from observations and CMIP5 ensembles of GHG, AERO, NAT, and ALL forcings superimposed with the 5-yr moving average (black) and post-1980 linear trend (orange) constructed for the (a) upper and (b) lower CPRB. Normalization of the time series is given by $[(\text{value of variable } x_i - \text{sample mean } \mu) / \text{sample std dev } \sigma]$. Annual mean is plotted against the overall mean as the zero line. The anomaly means above the overall mean are plotted as positive, and anomaly means below the overall mean are plotted negative. The r^2 and p values are given for those that are significant.

producing the sustained increase of premonsoon rainfall over the CPRB. Additional analysis is necessary to further the understanding of the physical processes linking GHG increase in the global context to the eventual increase in the regional rainfall, such as utilizing the full archive of daily CMIP5 outputs to examine and attribute the weather pattern change over CPRB.

Apart from climatic causes, the extreme flood in 2011 also could have resulted from other factors that involve human activities and civil engineering, such as types of land cover, land-use change (Sriwongsitanon and Taesombat 2011; Jothityangkoon et al. 2013), interactions between a river channel and its natural and/or constructed flood plain (Trigg et al. 2013), and impacts of reservoir operation (Mateo et al. 2014). Water

management factors appeared to exacerbate the scale of the 2011 flood, such as inefficient drainage canals with broken dykes, together with challenges in managing large dams of the Bhumibol and Sirikit Reservoirs (Aon Benfield 2012; Rakwatin et al. 2013; Haraguchi and Lall 2014; Mateo et al. 2014). As Komori et al. (2012) pointed out, had the water been drained from these reservoirs earlier in the monsoon season (instead of storing it as is common practice), $1 \times 10^9 \text{ m}^3$ of floodwater could have been stored in the reservoirs during the monsoon season.

Regardless, given the results in this study that the increases in both local rainfall and sea level height are tied to anthropogenic GHG, the potential for flooding events similar in intensity to that of 2011 will increase. Of particular concern is the inevitable increase in sea level in the Gulf of Thailand, which will make the lower CPRB prone to longer-duration floods. On the other hand, such flooding occurrence would not be sudden and can be progressively monitored. Thus, future water management can benefit from monitoring the premonsoon and monsoon onset rainfall, soil moisture, and sea level height; this could help determine the timing and volume to drain water from reservoirs in order to mitigate flooding at its onset stage. Solving these many puzzles is by no means trivial and will require a truly cross-disciplinary approach.

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