Regional trends in early-monsoon rainfall over Vietnam and CCSM4 attribution

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Abstract

The analysis of precipitation trends for Vietnam revealed that early-monsoon precipitation has increased over the past three decades but to varying degrees over the northern, central and southern portions of the country. Upon investigation, it was found that the change in early-monsoon precipitation is associated with changes in the low-level cyclonic airflow over the South China Sea and Indochina that is embedded in the large-scale atmospheric circulation associated with a “La Niña-like” anomalous Sea Surface Temperature (SST) pattern with warming in the western Pacific and Indian Oceans and cooling in the eastern Pacific. The Community Climate System Model version 4 (CCSM4) was subsequently used for an attribution analysis. Over northern Vietnam an early-monsoon increase in precipitation is attributed to changes in both greenhouse gases and natural forcing. For central Vietnam, the observed increase in early-monsoon precipitation is reproduced by the simulation forced with greenhouse gases. However, over southern Vietnam the early-monsoon precipitation increase is less definitive where aerosols were seen to be preponderant but natural forcing through the role of the Interdecadal Pacific Oscillation (IPO) may well be a factor that is not resolved by CCSM4. Increased early-monsoonal precipitation over the coastal lowland and deltas has the potential to amplify economic and human losses.

Keywords: Long-term precipitation trends; climate regimes of Vietnam; attribution analysis; greenhouses gases; aerosols; natural forcing; and climate change

1. Introduction

Vietnam is included within 10 countries ascribed most vulnerable to the effects of a changing climate (Bruun 2012), yet its long-term precipitation variations and trends along with associated forcing to date have not yet been satisfactorily understood. The one exigent issue lies in the spatiotemporal dynamics of future precipitation as impacted by a projected warming climate. A few recent studies have already investigated the interannual and decadal variability of precipitation in central Vietnam during autumn when tropical cyclones are frequent (e.g., Buckley et al. 2014; Wang et al. 2015), but these were somewhat wide-ranging analyses that did not focus regionally.

Vietnam comprises a narrow strip of mostly mountainous land that is oriented north to south along the Indochina Peninsula's eastern coast from roughly 9°N to 24°N latitude (Fig. 1a). The highest elevations are found along the Annamite Range along the western border with Laos and Cambodia while low-lying plains are common along the long eastern shoreline. Consequently, the distribution of annual precipitation is to some extent terrain-dependent, and so we can ascribe three major regions in terms of precipitation to northern, central, and southern Vietnam; these respectively (Fig. 1b) are in the north where precipitation reflects the summer monsoon regime (June – August) (Fig. 1c; Chen et al. 2004), in the central region reflecting the autumn regime (September – November) (Fig. 1d; Wang et al. 2015; Nguyen et al. 2007; Yen et al. 2011; Yokoi and Matsumoto 2008), and that in the south that is influenced by both regimes (Figs 1e). Of particular consequence is the extent of the autumn rainfall over central Vietnam which results from orographic lifting of the northeasterly monsoon flows and a greater frequency

of tropical cyclones impacting the region during autumn (Li et al. 2015; Nguyen et al. 2014). Lastly, it is worth noting that Vietnam's winter dry season (January to March) is the result of the annual migration of the Inter-Tropical Convergence Zone (ITCZ) to south of 10°N. The phenology of Vietnam then leans toward humid subtropical in the North, monsoon in the Central region and, monsoon & tropical savanna in the South as defined by the Köppen classification system.

Despite different seasonal precipitation regimes that occur over Vietnam, it was of interest to survey precipitation tendencies over the past few decades in the early-monsoon season for all three regions, given that the early stage of monsoon features increased instability and may be more sensitive to environmental changes (Wang et al. 2011). An analysis of the precipitation indicated a general-wide expansion and, in light of this, it was incumbent to investigate the associated atmospheric circulation features, with the aim to qualify and quantify any concomitant factors or attributes that have arisen over a period of planetary climate change aka global warming.

2. Data and Methods

For our analyses of rainfall distribution and timing we utilized the global gauge-based precipitation data from NOAA's Precipitation Reconstruction over Land (PREC/L) for the period 1948–2013 with a resolution of $1.0^{\circ} \times 1.0^{\circ}$; this was because its mean distribution and annual cycle of precipitation agree well with those in several other gauge-based datasets (Chen et al. 2002). For meteorological fields, we used the NCEP/NCAR Reanalysis data (Kalnay et al. 1996), which has a resolution of $2.5^{\circ} \times 2.5^{\circ}$ and covers the time period 1948–2013. The NOAA Extended Reconstructed Sea Surface Temperature (SST) V3b (Smith et al. 2008; Smith and Reynolds 2004), with a resolution of $2.0^{\circ} \times 2.0^{\circ}$ for the period 1854–2013 was used to analyze

the global SST patterns as they pertain to this study.

To perform detection and attribution analyses, we utilized 7 fully coupled climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012). The details of the 7 chosen models are listed in Table 1. The four sets of CMIP5 Historical Single-Forcing Experiments (Taylor et al. 2012) that were used to indicate anthropogenic factors in climate change over those that are natural were: (a) Aerosols Experiment (AERO) simulations that were driven with observational estimates of anthropogenic aerosols from 1861–2005 with all other forcing sources fixed at 1860 levels, (b) Natural Forcing Experiment (NAT) that comprises volcanic and solar forcing based on observational estimates of changes in solar irradiance and volcanic eruptions from 1861–2005, with all other forcing sources held at 1860 levels, (c) Greenhouse Gases Experiment (GHG) that was forced with observationally-based estimates of well-mixed greenhouse gases from 1861 to 2005, with all other forcing sources kept at 1860 levels, and (d) All Forcing Experiment (ALL) that were driven with observational estimates of changes in all forcing sources for 1861–2005.

3. Results

a. Observed trends

Prior analysis of Vietnam’s precipitation, over the past 65 years, had revealed three discrete rainfall regions, namely the north, the central and the south; these are outlined in Figure 1b. As already mentioned, a Vietnam’s orography plays a varied role in augmenting its regional climate. However, an analysis of early and post monsoon precipitation over the entire year had established that precipitation during the early-monsoon season has consistently increased in each of the regions; this analysis is plotted in Figures 2a, 2b and 2c. Note that the occurrence of early-monsoon conditions for each region is slightly lagged – for the north it is April-June, central,

July-September and south, February-April and these are indicated in Figures 1c through 1e. The increase in early-monsoon precipitation began in 1980 and is statistically significant ($p < 0.05$) in all three regions. As the Supplementary Figures S1-3 show, precipitation in the other seasons has increased slightly or not at all, though together they do contribute to a net increase in annual total precipitation (not shown).

The aforementioned early-monsoon precipitation increase is associated with the recent warming of the surface waters surrounding Vietnam and is illustrated in Figures 3a through 3f. As is observed in Figure 3, the South China Sea (SCS) along with the northern Indian Ocean have warmed, together with the development of a lower-level cyclonic circulation anomalies. Extending the analysis domain as shown in panels (d) through (f), the circulation changes over Vietnam are embedded in a large-scale anomalous circulation pattern known to be associated with “La Niña-like” SST changes that have occurred in recent times (e.g., England et al. 2014; L'Heureux et al. 2013). The predominant low-level cyclonic anomalies and the warming of the SCS are consistent features within each of the three seasons. Also worth mentioning is the overall strengthening of the trade winds in conjunction with enhanced westerly winds over the SCS and the northern Indian Ocean as is observed in observational data sets as well as in reanalysis data (de Boisseson et al. 2014). Tropical cyclones in the SCS may be linked to these trends especially in central and southern regions. Analyzing tropical cyclone tracks and frequency, Wang et al. (2015) showed that the peak tropical cyclone season for central Vietnam has shifted from October to November while, over the SCS in general, tropical depressions (with the maximum sustained wind speed under 33 kts) has undergone a pronounced increase by threefold throughout the September-December season. These tropical cyclone and depression changes are systematic of the observed increases in coastal precipitation.

In terms of the larger scale, an examination of 200 hPa circulation changes (Figures 4a-c) indicates a strengthening of Walker circulation across the tropical Pacific that is accompanied by enhanced rising motion over the western Pacific and sinking motion over the eastern Pacific (L'Heureux et al. 2013); these are consistent with previous studies that used different data sets (e.g., England et al. 2014). As shown in Supplemental Figure S4, the change in the Walker circulation towards the aforementioned regime (of the La Niña-like) has strengthened with an increase in amplitude only observed in the recent decades, apparently exceeding the low-frequency fluctuation through the entire 20th century.

b. Attribution of trends

The next question of consequence concerned the extent to which the pronounced increase in early-monsoon precipitation is attributable to climate change due to either greenhouse gas emissions or aerosols and, to what extent it might be due to natural forcing. Hence, we analyzed the CMIP5 Historical Experiments in a straightforward attribution analysis. A first step however was to conduct a baseline performance measure of the models to evaluate their ability to capture the seasonal variability of precipitation; this was accomplished by decomposing the seasonality into dominant modes (annual and semiannual cycles) through the application of principal component (PC) analysis on the harmonics-filtered precipitation (*sec*, Wang et al. 2009): First, by extracting the annual cycle (first harmonic) and semi-annual cycle (second harmonic) of the monthly long-term precipitation using Fourier analysis and second, the filtered cycles were processed using empirical orthogonal function (EOF) analysis. Third, each cycle was decomposed into two additional modes. The decomposed annual cycle uncovers the winter-summer (Figure 5a) and spring-fall (Figure 5b) modes, while the semi-annual cycle was disintegrated into two PCs that depict the first and second semi-annual modes (Figures 5c and

5d). The four panels of Figure 5 (a-d) therefore illustrate the spatial patterns of the eigenvectors of the four modes (indicated by EOF1-4) for the observations (i.e. PREC/L) followed by each CMIP5 precipitation simulation driven with ALL forcing. The eigencoefficients of the four PCs are given in Figures 5e-h. As was indicated in Wang et al. (2009) each of these isolated seasonal components represents the dominant feature of climate over each region. The percentage of each mode, indicated in the bottom right-hand corner of each panel, provides the variance of the seasonal precipitation explained in terms of the combination of annual and semiannual cycle modes. Next calculated was the spatial correlation coefficient (R) and Root Mean Square Bias (RMSB) of each EOF component between each model and the PRECL observed data. In the end, the CCSM4 model yielded the highest R and smallest RMSB values as well as being concomitant with PRECL, in essence capturing the patterns of all seasonality components.

As a further evaluation, simulated precipitation trends in ALL-forcing experiments was compared against the observations for each of the three regions; this assessment also indicated that CCSM4 was the only model that captured the broad increase in precipitation over all three regions (Figure 1b). Therefore, the CCSM4 simulations were selected as the most representative of the models for attribution analysis. Figure 6 shows the results of the attribution analysis for the three regions: The first row designates the observed early-monsoon precipitation trends whereas subsequent rows represent CCSM4 simulations of early-monsoon precipitation – sequentially ALL, AERO, NAT and GHGs forced conditions. For the Northern region, the simulations suggest that GHG and NAT play a role in driving the early-monsoon precipitation increase but it would seem that GHG, at $0.033 \text{ mm day}^{-1} \text{ year}^{-1}$ as compared to NAT ($0.012 \text{ mm day}^{-1} \text{ year}^{-1}$) is foremost (almost threefold) in forcing the increasing early-monsoon precipitation change. In the central region, however, the trend is more distinct and is redolent of GHG

dominance, especially so when the signals in AERO and NAT trends are slightly negative. In the case of southern region, CCSM4 implies that NAT forcing is predominant at $0.011 \text{ mm day}^{-1} \text{ year}^{-1}$ but atmospheric aerosols at $0.008 \text{ mm day}^{-1} \text{ year}^{-1}$ are also a contributor with GHG following at a close second to AERO at $0.005 \text{ mm day}^{-1} \text{ year}^{-1}$. Despite the breakdown by forcing, the ALL scenarios are emblematic of the observations.

The fact that NAT prevails in the south is not surprising, as the role of natural variation in southern Vietnam has been noted in a previous study (Buckley et al. 2014) that the Interdecadal Pacific Oscillation (IPO) is a primary driver of low-frequency climate variability. Being an important natural driver of the variation in Walker circulation, the IPO's impact on post-1990 climate variability has been studied (e.g., England et al. 2014; McGregor et al. 2012; Kosaka and Xie 2013; McGregor et al. 2014; Merrifield and Maltrud 2011; Nidheesh et al. 2013; Dong and Zhou 2014; Han et al. 2014). However, these previous studies mostly focused on the western tropical Pacific sea level, broad precipitation changes in the Pacific region, the Indo-Pacific ocean currents, and increased heat uptake in the equatorial Pacific thermocline. These studies have not reached a consensus regarding the causes of the pronounced, more recent trend in the Walker circulation. Distinguishing the effect of IPO on the early-monsoon precipitation increase from that of GHG forcing is as challenging (and perhaps as uncertain) as separating the IPO's effect on the warming hiatus (e.g., Kosaka and Xie 2013).

4. Summary and Discussions

A preliminary analysis disclosed that early-monsoon precipitation over Vietnam has increased in recent decades and this is the case for three geographical regions: While northern Vietnam early-monsoon precipitation is a summer phenomenon, central Vietnam's occurrence is

that of the autumnal monsoon, whereas southern Vietnam is influenced by both. When atmospheric instability arises, i.e. during the early-monsoon season, localized intensification of regional SST of the surrounding oceans (i.e. the SCS) further enhances instability. Wang et al. (2015) found that the convective available potential energy (CAPE), an indication of lower-to-middle tropospheric instability, did show an increasing trend along the Vietnam coast especially in the central region. It was in this context that the increasing early-monsoon precipitation trend can be connected with the change in a regional-scale atmospheric circulation pattern imbedded within a large-scale circulation, one associated with broad SST change in the Pacific and Indian Oceans. The aforementioned configuration exemplifies as cooling in the eastern Pacific and warming in the western Pacific and Indian Oceans; this coincided with a strengthened Walker circulation as reported in the literature.

Seven CMIP5 models were evaluated for their ability to represent the early-monsoon precipitation fields for the three geographical regions: CCSM4 demonstrated the greatest skill in reproducing the complex precipitation annual and semi-annual cycles and the increasing early-monsoon precipitation trends, hence it was chosen for the attribution analysis. CCSM4 would advocate that the observed increase in early-monsoon precipitation over central Vietnam may be in response mainly to anthropogenic GHG and secondary or insignificantly to AERO and NAT forcing. In northern Vietnam, the early-monsoon precipitation increase is suggestive of a likely consequence of GHG, but NAT forcing is also implied while AERO forcing results in a decrease in precipitation. In southern Vietnam, the individual trends were less definitive and are likely masked by the role the IPO plays in the region: the GHG and NAT runs are essentially flat while AERO forcing would seem to be a contributor to increased early-monsoon precipitation.

We note that attribution analysis using CMIP5 models should be interpreted with caution

since such models including CCSM4 are limited by their coarse resolution (which does not resolve Vietnam's complicated terrain) and inability to capture the full extent of tropical cyclones that are a crucial precipitation contributor to central Vietnam. Nonetheless, change in water cycles is always of concern in any part of the world. Increased early-monsoonal precipitation that manifest as storms and resultant flooding will only result in amplified economic and human losses; this due to the fact that a high proportion of the country's population and economic assets (including irrigated agriculture) are located in coastal lowlands and deltas. The potential socio-economic impact of a change in early-monsoon precipitation extremes is critical when it comes to agriculture, forestry, fisheries and energy, not to mention disruption in areas like transportation all of which have bearing on human and ecological health and well-being.

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338 **Table 1. CMIP5 (the Coupled Model Intercomparison Project Phase 5) models used in the**
339 **attribution analysis**

Acronym	Full name	Developers
CanESM	Canadian Centre for Climate modeling and Analysis The second Generation Earth System Model 2	Canadian Centre for Climate Modelling and Analysis
CCSM4	Community Climate System Model version 4	National Center for Atmospheric Research
CESM	The Community Earth System Model	The National Center for Atmospheric Research (NCAR)
CNRM-CM5	National Centre for Meteorological Research Coupled Model 5	Centre National de Recherches Meteorologiques /Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France
CSIRO	Commonwealth Scientific and Industrial Research Organization	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)
IPSL-CM5	Institute Pierre Simon Laplace Coupled Model 5	Institute Pierre-Simon Laplace
NorESM1	Norwegian Earth System Model 1	Norwegian Climate Centre (NCC)

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Supplemental Figures

Figure S1: (a) The time series of precipitation in January-March over northern Vietnam (light blue bars), superimposed with its 6-year running average (black line) and post-1980 trend (red line). (b)-(d): Same as (a) but for April-June, July-September, and October-December, respectively.

Figure S2: (a) The time series of precipitation in January-March over central Vietnam (light blue bars), superimposed with its 6-year running average (black line) and post-1980 trend (red line). (b)-(d): Same as (a) but for April-June, July-September, and October-December, respectively.

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Figure S4: The boreal winter zonal wind shear computed by zonal wind difference between 250hPa and 850hPa averaged over the climatological Walker Circulation region (5°S - 5°N , 160°E - 120°W), derived from the four reanalysis datasets as denoted in upper left. The thin line indicates the raw values while the thick line depicts the 5-year-running mean of the vertical shear. Units: m/s.