Reply to "Comments on 'Changes to the North Atlantic Subtropical High and Its Role in the Intensification of Summer Rainfall Variability in the Southeastern United States'"

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ABSTRACT

Recently Diem questioned the western ridge movement of the North Atlantic subtropical high (NASH) reported in a 2011 paper of Li et al. This reply shows more analysis that further strengthens the conclusions originally put forth by Li et al. Diem's analysis of the trend in the western ridge of the NASH was based on the data over a 30-yr period (1978–2007), whereas the main conclusions in Li et al. were drawn according to the data over a 60-yr period (1948–2007). Over the last 60 years, the NASH has shown a significant trend of westward movement, the meridional movement of the western ridge of the NASH has enhanced in the recent three decades, and the potential impact of global warming cannot be ruled out in an attempt to explain these changes of the NASH.

1. Introduction

In recent decades, summer precipitation over the southeastern United States (SE U.S.) has exhibited intensified year-to-year fluctuations (Wang et al. 2010). Li et al. (2011, hereafter LLFDW11) demonstrated that the enhanced summer rainfall variability in the SE U.S. was directly linked to variations in the location and intensity of the North Atlantic subtropical high (NASH), in agreement with Henderson and Vega (1996) and Katz et al. (2003). Specifically, LLFDW11 shows that the NASH has intensified and moved westward during the 60-yr period (1948–2007), and its western ridge has shown enhanced meridional movement on interannual time scales in the last 30 years compared to the previous 30 years. A counterpart diagnosis of climate model simulations suggests that these changes of the NASH are likely associated with global warming. Diem (2013, hereafter D13) did not challenge the fact of the increased rainfall variability in the recent decades, nor did he challenge the intensity change of the NASH. Instead, D13 questioned the results of the NASH western ridge in LLFDW11. He claimed that the western ridge had moved eastward over the past three decades and had no observable changes in its latitudinal movement. He also argued that global warming should not be linked to a westward movement of the NASH western ridge. In this reply, we show that the difference of the ridge trend between D13 and LLFDW11 is due to the different

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TABLE 1. Standard deviation of NASH western-ridge latitude in the first and second periods from the NCEP–NCAR reanalysis and the ERA-40. For the NCEP–NCAR reanalysis (ERA-40), the first and second periods are 1948–77 (1958–77) and 1978–2007 (1978–2002), respectively.

Standard deviation (°)	First period	Second period	First period without 1953 summer
NCEP–NCAR	1.56	1.60	1.03
ERA-40	1.56	1.93	1.56

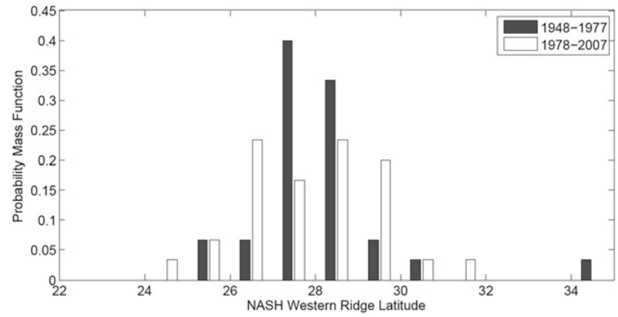

FIG. 1. Probability mass functions of the latitude of the NASH western ridge during the 1948–77 (gray) and 1978–2007 (white) periods based on the NCEP–NCAR reanalysis. The *y* axis is the probability of the NASH western ridge located in the corresponding latitudinal band (*x* axis).

study periods (1978–2007 vs 1948–2007) of the two analyses. The number of summers characterized by large anomalies in the ridge latitude has nearly doubled in the second 30-yr period and the possibility of a connection between the movement of the NASH western ridge and global warming during the 60-yr period (1948–2007) cannot be disregarded.

2. Results

a. Longitude movement of the NASH western ridge

The results of LLFDW11 are based on 60 years of data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (1948–2007; Kalnay et al. 1996) and 45 years of data from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; 1958–2002; Uppala et al. 2005). Figure 3 in LLFDW11 showed the normalized longitudinal change[1] of the summer (June–August) western ridge for the 60-yr (NCEP–NCAR) and 45-yr (ERA-40) periods, respectively. Secular trends are significant, as suggested by both datasets. Specifically, the 60-yr trend of $-1.22°$ decade^{-1} is significant at a 0.01 level (Mann–Kendall test; Hirsch et al. 1982); and the 45-yr trend is $-1.19°$ decade^{-1}, also at a significance level of 0.01. The Mann–Kendall tests suggest that westward extension of the NASH western ridge becomes increasingly significant when more recent years are added in the second period (not shown). LLFDW11 thus concluded that the western ridge had moved westward relative to its climatological mean position during the course of the 60 years under consideration. D13 found the same significant trend during the period 1948–2007 using the NCEP–NCAR reanalysis (D13). We further examined the trend for the period 1948–2010 and confirmed that the westward movement trend of the NASH western ridge is still significant over this 63-yr period, albeit at a slight lower level (0.05).

The ‘‘eastward movement’’ highlighted in D13 is only related to the position change of the NASH starting from the late 1970s. D13 was essentially comparing a 30-yr trend with the 60-yr trend reported in LLFDW11 and, not surprisingly, came up with a different conclusion given the sensitivity of trend analysis to the period chosen and to the lengths of the data (e.g., Chapman and Walsh 2007). The 60-yr period (1948–2007) was chosen in LLFDW11 since the objective of the study was to investigate the long-term, multidecadal changes in the NASH and the same period had been used in a previous analysis (Wang et al. 2010). Further, in LLFDW11, the results based on the 60-yr NCEP–NCAR reanalysis have also been verified by conducting the same analysis on another relatively long-term and high-quality reanalysis (ERA-40). The sentence ‘‘both datasets indicate a significant westward trend of the western ridge of the NASH since the late 1970s (Fig. 3)’’ in LLFDW11 (p. 1501, first paragraph of section 3) is a confusing statement that might have led readers to think that the intention of the paper was to show that the westward trend existed only in the latter 30 years, which is obviously not the case in Fig. 3 of LLFDW11.

b. Latitudinal movement of the NASH western ridge

D13 made the suggestion that there had been no changes in the latitudinal movement of the NASH based on the standard deviation of the latitude of the western ridge during 1948–77 (2.04°) and 1978–2007 (2.03°). However, the calculations in D13 differ from ours in LLFDW11. According to our calculations, the standard deviation of the latitude of the NASH western ridge is 1.56° in the first 30-yr period and 1.60° in the second

[1] Units in degrees should be deleted in the figure caption as the movement of the western ridge is the normalized change.

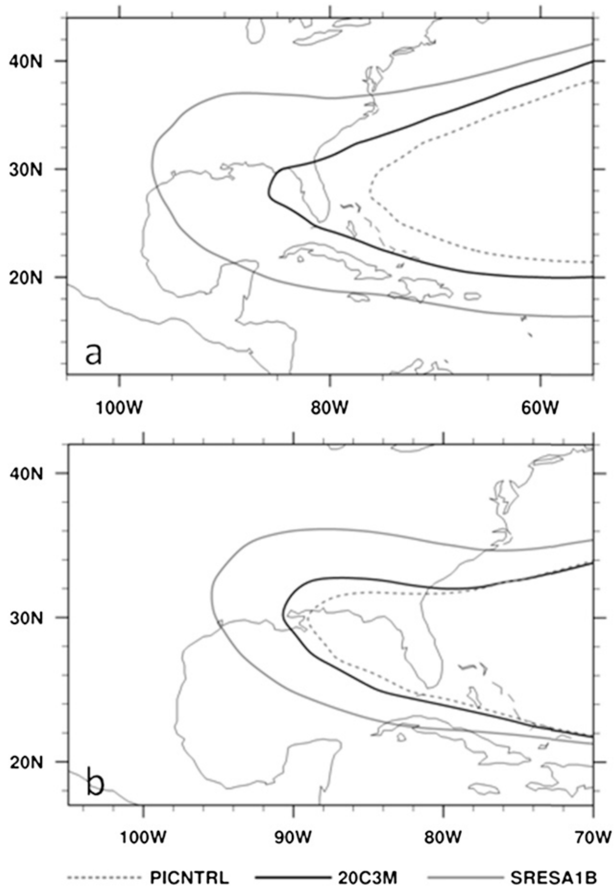

FIG. 2. Climatological position of the NASH western ridge at 850 hPa represented by (a) geopotential height (1564 gpm) and (b) streamfunction (10^7 m^2 s^{-2}) using the 23 CMIP3 models' multimodel ensemble mean in the preindustrial (50 yr, dashed contour), the twentieth century (1950–99, black solid contour), and the twenty-first century (2050–99, gray solid contour).

30-yr period (Table 1); the number of summers with large anomalies in the ridge latitude, defined as summers with anomalies greater than one standard deviation in the NASH western-ridge latitude, has nearly doubled in the second 30-yr period (significant at a level of 0.05 by the chi-square test) and therefore the interannual variation in the latitude of the western ridge has increased. The increase in latitudinal movement is also suggested by Fig. 1, where the latitudinal distribution of the NASH western ridge is visibly wider in the second period compared to the first period. The same results can be obtained from the ERA-40 (from 1.56° to 1.93°; Table 1). The relatively large value of the ridge-latitude standard deviation in the first 30-yr period in the NCEP–NCAR reanalysis is mainly due to the data in 1953. Outlier tests indicate that the summer of 1953 is indeed an outlier at the 0.01 significance level (Dixon 1953). Excluding the summer of 1953, the standard deviation of the western-ridge latitude in the first 30-yr period is 1.03°, much smaller than that in the second 30-yr period (Table 1); the number of summers with large anomalies in the ridge latitude increased 225%; and the both differences from the first to the second 30-yr period are significant at a level of 0.01 by the chi-square test.

c. *Global warming and changes in the NASH western ridge*

D13 claimed that global warming has not caused the western ridge to move westward since there is not a significant negative correlation between global surface temperature and western-ridge longitude during 1948–2010. It is important to recognize that the changes of the NASH intensity and its western ridge are mainly determined by dynamical effects (Rodwell and Hoskins 2001; Cook et al. 2008; Kelly and Mapes 2011; L. Li et al. 2012; W. Li et al. 2012); the relationship between the ridge and global mean temperature does not have to be linear. In addition, the NASH's western ridge can be influenced both by global warming and interannual to decadal variability of the climate system. Thus, a deviation from the long-term trend during the last 30 years of our analysis period does not preclude a significant long-term (60 yr) trend. It is thus quite possible that the linear correlation between the global surface temperature and the longitude of the NASH western ridge does not attain statistical significance, particularly on interannual time scales.

The conclusion regarding the potential connection between the NASH changes and global warming made in LLFDW11 was based on a preliminary attribution analysis that compares signals in forced climate model runs to those without anthropogenic greenhouse gas (GHG) forcing. Here the relationship between the NASH western ridge[2] and the increase of GHGs in the atmosphere has been further examined by analyzing the results of the climate models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4; Meehl et al. 2007) under three scenarios: the Preindustrial scenario (PICNTRL: fixed atmospheric concentration of CO_2 at 280–290 ppm); the twentieth-century anthropogenic external forcing scenario

[2] The NASH western ridge is defined using both 850-hPa geopotential heights and streamfunction to further test the westward expansion of the western ridge in a warming climate. To avoid the possible spread of the western ridge among the IPCC AR4 models and to make results comparable, we used the climatological contour straddling the longitude of 86°W to represent the western edge of the NASH for each model under scenario 20C3M. This longitude is derived according to observed climatological NASH location based on the NCEP reanalysis data.

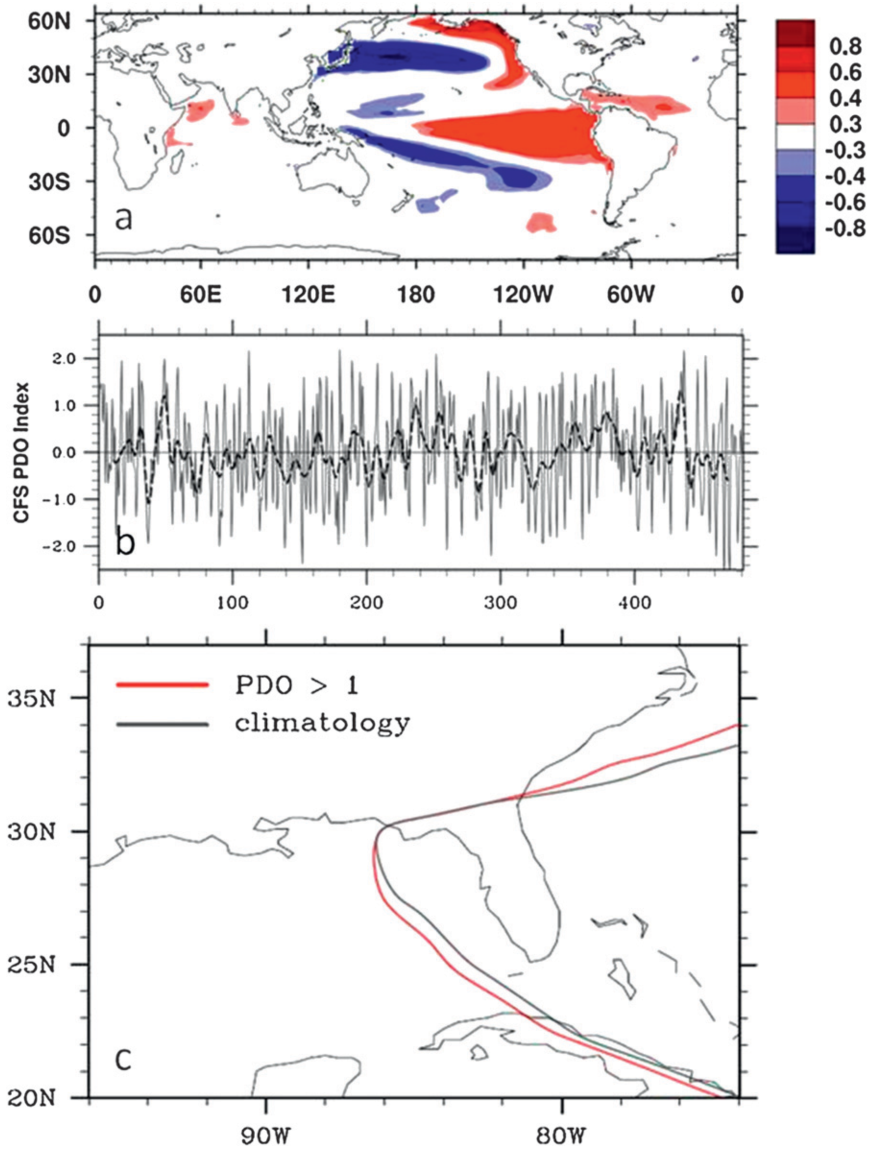

FIG. 3. (a) Spatial patterns of SST associated with the first EOF of monthly mean SST over the North Pacific (20°–65°N, 125°E–100°W) based on a 500-yr CFS free-run simulation. The first 20 years are discarded as model spinup. The spatial patterns are displayed as (a) the correlation between the SST at each grid point and (b) the corresponding PC1 time series. The thick dashed curve in (b) represents the low-pass filtered PC1 time series using Lanczos filters with a cutoff frequency of 0.1 cycles per year. (c) Composite of the NASH western ridge based upon the PDO [PC1 time series in (b)] > 1. The 1538-gpm contour is chosen to represent the western ridge in the CFS free run as the 1538-gpm contour is located at 86°W as in the NCEP–NCAR reanalysis.

(20C3M: the observed long-lived GHGs, solar radiation, and volcanic aerosols for the twentieth century); and the twenty-first century Special Report on Emissions Scenarios (SRES) A1B scenario (increase of the atmospheric concentration of CO_2 globally to 720 ppm by the year 2100). Figure 2 shows that the NASH western-ridge extends westward continuously from the Preindustrial (PICNTRL) to the twentieth century (20C3M) and to the twenty-first century (SRES A1B) using streamfunction and geopotential height when GHGs increase. This suggests that the link between enhanced GHG forcing and the westward movement of the NASH western ridge cannot be disregarded.

We also acknowledge the fact that although the movement of the NASH western ridge is likely related to global warming during the 60-yr period (1948–2007), it can also be significantly affected by other decadal modes of climate variability such as the Pacific decadal oscillation (PDO; L. Li et al. 2012) and Atlantic multidecadal oscillation (AMO). For example, the AMO index shows a strong positive trend during the last 30-yr period (1978–2007), and the correlation between the NASH ridge longitude and the AMO index (unfiltered)[3] is significant at the 0.01 level. However, the AMO index (both unfiltered and low-pass filtered) is not significantly correlated with the longitude of the NASH western ridge during the whole 60-yr period (1948–2007) or the first 30-yr period (1948–77). This complicated picture indicates that longer-term datasets and more detailed dynamical analyses are needed to clarify the interaction between the NASH and decadal modes such as the AMO. L. Li et al. (2012) found that the recent westward extension of the NASH western ridge is a combined result of the PDO and the NASH center intensification associated with global warming. In the positive phase of PDO, the NASH western ridge tends to move northwestward because of the presence of a stationary wave train driven by the PDO (L. Li et al. 2012). However, the PDO can impact the NASH western ridge only in a warming climate as suggested by our analysis of the NCEP Climate Forecast System (CFS; Saha et al. 2006) free run in which CO_2 concentration is fixed throughout the 500-yr simulation (Wang et al. 2012). The CFS free run reasonably captures the spatial pattern and periodicity of the PDO (Wang et al. 2012; also see our Figs. 3a and 3b); however, Fig. 3c suggests an insignificant change of the ridge location during the PDO positive phase compared to its climatological location.

3. Discussion and conclusions

In this reply, we have clarified and strengthened the conclusions originally put forth in LLFDW11. Over the last 60 years, the NASH has shown a significant trend of westward movement, the meridional movement of the NASH western ridge has enhanced in the recent three decades, and the impact of enhanced GHG forcing on these NASH changes cannot be ruled out.

D13 found the ''eastward movement'' of the NASH western ridge based on the most recent 30 years (1978–2007) of the NCEP–NCAR reanalysis. Since D13 and LLFDW11 are essentially discussing secular trends for two different periods, it is not a surprise to see different conclusions being reached.

The variation of the NASH intensity and its western ridge is mainly due to dynamical processes such as monsoon circulations and the associated diabatic heating (Rodwell and Hoskins 2001; Cook et al. 2008; Kelly and Mapes 2011; L. Li et al. 2012; W. Li et al. 2012). In a warming climate, the dynamical processes critical to the NASH western-ridge location are likely influenced by the increase of GHGs although the footprints of warming in these dynamical processes do not necessarily have a linear correlation with the global mean surface temperature. This implies that the nonexistence of a significant linear correlation between the global mean surface temperature and the ridge location does not provide enough evidence for us to rule out the possibility of enhanced GHG forcing influencing the NASH characteristics. On the other hand, we do recognize the modulation of the NASH western ridge by natural modes of variability such as AMO and PDO, particularly on interannual and decadal time scales. Without considering the potential impact of increased GHGs on those modes, it is fair to say that changes in the NASH western-ridge location are due to the NASH center intensifications that have been demonstrated to be mostly driven by global warming (W. Li et al. 2012) and are also partly influenced by phase changes in the PDO and/or AMO.

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[3] Compared to the unfiltered AMO index, high-frequency oscillations are damped when the filtered AMO index (using the Lanczos filter) is applied.

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