Impacts of non-canonical El Niño patterns on Atlantic hurricane activity

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Abstract

The impact of non-canonical El Niño patterns, typically characterized by warmer than normal sea surface temperatures (SSTs) in the central tropical Pacific, on Atlantic tropical cyclone (TC) is explored by using composites of key Atlantic TC indices and tropospheric vertical wind shear (VWS) over the Atlantic main development region (MDR). The highlight of our major findings is that, while the canonical El Niño pattern has a strong suppressing influence on Atlantic TC activity, non-canonical El Niño patterns considered in this study, namely central Pacific warming, El Niño Modoki, positive phase Trans-Niño, and positive phase Pacific meridional mode, all have virtually negligible impact on Atlantic TC activity. This result becomes more conclusive when the impact of MDR SST is removed from the Atlantic TC indices and MDR VWS by using the method of linear regression. Further analysis suggests that the tropical Pacific SST anomalies associated with the non-canonical El Niño patterns are not strong enough to cause a substantial warming of the tropical troposphere in the Atlantic region, which is the key factor that increases the VWS and atmospheric static stability over the MDR. During the recent decades, the non-canonical El Niños have been more frequent while the canonical El Niño has been less frequent. If such a trend continues in the future, it is expected that the suppressing effect of El Niño on Atlantic TC activity will diminish and thus the MDR SST will play as the single dominant factor to control Atlantic TC activity in the coming decades.

1. Introduction

Warm sea surface temperature (SST) anomalies in the tropical Pacific induce a global average warming of the tropical troposphere, via a fast tropical teleconnection mechanism (i.e., Kelvin waves), and thus increase the meridional tropospheric temperature gradient within and across the edge of the tropics [e.g., Horel and Wallance 1981; Yulaeva and Wallace 1994; Chiang and Sobel 2002]. This, in turn, directly increases the vertical wind shear (VWS) over the Atlantic main development region (MDR, 10°N – 20°N and 85°W – 15°W), via the thermal wind relationship. Additionally, the teleconnected tropospheric warming over the tropical Atlantic also tends to increase atmospheric static stability and thus causes anomalous diabetic cooling over the MDR [e.g., Tang and Neelin 2004; Lee et al. 2011]. This, in turn, may force the formation of a stationary baroclinic Rossby wave northwest of the MDR, consistent with Gill's simple model of tropical atmospheric circulations, to further increase the MDR VWS shear [e.g., Lee et al. 2011]. El Niño events are thus associated with decreased tropical cyclone (TC) activity in the Atlantic basin as a result of increased VWS and atmospheric static stability over the MDR [e.g., Gray 1984; Goldenberg and Shapiro 1997].

The canonical El Niño is characterized by warmer than normal SSTs in the eastern tropical Pacific Ocean. However, El Niño comes in many different flavors – every El Niño event has a somewhat different and distinct character [Trenberth and Stepaniak 2001]. Recently, a newly identified pattern of central equatorial Pacific warming event (non-canonical El Niño hereafter), which is referred to as central Pacific El Niño, El Niño Modoki, warm pool El Niño, Pacific meridional mode and Trans-Niño in the literatures [e.g., Yeh et al. 2009; Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009; Chiang and Vimont 2004; Trenberth and Stepaniak 2001], has received attention due to its increasing frequency in recent decades, and its potential link to the influence of anthropogenic global warming [Yeh et al. 2009; Lee and McPhaden 2010]. This non-canonical El Niño differs from the canonical El Niño in that its warm equatorial SST anomalies are concentrated in the central Pacific with cool SST anomalies flanked in a horseshoe pattern to the east and west [Ashok et al. 2007]. While the canonical El Niño is historically defined as warm SST anomalies in the Niño-3 region (NINO3; 5°S - 5°N, 150°W - 90°W) or Niño-3.4 region (NINO3.4; 5°S - 5°N, 170°W - 120°W), several different definitions of the non-canonical El Niño have been referenced in recent literature – central Pacific warming [CPW; Yeh et al. 2009], El Niño Modoki index [EMI; Ashok et al. 2007], Pacific meridional mode [PMM, Chiang and Vimont 2004] and Trans-Niño index [TNI, Trenberth and Stepaniak 2001]. These definitions were derived to describe the same anomalous central Pacific warming pattern that is captured by the 2nd mode of the empirical orthogonal function analysis of monthly tropical Pacific SST anomalies [EOF2, Trenberth and Stepaniak 2001; Ashok et al. 2007].

Given a strong dependence of overall Atlantic TC activity on the equatorial Pacific SST anomalies associated with El Niño, there is a clear need for understanding how the response of Atlantic TC activity to non-canonical El Niño differs from that to canonical El Niño. A recent study by Kim et al. [2009] suggested that CPW events are associated with a greater-than-average frequency of tropical storms and increasing landfall potential along the Gulf of Mexico coast and Central America. However, Lee et al. [2010] pointed out based on an independent data analysis that such conclusion could be premature because Kim et al. [2009] did not remove in their analysis the local impact of MDR SST, which is as important as the remote impact of tropical Pacific SSTs as shown overwhelmingly in earlier studies [e.g., Knaff 1997; Knight et al. 2006; Wang et al. 2006; Zhang and Delworth 2006; Vimont and Kossin 2007; Kossin and Vimont 2007; Saunders and Lea 2008].

Both Kim et al. [2009] and Lee et al. [2010] considered only a small number of CPW events to arrive at the contradicting conclusions. Therefore, here, we further attempt to isolate and quantify the impact of non-canonical El Niño on Atlantic TC by using composites of SST, VWS and key Atlantic TC indices for various non-canonical El Niño definitions, i.e, CPW, EMI, TNI and PMM. One of the key points in our analyses is that, the influence of MDR SST is objectively removed from the Atlantic TC indices and MDR VWS prior to making the composites by using the method of linear regression in order to isolate the impact of non-canonical El Niño.

2. Data

The SST dataset used in this study is the NOAA Extended Reconstructed Sea Surface Temperature version 3 [ERSST3; Smith et al. 2008] from 1950 to 2010 averaged for the Atlantic hurricane season of June to November (JJASON). The NCEP-NCAR Reanalysis-1 data for the same period is used to compute the VWS and geopotential thickness between 200 and 850 hPa [Kalnay et al. 1996]. The hurricane reanalysis database (HURDAT) from the National Hurricane Center for the same period is used to obtain various Atlantic TC indices.

As discussed earlier, in order to isolate the impact of non-canonical El Niños, the influence of MDR SST is removed from the Atlantic TC indices and VWS by using the method of linear regression. For example, the modified MDR VWS can be obtained by

$$\mathrm{MDR\ VWS\,(modified)} = \mathrm{MDR\ VWS} - a \times \mathrm{MDR\ SSTA}\,, \qquad (1)$$

where a is the regression coefficient of anomalous MDR SST onto the MDR VWS.

3. Indices for Non-canonical El Niño

As pointed out by Ashok et al. [2007], the EOF2 of monthly tropical Pacific SST anomalies captures the distinct SST anomaly structure characteristic of the non-canonical El Niño. Various indices, such as CPW, EMI, TNI, and PMM have been suggested and used to define this same phenomenon. Currently, there is no consensus on how to classify the non-canonical El Niño. Hence, CPW, EMI, TNI and PMM are all reproduced for this study as described below. The referenced regions of SST anomalies are depicted in Figure 1.

Ashok et al. [2007] proposed EMI to determine non-canonical El Niño years. EMI is calculated using the following equation:

$$\mathrm{EMI} = < \mathrm{SSTA(A)} - 0.5 \times \mathrm{SSTA(B)} - 0.5 \times \mathrm{SSTA(C)} >, \qquad (2)$$

where SSTA(A) is the SST anomalies averaged over a box region for 10°S - 10°N and 165°E - 140°W, SSTA(B) is for 15°S - 5°N and 110°W - 70°W, and SSTA(C) is for 10°S - 20°N and 125°E - 145°E. In this study, the index is normalized (< > represents normalization) by the standard deviation of the EMI time series.

Yeh et al. [2009] defined non-canonical El Niño years by establishing a set of criteria for what is called CPW. A CPW year occurs when warm SST anomaly in the Niño-4 region (NINO4; 5°S - 5°N, 160°E - 150°W) exceeds that of Niño-3 [Yeh et al. 2009]. Note that CPW is not an index but rather criteria for handpicking non-canonical El Niño years, thus a CPW time series cannot be computed. CPW years are defined as those years in which NINO4 is greater than NINO3, while NINO4 is positive.

Chiang and Vimont [2004] proposed PMM to describe an anomalous SST gradient across the mean latitude of the intertropical convergence zone (ITCZ) coupled to an anomalous displacement of the ITCZ toward the warmer region. PMM is calculated using the following equation:

$$\text{PMM} = \ll \text{ENP} > - < \text{NINO1}+2 \gg, \tag{3}$$

where ENP (eastern North Pacific) is the SST anomaly averaged over a box region for 10°N - 30°N and 140°E - 110°W. In this study, the index is normalized by the standard deviation of the PMM time series.

Trenberth and Stepaniak [2001] suggested that an optimal characterization of both the distinct character and the evolution of each El Niño and La Niña event requires a so-called TNI in addition to the conventional SST anomalies in the Niño-3.4 region. TNI is computed by taking the difference between the normalized SST anomalies averaged in the Niño-1+2 and Niño-4 regions then further normalizing the resulting time series to have unit standard deviation. By normalizing the Niño-1+2 and Niño-4 SST anomaly terms prior to subtraction, neither region’s SST anomaly can dominate the overall index. This is necessary because the magnitude of the equatorial eastern Pacific SST anomaly is usually larger than equatorial central Pacific SST anomaly. The resulting TNI is SST anomaly difference between the Niño-1+2 and Niño-4 regions. Note that Trenberth and Stepaniak [2001] calculate TNI by subtracting Niño-4 SST anomalies from Niño-1+2 SST anomalies so that a positive index corresponds to a cold central equatorial Pacific event. Here, in order for a positive TNI to correspond to a warmer than normal SST anomalies in the central tropical Pacific, the normalized Niño-1+2 SST anomalies are subtracted from the normalized Niño-4 SST anomalies in this study. Therefore, the equation for TNI is given by

$$\text{TNI} = \ll \text{NINO4} > - < \text{NINO1}+2 \gg, \tag{4}$$

where < > represents that the variable is normalized.

To represent each non-canonical El Niño definition, composites of the eight strongest positive (warm) phase years during which NINO4 is also positive are created for CPW, EMI, PMM and TNI. An additional criterion of NINO4 > 0 is required to eliminate years in which other regions' cold SST anomalies account for the positive index. For example, when calculating TNI, if <NINO4> is 0 and <NINO1+2> is negative, then TNI > 0. However, this is not a central tropical Pacific warming event but rather an eastern tropical Pacific cooling event. Therefore, including the criterion of NINO4 > 0 in selecting non-canonical El Niño years ensures that these types of years are discarded. The NINO3 index is also computed and normalized for the period 1950 – 2010. A composite of the eight strongest positive phase NINO3 years is created to represent the canonical El Niño.

Figure S1 displays a time series for each non-canonical El Niño index and NINO3 for the period 1950 – 2010. EOF2 contains a strong low frequency signal, and is largely positive during 1950-1970 and negative during 1997-2010 (not shown). EMI, TNI and PMM show more variability at the short time scales than EOF2. Overall, EMI and TNI agree in term of phase with the correlation coefficient of 0.86. Similarly, TNI and PMM are highly correlated with the correlation coefficient of 0.70, whereas EMI is poorly correlated with NINO3 with the correlation coefficient of 0.17. These indices vary in intensity because certain SSTA regions may capture local maxima and minima while others do not, thus resulting in a disagreement in amplitude between the time series.

4. Non-canonical El Niño and Atlantic TC Activity

To quantify the impact of non-canonical El Niño on Atlantic TC activity, the number of tropical storms (TS), hurricanes (HR), major hurricanes (MH, categories 3-5), accumulated cyclone energy (ACE), number of United States landfalling hurricanes (USL), and the MDR VWS are averaged for each index's eight-year composite before and after removing the effect of

Atlantic MDR SST and listed in Table 1. It is noted that only NINO3 shows all Atlantic TC indices (i.e., TS, HR, MH, ACE and USL) decreased and the MDR VWS increased at the 90% significance level. Removing the effect of the Atlantic MDR SST has very minor impact (parenthesized values).

In CPW and EMI, some Atlantic TC indices are decreased and the MDR VWS is slightly increased before and after the Atlantic MDR SST impact is removed. However, these changes are too small to be statistically significant at the 90% level. In TNI, on the other hand, some Atlantic TC indices (i.e., TS, HR and ACE) are increased and the MDR VWS is decreased before the Atlantic MDR SST impact is removed (non-parenthesized value). After the Atlantic MDR SST impact is removed (parenthesized value), however, all Atlantic TC indices and the MDR VWS recover their climatological values. In PMM, all Atlantic TC indices are virtually indistinguishable from their climatological values. Removing the effect of the Atlantic MDR SST has no impact in this case (parenthesized values).

In summary, consistent with earlier studies [Gray 1984; Goldenberg and Shapiro 1997], we find consistent evidence that the canonical El Niño suppresses Atlantic TC activity due to a large increase of the MDR VWS. Some non-canonical El Niño patterns (CPW and EMI) also tend to suppress Atlantic TC activity due to a weak-to-moderate increase of the MDR VWS. However, their impact is virtually negligible in comparison to that of the canonical El Nino. Therefore, here we do not find any evidence that links any of the four non-canonical El Niño patterns to Atlantic TC activity.

5. Tropical Teleconnection Induced by Non-canonical El Niño

Two key differences between the four non-canonical El Niño patterns and the canonical El

Nino pattern are seen in the tropical Pacific SST anomaly distributions in JJASON (Figure2). First, the maximum (warm) SST anomalies for the four non-canonical El Niño patterns are located in either the central tropical Pacific (EMI) or near the dateline (CPW, TNI and PMM), whereas those for the canonical El Niño are in the eastern tropical Pacific. But, more importantly, the amplitude of tropical Pacific SST anomalies associated with the non-canonical El Niños is much weaker than that of the canonical El Niño. Consequently, the tropical tropospheric warming associated with the four non-canonical El Niño patterns is relatively weak and largely confined in the tropical Pacific region (Figure 3a – d). In contrast, the tropical tropospheric warming associated with the canonical El Niño is much stronger, and its teleconnection to the tropical Atlantic region is clearly observed (Figure 3e). Therefore, we can conclude that the tropical Pacific SST anomalies associated with the non-canonical El Niño patterns are not strong enough to cause a substantial warming of the tropical troposphere in the Atlantic region, which is the key factor that increases the meridional tropospheric temperature gradient and atmospheric static stability over the MDR. Note that the meridional tropospheric temperature gradient over the tropical Atlantic has a direct influence on the MDR VWS via the thermal wind relationship. The atmospheric static stability and associated anomalous diabetic heating (or cooling) over the MDR also influence the MDR VWS via the formation of a stationary baroclinic Rossby wave northwest of the MDR [e.g., Lee et al. 2011]. Therefore, consistent with the lack of teleconnected tropospheric warming over the tropical Atlantic in Figure 3a – d, the MDR VWS anomalies for CPW, EMI, TNI and PMM are either neutral or only slightly increased (Figure 4).

6. Discussions

The highlight of our major findings is that some non-canonical El Niño patterns tend to slightly suppress Atlantic TC activity due to a weak-to-moderate increase of the MDR VWS. However, the overall impact of non-canonical El Niños is nearly negligible compared to that of the canonical El Nino. This result becomes more conclusive when the effect of MDR SST is removed from the Atlantic TC indices and MDR VWS. Recent studies reported that, during the recent decades, the non-canonical El Niños have been more frequent while the canonical El Niño has been less frequent [Yeh et al. 2009; Lee and McPhaden 2010]. Yeh et al. [2009] suggested that such trend may continue in the future due to anthropogenic greenhouse effect on the tropical Pacific thermocline. If this is indeed the case, an important implication is that the suppressing effect of El Niño on Atlantic TC activity may diminish and thus the MDR SST may play as the single dominant factor to control Atlantic TC activity in the coming decades.

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