On the impacts of central Pacific warming events on Atlantic tropical storm activity

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Abstract

A recent study by Kim et al. [2009] claim that central Pacific warming (CPW) events in 1969, 1991, 1994, 2002 and 2004 are associated with a greater-than-average frequency of tropical storms and increasing landfall potential along the Gulf of Mexico coast and Central America. Based on an independent data analysis of tropical cyclone activity in the five CPW years, it is shown here that only 1969, 2002 and 2004 are characterized with significantly greater-than-average cyclone activity in the Gulf of Mexico and Caribbean Sea, whereas 1991 and 1994 are characterized with significantly lower-than-average activity. Coincidently, the Atlantic warm pool (AWP) was significantly larger than average during 1969 and 2004, and significantly smaller than average during 1991 and 1994. By performing multiple sets of ensemble model experiments using the NCAR atmospheric general circulation model, it is shown here that the increased tropical storm frequency in 1969 and 2004 can be readily explained by a large AWP and the associated vertical wind shear reduction and enhanced moist convective instability in the main development region for Atlantic hurricane, without invoking a remote influence from the tropical Pacific. Therefore, we conclude that it is premature to associate CPW events to an increasing frequency of cyclone activity in the Gulf of Mexico and Caribbean Sea.

1. Introduction

The so-called central Pacific warming (CPW) phenomenon, which is characterized by anomalously warm sea surface temperature (SST) in the central equatorial Pacific Ocean, has received some attentions in recent years [e.g., *Ashok et al*., 2007; *Weng et al*., 2007; *Kug et al*., 2009; *Yeh et al*., 2009]. According to the externally forced model simulations for the 21st century used in the Intergovernmental Panel for Climate Change - 4th Assessment report, the frequency of CPW events is significantly increased between 2000 and 2100, whereas the frequency of eastern Pacific warming (EPW) events associated with El Niño is decreased [*Yeh et al*., 2009]. *Yeh et al*., [2009] argued that the change in the occurrence ratio of CPW to EPW (or shift in El Niño pattern) is associated with flattening of the thermocline in the equatorial Pacific under the influence of anthropogenic global warming [*DiNezio et al*., 2009]. By using the historical El Nino indices of Niño3 (90^{o}W-150^{o}W, 5^{o}N-5^{o}S) and Niño4 (150^{o}W-160^{o}E, 5^{o}N-5^{o}S) SSTs to distinguish two variations of El Niño for the period of 1954-2007, *Yeh et al*. [2009] further argued that the modification of El Niño pattern due to anthropogenic global warming is already in progress since the CPW has been occurring more frequently since the 1990s.

It is widely recognized that the canonical EPW pattern associated with El Niño suppresses Atlantic cyclone activity because the anomalous atmospheric circulation associated with El Niño tends to increase the vertical wind shear over the main development region (MDR) for Atlantic hurricane [e.g., *Goldenberg and Shapiro*, 1996; *Shaman et al*., 2009]. A recent study by *Kim et al*. [2009] (KWC09) claimed that, "*in contrast to EPW events, CPW episodes are associated with a greater-than-average frequency and increasing landfall potential along the Gulf of Mexico coast and Central America*". They also stated that "*compared to climatology, track density for CPW increases across the Caribbean, the Gulf of Mexico, and the U.S. east coast*".

However, it is shown in this study that neither our independent data analysis of Atlantic tropical cyclones nor further numerical modeling experiments supports the suggested impact of CPW events on increasing Atlantic tropical storm activity .

2. Data Analysis

KWC09 used a criterion of detrended Niño4 warming exceeding 1 standard deviation while Niño3 stays below this range in the extended reconstructed sea surface temperature version 2 (ERSST2) [*Smith and Reynolds*, 2004] to identify five CPW events in 1969, 1991, 1994, 2002 and 2004. Their conclusions are based on the five-year average of tropical storm data. To perform an independent data analysis on the impact of these five CWP events on Atlantic tropical storm activity, the hurricane reanalysis database of HURDAT at NOAA AOML (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html) for the period of 1950-2006 is used to generate detrended hurricane indices for the five individual years as shown in Table 1. The last column in Table 1 is the number of tropical storms that either form inside or pass through the Gulf of Mexico (100^{o}W – 80^{o}W, 20^{o}N – 30^{o}N) and Caribbean Sea (90^{o}W – 60^{o}W, 10^{o}N – 20^{o}N), referred to as Intra-Americas Sea (IAS) cyclone activity hereafter. Also included in this table are the detrended Niño4, the detrended size of Atlantic warm pool (AWP), which is defined as the tropical Atlantic sea surface area of its surface temperature exceeding 28.5^{o}C [*Wang and Enfield*, 2001], the detrended vertical wind shear between 200 and 850 mb in the main development region (MDR: 85^{o}W-15^{o}W, 10^{o}N-20^{o}N) for Atlantic hurricane, and the detrended convective available potential energy (CAPE) in the MDR, all averaged for the Atlantic hurricane season of June to November. KWC09 used hurricane indices averaged for August-September-October (ASO). However, it is important to include the early season of June and July because a large of portion of the IAS cyclones typically forms in those two months (e.g., *Inoue et al*., 2002). The AWP index is based on ERSST2, while both the vertical wind shear and CAPE are obtained from NCEP reanalysis [*Kalnay et al.*, 1996].

Table 1 shows that among the five CPW years, 1969, 2002 and 2004 were the only years of greater-than-average cyclone activity in the IAS region, whereas 1991 and 1994 were the years of significantly lesser-than-normal activity. To have a better perspective of the potential relationship between the CPW events and IAS cyclone activity, it is useful to examine other cyclone indices. According to the tropical storm index, for instance, only 1969 and 2004 can be characterized with a greater-than-average frequency of tropical storms, whereas 1991, 1994 and 2002 have either a neutral or a lesser-than-average frequency. The number of hurricanes, the number of major hurricanes, and the accumulated cyclone energy (ACE) index also show the same result. Coincidently, the AWP was significantly larger than average in both 1969 and 2004, whereas it was significantly smaller than average in 1991 and 1994.

Earlier studies based on theory, observations and models have consistently shown that local SST in the tropical North Atlantic can greatly influence the cyclone activity because warm (cold) tropical North Atlantic SSTs reduce (increase) the MDR vertical wind shear and increase (decrease) the MDR moist static instability at both interannual and multi-decadal time scales [e.g., *Goldenberg et al*. 2001; *Knight et al*., 2006; *Zhang and Delworth*, 2006; *Vimont and Kossin*, 2007; *Saunders and Lea*, 2008; *Wang et al*. 2008]. Consistent with this robust relationship among the AWP size, MDR vertical wind shear, MDR moist static instability (i.e., CAPE), and Atlantic tropical storm activity, Table 1 clearly shows that the MDR vertical wind shear is significantly reduced and the MDR moist static instability is significantly increased in the summer of 1969 and 2004, during which the AWP was significantly larger than average and the cyclone activity was significantly above normal. Therefore, it is quite logical to presume that the increased tropical storm frequency in 1969 and 2004 can be readily explained by the increased local SST index of the AWP without invoking a remote influence from the tropical Pacific.

This study is not meant for point-by-point comparisons with KWC09, but rather an independent data-model analysis on one of the major conclusions of KWC09. In that regard, it is worthwhile to point out that KWC09 used different storm indices. In particular, KWC09 used storm track density averaged for the most active hurricane months of ASO. Thus, Table 1 is regenerated for ASO in Auxiliary Material Table S1, and storm track density anomalies for ASO are plotted in Auxiliary Material Figure S1. Consistent with Table 1, both Table S1 and Figure S1 show that only 1969, 2002 and 2004 are characterized with a greater-than-average frequency of cyclonic activity in the IAS region, whereas 1991 and 1994 are characterized with a lesser-than-average frequency. The only noticeable change is that in both 2002 and 2004 the IAS cyclone index of 7 is now statistically significant. It is no surprise that the IAS cyclone index (or storm track density in the IAS region) is significantly increased in 1969 and 2004 because the AWP was significantly larger than average, and thus the large-scale environment factors were favorable for increased cyclone activity in those years. However, the increased IAS cyclone index (or increased storm track density in the IAS region) in 2002 is an unusual one because 2002 was in general an inactive year due to the significantly increased MDR vertical wind shear. It is noted here that, among the five CPW cases, the 2002 CPW may be qualified as the only CPW event relatively uncontaminated by the local impact of AWP.

3. Model Experiments

It is clear from the above discussion that the presence of a very large AWP in 1969 and 2004 makes it difficult to attribute the increased cyclone frequency to the CPW events. Therefore, in an effort to isolate the remote influence of the 1969 and 2004 CWP events from the local SST influence, we perform multiple sets of ensemble model experiments using the NCAR atmospheric general circulation model as summarized in Table 2.

The first group of model experiments is performed by prescribing the evolution of SSTs only in the tropical Pacific (15^{o}S-15^{o}N; 120^{o}E–coast of the Americas) for 1969 and 2004, and for a typical EPW year of 1987 (KWC09 used a criterion of detrended Niño3 warming exceeding 1 standard deviation in the ERSST2 to identify nine EPW years, which includes 1987), while prescribing the SSTs outside of the tropical Pacific using climatology. These experiments for the 1969, 1987, and 2004 cases are referred to as EXP_Y69_PAC, EXP_Y87_PAC and EXP_Y04_PAC, respectively. Similarly, the second group of model experiments is performed by prescribing the evolution of SSTs only in the tropical North Atlantic (5^{o}N-30^{o}N; coast of Americas-coast of Africa) for 1969 and 2004, while prescribing the SSTs outside of the tropical North Atlantic using climatology. These experiments for the 1969 and 2004 cases are referred to as EXP_Y69_ATL and EXP_Y04_ATL, respectively. These two groups of ensemble model experiments are compared with the control run (EXP_CLM), which is forced with climatological SSTs everywhere. It is important to note that these experiments are not designed to reproduce observations but to isolate the remote impacts of CPW from the local impact of AWP. The detailed methodology is described in *Lee et al.*, [2008].

Figure 1 shows the simulated vertical wind shear change for the EXP_Y69_PAC, EXP_Y87_PAC, and EXP_Y04_PAC. The simulated vertical wind shear for the 1987 EPW case is greatly increased over the MDR as in the observation (not shown), suggesting that the 1987

EPW event is responsible for significantly reduced cyclone activity in that year: the detrended tropical storm index for 1987 is 6, which is significantly less than the climatological mean of 11. The simulated MDR vertical wind shear for the 1969 CPW event is slightly increased from the climatology. The 2004 CPW case is more interesting because the vertical wind shear in the western and central parts of the MDR is increased as much as in the 1987 EPW case. The upshot is that the simulated MDR vertical wind shear responses to the 1969 and 2004 CPW events are positive as in the typical EPW case of 1987, if the local impacts of large AWP in those years are removed.

Figure 2 shows the simulated vertical wind shear change for the EXP_Y69_ATL, and EXP_Y04_ATL. In both cases, in the absence of the remote impact from the CPW, the simulated vertical wind shear is reduced over the MDR in response to the local impact of a large AWP, consistent with the observation (Table 1). As explained in Wang and Lee (2007), the anomalous diabatic-heating associated with a large AWP forces the formation of a stationary baroclinic Rossby wave northwest of the forcing region and thus reduces both the upper-level westerly wind and low-level easterly wind aloft the MDR. The combined effect of the upper- and lower-level wind changes results in a reduction of the MDR vertical wind shear.

The simulated CAPE changes for the EXP_Y69_ATL, and EXP_Y04_ATL are also shown in Figure 3. In both cases, in the absence of the remote impact from the CPW, the simulated CAPE is significantly increased over the MDR in response to the local impact of a large AWP, consistent with the observation (Table 1). On the contrary, the simulated MDR CAPE changes for the EXP_Y69_PAC and EXP_04_PAC are negligible as shown in Auxiliary Material Figure S2. Accordingly, the simulated CAPE changes indicate that the 1969 and 2004 CPW events are not likely to be responsible for the observed increases in the MDR moist static instability in 1969 and 2004.

In summary, both the simulated MDR vertical wind shear and moist static instability responses to the local impacts of the 1969 and 2004 large AWPs are consistent with the observation, whereas those to the remote impacts of the 1969 and 2004 CPW are inconsistent with the observation. Thus, the model experiments support our hypothesis that the large AWPs in the summer of 1969 and 2004 are primarily responsible for the decreased MDR vertical wind shear, increased MDR moist static instability and increased cyclone activity in those years.

4. Summary and Discussions

In summary, our independent data analysis of tropical cyclone activity in the five CPW years shows that only three (1969, 2002, and 2004) are associated with significantly greater-than-average storm activity over the Gulf of Mexico and Caribbean Sea, whereas the other two (1991, and 1994) are associated with significantly lower-than-average activity. Coincidently, the AWP was significantly larger than average during 1969 and 2004, and significantly smaller than average during 1991 and 1994. Therefore, we hypothesize that the increased tropical storm frequency in 1969 and 2004 can be readily explained by the increased local SST index of the AWP and the associated MDR vertical wind shear reduction and enhanced MDR moist static instability without invoking a remote influence from the tropical Pacific. Here, we test and confirm this working hypothesis by performing multiple sets of ensemble model experiments using the NCAR atmospheric general circulation model. Therefore, we conclude that it is premature to associate CPW events to an increasing frequency of cyclone activity in the Gulf of Mexico and Caribbean Sea.

Future investigations on the remote impact of CPW events must be supported by a much longer time series data (or many more cases of CPW events), with the effect of tropical North Atlantic SST removed, to achieve a statistically significant result. Nevertheless, our model experiments show that the simulated MDR vertical wind shear responses to the 1969, 1991, 1994, 2002, and 2004 CPW events are all positive if the local impacts of AWP in those years are removed (see Auxiliary Material Figure S3 for an additional group of ensemble model experiments for the 1991, 1994 and 2002 CPW cases as summarized in Auxiliary Material Table S2), suggesting that the anomalous Walker circulations in the MDR during CPW events may be similar to that during EPW events, only weaker because the amplitude of CPW events (i.e., Niño4 index) is generally smaller than that of EPW events (i.e., Niño3 index) [e.g., *Ashok et al.*, 2007].

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Table 1. Detrended hurricane indices for the five CPW years, the five-year mean and the climatological mean for 1950 - 2006 period. The 6th, 7th and 8th columns represent the number of tropical storm (TS), hurricane (HR) and major hurricane (MH, categories 3 - 5). The 9th column is the ACE. The 10th column is US landfalling hurricanes (USL). The last column is the number of tropical storms that either form inside or move into the Gulf of Mexico (100^{o}W – 80^{o}W, 20^{o}N – 30^{o}N) and Caribbean Sea (90^{o}W – 60^{o}W, 10^{o}N – 20^{o}N), referred to as IAS cyclone activity. Also included in this table are the detrended Niño4 index, the size of AWP, the vertical wind shear between 200 and 850mb in the MDR (85^{o}W-15^{o}W, 10^{o}N-20^{o}N), and the MDR CAPE, all averaged for the Atlantic hurricane season of June to November. To construct this table, the hurricane reanalysis database of HURDAT, the ERSST2, and NCEP reanalysis, all for the period of 1950-2006 are used. All data values are detrended. The detrended storm numbers are truncated to the nearest integer. Any value larger (smaller) than the climatological mean with above the 99% significance is in bold (italic). In the case of MDR vertical wind shear, the bold and italic are switched.

Year	Niño4 (^{o}C)	AWP (%)	VWS (m/s)	CAPE (J/kg)	TS (#)	HR (#)	MH (#)	ACE (10^4 kt^2)	USL (#)	IAS (#)
1969	**0.62**	**67.9**	**-0.8**	**189.6**	**19**	**12**	**5**	**159.3**	2	**10**
1991	**0.59**	*-33.8*	*1.4*	*-164.4*	*7*	*4*	2	*32.2*	*1*	*2*
1994	**0.70**	*-54.6*	-0.3	*-210.2*	*6*	*3*	*0*	*29.8*	*0*	*4*
2002	**0.69**	-7.0	*0.9*	-26.3	10	*4*	2	*62.7*	*1*	7
2004	**0.51**	**51.3**	**-1.5**	**50.7**	**13**	**9**	**6**	**220.4**	**6**	7
CPW mean	**0.62**	4.8	-0.1	**-32.1**	11	6	3	100.9	2	6
Climatology	0.00	0.0	0.0	0.0	11	6	3	101.9	2	6

Table 2. Prescribed SSTs in the tropical Pacific (15^{o}S-15^{o}N; 200^{o}E-cast of the Americas) and tropical North Atlantic (5^{o}N-30^{o}N; coast of Americas-coast of Africa) for the NCAR atmospheric general circulation model experiments. The SSTs outside of the tropical Pacific and tropical North Atlantic are prescribed using climatology.

Experiment	Tropical Pacific SST	Tropical North Atlantic SST
EXP_CLM	Climatology	Climatology
EXP_Y69_PAC	1969	Climatology
EXP_Y87_PAC	1987	Climatology
EXP_Y04_PAC	2004	Climatology
EXP_Y69_ATL	Climatology	1969
EXP_Y04_ATL	Climatology	2004

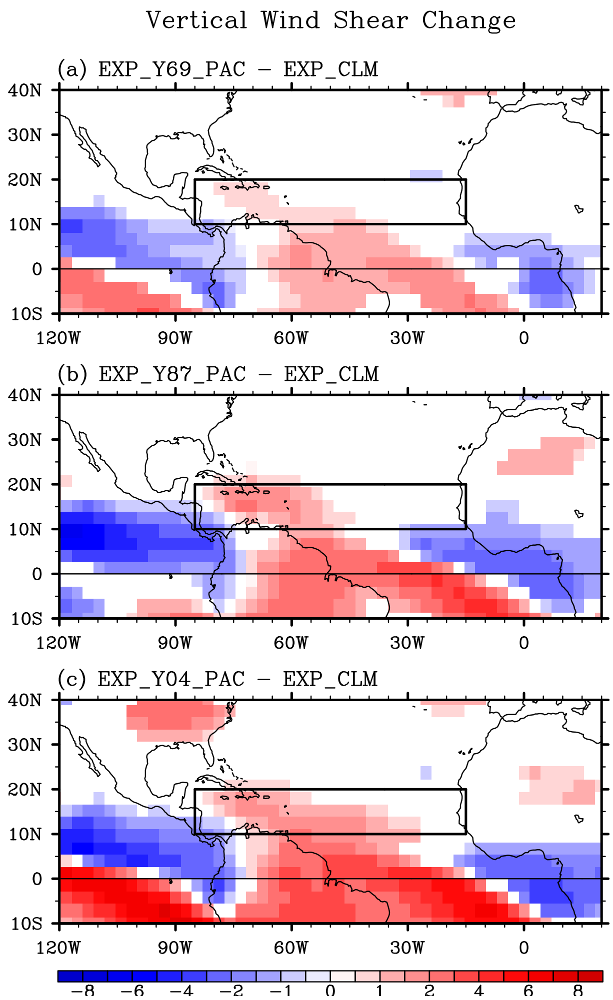

Figure 1. Tropospheric vertical wind shear (200mb minus 850mb) difference (ms^{-1}) in June-November between (a) EXP_Y69_PAC and EXP_CLM, between (b) EXP_Y87_PAC and EXP_CLM, and between (c) EXP_Y04_PAC and EXP_CLM. For EXP_Y69_PAC, EXP_Y87_PAC, EXP_Y04_PAC and EXP_CLM, the SSTs in the tropical Pacific region (15^{o}S-15^{o}N; 120^{o}E–coast of the Americas) are prescribed with those of 1969, 1987, 2004 and climatology, respectively, while prescribing the SSTs outside of the tropical Pacific using climatology. Each experiment consists of twenty model integrations that are initialized with slightly different conditions to represent internal atmospheric variability. Only significant values at 95% or above based on a student-t test are shown.

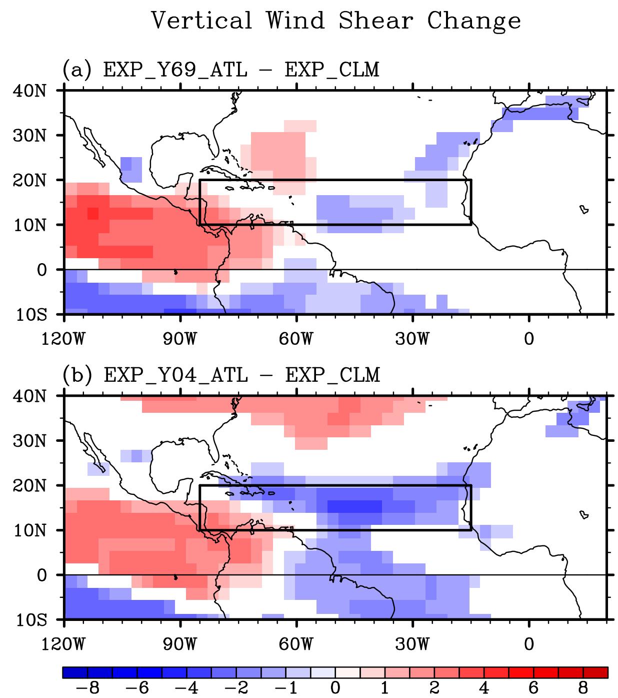

Figure 2. Tropospheric vertical wind shear (200mb minus 850mb) difference (ms^{-1}) in June-November between (a) EXP_Y69_ATL and EXP_CLM, and between (b) EXP_Y04_ATL and EXP_CLM. For EXP_Y69_ATL, EXP_Y04_ATL and EXP_CLM, the SSTs in the tropical north Atlantic region (5^{o}N-30^{o}N; coast of Americas–coast of the Africa) are prescribed with those of 1969, 2004 and climatology, respectively, while prescribing the SSTs outside of the tropical North Atlantic using climatology.

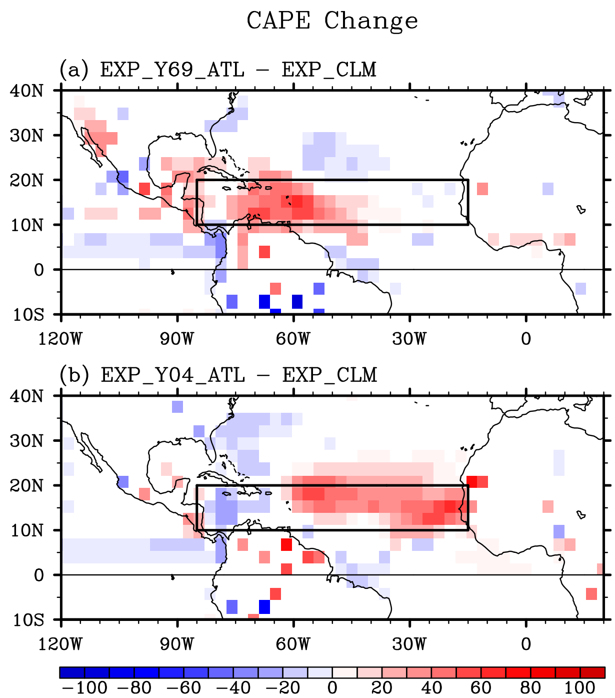

Figure 3. CAPE difference (J/kg) in June-November between (a) EXP_Y69_ATL and EXP_CLM, and between (b) EXP_Y04_ATL and EXP_CLM. Only significant values at 95% or above based on a student-t test are shown.