GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L06701, doi:10.1029/2009GL037260, 2009

# A new method for attributing climate variations over the Atlantic Hurricane Basin's main development region

Rong Zhang[1] and Thomas L. Delworth[1]

Received 10 January 2009; accepted 12 February 2009; published 17 March 2009.

[1] We propose a new approach to decompose observed climate variations over the Atlantic Hurricane Basin's main development region (MDR) into components attributable to radiative forcing changes and to internal oceanic variability. Our attribution suggests that the observed multidecadal anomalies of vertical shear (Uz) and a simple index of maximum potential intensity (SIMPI) for tropical cyclones are both dominated by internal variability, consistent with multidecadal variations of Atlantic Hurricane activity; changes in radiative forcing led to increasing Uz and decreasing SIMPI since the late 50's, unfavorable for Atlantic Hurricane activity. Physically, at least for the GFDL model, sea surface temperature (SST) anomalies induced by ocean heat transport variations are more efficient in producing negative Uz anomalies than that induced by altered radiative forcing. **Citation:** Zhang, R., and T. L. Delworth (2009), A new method for attributing climate variations over the Atlantic Hurricane Basin's main development region, *Geophys. Res. Lett.*, *36*, L06701, doi:10.1029/2009GL037260.

## 1. Introduction

[2] The time series of detrended SST averaged over the North Atlantic is often called the Atlantic Multidecadal Oscillation (AMO) index [*Enfield et al.*, 2001; *Knight et al.*, 2005]. This index is highly correlated with multidecadal SST variations over the tropical Atlantic MDR and multidecadal variations of Atlantic hurricane activity [*Goldenberg et al.*, 2001]. A warm AMO phase leads to a reduction in the vertical shear of the zonal wind (Uz, zonal wind difference between 200-hPa and 850-hPa) over the MDR that is favorable for the development of Atlantic major Hurricanes [*Zhang and Delworth*, 2006]. The SST variations over the Atlantic MDR also affect the maximum potential intensity (MPI), i.e., a theoretical upper limit of tropical cyclone intensity [*Emanuel*, 2000]. *Vecchi and Soden* [2007b] find that the local MPI [*Emanuel*, 2000] anomaly can be viewed approximately as a difference between local and tropical mean SST anomaly, i.e., a simplified index for MPI (SIMPI) anomaly. Warmer SST over the Atlantic MDR relative to the tropical mean will lead to an increase of SIMPI that tends to enhance tropical Atlantic cyclone activity [*Vecchi and Soden*, 2007b]. The multidecadal tropical North Atlantic SST variations are often speculated to be linked to fluctuations of the Atlantic meridional overturning circulation (AMOC) [*Delworth and Mann*, 2000; *Knight et al.*, 2005]. However, *Mann and Emanuel* [2006] suggest that the tropical anomalies in late summer are forced by changes in radiative forcing. *Delworth et al.* [2007] suggest that both processes may be important. *Zhang* [2007] finds that in the tropical North Atlantic, the observed detrended surface and subsurface ocean temperature are strongly anticorrelated. This anticorrelation is a distinctive signature of AMOC variations in coupled climate model simulations, suggesting that the AMOC variations are important for the observed multidecadal tropical North Atlantic SST variations.

[3] A quantitative attribution of multidecadal SST variations to a radiatively forced part and a part arising from internal variability is very important. *Mann and Emanuel* [2006] criticized the simple linear detrending method for defining the AMO index and proposed a regression model in which they found a negligible component of the recent late summer tropical Atlantic MDR warming attributable to internal variability. Their technique assumed that the global mean surface temperature anomalies are entirely induced by external radiative forcing. However, Atlantic oceanic variations might contribute to the global mean surface temperature anomaly [*Zhang et al.*, 2007], which would complicate their attribution technique. Further, the estimates of the aerosol forcing employed in the regression model [*Mann and Emanuel*, 2006] are also highly uncertain. In contrast, *Kravtsov and Spannagle* [2008] (hereinafter referred to as KS08) take the multi-model ensemble mean of the 20th century simulations used in the recent IPCC assessment as an estimate of the radiatively forced signal, and then subtract it from the observed data to estimate the internal variability component. KS08 found that the leading mode of the multi-region data-model difference resembles internal variations induced by changes in the AMOC, and is statistically significant and corresponds almost perfectly to the AMO signal derived from linear detrending.

[4] We propose a new method to attribute observed SST, Uz, and SIMPI multidecadal anomalies over the south-central part of the Atlantic MDR into a radiatively forced component, and a component arising from internal oceanic variability such as that associated with simulated AMOC variations. At the multidecadal timescale, the leading mode of observed ocean variability in the Atlantic appears similar to estimates of variability associated with AMOC variations (KS08). The contributions to Atlantic multidecadal variability from El Niño and Southern Oscillation (ENSO) are negligible. For example, the detrended observed Hurricane season south-central MDR SST anomaly is not significantly correlated with the ENSO index (r = 0.12), and its regression on the ENSO index (0.02 K) is much smaller compared to its standard deviation ($\sigma$ = 0.17 $K$) at the multidecadal timescale. Other variability, such as the North Atlantic Oscillation (NAO), might also contribute to the Atlantic multidecadal variability. The contributions to Atlantic multidecadal variability from all other sources of internal vari-

---

[1] GFDL, NOAA, Princeton, New Jersey, USA.

Published in 2009 by the American Geophysical Union.

ability are represented in the estimated attribution uncertainties. The detailed method for the calculation of the attribution uncertainties is described in the auxiliary material.[1]

[5] The attribution is based on the observed SST and Uz anomalies, and two different ratios between Uz and SST anomalies derived from GFDL climate models: one ratio for radiatively forced anomalies and the other for anomalies forced from internal oceanic variability. We found that the observed SST signal attributed to internal oceanic variability is significant and similar to the AMO signal found with simple linear detrending; furthermore, the observed multidecadal anomalies of Uz and SIMPI are both dominated by the internal oceanic variability signal, consistent with multidecadal variations of Atlantic Hurricane activity.

## 2. Description of Experiments and Observational Data

[6] The model used in this study is the latest version of the GFDL global coupled ocean-atmosphere model (CM2.1) [*Delworth et al.*, 2006]. First, we look into an ensemble of five 20th century simulations, each with different initial conditions but forced with the same estimates of changes in the radiative forcing (solar irradiance, volcanoes, anthropogenic greenhouse gases, ozone, aerosols, and land use changes), as made available to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4) [*Knutson et al.*, 2006] and included in the CMIP3 database. The ensemble is referred to as $MODEL_{RF}$ hereafter, because the ensemble mean smoothes out fluctuations from internal variations, and mainly reflects the response to radiative forcing changes.

[7] Secondly, we study the response to Atlantic oceanic forcing with a hybrid coupled model in which we replace the fully dynamic ocean component of CM2.1 with a motionless slab ocean in the Atlantic ocean. The slab ocean interacts with the atmosphere only through exchanges of surface heat fluxes. Ocean basins outside the Atlantic remain fully dynamic. A climatological heat flux is prescribed over the slab Atlantic so as to maintain observed seasonally varying SSTs. We further apply an anomalous heat flux over the slab ocean that redistributes heat meridionally only within the Atlantic with zero spatial integral. The positive phase of this anomalous heat flux leads to a warming in the North Atlantic and a cooling in the South Atlantic. This is equivalent to prescribing an anomalous northward ocean heat transport (0.165 PW) across the equator to mimic that induced by AMOC variations. The details of this hybrid coupled model are described by *Zhang and Delworth* [2006]. We conduct two experiments forced with steady positive phase and negative phase of the anomalous heat flux respectively for 50 years. All radiative forcings are kept constant at their 1860 levels. We take the 50-year averaged difference between these two experiments as the steady state response to the Atlantic oceanic forcing. These two experiments are referred to as the steady oceanic forcing experiments ($MODEL_{SteadyOF}$), and are used to evaluate the impact of ocean heat transport on SST and Uz changes.

[8] We also conduct a 10-member ensemble simulation with the hybrid coupled model; each has different initial conditions and forced with the same transient anomalous heat flux for 100 years to mimic low frequency variations in the ocean. The anomalous heat flux specified in the Atlantic has the same spatial pattern as that used in the above 50-year steady forcing experiments. It is modulated by the observed low-pass filtered AMO Index derived from linear detrending from 1901 to 2000 to include AMO-like fluctuations over the Atlantic. The simulated ensemble mean AMO index has similar phase and amplitude as the observed AMO index derived from linear detrending, thereby validating the experimental design as detailed by *Zhang and Delworth* [2006]. All radiative forcings are kept constant at their 1860 levels. The ensemble is referred to $MODEL_{OF}$ hereafter, because the ensemble mean reflects the response to the transient oceanic heat flux specified in the Atlantic, which is equivalent to prescribing a transient ocean heat transport across the equator.

[9] The observed SST used in this study is from the HADISST dataset [*Rayner et al.*, 2003]. The observed Uz are from the ECMWF reanalysis dataset (ERA-40) [*Simmons and Gibson*, 2000]. We also repeated the study using Uz data from the NCEP reanalysis [*Kistler et al.*, 2001] (auxiliary material). All analyses are performed for the Hurricane season June–November (JJASON) and all variables (unless otherwise noted) are averaged over the south-central part of the MDR for Atlantic Hurricanes (70°W–20°W, 10°N–14°N), where the correlations between the vertical shear and major hurricanes are strongest [*Goldenberg et al.*, 2001]. All time series are low-pass filtered with a 10-year cutoff period to focus on the multidecadal timescale. For each time series, the anomaly is defined as the difference from its climatology mean over the period considered.

## 3. Attributing Climate Variations Over the Atlantic MDR

[10] Figures 1a and 1b compares the observed SST and Uz time series with ensemble means from $MODEL_{RF}$. The SST and Uz anomalies from $MODEL_{RF}$ show positive trends, but smaller multidecadal variations than those observed. The SST variability from $MODEL_{RF}$ ($\sigma$ = 0.086 K) is about half of that observed ($\sigma$ = 0.17 K). The results suggest that changes in radiative forcing alone are not able to explain all the observed SST and Uz anomalies, at least to the extent the model accurately simulates the response to radiative forcing.

[11] To attribute the observed SST and Uz anomalies (i.e., $SST'$ and $Uz'$), we decompose $SST'$ into three parts: the linear trend ($SST'_{TR}$), the detrended SST anomaly induced by changes in radiative forcing ($SST'_{RF}$), and the detrended SST anomaly forced by Atlantic ocean (heat transport) variations ($SST'_{OF}$).

$$SST' = SST'_{TR} + SST'_{RF} + SST'_{OF} \tag{1}$$

The linear trend ($SST'_{TR}$) is also induced by changes in radiative forcing, because the Atlantic ocean variations do not produce long-term trends. Hence the sum of the first two parts ($SST'_{TR} + SST'_{RF}$) reflects the total effect of changes in

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL037260.

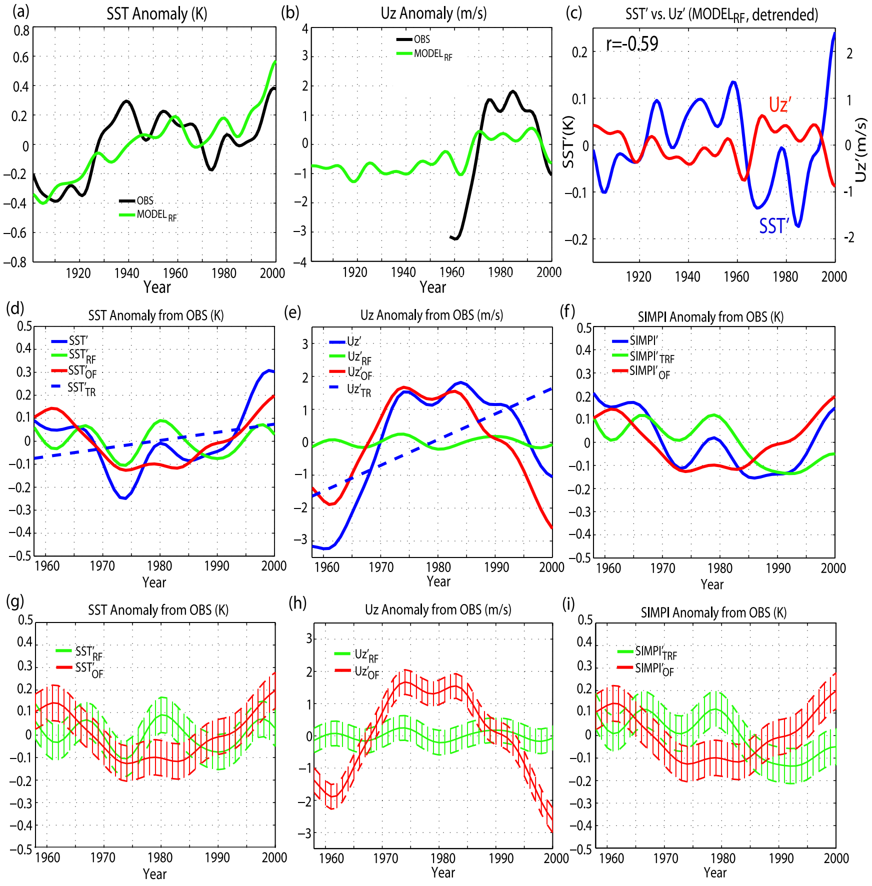

**Figure 1.** Time series for JJASON anomalies and decomposition of observed (OBS) JJASON SST, Uz, and SIMPI anomalies with uncertainty ranges. (a) SST anomaly (K) and (b) Uz anomaly (m/s) from observations (OBS) and modeling results of $MODEL_{RF}$. (c) Time series of detrended SST and detrended Uz anomalies from $MODEL_{RF}$. The cross correlation between anomalies is r = −0.59. (d) Decomposition of observed SST anomaly. (e) Same as Figure 1d but for Uz anomaly. (f) same as Figure 1d but for SIMPI anomaly. Attributed observed (g) SST, (h) Uz, and (i) SIMPI anomalies (thin solid lines) with uncertainty ranges. The areas covered with vertical lines between the thin dash lines show the uncertain range for each attributed variable, i.e., $\pm\sigma_{SST'_{RF}}$, $\sigma_{SST'_{OF}}$, $\sigma_{Uz'_{RF}}$, $\sigma_{Uz'_{OF}}$, $\sigma_{SIMPI'_{TRF}}$, $\sigma_{SIMPI'_{RF}}$. All time series are low-pass filtered with a 10-year cutoff period.

radiative forcing. Similarly, we can decompose $Uz'$ into three parts.

$$Uz' = Uz'_{TR} + Uz'_{RF} + Uz'_{OF} \qquad (2)$$

Again the sum of first two parts $Uz'_{TR} + Uz'_{RF}$ reflects the total effect of changes in radiative forcing, and $Uz'_{OF}$ represents the contribution from the Atlantic ocean (heat transport) variations.

[12] Given the observed time series of $SST'$ and $Uz'$, the linear trends can be computed, and our goal is to solve for the four unknown variables in equations (1) and (2): $SST'_{RF}$, $SST'_{OF}$, $Uz'_{RF}$, $Uz'_{OF}$, i.e., the attributed contributions of radiative forcing and oceanic forcing to detrended anomalies. Modeling results provide key relationships among these unknown variables. There is an anticorrelation (r = −0.59) between detrended SST and detrended Uz anomalies from $MODEL_{RF}$ (Figure 1c), significant at the 98% level with an effective degree of freedom (dof) of 14. The effective dof is the sample size divided by the decorrelation time between these two variables. We take the linear regression between these detrended Uz and detrended SST anomalies from $MODEL_{RF}$ as a ratio ($\alpha_{RF} = -2.35 \pm 0.13$ $m/s/K$) between radiative forced detrended anomalies.

$$Uz'_{RF} = \alpha_{RF} SST'_{RF} + \varepsilon_{RF} \qquad (3)$$

Here $\varepsilon_{RF}$ is the unexplained noise associated with the linear regression fit, which has a zero mean and a variance (uncertainty range) of 0.28 $m/s$ (see auxiliary material), i.e., $\varepsilon_{RF} = 0 \pm 0.28$ $m/s$.

[13] There is also a very strong anticorrelation (r = −0.82) between SST and Uz anomalies from the 10-member ensemble simulation with transient oceanic forcing ($MODEL_{OF}$, Figure S1d), significant at the 99% level with an effective dof of 7. We take the linear regression between these Uz and SST anomalies from $MODEL_{OF}$ as a ratio ($\alpha_{OF} = -13.21 \pm 0.94$ $m/s/K$) between anomalies induced by the Atlantic ocean variations.

$$Uz'_{OF} = \alpha_{OF} SST'_{OF} + \varepsilon_{OF} \qquad (4)$$

Here $\varepsilon_{OF}$ is the unexplained noise associated with the linear regression fit, which has a zero mean and a variance (uncertainty range) of 0.80 *m/s* (see auxiliary material), i.e., $\varepsilon_{OF} = 0 \pm 0.80$ *m/s*.

[14] The linear regression ratio between the Uz and SST anomalies from $MODEL_{OF}$ (−13.21 *m/s/K*) is very similar to the ratio between the averaged oceanic forced Uz and SST anomalies obtained from $MODEL_{Steady\ OF}$ - the 50-year experiments with steady oceanic forcing (−13.51 *m/s/K*). The slight difference in this ratio between the simulations with transient and steady oceanic forcing does not affect the robustness of the attribution solutions shown in the paper. This also shows that the attribution method depends on this ratio, and does not depend on the amplitude of simulated oceanic forced anomalies.

[15] Knowing the mean values of $\alpha_{RF}$, $\alpha_{OF}$, $\varepsilon_{RF}$, and $\varepsilon_{OF}$, we then are able to extract the four unknown variables: $SST'_{RF}$, $SST'_{OF}$, $Uz'_{RF}$, $Uz'_{OF}$ in the four independent equations (equations (1), (2), (3), and (4)) from the observed data. The key point here is that $\alpha_{RF} \neq \alpha_{OF}$. Even including the uncertainty range, the two ratios ($\alpha_{RF} = -2.35 \pm 0.13$ *m/s/K*; $\alpha_{OF} = -13.21 \pm 0.94$ *m/s/K*) do not overlap. Thus different mechanisms produce different ratios. If $\alpha_{RF} = \alpha_{OF}$, then we would have only three independent equations and could not obtain the attribution. The larger value for $\alpha_{OF}$ demonstrates that SST anomalies induced by oceanic heat transport variations are more efficient in producing negative Uz anomalies than are SST anomalies induced by changes in the radiative forcing prescribed in $MODEL_{RF}$. In the oceanic forced experiment, the warm North Atlantic is linked to an increase in the implied northward cross-equatorial ocean heat transport. This has little impact on heat flux at the top of the atmosphere (TOA), but leads to a similar decrease in the northward atmospheric heat transport across the equator for compensation, thus a northward shift of the Intertropical Convergence Zone (ITCZ) and a reduction of Uz over the tropical Atlantic MDR [*Zhang and Delworth*, 2006; *Zhang et al.*, 2007]. The radiatively forced detrended anomalies in $MODEL_{RF}$ are associated with significant heat flux anomalies at the TOA, which are mainly balanced by ocean surface heat flux anomalies, with much smaller changes in the cross-equatorial northward atmospheric heat transport, ITCZ, and Uz [*Zhang et al.*, 2007].

[16] The attribution solution is a weighted linear combination of detrended SST and Uz anomalies.

$$SST'_{RF} = \frac{-\alpha_{OF}\left(SST' - SST'_{TR}\right) + \left(Uz' - Uz'_{TR}\right) - \varepsilon_{OF} - \varepsilon_{RF}}{\alpha_{RF} - \alpha_{OF}} \tag{5}$$

$$SST'_{OF} = \frac{\alpha_{RF}\left(SST' - SST'_{TR}\right) - \left(Uz' - Uz'_{TR}\right) + \varepsilon_{OF} + \varepsilon_{RF}}{\alpha_{RF} - \alpha_{OF}} \tag{6}$$

$$Uz'_{RF} = \alpha_{RF}\frac{-\alpha_{OF}\left(SST' - SST'_{TR}\right) + \left(Uz' - Uz'_{TR}\right) - \varepsilon_{OF} - \varepsilon_{RF}}{\alpha_{RF} - \alpha_{OF}} + \varepsilon_{RF} \tag{7}$$

$$Uz'_{OF} = \alpha_{OF}\frac{\alpha_{RF}\left(SST' - SST'_{TR}\right) - \left(Uz' - Uz'_{TR}\right) + \varepsilon_{OF} + \varepsilon_{RF}}{\alpha_{RF} - \alpha_{OF}} + \varepsilon_{OF} \tag{8}$$

The attribution solution for observations depends on the availability of both observed SST and Uz data, and thus is limited to the period 1958–2000. Figures 1d–1f shows the attribution for observations. The variations of $SST'_{RF}$ and $SST'_{OF}$ are on the same order (Figure 1d), but the variations of $Uz'_{RF}$ are much smaller than that of $Uz'_{OF}$ (Figure 1e); both $SST'_{TR}$ and $Uz'_{TR}$ show increasing trends (Figures 1d and 1e). The radiatively forced trends are very important for the total anomalies, and the ocean-forced contribution becomes more important only for the detrended Uz anomalies. The increasing trend of Uz ($Uz'_{TR}$) over the Atlantic MDR, unfavorable for Atlantic Hurricanes activity, is mainly induced by tropical Indo-Pacific surface warming [*Latif et al.*, 2007; *Wang and Lee*, 2008]. This is consistent with a recent study [*Vecchi and Soden*, 2007a] showing that a radiatively forced tropical mean warming trend leads to an increasing Uz trend in the IPCC-AR4 model projections for the 21st Century, probably due to the weakening of the Walker circulation. Both the oceanic forced $SST'_{OF}$ and $Uz'_{OF}$ show clear multidecadal variations. The observed oceanic forced signal identified with this new attribution method is similar to the AMO signal found with the simple linear detrending, consistent with the results found by KS08. The observed $SST'_{RF}$ has cooling peaked in the mid 70's and 1990 (Figure 1d). The estimated attribution uncertainties of $SST'_{RF}$, $SST'_{OF}$, $Uz'_{RF}$, $Uz'_{OF}$ caused by uncertainty ranges in $\alpha_{RF}$, $\alpha_{OF}$, $\varepsilon_{RF}$, and $\varepsilon_{RF}$ are shown in Figures 1g and 1h. The detail method for the calculation of these uncertainties is described in section 2 of the auxiliary material. The attribution uncertainties caused by uncertainty ranges in $\alpha_{RF}$ and $\alpha_{OF}$ alone are much smaller than that caused by uncertainty ranges in $\varepsilon_{RF}$, and $\varepsilon_{OF}$. The attribution uncertainties depend on $\sigma_{\varepsilon_{RF}}$, and $\sigma_{\varepsilon_{OF}}$ which are calculated from $MODEL_{RF}$ and $MODEL_{OF}$.

[17] Similarly, we can decompose the SIMPI anomaly ($SIMPI'$). Following *Vecchi and Soden* [2007b], $SIMPI'$ is defined as following.

$$SIMPI' = SST' - \langle SST' \rangle \tag{9}$$

Here $\langle SST' \rangle$ is the tropical (30°S–30°N) mean SST anomaly. Given our attribution of $SST'$, we obtain the following relationship.

$$SIMPI' = SST'_{OF} + SST'_{RF} + SST'_{TR} - \langle SST' \rangle \tag{10}$$

In the oceanic forced experiments, the Atlantic oceanic forcing can induce local SST anomalies in the MDR region, but do not contribute much to the tropical mean anomaly $\langle SST' \rangle$, because of small Atlantic area and the opposite sign across the equator. Hence we can attribute $SIMPI'$ into the oceanic forced part ($SIMPI'_{OF}$), and the total radiative forced part ($SIMPI'_{TRF}$).

$$SIMPI' = SIMPI'_{OF} + SIMPI'_{TRF} \tag{11}$$

Here

$$SIMPI'_{OF} = SST'_{OF} \tag{12}$$

$$SIMPI'_{TRF} = SST'_{RF} + SST'_{TR} - \langle SST' \rangle \tag{13}$$

Figure 1f shows the attribution of observed $SIMPI'$. The observed multidecadal variations of $SIMPI'$ are dominated by $SIMPI'_{OF}$, the oceanic forced signal. Since the late 50's, there is a decreasing trend in the observed $SIMPI'_{TRF}$ (Figure 1f), indicating that the observed total radiatively forced tropical Indo-Pacific warming (which dominates the tropical mean) is larger than the observed total radiatively forced tropical Atlantic warming. This suggests a decreasing trend in the observed local MPI that has a potential to reduce Atlantic Hurricane activity since the late 50's. However, Atlantic Hurricane activity is actually above normal since 1995, indicating that the oceanic forced increase in observed $SIMPI'_{OF}$ since 1995 (Figure 1f) might have played an important role. The estimated attribution uncertainties of $SIMPI'_{OF}$, $SIMPI'_{TRF}$ caused by uncertainty ranges of $\alpha_{RF}$, $\alpha_{OF}$, $\varepsilon_{RF}$, and $\varepsilon_{RF}$ are also shown in Figure 1i.

## 4. Summary and Discussion

[18] We have used an attribution technique that exploits the fact that the relationship between SST and Uz anomalies in the MDR region is different for anomalies forced by radiative changes and for anomalies forced by changes in Atlantic ocean heat transport. Using this technique, the analysis suggests that multidecadal SST variations in the MDR have comparable contributions from both ocean heat transport variations and radiative forcing. The SST changes attributable to ocean variations using this technique are similar to the AMO signal derived from simple linear detrending as found by KS08. The radiatively forced detrended Uz variations are much smaller than those induced by the Atlantic ocean variations. The multidecadal Uz and SIMPI anomalies are both dominated by the oceanic forced signal. The Atlantic ocean variations lead to enhanced SST/SIMPI and reduced Uz during the early 1960's and the mid to late 1990's, consistent with observed above-normal Atlantic Hurricane activities during these periods. The total radiatively forced tropical Indo-Pacific warming is larger than the observed total radiatively forced tropical Atlantic warming since the late 50's, leading to the increasing trend of radiatively forced Uz anomaly and the decreasing trend of the total radiatively forced SIMPI anomaly, both unfavorable for Atlantic Hurricanes activities. The main conclusions using Uz data from the NCEP reanalysis (Figure S4) are similar to those using the ECMWF reanalysis (Figure 1). The Uz data from the NCEP reanalysis shows larger variation. Hence the NCEP-based attributed anomalies have larger amplitudes, i.e., the amplitudes of attributed anomalies are sensitive to the uncertainty in the reanalysis Uz data. This is a caveat of our study. It is important to improve observation of Uz variations in the future to obtain more accurate attributions.

[19] The only non-observed values involved in the attribution technique are the ratios ($\alpha_{RF} = Uz'_{RF}/SST'_{RF}$, and $\alpha_{OF} = Uz'_{OF}/SST'_{OF}$) estimated by dynamics from models. The SST anomalies induced by changes in ocean heat transport are more efficient in producing negative Uz anomalies than radiatively forced SST anomalies, at least in the context of the GFDL model and the forcing scenarios examined. The uncertainties of attributed SST and Uz anomalies induced by uncertainty ranges in $\alpha_{RF}$ and $\alpha_{OF}$ alone are very small. The attribution results could be affected by the uncertainty in modeled tropical response pattern and this is a caveat of this study. Future studies of how the ratios are affected by the uncertainty in modeled tropical response in various models need to be investigated.

## References

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–676.

Delworth, T. L., et al. (2006), GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics, *J. Clim.*, *19*, 643–674.

Delworth, T. L., R. Zhang, and M. E. Mann (2007), Decadal to centennial variability of the Atlantic from observations and models, in *Ocean Circulation: Mechanisms and Impacts*, *Geophys. Monogr. Ser.*, vol. 173, edited by A. Schmittner, J. C. H. Chiang, and S. R. Hemming, pp. 131–148, AGU, Washington, D. C.

Emanuel, K. (2000), A statistical analysis of tropical cyclone intensity, *Mon. Weather Rev.*, *128*, 1139–1152.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*, 474–479.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–268.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GL024233.

Knutson, T. R., T. L. Delworth, K. W. Dixon, I. M. Held, J. Lu, V. Ramaswamy, M. D. Schwarzkopf, G. Stenchikov, and R. J. Stouffer (2006), Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models, *J. Clim.*, *10*, 1624–1651.

Kravtsov, S., and C. Spannagle (2008), Multi-decadal climate variability in observed and modeled surface temperatures, *J. Clim.*, *21*, 1104–1121.

Latif, M., N. Keenlyside, and J. Bader (2007), Tropical sea surface temperature, vertical wind shear, and hurricane development, *Geophys. Res. Lett.*, *34*, L01710, doi:10.1029/2006GL027969.

Mann, M. E., and K. A. Emanuel (2006), Atlantic hurricane trends linked to climate change, *Eos Trans. AGU*, *87*(24), 233, doi:10.1029/2006EO240001.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Simmons, A. J., and J. K. Gibson (2000), The ERA-40 project plan, *ERA-40 Proj. Rep. Ser. 1*, 63 pp., Eur. Cent. for Medium Range Weather Forecasts, Reading, U. K.

Vecchi, G. A., and B. J. Soden (2007a), Increased tropical Atlantic wind shear in model projections of global warming, *Geophys. Res. Lett.*, *34*, L08702, doi:10.1029/2006GL028905.

Vecchi, G. A., and B. J. Soden (2007b), Effect of remote sea surface temperature change on tropical cyclone potential intensity, *Nature*, *450*, 1066–1070.

Wang, C., and S.-K. Lee (2008), Global warming and United States landfalling hurricanes, *Geophys. Res. Lett.*, *35*, L02708, doi:10.1029/2007GL032396.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic Multidecadal Oscillations on India/Sahel Rainfall and Atlantic Hurricanes, *Geophys. Res. Lett.*, *33*, L17712, doi:10.1029/2006GL026267.

Zhang, R. (2007), Anticorrelated multidecadal variations between surface and subsurface tropical North Atlantic, *Geophys. Res. Lett.*, *34*, L12713, doi:10.1029/2007GL030225.

Zhang, R., T. L. Delworth, and I. M. Held (2007), Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature?, *Geophys. Res. Lett.*, *34*, L02709, doi:10.1029/2006GL028683.

---

T. L. Delworth and R. Zhang, GFDL, NOAA, 201 Forrestal Road, Princeton, NJ 08540, USA. (rong.zhang@noaa.gov)