GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L01706, doi:10.1029/2008GL035111, 2009

Reply to comment by Joseph J. Barsugli on "Global warming and United States landfalling hurricanes"

Chunzai Wang[1] and Sang-Ki Lee[2]

Received 23 June 2008; revised 10 October 2008; accepted 18 November 2008; published 10 January 2009.

Citation: Wang, C., and S.-K. Lee (2009), Reply to comment by Joseph J. Barsugli on ''Global warming and United States landfalling hurricanes'', *Geophys. Res. Lett.*, *36*, L01706, doi:10.1029/2008GL035111.

[1] In our recent paper [*Wang and Lee*, 2008] (henceforth WL08), we perform an empirical orthogonal function (EOF) analysis on the global annual mean SST over the past 153 years (from 1854 to 2006). The first three EOF modes, which account for 28.3%, 15.3%, and 5.3% of the total variance in the SST data, may represent global warming, ENSO-like (including the Pacific decadal oscillation), and the Atlantic multidecadal oscillation (AMO), respectively. We then use the first EOF mode to study the relationship among global warming, vertical wind shear in the Atlantic hurricane main development region (MDR) and U.S. landfalling hurricanes. The second EOF mode (ENSO-like) and the third EOF mode (the AMO) are presented in another paper (see Figure 1 of *Wang et al.* [2008a] for these two modes).

[2] In his comment, *Barsugli* [2009] (henceforth B09) points out that the SST spatial pattern of the first EOF mode is similar to that of an El Niño event and that its time series contains variations on interannual timescale. He thus concerns that the first EOF mode of global warming may include the interannual ENSO signal and therefore the observed relationship between global warming and U.S. landfalling hurricanes (also vertical wind shear in the hurricane MDR) of WL08 may be partly attributed to interannual ENSO's effect. We appreciate and understand his concern since there is no "perfect" method for separating climate modes on various timescales from observational data such as global warming and ENSO modes. We agree that the first EOF mode contains some interannual variations possibly linked to ENSO and that it is difficult to distinguish anthropogenic climate change from natural low-frequency variability in observational data. However, here we show that the conclusion of WL08 is still true even after removing interannual signals from the first EOF mode. We also present some additional evidences that support the conclusion of WL08.

[3] B09 suggests that interannual variations are first removed by applying an 11-year running mean to the SST data prior to performing the EOF analysis. We agree that this approach may be a reasonable way to remove the interannual ENSO signal although it still keeps lower-frequency variations of ENSO. We re-perform our EOF analysis following B09's suggestion. The resulting spatial pattern and time series of the first EOF mode are shown in Figures 1a and 1b (Figure 1a is almost identical to Figure 1b of B09), which accounts for 57.4% of the total variance. In comparison with Figure 1 of WL08, the amplitude of SST in

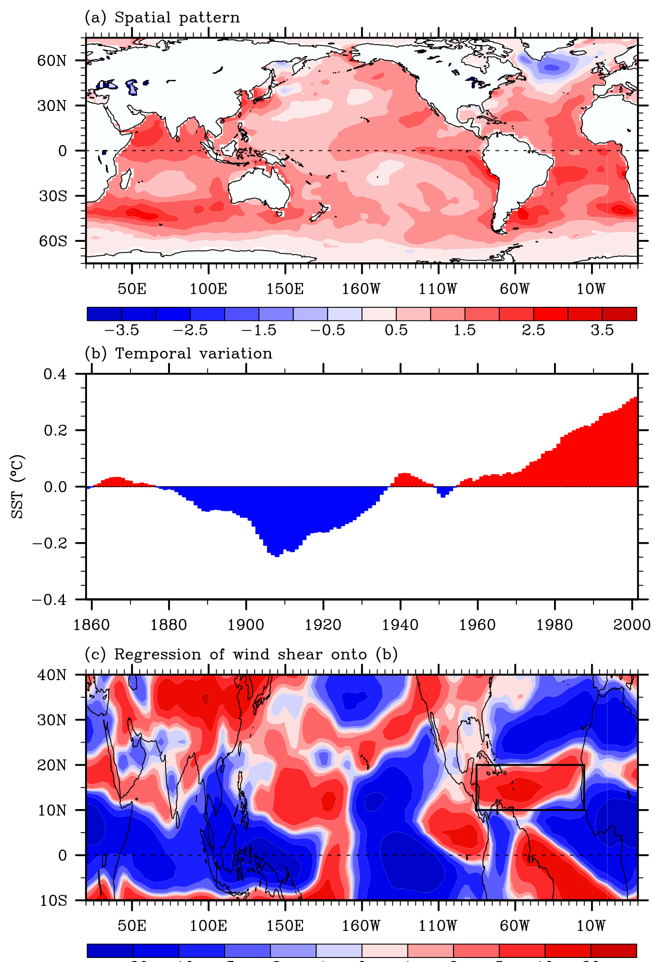

Figure 1. (a) The spatial pattern (°C per °C) and (b) temporal reconstruction (°C) for the first EOF mode and (c) regression coefficient (m/s per °C) of vertical wind shear onto the temporal variation of Figure 1b. The EOF analysis is the same as that of WL08 except that an 11-year running mean is applied to the SST data before the EOF analysis. The 95% significant level over the MDR (box) in Figure 1c is ±5.33 m/s per °C.

[1]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, Florida, USA.

[2]Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, Florida, USA.

0094-8276/09/2008GL035111$05.00

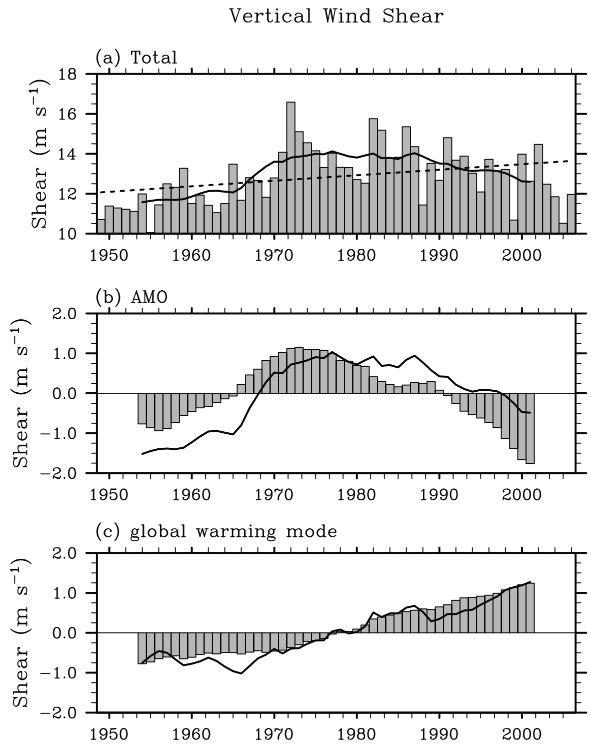

Figure 2. (a) Time series of the vertical wind shear (bars) in the MDR (85°W–15°W, 10°N–20°N) during the Atlantic hurricane season of June to November. The dashed and solid lines represent the linear trend and the 11-year running mean, respectively. (b) The projection of the 11-year running mean vertical wind shear onto the AMO (bars) and the 11-year running mean vertical wind shear with its mean value (13.1 m/s) removed (solid line). (c) The projection of the 11-year running mean vertical wind shear onto global warming index of Figure 1b (bars) and the difference between the 11-year running mean vertical wind shear (with the mean value removed) and the vertical wind shear projection onto the AMO (solid line). The vertical wind shear is calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb. The wind data is from the NCEP-NCAR reanalysis from 1949 to 2006.

the equatorial central Pacific is reduced and the time series is much smoothed. The peaks and valleys in Figure 1b of WL08, which possibly correspond to El Niño and La Niña events (as pointed out by B09), now disappear. This indicates that the first EOF mode in WL08 does contain some interannual variations. However, major features in the spatial pattern and temporal evolution of global warming mode are overall unchanged. In particular, all three tropical oceans are warmed up with a more or less constant warming rate in the 20th century. Figure 1c shows the map of regression coefficient of vertical wind shear onto the time series of Figure 1b. Note that this map of regression coefficient is almost the same as that in Figure 2 of WL08. The large positive and significant (above 95% level) regression still appears in the Atlantic hurricane MDR, suggesting that global warming is associated with an increase of the vertical wind shear, thus inhibits atmospheric convection and disfavors the formation and development of Atlantic hurricanes. Therefore, the conclusion of WL08 is still valid after removing the interannual ENSO signal from the first EOF mode by using the statistical methodology suggested by B09.

[4] The vertical wind shear in the hurricane MDR does show a secular increase. Using the NCEP-NCAR reanalysis, we calculate the time series of the vertical wind shear in the hurricane MDR during the Atlantic hurricane season of June to November (Figure 2a). In addition to the linear trend (dashed line in Figure 2a), we use two other methods to calculate the secular change of vertical wind shear. Similar to SST analysis, we apply an 11-year running mean to the total vertical wind shear (solid line in Figure 2a). We then project the 11-year running mean time series onto the global warming mode in Figure 1b (bars in Figure 2c). The second method is to first project the 11-year running mean time series onto the AMO signal of *Enfield et al.* [2001] and then subtract this projection from the 11-year running mean time series (solid line in Figure 2c). All of these calculations show a secular increase (about 2 m/s in 50 years) of the vertical wind shear in the hurricane MDR. It is indicated that as the global ocean is warmed up, the vertical wind shear in the MDR is also secularly increased and thus results in fewer hurricanes, consistent with a weak downward trend observed in U.S. landfalling hurricanes. The main point is that warmings in the tropical Pacific, Indian and Atlantic Oceans compete with one another, producing increased wind shear in the MDR and thus reducing U.S. landfalling hurricanes.

[5] Our time series of the first EOF mode are consistent with other indices representing global warming observed during the past. For example, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) uses the annual land-surface air temperature anomalies or the annual combined land-surface air temperature and SST anomalies to show global warming [e.g., *Trenberth et al.*, 2007]. Our indices from the first EOF mode are similar to those of global warming in the IPCC-AR4.

[6] Finally, the conclusion of WL08 is supported by future model projections under global warming scenarios for the 21st century. By analyzing a suite of coupled ocean-atmosphere model outputs, *Vecchi and Soden* [2007] report an increase in the vertical wind shear over the Caribbean Sea for future global warming. Our analysis of IPCC-AR4 models (D. B. Enfield et al., unpublished manuscript, 2008) shows that as the Atlantic meridional overturning circulation weakens under future global warming, a cooling effect will cause the North Atlantic to warm more slowly than other oceans (i.e., the Pacific and Indian Oceans) and thus the environment is physically consistent with that under a small Atlantic warm pool. It has been demonstrated that a small Atlantic warm pool enhances the vertical wind shear in the MDR and decreases the moist static instability of the troposphere, both of which disfavor Atlantic hurricane activity [*Wang et al.*, 2008b]. The consistency of our past observational data analysis and the future model projection analyses mentioned above suggests that the increase of the vertical wind shear in the Atlantic hurricane MDR, associated with global warming, is a robust feature.

[7] **Acknowledgments.** This work was supported by a grant from the National Oceanic and Atmospheric Administration (NOAA) Climate Pro-

gram Office and by the base funding of NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML). The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency.

References

Barsugli, J. J. (2009), Comment on "Global warming and United States landfalling hurricanes" by Chunzai Wang and Sang-Ki Lee, *Geophys. Res. Lett.*, *36*, L01705, doi:10.1029/2008GL034621.

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.

Trenberth, K. E., et al. (2007), Observations: Surface and atmospheric climate change, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 235–336, Cambridge Univ. Press, Cambridge, U. K.

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

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

Wang, C., S.-K. Lee, and D. B. Enfield (2008a), Atlantic warm pool acting as a link between Atlantic multidecadal oscillation and Atlantic tropical cyclone activity, *Geochem. Geophys. Geosyst.*, *9*, Q05V03, doi:10.1029/2007GC001809.

Wang, C., S.-K. Lee, and D. B. Enfield (2008b), Climate response to anomalously large and small Atlantic warm pools during the summer, *J. Clim.*, *21*, 2437–2450.

S.-K. Lee, Cooperative Institute for Marine and Atmospheric Studies, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA.

C. Wang, Atlantic Oceanographic and Meteorological Laboratory, NOAA, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. (chunzai.wang@noaa.gov)