Tropical sea surface temperature, vertical wind shear, and hurricane development

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[1] The anomalously strong hurricane activity in the Atlantic sector during the recent years led to a controversy about the impact of global warming on hurricane activity in the Atlantic sector. Here we show that the temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans (Indo-Pacific) is a key parameter in controlling the vertical wind shear over the Atlantic, an important quantity for hurricane activity. The stronger warming of the tropical North Atlantic relative to that of the Indo-Pacific during the most recent years drove reduced vertical wind shear over the Atlantic and is thus responsible for the strong hurricane activity observed. In 2006, however, the temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans is much reduced, which explains the relatively weak hurricane season. **Citation:** 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.

1. Introduction

[2] The hurricane season of 2005 in the Atlantic sector was the most intense on record, with 28 recorded tropical storms and 15 of them reaching hurricane intensity. It remains controversial, however, as to whether tropical storm activity over the Atlantic has changed in a statistically significant manner [*Webster et al.*, 2005; *Trenberth*, 2005; *Emanuel*, 2005; *Anthes et al.*, 2006; *Mann and Emanuel*, 2006; *Pielke et al.*, 2006; *Trenberth and Shea*, 2006]. One of the most commonly used indices to measure tropical storm activity is the so called Accumulated Cyclone Energy (ACE) Index which is shown for the Atlantic sector in Figure 1a. The ACE Index takes into account the number, strength and duration of all tropical storms in a season. It is calculated by summing the squares of the estimated maximum sustained velocity of every active tropical storm (wind speed 35 knots or higher), at six-hour intervals. The ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but no sustained long-term trend. Yet, the last decade appears to be somewhat exceptional in the light of the last 155 years. It should be pointed out, however, that the ACE Index is subject to large uncertainties prior to the 1940s.

[3] The role of tropical North Atlantic sea surface temperature (SST) in driving tropical storm activity was discussed extensively in the literature [e.g., *Landsea et al.*, 1999; *Knight et al.*, 2006; *Zhang and Delworth*, 2006; *Trenberth and Shea*, 2006]. A rather strong multidecadal variability in the SST of the Atlantic basin was described [e.g., *Enfield et al.*, 2001; *Kerr*, 2005; *Knight et al.*, 2005; *Latif et al.*, 2006], which is referred to as the Atlantic Multidecadal Oscillation (AMO). The AMO, which has opposite polarities in the North and South Atlantic, is most likely related to variations of the Atlantic meridional overturning circulation (MOC), as was inferred from global climate model simulations [*Knight et al.*, 2005; *Latif et al.*, 2006]. It modulates the SST of the tropical North Atlantic which therefore also exhibits pronounced multidecadal variability (Figure 1b). Interestingly, a clear warming trend is seen in the tropical North Atlantic SST which does not seem to influence the tropical storm activity (Figure 1a). A clear warming trend is also observed in the surface temperature of the other two tropical oceans, the tropical Indian and Pacific Oceans, which is described in terms of a combined SST index (Indo-Pacific) that averages SSTs over the region 40°E–80°W, 30°N–30°S and also shown in Figure 1b.

[4] The remote effect of tropical Pacific SST on tropical storm activity over the Atlantic is well established within the context of the El Niño/Southern Oscillation (ENSO) phenomenon [*Goldenberg and Shapiro*, 1996]. Both the tropical North Atlantic and tropical Pacific SSTs are known to change the vertical wind shear over the Atlantic, an important parameter for tropical storm development [*Goldenberg et al.*, 2003]. A warming of the tropical North Atlantic reduces, while a warming of the tropical Pacific enhances the vertical wind shear. Weak vertical wind shear favours tropical storm development and vice versa. Here we show by means of atmospheric general circulation model experiments that the tropical Indian Ocean may also play an important role in tropical storm development over the Atlantic by remotely changing the vertical wind shear. Thus all three tropical oceans have to be considered when discussing the tropical storm activity in the Atlantic sector.

2. Model and Experimental Setup

[5] In order to get further insight into the relative roles of the individual ocean basins on the vertical wind shear over the tropical North Atlantic, we analyzed the results of an atmospheric general circulation model (AGCM) forced by the history of observed global monthly (Hadley Centre) SSTs for the period 1870–2003. The model, ECHAM5 [*Roeckner et al.*, 2003], is a state-of-the-art AGCM and was used with a horizontal resolution of T106, corresponding to 125 × 125 km grid, and with 31 vertical levels. Five integrations were performed with different initial but identical boundary conditions. This allows to distinguish the

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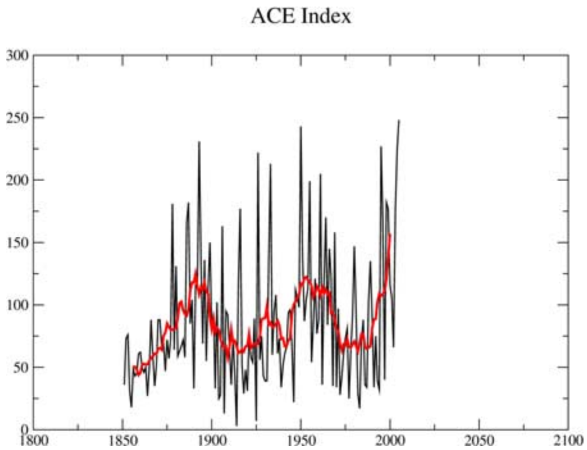

Figure 1a. Accumulated Cyclone Energy (ACE) Index for the Atlantic basin 1851–2005. The ACE Index is calculated by summing the squares of the estimated maximum sustained velocity of every active tropical storm (wind speed 35 knots or higher), at six-hour intervals. The ACE Index was downloaded from http://www.aoml.noaa.gov/hrd/tcfaq/E11.html. The red curve shows the low-pass filtered time series (applying an 11-year running mean). The ACE Index is normalized so that it has a value of 100 in an average year.

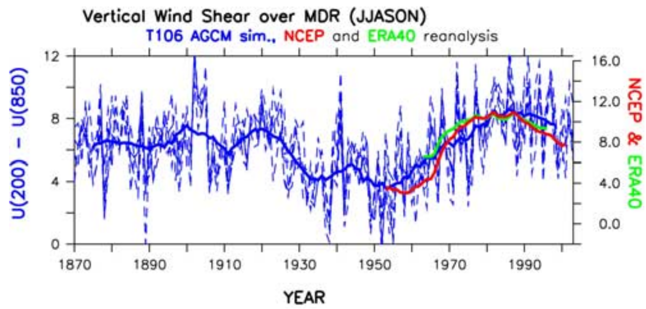

Figure 2. Simulation of the vertical wind shear with the T106 AGCM forced by observed SSTs (blue curves). The vertical wind shear is defined by the difference of the zonal wind between the upper (200 hPa) and lower (850 hPa) atmosphere. The vertical wind shear is averaged over the region 10–14°N and 20–70°W. The dashed lines show the individual realizations and the solid curve the ensemble mean. The ensemble mean is a measure of the SST-forced signal. Also shown are the low-pass filtered observational estimates from the NCEP (red) and ECMWF (green) reanalysis projects. Bold lines show the low-pass filtered (applying an 11-year running mean) timeseries. All timeseries are shown for the hurricane season (JJASON). Note the different scales. Units: m/s.

boundary (SST) forced signal from the internal (chaotic) variability of the atmosphere.

3. Simulation of Vertical Wind Shear

[6] The simulated vertical wind shear, defined by the zonal wind difference between the upper (200 hPa) and lower (850 hPa) atmosphere, is averaged over the tropical North Atlantic (10–14°N and 20–70°W) as in the work by *Goldenberg et al.* [2003] and shown in Figure 2 for the hurricane season June–November (JJASON). There is a rather good agreement among the five realisations, indicating a strong role of the boundary forcing for the vertical wind shear in the tropical Atlantic sector. The ensemble mean, a measure of the SST-forced signal, compares well with two observational estimates of the vertical wind shear from the ECMWF and NCEP reanalysis projects, although the observed changes are somewhat stronger. Furthermore, the variations of the vertical wind shear correspond nicely to those of the ACE Index (Figure 1a): Reduced wind shear goes along with enhanced tropical storm activity and vice versa. This indicates the important roles of the vertical wind shear in controlling tropical storm activity in the Atlantic sector during the last 130 years and of the global SSTs in driving the wind shear. The strongest correlation based on the raw summer/fall (JJASON) values amounting to −0.7 is found between the ECMWF vertical wind shear and the ACE Index, the NCEP vertical wind shear exhibits a correlation with the ACE Index of −0.5, and the model simulation of −0.6. The correlations were computed for the corresponding overlapping periods. It should be noted, however, that there remains a large fraction of the variance in the ACE Index that is not explained by the vertical wind shear.

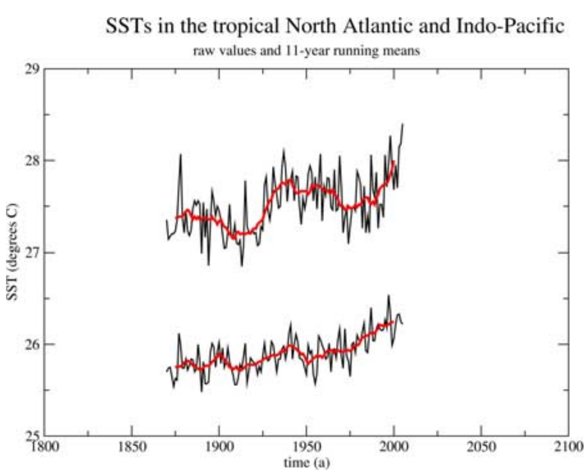

Figure 1b. SSTs in the tropical North Atlantic averaged over the region 10–14°N and 20–70°W (top curve) and SSTs in the Indo-Pacific region (40°E–80°W, 30°N–30°S) (bottom curve). The SSTs obtained from the Hadley Centre dataset are computed for the hurricane season (JJASON). The black lines denote the raw values, while the red lines depict the low-pass filtered (applying an 11-year running mean) timeseries which highlight the multidecadal variations. Units: °C.

4. Contribution of Individual Ocean Basins

[7] The question arises, however, why the obvious upward trend in tropical North Atlantic SST (Figure 1b) is neither reflected in the simulated vertical wind shear nor in the record of observed tropical storm activity (Figure 1a). It was shown that the tropical Indian Ocean exhibited a strong warming trend during the last decades which forced global

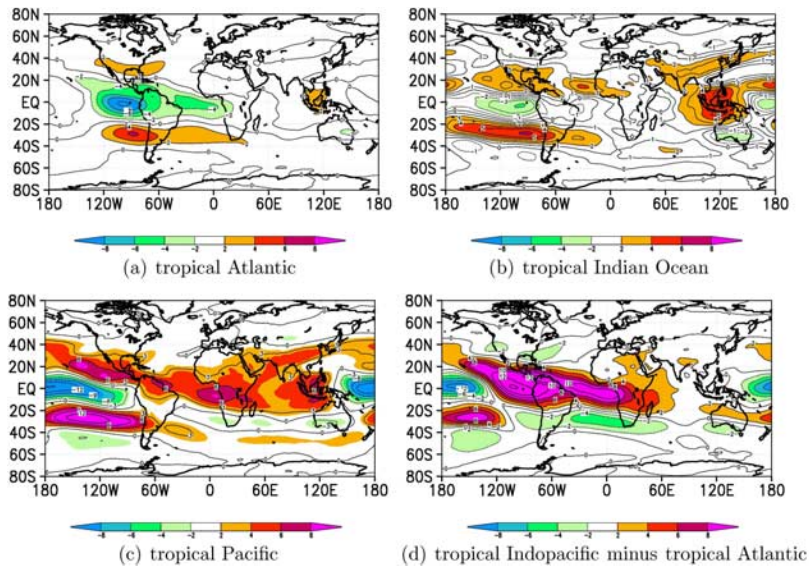

Figure 3. Maps of linear regression coefficients of AGCM-simulated vertical wind shear upon (a) tropical North Atlantic SST (10–14°N), (b) tropical Indian Ocean SST (30°N–30°S), (c) tropical Pacific SST (30°N–30°S), and (d) the tropical Indo-Pacific/tropical North Atlantic SST difference. Results are shown for the hurricane season (JJASON). Colour indicates statistical significance on the 95% level according to a t-test. Units: (m/s)/°C.

atmospheric anomalies [e.g., *Giannini et al.*, 2003; *Bader and Latif*, 2003]. Additional AGCM integrations of 30 years duration with a coarser-resolution version of the model (T63, 250 × 250 km grid), in which only the SST trend observed over the period 1951–2001 was prescribed in the tropical Indian Ocean, yield enhanced vertical wind shear over the tropical North Atlantic of the order of about 15% (not shown), so that the warming of the Indian Ocean acts to compensate, at least partly, the tendency of the tropical North Atlantic warming to reduce the wind shear.

[8] Furthermore, it is known that anomalously high tropical Pacific SST also drives enhanced vertical wind shear over the tropical Atlantic. Figure 3 depicts maps of linear regression coefficients of the vertical wind shear upon the SSTs in the three tropical oceans from the T106 integration. Clearly, warming of both the Indian and Pacific Ocean increases the vertical wind shear (Figures 3b and 3c), while warming of the tropical North Atlantic itself reduces the vertical wind shear (Figure 3a). Thus, the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic. This can be inferred from Figure 3d in which the regression of the vertical wind shear upon the Indo-Pacific/tropical North Atlantic SST difference is shown.

[9] The inverted SST difference, tropical North Atlantic minus Indo-Pacific, is plotted in Figure 4 together with the inverted ensemble mean wind shear from the T106 model simulation (Figure 2) and the ACE Index (Figure 1a). The timeseries are shown only from 1940 onwards, which is the period of most reliable observations. All three indices show a remarkable correspondence at decadal and longer timescales. Apparently, the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity remained rather stable and mostly within the range of the natural multidecadal variability. The correlation between the SST difference and the ACE Index amounts to 0.7 for the period 1940 to present and to 0.6 for the full overlapping period 1870 to present. The most recent period is characterized by an increased tropical North Atlantic/Indo-Pacific SST difference indicating that the tropical North Atlantic warmed more rapidly than the Indo-Pacific. This led to reduced vertical wind shear and

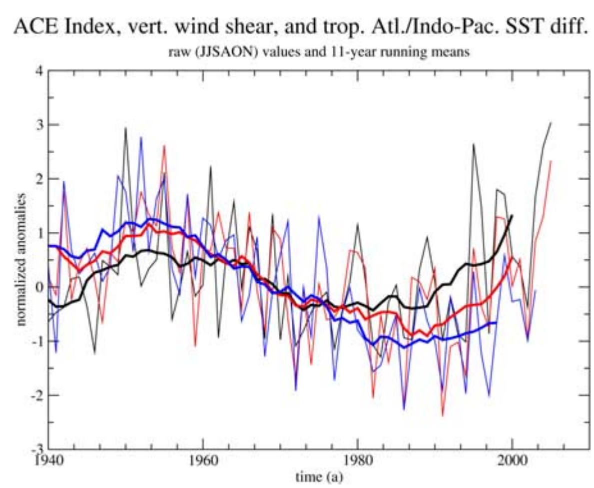

Figure 4. ACE Index (black), inverted simulated vertical wind shear (blue), and tropical North Atlantic/Indo-Pacific SST difference (red). Results are shown from 1940 onwards, since observations are most reliable for this period. The data were normalized with respect to their individual long-term standard deviations to ease comparison. The thin lines are the raw JJASON values. The thick lines denote the low-pass filtered (applying an 11-year running mean) values.

thus to enhanced tropical storm activity. In contrast, summer and fall of 2006 are characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans, and this explains the weak tropical storm activity.

[10] Thus, the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region. Changes in the MOC and their effect on tropical Atlantic SST have to be considered in this context. Likewise changes in ENSO statistics in the tropical Pacific may become important, as they affect the SSTs in all three tropical oceans. Other parameters than SST, however, such as the vertical stability of the atmosphere or changes in oceanic mixed layer depth also need to be considered in future projections of hurricane activity over the Atlantic.

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