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Increased tropical Atlantic wind shear in model projections of global warming

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[1] To help understand possible impacts of anthropogenic greenhouse warming on hurricane activity, we assess model-projected changes in large-scale environmental factors tied to variations in hurricane statistics. This study focuses on vertical wind shear (V_s) over the tropical Atlantic during hurricane season, the increase of which has been historically associated with diminished hurricane activity and intensity. A suite of state-of-the-art global climate model experiments is used to project changes in V_s over the 21st century. Substantial increases in tropical Atlantic and East Pacific shear are robust features of these experiments, and are shown to be connected to the model-projected decrease in the Pacific Walker circulation. The relative changes in shear are found to be comparable to those of other large-scale environmental parameters associated with Atlantic hurricane activity. The influence of these V_s changes should be incorporated into projections of long-term hurricane activity. **Citation:** 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.

1. Introduction

[2] Empirical relationships and dynamical considerations have identified several environmental factors that influence the development of tropical cyclones. Understanding the response of these environmental parameters to a warming climate, and the consequent changes in tropical cyclones, is a topic of profound societal significance and of intense scientific debate [e.g., *Goldenberg et al.*, 2001; *Knutson and Tuleya*, 2004; *Emanuel*, 2005; *Pielke et al.*, 2005; *Webster et al.*, 2005; *Zhang and Delworth*, 2006]. Variations in tropical cyclone characteristics have been connected to thermodynamic conditions, as well as changes in atmospheric circulation [e.g., *Gray*, 1984; *Emanuel*, 1995, 2005; *Holland*, 1997; *Knutson and Tuleya*, 2004; *Webster et al.*, 2005; *Camargo et al.*, 2007; *Knutson et al.*, 2007].

[3] Of particular importance is the vertical wind shear (V_s) which acts to inhibit tropical cyclone development [e.g., *Pielke and Landsea*, 1999; *Goldenberg et al.*, 2001; *Emanuel and Nolan*, 2004; *Camargo et al.*, 2007] and has a deleterious effect on the intensity of developed tropical cyclones [e.g., *DeMaria*, 1996; *Frank and Ritchie*, 2001]. The impact can be substantial for $V_s > 10\ \mathrm{ms}^{-1}$, with one modeling study finding that "[s]trong shear of 15 ms^{-1} literally tore an intense storm apart in about one day" [*Frank and Ritchie*, 2001].

2. Model-Projected Changes in Vertical Wind Shear

[4] We explore 21st Century projected changes in V_s over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions Scenario A1B (atmospheric CO_2 stabilization at 720 ppm by year 2100) for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4). Changes are computed between two 20-year periods: 2001–2020 and 2081–2100 (use of linear trends or other averaging periods does not alter the character of the results presented here). Our index of the strength of the Pacific Walker circulation is the difference of SLP averaged over the eastern (160°W–80°W, 5°S–5°N) and western (80°E–160°E, 5°S–5°N) equatorial Pacific Ocean [*Vecchi et al.*, 2006; *Vecchi and Soden*, 2007, hereinafter referred to as VS07]. We define V_s as the magnitude of the vector difference between monthly-mean winds at 850 hPa and 200 hPa ($V_s = |\boldsymbol{u}_{850} - \boldsymbol{u}_{200}|$) following a typical V_s definition in the literature [e.g., *Goldenberg et al.*, 2001; *Zhang and Delworth*, 2006]. For models where daily data was available we found little difference in the 21st Century V_s changes computed using daily winds and monthly winds over the global tropics. See Auxiliary Material Text S1 for a list of models used.[1] We restrict our attention to changes in V_s during the northern Atlantic hurricane season (Jun.–Nov.), though the results hold for other subsets of boreal summer/fall months.

[5] Figure 1a shows the 18-model ensemble-mean projected change in V_s (normalized per °C global warming) over the 21st Century; for reference, contours show the background V_s. There is a prominent increase in V_s over the tropical Atlantic and East Pacific (10°N–25°N) (Figure 1a), which is distinct from a tendency for weakened V_s across much of the northern hemisphere tropics (see below). The amplitude of the projected V_s increase is considerable, given the 1.5–3.5°C global-mean surface air temperature increase in these models by the end of the 21st Century [*Held and Soden*, 2006; VS07]. These V_s changes are robust across the multi-model suite, with all but a handful of models projecting an increase in the 21st Century (Figure 1b). We define the tropical Atlantic region in which there is large increase of V_s in the ensemble mean (90°W–40°W, 13°N–25°N) as the "Shear Enhancement Region" or SER (see

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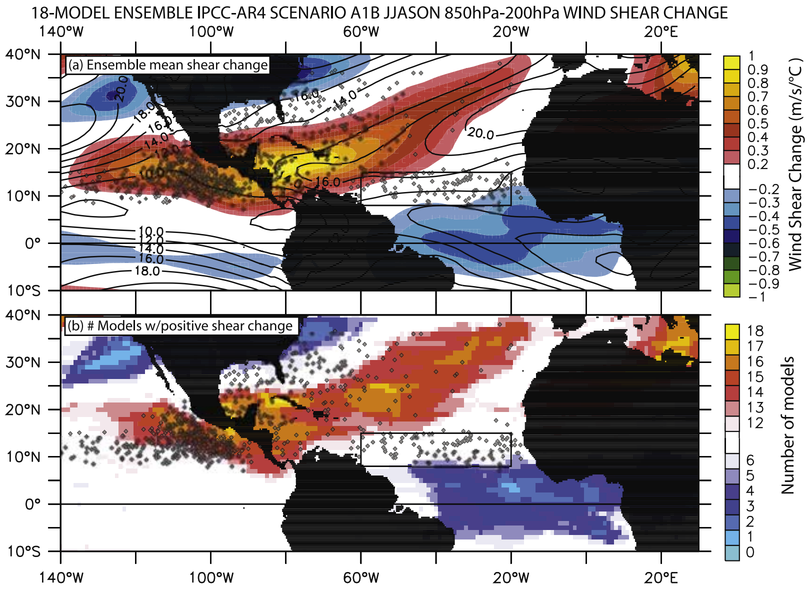

Figure 1. IPCC-AR4 multi-model projections of June–November V_s change. (a) The 18-model ensemble-mean change in June–November 850 hPa-200 hPa vertical wind shear (shaded, ms^{-1} $°C^{-1}$ warming), contours show ensemble-mean background shear (2001–2020 average, ms^{-1}); (b) Number of models (out of 18) showing positive change in V_s. Changes are normalized by each model's global mean June–November surface air temperature change before averaging. Dots indicate locations of tropical cyclone genesis over the period 1981–2005; box indicates a region of frequent cyclone development (MDR).

Figure 2a). The Scenario A1B 21st Century V_s changes in the SER are between −2% and 30% of the mean shear.

[6] On interannual timescales, changes in the Pacific Walker circulation associated with El Niño have been connected to enhanced shear over the tropical Atlantic, via atmospheric teleconnections from the related eastward shift of equatorial Pacific atmospheric convection [e.g., *Pielke and Landsea*, 1999; *Camargo et al.*, 2007]. Here we explore the extent to which the model-projected increase in V_s is related to the model projections of a weakened Pacific Walker circulation over the 21st Century [e.g., *Held and Soden*, 2006; VS07]. Figure 2a shows the inter-model correlation between the change in the Pacific Walker circulation index and the change in V_s at each location; warm colors in Figure 2a indicate regions where a decrease in the Pacific Walker circulation is associated with increased shear. Notice that the region of strongest correlation corresponds to the SER. That is, inter-model differences in the region of largest ensemble-mean shear increase are correlated to the deceleration of the Walker circulation in each model. The connection between decreased Pacific Walker circulation and increased shear in these models is further highlighted in Figure 2b. The models with larger Walker circulation weakening tend to show larger V_s increase over the SER region (the correlation coefficient across models is 0.71; $p < 0.05$).

[7] We note that the SER is displaced to the north of the region of most frequent cyclogenesis over the period 1981–2005, which we shall refer to as the "Main Development Region" or MDR (60°W–20°W, 8°N–15°N; see Figure 1).

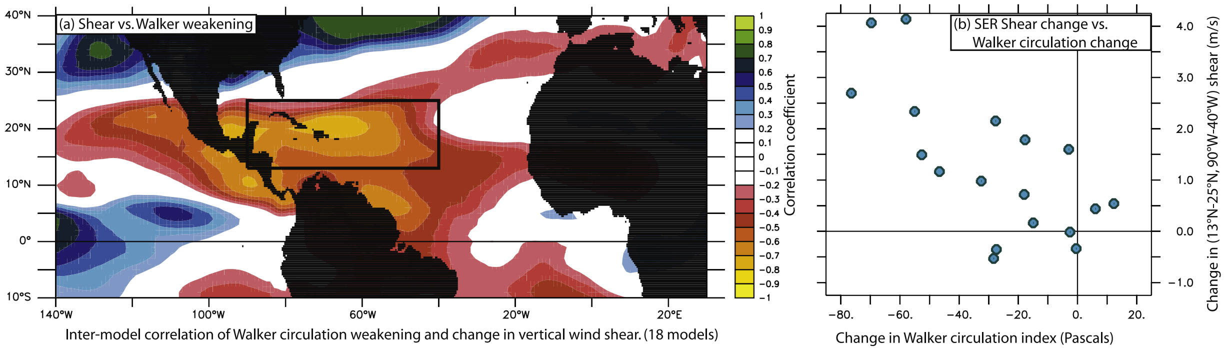

Figure 2. Relationship between IPCC-AR4 multi-model projections of June–November 850 hPa-200 hPa V_s change and Pacific Walker circulation change. (a) The 18-model inter-model correlation of V_s change at each point and Pacific Walker circulation change; (b) Change in the SER (90°W–40°W, 13°N–25°N) V_s change versus Pacific Walker circulation change in each model. Pacific Walker circulation index defined as sea level pressure difference between eastern and western equatorial Pacific [*Vecchi et al.*, 2006; *Vecchi and Soden*, 2007]. Box in Figure 2a indicates the region of strong ensemble mean shear increase (SER).

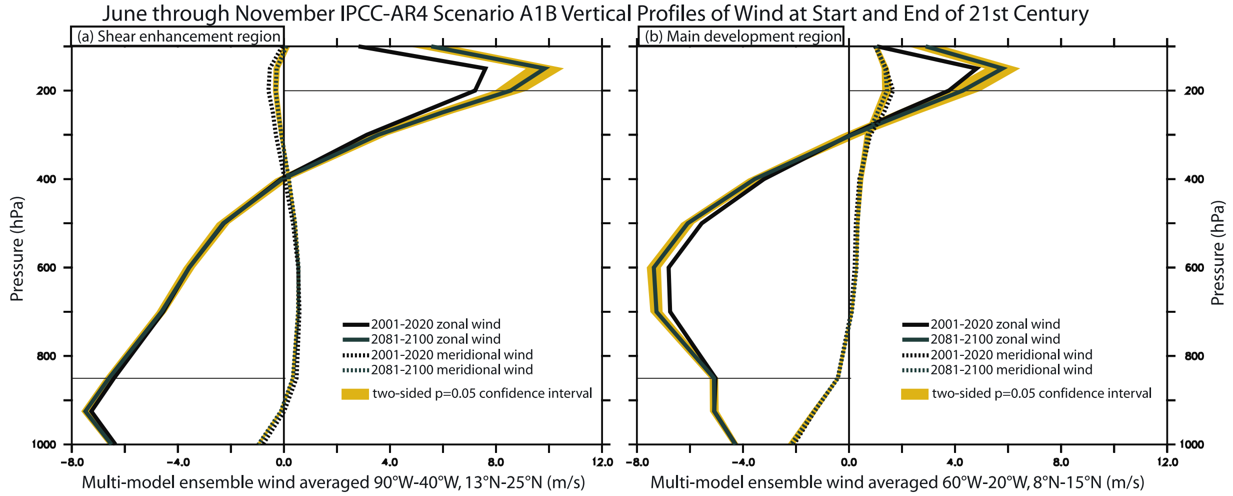

Figure 3. Profiles of June–November winds at start (black lines) and end (green lines) of 21st century from IPCC-AR4 Scenario A1B multi-model ensemble averaged over two regions in north tropical Atlantic. Zonal (meridional) winds are shown in solid (dotted) lines; orange shading shows the two-sided $p = 0.05$ interval on the 2081–2100 average based on a *Student's-t* test and the inter-model variance. (left) Region of robust V_s increase indicated in Figure 2a. (right) Region of frequent tropical cyclone formation indicated in Figure 1. Light horizontal lines indicate 850 hPa and 200 hPa.

We chose to define V_s as $|\boldsymbol{u}_{850} - \boldsymbol{u}_{200}|$ because there is substantial literature indicating some relationship between V_s defined in this manner and hurricanes. Over the SER this definition captures the principal wind features that contribute to vertical shear (Figure 3a). However, over the MDR, both the model background and ensemble-mean change of tropospheric vertical wind shear are better captured by the difference between 700 hPa and 150 hPa winds (Figure 3b). The IPCC-AR4 models show a statistically significant ($p < 0.05$) increase in MDR shear between 700 hPa and 150 hPa (Figure 3b). To the extent that the effect of an increase of 700 hPa to 150 hPa wind shear of equal relevance to that of 850 hPa to 200 hPa wind shear, the multi-model ensemble also projects an increase in shear over the MDR. If one adopts an alternative definition for vertical shear as the vertical standard deviation of wind over the model free troposphere (850 hPa–150 hPa), rather than the magnitude of the vector difference at two pressure levels, the models project a substantial increase of shear over both the MDR and SER (not shown).

[8] So far we have focused on the June–November tropical North Atlantic shear, though there are robust V_s changes evident globally, in other seasons (e.g., auxiliary material) and in the annual mean. For example, between 20°–40° latitude in the southern hemisphere (and both hemispheres in the annual-mean) there is a zonally-symmetric V_s increase (e.g., Figure 4a). Within 5° of the Equator there is a noticeable weakening of V_s over all three oceanic basins (Figure 4a), which is present in all seasons. In these models the near-equatorial V_s weakening appears related to their robust weakening of near-equatorial zonal overturning [e.g., *Vecchi et al.*, 2006; VS07], resulting from global thermodynamic constraints [*Held and Soden*, 2006].

3. Changes in Other Hurricane-Related Indices

[9] Increases in lower tropospheric absolute vorticity (η_{850}), mid-tropospheric relative humidity (rh_{700}) and *Emanuel*'s [1995] hurricane maximum potential intensity for velocity (MPI_v) have been linked to increased hurricane activity. *Emanuel and Nolan* [2004] have developed a "Cyclone Genesis Potential Index" – or GPI – which looks at the combined effect of all four parameters on storm genesis. As is shown in the auxiliary material, changes in the various terms would have comparable effects on *GPI* if their fractional changes are similar. In Figure 4 we compare the fractional changes in the parameters relevant to *GPI*.

[10] The changes in η_{850} are an order of magnitude smaller than those of the other parameters and therefore not shown. The tropical Atlantic rh_{700} changes are dominated by drying over the Caribbean Sea (Figure 4b). Tropical-mean rh_{700} shows very little change, consistent with the largely Clausius-Clapeyron driven increase in specific humidity of these models [*Held and Soden*, 2006]. Many of the regional rh_{700} changes appear connected to the local changes in 500 hPa pressure velocity (ω_{500}, contours in Figure 4b), with regions of anomalous descent (ascent) showing relative drying (moistening)-a relationship consistent with anomalous advection of drier (moister) air from above (below).

[11] While June–November MPI_v increases over most of the northern hemisphere tropics, there is a large region in the northern tropical Atlantic where the ensemble-mean MPI_v actually decreases (Figure 4c). This region of MPI_v decrease is associated with a relative minimum in the sea surface temperature (SST) warming (contours in Figure 4c). MPI_v changes around the globe track the structure of SST changes very tightly – with regions that warm more (less) than the tropical mean showing an MPI increase (decrease). Since changes in upper tropospheric temperatures are determined by changes in the tropical-mean SST, rather than changes in local SST [e.g., *Sobel et al.*, 2002], a local minimum (maximum) in surface warming results in an anomalous increase (decrease) in static stability. This relationship between MPI_v and local SST changes (relative to the tropical mean SST change) holds not only for the ensemble mean, but also for each of the models. A similar

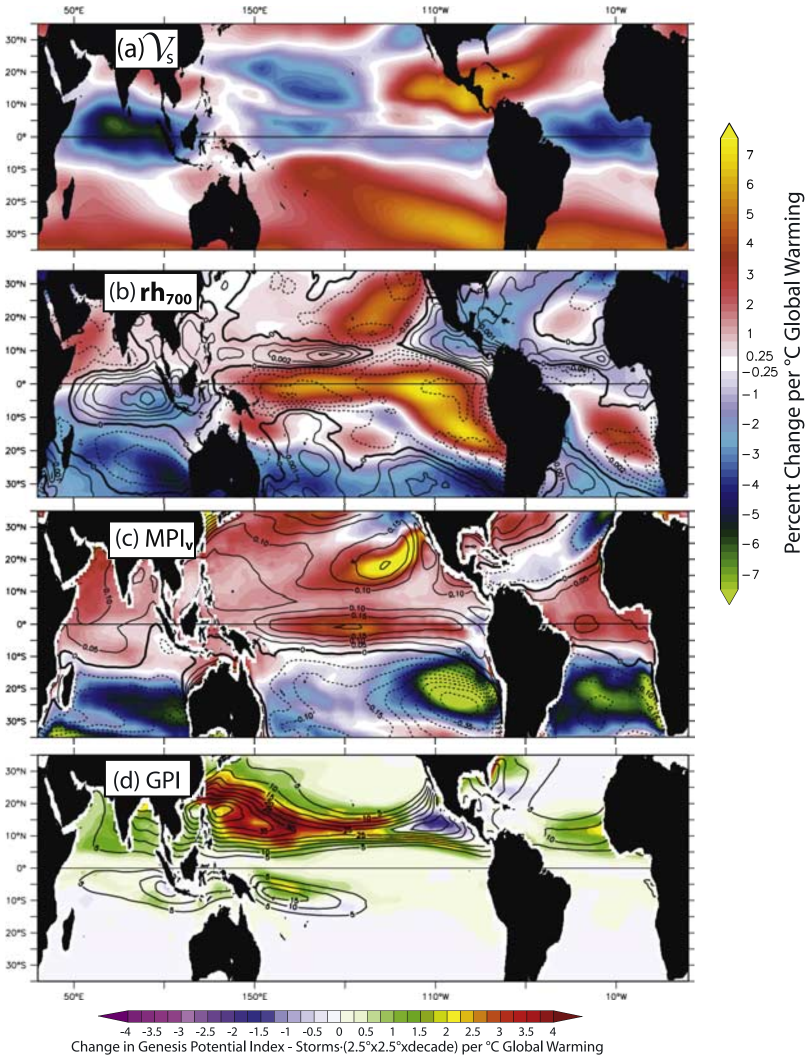

Figure 4. IPCC-AR4 Scenario A1B June–November ensemble mean projected fractional change in large-scale environmental parameters associated with hurricane intensity and activity: (a) V_s, (b) 700 hPa relative humidity, and (c) *Emanuel*'s [1995] wind maximum potential intensity (MPI_v). (d) Change in *Emanuel and Nolan*'s [2004] genesis potential index (GPI) is shown. Fractional changes are normalized by global surface air temperature increase. Contoured in Figure 4b is the ensemble-mean 500 hPa pressure velocity (ω_{500}) change (normalized by each model's global mean surface temperature change), upward motion is negative. Contoured in Figure 4c is the difference between the local SST change and the 35°S–35°N mean SST change, normalized by the 35°S–35°N mean SST change. Contoured in Figure 4d is the ensemble-mean GPI averaged over the period 2001–2020.

mechanism has been suggested to be important in the El Niño response of tropical Atlantic hurricane activity [*Tang and Neelin*, 2004]. Understanding the processes that control both regional and global tropical SST changes [e.g., *Knutson et al.*, 2006; *Santer et al.*, 2006] is essential for projecting regional MPI_v changes. The SST warming minimum in the tropical Atlantic is also present in the ensemble-mean of IPCC-AR4 climate model runs with a mixed-layer ocean forced with a doubling of CO_2 (not shown), suggesting that the minimum in surface warming may result primarily from changes in atmospheric forcing, rather than from ocean dynamics.

[12] The multi-model ensemble-mean change in *GPI* is shown in Figure 4d. Model-projected *GPI* increases substantially in the western and central Pacific, but the changes in the tropical Atlantic and East Pacific are more modest – showing both regions of increase and decrease – due in part to the local increase in wind shear (e.g., Auxiliary Figure S1). In the multi-model ensemble, the North Atlantic and East Pacific contribution of V_s to the fractional change in GPI is comparable to that of each of the other three terms (Auxiliary Figure S1), although the region of largest percentage Atlantic GPI changes caused by shear is a region of relatively modest GPI.

4. Summary and Discussion

[13] Global climate model projections for the 21st Century indicate a robust increase in June–November vertical wind shear in the tropical Atlantic and East Pacific Oceans. Over the Caribbean Sea, the northern tropical Atlantic (the SER) and the eastern tropical Pacific, the multi-model

ensemble-mean shear increases by 0.5-1 ms^{-1} per °C global warming (Figures 1 and 3). The Atlantic shear changes result largely from changes to upper tropospheric zonal winds (Figure 3). Aspects of the projected shear increase in the SER are strongly related to a reduction in Pacific Walker circulation, with the inter-model variability in Walker circulation changes explaining ~50% of the inter-model variability in SER shear change (Figure 2). The relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity (Figure 4), indicating that these shear changes should be considered in projections of future changes in tropical cyclone activity. Based on published connections between large-scale environmental parameters and hurricane activity [e.g., *Emanuel and Nolan*, 2004], the changes shown here alone would not suggest a strong anthropogenic increase in tropical Atlantic or East Pacific hurricane activity during the 21st Century; although other regions (e.g., Indian and western/central Pacific oceans) show consistent changes towards more hurricane-favorable conditions (Figure 4).

[14] In addition to impacting cyclogenesis, the increase in SER shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR to the Caribbean and North America (e.g., Auxiliary Material Figure S2). Although the response of the frequency and intensity of tropical storms to the shear changes documented here remains to be fully understood, the robustness of the shear changes across models, their impact on GPI (Figure 4d and Auxiliary Material Figure S1), and the potential influence of shear on cyclone intensity underscore their importance in projections of future Atlantic hurricane activity.

[15] The detailed mechanisms behind the modeled Tropical Atlantic V_s changes should be comprehensively explored, in order to fully understand the robustness and limitations of the model V_s projections. For example, the extent to which El Niño serves as a useful analogue for the mechanisms behind the projected shear changes should be further examined: although the sign of the relationship in Figure 2 is the same as during El Niño, the structure of the V_s changes differs from that associated with El Niño. It is also important to keep in mind that the Pacific Walker circulation can exhibit energetic variability – even on decadal timescales – independently of external forcing [e.g., *Vecchi et al.*, 2006], and that Atlantic shear is influenced by a variety of factors besides the Pacific Walker circulation. For example, both the meridional temperature gradient in the tropical Atlantic [e.g., *Zhang and Delworth*, 2006] and the extent of the Atlantic Warm Pool [e.g., *Wang et al.*, 2006] have been connected to changes in V_s. A full understanding of the projected and historical patterns of tropical Atlantic shears must take into consideration the full set of factors that influence shear, including those resulting from internal climate variability as well as forced climate change.

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