HAS THERE BEEN ANY DISCERNIBLE HUMAN INFLUENCE ON ATLANTIC HURRICANE CLIMATE?

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1. INTRODUCTION

In this report, we explore the contentious question of whether human-induced climate change has caused any noticeable or discernible change in past Atlantic hurricane activity. There is currently evidence both for and against the existence of such a discernible impact. We review the latest evidence and provide our current assessment of the issue, including some relevant new research results.

Detection and attribution of a human influence on climate, or some aspect of climate such as hurricane frequency, involves detection of an unusual change (outside the range of internal climate variability) in the data, and then attribution of the change to a specific anthropogenic influence, such as increasing greenhouse gas concentrations or anthropogenic aerosols. Attribution as used here means that the observed change is demonstrated to be consistent with the expected anthropogenic influence based on physical understanding (typically as incorporated in models and theory), and that the change is not consistent with alternative explanations, such as internal variability or volcanic forcing.

2. OBSERVATIONAL EVIDENCE

Emanuel's (2007) Power Dissipation Index (PDI) has been updated from his earlier study (Emanuel 2005), and includes a revised correction for overestimated intensities in the 1950s and 60s. The revised PDI series (Fig. 1) shows unprecedented high values in recent decades in the context of the past ~60 yr, and correlates remarkably well with low-frequency tropical Atlantic SST variations. Tropical Atlantic SSTs have increased over the past century, and studies indicate that anthropogenic forcing has very likely made a contribution to the warming since 1950 (e.g., Santer et al. 2006; Knutson et al. 2006).

A limitation of Emanuel's PDI estimate in Fig. 1 is that during the pre-satellite era (pre-1965), aircraft reconnaissance did not fully cover the basin, increasing uncertainty in PDI during that period. Landsea (2005; personal communication 2007) argues that this limitation leads to a low bias in PDI in the 1950s and 60s, although this remains unquantified. A second limitation is that the index does not extend back to the late 1800s and early 1900s, when Atlantic SSTs were apparently ~0.7C cooler than at present. If reliable PDI estimates were available from this earlier period, they would increase confidence in assessments of the sensitivity of PDI to century-scale climate warming.

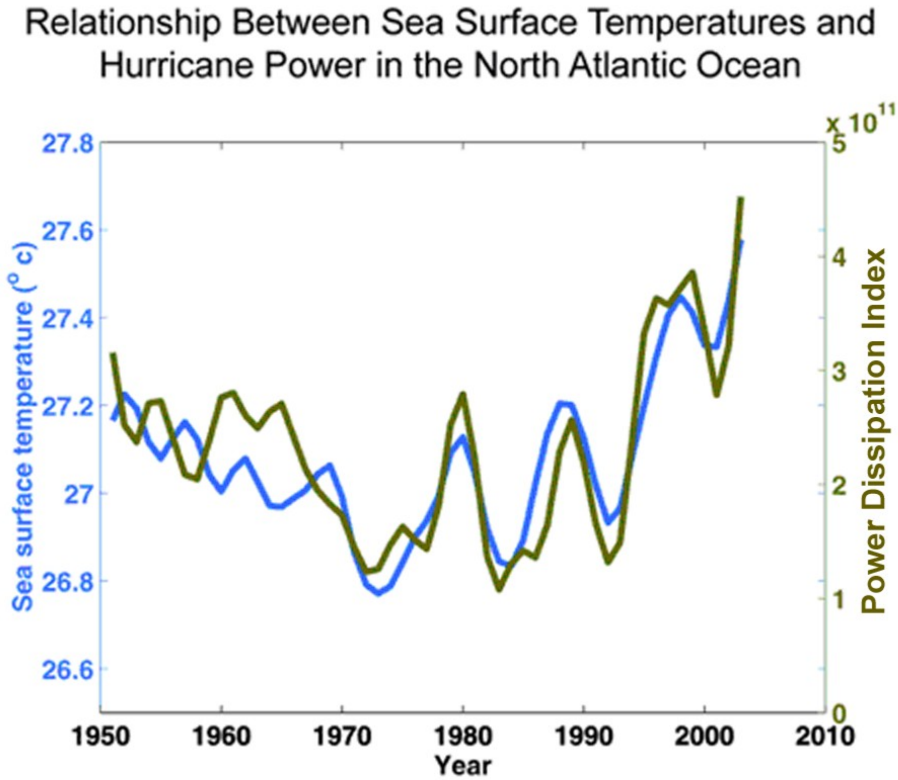

Figure 1. Sea surface temperatures (blue) versus the Power Dissipation Index for North Atlantic hurricanes (Emanuel, 2007). Sea surface temperature is from the Hadley Centre dataset and is for the Main Development Region for tropical cyclones in the Atlantic, defined as 6-18°N, 20-60°W. The time series have been smoothed using a 1-3-4-3-1 filter to reduce the effect of interannual variability and highlight fluctuations on time scales of 3 years and longer. Figure provided courtesy Kerry Emanuel.

Landsea (2007) used landfalling statistics to infer that there has been no significant increase in basin-wide tropical storm counts over the 20th century. His conclusion of no significant trend is based on trends computed between pairs of active or inactive epochs in the series (i.e., consistently starting and ending the trend period in either a high or low state of the Atlantic Multidecadal Oscillation). U.S. landfalling hurricane activity (frequency and PDI) show no increasing trend over the past century or so. Consistent with this, Landsea's adjusted storm series for the entire basin shows little or no trend. However, a critical assumption of Landsea's method is that the fraction of storms that make landfalling remains constant over time. This assumption has been disputed by Holland (2007). As there are physical reasons why the fraction of landfalling storm might not remain constant (such as possible multi-decadal variations in SST and storm track locations in the basin) such a strong assumption limits confidence in Landsea's assessment.

Holland and Webster (2007) examined relationships between numbers of all Atlantic named storms and hurricanes, minor hurricanes, and major hurricanes, and concluded that tropical cyclone and hurricane counts have increased dramatically during the past century, in close association with the rise in tropical Atlantic SSTs. While one might presume that hurricanes and major hurricanes are less likely to have been entirely missed in pre-satellite years than tropical storms, a key assumption of their findings is that the existing HURDAT data accurately portrays the intensity of these systems well enough to differentiate between tropical storms, hurricanes, and major hurricanes. While tropical storm behavior may serve as a surrogate for other types of activity (i.e., hurricanes and major hurricanes may occur as constant proportion of all tropical storms in basin-wide statistics) this inference also requires further substantiation. In addition, while raw (unadjusted) basin-wide hurricane counts show a significant rising trend beginning in years 1881, 1891, …, 1921, there are high levels of hurricane counts in the HURDAT data from the late 1800s, such that linear trends in the data are not significant if one begins in 1851, 1861, or 1871 (R. Smith, pers. comm. 2007).

As a step toward extending the reliable record of tropical storm counts back to the late 1800s, we have used historical Atlantic ship track and storm track data to estimate the expected number of missing tropical storms each year from 1878 until the satellite era began, around 1965 (Vecchi and Knutson 2007). Our use of ship track data avoids assumptions about constant landfalling fractions. After the adjustment, the tropical storm counts covary with tropical SSTs on multi-decadal time scales, but their long-term trend (1878-2006) is weaker than the trend in similarly normalized SSTs (though both are nominally positive). The linear trend in adjusted storm counts for 1900-2006 is strongly positive (+4.2 storms/century) and highly significant according to three tests which attempt to account for serial correlation. However, this trend begins near a local minimum in the time series and ends with the recent high activity, perhaps exaggerating the significance of the trend. The linear trend in this adjusted data beginning from 1878 is not statistically significant.

While we generally prefer using as long a series as possible to assess significance of trends, the uncertainty in the late 1800s is larger than that during the 1900s—an important caveat on the results using the earlier start dates. The results also suggest that the average duration of Atlantic tropical cyclones has decreased for reasons as yet unexplained. Tropical cyclone occurrence rates appear to have decreased in the western part of the basin (consistent with slightly declining U.S. landfalling hurricane counts) but may have increased slightly in the central and eastern basin, suggesting a structural change such as shifts in storm tracks. There are important remaining assumptions of our methodology (such as that all landfalling storms since 1878 which were not seen by ships were detected and reported upon landfall), and these will require further investigation.

The observational evidence thus provides mixed indications on whether there might have been a discernible human influence on past hurricane activity. For example, the strong statistical correlation between Atlantic SST and PDI found by Emanuel (2007) is suggestive of strong link between local SST and PDI that could be used to infer that anthropogenic warming has contributed to the substantial increase in PDI since 1950.

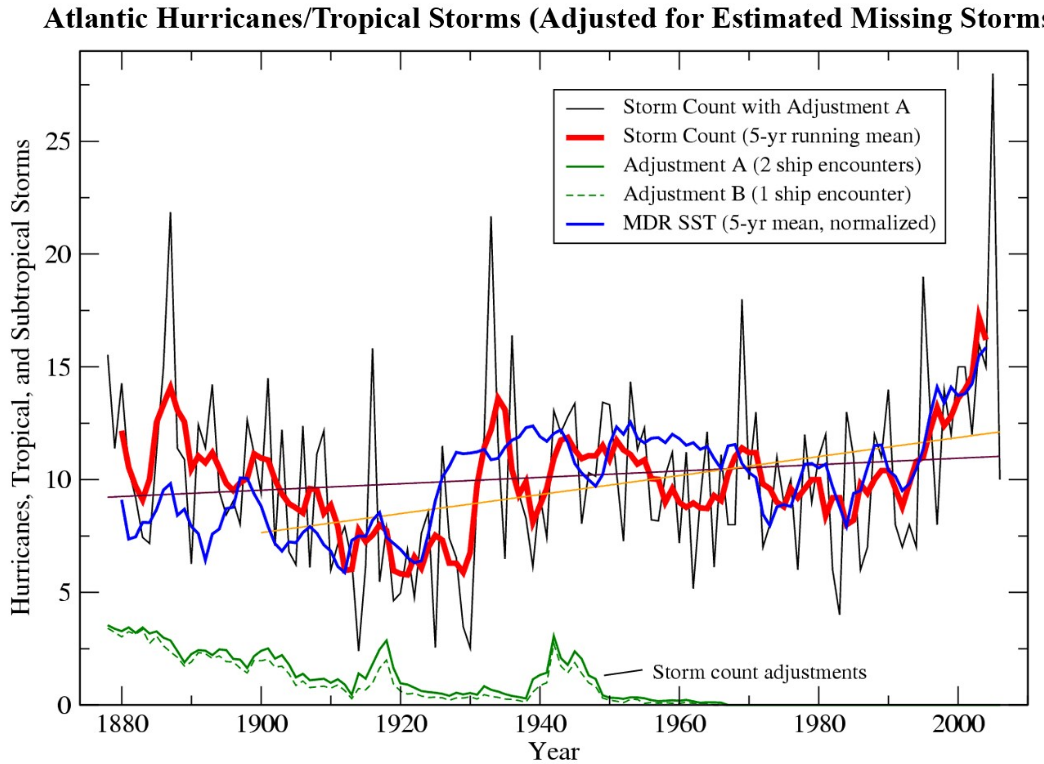

Figure 2. Atlantic hurricanes and tropical storms for 1878-2006, adjusted for estimated missing storms based on historical ship track coverage. Black curve is the adjusted annual storm count, red is the 5-yr running mean, and solid blue curve is a normalized (same mean and variance) 5-yr running mean sea surface temperature index for the Main Development Region of the tropical Atlantic (HadISST, 80-20W, 10-20N; Aug.-Oct.). Solid green curve show the adjustment that has been added for missing storms to obtain the black curve, assuming two simulated ship-storm "encounters" are required for a modern-day storm to be "detected" by historical ship traffic for a given year. Dashed green curve is an alternative adjustment sensitivity test requiring just one ship-storm simulated encounter for detection. Straight lines are least squares trend lines for the adjusted storm counts. (Adapted from Vecchi and Knutson, 2007).

This interpretation is supported by the analyses of Holland and Webster (2007), although their analysis is based on unadjusted tropical storm, hurricane, and major hurricane count data. On the other hand, the adjusted tropical storm count analyses of Landsea (2007) and Vecchi and Knutson (2007) do not support the existence of significant long-term increases in storm counts, once the data are adjusted for likely numbers of missing storms. As noted earlier, the uncertainty in all data sets increases as one proceeds further back in time, and due to known and potential data homogeneity problems, none of the existing time series studies can be viewed as definitive at this time. Nonetheless, there is at least the suggestion--particularly from Emanuel's (2007) statistical analysis of PDI/SST--of a possible substantial human influence on Atlantic hurricane activity.

3. MODELING EVIDENCE

As mentioned in the introduction, confident attribution of observed changes in hurricane activity to human influence requires a physical understanding, typically through models, of how the specific human influence has affected the hurricanes. In addition, alternative explanations must be considered and ruled out (or demonstrated to be unlikely). Here we review some of the modeling evidence we consider to be most relevant to the issue.

We have previously used an operational hurricane prediction model to estimate the sensitivity of hurricane intensity to SST increases caused by increasing greenhouse gas concentrations (Knutson and Tuleya 2004). Our results indicate that greenhouse gas-induced warming will cause hurricanes to become more intense (Fig. 3), with a wind speed sensitivity of about 3.7% per ^{o}C of tropical SST warming, in general agreement with a range of estimates obtained using hurricane potential intensity theories (e.g., Knutson and Tuleya 2004; Vecchi and Soden 2007; Emanuel 1987; Emanuel 2005).

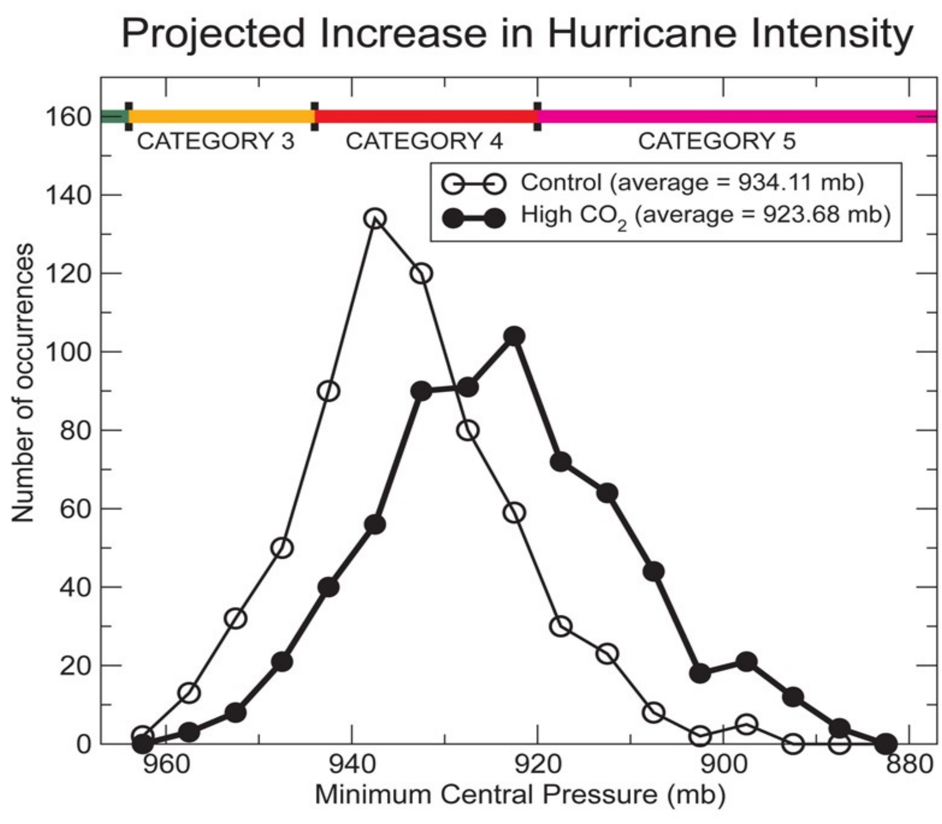

Figure 3. Frequency histograms of hurricane intensities in terms of central pressure (mb) aggregated across all idealized hurricane experiments in the Knutson and Tuleya (2004) study. The light curve shows the histogram from the experiments with present-day conditions, while the dark curve is for high CO_2 conditions (after an 80 yr warming trend in a +1%/yr CO_2 experiment). The results indicate that hurricanes in a CO_2-warmed climate will have significantly higher intensities (lower central pressures) than hurricanes in the present climate.

Of note, the sensitivity we find implies that if the 0.5-0.7°C warming of the tropical Atlantic to date were assumed also to be entirely due to human causes, the impact of this warming on hurricane intensities would on the order of 2 percent, which would be too small to be discernible in the record owing to data limitations and multi-decadal variations in the Atlantic. A limitation of the above studies is that the hurricane downscaling technique does not address the question of possible changes in hurricane frequencies.

To address the question of hurricane frequencies, we have developed a new regional modeling framework designed specifically for dynamical downscaling of seasonal Atlantic hurricane activity, including frequency (Knutson et al. 2007). The non-hydrostatic model has a grid spacing of 18km and is run without convective parameterization, but with internal spectral nudging toward observed large-scale (basin wavenumbers 0-2) atmospheric conditions from reanalyses.

The regional downscaling model reproduces the observed rise in Atlantic hurricane activity (numbers, Accumulated Cyclone Energy (ACE), Power Dissipation Index (PDI), etc.) over the period 1980-2005 fairly realistically, as well as ENSO-related interannual variations in hurricane counts. Annual simulated hurricane counts from a two-member ensemble correlate with observed counts at r=0.86 (Fig. 4). Although the model simulates a number of aspects of Atlantic hurricane climate and structure realistically (Fig. 5), it does not simulate hurricanes as intense as those observed, with minimum central pressures of ~937 hPa and maximum surface winds of ~47 m/s being the most intense simulated in these experiments.

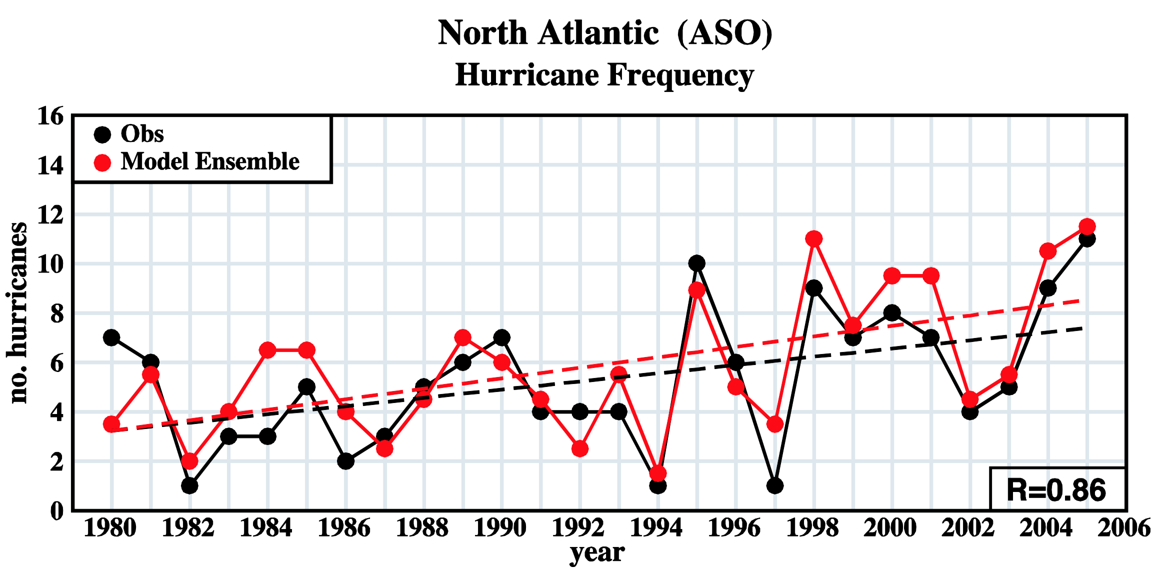

Figure 4. Annual number (Aug.-Oct.) of North Atlantic hurricanes (1980-2005). Results are shown for observations (black) and for a two-member ensemble of model experiments (red) obtained by dynamical downscaling from large-scale atmospheric reanalyses (NCEP/NCAR) using a regional atmospheric model (Knutson et al. 2007) . The dashed lines depict least squares best fit linear trends.

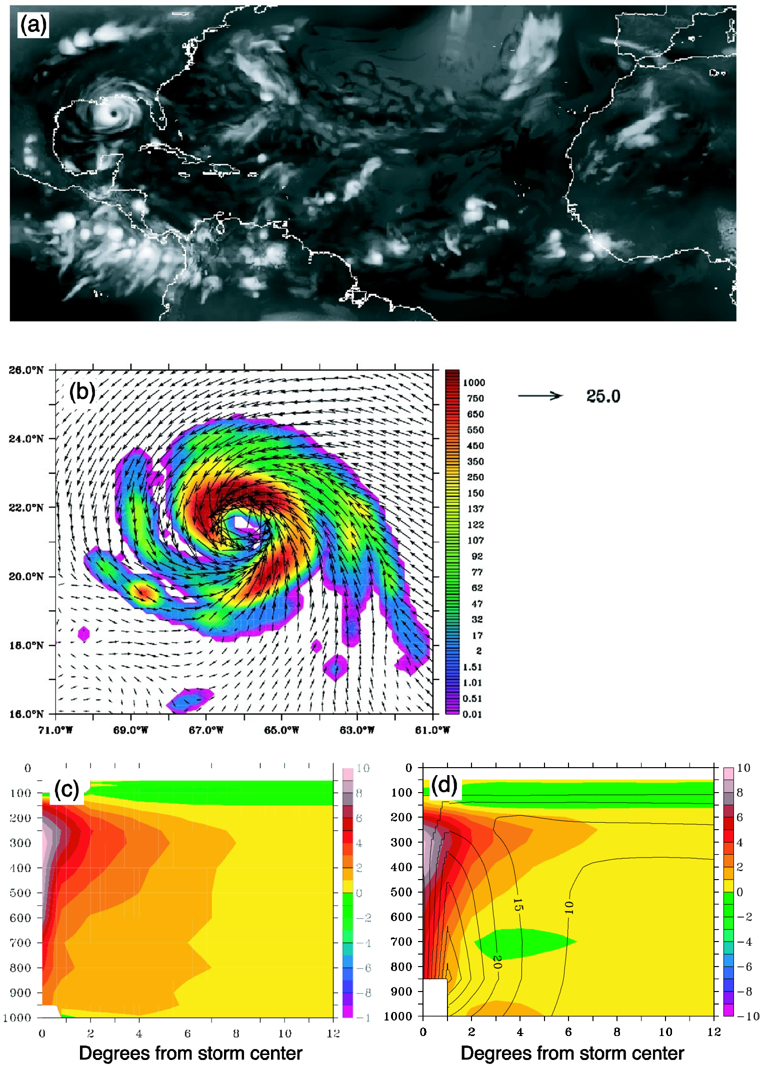

Figure 5. Sample hurricane fields obtained from the regional downscaling model of Knutson et al. (2007). A) Model outgoing longwave radiation field illustrating scales and structures of model disturbances. B) Rainfall rate (mm/day) and surface wind vectors (m/s) for a sample hurricane. C) Observed composite temperature anomaly from a steady-state typhoon (from Frank 1977). D) Model temperature anomaly and wind speed as a function of radius, composited axisymmetrically over all model hurricane periods.

To explore possible impacts of future climate warming on Atlantic hurricane activity, we are re-running the 1980-2006 seasons, keeping the interannual to multidecadal variations unchanged, but altering the August-October mean climate according to the changes simulated by an 18-member ensemble of AR4 climate models (years 2080-2099, IPCC A1B emission scenario). The warmer climate state features enhanced Atlantic SSTs, and also enhanced vertical wind shear, reduced mid-tropospheric relative humidity, and even some localized reductions in Emanuel Potential Intensity across parts of the Atlantic basin (Fig. 6, from Vecchi and Soden 2007). Enhanced vertical wind shear and reduced mid-tropospheric relative humidity are factors known to inhibit the development of tropical storms.

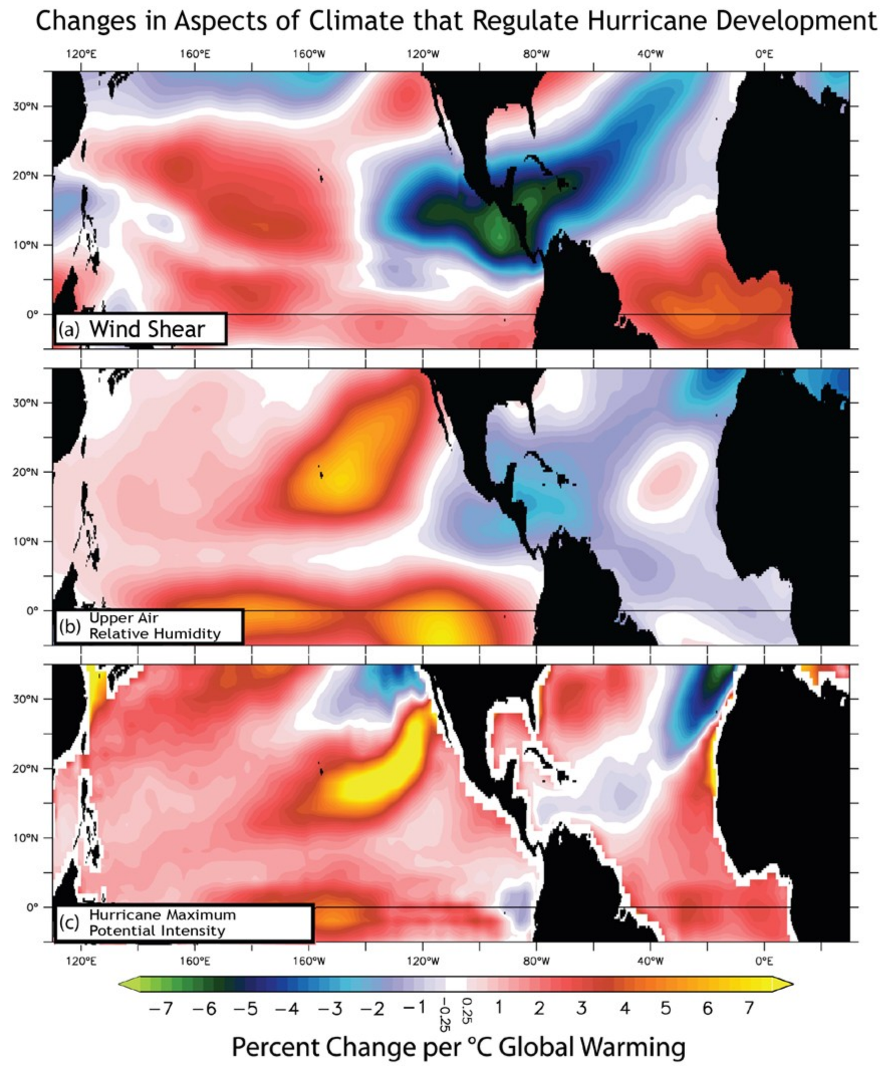

Figure 6. Percent changes in June-November ensemble mean a) vertical wind shear, b) mid-tropospheric relative humidity, and c) maximum potential intensity of tropical cyclones for the period 2081-2100 minus the period 2001-2021 for an ensemble of 18 GCMs, available in the IPCC AR4 archive, using the A1B scenario. The percentage changes are normalized by the global surface air temperature increase projected by the models. From Vecchi and Soden (2007).

A key assumption of our modeling approach is that the multi-model ensemble climate change from Vecchi and Soden (2007) is the best available projection of future climate change in the Atlantic. Some of the models that make up this ensemble show little increase in wind shear, or even a decrease, and thus there remains considerable uncertainty associated with the hurricane frequency results from our simulations, which will require further exploration. Another important limitation is the lack of very intense hurricanes in our control simulation. Results from our most recent simulations (which are not included here owing to “press embargo” issues) will be presented at the meeting.

4. CONCLUSION

Based on the available evidence, we conclude that there is some evidence suggesting that anthropogenic forcing has had a discernible influence on Atlantic hurricane activity. There is also evidence suggesting that there has been no discernible influence. Based on the current state of modeling results and ongoing data concerns, it is not appropriate at this time to make a likelihood statement attributing past changes in hurricane activity to increasing greenhouse gases or other human-caused factors.

The above finding--that we cannot yet make definitive statements on whether human-induced climate change has noticeably affected Atlantic hurricanes-- is a conclusion that has important implications for our level of confidence in future projections of hurricane activity in the Atlantic and elsewhere around the globe.

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