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Energy budgets of Atlantic hurricanes and changes from 1970

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[1] On the basis of the current observational record of tropical cyclones and sea surface temperatures (SSTs) in the Atlantic, estimates are made of changes in surface sensible and latent heat fluxes and hurricane precipitation from 1970 to 2006. The best track data set of observed tropical cyclones is used to estimate the frequency that storms of a given strength occur after 1970. Empirical expressions for the surface fluxes and precipitation are based on simulations of hurricane Katrina in August 2005 with the advanced Weather and Research Forecasting (WRF) model at 4 km resolution without parameterized convection. The empirical relationships are computed for the surface fluxes and precipitation within 400 km of the eye of the storm for all categories of hurricanes based upon the maximum simulated wind and the observed sea surface temperature and saturation specific humidity. Strong trends are not linear but are better depicted as a step function increase from 1994 to 1995, and large variability reflects changes in SSTs and precipitable water, modulated by El Niño events. The environmental variables of SST and water vapor are nonetheless accompanied by clear changes in tropical cyclone activity using several metrics.

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Theme: Interactions Between Climate and Tropical Cyclones on All Timescales
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1. Introduction

[2] From a climate standpoint, key questions are as follows: What role, if any, do hurricanes and tropical cyclones have in our climate system? Why do hurricanes exist? Why do they occur with observed characteristics of numbers, size, duration, and intensity? How has the activity of tropical storms changed? These rather fundamental questions were the motivation for research by *Trenberth et al.* [2007] and *Trenberth and Fasullo* [2007] on a global basis. In this paper, we examine some of these questions with the focus on the North Atlantic in which both the observational record is particularly strong and our cyclone simulations are more representative, thus allowing relationships and trends to be assessed with a higher degree of confidence than is possible globally.

[3] Storm activity includes considerations of their number, size, duration, intensity, and track, and the

integrated effects matter for the climate system, while the characteristics matter enormously for society. Most information is available on numbers and tracks of storms through the "best track" database in the Atlantic, and only recently has detailed information become available on other aspects. In particular, size estimates of tropical storms in the North Atlantic have been provided by *Kimball and Mulekar* [2004] but only after 1988. NOAA's Accumulated Cyclone Energy (ACE) index [*Levinson and Waple*, 2004] approximates the collective intensity and duration of tropical storms and hurricanes during a given season and is proportional to maximum surface sustained winds squared. The power dissipation of a storm is proportional to the wind speed cubed [*Emanuel*, 2005a], as the main dissipation is from surface friction and wind stress effects, and is measured by a power dissipation index (PDI). Consequently, the effects are highly nonlinear and one big storm may have much greater impacts on climate than several smaller storms. The PDI is very sensitive to data quality, and the initial *Emanuel* [2005a] report has been revised to show the PDI increasing by about 75% (versus about 100%) since the 1970s [*Emanuel*, 2005b]. *Sobel and Camargo* [2005] explore aspects of tropical storms in the Pacific Northwest that indicate a negative influence on the environment that affects later storms. Here we use further integrated metrics of 6-h activity related to energy exchanges and show changes over time for the Atlantic.

[4] In the work of *Trenberth et al.* [2007], the bulk water budgets for some high-resolution simulated hurricanes were assessed and some inferences drawn regarding the energy transports and the overall energy budget. A detailed analysis was made of the bulk atmospheric moisture budget of Ivan in September 2004 and Katrina in August 2005 from simulations with the advanced Weather and Research Forecasting (WRF) model at 4 km resolution without parameterized convection and with specified observed sea surface temperatures (SSTs). The heavy precipitation, exceeding 20 mm/h in the storms, greatly exceeded the surface flux of moisture from evaporation. Instead, vertically integrated convergence of moisture in the lowest 1 km of the atmosphere from distances up to 1600 km was the dominant term in the moisture budget, highlighting the importance of the larger-scale environment. Simulations were also run for the Katrina case with SSTs increased by +1°C and decreased by −1°C as sensitivity studies. With increased SSTs, the hurricane expanded in size and intensified, the environmental atmospheric moisture increased at close to the Clausius-Clapeyron equation value of about 6% K^{-1}, and the surface moisture flux also increased, mainly from Clausius-Clapeyron effects and the increases in intensity of the storm. Hence it was possible to deduce the role of some aspects of the environment on the storm.

[5] *Trenberth and Fasullo* [2007] suggested that hurricanes effectively pump large amounts of heat out of the ocean into the atmosphere and disperse it to regions where it can be radiated to space, thereby mitigating the heat buildup that would otherwise occur. In this perspective, the organized strong surface winds in hurricanes increase the surface evaporation significantly such that the latent heat losses by the ocean can exceed 1000 W m^{-2} over large scales, a value which is an order of magnitude larger than the summertime climatological value. On the basis of the simulations of hurricane Katrina in August 2005 with the WRF model, empirical relationships between the maximum simulated wind and the surface fluxes and precipitation were derived.

[6] The best track data set of global observed tropical cyclones was used to estimate the frequency that storms of a given strength occur over the globe after 1970. For 1990–2005 the total surface heat loss by the tropical ocean in hurricanes category 1 to 5 within 400 km of the center of the storms was estimated to be about 0.53×10^{22} J per year (0.17 PW). The enthalpy loss due to hurricanes computed based on precipitation was about a factor of 3.4 greater (0.58 PW), owing to the addition of the surface fluxes from outside 400 km radius and moisture convergence into the storms typically from as far from the eye as 1600 km. Globally these values are significant, for example the total meridional ocean heat transport at 40°N is about 0.5 PW, and correspond to 0.33 W m^{-2} for evaporation, or 1.13 W m^{-2} for precipitation. Changes over time reflect basin differences and a prominent role for El Niño, and the most active period globally was 1989 to 1997. Strong positive trends from 1970 to 2005 occur in the inferred surface fluxes and precipitation, arising primarily from increases in storm intensity and SSTs.

[7] The *Trenberth and Fasullo* [2007] study was global in extent and the uncertainties in the hurricane best track data are quite large in several basins [*Landsea et al.*, 2006]. The Atlantic has the best observational record [*Kossin et al.*, 2007] owing to extensive aircraft and satellite observations after about 1970, which is the period of this study. Here

we therefore use the methodology of *Trenberth and Fasullo* [2007] but focus on the Atlantic basin.

[8] In the Atlantic there are strong relationships between tropical storm numbers and SSTs in the main development region in the Tropics [*Emanuel*, 2005a; *Hoyos et al.*, 2006; *Sabbatelli and Mann*, 2007]. It is also well established that hurricanes in the Atlantic are greatly influenced by atmospheric conditions, including vertical wind shear, static stability, and atmospheric moisture, and these are influenced by atmospheric circulation throughout the global tropics, and especially by El Niño [e.g., *Elsner et al.*, 2000, 2001]. Hence changes in the Atlantic are not representative of global changes. Indeed, the large-scale tropical dynamics associated with SSTs and their gradients are important and determine where conditions for storm formation and intensification will be most favorable. Monsoonal and Walker circulations extend influences elsewhere in the tropics, and thus less favorable regions suffer from vertical wind shear and atmospheric stability structures (such as inversions) associated with the atmospheric circulation that make conditions less conducive to vortex development [*Latif et al.*, 2007].

[9] We make use of the historical best track global tropical cyclone record which originates from the Tropical Prediction Center of NOAA and the Joint Typhoon Warning Center of the U. S. Department of Defense. On the basis of the empirical relationships between surface latent heat and enthalpy fluxes and maximum wind speed in the model, and with the observed frequency with which storms of certain intensities occur from the best track data, we estimate a value for the enthalpy and moisture loss by the ocean due to hurricanes and how this has changed over recent decades for the North Atlantic. Values are computed based on the direct exchanges within 400 km of the eye of the storms and also approximately for the whole storm based on the resulting precipitation.

2. Empirical Relationships

[10] The Katrina control simulation results were used to derive the empirical relationships for surface fluxes of sensible and latent heat and precipitation. These were run with the WRF [*Davis et al.*, 2008]. A brief description of the model and the experiments run are given by *Trenberth et al.* [2007]. This version of WRF avoids the use of a cumulus parameterization by using the 4-km grid and treating deep convection and precipitation formation explicitly using a simple cloud scheme in which cloud water, rain, and snow are predicted variables. As SSTs were specified, the model lacks feedback from the developing cold wake caused by the storm. In addition to running more cases, this is an area where future improvements could be made.

[11] In the best track record, the information available about each storm is restricted although the position of the storm and maximum wind speed are available every 6 h. Size information is not available prior to 1988. The median radius of the outermost closed isobar of Atlantic storms is 333 km, with 75% being within 407 km [*Kimball and Mulekar*, 2004], and 90% of the storms have the radius of the 17.5 m s^{-1} winds within 370 km from the eye. Hence use is made of areal integrals to 400 km from the eye of the storm.

[12] The empirical relationships between the storm-integrated surface fluxes over a 400 km radius from the model experiments with the maximum 10 m wind speed V_{max} suggest a fairly linear increase of both surface latent heat (LH) and sensible heat (SH) flux with $V_{max} \cdot V_{max}$ correlated better with the LH flux (0.99) than with wind (0.98), while the correlation was 0.96 with SH flux and 0.82 with precipitation. The poorer result in the latter arises from the dependence of precipitation on moisture convergence from as much as 1600 km from the center of the storm [*Trenberth et al.*, 2007]. Given the established physical linkages between these fields, it is not surprising that all of these associations are highly statistically significant (<0.01%). For precipitation and the sensible heat flux, these empirical results were used to apply to other cases.

[13] There is a global constraint on evaporation E and precipitation P arising from the surface energy budget [*Trenberth*, 1998, 1999; *Held and Soden*, 2006] that limits the increases as surface temperatures change with global warming to about 2% K^{-1}. This does not constrain transient fluxes, although it does have implications for overall frequency or duration of such events [*Trenberth*, 1998; *Trenberth et al.*, 2003].

[14] In the work of *Trenberth et al.* [2007] it was argued that the surface flux has a component that should respond to changing water-holding capacity as given by the Clausius-Clapeyron equation. A highly simplified bulk flux formula gives the evaporation as

$$E = \rho_a C_L V(q_s(T_s) - q(T)) = \rho_a C_L V q_s(T_s)(1 - RH^*) \quad (1)$$

where C_L is the exchange coefficient, ρ_a is the air density, q is the specific humidity at temperature T

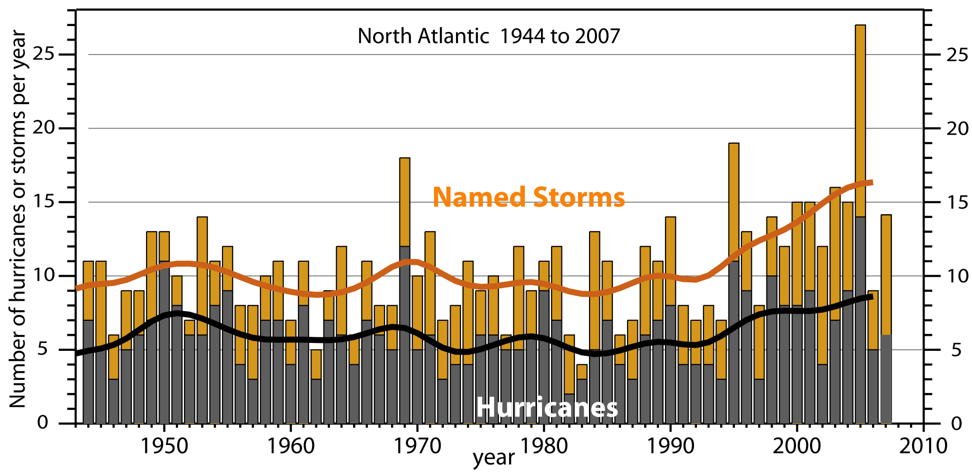

Figure 1. The record of numbers of named storms and hurricanes for the Atlantic from 1944 to 2006 (with 2007 recently added) based on the best track data. The smoothed curves show decadal variability using a 13 point filter with end values computed using reflected values.

or T_s = SST, q_s is the saturation value of q, RH is the relative humidity, and V is the wind speed. Here $RH^* = RH\ q_s(T)/q_s(T_s)$. The dominant dependencies for E are the saturation specific humidity at the SST, which is governed by Clausius-Clapeyron, and the wind speed V. Hence for transient changes, a component of E is likely to go up at about the same rate as observed in the atmosphere for the change in storage, or about 6% per K rise in atmospheric temperature in the Tropics. E is also dependent on V. Although the RH^* term could be important, it is not available from observations and our experiments suggest that its effects are fairly small.

[15] To account for SST dependence and broaden the results to apply to other cases, *Trenberth and Fasullo* [2007] simplified the bulk flux formula (1) to give the evaporation as

$$E \approx aVq_s(T_s) + \varepsilon \quad (2)$$

where a is a regression coefficient and ε is the error. SST is not recorded with the best track data and, accordingly, we have taken a single SST value for the center of each storm every 6 h for the month of the storm from the HADISST monthly data set [*Rayner et al.*, 2003] and assigned it to each storm and time. This does not capture the detailed daily variations of SST distribution across the storm, but it does capture the main changes with month and location that are dominant.

3. Application to Best Track Data

[16] In the North Atlantic, the best track record is believed to be quite reliable after about 1944 owing to the advent of aircraft surveillance of tropical storms, although coverage was incomplete over the eastern part of the basin. The time series for named storms and hurricanes (Figure 1) provide a context for the record after 1970 and reveal the marked increase in activity after 1994.

[17] We have computed tropical cyclone statistics and broken them up into 5 knot categories (it is desirable to use knots rather than conversions into other units owing to the way the original data were recorded; 1 knot = 0.51 m s^{-1}). Hence we have exploited the best track data set to examine in detail the frequency of occurrence of storms based on the recorded maximum wind speed and how that has changed over time from 1970 to 2006 (Figure 2).

[18] We also sort out only those tropical cyclones between 30°N and 30°S. The categories used are given in Table 1 in m s^{-1} but are rounded and correspond to category 1: 64–82 kt; category 2: 83–95 kt; category 3: 96–113 kt; category 4: 114–135 kt; and category 5: > 135 kt. For the Atlantic for 1990 to 2006, hurricanes occur 8% of the time, or 22% of the time during July–August–September–October (JASO).

[19] Figure 2 shows the frequency distribution of maximum winds for Atlantic storms and also the distribution of named storms as a function of latitude. Unique to the Atlantic is the bimodal distribution with latitude, with peak occurrences at 16 to 18°N and near 30°N. The higher-latitude storms are weaker with maximum winds mostly less than 50 m s^{-1}. The biggest change when storms poleward of 30°N are excluded is for the

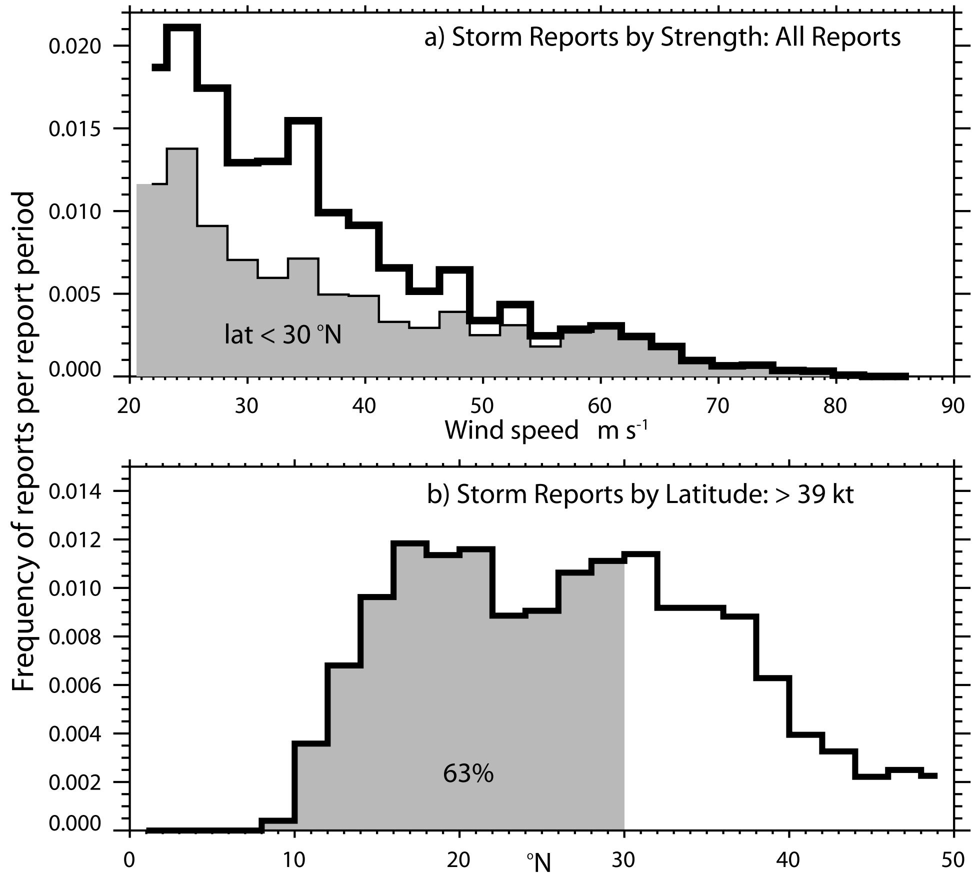

Figure 2. For July to October, frequency distribution of (a) maximum wind speeds and (b) storm reports exceeding 39 kt as a function of latitude for the Atlantic based on best track storm reports by 5 knot category for 1990 to 2006. Storm reports between 30°N and 30°S are shaded.

weaker named tropical storms. Although the frequency of maximum winds generally falls off with wind speed, there are peaks near 33–35 m s^{-1} and 60 m s^{-1}.

[20] Figure 3 shows the linear trends of SST and total column water vapor for the core of the hurricane season (JASO) from 1988 to 2006. This period is chosen because it corresponds to the time of availability of SSM/I water vapor retrievals, which are deemed to be the most reliable estimates of water vapor variability over ocean [*Trenberth et al.*, 2005]. There is a strong pattern resemblance between the two fields and the general global relationship found by *Trenberth et al.* [2005] was close to that expected from the Clausius-Clapeyron equation of 6 to 7% per K air temperature and

Table 1. Best Track Frequency of Tropical Cyclone Reports for the North Atlantic Basin From 1990 to 2006 of Given Peak Wind Strength by Tropical Storm or Hurricane Category Along With the Value for Just 0 to 30°N[a]

	TS 18–32	Category 1 33–42	Category 2 43–49	Category 3 50–58	Category 4 59–69	Category 5 >70
Best track frequency	12.3	4.4	1.5	1.0	0.9	0.1
Best track frequency (0–30°N)	7.3	2.1	1.0	0.8	0.9	0.1
LH flux		548	623	682	766	865
SH flux		80	85	101	129	154
Enthalpy flux		628	708	783	895	1019
Precipitation		3.20	2.99	4.31	4.71	5.09

[a] Here TS is tropical storm. Peak wind strength is measured in m s^{-1} and frequency is given in %. Also given are the surface fluxes as latent heat (LH), sensible heat (SH) and their sum as the enthalpy flux in W m^{-2}, and precipitation in mm h^{-1}, for the Katrina simulations when it was in each category based on the maximum 10 m winds.

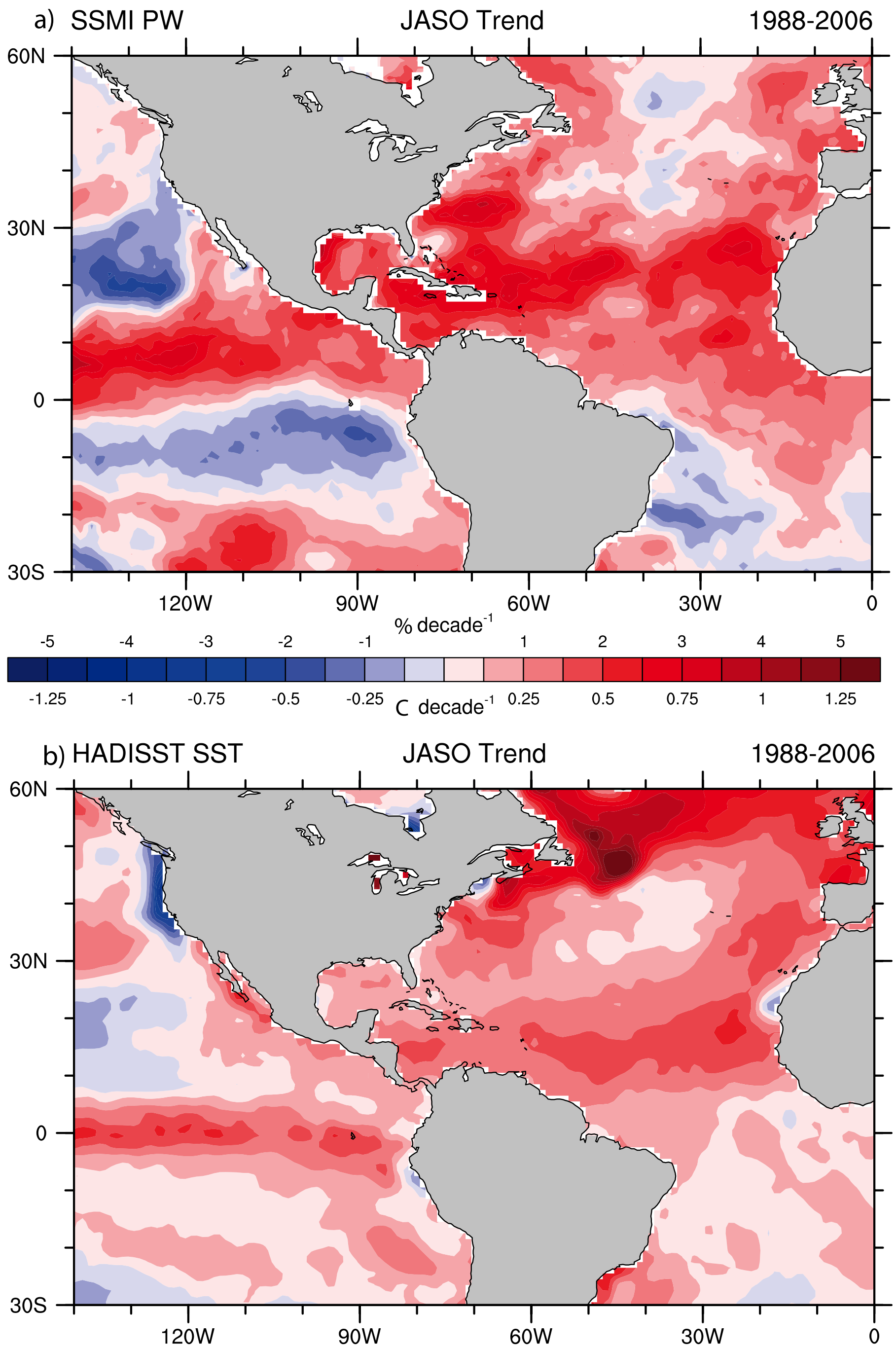

Figure 3. For July to October, linear trends from 1988 to 2006 of (a) column water vapor (precipitable water; bottom) in % decade^{-1} and (b) SST in °C decade^{-1}.

7.8% per K of SST for 30°N to 30°S. In the Pacific, the patchy nature of the changes relates to El Niño variability, so that the trends depend on the period of record. In contrast, rising values are ubiquitous across the tropical Atlantic. Nevertheless, even in the Atlantic the trends of several metrics of tropical storms are not very linear (see Figures 1 and 4). Warming and increased water vapor are especially apparent for the main development region of the tropical Atlantic, and we use the averages over 10 to 20°N to reveal the strong relationship in Figure 5 (shown later) and how the changes have come about. The relationship for the Atlantic from 1988 to 2006 is 2.3 mm K^{-1} or ~7% K^{-1}, in line with expectations based on Clausius-Clapeyron.

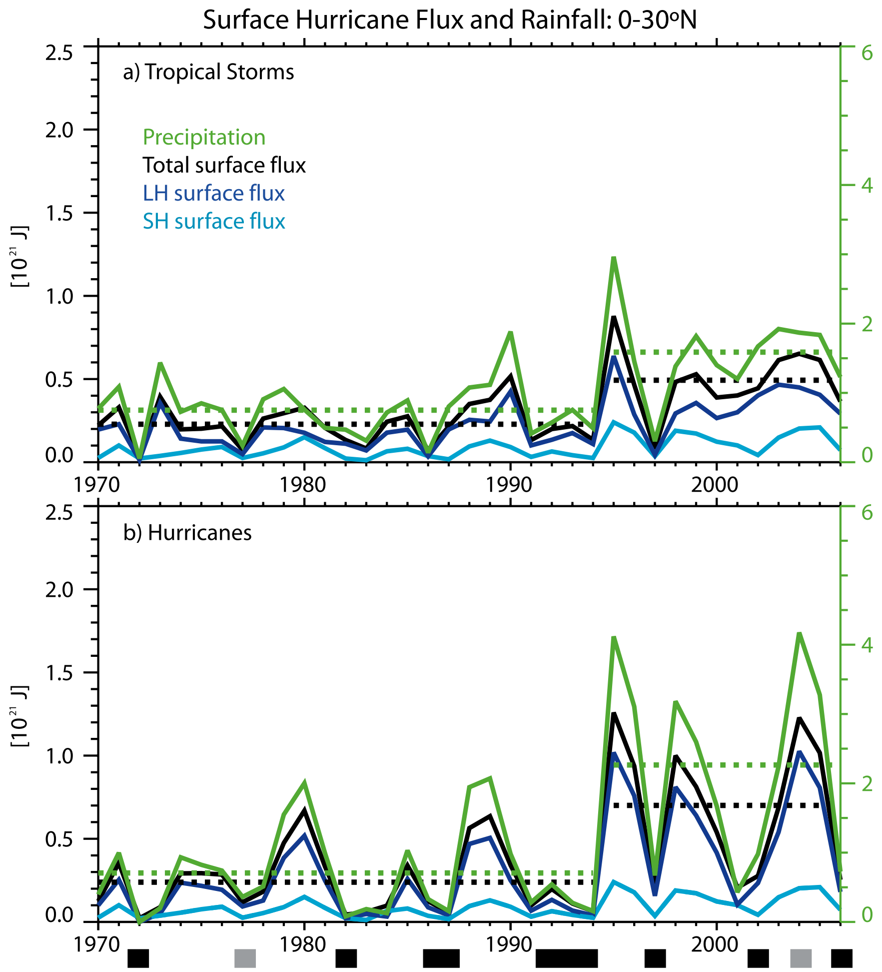

Figure 4. Time series of July–August–September–October (a) inferred sensible heat (SH) (light blue), latent heat (LH) (dark blue), and total surface enthalpy fluxes (black) (left axis), and precipitation (green, right axis) from named tropical storms below hurricane strength, and (b) hurricanes, all in units of energy (10^{21} J). Mean values for 1970 to 1994 and 1995 to 2006 are indicated for each curve. The black or gray bars under the abscissa in Figure 4b indicate El Niño events, with the two weaker events in gray.

[21] To make an assessment of the main component of the energy budget associated with hurricanes, we use (1) the surface heat fluxes from (2) and (2) the precipitation amount as estimated empirically from the Katrina simulation. Figure 4 shows the inferred integrated surface fluxes for only the ocean over the 400 km radius. Shown separately are the contributions for reports of tropical storms and hurricanes; while their total is given in Figure 5. The year to year fluctuations are greater for the hurricane component. For the total surface flux, the hurricanes make up about 63% of the total overall, increasing from 59% before 1994 to 67% after 1994. For precipitation, the ratio is 58% overall, increasing from about 52% to 62% after 1994.

[22] For hurricanes, peak values of surface fluxes and precipitation in the Atlantic (Figure 4) occur in 2004 and 1995, with 2005 ranked third. In contrast, globally, peak values occurred in 1997, when the 1997–1998 El Niño played a major role in enhancing tropical cyclone activity in the Pacific, while activity in the Atlantic was suppressed, and the second highest year of global activity was 1992, also an El Niño year. In general, tropical storm activity in the El Niño years is relatively low in the Atlantic and local SST plays a smaller role in storm intensification, as can be seen in Figures 4 and 5 by the bars indicating the El Niño events occurring during the northern hurricane season.

[23] The derived surface fluxes and precipitation from Figure 4 are combined to provide their sum in Figure 5, along with other indicators for just the JASO season. For SST and water vapor from 10 to 20°N the highest values are in 2005, although column water vapor is also very high in 1995.

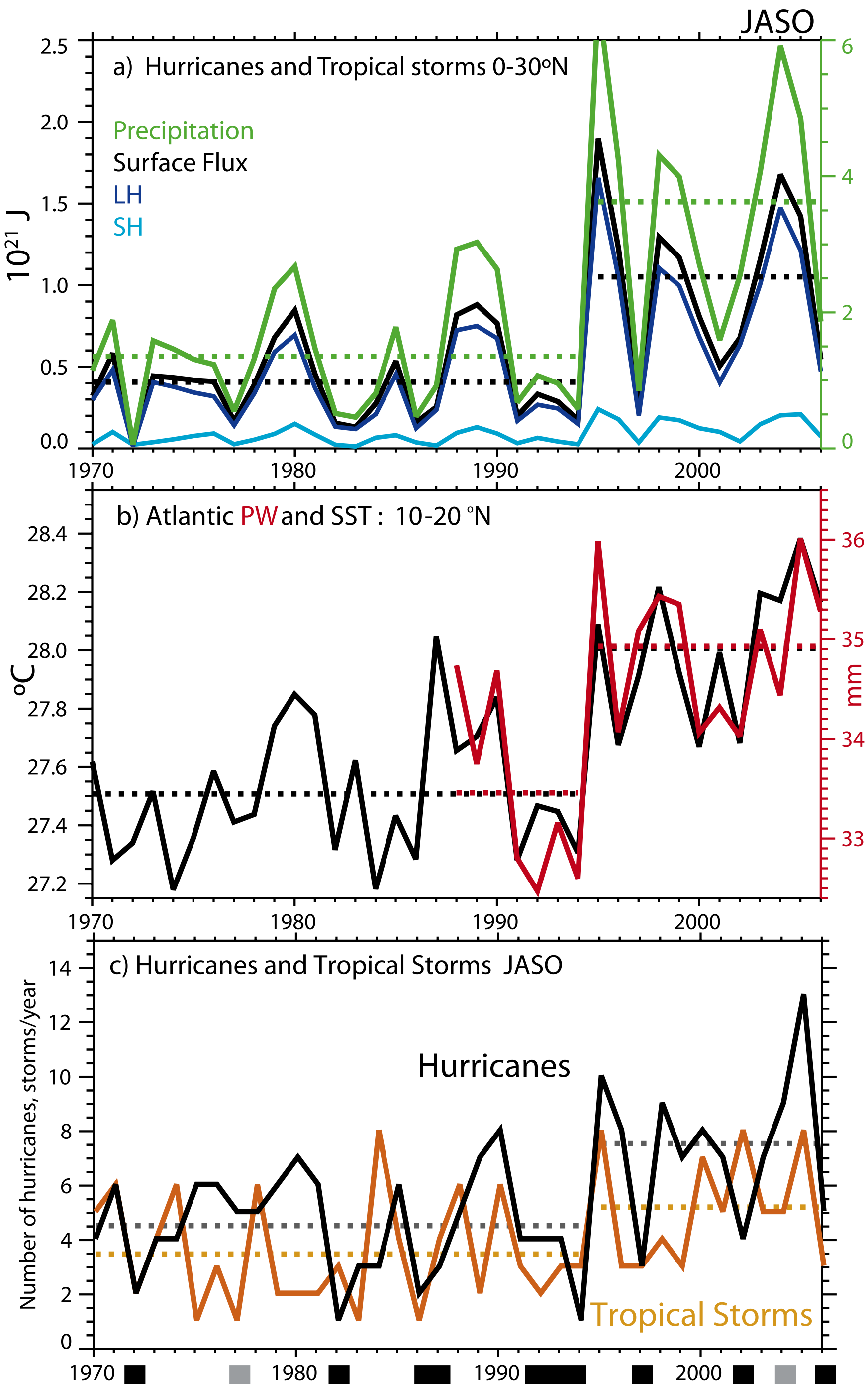

Figure 5. Time series of July–August–September–October (a) inferred total (from named tropical storms plus hurricanes) surface SH, LH, and enthalpy fluxes (left axis) and precipitation (right axis) in units of energy (10^{21} J), (b) SST anomalies (°C, black) and total column water vapor (mm, red), and (c) numbers of tropical storms (gold) and hurricanes (black). Mean values for 1970 to 1994 and 1995 to 2006 are indicated for each curve. The black or gray bars under the abscissa in Figure 5c indicate El Niño events, with the two weaker events in gray.

The numbers of storms peak even more strongly in 2005. The energy fluxes though show a different time sequence highlighting the importance of not just numbers but also duration and intensity of storms and the underlying SST. A detailed examination of the probability distribution for 2004 versus 2005 shows that while more storms occurred in 2005, the main increase was for storms with maximum winds of 22 to 40 m s^{-1}, while in 2004 more storms occurred with maximum winds from 40 to 60 m s^{-1}. Presumably the size of storms is also a key factor but this has not been addressed in this analysis. However, the 2005 season was more active outside of JASO.

[24] Otherwise, there is strong relationship with local SST, as found by *Hoyos et al.* [2006] and *Sabbatelli and Mann* [2007], with linear regressions from 1988 to 2006 of 7% K^{-1} for water vapor, 123% K^{-1} for total surface heat flux, and 90% K^{-1} for precipitation associated with the cumulative contribution of both hurricanes and tropical storms.

[25] The estimated hurricane precipitation latent heat release from 0 to 30°N is about 3 times as large as the surface flux, with their difference balanced primarily by the transport of latent energy from outside the 400 km cylinder. This ratio from the integral of hurricanes in Figure 4b is lower than the ratio for Katrina (3.9) or Ivan (4.95) [*Trenberth et al.*, 2007]. However, the regressed precipitation latent heat estimate is also too low as it was computed over the ocean only, and the land precipitation component is missing. Indeed, much of the heavy precipitation may occur after the storm has made landfall and is weakening, yet this has been omitted from values in Figures 4 and 5. As the hurricane precipitation inside 400 km radius is typically accompanied by suppression of precipitation in surrounding areas owing to the hurricane-related circulation, it partially constitutes a reorganization of rainfall.

[26] In addition to the annual average values, Figures 4 and 5 also reveal upward trends that are statistically significant at <1% level for both surface latent heat and precipitation, where significance is gauged from comparison with both the distribution of trends generated by random recombination of the yearly values, and with randomly generated time series of equal variance, as well as other methods. Comparing the pre- and post-1994–1995 periods also yields an increase in fluxes for the 1995–2006 period that exceeds the 99% confidence limit. For comparison with the total (tropical storm plus hurricane) flux estimates, for the same months, the evolution of SST and water vapor, and the total number of tropical storms and hurricanes have been plotted in Figures 5b and 5c. For hurricane precipitation (Figure 4b), the linear trend from 1988 to 2006 corresponds to 3.7% per year, approximately 14 times as large as the trend in independent estimates of water vapor in the Atlantic from 10 to 20°N, and 28 times as large as the trend in water vapor of 1.3% $decade^{-1}$ over the global ocean overall [*Trenberth et al.*, 2005].

[27] However, the changes in Figure 5 over time are not linear in nature, and they feature higher values after 1994, although with relatively low values still in El Niño years. There was an unusual prolonged El Niño from about 1990 to 1995 (or a series of three El Niño events between which SSTs in the Pacific failed to return to normal) [*Trenberth and Hoar*, 1996] that suppressed Atlantic activity, and the bonanza year in 1995 (e.g., Figure 5c) may have partially been a rebound effect as the pent up energy in the ocean was finally released when atmospheric conditions became more favorable. This was followed shortly thereafter by the 1997–1998 El Niño event, as the biggest on record by several measures. It was a period when the tropical cyclone activity was most prominent in the Pacific. Activity was again suppressed in the North Atlantic in the 1997 El Niño season (Figure 5c) in spite of this being the most active global year overall. On the other hand, the most active seasons by our energy metrics (Figures 4 and 5a) are 1995 and 2004, and during the latter there was a weak El Niño event that developed late in the season.

[28] All metrics in Figure 5 reveal a significant change across 1994–1995 for the JASO season. Modest SST increases from 27.5 ± 0.1 to 28.0 ± 0.1°C (where the error bars are ±2 standard errors) in the 10 to 20°N zone are accompanied by column water vapor changes from 33.5 ± 0.7 to 34.9 ± 0.4 mm, or 1.4 mm (4.1 ± 3.2%) and thus 8.2% K^{-1}, fairly consistent with Clausius-Clapeyron (as noted earlier, the change per unit of SST is greater than for air temperature). On the basis of the SST relationship, the mean columnar water vapor from 1970 to 1987 can be further estimated at 33.4 mm. Numbers of tropical storms (not reaching hurricane strength) change from 3.4 ± 1.2 to 5.2 ± 2.4 per year, and numbers of hurricanes increase from 4.5 ± 0.9 to 7.5 ± 1.6 per year, giving a total number of named storms increase from 7.9 ± 1.9 to 12.7 ± 3.8, or 43% of the mean. Meanwhile, in units of 10^{21} J, the surface enthalpy flux increases from 0.41 ± 0.10 to 1.05 ± 0.29 (an increase of 105% of the 1970–2006 mean) and the precipitation flux goes from 1.36 ± 0.33 to 3.63 ± 1.01, or 109% of the mean. Hence the increase in number of storms, although important, is not the only factor in the observed changes. From Clausius-Clapeyron alone, one expects a 6 to 8% increase in precipitation per K of SST increase [*Trenberth et al.*, 2007], and the difference of this value with our calculated fluxes

and rainfall highlights the increases in intensity and duration, in addition to numbers.

4. Discussion

[29] The basic source of energy for tropical cyclones is enthalpy fluxes from the ocean, mainly in the form of evaporation of moisture, while cyclone activity is limited mostly by surface drag. Tropical cyclones therefore play a role in the climate system of moderating temperatures at the surface and in the ocean in the Tropics through evaporative heat losses [*Trenberth and Fasullo*, 2007]. The tropical storm produces a net cooling of the ocean, but it also deepens the mixed layer by many tens of meters and lowers the SST locally by as much as 5°C [*Emanuel*, 2001, 2003]. Most of the cooling is from entrainment caused by turbulence generated from the strong shear of the near-inertial currents across the base of the mixed layer. *Walker et al.* [2005] show that the cold wake left behind hurricane Ivan in 2004 produces SST cooling of 3–7°C in two areas along Ivan's track that are related to the depth of the mixed layer and upper ocean heat content. Similar results for hurricane Frances in 2004 are given by *Chen et al.* [2007] and for Katrina in 2005 by *Davis et al.* [2008]. *Emanuel* [2001] has argued that much of the thermohaline circulation is actually driven by global tropical cyclone activity through vertical mixing, and increased mixing in the upper ocean layers by tropical storms is supported by observational evidence [*Sriver and Huber*, 2007].

[30] In this study, we quantify crude estimates of the actual enthalpy exchange from the ocean to atmosphere in the Atlantic using several metrics. For the equator to 30°N, the latent heat flux as the net ocean loss within 400 km of the eye of the hurricanes in the Atlantic changes from 0.18 to 0.58×10^{21} J per year for JASO 1970 to 1994 versus 1995 to 2006. When tropical storms are included the surface enthalpy flux changes from 0.41 to 1.05×10^{21} J per year, or equivalently 0.04 and 0.10 PW for JASO. For precipitation, the total values are 1.36 and 3.63×10^{21} J per year (0.13 and 0.34 PW). These increased intensities in the later time period represent a transition from the earlier data record that exceeds the 99% confidence interval based on a *t*-test. At the same time the SST increased by 0.5°C while the column water vapor increased by 4.1%. In contrast, the mean SST from 1970 to 1987 is less than 0.1°C lower than for the 1988–1994 period. The trends in the Atlantic over the last 37 years are thus not very linear but rather are better characterized by a rapid transition occurring in the mid-1990s. The net surface tropical storm fluxes after that time are a substantial fraction of the estimated meridional heat transports in the ocean (of order 1.2 PW in the Atlantic [*Bryden et al.*, 1991]).

[31] *Emanuel* [1987, 2003] argued that increasing greenhouse gases alter the energy balance at the surface of tropical oceans in such a way as to require a greater turbulent enthalpy flux out of the ocean (largely in the form of greater evaporation), thereby requiring a greater degree of thermodynamic disequilibrium between the tropical oceans and atmosphere. It is therefore expected that global warming will be accompanied by an increase in tropical storm activity [*Trenberth*, 2005]. However, this could be manifested as increases in numbers, intensity, duration, and size. The perceptions of variability and change can depend a lot on the metric used (e.g., see Figure 5) and integrated metrics should be more robust and meaningful, but are generally not available. Our surface flux metrics integrate over the lifetime of the storm as long as its maximum winds exceed 39 kt and thus appropriately take the duration and varying intensity into account. The total number of hurricanes is potentially sensitive to a few storms that only momentarily cross the threshold intensity. It is encouraging that our overall trends generally reinforce those given by the ACE and PDI indices. The SST and water vapor metrics are given for the 10 to 20°N region, but many storms occur outside of this domain (e.g., Figure 2). The differences between Figures 1 and 5c also highlight the JASO season perspective versus the whole season. For instance in 2005, two hurricanes and five tropical storms occurred either in June or after October.

[32] The dynamics and thermodynamics suggest that tropical storms are likely to become more intense and possibly greater in size [*Trenberth and Fasullo*, 2007] but may also be fewer in number. In part the latter arises from the much greater surface heat flux out of the ocean, and cooling and mixing associated with a bigger storm, so that the net effect on the heat budget of one big storm may accomplish what several smaller storms might otherwise do. In this context the nonlinearities of surface impacts, the kinetic energy goes up as the square of the wind speed and the PDI goes with the cube of the surface wind speed [*Emanuel*, 2005a], are a factor, and in addition, the transports and stabilization of the atmosphere are greater in more intense storms.

[33] The climatic influence of tropical cyclones depends more on area and time-integrated quantities than on local, instantaneous values. Here we have provided some initial estimates of some of these quantities although they are based upon empirical formulae that are likely to contain biases. The use of maximum sustained wind may be useful to classify hurricane damage, but it is not obviously relevant to large-scale climatic effects of hurricanes, except to the extent that maximum wind correlates with other parameters, which we found to be the case [*Trenberth and Fasullo*, 2007]. However, it is possible that our results, based on limited simulations of Katrina, are not representative in general and, because the available observational data do not include size and integrated metrics, it is not yet possible to address this issue, so that it may be better to regard the results in Figures 4 and 5 as depicting a "hurricane surface flux index" or "hurricane precipitation index". Other studies using the ACE and PDI also do not yet account for changes in size of storms.

[34] We have found that hurricanes pump a considerable amount of heat out of the oceans into the atmosphere every year and that the amount is apparently generally increasing over time after 1970 but also depends strongly on ENSO [*Sobel and Camargo*, 2005; *Trenberth and Fasullo*, 2007]. These facts represent a fundamental role for hurricanes in the climate system. Locally, outgoing longwave radiation decreases from the high cold cloud tops but with compensation elsewhere, often in association with a Madden-Julian Oscillation [*Sobel and Camargo*, 2005]. The climate system as a whole likely cools as there is a transport of energy away from the tropics by the tropical storm circulation links to higher latitudes, where the energy can be radiated to space [*Trenberth and Stepaniak*, 2003a,2003b; *Trenberth and Fasullo*, 2007]. It is therefore suggested that the storms act to systematically cool the ocean and thus play a vital role in climate. The evaporative cooling is only a small component of the cold wake, in the immediate vicinity of the hurricane track, whereas the enhanced evaporation extends out to a radius of order 1600 km. The hurricane values in Figure 4a thus also provide an initial rough estimate of the effects that have been omitted from surface flux and precipitation climatologies that have an insufficient consideration of hurricanes.

[35] Figure 5 also provides insight into the results from *Emanuel* [2005a, 2000b] and *Sriver and Huber* [2006] for the Atlantic using the PDI, and *Webster et al.* [2005] who found a large increase in numbers and proportion of hurricanes reaching categories 4 and 5 globally since 1970 even as total number of cyclones and cyclone days decreased slightly in most basins. These results have been challenged by several studies [*Landsea*, 2005; *Landsea et al.*, 2006; *Klotzbach*, 2006] that have questioned the quality of the data and the start date of 1970, but other studies have found that the record is quite reliable, especially after 1985 [*Emanuel*, 2005b; *Fasullo*, 2006; *Kossin et al.*, 2007].

[36] Observed and potential changes in hurricanes with global warming are discussed in detail by *Trenberth* [2005], *Emanuel* [2005a, 2005b], and *Webster et al.* [2005] who show that intense storms are observed to be increasing and with longer lifetimes, in line with theoretical and modeling expectations, and this is also evident in our preliminary results for energy exchange globally [*Trenberth and Fasullo*, 2007] and for the Atlantic (Figures 4 and 5). Empirically there is a very strong relationship between intensity and potential destructiveness of such storms with SSTs in the genesis regions in the Tropics [*Emanuel*, 2005a, 2005b]. Our results use a novel technique of exploiting model results from simulations to make extrapolations to the global domain by also utilizing the best track data. They are only as good as the best track data and accordingly subject to future revision and can no doubt be improved upon. Moreover, they depend on relationships established during Katrina which, while adjusted for SST effects, may not apply to all other storms. When reprocessed data on tropical storms are available, it would be desirable to redo these statistics. Nonetheless, they provide some high level diagnostics on aspects of the variability of hurricane impacts that are likely to reflect real world changes. The enthalpy flux and precipitation time series given here are also likely to provide a legitimate index of the changing role of hurricanes in the climate system that complement the PDI and other indices.

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