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# Water and energy budgets of hurricanes and implications for climate change

Kevin E. Trenberth[1] and John Fasullo[1]

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[1] On the basis of simulations of hurricane Katrina in August 2005 with the advanced Weather and Research Forecasting (WRF) model at 4 km resolution without parameterized convection, empirical relationships are computed between the maximum simulated wind and the surface fluxes and precipitation and provide a reasonable fit to the data. The best track data set of global observed tropical cyclones is 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 is estimated to be about $0.53 \times 10^{22}$ J a$^{-1}$ (where a is year) (0.17 PW). The enthalpy loss due to hurricanes computed on the basis of precipitation is 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 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 these inferred surface fluxes and precipitation arising from increases in intensity of storms and also higher sea surface temperatures. Confidence in this result is limited by uncertainties in the best track tropical cyclone data. Nonetheless, the results highlight the importance of surface energy exchanges in global energetics of the climate system and are suggestive of the deficiencies in climate models owing to their inadequate representation of hurricanes.

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## 1. Introduction

[2] What role, if any, do hurricanes and tropical cyclones have in our climate system? Why do hurricanes exist? These rather fundamental questions are the motivation for the research outlined here and have substantial implications for both our understanding and modeling of the climate system and its variability. For instance, if hurricanes do play a key role in climate, as many researchers suspect, and such storms are not well simulated in climate models [e.g., *Yoshimura et al.*, 2006], then it means that climate models have basic errors as the tropical storm processes have to be compensated for in some other way. Moreover, clear answers to these questions are essential if we are to understand better how hurricanes are altered by and affect a changing climate.

[3] The perspective put forward here is in the context of the energy and water cycles. In a companion paper [*Trenberth et al.*, 2007], the bulk water budgets for some high-resolution simulated hurricanes are assessed and some inferences regarding the energy transports and overall energy budget are made. It is well known that the main fuel for hurricanes is the latent heat release in convection acting collectively and organized by the hurricane circulation to drive the storm [e.g., *Krishnamurti et al.*, 2005; *Braun*, 2006]. This provides the reason to focus on the water cycle and the latent energy that arises from condensation of moisture in precipitation, while the moisture in turn comes from evaporation from the ocean surface, in part brought about by the storm itself. Changes in precipitation and associated flooding over land are also of considerable interest from a societal standpoint.

[4] It is suggested here that a primary role for hurricanes comes about because they are the only phenomenon that can 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 otherwise occurs. In this perspective, the organized strong surface winds in hurricanes sufficiently increase the surface evaporation such that the latent heat losses by the ocean can exceed 1,000 W m$^{-2}$, which is an order of magnitude larger than the summertime climatological value. Although hurricanes can be analyzed in terms of vortex dynamics and the favorable conditions required for them to exist and develop,

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[1] National Center for Atmospheric Research, Boulder, Colorado, USA.

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the more fundamental question is why those conditions develop in the first place? It is argued that at least somewhere around the tropics in summer, in the neighborhood of the highest sea surface temperatures (SSTs), is where the main tropical cyclone activity will be favored [e.g., *Yoshimura et al.*, 2006]. The tradewinds are strongest away from that region and occur where the SST temperature gradients and associated surface pressure gradients are strong. There may be two or perhaps three such regions in the tropics in any season, but large-scale tropical dynamics associated with monsoonal and Walker circulations guarantees competition for the primary location and thus where conditions for storm formation and intensification will be most favorable. 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].

[5] A review of early estimates of the water and energy budgets in hurricanes is given by *Trenberth et al.* [2007] and several estimates for individual tropical cyclones stand the test of time [*Palmén and Riehl*, 1957; *Malkus and Riehl*, 1960; *Riehl and Malkus*, 1961; *Miller*, 1962; *Anthes*, 1974]. A comprehensive summary of the understanding of hurricanes and their relationship to climate is given by *Emanuel* [2003] in which he describes the current understanding of the energetics of tropical storms, the role of air-sea interaction and effects on upper ocean mixing, and how tropical storm activity may change as the climate changes, providing an excellent basis for the perspective put forward here, and hence a summary is provided below.

[6] In this paper we make use of the control run simulation results of *Trenberth et al.* [2007] for Katrina in August 2005 made with the high-resolution (4 km) Advanced Research Weather and Research Forecasting (WRF) model that avoids the use of parameterized convection. We also 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. Concerns about this record are discussed in sections 3.2 and 4. On the basis of the relationships between surface latent heat and enthalpy fluxes and maximum wind speed in the model results, and with the observed frequency with which storms of certain intensities occur from the best track data, we estimate a preliminary global value for the enthalpy and moisture loss by the ocean due to hurricanes and how this has changed over recent decades. Values are computed on the basis of the direct exchanges within 400 km of the eye of the storms and also approximately for the whole storm on the basis of the resulting precipitation. While this may seem to be a huge extrapolation of the data from both the limited model runs and the best track data, the exercise itself demonstrates how far we can go and still get reasonable results. Even if not quantitatively correct, the results provide what may be regarded as an index of changes over time for this set of best track data, and they provide an initial estimate of the effects of hurricanes on the ocean in terms of heat exchanges for the first time. Subsequent refinements in the observational record of storms will undoubtedly improve upon the values presented here.

[7] In the following section we first review the background state of knowledge on both the energetics and water cycle of storms and tropical storms and introduce some outstanding issues. Section 3 presents results using the best track data along with inferences based on WRF model results and places them in the context of the global energy cycle. Section 4 discusses these results, and ways to improve these preliminary estimates.

## 2. Storm Energetics and Water Cycle

### 2.1. Energetics

[8] An overall view of the flow of energy through the climate system and the annual cycle of uptake and storage of heat by the ocean at the surface is given in *Trenberth and Stepaniak* [2003a, 2003b, 2004]. The basic source of energy for tropical cyclones is heat transfer from the ocean. Divergence of ocean heat in a column from heat transports is fairly small, and long-wave radiation to space directly from the surface is limited by the optically thick layer of water vapor. Hence to a first approximation over the tropical oceans, absorption of solar radiation at the surface is largely offset by evaporative cooling. While background climatological latent heat fluxes in the tropical regions are order 120 W $m^{-2}$ [*Josey et al.*, 1998] it is likely that these estimates do not reflect hurricane effects adequately.

[9] *Emanuel* [2003] likens the energy cycle of a mature tropical cyclone to that of an ideal Carnot cycle. In this analogy, air at the surface air spirals into the center of the storm in contact with the ocean and picks up moisture from the surface, increasing entropy, while dissipating kinetic energy in the boundary layer through surface friction and momentum exchange with the ocean [*Bister and Emanuel*, 1998]. In the eyewall convection, predominantly adiabatic expansion and cooling occurs as air rises and moisture is condensed in precipitation, with the latent heat realized as sensible heat and potential energy (dry static energy), but entropy is roughly conserved. The air diverges at the top of the storm, flows out and the now dry air warms adiabatically as it subsides in the downward branch some distance from the storm center. It is in these legs that radiation to space can occur as the air is above the boundary layer water vapor. As some of this energy is transported out of the subtropics to higher latitudes before it is radiated to space [*Trenberth and Stepaniak*, 2003b], the circulation is not closed. Also, as the lifetime of a typical tropical cyclone is order 6 d, it is not in equilibrium with the environment. Hence the Carnot cycle is approximate.

[10] In tropical cyclones, work is used up in turbulent dissipation in the storm's atmospheric boundary layer, where it is turned back into heat. Because this conversion occurs at the highest temperature in the system, the hurricane recycles some heat back into the Carnot cycle [*Bister and Emanuel*, 1998]. Hence tropical cyclones are driven by enthalpy fluxes from the sea, mainly in the form of evaporation of moisture, and are limited mostly by surface drag. *Emanuel* [2003] discusses uncertainties at high wind speeds and how sea spray may enhance the sea-air enthalpy flux at high wind speeds. Estimates of the kinetic energy dissipation in real storms [*Emanuel*, 2003] suggest that the average tropical cyclone dissipates approximately $3 \times 10^{12}$ W, and very large and intense storms can dissipate an order of magnitude more power. However, as shown here and by *Palmén and Riehl* [1957], tropical cyclones move

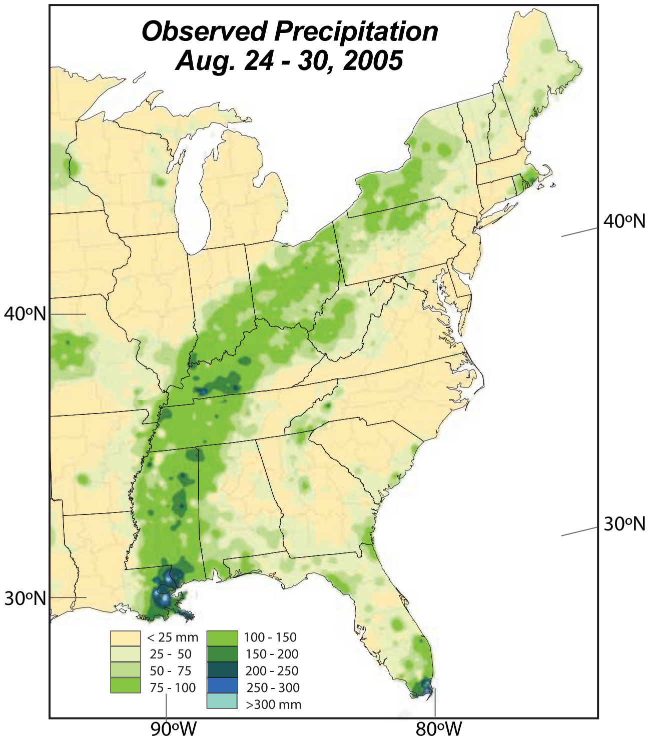

**Figure 1.** Estimate of observed precipitation based on surface gauges, adapted from a compilation by Climate Prediction Center, NOAA (printed with permission, courtesy Rich Tinker and Jay Lawrimore). These may be underestimates as many data were missing in the vicinity of New Orleans.

even larger amounts of energy around from the ocean to the atmosphere and ultimately to space.

[11] From the standpoint of the ocean, therefore, the tropical storm produces a net cooling, but it actually does much more. *Emanuel* [2001, 2003] review the evidence for the large effects of hurricanes on the uppermost 200–300 m of the ocean, in which a storm deepens the mixed layer by many tens of meters, and cools the SST locally by as much as 5°C. Most of the cooling is owing to entrainment caused by turbulence generated from the strong shear of the near-inertial currents across the base of the mixed layer. A detailed analysis by *Walker et al.* [2005] of the cold wake left behind hurricane Ivan in 2004 reveals SST cooling of 3–7°C in two areas along Ivan's track, related closely 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.* [2007].

[12] In spite of their intense air-sea interactions, tropical cyclones are usually considered to respond passively to climate changes on many timescales [*Emanuel*, 2003]. *Emanuel* [2001] estimated for 1996 the net cold wake from both effects of mixing and heat loss of 1.4 ± 0.7 PW and suggested that subsequent heating of the ocean would restore this, so that ocean heat transports were required to achieve a balance. Accordingly, *Emanuel* [2001] has argued that much of the thermohaline circulation is actually driven by global tropical cyclone activity, and this is supported by observational evidence [*Sriver and Huber*, 2007]. Perhaps even more fundamentally, tropical cyclones assist the climate system to moderate temperatures at the surface and in the ocean in the tropics through the evaporative heat losses. The question of how much is taken up here.

[13] *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. This theory provides a theoretical basis for expected changes in the observational record as global warming proceeds.

### 2.2. Water Vapor and Precipitation in Storms

[14] Observations reveal increases in heavy precipitation in the United States [*Groisman et al.*, 2004], where heavy rains (the top 5%) increased 14% over the 20th century, and many other parts of the globe [*Groisman et al.*, 2005; *Alexander et al.*, 2006], often at the expense of more moderate rains and even in places where overall precipitation amounts are declining. Although precipitation estimates in hurricanes and tropical storms now exist [*Lonfat et al.*, 2004] and are regularly made every 6 h in the Hydrological Data and Information System (HyDIS) project http://hydis8.eng.uci.edu/hydis-unesco/, sampling issues remain [e.g., *Fasullo*, 2006]. Once tropical storms make landfall, then the observed precipitation estimates, which often show rainfalls over 300 mm (~12 inches), can be used. For instance in Katrina, rainfalls exceed 300 mm in spots >100 mm over a 100 mile swath north from New Orleans, and 50–75 mm over a wide swath from the Gulf Coast to Canada (Figure 1). In Newton, MS (60 miles east of Jackson, MS) measured rainfall rates exceeded 35 mm $h^{-1}$ on 29 August (see http://www.ncdc.noaa.gov/img/climate/research/2005/katrina/newton-prcp.jpg).

[15] Observed changes in precipitation in hurricanes are uncertain, although *Trenberth et al.* [2007] suggest that rainfall rates may have increased of order 6 to 8% since about 1970 in association with increased water vapor in the atmosphere of about 4% over the global oceans[*Trenberth et al.*, 2005] and warming. This is because of the dominant reliance of storms on the resident moisture in the atmosphere and the moisture convergence for precipitation and latent heating in storms.

## 3. Empirical Relationships

[16] *Trenberth et al.* [2007] argued that the surface flux has a component that should respond with Clausius Clapeyron. The simplified bulk flux formula gives the evaporation as

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

where $C_L$ is the exchange coefficient, $\rho_a$ is the air density, $q$ is the specific humidity at temperature $T$ or $T_s$ = SST, $q_s$ is the saturation value of $q$, $RH$ is the relative humidity, and $V$ is the wind speed. Here $RH^* = RH\, q_s(T)/q_s(T_s)$. Because the relative humidity is observed to not change much, the term $RH^*$ may not vary much and a dominant dependency for $E$ is the saturation specific humidity at the SST which is

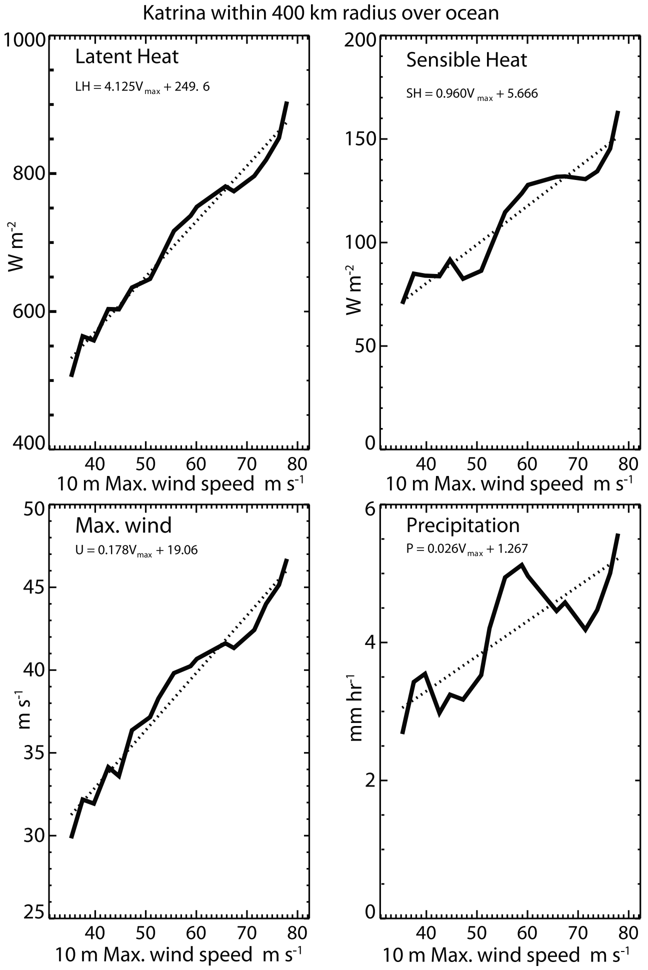

**Figure 2.** Empirical relationships from WRF model runs for Katrina showing the ocean area integrated over 0–400 km radius for the surface (top left) LH and (top right) SH fluxes in W m$^{-2}$, (bottom left) the wind speed m s$^{-1}$ and (bottom right) precipitation mm h$^{-1}$ as a function of the maximum 10 m wind speed at any location.

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% K$^{-1}$ rise in atmospheric temperature in the tropics. *E* is also dependent on *V*.

[17] The bulk flux formula (1) is simplified to give the evaporation as

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

where $a$ is a regression coefficient and $\varepsilon$ is the error. *Trenberth et al.* [2007] used simulations of Katrina 42 h into the integration to allow equilibration to occur, and find that much of the change in surface latent heat flux with changes in SST can be accounted for by the two variables $V$ and $q_s$. We now use the Katrina control simulation results to empirically explore relationships in (2).

### 3.1. WRF Model

[18] The WRF model [*Skamarock et al.*, 2005; *Davis et al.*, 2007], specifically the Advanced Research WRF (hereafter referred to simply as WRF) has been used in real time to forecast several hurricanes during 2004 and 2005. 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. We consider this to be a major advantage over the parameterized convection model results of *Knutson and Tuleya* [2004] and *Oouchi et al.* [2006]. Results with more sophisticated schemes in WRF show similar results concerning fluxes and precipitation [*Davis et al.*, 2007]. The boundary layer scheme is a first-order closure scheme, meaning that turbulence is diagnosed entirely in terms of grid-scale variables [*Noh et al.*, 2003].

[19] 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. Accordingly, we first empirically relate the storm-integrated surface fluxes over a 400 km radius from the model experiments we have performed to the maximum 10 m wind speed $V_{max}$. Thus we use the control model results for Katrina described by *Trenberth et al.* [2007] to empirically estimate the surface fluxes simply as a function of the maximum wind speed at any grid point. Perhaps remarkably, the results suggest a fairly linear increase of both surface latent heat (LH) and sensible heat (SH) flux with $V_{max}$ (Figure 2). In any case, to the extent that it is nonlinear, we compute histograms of storm-integrated flux versus $V_{max}$ for use in our global synthesis. Also, perhaps surprisingly, $V_{max}$ correlates better with the LH flux (0.99) than with wind (0.98), while the correlation is 0.96 with SH flux and 0.82 with precipitation. The poorer result in the latter is not surprising given 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%).

[20] In equation (2) it would be possible to set $b = aq_s(T_s)$ and ignore the dependence on Clausius-Clapeyron. However, as Katrina operated in an environment of high SSTs averaging about 31°C it seems likely that the surface latent heat fluxes are much larger than they would be in a cooler SST environment. For example, for simulations of Ivan [*Trenberth et al.*, 2007], in which SST is about 29°C, surface fluxes are notably reduced. Including the SST dependence gives about a 12% reduction for Ivan and goes a long way to accounting for the differences in the simulated fluxes.

### 3.2. Best Track Data

[21] Over the globe, there is considerable uncertainty in the hurricane record prior to 1970 when observations from satellites with suitable sensors became available. Even after that time the techniques used to interpret satellite imagery have improved, and this casts some doubt on the reliability of changes in tropical cyclones over time [*Landsea et al.*,

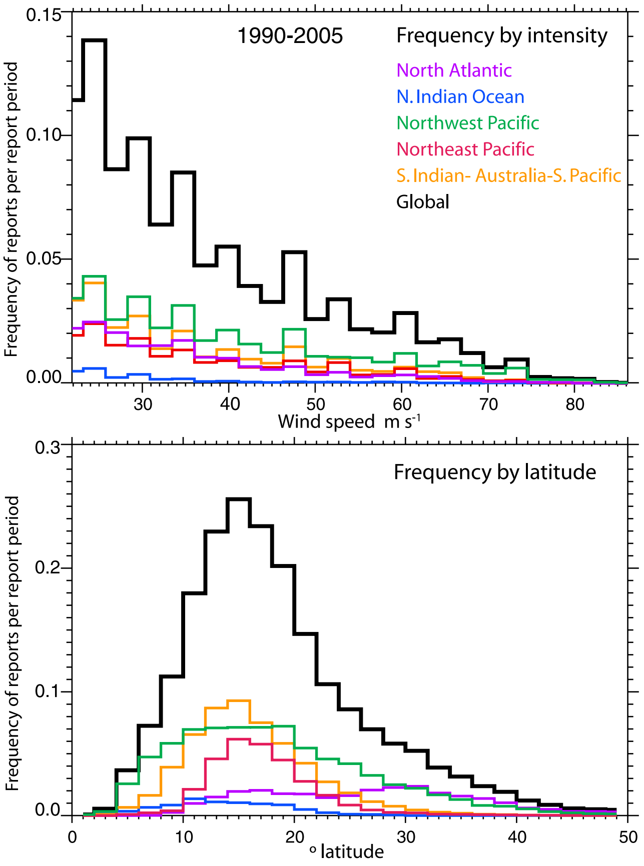

**Figure 3.** Histogram of wind speed recorded in the best track data by 5 knot category for 1990 to 2005. (top) Frequency per report period for each basin as well as the global total and (bottom) the corresponding latitudes at which the tropical cyclones occurred. Owing to lack of clearly defined boundaries, all the Southern Hemisphere basins are combined (labeled as S. Indian-Australian-S. Pacific).

2006]. *Fasullo* [2006] has analyzed the observed best track hurricane record for sampling biases that might account for trends in intense storms, but the signatures of increased duration and frequency of weaker storms that might arise from such biases are not present in the data. In the North Atlantic, moreover, the 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. We focus therefore only on the record after 1970, and proceed with recognition that a much needed reanalysis of the satellite record to provide revised tropical cyclone statistics could well improve results [e.g., *Kossin et al.*, 2007].

[22] According to *Webster et al.* [2005], hurricanes and named storms (above 18 m $s^{-1}$) account for about 640 to 840 storm days per year. *Lonfat et al.* [2004] consider all tropical storms and divide them into categories given by the Saffir-Simpson scale of tropical storms for which they used TS 18–33 m $s^{-1}$, category 1 + 2 34–48 m $s^{-1}$ and category 3–5 > 49 m $s^{-1}$. For their analysis for 1998–2000, the TS category makes up 67% of the total in the best track data set (versus 64% from TRMM). Category 1 + 2 hurricanes make up 23% of the storms and category 3–5 storms 10%. However, for 1998–2000 they find an average of 1875 observations of such storms for 6 h observations per year. Accordingly, category 1 + 2 storms occur 29.17% of the time (106.5 d $a^{-1}$) and category 3–5 storms occur 13.05% of the time (47.6 d $a^{-1}$).

[23] We have computed further tropical cyclone statistics, after verifying the *Lonfat et al.* [2004] results, 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 2005. Results are given in Figure 3 by basin, and in Figure 4 and Table 1 along with the surface flux data. 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 1990 to 2005, hurricanes occur 51.1% of the time. While category 1 storms dominate in numbers, there is a surprisingly similar incidence of category 3 and 4 hurricanes (in part because the category 4 wind limits are wider); see Figure 3 for the full histogram. The mode of the distribution is 15° latitude (Figure 3) and it is mainly in the North Atlantic, and to a lesser extent in the Northwest Pacific, where the storms extend outside of 30°N to 30°S. Further, the higher-latitude storms are weaker with winds mostly less than 50 m $s^{-1}$. The biggest change when storms outside 30° latitude are excluded is for the weaker named tropical storms.

[24] 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. Obviously this does not capture the detailed daily variations of SST distribution

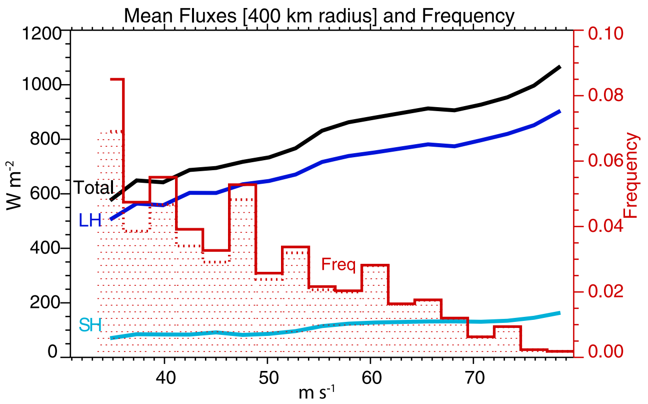

**Figure 4.** As a function of maximum wind speed, given are (1) the frequency of occurrence of storms with peak winds from observed best track data 1990–2005 (red, right axis) for the total global domain and also for 30°N to 30°S (dotted) and (2) surface fluxes as latent (blue), sensible (cyan) and total (black) energy (W $m^{-2}$) based on the Katrina simulation.

**Table 1.** Best Track Frequency of Tropical Cyclones for 1990–2005 of Given Peak Wind Strength by Tropical Storm (TS) or Hurricane Category Along With the Value for Just 30°N to 30°S[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 | 68.8 | 22.7 | 11.1 | 7.6 | 8.05 | 1.55 |
| Best track 30°N–30°S | 58.9 | 18.8 | 10.1 | 7.3 | 8.00 | 1.54 |
| 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] 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. Unit for wind strength is m s$^{-1}$, and unit for best track frequency is %.

across the storm, but it does capture the main changes with month and location that are dominant.

### 3.3. Inferred Global Climatology of Surface Fluxes From Hurricanes

[25] To make an assessment of the main component of the energy budget associated with hurricanes, we use (1) the surface heat flux as estimated empirically from Katrina from equation (2) and (2) the precipitation amount. It is likely that the results based on Katrina alone, where there were relatively high SSTs, are somewhat exaggerated relative to most storms. When we apply equation (2) to the best track data, we therefore include the $q_s$ dependence of surface latent heat flux. This reduces the magnitude of the inferred best track fluxes typically by up to 20% (for instance in 2003 the global LH flux is reduced from 5.1 to 4.3 × 10$^{21}$ J), and the trend is reduced by 18%. In other words, this is the change due to taking account of the observed SSTs versus those during Katrina, and it suggests SSTs lower than for Katrina by about 3°C on average. The results presented here are therefore conservative as the fluxes are generally reduced. The precipitation estimate benefits from the transport from afar, including the moisture stored in the atmosphere at the start of the storm and the surface flux from outside the storm's precipitation bands, but which spirals into the storm. We do this by basin as well as globally (e.g., Figure 3).

[26] To comprehend the sampling in time, Figure 5 shows the inferred integrated surface fluxes for only the ocean over the 400 km radius. Peak values occur in 1997 when the 1997–1998 El Niño played a major role in enhancing tropical cyclone activity in the Pacific, while suppressing activity in the Atlantic, and second highest is 1992, also an El Niño year. These peaks also occur in the global values of NOAA's Accumulated Cyclone Energy (ACE) index [*Levinson*, 2005; *Klotzbach*, 2006].

[27] When the values based on the 16 years 1990–2005 are combined to provide the total from hurricanes alone over 0–400 km radius (5 × 10$^{11}$ m$^2$), the total evaporative (enthalpy) flux gives a tropical ocean cooling of 5.08 (5.84) × 10$^{21}$ J a$^{-1}$, or equivalently 0.16 (0.185) PW annual average. For 30°N to 30°S these change to 4.60 (5.30) × 10$^{21}$ J a$^{-1}$ or 0.15 (0.17) PW. The background value is order 4 × 10$^{23}$ J a$^{-1}$ in the absence of such storms.

[28] However, the estimated hurricane precipitation latent heat release from 30°N to 30°S is about 3.4 times these values (although this applies only to the latent component), as this accounts for the transport of latent energy from outside the 400 km cylinder. This ratio is lower than the 3.9 for Katrina or 4.95 for Ivan [*Trenberth et al.*, 2007]. However, the precipitation latent heat is an underestimate as it was computed only over the ocean, and the land precipitation, such as in Figure 1, is missing. Indeed, much of the heavy precipitation may occur after the storm has made landfall and lost intensity. Nevertheless, the mean ocean latent heat for 1990 to 2005 is 1.84 × 10$^{22}$ J a$^{-1}$, or equivalently 0.58 PW over the year. 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.

[29] In addition to the annual average values, Figure 5 also reveals 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 in Figure 5, and with randomly generated time series of equal variance, as well as other methods. For precipitation, the trend corresponds to 1.4% a$^{-1}$, a factor of 10 larger than water vapor trends over the global ocean

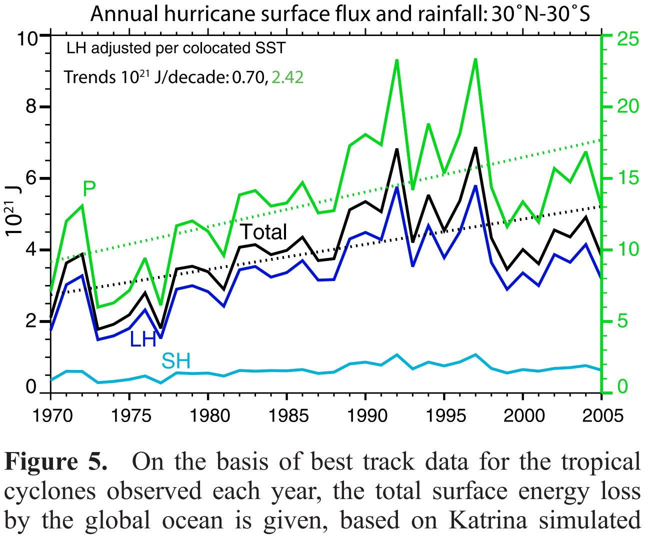

**Figure 5.** On the basis of best track data for the tropical cyclones observed each year, the total surface energy loss by the global ocean is given, based on Katrina simulated fluxes within 400 km of the eye of the storms as given by (2) for latent (blue), sensible (cyan) and total enthalpy (black) flux in 10$^{21}$ J a$^{-1}$. Also given in green (right-hand scale) is the precipitation in the same units. The dotted lines are linear trends and values are given in 10$^{21}$ J decade$^{-1}$.

based on independent data [*Trenberth et al.*, 2005]. However, the changes in Figure 5 over time are not linear, as they feature higher values from 1989 to 1997. This was an unusual period in that a prolonged El Niño occurred 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], followed 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. The prolonged El Niño terminated in 1995 just in time for the 1995 hurricane season which was the beginning of a burst of enhanced activity in the North Atlantic. Activity was again suppressed in the North Atlantic in the 1997 El Niño season in spite of this being the most active global year overall.

## 4. Discussion and Conclusions

[30] Surface fluxes are not well known even in the climatology [*Josey et al.*, 2003; *Liu and Curry*, 2006]. A recent evaluation of two satellite based products and two reanalysis based products find that agreements are better than in the past [*Liu and Curry*, 2006], but spurious changes are evident as satellites have changed and reanalyses have biases and spurious trends [*Trenberth et al.*, 2005] and hurricanes are not well depicted. Large increases in SST with the 1997–1998 El Niño event correspond to large increases in atmospheric surface specific humidity [*Liu and Curry*, 2006] and total column water vapor [*Trenberth and Smith*, 2005], as well as hurricane activity (Figure 5), although surface latent heat fluxes seem to depend more on changes in wind speed [*Chikamoto and Tanimoto*, 2005; *Liu and Curry*, 2006]. The Coupled Boundary Layer Air-Sea Transfer Experiment (CBLAST) [*Black et al.*, 2007] was carried out to improve in part the surface fluxes in hurricanes at high winds and results are being evaluated as to their effects on models [*Chen et al.*, 2007] including WRF [*Davis et al.*, 2007].

[31] The moisture budget in tropical cyclones is dominated by the inflow of moisture mainly in the lowest 1 km of the storm and, inside about 100 km of the center of the storm, the inflow is about a factor of 10 greater than the latent heat flux from the surface in spite of the fact that it is ultimately the latter that mainly causes the inflow to occur [*Trenberth et al.*, 2007]. Together these moisture fluxes contribute to the heavy rainfall in tropical cyclones and thus latent heat release that drives the storms. Moreover, the sensitivity experiments by *Trenberth et al.* [2007] reinforce the likelihood of substantial increases in precipitation as the SSTs increase, with important but small increases in intensity of the storms.

[32] The climatic influence of tropical cyclones depends more on area and time-integrated quantities than on local, instantaneous values. The use of maximum sustained wind may be useful to classify hurricane damage, but it is not obviously useful to understand large-scale effects of hurricanes, except to the extent that maximum wind correlates with other parameters, which we found to be the case (Figure 2). However, hurricanes Charley and Ivan from 2004 were both category 4 storms, but the circulation from Ivan was an order of magnitude larger than for Charley, and the total fluxes and precipitation may not scale accordingly. Further, it is likely that tropical cyclones in other basins, and hence somewhat different environments, may have systematically different characteristics and this is a major caveat on efforts to generalize the satellite record globally by *Kossin et al.* [2007]. Further research is desirable to explore this aspect with TRMM data and further model simulations. Nonetheless the issue is whether the integral values in Figure 5 are biased and the answer is far from obvious. Because the available observational data do not include size and integrated metrics, it is not possible to address this issue, and hence it may be better to regard the results in Figure 5 as depicting a "hurricane surface flux index" or "hurricane precipitation index."

[33] We have found that hurricanes pump a considerable amount of heat out of the oceans every year and that the amount is apparently generally increasing over time after 1970 and depends strongly on ENSO. These facts represent a fundamental role for hurricanes in the climate system. *Palmén and Riehl* [1957] estimated an energy export of 0.88 PW for "average" hurricanes, while for Bonnie [*Braun*, 2006] it was 1.34 PW. These values are consistent with ours which are extended to the global domain for all seasons. As our values do not include the contributions from tropical storms that do not reach hurricane strength, they are conservative in terms of the effects of tropical cyclones on the climate system. However, they are probably representative of the effects that are not included in climatologies because of lack of observations within hurricanes.

[34] The main result of this work is that the net surface enthalpy flux from global hurricanes from 30°N to 30°S is 0.17 PW when the region within 400 km of the center of the storms is considered, or about 0.58 PW for the full domain of hurricanes. The storms act to systematically cool the ocean and thus play a vital role in climate. If the enhanced evaporation value inside 400 km radius were redistributed over the tropical ocean area from 30°N to 30°S it amounts to 0.9 W $m^{-2}$ heat loss, or equivalently 0.7°C $a^{-1}$ cooling over a 10 m thick layer. The evaporative cooling corresponding to the tropical storm precipitation amounts to 2.3°C $a^{-1}$. Although this is a modest rate, it is a systematic cooling of the tropical ocean by hurricanes over about 40% of the globe, and in actuality is concentrated into perhaps just one fifth of that area. Globally, this corresponds to 0.33 W $m^{-2}$ for evaporation, or 1.13 W $m^{-2}$ for precipitation. Although these estimates are somewhat less than the human-induced radiative forcing (about 1.5 W $m^{-2}$), the latter is larger than the actual radiative imbalance which is estimated to be 0.7 to 1 W $m^{-2}$ [*Hansen et al.*, 2005]. Also for comparison, the global ocean to 3000 m depth gained $1.45 \times 10^{23}$ J [*Levitus et al.*, 2005] from 1955 to 1998, or an average of $0.33 \times 10^{22}$ J $a^{-1}$, and most of this increase took place after 1970 at a rate of $0.5 \times 10^{22}$ J $a^{-1}$, which is very similar to the annual hurricane heat loss within 400 km of the storm centers.

[35] The surface flux values in Figure 5 can be compared with the *Emanuel* [2001] estimate of 1.4 PW for 1996 total cold wake effects which include ocean heat transport and surface fluxes. From Figure 5 in 1996 the surface flux estimate is $4.8 \times 10^{21}$ J or about 0.15 PW from surface evaporative and sensible heat cooling leaving about 1.2 PW that is mixed deeper into the ocean and which must then be compensated for by ocean heat transports. This is consistent

with the view that the evaporative cooling is only a small component of the cold wake, but it is a local result in the immediate vicinity of the hurricane track, whereas the enhanced evaporation extends out to a radius of order 1600 km, and over that domain the 0.58 PW makes up 41% of the Emanuel value. This also suggests that a lot of the compensation for this effect is likely to come from other parts of the tropics, leaving about 59% of Emanuel's estimated value for ocean transport to higher latitudes.

[36] We have suggested that tropical cyclones are integral to the Earth's climate system. Yet hurricanes are not well depicted in global climate models. The distribution of tropical storms can be somewhat simulated but the maximum winds and vortices are not realistic even in a model at T106 (110 km) resolution [*Yoshimura et al.*, 2006], and we suggest that the value of the surface enthalpy flux computed in Figure 5 is a reasonable estimate of that which is absent from coarse resolution coupled climate models. If a model on a 50 km grid produces a cyclone, it will probably have a circulation that is too large, but also too weak, although the integral of some fields might be about right. A model with a grid spacing of 200 km can depict tropical cyclones, although they are not realistically simulated [*Broccoli and Manabe*, 1990] and even at T106 (110 km) resolution, tropical cyclones with hurricane force winds are uncommon [*Yoshimura et al.*, 2006]. This highlights the large sensitivity to resolution and numerics.

[37] In addition, there is large sensitivity to convective parameterization and the stability of the atmosphere in global models [e.g., *Shen et al.*, 2000; *Yoshimura et al.*, 2006] even when resolution has been increased to 20 km in the atmospheric runs on the Earth Simulator in Japan [*Oouchi et al.*, 2006] or in regional models [*Knutson and Tuleya*, 2004]. Climate models prematurely trigger convection and stabilize the atmosphere as has been established by examining the diurnal cycle, where model precipitation onsets too quickly and occurs too often and with insufficient intensity compared with observations [*Yang and Slingo*, 2001; *Trenberth et al.*, 2003; *Dai and Trenberth*, 2004; *Trenberth*, 2005]. A consequence is that resolved disturbances in the tropics in global climate models are much too weak [*Lin et al.*, 2006]. The WRF model used here avoided use of parameterized convection and thus provides an alternative basis for estimating tropical storm effects.

[38] Given the missing hurricane processes, the climate models therefore compensate in other ways, such as with somewhat stronger tradewinds in the control climate. However, a key question is whether the changes projected to occur by such a model as the climate changes will be realistically depicted in the absence of processes represented by hurricanes? Hence we raise the question of whether tropical SSTs and associated upper ocean heat content may not increase as much as widely predicted in future climate projections with increases in greenhouse gases [*Intergovernmental Panel on Climate Change*, 2001], and instead that there could be increases in intensity and more overall activity of tropical cyclones [*Trenberth*, 2005]. We put forward this as a hypothesis to be tested in future work.

[39] In addition to the average values over a certain period, Figure 5 also reveals an upward trend that is consistent with results from *Emanuel* [2005a, 2005b] and *Sriver and Huber* [2006] using the power dissipation index (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. The largest increase was in the North Pacific, Indian and Southwest Pacific oceans. 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. The historical record typically records the central pressure and the maximum winds, but these are not physically consistent in older records (mainly prior to about the early 1970s). However, attempts at mutual adjustments result in increases in some years and decreases in others, with little effect on overall trends. In particular, in the satellite era after about 1970, the global trends found by *Emanuel* [2005a] and *Webster et al.* [2005] are thought to be robust [*Emanuel*, 2005b; *Fasullo*, 2006]. *Kossin et al.* [2007] have reprocessed some of the tropical storm record and raise questions about the quality of the best track data in the Northwest Pacific, South Pacific and Indian Oceans, although PDI values are found to agree in the Norwest Pacific provided missing storms from the Kossin data set are included (K. Emanuel, personal communication, 2007). Moreover there are questions about the applicability of a method trained on the Atlantic to other basins. These uncertainties highlight the great need to reanalyze the satellite record and produce more reliable and comprehensive tropical storm characteristics that include size, intensity, duration, cyclone energy, and power, as well as track. In the Atlantic and west Pacific combined, the PDI suggests higher values in recent decades in strong association with higher SSTs [*Emanuel*, 2005b]. Our results (Figure 5) also suggest that the study by *Klotzbach* [2006] of hurricanes after 1986 is based on too short a period to establish reliable trends, especially because of the large interannual variability and the El Niño-related peaks in 1997 and 1992.

[40] 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 (Figure 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. Nonetheless they provide some high-level diagnostics on aspects of hurricanes over time that are likely to reflect real world changes. Use of other models, perhaps run for each hurricane, may allow improved estimates and help determine the extent to which the theory outlined here is valid. Future research can help to quantify these aspects. However, the latent heat and precipitation time series given

here provide a legitimate index of the changes over time that complement the PDI and other indices.

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J. Fasullo and K. E. Trenberth, National Center for Atmospheric Research, Boulder, CO 80307, USA. (trenbert@ucar.edu)