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CHANGES IN CLIMATE AND HURRICANES

Kevin E. Trenberth
National Center for Atmospheric Research[1]
Boulder, Colorado

1. INTRODUCTION

Are the bonanza Atlantic hurricane seasons of 2004 and 2005 becoming the norm? Is the record breaking number of typhoon hits in Japan in 2004 a wave of the future? Does the first known hurricane, Catarina, in the South Atlantic in March 2004 signal that more are on the way? The climate is changing, and humans are partly responsible. This paper summarizes recent climate change with a special focus on variables relevant for hurricanes in the context of the global climate system, and new results on energy and water budgets and their implications for hurricanes is given. Relevance to the southern hemisphere is discussed.

A key question is why hurricanes exist at all, and in particular, what role, if any, do they play in climate and the atmospheric general circulation? See Emanuel (2003) for a background discussion. The tropics are a region where the sun beats down and incoming radiation exceeds the outgoing longwave radiation at the top of atmosphere. Outgoing longwave radiation is not an effective cooling regulating mechanism at the surface over the oceans owing to high water vapor amounts, which have a strong greenhouse effect and limit losses to space. Heat goes into the oceans, where some is carried away by ocean currents, but the main loss is into the atmosphere through evaporation, which cools the ocean and moistens the atmosphere. The realization of latent heat in the atmosphere comes when moisture is condensed in precipitation.

In winter, sufficient connections exist between the tropics and higher latitudes through extratropical storms and the Hadley circulation in the atmosphere, so that the atmosphere transports excess heat to higher latitudes where it can radiate to space (Trenberth and Caron 2001; Trenberth and Stepaniak 2003). In summer, this connection is much weaker, although monsoons can play a key role in moving heat between land and ocean, driven by land-sea contrasts. But over much of the tropical ocean in summer, the only relief valve for heat is to transport it upwards. Of course this occurs in convection, which also converts the moisture into latent heat, and thus into dry static energy, and so it can be at least partially radiated to space once the energy is either above the moisture layer or in the drier subsidence regions (subtropical anticyclones) nearby.

Convection is accompanied by gusty winds, but nonetheless, surface moisture fluxes are only up to order 6 mm/day over most of the tropics, equivalent to about 175 W m^{-2}. In tropical storms, however, and especially in strong hurricanes, surface evaporation may be over 30 mm/day and thus order 1000 W m^{-2}. Tropical storms mix heat within the ocean and this, along with the large surface fluxes, cools the ocean surface leaving a cold wake behind the storms (e.g., Walker et al. 2005). Tropical storms are effectively a collective of thunderstorms, and also achieve the transformation of moisture into latent heat and thus dry static energy that can be radiated to space.

Note that the importance here lies in the total movement of energy, which might be accomplished by many thunderstorms, a lot of weak tropical storms, or perhaps by a few major hurricanes. This point is made to highlight the fact that it is not the numbers that matter, but rather the combination of intensity, duration and numbers that combine into the total amount of activity. This theory suggests that as intensity increases, numbers might even diminish.

It is thus suggested that tropical storms, and hurricanes in particular, play a unique role in the overall heat budget by cooling the ocean and providing a relief valve for the buildup of heat that would otherwise occur. Hence they should also play this role as the climate changes, and inability to represent such storms in climate models provides good reasons to be skeptical of some climate model results.

2. RELEVANT OBSERVED CLIMATE CHANGES

The basic concept is that we are dealing with slow but steady increases in greenhouse gases

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[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Kevin E. Trenberth, NCAR, P.O. Box 3000, Boulder, CO 80303; email: trenbert@ucar.edu that are certainly caused by human activities (IPCC 2001); see Fig. 1 for the increase in annual mean carbon dioxide (updated from Karl and Trenberth 2003). Moreover the climate is changing. In particular, the global mean temperature has increased about 0.75ºC in the last hundred years or so (Fig. 1) (e.g., Jones and Moberg 2003). The global record can be characterized by no change until about 1920, an increase in temperature of 0.3ºC until about 1940, a slight decrease of 0.1ºC until 1970, and a fairly linear increase since then of 0.55ºC. The warmest year on record remains 1998, as warming was enhanced by the major El Niño event then, followed closely by 2005, 2002, 2003 and 2004. Global sea surface temperatures (SSTs) have meanwhile increased 0.67±0.04ºC (Rayner et al. 2005; Smith and Reynolds 2005), where this is based on low-pass filtered data, not a linear trend.

Although increases in atmospheric temperature over land, and especially over the northern continents are somewhat larger than over the oceans, global SSTs have also increased by over 0.5ºC since 1970 (Rayner et al. 2003; 2005). In the tropics, the region relevant for hurricanes, the SST increase in the past few decades is also clear (Fig. 2) and the value is close to 0.5ºC since about 1970. A linear trend fit for 1970 to 2004 for tropical SSTs between 20ºN and 20ºS gives 0.50±0.25ºC.

Ocean temperatures have also warmed at depth (Willis et al., 2004), and global sea levels rose 15-20 cm over the 20th Century, with some evidence of an accelerating rate in the past decade (3.0 cm) (e.g., Cazenave and Nerem 2004; Lombard et al. 2005). As the oceans warm, seawater expands and sea level rises, but glacier melt also contributes. Hence the rise in SSTs is supported by storage of heat within the ocean.

These changes have been definitively linked to increases in greenhouse gases in the atmosphere, most notably carbon dioxide, which has increased 32% in the past century, and half of that increase has occurred since 1970 (Fig. 1) (e.g., IPCC 2001; Meehl et al. 2004; Barnett et al. 2005; Hansen et al. 2005). This increase is from human activities and especially the burning of fossil fuels.

Of particular relevance for storms is total column water vapor amounts in the atmosphere, which have increased over land, but not as uniformly as over the oceans (Trenberth et al. 2005). Over the oceans, where the relationship is more straightforward owing to the constantly wet surface underneath, both the spatial patterns of trends and temporal variability of total column water vapor (precipitable water) are strongly and significantly correlated with SSTs. In this domain, the Special Sensor Microwave Imager (SSM/I) Version 5 dataset from Remote Sensing Systems (RSS) has credible means, variability and trends for the oceans but it is available only for the post-1988 period (Trenberth et al. 2005). The evidence from SSM/I for the global ocean suggests that recent trends in precipitable water are generally positive and, for 1988 through 2003, average 0.40±0.09 mm decade^{-1} or 1.3±0.3% decade^{-1} for the ocean as a whole, where the error bars are 95% confidence intervals. Nevertheless, the regression relationships with SST are sufficiently strong that there is good confidence in extending the record based solely on the SSTs. Trenberth et al. (2005) find that the regression coefficient is 7.83±0.1% per K SST for 30ºN-30ºS or 8.87±0.1% K^{-1} for the global ocean, where the main amplification appears to come from sea ice changes in the North Atlantic.

Note that the nonlinear relationship governing the water-holding capacity of the atmosphere, the Clausius-Clapeyron equation, suggests for the conditions in the lower atmosphere, there is about a 7% per K change (Trenberth et al. 2003). The exponential relationship is accounted for by using the % change rather than units of mm. The small difference in the empirical observed value versus the theoretical value can be accounted for by the difference between SST and lower atmospheric temperatures, which increase in magnitude of variability with height (Santer et al. 2005). Hence the observed changes are consistent with the assumption of fairly constant relative humidity. Since 1970 the inferred increase in precipitable water over the oceans, therefore, is 3.9% where we used the regression based on 30°N to 30°S.

Increases in water vapor feed heavier precipitation in storms. Observations clearly reveal increases in heavy rains 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), often at the expense of more moderate rains and even in places where amounts are declining. Increased intensity of precipitation further implies stronger latent heating and perhaps increases in intensity of weather systems.

3. ENERGY & WATER IN TROPICAL STORMS

There is typically a huge mismatch between evaporation rates and precipitation rates in storms except where precipitation is light. One exception is rapid cyclogenesis off the East Coast of the

United States where surface latent heat fluxes exceed 1500 W m^{-2} for very short times (e.g., Nieman and Shapiro 1993), equivalent to order 50 mm/day evaporation (but typically occurring for only a few hours). Are hurricanes another exception? Evaporation from high SSTs above about 26.5ºC helps fuel the storm along with larger-scale moisture convergence as it spirals into the storm (e.g., Krishnamurti et al. 2005) as part of a larger-scale overturning circulation. The relative proportion of local evaporation vs moisture transport into hurricanes is evaluated below for some case studies.

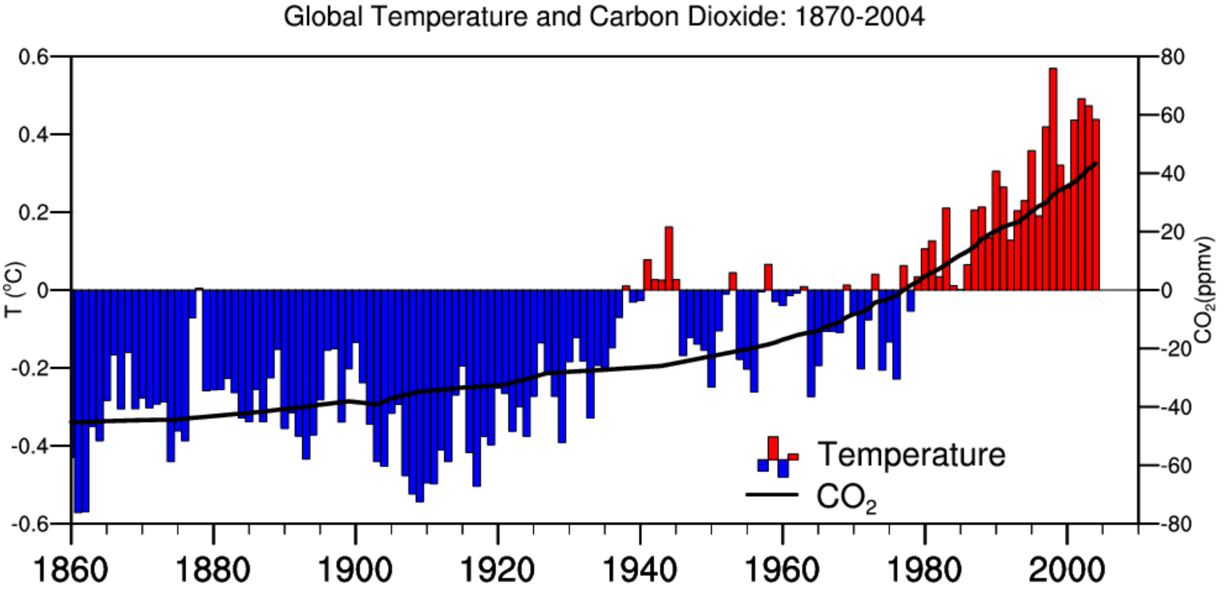
Global Temperature and Carbon Dioxide: 1870-2004

Fig. 1. Time series of annual global mean temperature departures from a 1961-90 mean (bars), left scale, and the annual mean carbon dioxide from Mauna Loa after 1957 linked to values from bubbles of air in ice cores prior to then. Updated from Karl and Trenberth (2003).

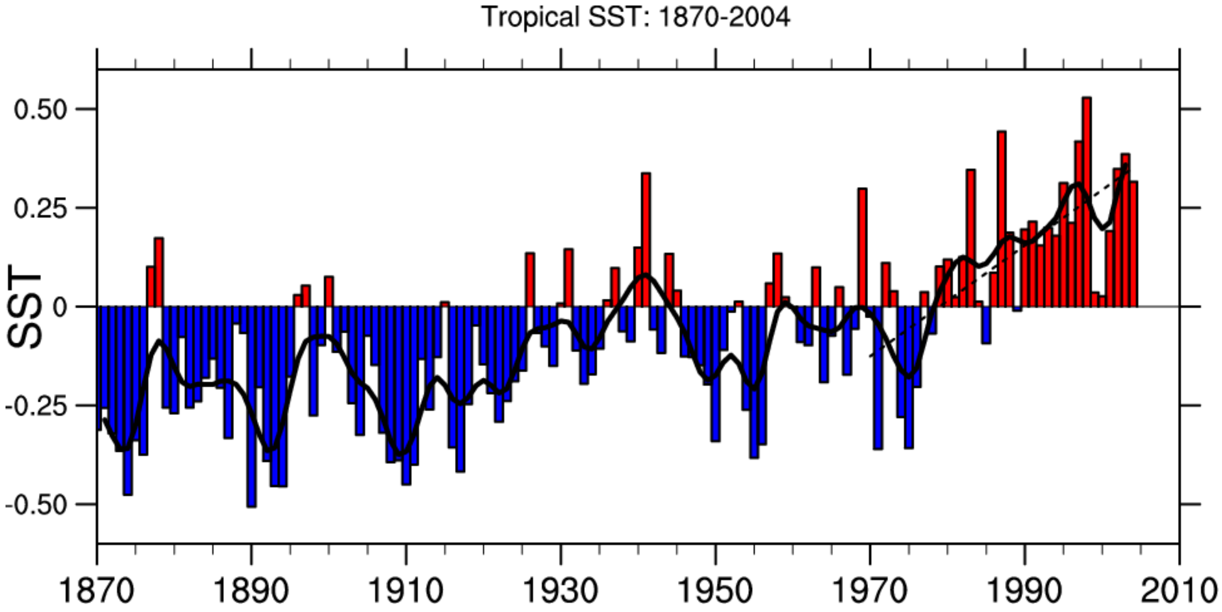
Tropical SST: 1870-2004

Fig. 2. Annual tropical SSTs for 20ºN to 20ºS along with a low pass filter and the linear trend since 1970 in ºC.

The most definitive climatology of rainfall in hurricanes comes from Tropical Rainfall Measurement Mission (TRMM) estimates (Lonfat et al. 2004). They show that average rain rates are 11 to 13 mm/h from the eye to 50 km radius for category 3-5 hurricanes, dropping to 7 and 3 mm/h at 100 and 180 km radii. On average for cat. 1-2 hurricanes the peak values are 6 to 7 mm/h. Over land in a major hurricane like Katrina, rainfalls exceed 12 inches (300 mm) in spots >4 inches (100 mm) over a 100 mile swath north from New Orleans, and 2-3 inches (50-75 mm) over a wide swath from the Gulf Coast to Canada.

We are unaware of reliable estimates of evaporation in hurricanes, and measurements do not exist in winds above about 20 m s^{-1}. Nonetheless, we can evaluate the surface fluxes of moisture in hurricane model simulations and forecasts and assess the relative contributions in the model framework.

4. CASE STUDIES USING WRF

The Weather Research and Forecasting (WRF) model (Michalakes et al. 2001), 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. The WRF avoided the use of a cumulus parameterization by using a 4-km grid and treating deep convection and precipitation formation explicitly using a simple cloud scheme in which cloud water, rain and snow were predicted variables. Results with more sophisticated schemes show similar results concerning fluxes and precipitation. The surface layer formulation utilized the bulk aerodynamic formulations in which the drag and enthalpy coefficients are a specified function of surface wind speed. The boundary layer scheme was a first-order closure scheme, meaning that turbulence is diagnosed entirely in terms of grid-scale variables (Noh et al. 2001).

The WRF simulations were initialized from the Global Forecast System (GFS) on a 1ºx1º grid from the National Centers for Environmental Prediction (NCEP). However, WRF was able to spin up a highly realistic structure in about 12 h, as seen from the fluctuations in intensity (Fig. 4) for hurricane Ivan. In many cases the forecasts of track and intensity have been excellent for more than 48 hours in advance.

Examination of surface latent heat fluxes in several major hurricanes simulated by the WRF model revealed peak fluxes between 800 and 1200 W m^{-2} (27.6 to 41.4 mm/day or 1.15 to 1.73 mm/h). These storms were Ivan and Frances from 2004 and Katrina and Rita from 2005. Peak rainfall rates were generally consistent with the Lonfat et al. (2004) climatology, averaging approximately 8-15 mm h^{-1} in the eye wall region (30-70 km radius). Thus even for hurricanes, where the surface evaporation rates in the model are 5 to 10 times the background rates, rainfall amounts are greater by an order of magnitude in the inner part of the storm.

Results for Ivan are now detailed further for one particular simulation. Hurricane Ivan occurred in September 2004 and Fig. 3 shows the forecast path and actual track of Ivan. The background field of SST for the same interval partly reflects the cold wake left behind Ivan, with SST cooling of 3-7°C in two areas along Ivan's track, as shown by Walker et al. (2005). The lower boundary condition for the model was for SSTs all between 302 and 303K throughout the integration in the neighborhood within 360 km of the eye.

To examine the storm, we use a coordinate centered on the eye of the storm, and generate statistics for the radial mean, such as those given in Figs. 4 and 5. The wind velocity is detailed in Fig. 4 for the tangential and radial components, and the latter is typically an order of magnitude smaller except very locally in the vicinity of the eyewall. Note that the first 12-hours are the main time when the storm is spinning up from the coarse resolution input initial state.

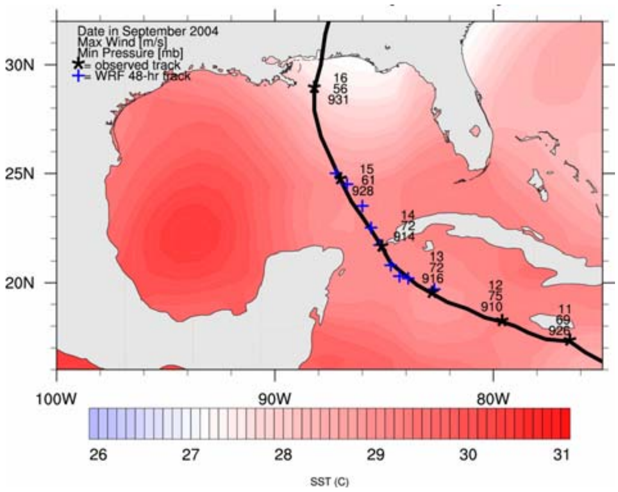

Fig. 3. Hurricane Ivan track September 11-16 2004 along with mean SST for the same period. The dates are given along with maximum wind in m s^{-1} and central pressure in hPa. At landfall, 16 September, Ivan was a category 3 hurricane, with 130 mph sustained winds and a central pressure of 943 mb. Forecast locations from WRF are given by blue crosses.

The moisture budget of the storm, as seen by the precipitation and surface latent heating (or moisture) fluxes (note that 29 W m^{-2} latent heat flux corresponds to an evaporation rate of 1 mm/day) (Fig. 5), allows the large-scale bulk flow of moisture to be diagnosed. Integrated from the center outwards to 120, 240 and 360 km radii produces values given in Table 1 as energy units. For 0–240 and 360 km for the 12 to 48 hours simulation, the ratio of precipitation to surface moisture flux is 8.3 and 5.7, respectively. The surface latent heat flux falls off from the eye and, relative to the circle 0-120 km radius, values drop per unit area by about factors of 1/3 and 2 for the 120-240 km and 240-360 km annulus areas; the reason the values increase in Table 1 is because the annulus areas increase by factors of 3 and 5. However, even though the drop off is much sharper for precipitation (about factors of 4 and 12 per area), one still has to integrate out to over 1600 km radius to obtain a rough balance.

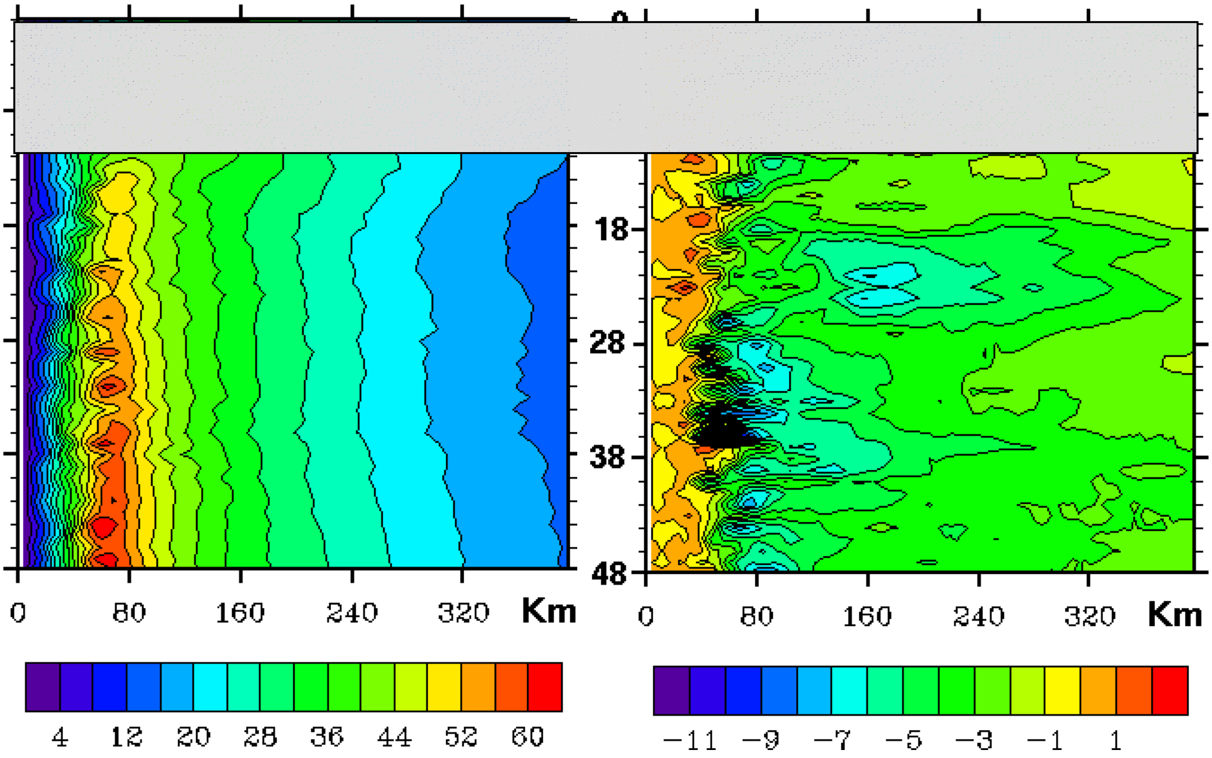

Fig 4. For Hurricane Ivan, given as a function of time throughout the 48 forecast starting 0000 UTC September 13, 2005, are radial means from the eye of tangential (left) and radial (right) velocity in m s^{-1}.

Table 1. Hurricane IVAN: September 13, 2004: 48 hour forecasts with WRF @4km resolution initialized from global analyses. Precipitation (left) and latent energy (right) (moisture) budget quantities integrated radially to 120, 240 and 360 km radius for times of 12, 24, 36 and 48 hours. All fields in units of 10^{14} Watts. Below the total for 24 to 48 hours is given, along with the ratio of precipitation to latent heat flux.

Precipitation

Annulus	0-120	120-240	240-360	0-360 km
12	1.50	2.81	4.48	8.79
24	4.16	4.58	1.43	10.18
36	4.52	2.60	2.02	9.14
48	3.33	4.50	1.64	9.47
Total 24-48	4.00	3.89	1.70	9.60

Surface Latent Heat Flux

Annulus	0-120	120-240	240-360	0-360 km
12	0.28	0.80	0.76	1.84
24	0.28	0.67	0.74	1.69
36	0.30	0.64	0.73	1.67
48	0.29	0.65	0.80	1.74
Total 24-48	0.29	0.65	0.76	1.70

Ratio (0-240 km) 8.34; (0-360 km) 5.65

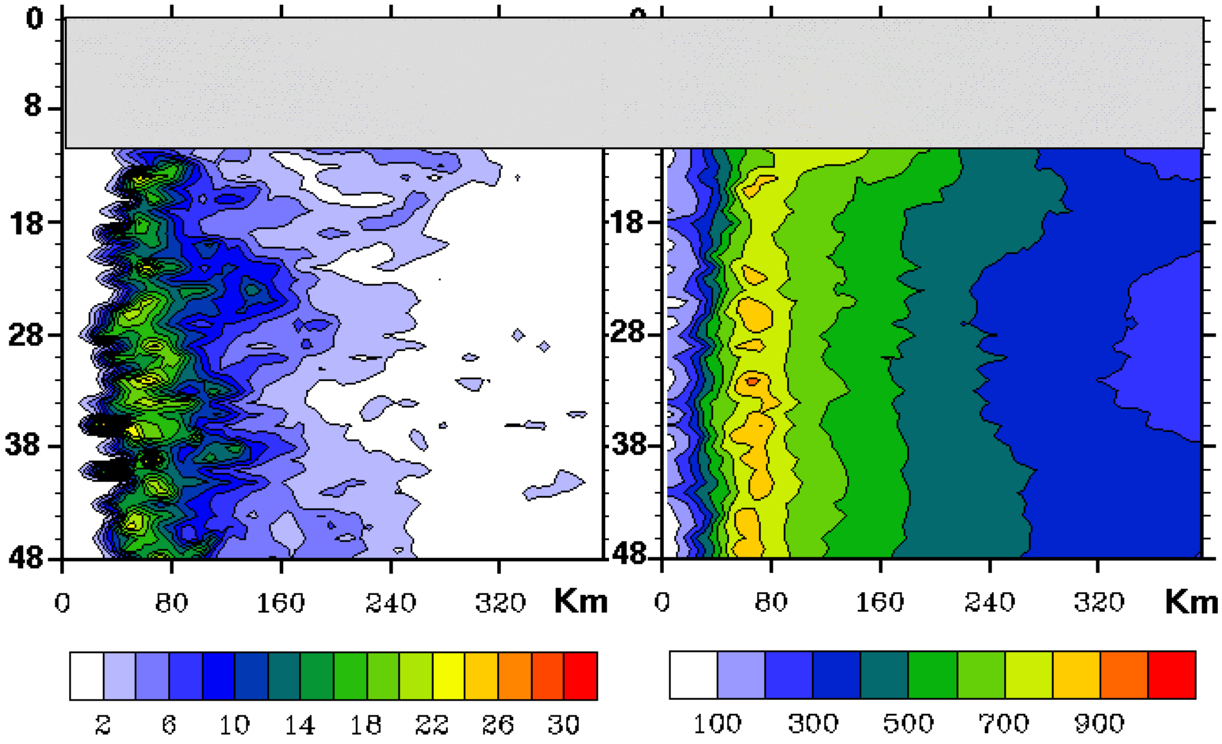

Fig. 5: For Hurricane Ivan, given as a function of time throughout the 48 forecast starting 0000 UTC September 13, 2005, are radial means from the eye of hourly rain rate mm/h (left) and surface latent heat flux W m^{-2} (right). Note that 700 W m^{-2} corresponds to 1 mm/h. The 12-hour spin-up period is shaded.

5. GLOBAL WARMING IMPACT ON STORMS

We have argued above that the broad trend in global increase in surface air temperature and SST since about 1970 is due to increases in greenhouse gases from human activities. Variations occur from year to year associated with natural variability, such as El Niño. For 1970 to 2004 tropical SSTs rose 0.50±0.25ºC and the increase in water vapor over the oceans of 3.9±2.0% is the main source of storm moisture.

It is now argued that the transient flux of moisture and thus latent energy into the atmosphere increases at least at a comparable rate during the course of the storm. The simplified bulk flux formula gives the evaporation as

$$E = \rho C_L V(q_s(T_s) - q_s(T)) = \rho C_L V q_s(T_s)(1\text{-}RH)$$

where C_L is the exchange coefficient, ρ is the density, q is the specific humidity at temperature T or T_s=SST, RH is the relative humidity, and V is the wind speed. Because the relative humidity is observed to not change much, a dominant dependency for E is the saturation specific humidity q_s at the SST which is governed by Clausius Clapeyron. Hence for transient changes, E is likely to go up about 6% per K rise in temperature. Moreover, this is converted to enhanced precipitation at the same rate, given the same boundary layer mass convergence. But then the extra latent heat has to be compensated for by adiabatic cooling as the air rises and thus it increases upward motion overall by the same amount. This means there should also be an increase in convergence of winds into the storm by a similar amount that in turn may carry more moisture into the storm (however, it may not be at the surface). This refers only to the radial component of velocity v_r, which is order 10% or less of the tangential velocity (Fig. 4). Hence, we argue that moisture transport $v_r q$ could have experienced average enhancements since 1970 of both v_r and q by order 3.9%, so the total increase could be about 7.8% (coming from 1.039^2), which corresponds to the potential increase in rainfall in the storm, with 3.6 to 11.8 % as the 95% confidence limits.

Whether or not the intensity of the storm is affected depends on the covariability of the temperature perturbations and the latent heating, and this will depend on the large-scale dynamics of the storm and atmospheric structure. Short-term fluctuations in intensity arise from complex processes such as eye-wall replacement and are not well understood or predicted. Various other feedbacks also kick in, and many other processes are known to be important, such as the stability changes, changes in sea spray, frictional effects, cold wake effects on SSTs, and so on. So the net effects could easily be greater or smaller, and likely vary in sign depending on whether the storm is developing or not.

Emanuel (1988) estimated a sensitivity of the central pressure in the eye as being –6 hPa K^{-1} of SST. In summarizing understanding of hurricanes and climate, Emanuel (2003) notes that increases in greenhouse gases in the atmosphere are likely to require a greater turbulent enthalpy flux out of the ocean (largely in the form of greater evaporation), and has found with a simple model that potential maximum winds would increase by about 3.5 m s^{-1} for each 1°C increase in tropical SSTs. Our estimate is reasonably consistent [for a cat. 1 (wind speeds 33 to 43 m s^{-1}) or cat. 2 hurricane (43 to 50 m s^{-1}), 3.5 m s^{-1} is order 8%]; the arguments here focus on the thermodynamic aspects.

There are uncertainties that may be better pinned down with further numerical experiments, but the key point is that the value is not negligible, and nor is it large enough to dominate over the natural processes already in place. Nevertheless it may well enhance flooding that can breach levees designed without this in mind (the straw that breaks the camel's back).

Observed and potential changes in hurricanes with global warming are discussed in detail in Trenberth (2005), Emanuel (2005) and Webster et al. (2005) who show that intense storms are observed to be increasing and lasting longer, in line with theoretical and modeling expectations. The main fuel for hurricanes is the latent heat release in convection acting collectively and organized by the hurricane circulation to drive the storm (Krishnamurti et al. 2005). 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 2005). Future research can help to quantify these aspects. An unanswered question is how many of the hurricanes will make landfall and where. Nevertheless, the environmental changes related to human influences on climate have very likely changed the odds in favor of more intense storms and heavier rainfalls, and here we suggest that the latter can be approximated to be order 4 to 12% with a central value of about 8% since 1970.

While a lot of attention has recently been focused on the North Atlantic record breaking 2005 hurricane season, tropical storms in the N. Atlantic constitute only 11% of the total on average. 33% of the storms occur in the Southern Hemisphere, with 21% in the southern Indian Ocean and the rest in the Australian and South Pacific region, except for March 2004 when Catarina (Pezza and Simmonds 2005) surprised everyone in the South Atlantic off the coast of Brazil. With Vince making landfall in the Iberian Peninsula in 2005 for the first time, the evidence is mounting for expanded domains and more intense storms, nourished by global warming.

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