The Influence of Tropical Cyclones on Climate and the Possible Application to Equable Climates

12.842 Climate Physics and Chemistry
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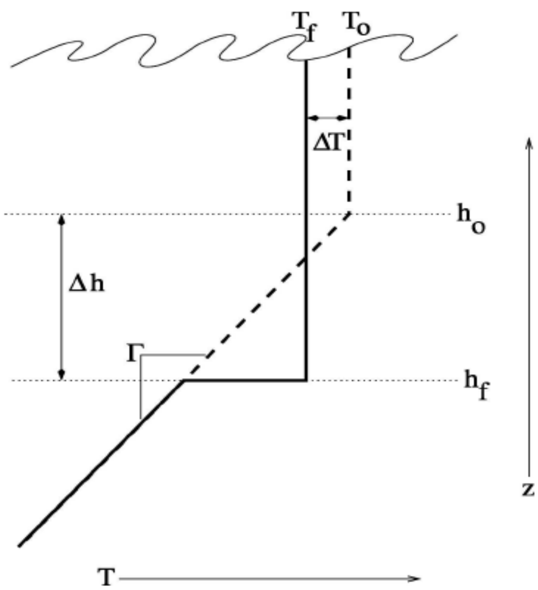
Tropical cyclones are undoubtedly among the mostly deadly and destructive natural phenomena found on Earth today. Over the past hundreds of years, hurricanes have altered our landscapes and changed history. While tropical cyclones are capable of great destruction, they may also be important drivers of the global heat budget and have a role in maintaining the stability of the climate in the tropics. Poleward heat transport driven by tropical cyclone-induced mixing has been suggested as an explanation for the equable nature of past warm climates. This paper will discuss the mechanisms by which tropical cyclones influence climate and the possible application of this to equable climates.

Just as the environmental conditions have an enormous influence on the evolution of a tropical cyclone, a tropical cyclone has a profound impact on its environment. The most obvious impact is that the intense precipitation resulting from tropical cyclones takes a lot of water out of the atmosphere and drops it on the surface. This could have implications for climate, in that the storm is effective at drying out the atmosphere, and therefore removing a powerful greenhouse gas (water vapor). The strong winds of a tropical cyclone also cause vigorous mixing in the upper ocean. This mixing of warm surface waters with colder waters below has the effect of deepening the ocean mixed layer. It creates anomalous cold waters at the surface and anomalous warm waters at the bottom of the mixed layer. The top figure on the next page depicts this (Korty and Emanuel, 2008). Satellite observations confirm the cold wake due to the passage of a hurricane (see bottom figure on next page, which shows the sea surface temperatures after the passage of Hurricane Edouard (Emanuel, 2001)).



This figure shows the vertical temperature structure of the upper ocean before (dashed) and after (solid) the passage of a tropical cyclone. (Korty and Emanuel, 2008)

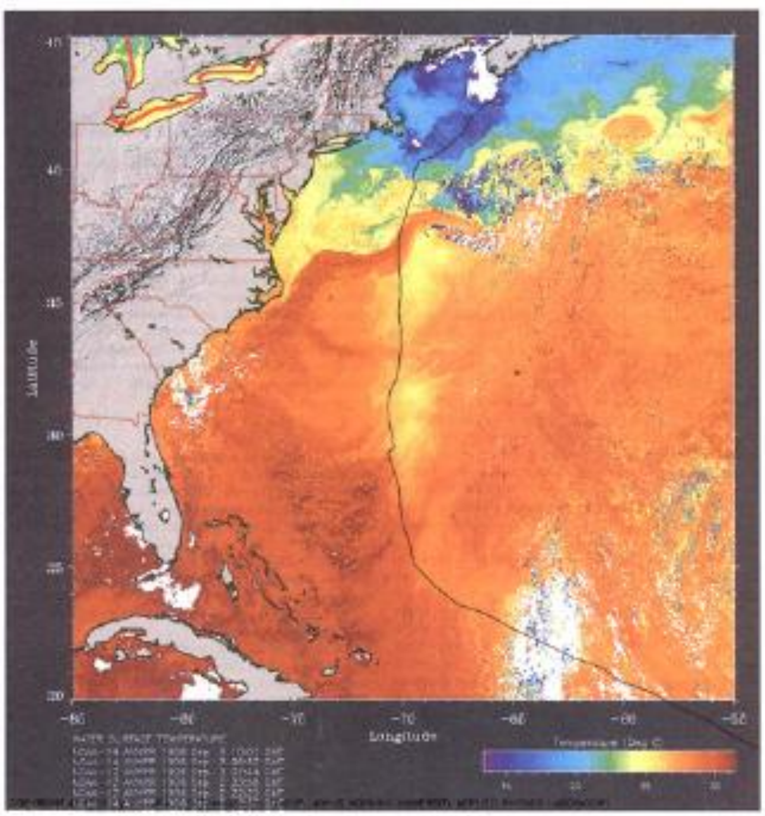


Plate 1. Satellite-derived water surface temperature shortly after the passage of Hurricane Edouard in 1996. Storm center track indicated by thin black line. Courtesy of the Johns Hopkins University Applied Physics Laboratory.

This figure shows the satellite derived sea surface temperature shortly after the passage of Hurricane Edouard in 1996. The track of the storm center is indicated by the black line. There is clearly cooling of the sea surface along the track, with the most intense cooling to the right of the storm track. (Emanuel, 2001)

Colder sea surface temperatures could cause a negative feedback on the intensity of the hurricane, but there is also a possible impact from the climate standpoint. The basic hypothesis is that the cold wakes left by a passing hurricane recover due to mixing and surface fluxes, which is associated with a net vertically integrated heating of the water column. Emanuel (2001) suggested that in statistical equilibrium, this must be balanced by a lateral heat flux away from the regions affected by the hurricane's passage.

The mechanism by which hurricanes mix the upper ocean was described by Price (1981) as an excitation of inertial oscillations in the ocean because of the horizontal scale and translational speeds associated with a hurricane. Price (1981) showed that about 85% of the surface cooling results from entrainment, which arises from turbulence associated with vertical shear of ocean currents across the bottom of the mixed layer. The ocean internal wave field is excited with an energy distribution capable of being transferred across the wave spectrum to the small dissipation scales of diapycnal mixing. Small scale turbulence mixes the colder thermocline waters below into the mixed layer, cooling it and warming the upper thermocline. This mixing redistributes enthalpy in the vertical. The amount of cooling at the surface depends on the intensity of the hurricane, its speed, the initial depth of the mixed layer, and the temperature gradient of the upper thermocline (Price, 1981).

The mixing of the upper ocean by tropical cyclones doesn't directly cause a net change in enthalpy; it merely redistributes it in the water column. However, the cold wake recovers to approximately the temperature it was before the passage of the tropical cyclone, which requires a certain amount of heating. Under normal conditions, there is a large downward flux of IR radiation from the atmosphere into the ocean, which is balanced by a small IR flux out of the ocean and a large latent heat flux out of the ocean.

The latent heat flux is driven by evaporation of the ocean water, because the atmosphere is usually subsaturated in the tropics (typical relative humidities are around 80%). After a hurricane passes and causes turbulent mixing, the upper ocean is now colder. There is no longer the latent heat flux out of the ocean, but there is still the large downward IR flux from the atmosphere into the ocean. The small IR flux out of the ocean can't balance this, so there is disequilibrium between the ocean and that atmosphere, which causes a net enthalpy increase in the ocean column. As noted above, Emanuel (2001) hypothesized that this heating must be balanced by lateral heat transport out of the regions affected by the hurricanes, in the long term. Calculations of the magnitude of this heating were performed to asses its importance relative to the total poleward heat transport by the oceans. Emanuel (2001) estimated that an average net heat input rate of $1.4 \pm 0.7 \times 10^{15}$ W is required to restore the cold wakes of global tropical cyclone activity, which is on the same order as the estimated meridional heat flux carried by the ocean (2×10^{15} W). Other estimates of the net column heating resulting from tropical cyclone activity include that of Sriver and Huber (2007), who estimated a more conservative 0.3×10^{15} W. However, both these calculations were made assuming that the entire depth of the cold anomaly recovers. Satellite observations clearly show that the sea surface temperatures recover, but in situ measurements are needed to know how the temperature profile of the whole depth of the mixed layer responds. Attempts have been made to infer this using satellite-based sea surface altimetry, based on the premise that the heat uptake increases the elevation of the sea surface during the recovery of the cold wake. Analysis of sea surface height anomalies from satellites show that the sea surface rose about 5 cm due to the wake recovery of Hurricane Edouard, as an example. This change in elevation corresponds to a heat uptake that, when integrated over the area of the wake and the number of events globally per year, gave an average rate of induced heat uptake of about 1×10^{15} W (Emanuel 2008). This is consistent with earlier estimates, indicating that the entire depth may recover.

The implications of this for climate depend on several factors. The concept that the column-integrated heating due to vertical turbulent mixing must be balanced by a lateral heat flux (in equilibrium) makes sense, but this type of reasoning usually applies to some sort of broadly distributed mixing. The type of mixing induced by tropical cyclones, however, would be spatially and temporally isolated, since tropical cyclones themselves are spatially localized and temporally isolated. However, Boos et al (2004) showed that transient mixing, with a distribution similar to that which would be expected if tropical cyclones were the cause, can successfully drive a meridional overturning circulation. If this is true, long term variations in poleward heat flux by the ocean (and therefore regulation of climate), would be affected by long term variations in net global tropical cyclone activity. This brings up the issue of how global tropical cyclone activity responds to climate change, an issue that has received a lot of attention over the last couple of years and a great deal of debate. There is evidence that tropical cyclone intensity would increase in a warmer climate (Emanuel 2005, 2006). Model simulations of tropical cyclones with initial environmental conditions provided by global climate models and techniques of downscaling global climate models to infer tropical cyclone activity indicate several tendencies under global warming. They indicate, generally, that tropical cyclone frequency would decrease but intensity would increase. (e.g., Emanuel 2008, Emanuel et al 2008). These results, however, vary greatly from model to model and also between ocean basins, so there is still much uncertainty.

If net global tropical cyclone activity were to be enhanced in a warmer climate, this would increase the amount of upper ocean heating caused by tropical cyclone-induced mixing. This would in turn increase the poleward heat flux out of the tropics. It is in this way that the effect of tropical cyclones on climate may have an application to equable climates. An equable climate is one in which there is a reduced meridional temperature gradient, meaning that the climate doesn't vary much between the tropics and the poles, or at least not as much as it does today. A particularly puzzling example of an equable climate is the Eocene (55 to 34 million years ago). Until very recently, all the paleoclimate proxy data indicated that middle to high latitudes were much warmer than today while tropical sea surface temperatures were close to what they are currently, causing a low meridional temperature gradient (Greenwood and Wing, 1995). There is evidence that the continental interiors had climates with much higher winter temperatures than they do today, with freezing only north of 60N. The meridional temperature gradients were less than half of what they are today for the interior of North America (Greenwood and Wing, 1995). However, climate models have been unable to simulate these conditions, requiring much higher temperatures in the tropics than paleoclimate proxy data suggested in order to model the warmth in high latitudes (Huber, 2008). The inability of the models to simulate the temperature gradients seems strange at first, because it is known that high latitudes are especially sensitive to a climate forcing, which seems to indicate that a climate forcing could decrease the gradient between tropical temperatures and high latitude temperatures. However, the sensitivity of high latitudes to climate forcing in models results largely from the ice-albedo feedback, and since equable climates were nearly ice-free, this feedback would not have such a large effect (Farrell, 1990). Thus, the inability of models to simulate equable climates implies that there is something missing in the models or something wrong with the data. There are many hypotheses that attempt to explain the conditions of equable climates such as that of the Eocene.

One of the proposed mechanisms to maintain the weak meridional temperature gradient is that increased tropical cyclone activity in the warm Eocene enhanced the poleward transport of heat, as discussed above. Korty et al. (2005) investigated the viability of this mechanism by using a coupled model to ascertain whether tropical cyclones-induced mixing of the upper ocean was sufficient enough to cool tropical temperatures and drive a stronger poleward ocean heat flux during warm climates. They found that high carbon dioxide levels caused a reduction of the meridional temperature gradient and surface warming, but also showed that increased mixing in the upper ocean in the tropics increased the poleward ocean heat flux. This leads to an increase in mid-latitude temperatures and a reduction of tropical temperatures. Korty et al (2005) also developed a parameterization to represent mixing from tropical cyclones and showed that this increases when radiative forcing increases greatly (i.e. in a warm climate). Despite this evidence for tropical-cyclone induced mixing of the upper ocean as a plausible mechanism for explaining equable climates, the question is far from answered. There are several problems with the theory, some of which were already mentioned above. First of all, it isn't entirely clear exactly how tropical cyclone activity would be different in different climates. There are large variations in the predictions from the models and in the different ocean basins, and since the mechanism for maintaining a weak meridional temperature gradient in a warmer climate requires that tropical cyclone activity, (and therefore the mixing and heat transport it causes), is enhanced, this is an important issue. The theory also assumes mixing occurs over some depth and not just at the surface, and also that the entire depth recovers. While sea surface altimetry provides some evidence that this is the case, direct measurements are needed to be sure. In addition, the vertically integrated column heating isn't necessarily transported to high latitudes. Some portion of this could be given off to the subtropical atmosphere the following winter when the atmosphere has cooled. If this was the case, the mixing due to tropical cyclones could still be important for climate, because heat can be transported via either the ocean or the atmosphere, or both. Finally, there are many other hypotheses that attempt to explain the conditions of equable climates such as that of the Eocene, and one of those might be more viable. Several of these hypotheses are described briefly below.

One suggestion for explaining equable climates is that major climate change results from changes in the poleward heat transport due to changes in the global circulation. Farrell (1990) suggested that changes in the symmetric circulation (a Hadley cell that stretched from the equator to the pole) maintained a nearly constant temperature over global space scales. He described a scenario in which more angular momentum loss in the poleward branch of the Hadley circulation reduced the meridional temperature gradient, the mechanism for which was an alteration of the radiative-convective structure of the atmosphere. Another possible explanation for equable climates is interactions with the stratosphere. Sloan et al. (1992) suggested that increased concentrations of methane provided a source for stratospheric water vapor. This would allow thick clouds to form in the polar stratosphere, which would cause surface temperatures at high latitudes to increase substantially. Kirk-Davidoff et al. (2002) suggested that the weaker meridional temperature gradient found in equable climates created conditions favorable for polar stratospheric clouds. Korty and Emanuel (2007) further investigated whether the state of the winter stratosphere was a function of surface temperature, and found that changes in just the surface temperature gradient were insufficient to alter winter stratospheric temperatures, although they could be altered by other factors. Yet another hypothesis for the equable climate problem is that it is the result of a stable, positive Arctic Oscillation. Sewell and Sloan (2001) hypothesized that low pressure over the Arctic Ocean reduced the sea ice in the Arctic Ocean, and coupled with high pressure at 45N, increased the mid-latitude westerlies which increased advection of warm, moist air over the Northern Hemisphere continents, therefore warming their interiors. Another high-latitude explanation is that of Abbot and Tziperman (2008), who argued that high tropospheric clouds due to high-latitude deep convection cause a positive radiative forcing. This has a strong positive feedback on increases in high-latitude surface temperature. They also argued that winter convection depends on a sea ice-free ocean, but also helps keep the oceans sea-ice free.

A final possibility is that the Eocene was not quite as equable as previously thought. Recent paleoclimate proxy data indicates that the tropical temperatures in the Eocene were much warmer than previous data indicated (Pearson et al, 2001; Huber, 2008), which means that the meridional temperature gradient would be much closer to that of today. According to Huber (2008), efforts to develop better proxies and calibrations indicate that the warmest Eocene tropical SSTs were in the "35°C to 40°C range, not the 28°C to 33°C range published in 2007, or the 25°C to 30°C range as thought a decade ago, or the 20°C or 25°C range accepted two decades ago." This indicates that maybe there is no mechanism that moderates tropical SST's and maintains a weak meridional temperature gradient, and that the inability of models to simulate equable climates is because there really wasn't such a weak temperature gradient; the data was wrong. However, these important conclusions are a lot to base on just the few new proxy records; they may not be entirely accurate either. Clearly, this issue is not yet resolved.

In conclusion, the influence of tropical cyclones may stretch far beyond the destruction they cause in the short term. Tropical cyclone induced mixing of the upper ocean causes a cold wake along the storm path. Recovery of this cold wake to pre-storm conditions requires a net increase in the vertically integrated enthalpy of the layer of sea water affected by the storm. In statistical equilibrium, this must be balanced by a lateral heat flux away from the region of tropical cyclone activity. Several studies have shown that this could be a viable way to drive poleward heat transport. The application to equable climates comes from the fact that enhanced tropical cyclone activity in a warmer climate would cause increased poleward heat transport, leading to a cooling effect in the tropics and a warming effect in mid-high latitudes, which would maintain a weak meridional temperature gradient. While this is a possible explanation for equable climates, the question is not yet resolved for several reasons, one being new data indicate past climates previously thought to be equable in nature may actually have had warmer tropical sea surface temperatures than though. There is also uncertainty in how tropical cyclone activity would change in a warmer climate, and there are a large number of other possible explanations for equable climates. Nevertheless, there is at least the potential for tropical cyclones to have a large effect on climate, a factor that should be taken into account when thinking of future climate change.

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