Hurricanes and Climate

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Hurricanes[1] are the most lethal and destructive wind storms on our planet, taking thousands of lives and causing many billions of dollars in damage every year. Some 90 of these storms occur around the world every year; Figure 1 is a map showing their paths over a 21-year period. Although only about 12% of the hurricanes occur in the Atlantic, they receive by far the most attention because of poor adaptation to them by the United States and by many Caribbean nations.

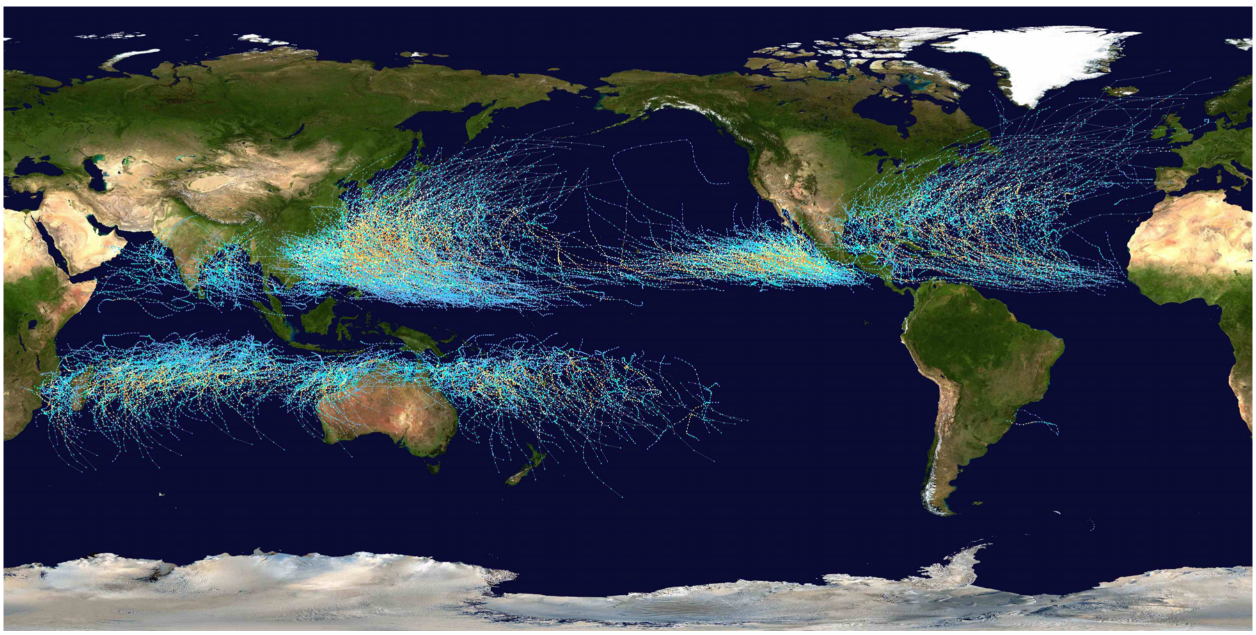

Figure 1: Tracks of all tropical cyclones during the period 1985-2005. Coloring indicates maximum wind speeds, with blue being the weakest and red being the strongest categories. Storms generally move westward and poleward, but often recurve toward the east as they mature. Source: Wikipedia.

Because they are so destructive, but also because they play an important role in regulating climate, understanding their control of and by climate is important.

Tropical cyclones are driven by enthalpy (heat) fluxes from the ocean and quickly dissipate after moving over land or cold water. The enthalpy flux from the sea is mostly in the form of a latent heat flux that accompanies evaporation of seawater into the overlying atmosphere. This enthalpy flux is possible because the tropical ocean and atmosphere are not in thermodynamic equilibrium, owing to the presence of greenhouse gases in the atmosphere

[1] "Hurricane" is a regional name given to a general class of storms called "tropical cyclones" when they occur over the North Atlantic or eastern North Pacific oceans and have maximum winds in excess of 32 meters per second. Although "tropical cyclone" is the proper generic term, we shall use "hurricane" here to denote this general class of storm.

that prevent the surface from radiating enough heat to space to balance incoming sunlight. The storms themselves are giant heat engines, converting the enthalpy they acquire from the ocean into wind energy, which is then dissipated in regions of high turbulence near the sea surface, where the winds are very strong. The hurricane heat engine is very efficient, coming close to the maximally efficient thermodynamic cycle discovered by Sadi Carnot and now called a Carnot cycle. The mathematics of this cycle permit one to formulate an equation for the maximum sustainable wind speed in a hurricane, given the temperature of the underlying ocean and of the surrounding atmosphere. This maximum intensity, called the *potential intensity*, is a function of the whole thermodynamic environment, though it is often mistakenly taken to be a function of the sea surface temperature alone. Figure 2 shows the annual maximum potential intensity over the globe. More on the thermodynamics and dynamics of hurricanes is available here.

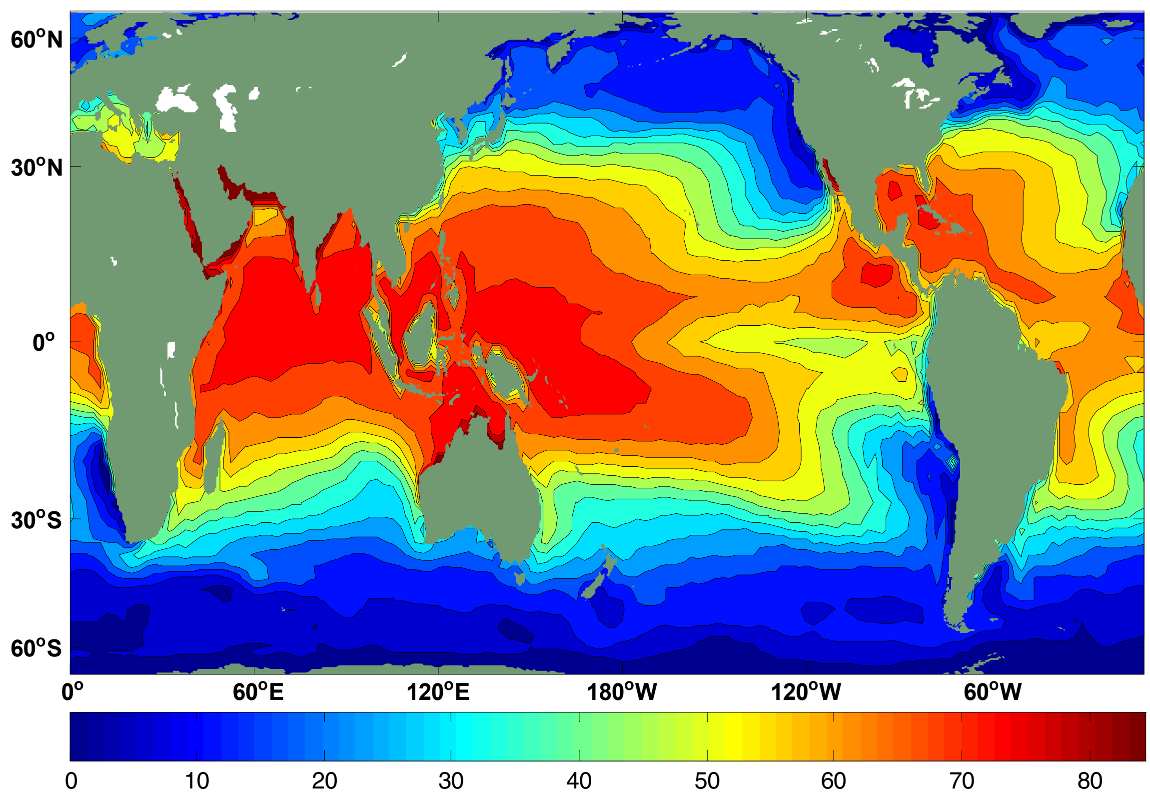

Figure 2: Annual maximum value of the potential intensity, in meters per second, with color scale at bottom. Source: Created by the author.

Comparison with Figure 1 shows that hurricanes always originate where the potential intensity is high. However, they never form within about 3° latitude of the equator, because there is not enough projection of the earth's rotation axis on the local vertical direction to sustain a rotating storm at such low latitudes.

Many environmental factors besides potential intensity affect the formation of hurricanes. These include the variation with the large-scale environmental winds with altitude and the humidity of air from 1 to 6 km above the surface. Nevertheless, variations of hurricane activity on time scales greater than a few years appear to be controlled mostly by variations of potential intensity. These variations are generally accompanied by variations in the ocean temperature, but the relationship is not simple. Figure 3 shows how potential intensity varies in a simple one-dimensional climate model, that simulates only the effects of radiative and convective heat transfer, when two quantities are separately varied in the model: the mean speed of the surface winds, and the amount of carbon dioxide in the atmosphere. The variations of both potential intensity and sea surface temperature are graphed against each other in this figure. As the surface wind speed is reduced, more thermodynamic disequilibrium is required to counter absorption of sunlight by the surface, and so the potential intensity increases. Similarly, when the amount of greenhouse gas increases, more thermodynamic disequilibrium is necessary for surface energy balance. But note that the rate of change of potential intensity with sea surface temperature depends on the physical causes of the variations of each.

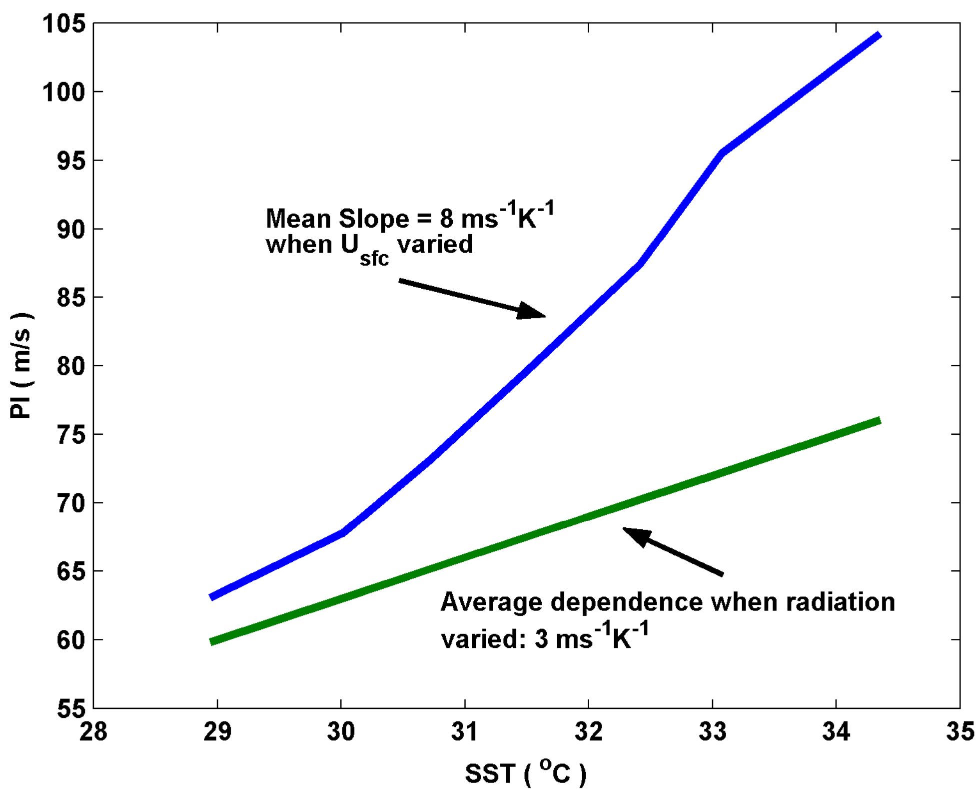

Figure 3: Variations of potential intensity (meters per second) and sea surface temperature (°C) when the mean surface wind speed is varied (blue curve) and when the amount of carbon dioxide in the atmosphere is varied (green line). As one travels up the blue line, the surface wind speed is decreasing, while going up the green curve is associated with increasing greenhouse gas concentration. Source: Created by the author.

While the annual, global number of tropical cyclones appears to have been stable over the past 25 years of robust measurements of this number by satellites, this particular metric is not very meaningful since it includes weak storms that may last a few hours as well as strong storms that may last two weeks and release many orders of magnitude more energy. A better metric is power dissipation, which is just the total amount of kinetic energy dissipated by each storm over its lifetime. Figure 4 shows power dissipation of the North Atlantic hurricanes graphed with potential intensity over the period 1980 to 2007. Each quantity has been filtered to remove most of the influence of fluctuations on time scales of a few years and less. Potential intensity has increased by about 12% over the period 1980-2007, while power dissipation has increased nearly threefold over the same period. This would appear to suggest a sensitive dependence of hurricane power on potential intensity. Potential intensity in the tropical North Atlantic has been increasing over the past quarter century owing to increasing greenhouse gases, slackening surface winds, and a cooling lower stratosphere. (Read more about this here.)

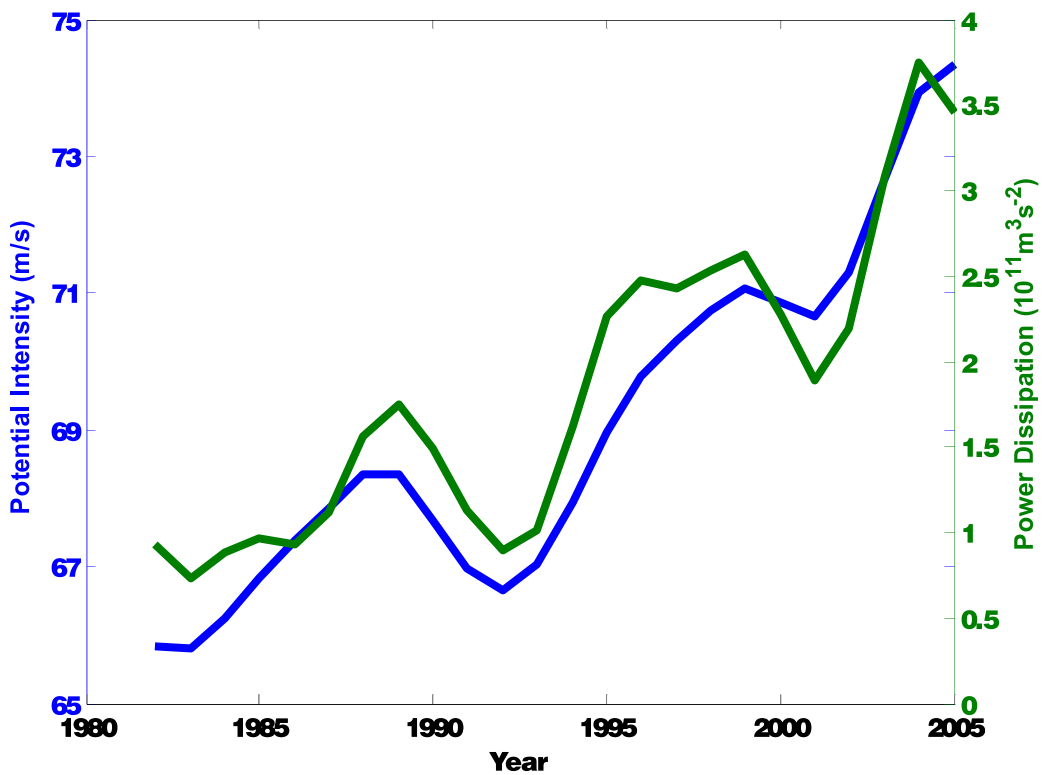

Figure 4: Power dissipation of North Atlantic hurricanes (green) and potential intensity (blue) averaged over the so-called "main development region" of the North Atlantic, 6-18 N and 20-60 W, during the years 1980-2007. The time series have been smoothed using a 1-3-4-3-1 filter than damps variations on time scales of a few years and less. Source: Created by the author.

Much work remains to be done on the complex control of hurricanes by climate. At the same time, there is growing evidence that hurricanes may affect climate itself, through their effects on both the ocean and the atmosphere. You may read more about possible atmospheric effects here, and about effects on the ocean here.

Work on hurricanes involves many different threads of mathematical science. The motion and thermodynamics of fluids are governed by partial differential equations, which depending on the exact nature of the problem, can admit steady, periodic, and/or chaotic solutions. Analytical solutions are often sought for small perturbations to known steady solutions of the equations; for sufficiently small perturbations, these equations are linear and can often be solved analytically. Non-trivial nonlinear solutions are also sought and can sometimes be found analytically, especially for steady flows. Computational mathematics plays an important role in contemporary atmospheric and oceanic science and is used to build models of fluid systems like hurricanes. Advanced statistical methods are applied throughout these fields, in analyzing observations, in characterizing dynamical systems, and in constructing and interpreting large solution sets of chaotic systems.

The science of atmospheres, oceans, and climate is in fact so heavily mathematical that many of the most successful scientists in the field began their studies as mathematicians. The science of hurricanes in particular involves high level mathematics and should be particularly attractive to the mathematically inclined student with an interest in the workings of the natural world.