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TROPICAL CYCLONES AND CLIMATE

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1. INTRODUCTION

Although there has been much research on the effects of climate change on tropical cyclone activity, there has been very little work done on the question of whether or how tropical cyclones (TCs) affect climate. Here I propose that TCs are fundamental agents of climate regulation, through their control of meridional heat transport by the ocean. When included with a few other key feedbacks in a simple two-column coupled climate model, this TC-thermohaline feedback leads to a climate that exhibits multiple, stable regimes. The existence of such regimes could help explain such disparate phenomena as the observed response of the earth's climate to orbital variations, and the very warm climates that prevailed even at high latitudes during the Cretaceous and early Eocene.

2. TCs AND THE THERMOHALINE CIRCULATION

Sandstrom (1908) and Jeffreys (1925) demonstrated that, owing to the fact that there are no substantial heat sources or sinks in its interior, deep overturning of the ocean requires vertical mixing. More recent work (e.g. Scott and Marotzke, 2002) suggests that the poleward heat flux by the ocean, *F*, scales as

$$F \sim P^{2/3} B^{2/3}, \tag{1}$$

where *P* is the power expended in vertical mixing, and *B* is the total difference in buoyancy imposed at the ocean surface. Thus the heat flux is controlled not only by the temperature gradient but by the vertical mixing. Sensitivity studies using the adjoint of a full physics ocean model show that virtually all the sensitivity to vertical mixing resides in the uppermost 200 m of the tropical oceans (Bugnion, 2001). By using observations made in the wakes of TCs together with coupled model simulations, the author (Emanuel, 2001) showed that vertical mixing by TCs can potentially account for most and perhaps all the vertical mixing required to drive the global thermohaline circulation. Since TCs are themselves sensitive to climate, this coupling leads to new and very different climate dynamics.

3. A SIMPLE COUPLED CLIMATE MODEL

As a first step towards exploring the consequences of the dependence of ocean heat transport on global TC activity, the author constructed a simple two-column coupled climate model (Emanuel, 2002). The basic design of the model is illustrated in Figure 1.

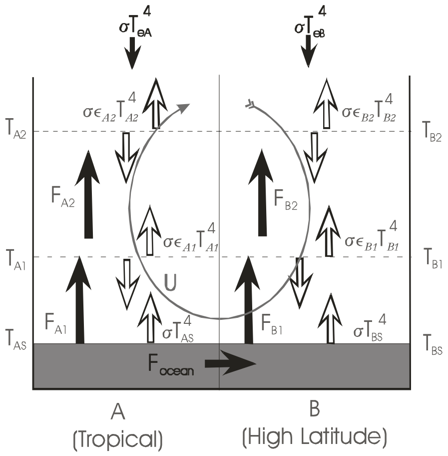

Figure 1: Two-column model. Solid arrows denote radiative fluxes; open arrows show convective fluxes. See text for explanation.

Insolation into each column is specified in terms of effective black body emission temperatures. All solar radiation is absorbed at the ocean surface, whose emissivity is taken to be unity. Radiative fluxes are formulated in terms of bulk emissivities that depend on the amount of water vapor and CO_2 in the column. Convective fluxes from the surface to the first layer and between the layers are formulated to ensure that the temperature lapse rate does not exceed its moist adiabatic value. A large-scale atmospheric circulation transports heat between the columns; its magnitude is calculated to prevent the lateral temperature gradient from exceeding a critical value. The moisture content of each column is calculated from an assumption of fixed relative humidity, except that the relative humidity in the upper poleward box is assumed to decrease in proportion to the circulation strength. The CO_2 content of the atmosphere depends linearly on a weighted mean ocean temperature, so as to match the correspondence between global temperature and CO_2 observed in ice cores. The poleward heat flux in the ocean is assumed to vary as the two-thirds power of the temperature difference between the columns, and the square of the potential maximum wind speed of tropical cyclones, which is determined from the surface heat flux in the tropical column.

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4. RESULTS

Time-dependent equations for the energy balance of each level and the ocean in each box are integrated until a steady state is achieved. This is done for multiple initial conditions, to ensure that multiple equilibria are found if they exist. The calculations are repeated for different relative values of the insolation received by each column. Depending on the relative insolation and parameter values, one, two or three equilibria are found. An example of solutions to this model are shown in Figure 2, which depicts the tropical sea surface temperature as a function of the high latitude insolation.

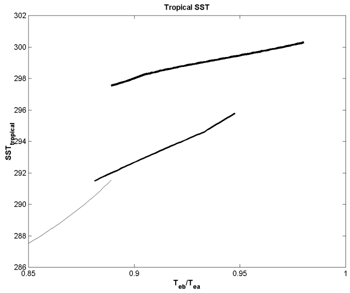

Figure 2: Equilibrium tropical sea surface temperatures as a function of the ratio of high to low latitude effective emission temperatures.

Three distinct, partially overlapping regimes exist. As shown in Figure 3, these are characterized by very different relative roles of the ocean and atmosphere in poleward heat transport.

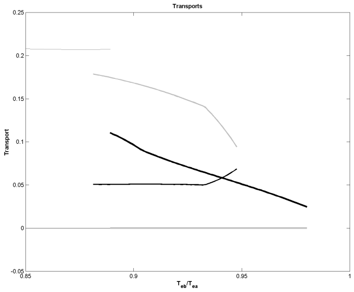

Figure 3: Equilibrium poleward heat transports by the ocean (thick lines) and the atmosphere (this lines).

In the "cold" regime, all of the transport is carried by the atmosphere. The atmospheric overturning is so strong and the atmosphere so cold that TCs cannot form, and thus, in this model, there is no thermohaline circulation. In the "hot" regime, all the heat transport is by the ocean. This transport is so strong that it drives the atmospheric temperature gradient to subcritical values and thereby shuts down the atmospheric circulation. The tropical column is so warm that TCs are plentiful and strong, consistent with the very strong thermohaline circulation. In the "intermediate" regime, both media share in the poleward heat transport.

5. DISCUSSION

By vigorously mixing heat downward deep into the tropical oceans, TCs appear to be major drivers of the deep overturning circulation of the ocean. Since poleward heat transport by the oceans obeys (1), TCs potentially solve the riddle of climates such as those that prevailed in the early Eocene, when high latitude temperatures were much warmer than present, while the Tropics were about the same. Because (1) is sensitive to the power expended in mixing, there can be a large poleward heat flux in the face of weak temperature gradients, unlike in the atmosphere, where fluxes are controlled almost entirely by temperature gradients.

The appearance of multiple climate equilibria when TCs are included as drivers of the ocean heat transport represents a very different dynamic from that represented by virtually all global coupled climate models. In particular, it is consistent with the observed response of the climate system to small variations in high latitude insolation, as recorded in ice cores and deep sea sediments. As demonstrated by Paillard (1998), a very simple quantum climate model containing three states and simple transition rules reproduces all of the major glacial and interglacial cycles recorded over the past 4 million years. The model presented here may contain the essential elements of the physics that might underlie such a quantized climate system. This would help explain why the earth's climate appears to be exquisitely sensitive to subtle changes in insolation brought about by orbital variations, while at the same time being fairly stable to the much larger changes in insolation that have occurred over the history of the solar system.

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