Increased hurricane intensities with CO₂-induced warming as simulated using the GFDL hurricane prediction system

Received: 20 July 1998/Accepted: 24 December 1998

Abstract The impact of CO₂-induced global warming on the intensities of strong hurricanes is investigated using the GFDL regional high-resolution hurricane prediction system. The large-scale initial conditions and boundary conditions for the regional model experiments, including SSTs, are derived from control and transient CO₂ increase experiments with the GFDL R30-resolution global coupled climate model. In a case study approach, 51 northwest Pacific storm cases derived from the global model under present-day climate conditions are simulated with the regional model, along with 51 storm cases for high CO₂ conditions. For each case, the regional model is integrated forward for five days without ocean coupling. The high CO₂ storms, with SSTs warmer by about 2.2 °C on average and higher environmental convective available potential energy (CAPE), are more intense than the control storms by about 3–7 m/s (5%–11%) for surface wind speed and 7 to 24 hPa for central surface pressure. The simulated intensity increases are statistically significant according to most of the statistical tests conducted and are robust to changes in storm initialization methods. Near-storm precipitation is 28% greater in the high CO₂ sample. In terms of storm tracks, the high CO₂ sample is quite similar to the control. The mean radius of hurricane force winds is 2 to 3% greater for the composite high CO₂ storm than for the control, and the high CO₂ storms penetrate slightly higher into the upper troposphere. More idealized experiments were also performed in which an initial storm disturbance was embedded in highly simplified flow fields using time mean temperature and moisture conditions from the global climate model. These idealized experiments support the case study results and suggest that, in terms of thermodynamic influences, the results for the NW Pacific basin are qualitatively applicable to other tropical storm basins.

1 Introduction

Greenhouse gas-induced climate warming could potentially affect hurricanes in a number of important ways, including intensity, frequency or location of occurrence, storm size, tracks, rainfall amounts, and so forth. Studies of possible changes in storm frequency/location changes have been attempted using global climate models (Broccoli and Manabe 1990; Haarsma et al. 1993; Bengtsson et al. 1996; Krishnamurti et al. 1998; Royer et al. 1998) with variable results. In this study, we examine primarily the question of possible CO₂-induced changes in hurricane intensities. Recent assessments of this issue include Kattenberg et al. (1996) who concluded in the 1995 Intergovernmental Panel on Climate Change (IPCC) report that “…it is not possible to say whether the … maximum intensity of tropical cyclones will change” due to increased greenhouse gas concentrations; and Henderson-Sellers et al. (1998) who conclude that “…the MPI (maximum potential intensity) of cyclones will remain the same or undergo a modest increase…” in response to doubled CO₂.

Observational studies of hurricane intensities (Merrill 1988; Evans 1993; DeMaria and Kaplan 1994a; Whitney and Hobgood 1997; Baik and Paek 1998; Kuroda et al. 1998) suggest an increase in the upper limit intensities of tropical cyclones with increasing SST. However, such an empirical SST/intensity relationship cannot be reliably extrapolated to the question of hurricane intensity changes under CO₂-induced warming, since other environmental factors, such as wind shear, lapse rates (Holland 1997), and large-scale regions of ascent and descent, may also change regionally in various ways. In terms of historical trends, Henderson-Sellers et al. (1998) report no clear evidence
for long-term trends in storm intensities for the north Atlantic and western North Pacific, although Landsea et al. (1996) noted an apparent decrease in the occurrence of intense Atlantic hurricane in recent decades.

Theoretical models of hurricane intensity predict that the MPI of hurricanes will increase in a warmer climate (Emanuel 1987; Henderson-Sellers et al. 1998) based on thermodynamical considerations. Since the MPI theories contain assumptions and caveats (Emanuel 1986, 1988, 1995a; Holland 1997; Henderson-Sellers et al. 1998) it is important to test their conclusions using alternative methods. Rotunno and Emanuel (1987) have shown that MPI theory agrees well with simulation results from a convection-resolving non-hydrostatic axisymmetric model; here we use a hydrostatic, three-dimensional hurricane model to investigate the sensitivity of hurricane intensities to CO2-induced changes in large-scale environmental conditions.

Although global climate models could in principle be used directly to examine both thermodynamical and dynamical (e.g., shear, storm interaction) influences on storm intensities, unfortunately the resolution of the models used to date for CO2-induced climate change studies has been too coarse to allow a simulation of realistic hurricane structure or of the most intense storms. For example, Bengtsson et al. (1995) report that even using a T106 global model (grid resolution of 1.1°) the lowest central surface pressure simulated was 957 hPa. This is much weaker than the observed record low central pressure of 870 hPa, the 906 hPa storm simulated in Hamilton and Hemler’s (1997) exploratory 1/3° resolution global model simulation, or the 849 hPa minimum pressure simulated for one of the control storms in the present study. Thus, the reliability of global models used to date to address possible climate-related intensity changes has been questioned (Henderson-Sellers et al. 1998 and references therein). Nonetheless, some global climate models have provided suggestive, though not highly convincing, indications of increased hurricane intensities in a warmer climate (Haarsma et al. 1993, Krishnamurti et al. 1998).

Regional models have a long history in explorations of the influence of SST on storm intensities (e.g., Ooyama 1969; Tuleya and Kurihara 1982; Evans et al. 1994), although these early studies mostly involved altering only SST and without changes to the atmosphere temperature/surface profile. This contrasts with the MPI methods mentioned, which either explicitly (Holland 1997) or implicitly (Emanuel 1986, 1988, 1995a) incorporate enhanced warming of the upper troposphere, relative to lower levels, with increased SST. Drury and Evans’ (1993) numerical experiments explored the impact on hurricane intensity of increasing SST under different atmospheric temperature change conditions. Although their study was limited to a few cases, they found that the degree of SST-induced storm intensification was considerably reduced if atmospheric temperatures were adjusted in such a way that convective available potential energy (CAPE) was unchanged in the warm SST scenario.

Recently, Knutson et al. (1998) used a three-dimensional high resolution regional hurricane model with boundary conditions from a global climate model to study of hurricane intensity/climate relationships. The simulated NW Pacific typhoon intensities in these experiments increased by 5–12% for an SST warming of 2.2°C. Here we expand on this study, examining possible CO2-induced changes in storm structure, storm precipitation, and mean storm tracks for the NW Pacific basin. We also examine CO2-induced changes in the large-scale environmental conditions from the global climate model; explore the relationship between storm intensities and several environmental measures (e.g., CAPE, vertical wind shear); and test the robustness of CO2-induced intensity changes to modifications of the storm initialization procedure. In addition, we use an idealized model framework to explore the effect of CO2-induced environmental changes on storm intensities in each of the major tropical storm basins.

2 Methodology

In our case study approach, 51 tropical storm cases were selected from a control simulation of a global climate model and 51 cases from a high CO2 simulation. Each case was then integrated for five-days using a regional high-resolution hurricane forecast system, and the statistics of the resulting storms compared. The cases were selected from the northwest tropical Pacific region, where the strongest tropical cyclones are observed in the present climate. The simulated tropical storm frequency climatology in the R30 global climate model (to be reported in detail elsewhere, see also Broccoli and Manabe 1992) is more realistic in the NW Pacific than in other basins, (e.g., the NW Atlantic and NE Pacific) which discourages our use of the case study technique in those basins. For our more idealized experiments (described in more detail in Sect. 5), the hurricane forecast system was used with temporally and spatially averaged environmental fields derived from the climate model for each of the major tropical storm basins.

2.1 Global climate model

The global model used is the GFDL R30 coupled ocean-atmosphere climate model (Manabe et al. 1991; Knutson and Manabe 1998). The atmosphere has resolution of about 2.25° latitude (250 km) by 3.75° longitude (400 km) and 14 vertical finite difference (σ = pressure/surface pressure) levels. The spectral domain representation of variables has rhomboidal truncation at wave number 30 (i.e., R30). Tropical storm-like features (weaker and much broader than observed) have previously been analyzed by Broccoli and Manabe (1990) for an R30 global atmospheric model very similar to that used here. The ocean model is an 18-level GCM (Modular Ocean Model, version 1) with a top layer thickness of 32 m, and with the same latitudinal resolution and twice the longitudinal resolution as the atmospheric model. The coupled model uses a flux adjustment technique for heat and salinity fluxes at the ocean surface to reduce model drift (Manabe et al. 1991). Two 120-y experiments were done with the model (Knutson and Manabe 1998): a control integration with CO2 constant at present day levels,