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CAN EXISTING CLIMATE MODELS BE USED TO STUDY ANTHROPOGENIC CHANGES IN TROPICAL CYCLONE CLIMATE?

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Abstract. The utility of current generation climate models for studying the influence of greenhouse warming on the tropical storm climatology is examined. A method developed to identify tropical cyclones is applied to a series of model integrations. The global distribution of tropical storms is simulated by these models in a generally realistic manner. While the model resolution is insufficient to reproduce the fine structure of tropical cyclones, the simulated storms become more realistic as resolution is increased. To obtain a preliminary estimate of the response of the tropical cyclone climatology, CO_2 was doubled using models with varying cloud treatments and different horizontal resolutions. In the experiment with prescribed cloudiness, the number of storm-days, a combined measure of the number and duration of tropical storms, undergoes a statistically significant increase in the doubled-CO_2 climate. In contrast, a smaller but significant reduction of the number of storm-days is indicated in the experiment with cloud feedback. In both cases the response is independent of horizontal resolution. While the inconclusive nature of these experimental results highlights the uncertainties that remain in examining the details of greenhouse-gas induced climate change, the ability of the models to qualitatively simulate the tropical storm climatology suggests that they are appropriate tools for this problem.

Background

Over twenty years of studies with climate models of increasing realism suggest that the continuing increase in concentrations of atmospheric greenhouse gases is likely to produce global warming (Schlesinger and Mitchell, 1987). While substantial uncertainties remain about the rate and geographical distribution of this warming, interest in this phenomenon and its impact has led to questions about potential changes in the climatology of tropical storms. Since these storms derive their energy from the warm tropical oceans, some have speculated that an increase in the frequency or intensity of tropical cyclones may occur as a result of global warming. Indeed, climate models suggest that a doubling of atmospheric CO_2 would raise tropical sea surface temperatures (SSTs) by as much as several degrees, so this speculation would appear to have some physical basis.

Emmanuel (1987) attempted to examine this issue quantitatively by modeling the tropical cyclone as a Carnot heat engine in which the energy input takes place at the temperature of the sea surface. Based on this idealized model, he suggested that the warmer SSTs of a high-CO_2 world would increase the maximum sustainable pressure drop in tropical cyclones. He noted, however, that his analysis has no direct implication for either the average intensity of tropical cyclones or their frequency of occurrence. A more comprehensive study of the interaction between tropical cyclones and their environment is needed in order to understand how the frequency and intensity of tropical cyclones will respond to climate change.

A number of studies have related geographical and interannual variability in tropical cyclone activity to various factors such as static stability, relative humidity, SST anomalies, vertical wind shear, and anomalies in atmospheric circulation (e.g., Gray, 1975, 1984; Shapiro, 1982a,b). While they may be useful in forecasting seasonal tropical cyclone activity, it is not likely that the results from these studies can be applied readily to greenhouse warming, since the spatial and temporal scales of much of the variability in the observed climate record are quite different from those of greenhouse warming.

A different approach is to look for changes in tropical cyclone activity in the same climate models that have been used to estimate the magnitude of greenhouse warming. While these are typically of relatively coarse resolution, previous studies have shown that models of comparable resolution are capable of simulating cyclonic vortices that resemble real tropical cyclones in their thermal structure and regions of formation (Manabe et al., 1970; Bengtsson et al., 1982). In subsequent sections we will explore the possibility of using such models to study the response of the tropical cyclone climate to increased CO_2. We will examine their ability to simulate the global tropical cyclone distribution, and present preliminary results regarding the sensitivity of tropical cyclone activity to a doubling of atmospheric CO_2.

Model Description

All of the experiments used in this study were performed with the GFDL global climate model. The basic atmospheric component employs the spectral transform method, in which the horizontal distributions of atmospheric variables are represented by both spherical harmonics and grid point values (Gordon and Stern, 1982). Nine unevenly-spaced levels are used for vertical finite differencing, employing terrain-following sigma coordinates. Solar radiation at the top of the atmosphere varies seasonally but not diurnally. Surface temperatures for land points are computed from a heat balance assuming no heat storage in the ground, and both snow cover and soil moisture are predicted. The moist convective adjustment scheme of Manabe et al. (1965) is used to parameterize convection.

Two versions of the model were used: a low resolution version with spherical harmonics truncated rhomboidally at zonal wavenumber 15 (R15) and a high resolution version with truncation at wavenumber 30 (R30). The latitude-longitude spacing of the transform grids are 4.5° by 7.5° and 2.25° by 3.75°, respectively. A parameterization of the drag that results from the breaking of orographically-induced gravity waves is used in the higher resolution model.

The oceanic component of the low resolution model is a simple model of the oceanic mixed layer, and consists of a static, vertically isothermal layer of water with a uniform thickness of 50 m. The model also includes the thermodynamical processes responsible for the freezing and melting of sea ice. While the ocean circulation is

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not explicitly represented, the rate of heat exchange between the mixed layer and the deep ocean is prescribed such that the geographical and seasonal variation of SST and sea ice are realistic. In order to save computer time, SST and sea ice in the R30 version are prescribed as determined from the R15 integrations.

In view of our inability to convincingly parameterize cloud cover and its optical properties, two different cloud treatments were adopted. In the simpler version, identified as FC (for fixed cloud), the cloud distribution is prescribed based on climatological data as a function of latitude and height. In the other version, identified as VC (for variable cloud), overcast cloud with specified optical properties is predicted when the relative humidity exceeds a certain critical value; otherwise, clear sky is predicted. The cloud microphysical processes controlling the liquid water content of clouds are not explicitly incorporated (Wetherald and Manabe, 1988).

Experimental Design

All integrations were initiated from an isothermal, resting atmosphere with an ice-free, isothermal mixed layer ocean. The first segment of each integration was performed over a period of ~30 years using an R15 atmosphere-mixed layer ocean model. Output for the last ten years of this segment, during which the temporal variation of model climate had no systematic trend, was retained for further analysis. To better resolve the atmospheric circulation, the integration was extended for an additional period using the R30 model. During this second segment, the annual cycle of SST was prescribed as determined from the analysis period of the first segment. After a short time, a quasi-equilibrium was reached and a second analysis period defined for the R30 segment of the integration.

To obtain preliminary results on the influence of CO_2 on the frequency of tropical storms, the following experiment was performed with both the FC and VC versions of the model. Integrations were conducted in pairs. The control (1X) and perturbed (2X) integrations used atmospheric CO_2 concentrations of 300 and 600 ppmv, respectively. The climatic influence of the CO_2 increase was evaluated by comparing the quasi-equilibrium states that emerge from each pair of integrations. By comparing the responses from the FC and VC experiments, the influence of the cloud-radiation feedback process on the tropical cyclone climatology was evaluated.

Tropical Cyclone Simulation

An automated procedure was employed to identify tropical cyclones and study their spatial, frequency, and intensity distributions. Only oceanic grid points equatorward of ~30° latitude were considered. No attempt was made to distinguish between tropical and extratropical systems based on thermal structure; instead, the search for tropical cyclones was conducted in each hemisphere only during a six-month "hurricane season" defined as May-October and November-April in the Northern and Southern Hemispheres, respectively. We required that the sea level pressure be a local minimum, less than an arbitrary critical value, and lower than the mean of the surrounding points by 1.5 mb and 0.75 mb in the R15 and R30 integrations, respectively. While these criteria are arbitrary, tests on a small sample found them to yield results very similar to a manual search. A tropical cyclone identified according to these criteria was designated as a tropical storm if the surface wind speed at the central or any of the eight surrounding grid points was stronger than gale force (17 m/s), the threshold for tropical storm intensity.

To count the number of storms, a tracking procedure was also developed. For each cyclone that was identified, the cyclone positions for the following day were scanned to determine if any were within a radius of 1200 km. This allows a daily average speed of 50 km/hr, an upper limit for tropical cyclones. If there was one cyclone, it was assumed to be the same system. If there was more than one, the one closest to the previous day's position was assumed to be the same system.

Several tropical storms identified by the procedure were analyzed in detail on a daily basis. Synoptic maps of sea level pressure, surface wind, precipitation, and 350 mb temperature anomaly from one of the most intense and long-lived storms of the R30VC-1X integration segment are shown in Figure 1. Developing as a rather weak disturbance east of the Philippines, the cyclone moved northwest and deepened gradually. The maps correspond to the time of maximum intensity, when the central pressure was 961 mb and the surface wind 47 m/s. The storm then crossed southern Japan before weakening over the Asian mainland.

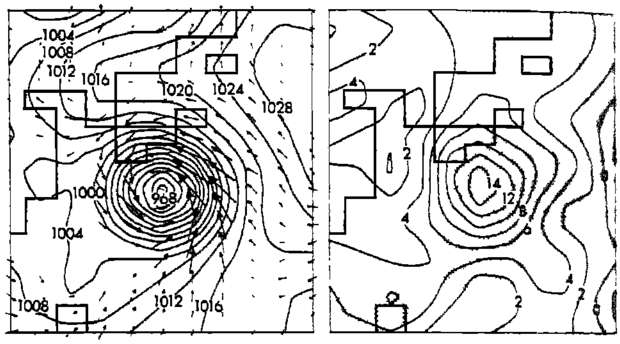

Fig. 1. Synoptic maps of [top] sea level pressure (in mb) and surface wind vectors, and [bottom] 350 mb temperature departure from zonal mean (deg) for an intense simulated tropical cyclone. The stippling on the bottom panel indicates 24-hour precipitation rates greater than 10 mm/day.

Many of the features of the tropical storm simulated and described by Manabe et al. (1970) are present in this system, such as the warm core, strong upward motion, and near saturation at the cyclone center. Winds are strongest in the right front quadrant of the storm, as is often observed in Northern Hemisphere tropical cyclones (Shea and Gray, 1973). A very large, comma-shaped area of precipitation surrounds the storm center, a characteristic of many tropical systems as observed by satellite and simulated by Tuleya and Kurihara (1984) using a much higher resolution hurricane model. The distribution of surface wind and precipitation also suggest something similar to a feeder band extending southwest of the center.

A comparison between storms from the R15 and R30 integration segments is consistent with the findings of Manabe et al. (1970) that higher resolution produces storms stronger and more realistic in appearance. In prediction experiments, Krishnamurti and Oosterhof (1989) also found that forecast tropical storm intensities became more realistic as resolution was increased. While the resolution remains insufficient to resolve such features as eyewalls or spiral bands, the increased realism of the R30 storms suggests that other aspects of storm structure found in observed tropical cyclones may become evident with higher resolution.

Tropical Cyclone Climatology

The average number of tropical storms for the six-month "hurricane season" was computed for each of the control integration segments and compared to the observed averages for each of seven tropical ocean regions, each hemisphere, and the globe (Table 1). Since observed frequencies by region are not readily available on a monthly basis, those for the entire year are used for comparison. Due to the highly seasonal nature of their formation, 85-90% of observed tropical storms occur during the six-month seasons used in this study, so this practice should not introduce serious error into the comparisons.

Table 1. Mean number of tropical cyclones reaching storm strength (surface winds >17 m/s) by region during the six-month "hurricane season" from the 1X integrations of each experiment. The observed annual mean number of storms (Frank, 1985) is given for comparison.

	R15 FC	R30 FC	R15 VC	R30 VC	Obs.
N.W. Pacific	20.7	20.4	30.2	40.6	26.1
N.E. Pacific	3.2	0.4	2.5	1.8	14.2
N. Atlantic/Caribbean	8.6	6.0	7.6	8.7	8.9
N. Indian	3.1	5.8	4.7	8.9	5.5
Australia/S. Pacific	13.9	15.6	20.8	29.6	16.4
S. Indian	10.8	4.0	10.5	8.2	9.0
S. Atlantic	8.0	2.8	4.7	4.0	0.0
N. Hemisphere	35.6	32.6	45.0	60.0	54.7
S. Hemisphere	32.7	22.4	36.0	41.8	25.4
Global	68.3	55.0	81.0	101.8	80.1

The global distribution of tropical storms is reasonably similar to the observed, with many characteristics common to all the 1X integration segments. As in nature, the western North Pacific and Australia/South Pacific regions are the most active, with more modest numbers occurring in the North Atlantic, North Indian, and South Indian regions. Poor aspects of the simulations include the dearth of storms in the eastern North Pacific (also found in the simulations by Bengtsson et al., 1982), and the formation of storms in the South Atlantic, where no tropical storms form in reality.

The different cloud treatments also produce systematic differences in tropical storm numbers. At both resolutions, tropical storms are more frequent in the VC experiment. This is probably due to the trapping of upward terrestrial radiation by cloud cover, which decreases the radiative cooling from the cyclone's warm core, as shown by Kurihara and Tuleya (1981) in experiments with a high resolution hurricane model. Thus the radiative destruction of eddy available potential energy (EAPE) is reduced, allowing more disturbances to reach tropical storm intensity in the VC experiment.

Given the coarse resolution of the models and the assumptions implicit in the scheme for identifying tropical storms, a healthy skepticism regarding the correspondence between the simulated and observed numbers of storms is appropriate. However the similarity between the simulated and observed geographical distribution of tropical storm numbers is another important indication of the success of the models. Despite the simplicity of the selection algorithm, the use of a consistent, objective scheme for identifying tropical storms allows quantitative comparisons to be made among the model simulations.

Sensitivity To Increased CO_2

We studied the sensitivity of the simulated tropical storm climatology to a doubling of CO_2 by examining three parameters from each pair of integrations: the average number of storms during the respective six-month "hurricane seasons" for both hemispheres, the average number of days a cyclone is at tropical storm intensity, and the average number of storm-days (Table 2). The number of storm-days is computed by counting the number of storms of tropical storm intensity on each day and aggregating these over the respective hurricane seasons.

Table 2. Global number of tropical storms per six-month "hurricane season," number of storm-days, and average duration at of above tropical storm strength (days) from each integration. Percent changes resulting from the doubling of CO_2 are also shown. Asterisks indicate statistical significance at the 5% level. (No significance testing was done for the duration statistics.)

Experiment	Integration Segment	Number of Storms	Storm-Days	Average Duration
FC	R15FC-1X	68.3	117.2	1.72
	R15FC-2X	72.3	139.4	1.93
	% diff. (2X-1X)	+5.9	+18.9*	+12.2
	R30FC-1X	55.0	100.2	1.82
	R30FC-2X	56.6	116.2	2.05
	% diff. (2X-1X)	+2.9	+16.0	+12.6
VC	R15VC-1X	81.0	171.4	2.12
	R15VC-2X	75.8	148.9	1.96
	% diff. (2X-1X)	-6.4	-13.1*	-7.5
	R30VC-1X	101.8	245.3	2.41
	R30VC-2X	95.3	217.5	2.28
	% diff. (2X-1X)	-6.4	-11.3*	-5.7

For both model resolutions in the FC experiment, the number of storms increases in response to higher CO_2, and the average duration at tropical storm strength increases. Since both the number and duration of storms increase, the number of storm-days also increases by 16-19%. For the R15 integration segments this increase is statistically significant at the 5% level according to the nonparametric Mann-Whitney test for differences in means, although the increase in the number of storms is not significant. The response to increased CO_2 is quite different in the VC experiment. Both the number of storms and the average duration at or above tropical storm strength decreases, leading to a decrease in the number of storm-days of 11-13%, a change that is significant at the 5% level in both integration segments. As in the FC experiment, the change in the number of storms is not significant.

One approach in identifying a mechanism for the changes in tropical storm activity is to consider the energetics of tropical disturbances. Manabe et al. (1970) found that the in situ conversion of EAPE generated by latent heating was the most important source of transient eddy kinetic energy (TEKE) in the tropics of their general circulation model. Since evaporation from the tropical oceans is the ultimate source of this heating, an increase in SST could influence the energy supply for tropical disturbances by increasing the evaporation rate, due to the nonlinearity of the temperature-vapor pressure relationship.

Results from the FC experiments indicate that tropical SSTs typically increase by ~1.5° C in response to doubled CO_2, yielding an evaporation increase of ~5%. An energetics analysis of the R15 integration segment shows that increases of about 26-43% in the generation of EAPE and about 12-18% in its conversion to TEKE also occur in the regions of active tropical cyclone formation. Thus it is plausible that the increase in storm activity results from increased evaporation from the warmer oceans of the high-CO_2 world.

Unfortunately, this approach does not satisfactorily explain the results from the VC experiment. Based on the previous argument, an even larger increase in storm activity would be expected, since the use of interactive cloudiness increases the sensitivity of the model (Wetherald and Manabe, 1988). Tropical SSTs increase by ~2.5° C in the VC experiment, a warming almost double that occurring in the FC experiment, and thus evaporation increases by ~7%. Analysis of energetics indicates that while generation of EAPE and conversion to TEKE also increase, the magnitudes are substantially smaller than in the FC experiment, with generation increasing by 8-26% and conversion increasing by only 1-4%. Lower tropospheric TEKE decreases in the VC case by 1-5%, consistent with the decrease in tropical storm activity.

There are deficiencies in the energetics approach. While Manabe et al. (1970) found a spatial correspondence between low-level TEKE and regions of observed tropical cyclone activity, tropical storms represent only the most intense portion of the tropical disturbance spectrum. Other factors such as the large scale circulation and the availability of nascent disturbances undoubtedly are important in determining how the kinetic energy of tropical disturbances is partitioned between tropical storms and other systems. Further work is necessary to explore the possibility that such factors are responsible for the disparity between the FC and VC experiments, and to identify the role of cloud feedback in the altered response.

Concluding Remarks

In this study, we have proposed that current generation climate models can be used to study the influence of greenhouse warming on the tropical storm climatology. While the resolution of current models is insufficient to reproduce the small scale structure characteristic of observed tropical storms, the global distribution of tropical storms is simulated in a generally realistic manner, and simulated storms appear more realistic as resolution is increased.

Preliminary results on the response of the tropical storm climatology to doubled CO_2, using models with varying resolution and treatment of clouds, are inconclusive. In the experiments with prescribed cloudiness, the number of storm-days, a combined measure of the number and duration of tropical storms, undergoes a statistically significant increase in the doubled-CO_2 climate for the R15 integration segment. In contrast, a significant reduction of the number of storm-days is indicated in the experiment with cloud feedback. The results from both these experiments are independent of horizontal resolution.

No obvious reason for the disparity between the experiments has been identified. While it may be tempting to believe that the incorporation of cloud feedback in the VC experiment makes it more realistic, the large uncertainty involved in the parameterization of cloudiness suggests that such a conclusion is premature. Furthermore, our inability to identify the physical mechanism by which cloud feedback alters the response of the model tropical storm climatology to increased CO_2 makes us hesitant to accept the results from the VC experiment at face value.

While our preliminary sensitivity results are inconclusive, we are encouraged by the ability of the present models to simulate, at least qualitatively, the frequency distribution of tropical storms. Coupled with the tendency for more realistic storm structure as resolution is increased, we feel it makes these models appropriate tools for exploring the mechanisms that control the relationship between greenhouse warming and tropical storm activity.

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