P1F.9 AN EDGCM MODELING STUDY OF THE EFFECTS OF ATMOSPHERIC TRACE GAS CONCENTRATION CHANGE ON ATLANTIC TROPICAL CYCLONE DEVELOPMENT PARAMETERS

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1. INTRODUCTION

Many studies of the effects of changes in trace gas concentrations in the atmosphere focus on variations in average temperature and precipitation. In addition to changes in climate averages, the effects on extreme weather events are also of interest when evaluating potential climate change. Tropical cyclones are one of the more significant forms of extreme weather that could be affected by climate change in terms of damage to life and property.

The IPCC Fourth Assessment Report states that an increase in tropical cyclone intensity, both in precipitation and wind speed, is likely (Solomon *et al.*, 2007). The reason cited for increases in tropical cyclone strength is an increase in sea surface temperatures in the tropics. A variety of model solutions supported the finding that an increase in the strength of tropical cyclones is likely. Additionally, models have not simulated well the increase in intense tropical cyclones noted since 1970. Projecting a trend in overall tropical cyclone activity was less certain.

Emanuel *et al.* (2008) analyzed models used in producing the IPCC Fourth Assessment Report and applied a technique for simulating tropical cyclone activity. The findings suggest an overall decrease in tropical cyclone activity globally with some regional increases in activity. In particular, a decrease in tropical cyclone numbers in the Caribbean and western Atlantic basin is expected. However, the results also suggest increasing numbers of tropical cyclones in the eastern Atlantic basin.

Both anthropogenic and natural release and absorption and removal of trace gases from the atmosphere are controlled by a variety of sources and sinks. Some of these sources and sinks are subject to many factors that cannot be predicted with current technology or are subject to human influence. For these reasons, it is useful to run climate models under a variety of scenarios for greenhouse gas concentrations.

2. METHODOLOGY

For this climate modeling study, the Goddard Institute for Space Studies (GISS) Model II Global Climate Model (GCM) was used. The GISS Model II described by Hansen *et al*. (1983) is a global grid-point model that operates with a grid spacing of eight degrees latitude and ten degrees longitude. Other horizontal grid-point spacing is possible in the model; however, these are not available within EdGCM. The model has nine vertical levels and uses the σ vertical coordinate system, which is based on the position of the level between the ground and the top of the atmosphere. In the GISS Model II, there are two layers in the boundary layer, two layers in the stratosphere, and five layers in between in the troposphere. GISS Model II assumes hydrostatic balance.

Although tropical cyclones cannot explicitly be modeled using the grid spacing in the GISS Model II GCM, the model is sufficient to model many of the parameters that are favorable or unfavorable for tropical cyclone development, such as sea surface temperature, vertical wind shear, and moisture. The purpose of this work is to use the Educational Global Climate Modeling (EdGCM) software developed at Columbia University, which incorporates the GISS Model II to evaluate parameters for tropical cyclone formation and development simulating various scenarios for increasing concentrations of trace gases in the atmosphere.

EdGCM provides a simple interface to design and execute the model simulation permitting the user to adjust parameters. In addition to adjusting the data used by the model for parameterizing interactions between the atmosphere and the surface, it is possible to alter how the concentration of trace gases change over time. The user can choose settings for carbon dioxide, Nitrous Oxide, Methane, and Chlorofluorocarbons. Additionally, it is possible to define trends in solar activity and the orbit of the Earth. For the purposes of this study, only carbon dioxide concentration was varied.

Brasseur *et al*. (2006) simulated the possible effects of climate change on trace gas concentrations in the troposphere. The model used a carbon dioxide concentration of 370 ppm to represent the current state of the atmosphere. It is suggested that an approximate doubling of carbon dioxide contentration will occur by 2100 with a concentration of 740 ppm. The simulation increased carbon dioxide concentrations exponentially by 1% each year, which was used to represent the radiative forcing by all greenhouse gases. In this study, carbon dioxide concentrations were increased by 0.5% and 1% yearly along with a control simulation in which carbon dioxide concentrations did not change. Initial conditions used carbon dioxide concentrations from 1995. The simulation was performed from 1995 to 2050.

Output was generated and examined from the first ten years of the simulations (1995-2004) and the final ten years (2041-2050). These periods were chosen to represent average conditions at the beginning and end of the simulations. Although many output fields are available, a few fields from the model simulations were examined because of their potential relevance to tropical cyclone activity. These fields were precipitation, jet speed, tropospheric static stability, 700 hPa geopotential height, sea level pressure, and sea surface temperatures (SST).

The northwestern most grid point used in the analysis was at 95°W and 44°N. The southernmost point was 5°W and 4°N. Grid points that do not contain any sea surface were removed from the analysis. Aggregate values were calculated for each half of the Atlantic hurricane season. The domain for the study includes portions of the subtropical Atlantic that, although frequently are less favorable for tropical cyclones, still frequently are traversed by tropical cyclones. One half consisted of June, July, and August, with the other half including September, October, and November.

In addition to analyzing the entire Atlantic basin, an emphasis was placed on the western part of the basin. This includes much of the Gulf of Mexico, the Caribbean, and the far western Atlantic. Changes in fields over the western Atlantic basin were compared against fields over the entire basin for the purpose of evaluating the potential impact on tropical cyclone activity in waters near the United States.

The final ten years of the control solution were differenced with the first ten years of the control solution. Additionally, both the final ten years of the 0.5% exponential carbon dioxide increase and the 1% exponential carbon dioxide increase were differenced with the final ten years of the control solution.

It was hypothesized that although carbon dioxide does not increase during the control simulation that there will still be a change in some quantities including SSTs. This is because the initial conditions were data observed in 1995. Due to increasing carbon dioxide prior to 1995, the system was not in equilibrium. As a result, climate should change during the time it takes for the system to find a new equilibrium.

Sea surface temperatures and 700 hPa geopotential heights are a measure of surface and low level temperature. These fields are directly related to temperature in the lower atmosphere and at the ocean surface and should be useful in determining the degree of warming in simulations.

Although affected by temperatures in the upper atmosphere, static stability also varies when temperatures in the lower atmosphere vary. Steeper lapse rates indicate greater instability and are supportive of convection. Tropical cyclones develop and sustain as a result of latent heat release in convection. Precipitation is another measure of latent heat release. Because precipitation in the tropics is largely convective in nature, precipitation is related to the amount and invensity of convection in the tropics.

Lower sea level pressure is another useful indicator for tropical cyclone activity. Pressure is useful because lower pressure is favorable for low-level vorticity, which is an ingredient in the formation of tropical cyclones. For this reason, it was chosen as a parameter in this study.

Vertical wind shear is very unfavorable for tropical cyclone development. Tropical cyclones are strongly affected by nearby mid-latitude cyclone activity. Although not directly a measure of vertical wind shear, strong upper-level jets will likely be found in the vicinity of extra-tropical cyclones. Jet speed is used for the purpose of estimating the influence of mid-latitude cyclones.

3. RESULTS

The results of the model simulations will be presented in two parts. Initially, the results will account for changes in the six parameters throughout the entire domain. Following those results, additional data will be presented focusing on the western part of the tropical North Atlantic. This will focus on comparing variations in parameters in the western basin against the entire basin and on examining trends in parameters in the western basin.

3.1. Results for the entire domain

Although some of the parameters examined did not examine a clear trend as the rate of carbon dioxide increase was raised, many of the parameters did exhibit at least some difference. Tables 1 and 2 show variations in the six parameters studied in the JunJulAug and SepOctNov seasons, respectively.

	Control	**+0.5%**	**+1.0%**
700 hPa geopot.	+3.998 gpm	+15.142 gpm	+24.517 gpm
Jet speed	+0.138 m/s	+0.565 m/s	-0.136 m/s
Sea level pres.	-0.137 hPa	-0.409 hPa	-0.886 hPa
Precip.	+0.071 mm/day	-0.014 mm/day	+0.060 mm/day
SST	+0.562 K	+1.585 K	+2.727 K
Static stability	+0.083 K/km	+0.219 K/km	+0.344 K/km

Table 1: Shown are the variations in the six parameters studied in the JunJulAug season.

	Control	**+0.5%**	**+1.0%**
700 hPa geopot.	+6.887 gpm	+19.892 gpm	+29.512 gpm
Jet speed	+0.360 m/s	+0.595 m/s	+0.546 m/s
Sea level pres.	+0.087 hPa	-0.017 hPa	-0.427 hPa
Precip.	+0.067 mm/day	+0.077 mm/day	+0.150 mm/day
SST	+0.537 K	+1.584 K	+2.754 K
Static stability	+0.062 K/km	+0.209 K/km	+0.340 K/km

Table 2: Shown are the variations in the six parameters studied in the SepOctNov season.

There is a clear increase in 700 hPa geopotential height at higher rates of carbon dioxide increase. The thickness of a layer, which behaves similarly to geopotential height, increases as layer average temperature rises. This would suggest a low-level warming of the tropical regions consistent with the direct effects of increasing carbon dioxide concentration in the atmosphere. Greater increases in 700 hPa geopotential height were noted during the SepOctNov season than during the JunJulAug season. Figure 1 shows the change in 700 hPa geopotential height in SepOctNov between the control simulation in 1995-2004 and the 1.0% exponential carbon dioxide increase simulation in 2041-2050.

Also notable is a clear increase in SSTs over the domain as the rate of carbon dioxide increase becomes larger, which is demonstrated in figure 2. This is again consistent with the warming suggested by an increase of carbon dioxide concentration. Very little difference was present between the two seasons when examining SST increases.

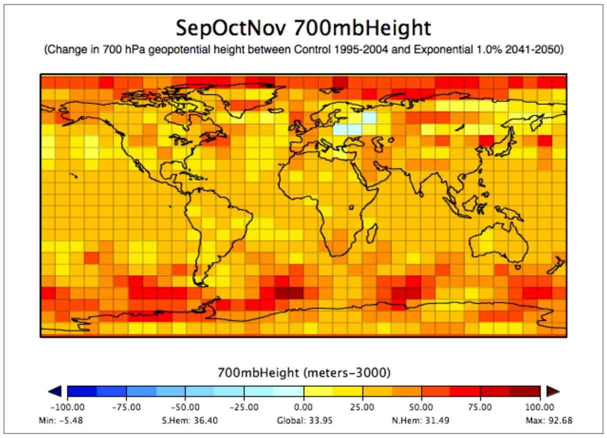

Figure 1: Shown is a chart of the variation in 700 hPa geopotential height in SepOctNov between the control in 1995-2004 and the exponential 1.0% carbon dioxide increase in 2041-2050.

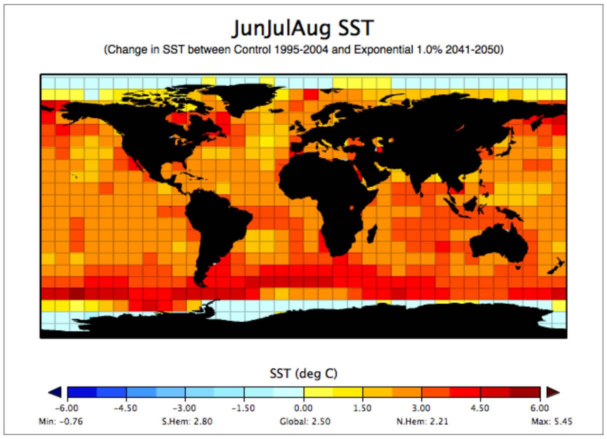

Figure 2: Shown is a chart of the variation in SST in JunJulAug between the control in 1995-2004 and the exponential 1.0% carbon dioxide increase in 2041-2050.

In all the simulations, an increase in tropospheric lapse rate was present, the magnitude of which increased as the carbon dioxide forcing also increased. In all but the control simulation, the troposphere decreased in stability more during the SepOctNov season than during the JunJulAug season. This is also consistent with low level warming with less warming aloft, which would cause lapse rates to become steeper.

Throughout the simulations, there is a decrease in sea level pressure in both seasons as carbon dioxide forcing increases. The decrease in sea level pressure is more pronounced in the JunJulAug season than during the SepOctNov season.

Trends in jet speed and precipitation were less clear, particularly during the summer. The jet was stronger in each of the simulations for the SepOctNov season, however, a trend with varying carbon dioxide forcing was less evident. Additionally, greater precipitation was evident during the SepOctNov season, but a trend was not apparent with changes in carbon dioxide forcing.

3.2. Results for the western basin

Many of the parameters trended similarly in the western part of the Atlantic basin as they did for the entire Atlantic. However, a few notable differences are evident when examining the data. The entire data for the western basin is shown in tables 3 and 4 for the JunJulAug and SepOctNov seasons, respectively.

	Control	**+0.5%**	**+1.0%**
700 hPa geopot.	+5.121 gpm	+15.361 gpm	+23.552 gpm
Jet speed	+0.039 m/s	+0.618 m/s	+0.176 m/s
Sea level pres.	-0.122 hPa	-0.332 hPa	-0.764 hPa
Precip.	-0.004 mm/day	+0.058 mm/day	+0.373 mm/day
SST	+0.437 K	+1.578 K	+2.853 K
Static stability	+0.070 K/km	+0.234 K/km	+0.401 K/km

Table 3: Shown are the variations in the western basin in the six parameters studied in the JunJulAug season.

One significant difference was noted in jet speed over the western north Atlantic as compared to jet speed over the entire north Atlantic. As carbon dioxide forcing increased, jet speeds became stronger in the western Atlantic than in the entire basin during the JunJulAug season. However, the trend reversed in the SepOctNov season with jet speeds not increasing as much in the western Atlantic than for the entire basin.

	Control	**+0.5%**	**+1.0%**
700 hPa geopot.	+5.450 gpm	+21.148 gpm	+29.005 gpm
Jet speed	+0.313 m/s	+0.311 m/s	+0.272 m/s
Sea level pres.	-0.088 hPa	-0.076 hPa	-0.537 hPa
Precip.	+0.004 mm/day	+0.097 mm/day	-0.032 mm/day
SST	+0.364 K	+1.715 K	+2.884 K
Static stability	+0.060 K/km	+0.207 K/km	+0.352 K/km

Table 4: Shown are the variations in the western basin in the six parameters studied in the SepOctNov season.

During the JunJulAug season, a trend toward more precipitation in the western basin was noted, which is shown in figure 3. This is in contrast to the results for the entire basin in which no trend in precipitation was noted in this season.

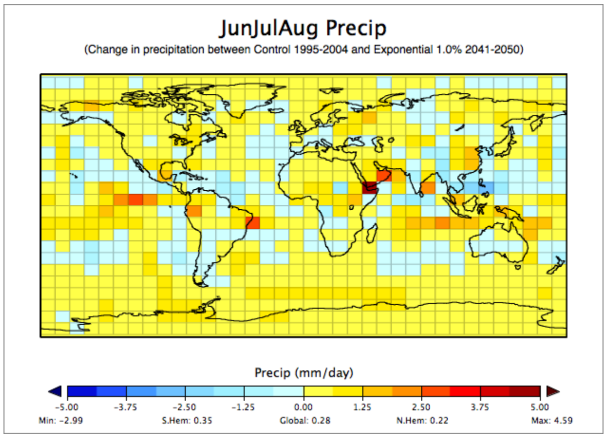

Figure 3: Shown is a chart of the variation in precipitation in JunJulAug between the control in 1995-2004 and the exponential 1.0% carbon dioxide increase in 2041-2050.

4. DISCUSSION

In the Atlantic basin, many of the parameters trend toward more favorable conditions for tropical cyclones as carbon dioxide forcing increases. A warming of the lower atmosphere is suggested by the model simulations with increasing 700 hPa geopotential height, warming SSTs, and decreasing stability. A trend toward lower pressure as carbon dioxide forcing increases was noticed as well. This, as with the parameters directly related to temperature, favors an increase in tropical cyclone activity.

For the entire Atlantic basin, a trend toward stronger jet speeds was noticed in the SepOctNov season. This would favor a decrease in tropical cyclone activity. However, in the JunJulAug season, a trend in jet speed was less evident. The increasing jet speed in the western Atlantic during the JunJulAug season would suggest some suppression of tropical cyclone activity during the summer. However, despite a strengthening average jet speed over the entire basin during the SepOctNov season, the average jet speed does not increase as greatly in the western basin. This suggests that a greater portion of the overall tropical cyclone activity during these months will occur in the western part of the basin. Although the overall trend in jet speed in the Atlantic basin may favor a suppression of hurricane activity, it also favors a shift in where the activity is greatest. Summer tropical cyclone activity should shift eastward into the central and eastern part of the basin. However, fall tropical cyclone activity should shift into the western part of the basin.

Increasing sea level pressure in the western part of the basin during the JunJulAug season further suggests a suppression of tropical cyclone activity during these months. No such trend was found during SepOctNov when examining sea level pressure. Additionally, although there is an increase in precipitation, and therefore greater convection, in the western basin during the JunJulAug season, the convective activity may be less likely to develop into tropical cyclones.

The strongest signals were noted in parameters that vary directly as temperature changes. The direct effect of increasing carbon dioxide concentration is to increase temperatures through absorption and reemission of outgoing longwave radiation. Additional processes and indirect effects may affect or even overwhelm the effects of additional carbon dioxide for other parameters that are not directly affected by warming. Sea surface temperature, 700 hPa geopotential height, and static stability are directly affected by temperature, and indeed are where the strongest signals are found.

If other parameters, particularly those that may inhibit tropical cyclone formation, are affected to a much lesser degree by warming, it suggests that the greatest effect of carbon dioxide increases is a warming. Although other parameters for tropical cyclone development may change, this suggests that the most significant effects will be a low-level warming. This would likely favor an increase in tropical cyclone occurrence and intensity.

5. CONCLUSION

Although carbon dioxide did not increase during the control simulation, it was noted that there was still a large variation in some parameters from the beginning of the simulation to the end. This is likely due to the carbon dioxide increase prior to 1995 and the lag time for the system to regain an equilibrium state following the cessation of the forcing. It is of interest to investigate the lag time to regain equilibrium following various radiative forcings, which will be the focus of a follow-up study to this work.

Another goal of future work is to perform more model simulations. Although some trends can be noted from the very small number of simulations in this study, more simulations would be useful in identifying more trends and determining the significance of trends that are noted.

However, even without examining additional model simulations, some parameters exhibited strong variations. A low level warming was evident in each of the simulations performed, with greater warming occurring as the carbon dioxide forcing was increased. It is less clear, however, whether or not this will result in an increase in tropical cyclone activity or if other factors will cancel the effect of the warming. For example, although the trend in jet speed is less conclusive, it did increase in most of the simulations. This would have a negative effect on tropical cyclone activity. It is unclear, however, whether or not one of these variations will overwhelm the other of if the effects would be negated. Concluding that a warming of SSTs and of the lower atmosphere will not necessarily result in an increase in tropical cyclone activity is in agreement with some previous work such as Zuki and Lupo (2008).

It is also likely that increases in carbon dioxide will cause some regions of the Atlantic basin to become more favorable for tropical cyclone activity than other regions. The results would suggest a shift in activity into the eastern and central basin during the early season. However, later in the tropical cyclone season, activity would shift into the western part of the basin, including the Gulf of Mexico and Caribbean.

6. ACKNOWLEDGEMENT

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