INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **19**: 607–617 (1999)

A GCM INVESTIGATION OF GLOBAL WARMING IMPACTS RELEVANT TO TROPICAL CYCLONE GENESIS

LEONARD M. DRUYAN[a,*], PATRICK LONERGAN[b] and TIMOTHY EICHLER[c]
[a] *Center for Climate Systems Research, Columbia University and NASA/Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA*
[b] *Science Systems and Applications, Inc. and NASA/Goddard Institute for Space Studies, New York, USA*
[c] *Geological Science Department, Columbia University, New York, USA*

Received 8 April 1998
Revised 21 October 1998
Accepted 11 November 1998

ABSTRACT

Two approaches that consider how greenhouse warming might impact the frequency of tropical cyclone (TC) genesis are explored. Results are based on GCM experiments with the q-flux version global climate model of the NASA/Goddard Institute for Space Studies (GISS); one set representing contemporary atmospheric concentrations of CO_2, contrasting with the second set representing the global climate in double CO_2 equilibrium. July–September means of climate parameters relevant to TC genesis are computed from the simulations and combined to formulate a seasonal genesis parameter (SGP), as suggested in an empirical study by Gray (in Shaw, D.B. (ed.), *Meteorology Over the Tropical Oceans*, 1979, pp. 155–218). The spatial distribution of the July–September SGP based on the control simulations is compared with the observed distribution and results using other models. The corresponding spatial distribution of the July–September SGP derived from the double CO_2 simulations, when compared with the control results, projects a 50% increase in the genesis frequency of TC over the western North Atlantic/Gulf of Mexico basin, but 100–200% increases over the North Pacific Ocean. The increases, most of which are attributable to enhanced ocean temperatures, may be exaggerated, suggesting that the original SGP formulation requires tuning or other revisions. For example, it is noted that SGP computed from the NCEP 1982–1994 re-analysis climatology do not accurately reflect the known spatial distributions of TC genesis frequency. The second approach detects easterly waves over the eastern North Atlantic Ocean by spectral analysis of vorticity and wind component time trends, comparing wave activity in the control and double CO_2 simulations. Results indicate a southward shift in future trajectories of easterly waves over West Africa and significant increases in their average amplitude as they cross the African coast and begin to traverse the Eastern Atlantic along 14°N. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: global warming; climate change; tropical storm frequency; GISS GCM

1. INTRODUCTION

Tropical cyclones (TC) become named tropical storms when the sustained winds associated with deepening pressure minima in the tropics first exceed 17 $m\,s^{-1}$. The extreme wind and storm surge property damage and related loss of life accompanying landfall of TC have motivated a keen interest in forecasting their genesis, intensity and their trajectories. Moreover, several sectors of government and industry have turned to the scientific community for guidance regarding possible changes in the climatology of TC spurred by anticipated future increases in surface air temperatures and sea surface temperatures (SST).

* Correspondence to: Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, USA.

Contract/grant sponsor: Risk Prediction Initiative of the Bermuda Biological Station for Research; Contract/grant number: RPI 96-008
Contract/grant sponsor: National Science Foundation; Contract/grant number: ATM-9725142

CCC 0899–8418/99/060607–11$17.50

The 1995 Intergovernmental Panel on Climate Change report concludes that '... it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change...' (Kattenberg *et al.*, 1996), as the global climate warms from the radiative forcing of increasing atmospheric concentrations of greenhouse gases. More recently, Henderson-Sellers *et al.* (1998) stated that while global frequencies of TC may not change, regional frequencies of TC genesis '... could change substantially in either direction.'

Recognizing how important it is for risk assessment to anticipate future trends in tropical storm behavior (because of the tremendous destructive potential of TC), the authors have addressed this question as it applies to the northern hemisphere summer season, using simulations of the 9-layer general circulation model of the NASA/Goddard Institute for Space Studies (GISS GCM) (Hansen *et al.*, 1996). In considering how greenhouse warming might impact the frequency of TC genesis, an approach previously undertaken with the CSIRO9 GCM (Ryan *et al.*, 1992; Watterson *et al.*, 1995) was pursued in order to gauge the importance of model dependence on the results. In this context, the authors evaluate how each of several relevant modeled and analyzed atmospheric parameters impacts estimates of TC frequency and how these components of the climate system change in a double CO_2 equilibrium simulation. Additionally, they examine the impact of the double CO_2 environment on the generation of easterly wave disturbances near the Atlantic coast of West Africa.

The results do not offer definitive answers. They represent an exploration of two approaches to the problem. First, previous research which discusses the association of TC with seasonal climatic means as well as the application of GCMs for projecting climate change impacts on TC behavior are reviewed. For the purposes of this paper, tropical cyclones, named tropical storms, hurricanes and typhoons collectively, will be referred to as TC.

2. BACKGROUND

Gray (1979) related spatial distributions of seasonal and yearly averages of six climatological indexes to the spatial distribution of named tropical storms' genesis frequency. In particular, he showed that the spatial distribution of 1958–1977 means of a 'genesis parameter' (GP) were highly correlated to the observed distribution of TC genesis frequency per 20 years within each 5° square area. The dependence of TC genesis frequency on these particular indexes, discussed below, has more recently been sustained by authoritative sources (Lighthill *et al.*, 1994; McBride, 1995).

Given the prominence of ocean temperature in the aforementioned discussions, anticipated warming of the tropical oceans suggests that future tropical cyclone activity could be different than in the current climate. However, other environmental factors are also relevant and must be considered. GCMs are an established tool for most projections of climate change, but the horizontal resolution of most GCMs used in such research is too coarse to simulate the dynamics of a deepening TC (Lighthill *et al.*, 1994). Accordingly, there is a reluctance to estimate how expected future climate changes will affect the occurrence of TC.

Bengtsson *et al.* (1995) identified TC vortices in simulations of the ECHAM3 global general circulation model run at T106 (1.1°) horizontal resolution. Although the 5 year simulation did not include interannually varying SSTs, it nevertheless produced a variable number of TC during each season, with realistic frequencies and geographical distributions. The same model run, at a more conventional horizontal resolution (T42), also created 'hurricane-type' vortices, but with more diffuse gradients and wider horizontal dimensions. They were not able to compute a meaningful model analog for the index of Gray (1979) from their simulations because its variability in the simulations was apparently too great. On the other hand, SST > 26°C proved to be a necessary condition for their modeled TC analogs. Seasonal TC frequency in the GCM appeared to be sensitive to the modeled strength of the Hadley circulation, with more TC during seasons of stronger implied large-scale uplift over tropical oceans.

In the sequel investigation, Bengtsson *et al.* (1996) monitored similar tropical vortices in a parallel 5 year double CO_2 simulation with the same model. SST anomalies for the lower boundary condition came from Year 60 of a transient run of the fully coupled ECHAM3 ocean–atmosphere GCM (Cubasch *et al.*, 1992) run at a much coarser horizontal resolution (T21) with monotonic increases in CO_2. At Year 60 in the coupled model run, the global mean surface air temperature had increased by only 1°C and the largest SST increases were 0.5–1.5°C. They found that the global distribution of simulated TC agreed with that of the present climate, but compared with the control, the number of TC was significantly reduced, particularly in the southern hemisphere. Changes were attributed to a weakening of the Hadley circulation and stronger subtropical upper air westerlies, which increased vertical wind shears over TC genesis areas. The implications of this study have been debated (Landsea, 1997; Henderson-Sellers *et al.*, 1998) and are discussed in the 'Discussion and conclusion' section.

3. GCM-DERIVED GENESIS PARAMETER

The authors suggest that GCM simulations are suitable for analysis of the meteorological/climatological conditions favorable for TC genesis, such as those discussed by Gray (1979), Lighthill *et al.* (1994) and McBride (1995). Deducing the evolution of climatic conditions that are correlated with TC frequency from simulations with a range of climate forcings implies projections of TC frequency compatible with each scenario. Gray's 'genesis parameter' (GP) has six components:

(i) ocean thermal energy, proportional to SST minus 26°C;
(ii) moist stability, proportional to the absolute value of the lapse rate of equivalent potential temperature between the surface and 500 mb;
(iii) relative humidity, proportional to the mean relative humidity between 700–500 mb, scaled between 0–1 for values ranging 40–70%;
(iv) vertical wind shear, proportional to the inverse of the absolute value of the wind shear between 950–200 mb;
(v) vorticity of the near surface circulation;
(vi) Coriolis parameter.

The first three of these comprise a 'thermal potential', while the second three combine to form a 'dynamic potential'. Gray used seasonal climatologies to compute spatial distributions of indexes based on each of the six components. The indexes were tuned so that their multiplication yielded a seasonal genesis parameter (SGP) indicating the frequency of TC genesis for each 5° square per 20 years. Thus, each component serves as a necessary condition for TC genesis, since SGP will not exceed zero unless all of the individual components are positive. The spatial distribution of SGP based on Gray's data from 1958–1977 is remarkably similar to the distribution of observed TC frequency for that period.

Ryan *et al.* (1992) computed a yearly GP (YGP) for a 15 year double CO_2 equilibrium simulation with the CSIRO9 GCM, with 9-level vertical and R21 (3.2° × 5.6°) horizontal resolution. SST evolution was computed for a slab ocean with prescribed ocean heat convergence. The global mean surface temperature increase for this $2 \times CO_2$ run was a rather large 4.8°C compared with the 15 year $1 \times CO_2$ control run, whose climatology was also used to generate a YGP distribution. YGP based on the control simulation was globally 37% higher than Gray's YGP total, the excess being attributed in large measure to overestimates of ocean thermal energy. The spatial distribution of YGP computed from the control climatology was overall, reasonable, although several discrepancies from observations were noted. For example, the model indicated YGP between 1–5 (TC per 5° square per 20 years) in regions where TC genesis is not observed, such as along the tropical coastlines of the South Atlantic. Results for the western North Pacific and Australia vicinity were skillful, but YGP was underestimated in the eastern North Pacific and the North Atlantic maximum was displaced westward into the Caribbean. The global sum of predicted TC genesis for the $2 \times CO_2$ experiment was about three times the control value. Maxima more than doubled in the western North Pacific and Australia vicinity. The area of predicted genesis in the North Atlantic spread eastward to Africa compared with the control results. These increases in YGP due to global warming resulted from the model's predicted increases in SST, which increased the ocean thermal energy and destabilized the lower troposphere. No significant changes in vorticity or vertical wind shear were evident between the experiment and control runs.

YGP was also computed from simulations with the ARPEGE GCM (Centre National Recherches Météorologiques, France), a control with Atmospheric Model Intercomparison Project (AMIP) SST and two $2 \times CO_2$ experiments (Royer *et al.*, 1998). The model has 30 vertical levels and an equivalent horizontal resolution of about 2.8°. SST for the $2 \times CO_2$ were simulated by two different coupled atmosphere–ocean models that were forced by transient increases of atmospheric CO_2 concentration. Although the global mean increase of surface air temperature for the $2 \times CO_2$ simulations was less than 2°C, a near doubling of YGP in the northern hemisphere resulted, influenced mostly by higher ocean thermal energy and hardly at all by changes in dynamic potential.

Watterson *et al.* (1995) showed that YGP derived from the European Center for Medium-Range Weather Forecasts (ECMWF) gridded observational analyses were extremely sensitive to modifications in the ECMWF GCM. Indeed, the average yearly global number of TC predicted by 1985–1989 data (74) was less than half the number for 1980–1984 (184). In particular, the humidity term during the later years was on average about one-third of its value up until 1984.

Watterson *et al.* (1995) also computed seasonal genesis parameters (SGP) from ECMWF gridded observational analyses, 1985–1989, as well as from the seasonal climatologies of 10 year CSIRO9 model simulations (3.2° × 5.6° horizontal resolution) forced by observed AMIP SST. The ECMWF SGP for July–September showed a 0.57 correlation over ocean points 40°S–40°N with the record of TC frequency distribution observed 1967–1986, while the correlation coefficient between model results and the same observations was only 0.44. In particular, model results underestimated TC activity in the tropical North Pacific by about 60%. In the North Atlantic, the model SGP was only slightly high, but the mid-ocean maximum was not diagnosed, the higher frequencies being confined to the Caribbean sector.

The central North Pacific had more TC activity in June–September 1982 than in the following year. Watterson *et al.* (1995) forced the CSIRO9 model with SST for those seasons and computed the corresponding SGP that successfully reflected the observed relative surplus of TC activity in JAS 1982. They found that both the dynamic and thermal components were important in establishing the interannual differences in SGP. Time series of the JAS SGP, 1979–1988, from model runs were correlated with corresponding observations best in the central North Pacific (0.70), moderately in the North Atlantic (0.56) and more poorly in the western (0.23) and eastern (0.41) North Pacific. They also found that the modeled SGP time series for January–March was not a useful indicator of observed TC interannual variability (mostly in the southern hemisphere).

In a more recent study, January spatial distributions of SGP were computed from simulations with a limited area model run at 125 km horizontal resolution over a domain centered on Australia (Walsh and Watterson, 1997). These SGP arrays were found to bear some relationship with the spatial distributions of explicitly modeled TC genesis frequency, but the correlation was limited, only 0.26 for the strongest tropical cyclone-like vortices. For example, the model generated a rather high frequency of TC over the South China Sea where SST did not generally exceed the 26°C threshold that makes SGP non-zero. Moreover, SGP patterns based on the modeled climate were better correlated with observed TC patterns than the explicitly modeled frequency of tropical cyclone-like vortices.

4. GISS GCM STUDY

The authors used the 9-layer general circulation model of the NASA/Goddard Institute for Space Studies (GISS GCM) (Hansen *et al.*, 1996), running on a Cartesian grid with 4° latitude by 5° longitude horizontal resolution. A control model climate for July–September (JAS) was computed from the last 30 years of a 50 year simulation. The moist convection parameterization of the GISS GCM (Del Genio and Yao, 1993), which is very relevant to this application, specifies a vertical mass flux proportional to the moist static instability. Cumulus mass fluxes are constrained to relax the atmosphere to a neutrally stable state at the cloud base.

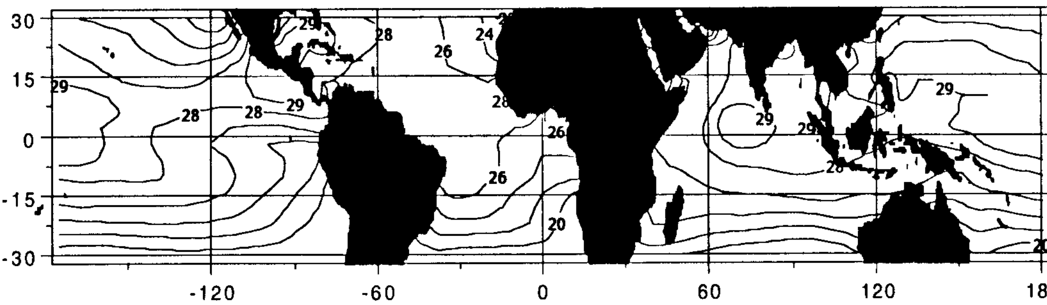

Figure 1. Distribution of July–September mean SSTs (°C) computed by the GISS GCM 'q-flux' ocean formulation for years 21–35 of the control (1 × CO_2) simulation

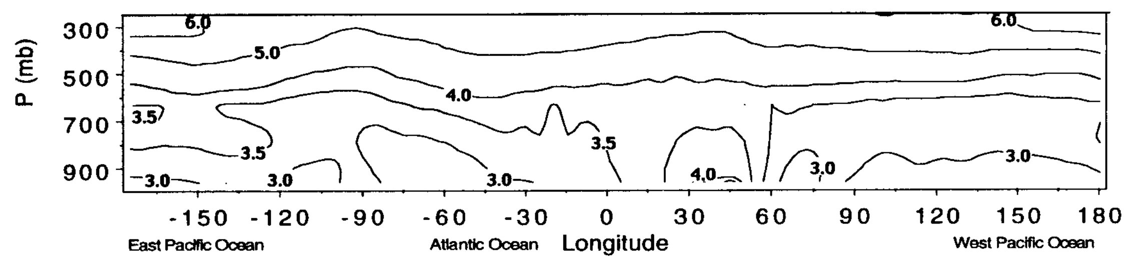

Figure 2. Pressure–longitude cross-section of atmospheric temperature impacts, 2 × CO_2 minus 1 × CO_2, averaged over 14–18°N for multi-year July–September means (°C)

This simulation was made with a mixed layer ocean lower boundary (Russell *et al.*, 1985) in which vertical and horizontal heat transports are prescribed to be consistent with the seasonal march of climatological SST. The mixed layer ocean formulation allows SST evolution to be driven by simulated energy balances at the ocean–atmosphere boundary, resulting in realistic equilibrium SST distributions, as for example the July–September mean shown in Figure 1. The 30 year 'q-flux' run serves as the control for a 20 year double CO_2 (2 × CO_2) equilibrium experiment (the last 20 years of a 50 year simulation). Characteristics of this 2 × CO_2 simulation were previously described by Rind (1998). Atmospheric warming is represented by an increase of 3.5°C in the annual global mean surface temperature compared with the control climate, while this increase was 3.7°C for July–September. Figure 2 shows a height–longitude cross-section of July–September temperature impacts along 14–18°N. Corresponding SST increases for the 2 × CO_2 simulation ranged between 2 and 3°C (Figure 3). The global mean annual increase in SST was 2.3°C and the global mean increase in precipitable water was 6.3 mm or 27% (Rind, 1998).

In an effort somewhat parallel to the studies of Ryan *et al.* (1992) and Watterson *et al.* (1995), the authors computed the July–September SGP from the 20 year 2 × CO_2 equilibrium experiment and the 30 year control. They offer here brief highlights that can be compared with the previously published results

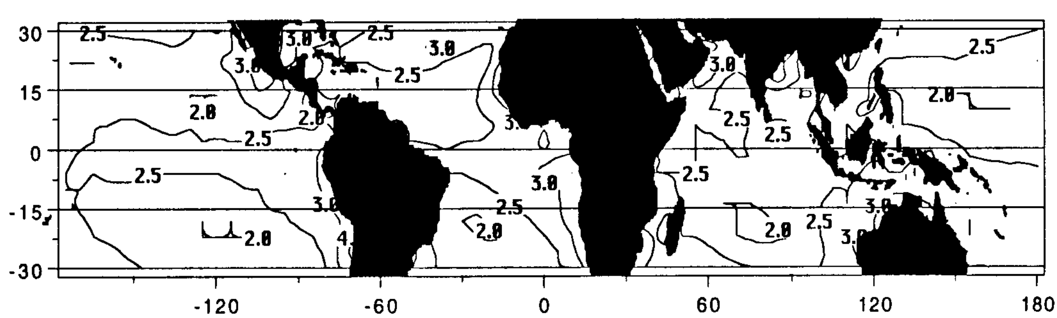

Figure 3. Impact of 2 × CO_2 on SSTs (°C, 2 × CO_2 minus 1 × CO_2)

using the CSIRO9 GCM. The ineffectiveness of this approach for diagnosing TC genesis over the central tropical North Atlantic Ocean (discussed below) provides impetus for the study discussed in Section 5 which examines the impact of the $2 \times CO_2$ regime on easterly wave generation.

4.1. SGP in control simulation

SGP based on the GISS GCM control simulation indicate a maximum in the Gulf of Mexico that slightly overestimates observed TC genesis values given by Gray (1979), as did Gray's SGP values based on 1958–1977 climatological data (Figure 24 in Gray, 1979).

However, a second observed maximum in the central tropical North Atlantic is not predicted by the model climatology, due in large measure to underestimates of near-surface vorticity in the Inter-tropical Convergence Zone (ITCZ), GCM wind shears that are slightly higher than observed and model relative humidities that seem to be some 10–15% too low along 10°N compared with Gray's climatology (against which the formulation for SGP was tuned; Gray, 1979). The authors found that NCEP reanalysis relative humidities in a 1982–1994 climatology validate the GISS GCM values quite well, so it is not clear whether the SGP formulation lacks tuning or whether climatological relative humidities are just uncertain. In addition, the GCM simulated instability parameter is considerably weaker than that given by Gray (1979) over most of the Atlantic. Watterson *et al*. (1995) reported wide interannual fluctuations in both the humidity and instability terms based on ECMWF gridded analyses.

In summary, the GCM climatology 'predicts' a reasonable pattern of TC genesis over the Gulf of Mexico and Caribbean Sea. However, over the central Tropical Atlantic, modeled vorticity is too weak, humidity too low and wind shear excessive, leading to gross underestimates of TC genesis based on the original SGP formulation. Of course, there is significant decadal variability of observed TC genesis frequency (Landsea and Gray, 1992) that may be reflected by large variability in climate fields. Calculations of TC genesis frequencies based on control simulations with the ARPEGE GCM incurred similar underestimates over the central Tropical Atlantic, even when Gray's thermal potential was replaced by a newly formulated convective potential (Royer *et al*., 1998).

The spatial pattern of SGP based on the control simulation over the eastern quarter of the tropical North Pacific Ocean was highly correlated ($R = 0.81$) with the observed pattern. However, the values of SGP implied by the GCM climatology were somewhat underestimated. Over the tropical Western Pacific, the July–September SGP derived from model variables bears a close resemblance to observed 1958–1977 frequencies of TC genesis, except that the modeled maximum is displaced to the northeast, probably because of a similar displacement of the model's representation of the ITCZ.

4.2. Double CO_2 equilibrium impact on SGP

The authors next examine how the climate parameters relevant to TC genesis frequency change in the $2 \times CO_2$ simulation. There was no significant impact of $2 \times CO_2$ on July–September mean lower tropospheric vorticity or wind shear in the Gulf of Mexico or the western Tropical Atlantic. However, SST increased by about 2.5°C (Figure 3), causing a concomitant decrease in vertical thermal stability.

In an effort to calibrate the modeled values of SGP, a least squares linear regression relationship between the simulated (control) and observed SGP patterns over the western section of the Atlantic basin (95°–75°W) was computed. The resulting relationship was then used to scale the results of the $2 \times CO_2$ simulation. An additional regression for control results over the Tropical Eastern Pacific provided similar scaling for projected $2 \times CO_2$ SGP in that region. No calibration was necessary for results over the Tropical Western Pacific. The July–September distribution of these scaled SGP based on the $2 \times CO_2$ imply increases of 2–3 TC per 5° square per 20 years (about a 50% increase over the control values) in the Gulf of Mexico and the western Tropical North Atlantic along 25°N. Over the North Pacific, $2 \times CO_2$ implied increases in TC frequency of 100–200%, most of which is related to model projected increases of 2–3°C in SST. However, modest increases from $2 \times CO_2$ in the July–September mean near-surface vorticity over the north-western Pacific Ocean also favored higher frequencies of TC genesis.

These projections of large increases in TC genesis frequency are probably gross overestimates because the present SGP formulation may not be realistic for future climates. A qualitative analysis of $2 \times CO_2$

impacts on relevant climate components may, therefore, be more meaningful than the absolute changes in SGP itself. This is discussed in more detail in Section 6.

5. SIMULATED EASTERLY WAVES IN THE EASTERN NORTH ATLANTIC

Motivated by the poor representation of tropical storm genesis in the eastern North Atlantic Ocean by SGP, even for the current climate, the authors suggest another approach for evaluating how climate change will impact the frequencies of tropical storm genesis in this region. Their analysis examines the impact of $2 \times CO_2$ on simulated easterly waves. The summary of the results is preceded by a background discussion.

Landsea and Gray (1992) relate hurricane activity in the North Atlantic with Sahel summer rainfall, since African wave disturbances moving through the Sahel and out over the adjacent coastal waters are often precursors of North Atlantic tropical cyclones. Reed *et al.* (1988) detected African and North Atlantic wave tracks in ECMWF analyses by examining distributions of 3–5 day period filtered 700 mb vorticity variances. Variance maxima indicate regions of large fluctuations of cyclonic and anticyclonic vorticity, hence trajectories of transient cyclonic disturbances. Druyan and Hall (1994, 1996) described African waves in the GISS GCM and showed the spatial distribution of transient wave spectral amplitudes based on simulated 780 mb meridional wind time series. African waves in the GISS GCM generally had longer periods than their observed counterparts.

Encouraged by these diagnostics for detecting easterly waves over West Africa and the North Atlantic, the authors made relevant spectral analyses of the GCM-simulated vorticity and mid-tropospheric meridional wind over the North Atlantic Ocean. Since this analysis is based on time series with daily temporal resolution, archived monthly means from the GCM experiments described above could not be used. They therefore repeated the July–October portion of the control and $2 \times CO_2$ simulations, each from eight arbitrarily different initial conditions, saving GCM climate data at 6 h intervals over the tropics.

Results based on means from the eight-run ensembles are discussed below for the spectral band of 3–6 day periods. The authors ascertained, however, that the major conclusions are not particularly sensitive to small adjustments in the spectral interval. Figure 4A shows the variance of modeled vorticity at 780 mb for 3–6 day period filtered time series for July–October in the control run. The maximum over West Africa, representing the area of wave genesis, extends westward out over the Atlantic along 20–25°N, similar to the ECMWF pattern analyzed by Reed *et al.* (1988). The corresponding distribution for the $2 \times CO_2$ simulation indicates a more narrow swath that is displaced southward to about 14°N, with higher values of the variance from West Africa westward across most of the North Atlantic (Figure 4B). Positive differences between the $2 \times CO_2$ and control simulations (Figure 4C) are generally 2–6-times the combined standard deviations of the two eight-run ensembles, indicating statistical significance over a broad region of the eastern tropical Atlantic Ocean, where so-called Cape Verde hurricanes form. Such increases in the vorticity variance imply greater amplitudes of the average disturbance intensity and/or greater numbers of transient wave traversals over the eastern North Atlantic in the warmer climate. Inspection of a number of 3–6 day band pass filtered vorticity time series, one of which is shown in Figure 5, indicates that easterly waves in the $2 \times CO_2$ have considerably larger amplitudes than in the control, but occur with about the same frequency.

A similar conclusion can be deduced from examination of the spatial distribution of 3–6 day spectral amplitudes based on July–October time series of the 780 mb meridional wind from the two sets of simulations. Power spectra of this variable were previously used to monitor African wave disturbances simulated by the GISS GCM (Druyan and Hall, 1994, 1996). Figure 6A shows a maximum over West Africa, roughly corresponding to the location of the vorticity variance maximum, while Figure 6B shows the organization of a stronger maximum at 14–18°N along the African Atlantic coast for the simulated warmer climate. The swath of maximum $2 \times CO_2$ minus control differences (Figure 6C), statistically significant along the West Africa coast and over the Cape Verde region of the North Atlantic, also implies that the warmer climate experiences stronger 3–6 day period waves that move westward off the coast of West Africa out into the North Atlantic. The center of maximum differences is farther north than the

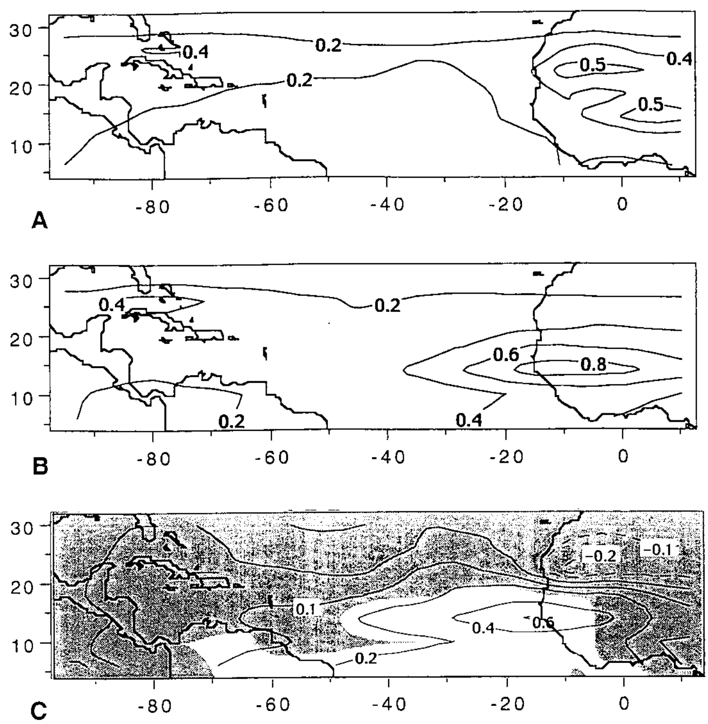

Figure 4. A. Variance of modeled 780 mb vorticity (10^{-12} s^{-2}) for 3–6 day period band pass filtered time series for July–October averaged over eight control ($1 \times CO_2$) simulations. B. Same as A, but for eight $2 \times CO_2$ simulations. C. Impacts of $2 \times CO_2$ on vorticity variance (B – A). Whitened area highlights region for which differences are significant at the 95% or higher confidence level

corresponding maximum in Figure 4C because the strongest meridional winds associated with such disturbances are often north of the vorticity maximum.

6. DISCUSSION AND CONCLUSION

Model projections of SST change were of considerable importance to the evaluations of possible increases in TC activity over northern hemisphere oceans for the $2 \times CO_2$ climate. SST warming predicted by the

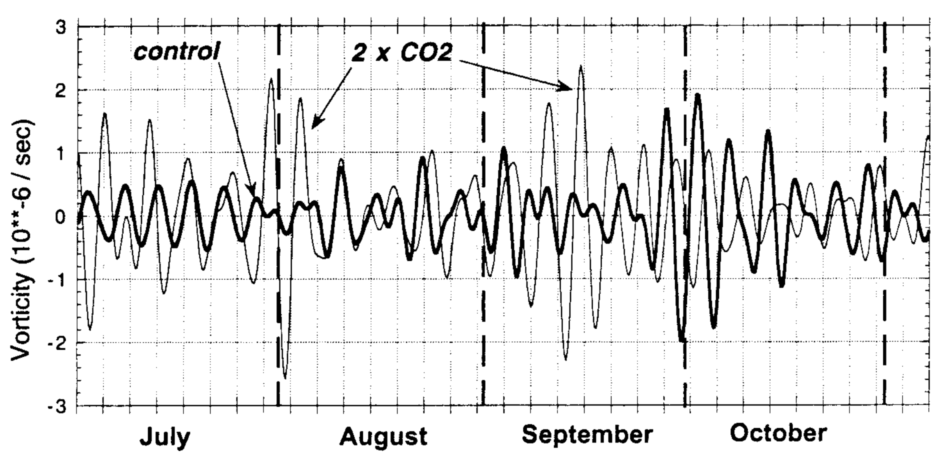

Figure 5. July–October time series of 780 mb vorticity for single simulations of $1 \times CO_2$ and $2 \times CO_2$ at 14°N, 25°W, band pass filtered for 3–6 day periods. Vertical lines are placed at 4 day intervals

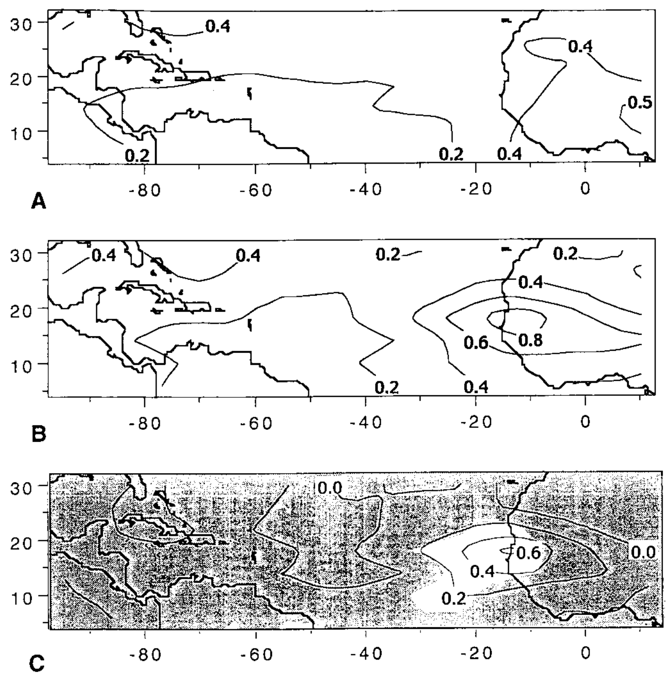

Figure 6. A. Spatial distribution of 3–6 day period spectral amplitudes (m s^{-1}) of 780 mb meridional wind component (V_{780}) July–October time series averaged from eight control ($1 \times CO_2$) simulations. B. Same as A, but for eight $2 \times CO_2$ simulations. C. Impacts of $2 \times CO_2$ on V_{780} spectral amplitudes (B − A). Whitened area highlights region for which differences are significant at the 95% or higher confidence level

GISS GCM $2 \times CO_2$ simulation (mostly 2–3°C) may be overestimated because the 'q-flux' modeling approach does not account for negative feedbacks in ocean circulation that could mitigate the warming. Still, even projections of smaller SST increases from coupled atmosphere–ocean models in another study implied a near doubling of future TC genesis frequency (Royer *et al.*, 1998).

The more than doubling of control frequencies of the seasonal TC genesis parameter over the North Pacific based on the GISS GCM $2 \times CO_2$ simulation recalls similar results from the comparable CSIRO9 GCM (Ryan *et al.*, 1992). Moreover, the authors also found, as they did, that most of the projected increases in TC genesis frequency can be attributed to the predicted ocean warming and not to changes in vorticity, wind shear or humidity. The exception is that for the GISS $2 \times CO_2$ scenario there were positive contributions from increases in near surface vorticity east of the Philippines, a major breeding ground for TC associated with a rather large displacement of the ITCZ from the equator. Perhaps, therefore, the future climate will experience more frequent TC activity in this region partly owing to stronger convergence (hence vorticity) into that segment of the ITCZ.

The current analysis found that the vorticity of easterly wave disturbances in the $2 \times CO_2$ simulations was consistently and significantly stronger than in the control. This suggests that a warmer climate might generate stronger incipient disturbances over West Africa and the adjacent North Atlantic, no doubt in part owing to elevated SST. All other things being equal, the greater vorticity of each disturbance could presage a more efficient intensification to tropical storm strength than in the current climate. In addition, vorticity variance maxima, indicating preferred trajectories of African waves in the $2 \times CO_2$, were simulated along 14°N. This represents a southward displacement of easterly waves' tracks compared with the control simulation.

A recent assessment (Henderson-Sellers *et al.*, 1998) states that the environmental parameters that appear important for TC genesis in the current climate will likely change to as yet undetermined thresholds. The 26°C SST threshold adopted by Gray (1979) identifies areas of high ocean thermal energy, but it also demarcates areas of vertical thermal instability that are prone to deep convection (Royer *et al.*, 1998; Evans, personal communication). Since the mid-troposphere will also be warmer in future climates, instability could require higher SST thresholds as necessary conditions for TC genesis. Using the 26°C threshold, therefore, probably also contributes to exaggerated estimates of TC genesis frequency implied by SGP for both the current and the Ryan *et al.* (1992) $2 \times CO_2$ scenarios. Accordingly, Royer *et al.* (1998) found that increases in TC genesis frequency over the northern hemisphere for their $2 \times CO_2$ experiments were smaller when they replaced Gray's thermal potential (including the 26°C threshold) with a convective potential. Nevertheless, since the vertical moist stability component of SGP monitors the impact of changes in the (equivalent potential) temperature lapse rate, even in its present formulation, SGP cannot be large wherever the vertical thermal structure has been stabilized. It may, therefore, still be relevant to refer to an as yet undetermined SST threshold to represent the minimum reservoir of ocean thermal energy needed to power the storms.

The authors examined the relative warming at each vertical level experienced by their $2 \times CO_2$ simulation. Figure 2 shows a cross-section of $2 \times CO_2$ minus control temperature changes along 14–18°N, traversing the centers of maximum observed TC genesis frequency in the North Atlantic and North Pacific Oceans. Relative to the control, temperatures in the lowest model layer have warmed by about 3°C, compared with warming of about 4°C at 500 mb. This differential warming of the mean temperature structure stabilizes the lower troposphere and undoubtedly inhibits dry convection. Rind (1998) found a slight stabilization in the annual/global mean tropospheric lapse rate from $-6.01°C\,km^{-1}$ to $-5.87°C\,km^{-1}$ between the control and $2 \times CO_2$ simulations. However, the frequency of TC genesis is more likely sensitive to the vertical lapse rate of the *equivalent potential* temperature (Gray, 1979), which accounts for the enhancement of convection by condensational heating. Accordingly, large increases in near-surface specific humidity accompanying a future warmer climate make the lower troposphere *conditionally* more unstable. Indeed, for this reason, the authors found the vertical stability component of the SGP to be significantly *more favorable* for TC genesis in the $2 \times CO_2$ over the tropical oceans, despite the simulated moderation in the vertical temperature lapse rate.

Henderson-Sellers *et al.* (1998) also questioned whether the lowered frequencies of TC reported by Bengtsson *et al.* (1996) for the double CO_2 climate might have been different if the SST had also been predicted at the finer horizontal resolution. Landsea (1997) found it inconsistent that the hydrological cycle speeded up with increasing atmospheric CO_2 concentration using the low resolution coupled model which provided the SST boundary conditions for the Bengtsson *et al.* (1996) simulation, whereas the hydrological cycle slowed relative to the control in the high resolution experiment itself. Moreover, their approach of counting explicitly simulated vortices also introduces uncertainties because, even at 1.1°, the model's horizontal resolution may be inadequate to mimic actual genesis processes that have been observed to occur on scales of 50 km (Emanuel, personal communication). Finally, the SST forcing in this global warming experiment (increases of 0.5–1.5°C) was rather small compared with the ocean warming in the current GISS GCM double CO_2 simulation. One reason is that the SST in the ECHAM3 experiment were not double CO_2 equilibrium values, but rather values reached during the 60th year of a scenario with monotonic increases in atmospheric CO_2 concentrations. A similar experiment with the GISS coupled atmosphere–ocean model (Russell *et al.*, 1995) predicts SST increases by Years 64–75 ($2 \times CO_2$) mostly between 1–1.5°C in the tropics, but with substantial areas warming to more than 1.5°C in key hurricane genesis regions in the North Atlantic and the East North Pacific.

The authors computed the July–September SGP based on NCEP reanalysis data for 1982–1994. NCEP reanalysis data are of course quite different and presumably more realistic than the distributions analyzed by Gray (1979) for the years 1958–1977. SGP values are considerably lower based on these NCEP data than SGP given by Gray (1979) in the North Atlantic and North Pacific Oceans. Seasonal mean values of the relevant climate parameters from the NCEP spatial distributions were in many cases less favorable to TC genesis according to the original criteria, as for example, the mean relative humidity from 700–500 mb. Over many key TC genesis areas, NCEP analyzed relative humidity is 15–20% lower than the values Gray used to derive his SGP. This suggests that the index could be better tuned to reflect even the current definitions of environmental seasonal means. A TC genesis index that could be derived from realistic simulations of future climate scenarios should therefore

(i) have a more robust relationship with the observed variability of TC genesis frequency and
(ii) be as relevant to an overall warmer climate as it is to the present one.

Explicit simulation of more realistic tropical vortices should steadily improve as technology brings ever increasing computing speed and memory, allowing computations to be made at higher and higher resolution. Numerical simulation experiments with fewer flaws than heretofore may soon offer more satisfying evidence regarding the impact of climate change on tropical cyclones. The present study can serve as a benchmark against which future results should be compared.

ACKNOWLEDGEMENTS

This research was partially funded by Risk Prediction Initiative of the Bermuda Biological Station for Research under Grant RPI 96-008 and the National Science Foundation under Grant ATM-9725142. The support of the NASA Climate and Earth Observing System Programs is also gratefully acknowledged.

REFERENCES

Bengtsson, L., Botzet, M. and Esch, M. 1995. 'Hurricane-type vortices in a general circulation model', *Tellus*, **47A**, 175–196.

Bengtsson, L., Botzet, M. and Esch, M., 1996. 'Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?', *Tellus*, **48A**, 57–73.

Cubasch, U., Hasselmann, K., Hock, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B. and Sausen, R. 1992. 'Time-dependent greenhouse warming computations with a coupled ocean–atmosphere model', *Clim. Dyn.*, **8**, 55–69.

Del Genio, A. and Yao, M.-S. 1993. 'Efficient cumulus parameterization for long-tern climate studies: The GISS scheme', *Am. Meteorol. Soc. Monogr.*, **46**, 181–184.

Druyan, L. and Hall, T. 1994. 'Studies of African wave disturbances with the GISS GCM', *J. Clim.*, **7**, 261–276.

Druyan, L. and Hall, T. 1996. 'The sensitivity of African wave disturbances to remote forcing', *J. Appl. Meteorol.*, **35**, 1100–1110.

Gray, W. 1979. 'Hurricanes: their formation, structure and likely role in the tropical circulation', in Shaw, D.B. (ed.), *Meteorology Over the Tropical Oceans*, Royal Meteorological Society, London, pp. 155–218.

Hansen, J., Sato, M., Ruedy, R., Lacis, A., Asamoah, K., Borenstein, S., Brown, E., Cairns, B., Caliri, G., Campbell, M., Curran, B., de Castro, S., Druyan, L., Fox, M., Johnson, C., Lerner, J., McCormick, M., Miller, R., Minnis, P., Morrison, A., Pandolfo, L., Ramberran, I., Zaucker, F., Robinson, M., Russell, P., Shah, K., Stone, P., Tegen, I., Thomason, L., Wilder, J. and Wilson, H. 1996. 'A Pinatubo climate modeling investigation', in Fiocco, G., Fua, D. and Visconti, G. (eds), *The Mount Pinatubo Eruption: Effects on the Atmosphere and Climate*, NATO ASI Series Vol. I 42, Springer, Heidelberg, pp. 233–272.

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P. and McGuffie, K. 1998. 'Tropical cyclones and global climate change: A post-IPCC assessment', *Bull. AMS*, **79**, 19–38.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G., Mitchell, J., Stouffer, R., Tokioka, T., Weaver, A. and Wigley, T. 1996. 'Climate models, projections of future climate', in Houghton, J., Filho, L., Callander, B., Harris, N., Kattenberg, A. and Maskell, K. (eds), *Climate Change 1995*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and World Meteorological Organization, Geneva, Chapter 6, pp. 289–357.

Landsea, C. 1997. 'Comments on "Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?" ', *Tellus*, **49A**, 622–623.

Landsea, C. and Gray, W. 1992. 'The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes', *J. Clim.*, **5**, 435–453.

Lighthill, J., Holland, G., Gray, W., Landsea, C., Craig, G., Evans, J., Kurihara, Y. and Guard, C. 1994. 'Global climate change and tropical cyclones', *Bull. AMS*, **75**, 2147–2157.

McBride, J. 1995. 'Tropical cyclone formation', in Elsberry, R. (ed.), *Global Perspectives on Tropical Cyclones*, TSP-38/WMO TD # 693, World Meteorological Organization, Geneva, Chapter 3, pp. 63–105.

Reed, R., Klinker, E. and Hollingsworth, A. 1988. 'The structure and characteristics of African easterly wave disturbances as determined from the ECMWF operational analysis/forecast system', *Meteorol. Atmos. Phys.*, **38**, 22–33.

Rind, D. 1998. 'Latitudinal temperature gradients and climate change', *JGR*, **103**, 5943–5971.

Royer, J.-F., Chauvin, F., Timbal, B., Araspin, P. and Grimal, D. 1998. 'A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones', *Clim. Change*, **38**, 307–343.

Russell, G., Miller, J. and Tsang, L.-C. 1985. 'Seasonal oceanic heat transports computed from an atmospheric model', *Dyn. Atmos. Oceans*, **9**, 253–271.

Russell, G., Miller, J. and Rind, D. 1995. 'A coupled atmosphere–ocean model for transient climate change studies', *Atmos.–Oceans*, **33**, 687–730.

Ryan, B., Watterson, I. and Evans, J. 1992. 'Tropical cyclone frequencies inferred from Gray's yearly genesis parameter: validation of GCM tropical climates', *Geophys. Res. Let.*, **19**, 1831–1834.

Walsh, K. and Watterson, I. 1997. 'Tropical cyclone-like vortices in a limited area model: comparison with observed climatology', *J. Clim.*, **10**, 2240–2259.

Watterson, I., Evans, J. and Ryan, B. 1995. 'Seasonal and interannual variability of tropical cyclogenesis: diagnostics from large-scale fields', *J. Clim.*, **8**, 3052–3066.

