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Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?

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ABSTRACT

The use of a high resolution atmospheric model at T106 resolution, for studying the influence of greenhouse warming on tropical storm climatology, is investigated. The same method for identifying the storms has been used as in a previous study by Bengtsson et al. The sea surface temperature anomalies have been taken from a previous transient climate change experiment, obtained with a low resolution ocean-atmosphere coupled model. The global distribution of the storms, at the time when the CO_2 concentration in the atmosphere had doubled, agrees in geographical position and seasonal variability with that of the present climate, but the number of storms is significantly *reduced*, particularly at the Southern Hemisphere. The main reason to this, appear to be connected to changes in the large scale circulation, such as a weaker Hadley circulation and stronger upper air westerlies. The low level vorticity in the hurricane genesis regions is generally reduced compared to the present climate, while the vertical tropospheric wind shear is somewhat increased. Most tropical storm regions indicate reduced surface windspeeds and a slightly weaker hydrological cycle.

1. Introduction

The possibility of climate change due to the ongoing rapid increase in the atmospheric concentration of the greenhouse gases has been intensely investigated over the last couple of years. The question that an overall warming of the earth atmosphere will take place in the next century is virtually unanimously accepted by the scientific community, although some disagreement is related to the magnitude of the change and how long it may take before it may become indisputably noticeable (Houghton et al., 1990, 1992). The magnitude of the change as well as the delay, has to do with the many complicated and still not completely understood feedback processes in the climate system, including the carbon cycle and the carbon dioxide budget. The rôle of clouds and water vapour is here one of the most important mechanisms, another one is the ocean circulation.

Although an overall change in temperature will have consequences for mankind, the possible change in precipitation and in different kinds of extreme weather is more serious due to the effect it may have on the production of food and the damage severe weather can do to society. Among the extreme weather events, tropical cyclones are by far the most devastating, both by causing loss of human life as well as giving rise to large economic losses. The tropical storm which affected Bangladesh 25 years ago and killed more than 300,000 people is probably one of the most terrible natural catastrophies in this century. With respect to economic damages it has now been estimated that the hurricane Andrew in the United States in August 1992 led to damages in the order of 30 billion US dollars. In addition to all the individual sufferings, the world's big insurance companies have met with some financial difficulties due to the extraordinarily high compensation claims.

It is therefore of considerable interest to explore whether extreme events like hurricanes and typhoons may be more common and more

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devastating or influencing larger areas in the future due to an increase in the sea surface temperature as a consequence of greenhouse warming. Empirical evidence as well as numerical simulation studies (Bengtsson et al., 1995) do indicate that the tropical storms only develop in areas where the sea surface temperature is higher than some 26°C. At first estimate therefore, an increase of such an area would have the consequences that tropical storms may affect larger areas and occur in regions where they presently do not occur.

Although several climatologists, e.g., Committee on Earth Sciences (1989), Schneider (1990), argue that the climate warming may have started and that there exist indications that the intensity of tropical storms as well as extratropical storms may have increased, there are also other studies (Idso, 1989; Idso et al., 1990) which claim that such signs cannot yet be detected. The long series of tropical cyclones of the North Atlantic Ocean 1871–1992 (Neumann et al., 1993) does not show any particular trend in the number of storms over the last 60 years, but instead typical large variations from year to year. Gray (1989) has made the point that warmer sea surface temperatures do not necessarily mean increased hurricane activity, since high sea surface temperature is just one of several conditions favouring hurricane development.

There have also been a few numerical studies (Broccoli and Manabe, 1990, Haarsma et al., 1992), which have been undertaken with low resolution climate models, indicating that the tropical vortices generated by the model may increase with increased greenhouse warming. But as was demonstrated in the paper by Broccoli and Manabe, their result was crucially dependent on the parameterization of clouds. In the case of climatologically prescribed clouds there was an increase in the number of intense tropical storms with a doubling of CO_2, while in the case of clouds dynamically predicted by the model the result was a decrease.

Bengtsson et al. (1995, this study to be notated B95 in the following) reported of the simulation of tropical intense storms with a high horizontal resolution climate model. In that study, the ECHAM3 model (Roeckner et al., 1992) at T106 resolution was used in a 5-year simulation of the present climate. The experiment demonstrated a remarkably good agreement with the observed distribution of tropical storms both with respect to the geographical distribution, and the typical annual variability in different parts of the world where the tropical storms are observed.

In this study, we have undertaken another 5-year integration with the same model and at the same horizontal resolution, but instead of using the present SST conditions we have used the SST resulting from a coupled model experiment (Cubasch et al., 1992) calculating the transient climate change with a coupled ocean/atmosphere model. This model was integrated for 100 years from 1985 to 2085, assuming approximately 1% annual increase of CO_2 (IPCC Scenario A, business as usual according to Houghton et al. (1990)). The atmospheric model had a horizontal resolution of T21. In the present experiment we used the simulated SST data at the time of the CO_2 doubling as boundary conditions for the T106 model. Furthermore we assumed a doubling of the CO_2 concentration in the atmosphere. The same diagnostic evaluation as in B95 was carried out.

In Section 2, we will describe the climate change experiment, in Section 3 the results obtained, followed by the discussion of the results in Section 4.

2. The climate change experiment

The experiment has been carried out in the same way as in B95, where the ECHAM3 model (Roeckner et al., 1992) was used to explore how well a high resolution GCM can simulate hurricane type vortices.

It was found, when using a T106 horizontal resolution, that the model was capable with a remarkable realism in reproducing not only the characteristic structure of hurricanes, but also their geographical distribution and seasonal variability. Experiments with coarser resolutions of the same model generally generated a smaller number of storms. It was also apparent that in certain areas, in particular in the North East Pacific, a realistic number of hurricanes was not generated by the model unless the horizontal resolution was set to T106. The reason is apparently that orographical details and coast lines have to be well described. The hurricane genesis region is geographically limited in the North East Pacific, and this may be the reason why the impact of the higher resolution is so large in this region.

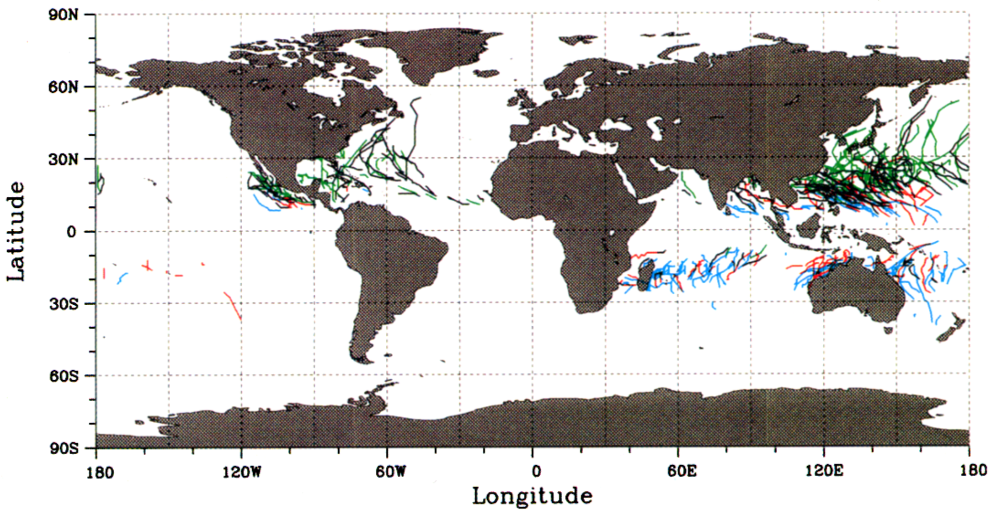

Fig. 1. Simulated cyclone tracks during 5 years for the present climate (from B95). The tracking is only indicated when the hurricanes satisfy the selection criteria. All tracks for 5 years. Blue colour for DJF, red colour for MAM, green colour for JJA and black colour for SON.

In view of the realistic distribution obtained for the present climate, shown in Fig. 1, it was found worthwhile to explore how the hurricanes may change in a warmer climate as is anticipated to be the case in the future.

Since it was not feasible to undertake a completely new climate scenario run at such a high resolution as we wanted to study in this experiment, we decided to make use of a previous climate change experiment carried out by Cubasch et al. (1992).

In this experiment, a coupled ocean-atmosphere model was integrated during 100 years under the assumption of a monotonous increase in CO_2 in agreement with the IPCC Scenario A (Houghton et al., 1990) leading to a doubling of CO_2 after some 60 years of integration. At this time the global surface temperature has increased by about 1°C but with a larger warming over land than over sea. Fig. 2 shows the increase in SSTs over the tropical oceans.

The high resolution experiment was arranged as follows. The SST anomaly at the time when the atmospheric concentration of CO_2 had doubled was used as boundary condition for a 5-year T106-L19 integration. The only change to the atmospheric model compared to the B95 was a doubling of the CO_2 concentration.

The averaged SST anomaly (SST-SST control) was added to the actual SST values used in the previous study (averaged for the period 1979–1988). The hurricane-type vortices were determined automatically by systematically going through the archived data records. This archive includes all basic model parameters at all model levels, together with additional derived quantities, precipitation, fluxes etc. These data were stored twice daily.

The vortices were determined based on dynamical and physical criteria only, in order to avoid empirical conditions on geographical distribution, sea surface temperature or specific time of the year. The search was further limited to ocean areas, since inspection of a large number of maps showed that the hurricanes fizzled out at land fall. As in B95, we only considered storms with a lifetime larger than 36 h.

The following criteria were used for the classification of model hurricanes:

(1) Relative vorticity at 850 hPa $> 3.5 \times 10^{-5}\,s^{-1}$.

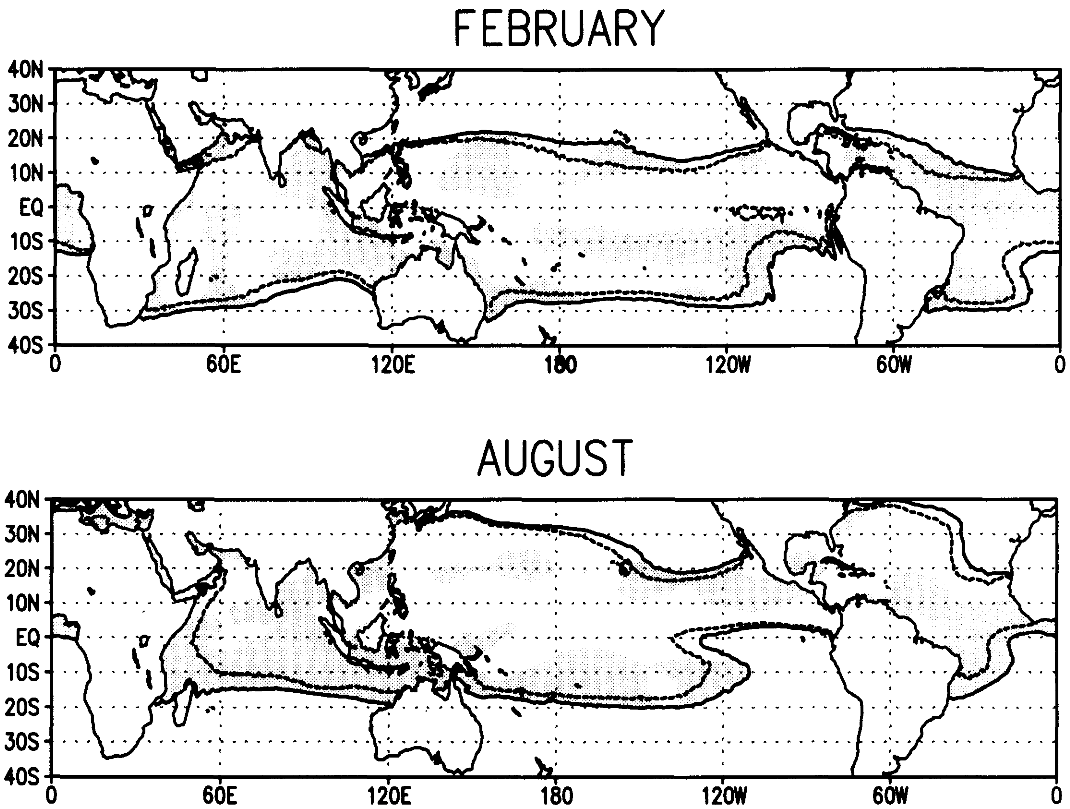

Fig. 2. Sea surface temperature increase in the tropics in the double CO_2 experiment. Dashed lines show the 26°C isoterm for the present climate and full lines the 26°C for the double CO_2 experiment. The sea surface temperature increases are between 0.5°C and 1.5°C generally within the 26°C isoterm. Temperatures increase from present climate to double CO_2 with more than 1°C are shaded. Top figure February conditions, bottom figure August conditions.

(2) A maximum velocity of 15 m s^{-1} and a minimum surface pressure within a 7 × 7 grid point area around the point which fulfils condition 1.

(3) The sum of the temperature anomalies (deviation from the mean, consisting of 7 × 7 grid points) for the levels 700, 500 and 300 hPa > 3°C.

(4) The temperature anomaly at 300 hPa > temperature anomaly at 850 hPa.

(5) The mean wind speed at 850 hPa > mean wind speed at 300 hPa.

(6) Minimum duration of the event ⩾ 1.5 days.

3. Results

We will here concentrate the discussion of the results by putting the main emphasis on the geographical distribution of the storms and with an intercomparison of the result from the present climate study, B95.

The averaged number of simulated tropical cyclones over the 5 years amounts to 54 per year, varying between 50 during the first and fourth year and 57 during the 5th year. The averaged relation between the number of storms at the Northern Hemisphere and the Southern Hemisphere in the simulation is 3.5 compared to 2.1 in B95 (present climate) and 2.2 in Gray's observational study. As will be demonstrated in more detail in Tables 1 and 2, this is a somewhat surprising result, in particular the significant reduction in the number of storms at the Southern Hemisphere. This is illustrated clearly in Fig. 3 which shows the total number of storms in the double CO_2 experiment.

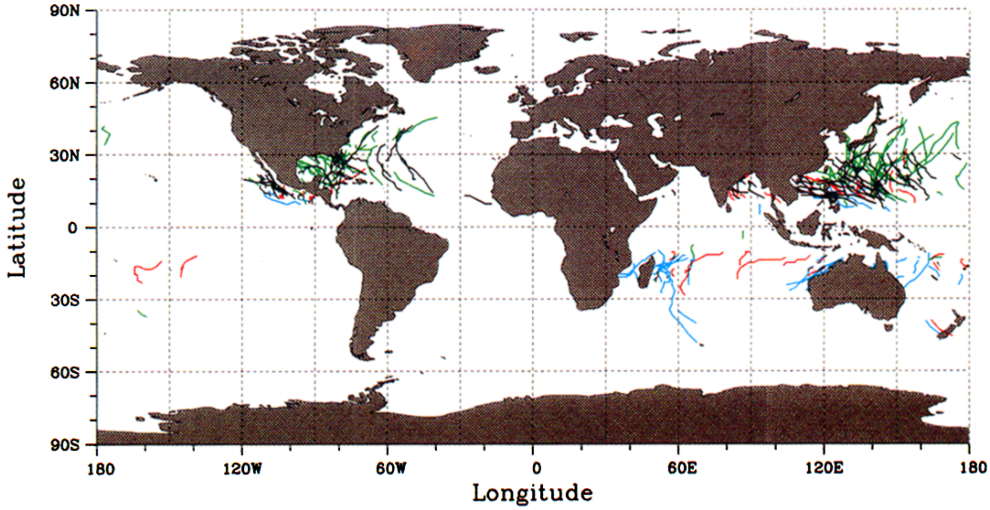

Fig. 3. The same as Fig. 1, but for the double CO_2 experiment.

Table 1 shows the number of simulated Northern Hemisphere cyclogenesis by year and month compared to B95 as well as to the 20 year observational study by Gray (1979). For each month there is a significant reduction, except for July, where the double CO_2 experiment has a larger number of storms.

Table 2 shows the same for the Southern Hemisphere. Here all months show a reduction compared to B95, and two additional months, October and November, show no storms at all. Fig. 4 summarizes the global result for the control and the double CO_2 experiment, respectively.

Table 3 shows the variation of storms by ocean basins. As in B95, as well as observed in nature, there is a considerable variation from year to year suggesting that caution must be exercised in drawing any firm conclusions from the results. However, for the hurricane exposed ocean basins at the Southern Hemisphere, it appears safe to conclude that the result is significant. In the Southern Indian Ocean, for example, all separate years in the double CO_2 experiment have *less hurricanes than all separate years in B95.*

In Table 4, we have ordered the storms by their maximum achieved wind speed and by ocean basins. Comparison with B95, Table 4 shows a very similar distribution and almost the same average maximum windspeed (difference less than 1 m/s). As a rare occasion, although hardly significant, one particular storm in the North East Pacific has a higher maximum windspeed, 56.7 m/s, than any of the storms examined in B95. Fig. 5 summarizes the results.

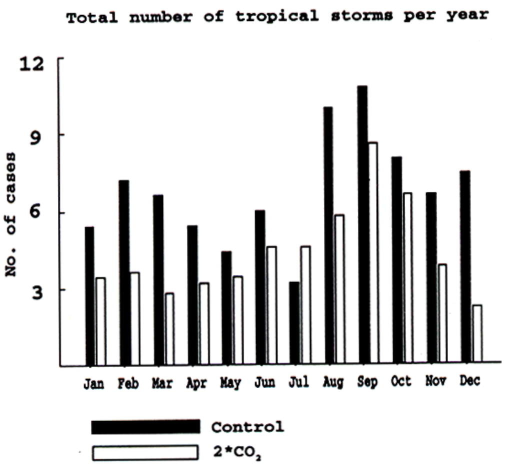

Fig. 4. Total number of simulated tropical cyclones over 5 years by month. Solid bars show the number of cyclones for present climate conditions, unfilled bars for the double CO_2 case.

Table 1. *Number of simulated Northern Hemisphere tropical cyclones by year and month*

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total	Range
1	0	1	1	2	1	8	3	7	6	8	3	1	41	
2	0	1	0	3	2	2	2	9	10	5	5	3	42	
3	0	0	0	2	6	2	10	2	11	5	6	2	46	38–46
4	0	2	1	2	4	3	5	5	7	5	3	1	38	
5	1	0	1	0	2	5	3	5	9	10	2	0	38	
$2CO_2$														
total	1	4	3	9	15	20	23	28	43	33	19	7	205	38–46
average	0.2	0.8	0.6	1.8	3.0	4.0	4.6	4.4	8.6	6.6	3.8	1.4	42.0	
CTRL														
total	11	5	10	7	17	30	16	48	54	38	24	21	281	49–63
average	2.2	1.0	2.0	1.4	3.4	6.0	3.2	9.6	10.8	7.6	4.8	4.2	56.2	
OBS														
(1958–1977) average	0.7	0.3	0.3	1.0	2.9	4.5	8.6	10.9	11.5	7.9	4.3	1.7	54.6	46–70

For comparison the total and average number as calculated from the simulation of the present climate (B95) and the averaged observed number for the years 1958–1977, according to Gray (1979) are given. The column to the right shows the range in the number of storms (lowest and highest number) for the $2CO_2$ simulation, the control and the observed storms, respectively. Reduction of storms in the double CO_2 case is statistically significant within the 99.0% confidence limit.

Table 2. *The same as Table 1 but for the Southern Hemisphere*

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total	Range
1	2	3	1	2	0	1	0	0	0	0	0	0	9	
2	4	1	4	0	1	0	0	0	0	0	0	0	10	
3	1	4	0	1	0	1	0	0	0	0	0	1	8	8–19
4	5	2	1	3	0	0	0	1	0	0	0	0	12	
5	4	4	5	1	1	1	0	0	0	0	0	3	19	
$2CO_2$														
total	16	14	11	7	2	3	0	1	0	0	0	4	58	8–19
average	3.2	2.8	2.2	1.4	0.4	0.6	0.0	0.2	0.0	0.0	0.0	0.2	11.6	
CTRL														
total	26	31	23	20	5	0	0	2	0	2	9	16	134	23–28
average	5.2	6.2	4.6	4.0	1.0	0	0	0.4	0	0.4	1.8	3.2	26.8	
OBS														
(1958–1977)	6.1	5.9	4.7	2.1	0.5	0	0	0	0	0.4	1.5	3.6	24.5	16–35

Table 3. *Number of simulated tropical cyclones by ocean basin and year*

Year	NWatl	NEPac	NWPac*	NInd.	SInd.*	Aust.*	S. Pac.	Others	Total
1	10	6	20	5	3	5	1	0	50
2	12	7	22	1	6	2	2	0	52
3	9	6	24	7	2	4	1	1	54
4	6	9	22	1	6	3	3	0	50
5	10	3	20	4	6	8	4	2	57
$2CO_2$									
total	47	31	108	18	23	22	11	3	263
average	9.4	6.2	21.6	3.6	4.6	4.4	2.2	0.6	52.6
range	6–12	3–9	20–24	1–7	2–6	2–8	1–4		
CTRL									
total	54	39	164	20	64	47	20	7	415
average	10.8	7.8	32.8	4.0	12.8	9.4	4.0	1.4	83.0
range	9–14	6–11	24–41	1–7	7–18	6–12	3–6		
OBS									
(1958–1977)	8.8	13.4	26.3	6.4	8.4	10.3	5.9	—	79.1
range	4–14	8–20	17–35	4–9	4–12	5–17	3–10		

The control simulations (present climate) and the observed number 1958–1977 according to Gray (1979) are shown on the bottom lines. For a specification of the areas, see B95. Others refer to hurricane developments elsewhere. Regions where the reduction of the number of storms are statistically significant (within the 97.5–99.0% confidence limit) are indicated by *.

Table 4. *Maximum windspeed of tropical cyclones by ocean basins*

	Windspeed (m/s)								
Basin	20–25	25–30	30–35	35–40	40–45	45–50	50–55	>55	Total
NWAtl.	2	10	13	10	8	3	1	0	47
NEPac.	5	15	8	2	1	0	0	0	31
NWPac.	6	21	32	24	20	3	1	1	108
NInd.	2	5	7	4	0	0	0	0	18
SInd.	1	3	7	8	2	2	0	0	23
Aust.	2	9	8	1	2	0	0	0	22
S. Pac	0	2	6	2	1	0	0	0	11
Others	0	0	2	1	0	0	0	0	3
Total	18	65	83	52	34	8	2	1	263
CTRL Total	36	111	131	73	40	18	6	0	415

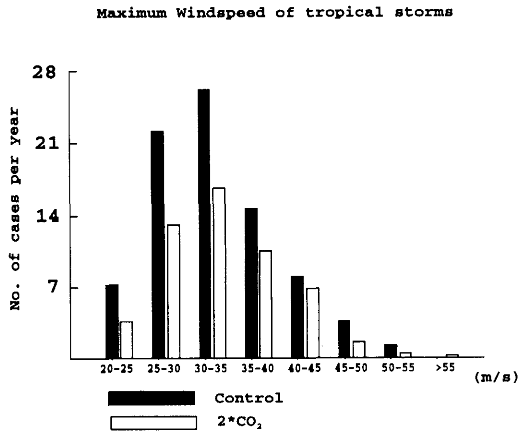

Fig. 5. Maximum windspeed obtained for each individual simulated tropical cyclone for present climate conditions (solid bars) and for the double CO_2 case (unfilled bars).

The statistical significance of the results has been estimated in two different ways. In the first of these estimates we have been making use of the number of observed tropical storms in the North Atlantic area for the period 1931–1990 (Neumann et al., 1993) has been added up in five year intervals in order to make it easier to compare the experiments with observations. In doing so it is also found that the variability is significantly reduced compared to the changes from year to year. The average number of storms in five years is 49.2, with 53.2 and 45.1 being the upper and the lower bound for the 99% confidence interval. We have also examined the complete 120 year dataset (Neumann et al., 1993), which has a variability range, which is twice as large with respect to the 99% confidence limit. However, the reports from the former period are probably less reliable due to the observational deficiencies of earlier years.

In view of the realism of the simulation of the number and the spatial and temporal distribution of hurricanes in the present climate (B95) we may assume that the statistical distribution of hurricanes in a much larger integration will be similar to that of the real atmosphere. We will furthermore restrict the comparison to the two hemispheres and assume that the variability for a five year average is as high as the variability in the North Atlantic area. Such a calculation shows that the reduction in the total number of storms in the double CO_2 case for both hemispheres is within the 99% confidence limit.

In the 2nd statistical test, we disregard any comparison with observed data and instead base the statistical evaluation on the internal variability of the model itself. We will thereby make use of the non-parametric Mann-Whitney test, Conovar (1980), whereby the probability estimate is based on an individual ranking of the number of storms for each individual year for the present and the double CO_2 climate.

If we first consider Tables 1 and 2 on the overall number of storms for the Southern and Northern Hemisphere respectively, it follows that the results for each of the two hemispheres are significant within the 99% confidence limit.

Concerning Table 3, on the results for the individual ocean basins separately, and again each year as one independent experiment, one finds that the reduction of storms in the double CO_2 experiment is significant only for the North-West Pacific, South Indian Ocean and Australia (one-sided significance level 97.5–99% with Mann-Whitney). In Table 3, we have indicated by an asterisk the 97.5–99% confidence level according to the Mann-Whitney test.

4. Discussion

At first consideration it seems reasonable to assume that climate warming leading to higher SST values may also favour a higher frequency of hurricanes as well as more intensive hurricanes. This is based upon the general observation that hurricanes only occur over oceans where the temperature is higher than some 26°C, and that they are found to be particularly violent over the very warm ocean regions in the North West Pacific. The study by Emanuel (1988), using the concept of a Carnot engine, has provided a convincing rationale that the maximum possible hurricane in a particular region is related to the SST and increasing with higher SST. However, Emanuel's study has perhaps also been misconstrued by some readers that more powerful hurricanes a priori will occur as a consequence of climate warming with higher SSTs.

For one thing, most coupled ocean-atmosphere models predict that ocean surface temperature will increase rather little with a doubling of the CO_2

content in the atmosphere. This is particularly true in a transient case, where the heat capacity of the ocean leads to a considerable delay in the increase of SST. Fig. 2 shows the warming for the MPI coupled model (Cubasch et al., 1992) which we have used in this experiment. Areas which have been warmed by more than 1°C are shaded. For the hurricane genesis regions the warming is around 1°C. Although we must consider the simulated SST data with some caution, due to model deficiencies and empirical correction of systematic errors related to incompleteness in the ocean-atmosphere coupling, the data are probably the most realistic estimate which we can presently obtain.

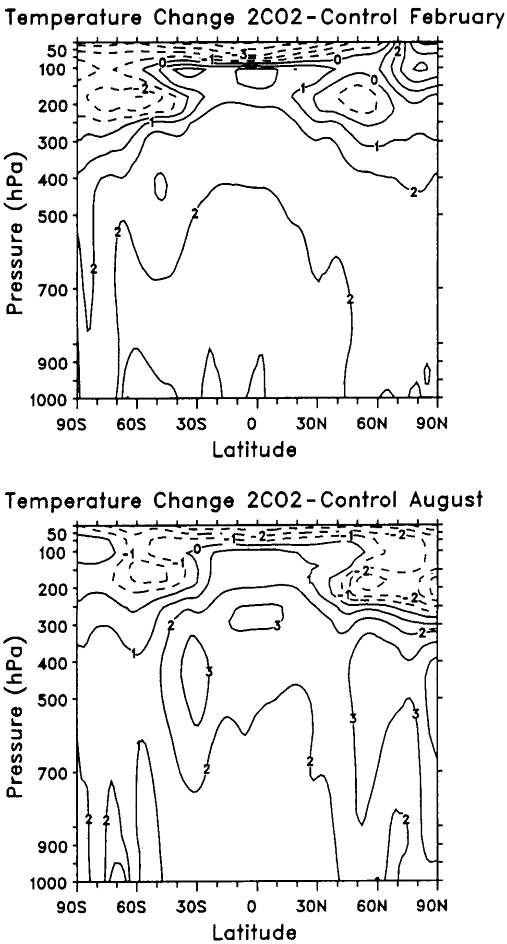

Fig. 6. Vertical cross section showing the change in temperature between the control (present climate) and the double CO_2 simulation for February and August, respectively.

Before a general discussion on the possible causes to the reduction in the number of storms, we give a short description on the overall changes in the atmospheric general circulation between the control and the double CO_2-experiment. We will generally restrict the discussion to the averaged conditions during February and August. Fig. 6 shows the average change in temperature in comparison to the control for February and August. It shows a general warming in the troposphere and cooling in the stratosphere. The tropospheric warming indicate two separate maxima, one between 500 and 300 hPa and another one in the tropics between 100 and 150 hPa. This second maximum is due to the raising of the tropopause.

Model studies also suggest that the upper troposphere and the tropical tropopause will warm more than the troposphere anywhere else, and that it will warm more than the tropical ocean surface (Schlesinger and Mitchell, 1987; Mitchell et al., 1987, Sellers and Liu, 1988). This warming is largely a consequence of the fact that the lapse of temperature along a moist adiabat is less in a warmer atmosphere. In Fig. 7 we have calculated the moist adiabat and the corresponding moist static stability for the control and the double CO_2, respectively. It represents averaged conditions for the North West Pacific during August, but practically identical stability conditions are found for the other hurricane regions (August for the Northern Hemisphere and February for the Southern Hemisphere).

The warming is slightly higher in August but generally the warming pattern in the troposphere is rather similar for all seasons. The stratosphere is undergoing a cooling as a consequence of the increased outgoing infrared radiation in the double CO_2 stratosphere. In the upper troposphere this is leading to an increased pole-to-equator temperature contrast, Fig. 8.

The subtropical jet in the double CO_2 case is slightly increased and displayed polewards. This is somewhat more pronounced at the Southern Hemisphere during February, Fig. 9. The meridional circulation is weakened, as can be seen from the cross-section of the meridional and vertical wind for February, Fig. 10, and August, Fig. 11. The associated reduction in the intensity of the

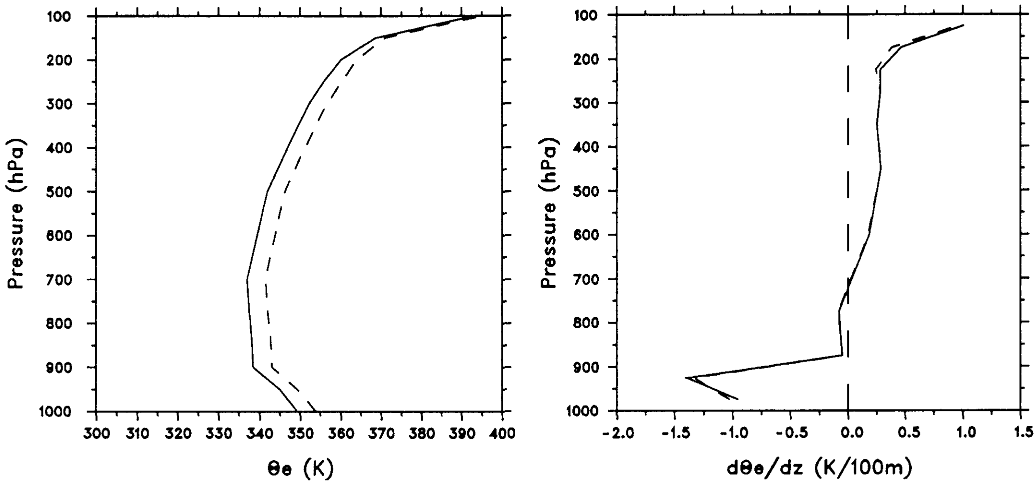

Fig. 7. Moist adiabat (left) and moist static stability (right) for the North West Pacific during August. Full lines present climate, dashed lines double CO_2 climate. Represent conditions between 5° N and 25° N, sea points only.

ITCZ (less precipitation) can be seen in Fig. 12 (February only).

There is a minor global decrease in the evaporation and precipitation in the double CO_2 experiment compared to the control. The largest differences are found over the Southern Indian Ocean in February, where evaporation is reduced from 4.6 mm/day to 4.2 mm/day and precipitation from 4.5 mm/day to 3.7 mm/day.

While the hydrological cycle (global precipitation) is some 5 % higher in the T106 case in comparison to the T42 integration (Perlwitz, personal communication) the hydrological cycle in the T42 integration responds differently in the double CO_2

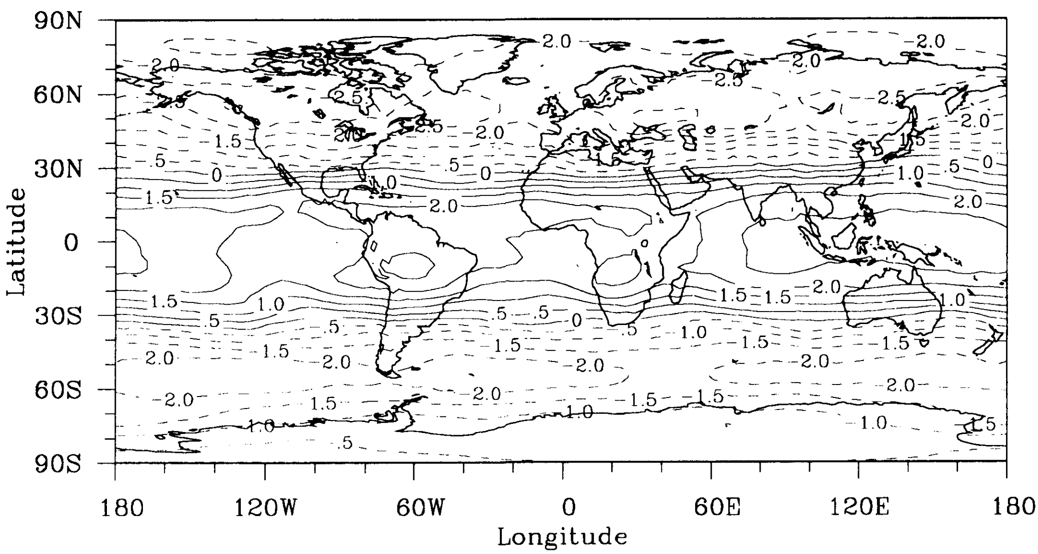

Fig. 8. The temperature change at 200 hPa between the control and the double CO_2 simulation (annual mean).

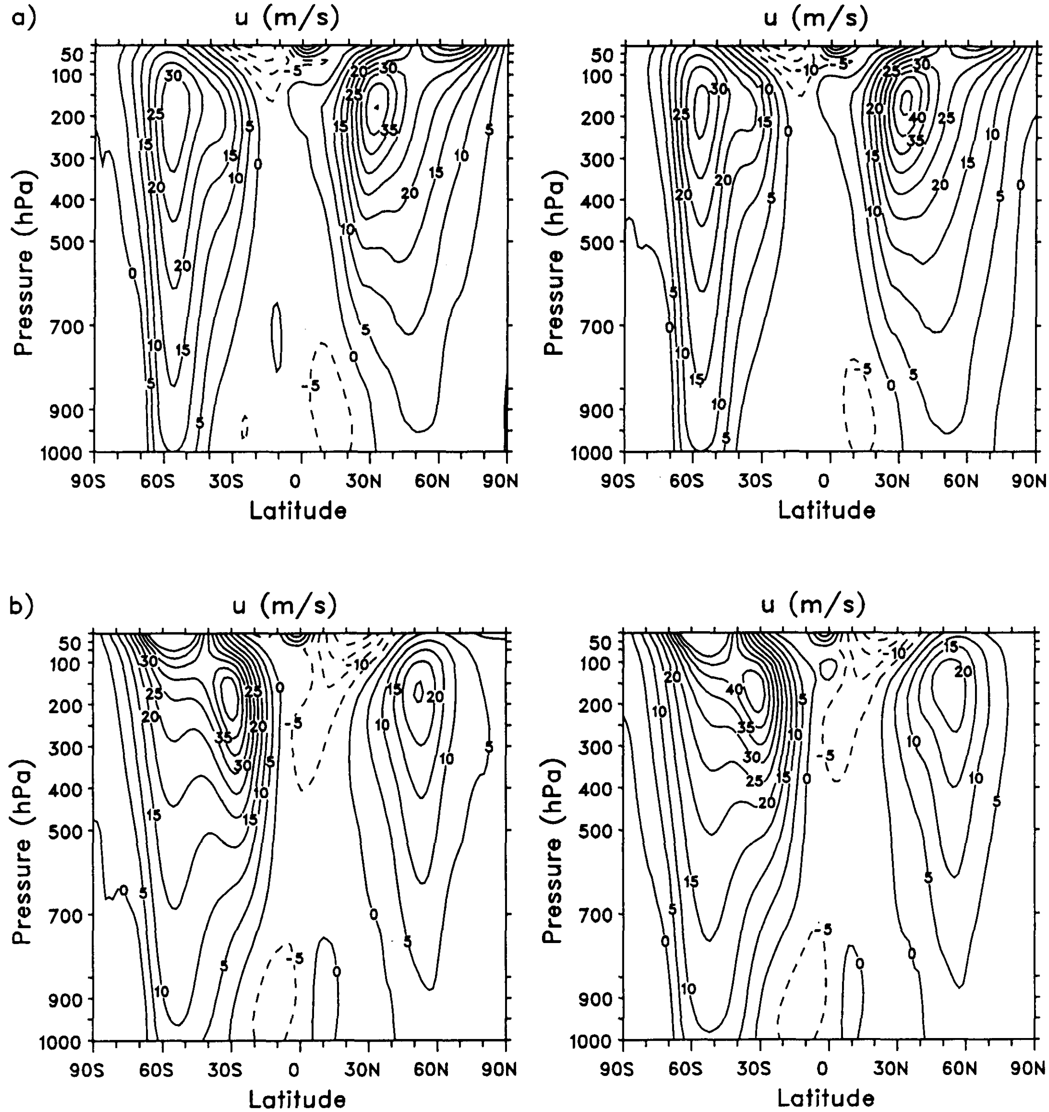

Fig. 9. (a) Zonal wind during February for the control (left) and the double CO_2 case (right). (b) The same but for August.

integration, by instead showing *slight intensification* of the hydrological cycle. The explanation to this is presumably a more realistic representation of small scale dynamical eddies in the T106 resolution, which while being more frequent in the control integration, do compensate for the enhanced warming and increased moisture in the double CO_2 case. The result suggests that the resolution of the atmosphere model may be of importance in extended coupled ocean-atmosphere models since it may influence ocean circulation differently because of the difference in the response of the hydrological cycle to horizontal resolution.

Sadourny (1994) has shown that the Hadley

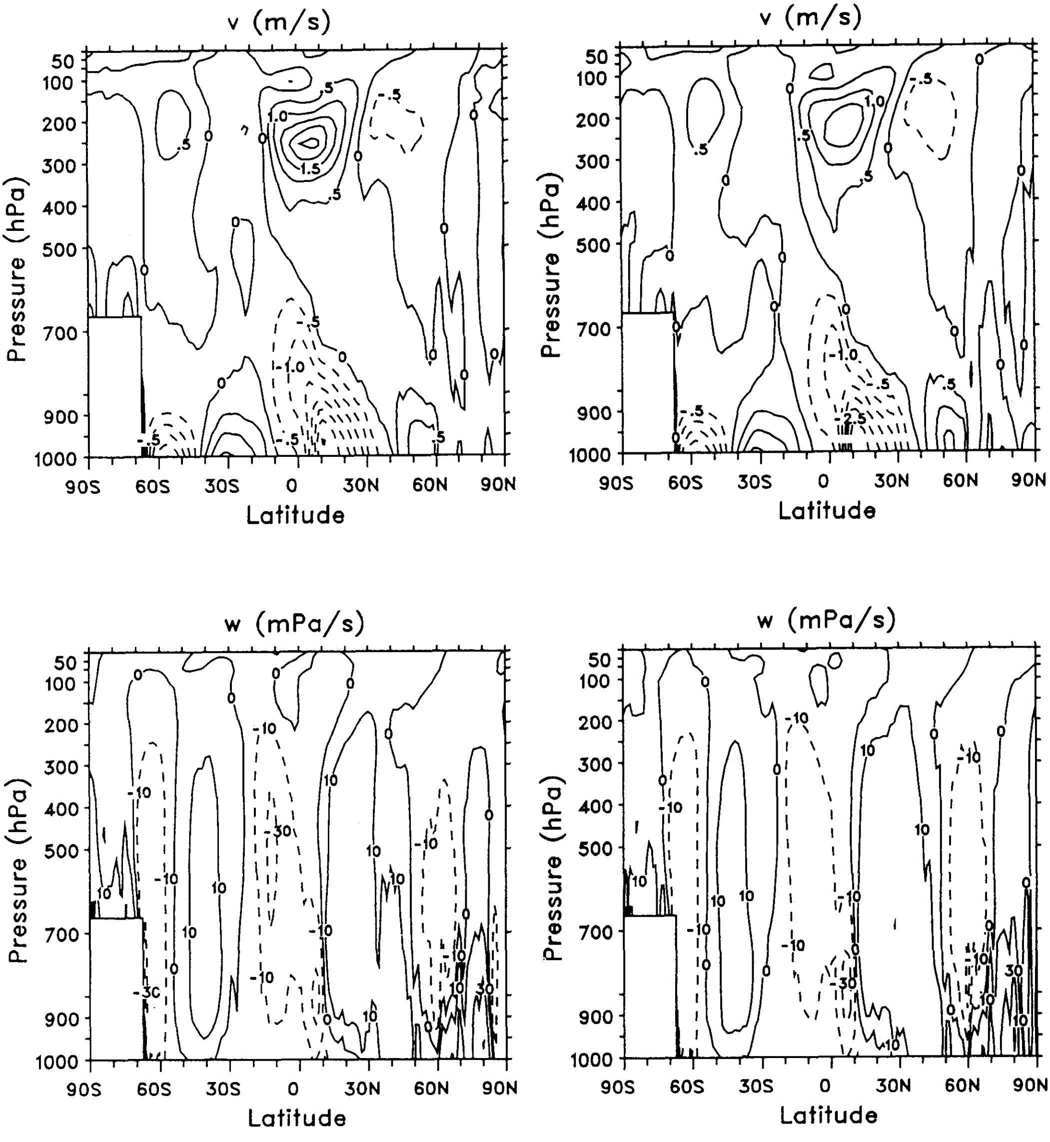

Fig. 10. Vertical cross section of the meridional and vertical wind during February for the control (left) and the double CO_2 case (right).

circulation is weakened in the LMD model, in a climate which is either warmed by increased insolation or by an increased concentration of greenhouse gases. The same is happening here and the following explanation is proposed. The Hadley circulation is basically driven by the need of the atmosphere to transport the excess of energy from the meteorological equator to the energy sinks of the subtropical desert belts. The energy difference between the sources and the sinks will govern the magnitude of energy transport in the tropics. In the ECHAM model used here, the water vapour and the cloud feedbacks appear to be proportionelly stronger in the subtropics than in the

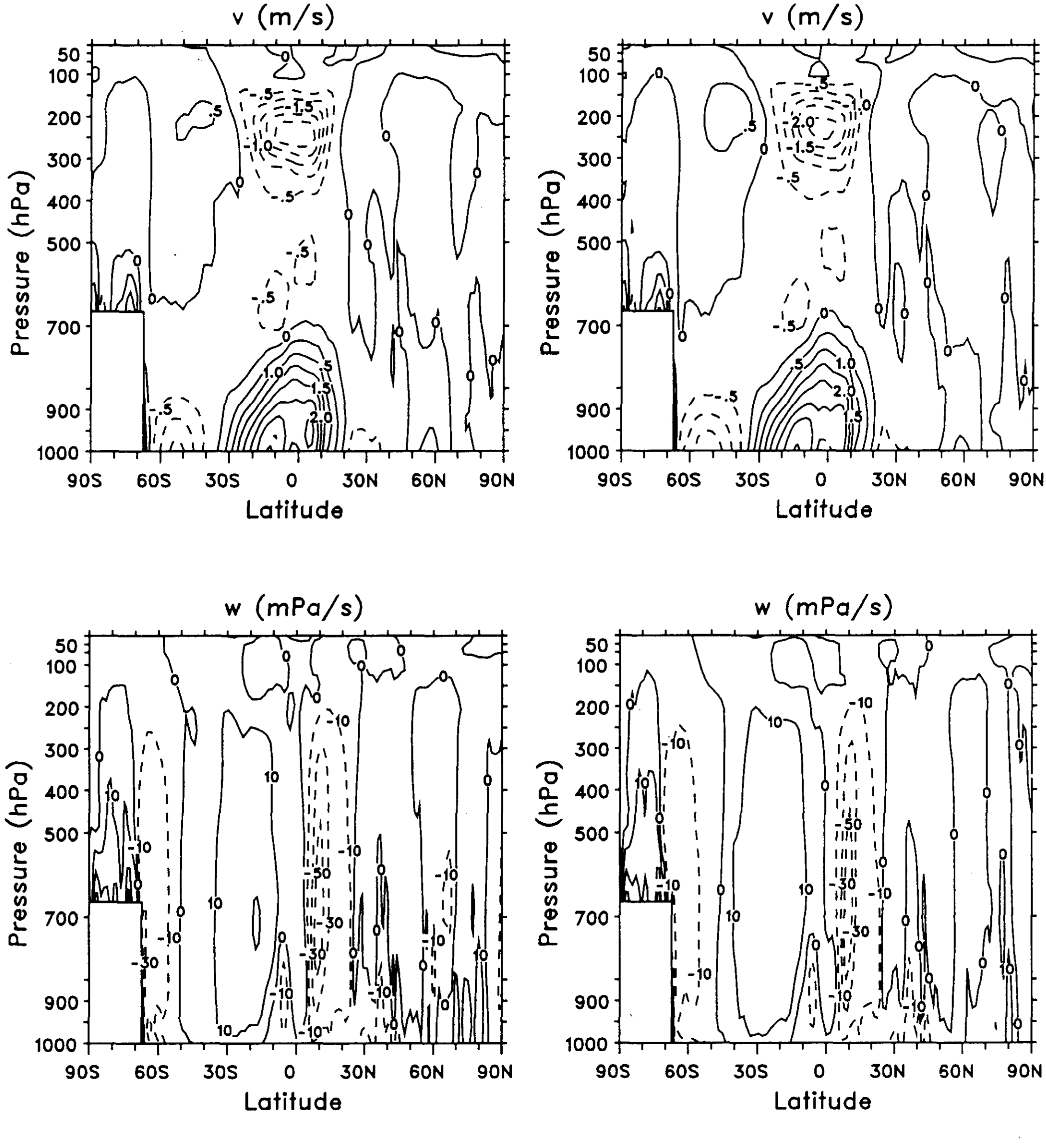

Fig. 11. The same as Fig. 10, but for August.

already moist equatorial belt. Then, because the subtropical energy deficit weakens, the Hadley circulation must reorganise itself to transport less energy towards the subtropics. It is not clear whether the intensity of Hadley circulation will contribute to more favourable conditions for the development of tropical storms or not, but it was found in B95 that a higher number of storms was normally associated with a more active Hadley-Walker circulation.

It was suggested in B95 that a necessary condition for the development of hurricanes is the existence of large scale areas of convergence in the lower part of the troposphere occuring in areas

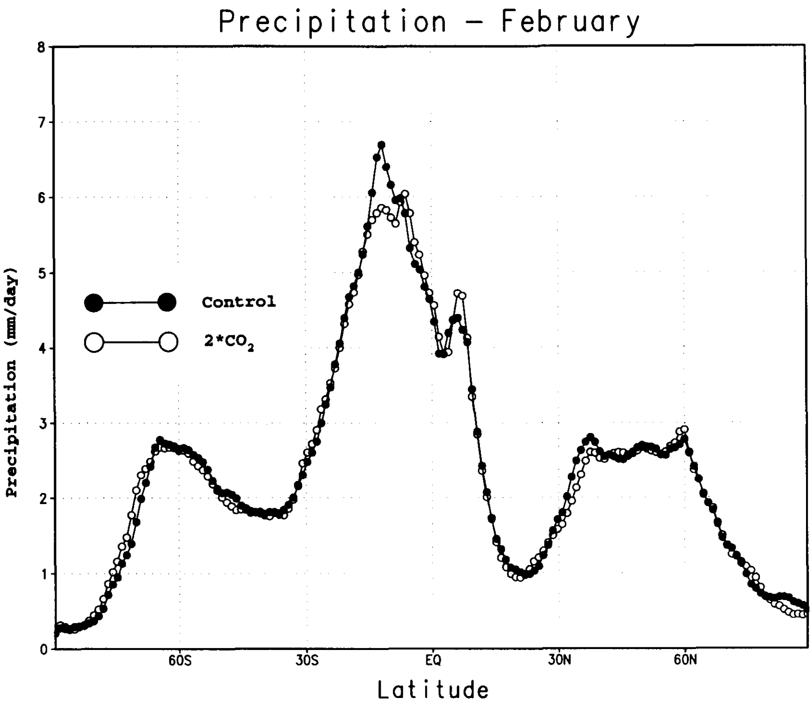

Fig. 12. Zonal cross section of precipitation during February. Present climate conditions (filled circles), double CO_2 climate (unfilled circles) unit mm/day.

where the Coriolis force is sufficiently large to provide the required convergence. The areas of large scale convergence do change relatively slowly, the vertical windshear is weak, allowing the storm to develop the required vertical structure.

In Fig. 13, we have calculated the averaged low level (900 hPa) relative vorticity separately for each tropical storm region; Northern Hemisphere for August and Southern Hemisphere for February. The figure suggests generally a higher level of relative vorticity in the control than in the double CO_2 case. An inspection of individual years suggests that this change is significant, although we must reserve ourselves because of the small sample. Another contributing factor could be the magnitude of the vertical difference in relative vorticity between 900 and 200 hPa, Gray (1979) and Erickson (1977). We have undertaken such a calculation as well, which indicates a minor reduction in the vorticity difference in a double CO_2 case. However, the contribution comes essentially from the decrease in relative vorticity at 900 hPa and therefore does not add any new information compared to what can be found from Fig. 13.

Finally, a further contributing factor to the overall reduction in the generation of hurricane type vortices in the double CO_2 experiment may be due to an increase in the vertical gradient of the zonal wind, in its turn caused by the enhanced meridional temperature gradient (Fig. 8). As discussed by Gray (1979), a vertical wind shear influences the organised convection of the hurricane in a negative way, leading to the creation of a smaller number of storms or to less developed ones. The increase in the vertical gradient of the zonal wind is more pronounced in the hurricane generating areas of the Southern Hemisphere. This could be another contributing factor to the strong reduction of tropical storms in the Southern Hemisphere.

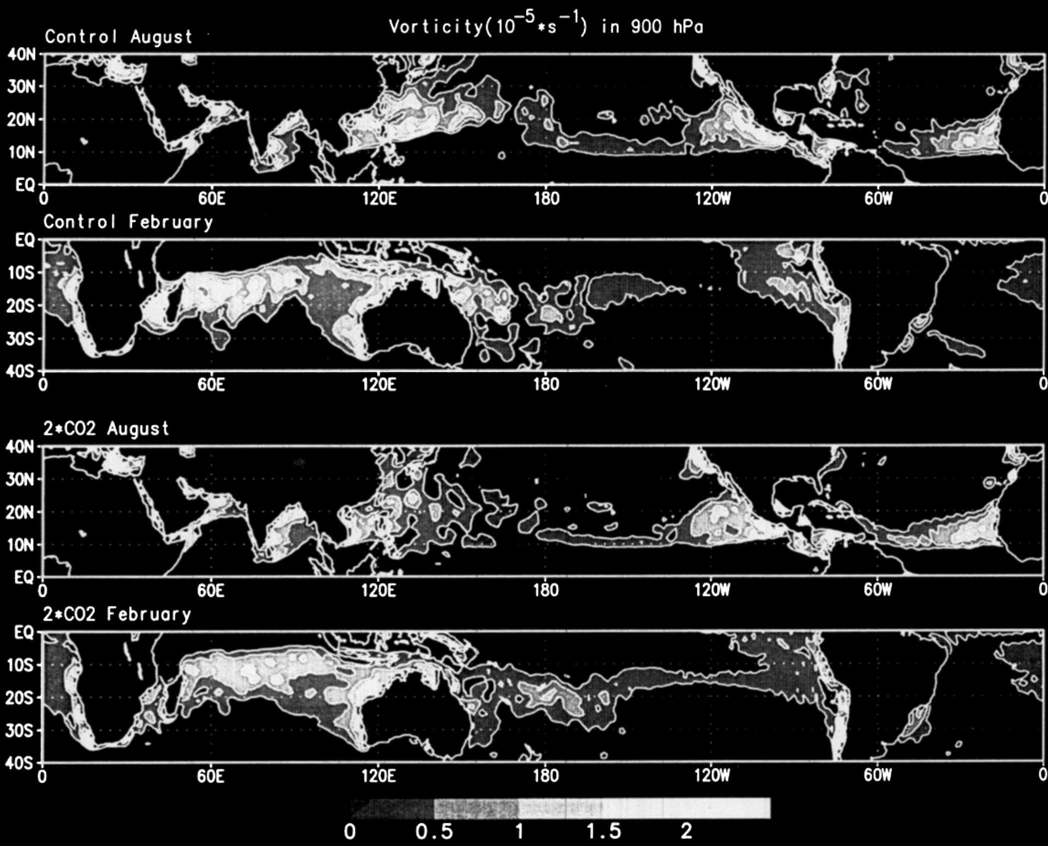

Fig. 13. Relative vorticity at 900 hPa (ζ_{900}) for the present climate (top) and double CO_2 climate (bottom). Values for the Northern Hemisphere refer to August and for the Southern Hemisphere to February. Units $5 \times 10^{-6}\ s^{-1}$.

5. Conclusions

In this study we have demonstrated the feasibility of using high resolution climate models for the study of the change in hurricane climatology caused by the increase of the concentration of greenhouse gases in the atmosphere. Since we have not had the computational resources to run a fully coupled, high resolution ocean-atmosphere model, for half a century and longer, we have undertaken the study in two steps. In the first step, which was already undertaken by Cubasch et al. (1992), a low resolution atmospheric model, T21, was coupled to an ocean model in a transient climate run, assuming an annual CO_2 increase by about 1%. At the time when the increase had doubled (after ca. 60 years) we calculated the annual SST difference to the present climate. This anomaly was then added to the monthly SST climate, which in turn was used to force the ECHAM3 model at a T106 horizontal resolution in a five year integration.

In view of the very realistic results in simulating the distribution of hurricanes for the present climate (B95), we believe this investigation is of interest. The overall finding is *a substantial reduction in the number of storms* particularly at the Southern Hemisphere. In comparison to the control experiment there are no changes in the distribution of the storms, neither in space, nor in time. The low level vorticity in the hurricane genesis regions is generally reduced compared to the present climate, while the vertical tropospheric wind shear is slightly increased. Most tropical storm regions indicate reduced surface windspeeds and a slightly weaker hydrological cycle.

The comparatively short integration time of 5 years does not make it possible to draw any firm conclusions as to the main cause of the reduction in the number of storms. We have tried here to make a first attempt to such an analysis. We suggest that the probable causes are due to large scale changes in the tropical circulation, such as reduced low level relative vorticity in the genesis regions providing overall less favourable dynamical conditions for the development of storms.

Although there is a substantial reduction in the number of storms, there is no reduction in their overall strength. In fact, the most intense storm in the double CO_2 study reached a higher maximum wind speed than the most powerful storm did in the control case. Our interpretation is that, given maximum favourable conditions, more powerful storms may develop in agreement with the general findings of Emanuel (1988). However, such situations are apparently rare in this double CO_2 study and perhaps also in nature.

Broccoli and Manabe (1990), in a similar study, noted that their results were crucially dependent on the parameterization of clouds. However, in the more realistic case, where the clouds were related to the flow pattern in a dynamically consistent way, and not just climatologically prescribed, their findings agree with this one. The parameterization of clouds and deep convection appear to play an important rôle and it is the hope of the authors of this paper to repeat their investigation with another set of parameterizations.

5 years of integration is a very short time, in view of the large inherent interannual variability found for the hurricane vortices. In order to obtain further support for the results of this study, a series of 30 years of integration with a T42 version of the same model (Perlwitz, personal communication), but for a situation equivalent to a tripling of the CO_2 concentration, was investigated in a similar way. In comparison with the T42 control integration, the T42 climate change experiment also showed a clear reduction in the number of hurricane vortices.

Broccoli and Manabe (1990) raised the general question whether general circulation models are appropriate tools in exploring the mechanisms between greenhouse warming and tropical storm activity. The present authors have no difficulties in answering that question in the affirmative. Nevertheless, any investigator of climate change should use this result, as well as other similar results, with great caution, in view of the many different assumptions underlying this work, both in obtaining the SST changes in the first place, and then in the many assumptions done in the development of the parameterization scheme of the model.

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