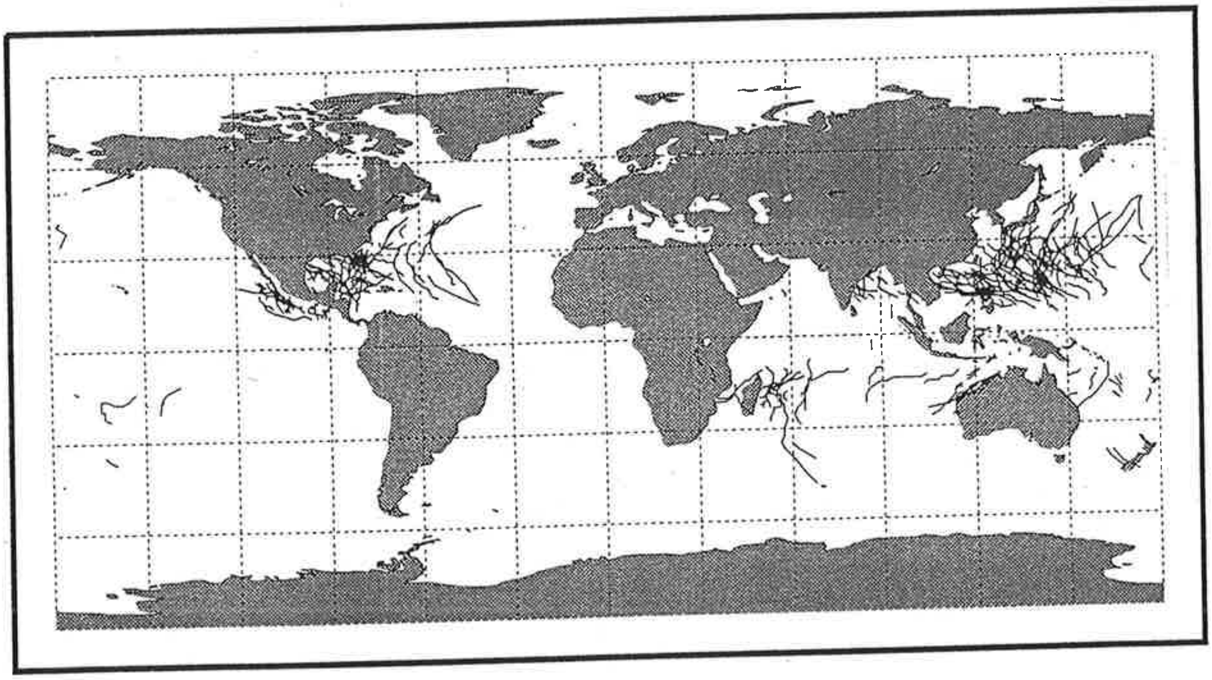
Max-Planck-Institut
für Meteorologie

REPORT No. 139



WILL GREENHOUSE GAS-INDUCED WARMING OVER THE NEXT 50 YEARS LEAD TO HIGHER FREQUENCY AND GREATER INTENSITY OF HURRICANES ?

by

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HAMBURG, August 1994

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REPb 139

ISSN 0937-1060

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 a of high resolution atmospheric model at T106 resolution, for studying the influence on 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 (1994). The sea surface temperature anomalies have been taken from a previous climate change experiment, obtained with a low resolution ocean-atmosphere coupled model. The global distribution of the storms agree in their 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 is related to increased tropospheric stability, associated with increased warming at the upper troposphere and changes in the large scale circulation such as a weaker Hadley circulation and stronger upper air westerlies. The surface winds in the tropics are generally weaker and evaporation is also somewhat reduced, in spite of higher sea surface temperatures.

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. 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 U.S. 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 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., 1994) do indicate that the tropical storms only developed 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 (1989) 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. 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*.

The paper by Bengtsson et al. (1994) reported of the simulation of tropical intense storms with a high horizontal resolution climate model. In that experiment, the ECHAM3 model (Roeckner et al., 1992) at T106 resolution was used in a five-year simulation of the present climate. The experiment demonstrated a remarkably good agreement with the observed distribution of hurricanes 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 the following 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., 1993) 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 (business as usual according to Houghton et al., 1990). The atmospheric model had a horizontal resolution of T21. In the present experiment we have used the simulated SST data at the time of the CO_2 doubling and used these as boundary conditions for the T106 model. We have further assumed a doubling of the CO_2 concentration in the atmosphere. The same diagnostic evaluation as in the previous experiment, (Bengtsson et al., 1994) was carried out.

In section 2 we will describe the climate change experiments, 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 a previous study (Bengtsson et al., 1994) where the ECHAM3 model was used in an investigation 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 of 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 also 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.

In view of the realistic distribution obtained for the present climate, shown in Figure 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 possible 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. (1993).

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. Figure 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 Bengtsson et al. (1994) study (this experiment to be notated B94 in the following) 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 B94, we only considered storms with a lifetime larger than 36 hours.

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

1. Relative vorticity at 850 hPa > 3.5 *10-5 s^{-1}.
2. A maximum velocity of 15 ms^{-1} and a minimum surface pressure within a 7* 7 grid poi area around the point which fulfils condition 1.
3. The sum of the temperature anomalies (deviation from the mean, consisting of 7*7 gri points) at 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 ge graphical distribution of the storms and with an intercomparison of the result from the presen climate study, B94.

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 fifth year. The average 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 B94 (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 somew hat surprising result, in particular the significant reduction in the number of storms at the Southern hemisphere. This is illustrated clearly in Figure 3 which shows the total number of storms in the $2CO_2$ experiment.

Table 1 shows the number of simulated Northern hemisphere cyclogenesis by year and mont compared to B94 as well as to the 20 year observational study by Gray (1979). For each mont there is a significant reduction, except for July, where the $2CO_2$ experiment has a larger number of storms.

Table 2 shows the same for the Southern hemisphere. Here all months show a reduction compared to B94, and two additional months, October and November, show no storms at all.

Table 3 shows the variation of storms by ocean basins. As in B94, 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 $2CO_2$ experiment have *less hurricanes than all separate years in B94.*

In Table 4 we have ordered the storms by their maximum achieved wind speed and by ocean basins. Comparison with B94, table 4 shows a very similar distribution and almost the same average maximum windspeed (difference less than 1m/s). As a rare occasion one particular storm in the North-East Pacific has a higher maximum windspeed, 56.7 m/s, than any of the storms examined in B94.

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-East 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. Figure 2 shows the warming for the MPI coupled model (Cubasch et al., 1993) which we have used in this experiment. 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.

Model studies also suggest that the upper troposphere and the tropical tropopause will warm more than tropopause anywhere else, and that it will warm more than tropical ocean surface (Schlesinger and Mitchell, 1987; Mitchell et al., 1987, Sellers and Liu, 1988). Consequently, the tropical troposphere may be somewhat more stable in an atmosphere with an increased concentration of greenhouse gases than it is at present, implying a mechanism which may work in the opposite direction.

Since this experiment de facto has indicated a reduced hurricane activity in the double CO_2 experiment, it is obvious that there are physical processes in the model which more than compensate for the sea surface warming. Figure 4 shows the average temperature change in temperature in comparison to the control for February and August respectively.

The warming reaches a maximum around 300 hPa in the Tropics with another secondary maximum around 150 hPa. The warming is slightly higher in August but generally the warming pattern in the troposphere is rather similar. The stratosphere is undergoing a cooling as a consequence of the increased outgoing infrared radiation in the 2 CO_2 stratosphere. In Table 5 we have summarized the average temperature change for the different hurricane regions for February and August respectively, demonstrating quite clearly the increased average stability for practically all hurricane regions.

The dynamical response to climate warming is characterized by a general decrease in the pole-to-equator temperature contrast at the surface. This is partly a direct radiation effect but also due to a positive feedback with the surface albedo following from an increased melting of snow and ice at high latitudes. This will in turn decrease the energy deficit of the winter hemisphere and hence lead to a general decrease in the mass and energy fluxes of the Hadley circulation. That such a weakening of the Hadley circulation is indeed taking place can be seen in Figure 5, displaying the situation during February and August respectively.

In the upper atmosphere there is an increase in the pole-to-equator temperature contrast essentially due to increased moisture contrast and associated non-linear dependency on temperature through the Clausius-Clapeyron relation; Fig. 6 shows this effect quite clearly. An associated increase in the suptropical jet can also be noted, Fig.7. The question is whether the increased static stability and the weakening Hadley circulation result in a reduced evaporation from the oceans and hense reduced energy uptake to drive the hurricanes.

The experiment shows that this is indeed taking place, although the reduction in evaporation is rather small. Table 6 provide some averaged data for the seven different hurricane regions showing that a reduction in evaporation is taking place, particularly in the Pacific region during August and in the Southern Indian Ocean during February. Variations occur between different years, and the sample of five years is probably too small to make any firm conclusions. Table 6 also give some key data for the relative humidity in the lower and upper part of the troposphere. Generally the relative humidity drops by a few percent in the $2CO_2$ experiment, with the largest reduction in the upper troposphere in the Tropics between 400 and 200 hPa.

A tendency to a possible drying out in the upper troposphere, due to the effect of deep convection, has been suggested by Lindzen (1990), as a mechanism for a possible negative water vapour feedback. However, a further increase in the relative humidity occurs in the uppermost part of the troposphere, and the overall feedback is thus difficult to estimate, and will require a more substantial investigation, outside the scope of this study.

Finally, a further contributing factor to the overall reduction in the generation of hurricane type vortices in the $2CO_2$-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 between 10°-40°, Fig. 4. As discussed by Gray (1979), a vertical wind sheer influences the organised convection in the hurricane in a negative way, leading to the creation of a smaller number of storms or to less developed ones.

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. (1993), 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 (Bengtsson et al, 1994), we believe this investigation is of interest. The overall finding is *a substantial reduction in the number of storms* particularly at the Southern hemisphere. The reason for this is the increased stabilization of the tropical atmosphere, due to a warming in the upper troposphere through deep convection. In comparison to the control experiment there are no changes in the distribution of the storms, neither in space, nor in time. There is also a reduction in the intensity of the Hadley circulation, leading to a reduction in the surface wind speed as well as a reduction in evaporation, and hence in general giving rise to a somewhat drier atmosphere than the present one. Whether this is due to a different large scale circulation or to the collected effect of the storms on the large scale circulation is not possible to determine, but it is more likely to be the former than the latter.

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 $2CO_2$ study reached a higher maximum wind speed, than the most powerful storm did in the control case. Our interpretation of this is that , given maximum favourable conditions, more powerful storms may develop in agreement with the general findings of Emanuel (1987) . However, such situations are apparently rare in this $2CO_2$ 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 role and it is the hope of the authors of this paper to repeat their investigation with another set of parameterizations.

Five 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 (1994), 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.

6. Acknowledgements

The authors are indebted to the Swiss Climate Computing Center which has been providing computational resources for this experiment under a joint co-operative program between the Max-Planck-Institut für Meteorologie in Hamburg and the Eidgenössische Technische Hochschule in Zürich, and they are grateful to colleagues at both places for discussion and support.

They are likewise obligated to their colleagues at the German Climate Computing Centre and in particular to Mr U. Schlese who overlooked and carried out the high resolution experiment. The authors also wish to acknowledge the technical assistance of Norbert Noreiks and Kornelia Müller.

Table 1. *Number of simulated Northern hemisphere tropical cyclones by year and month. For comparsion the total and average number as simulated for the simulation of the present climate (B94) and the averaged observed number for the years 1958-77, according to Gray (1979). The column to 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.*

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 Average	1 0.2	4 0.8	3 0.6	9 1.8	15 3.0	20 4.0	23 4.6	28 4.4	43 8.6	33 6.6	19 3.8	7 1.4	205 42.0	
CTRL Total Average	11 2.2	5 1.0	10 2.0	7 1.4	17 3.4	30 6.0	16 3.2	48 9.6	54 10.8	38 7.6	24 4.8	21 4.2	281 56.2	49-63
OBS (1958-77) 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

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 Average	16 3.2	14 2.8	11 2.2	7 1.4	2 0.4	3 0.6	0 0.0	1 0.2	0 0.0	0 0.0	0 0.0	4 0.2	58 11.6	
CTRL Total Average	26 5.2	31 6.2	23 4.6	20 4.0	5 1.0	0 0	0 0	2 0.4	0 0	2 0.4	9 1.8	16 3.2	134 26.8	23-28
OBS (1958-77)	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. The control simulations (present climate) and the observed number 1958-77 according to Gray (1979) are shown on the bottom lines. For a specification of the areas, see B94. Others refers to hurricane developments elsewhere.*

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 (1958-77)	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		

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

Basin / Windspeed [m/s]	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

Table 5. *Temperature at 1000 and 150 hPa for February and August. The first two columns show the mean temperature for the seven hurricane areas. Columns three and four show the change in temperature between the experiment ($2CO_2$) and the control (CO_2). The last column shows the corresponding change in the temperature between 1000 and 150 hPa. Note the stabilization, particular during the hurricane seasons.*

February					
Area	Temperature experiment ($2CO_2$)		Temperature change		
	T_{1000}	T_{150}	ΔT_{1000}	ΔT_{150}	$\Delta(T_{1000}-T_{150})$
NWAtl.	25.6	-57.1	1.1	1.0	+0.1
NEPac.	25.8	-56.7	0.9	1.5	-0.6
NWPac.	26.9	-58.6	0.9	1.8	-1.0
NInd.	26.9	-56.9	1.3	2.1	-0.8
SInd.	27.9	-56.6	0.9	2.3	-1.4
Aust.	28.2	-58.6	1.0	2.0	-1.0
S.Pac	28.5	-58.4	1.0	1.8	-0.9

August					
Area	Temperature experiment ($2CO_2$)		Temperature change		
	T_{1000}	T_{150}	ΔT_{1000}	ΔT_{150}	$\Delta(T_{1000}-T_{150})$
NWAtl.	26.8	-57.3	1.1	1.0	0.0
NEPac.	26.2	-58.0	1.1	1.5	-0.4
NWPac.	28.7	-58.6	1.1	1.5	-0.4
NInd.	28.1	-57.3	1.1	1.5	-0.3
SInd.	25.6	-57.0	1.3	1.0	+0.3
Aust.	26.2	-57.9	1.3	1.6	-0.3
S.Pac	26.9	-57.5	1.3	1.5	-0.2

Table 6. *Changes in evaporation (mm/day) and in relative humidity (in percent) for the seven difference hurricane regions and for February and August respectively.*

Area	*February*			*August*		
	Evaporation mm/day	rel. / hum. 950 hPa	rel. / hum. 350 hPa	Evaporation mm/day	rel./hum 950 hPa	rel. / hum. 350 hPa
NWAtl.	-0.07	0.7	-3.1	-0.08	0.2	-3.7
NEPac.	-0.03	-0.2	-2.8	-0.18	-0.6	-4.9
NWPac.	0.15	1.0	0.2	-0.33	0.4	0.4
NInd.	0.00	-1.7	-1.5	0.02	-0.6	1.9
SInd.	-0.19	-0.7	-7.0	0.00	0.2	-1.8
Aust.	0.22	-0.4	1.6	-0.03	0.6	1.9
S.Pac	0.08	-0.1	-0.4	0.01	0.4	-0.9

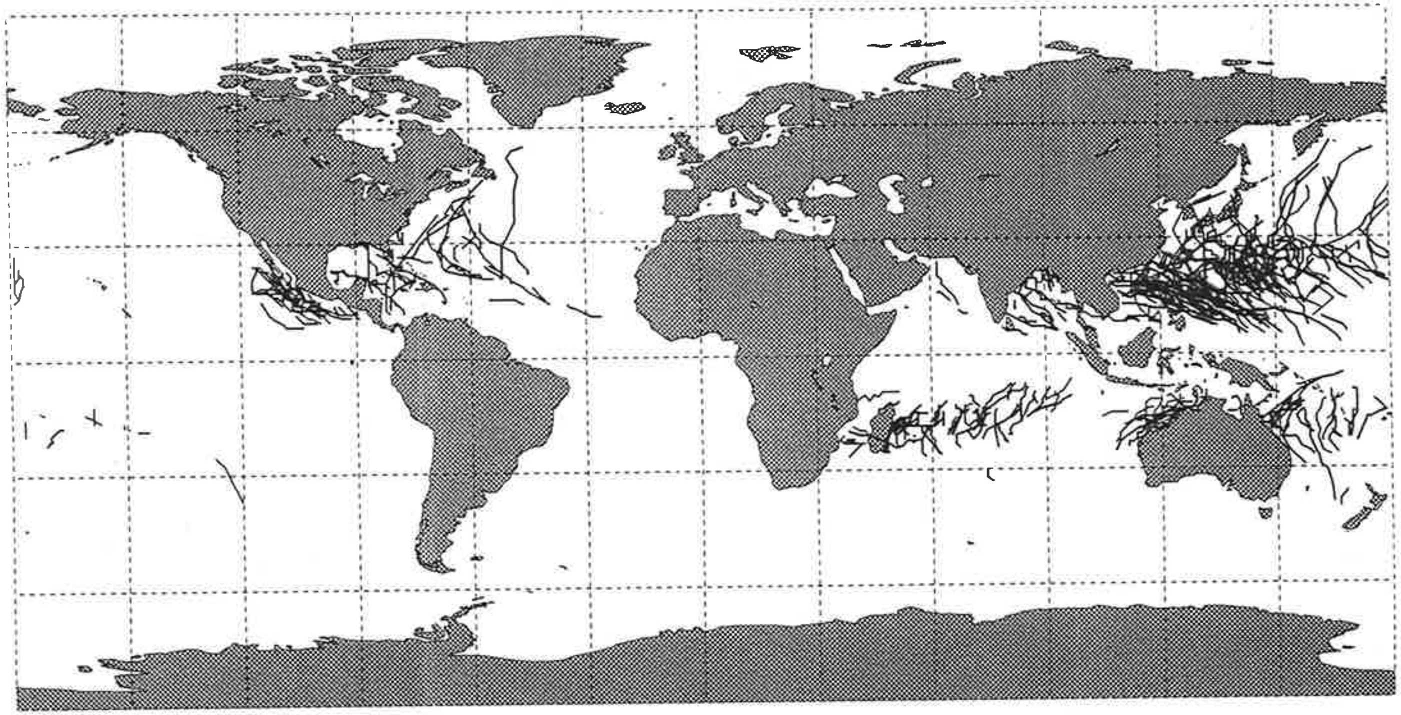
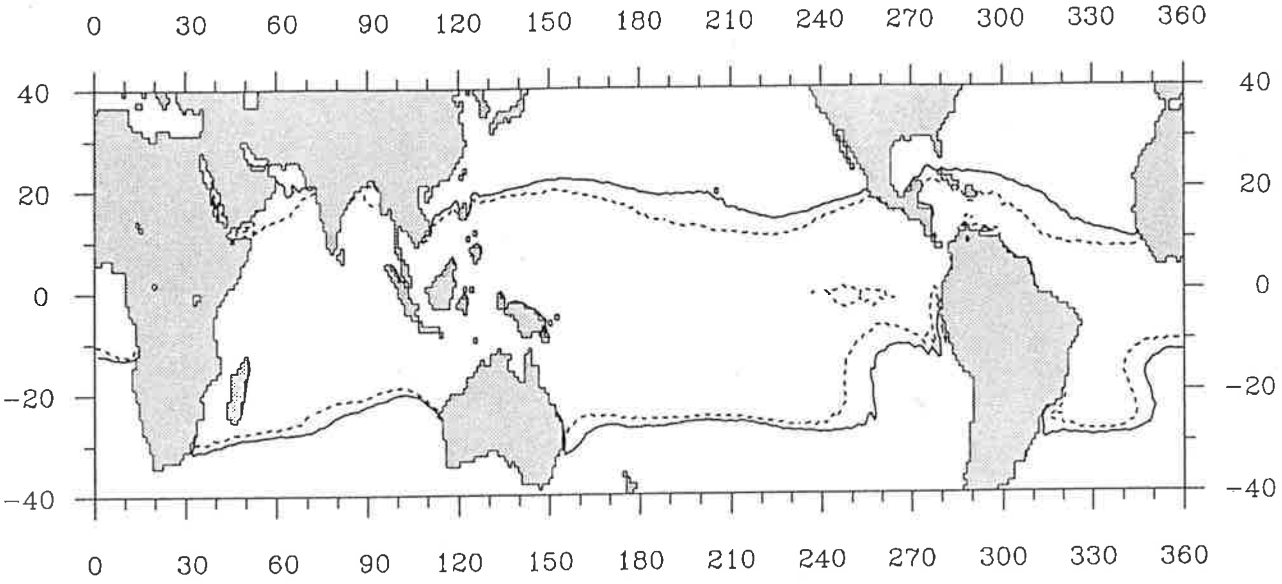


Fig. 1: Simulated cyclone tracks during five years for the present climate (from B94). The tracking is only indicated when the hurricanes satisfy the selection criteria. All tracks for 5 years. Blue colour for DJF, red colour for HAM, green colour for JJA and black colour for SON.

ECHAM3 T106 – SST – 26°C – FEBRUARY



ECHAM3 T106 – SST – 26°C – AUGUST

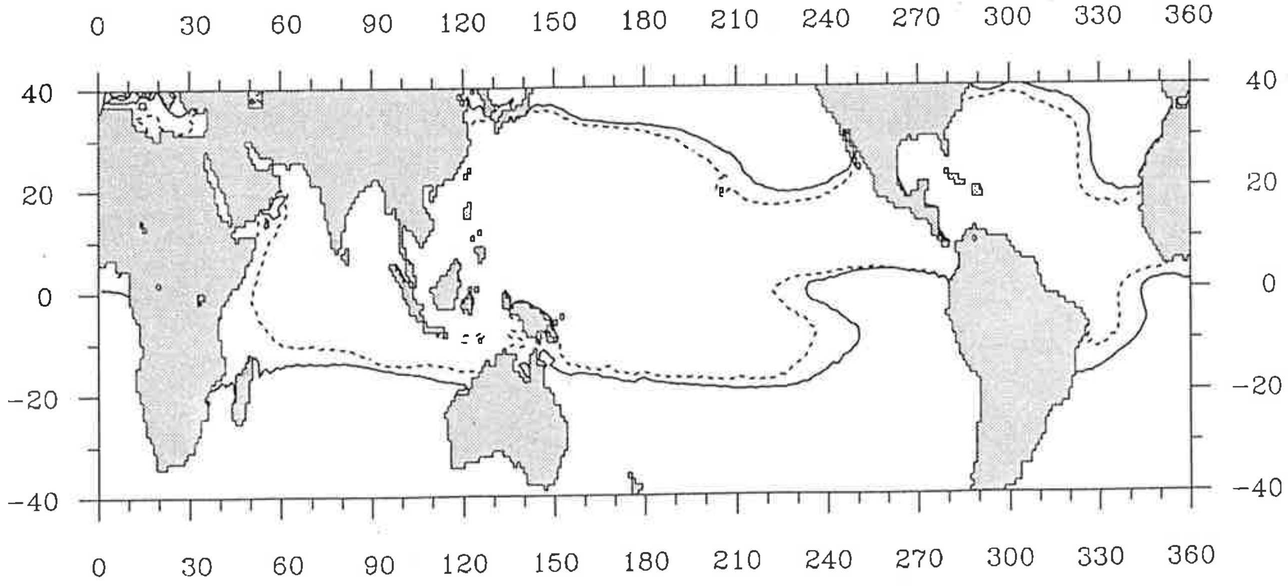


Fig. 2: Sea Surface Temperature increase in the Tropics in the $2CO_2$ experiment. Dashed lines show the 26°C isoterm for the present climate and full lines the 26°C for the $2CO_2$ experiment. The Sea Surface Temperature increases are between 0.5°C and 1.5°C generally within the 26°C isoterm.

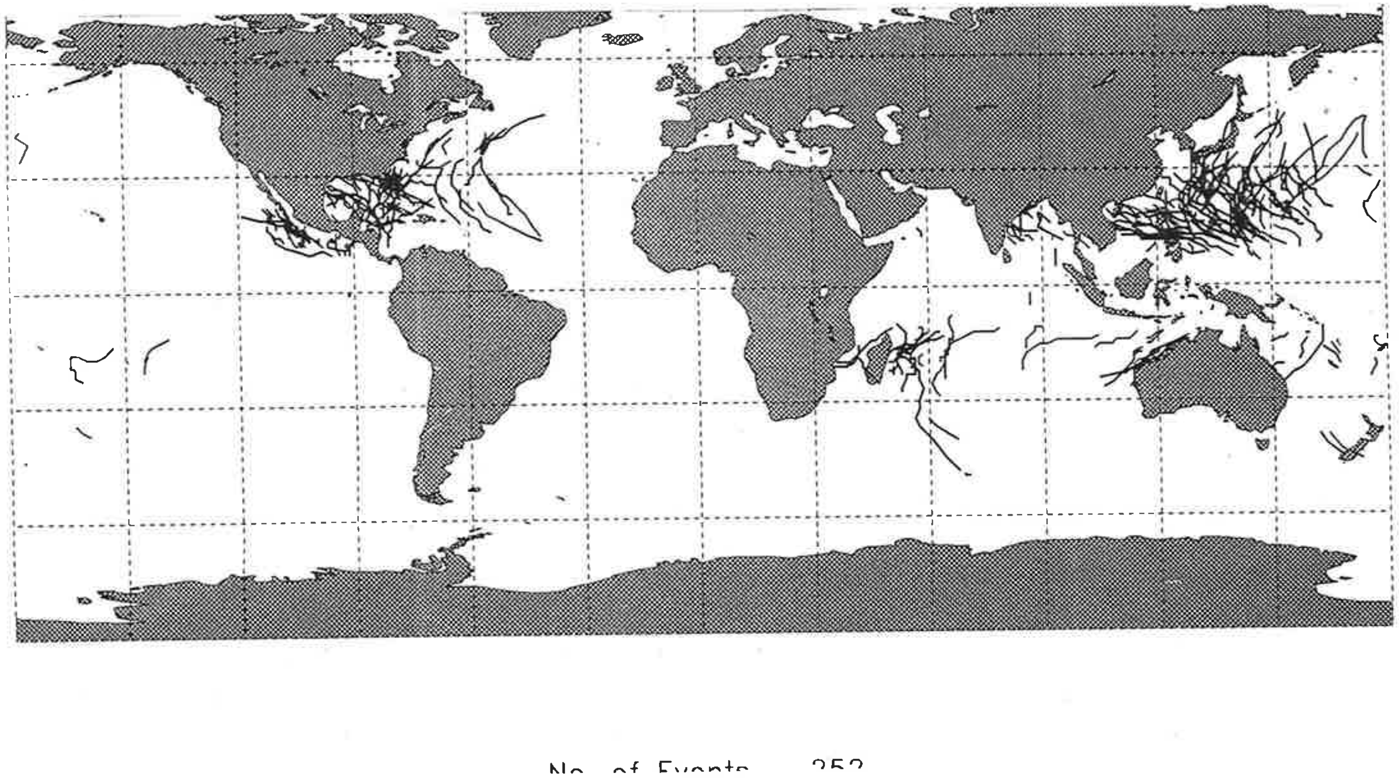
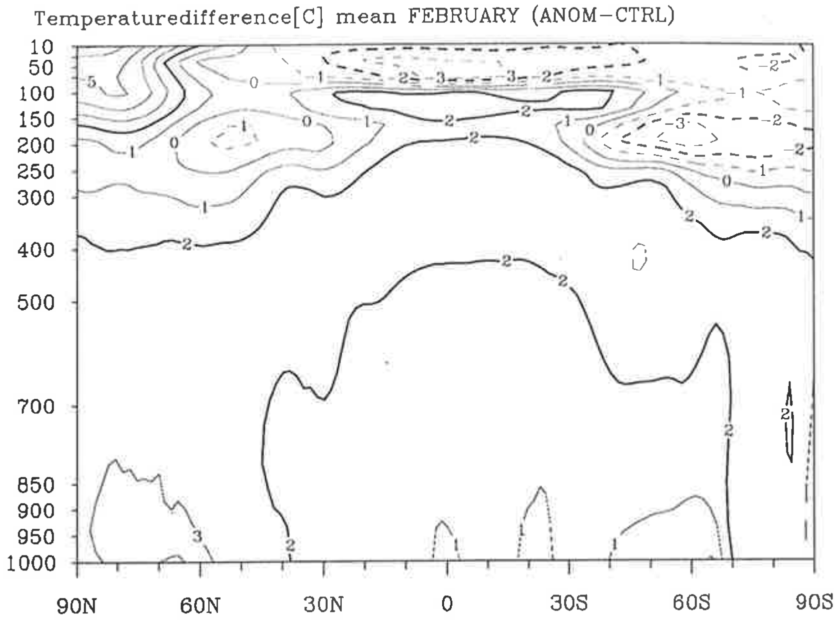


Fig. 3: The same as Fig. 1 but for the $2CO_2$ experiment.



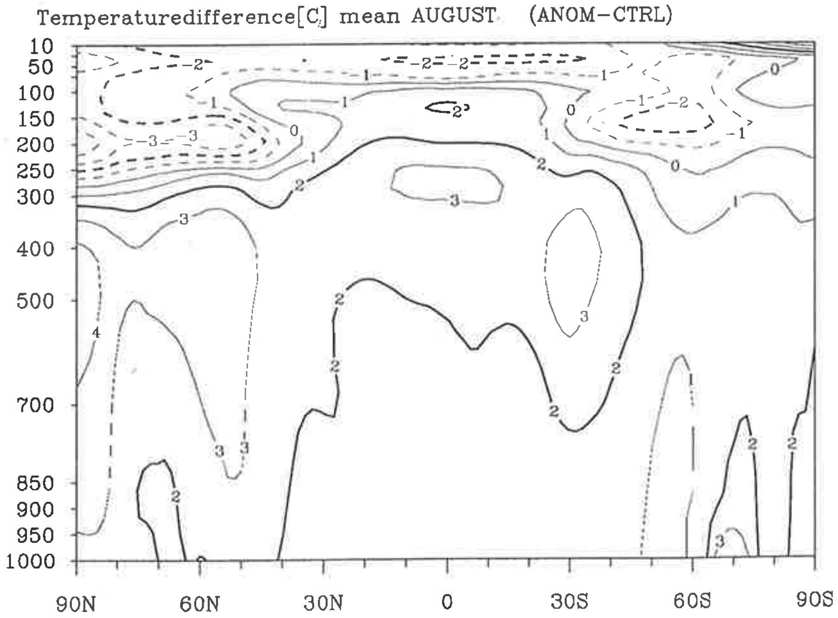


Fig. 4: Vertical cross section showing the change in temperature between the control (present climate) and the $2CO_2$ simulation for February and August respectively.

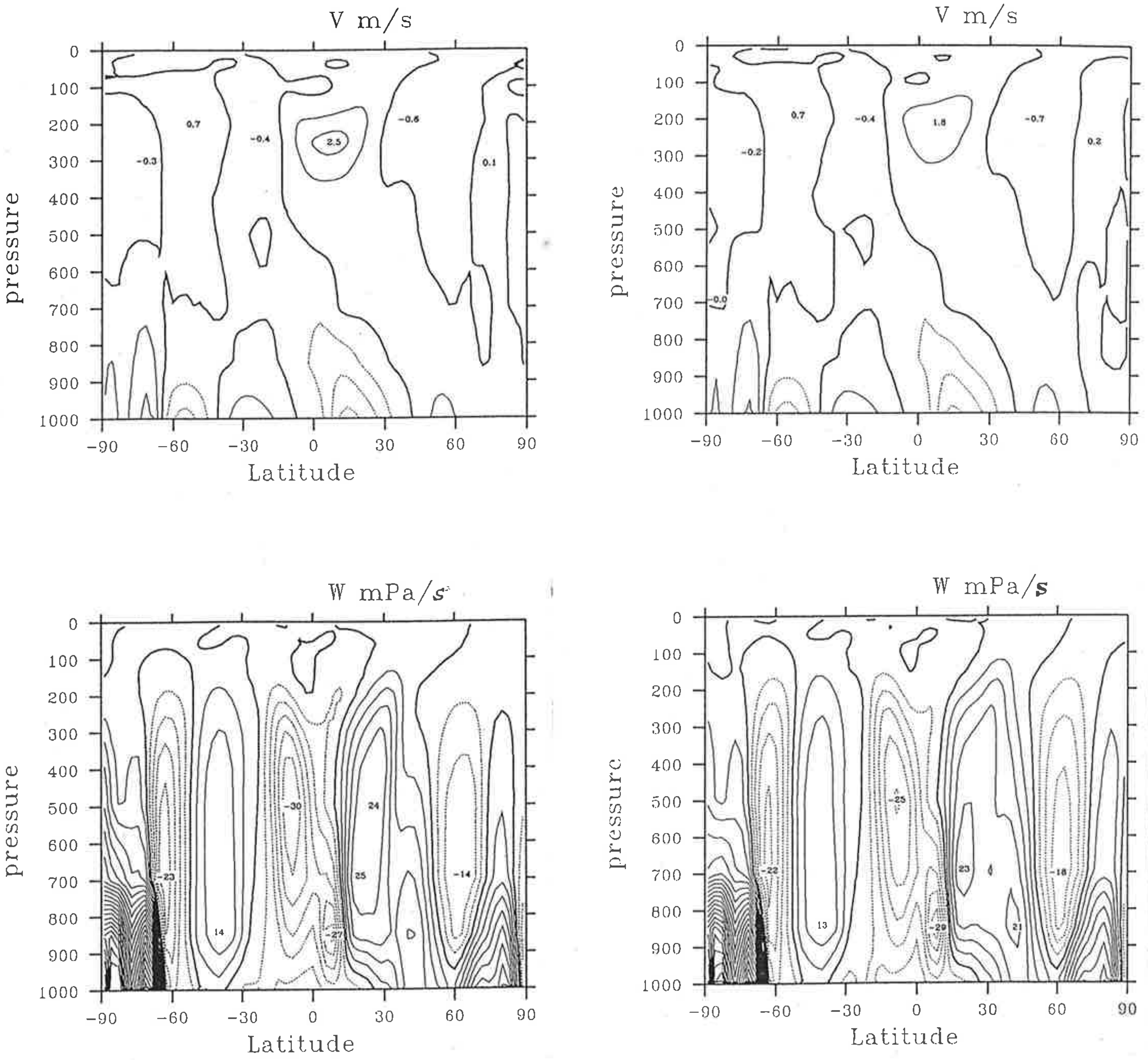


Fig. 5: (a) Vertical cross section of the meridional and vertical wind during February for the control (left) and the $2CO_2$ case (right).

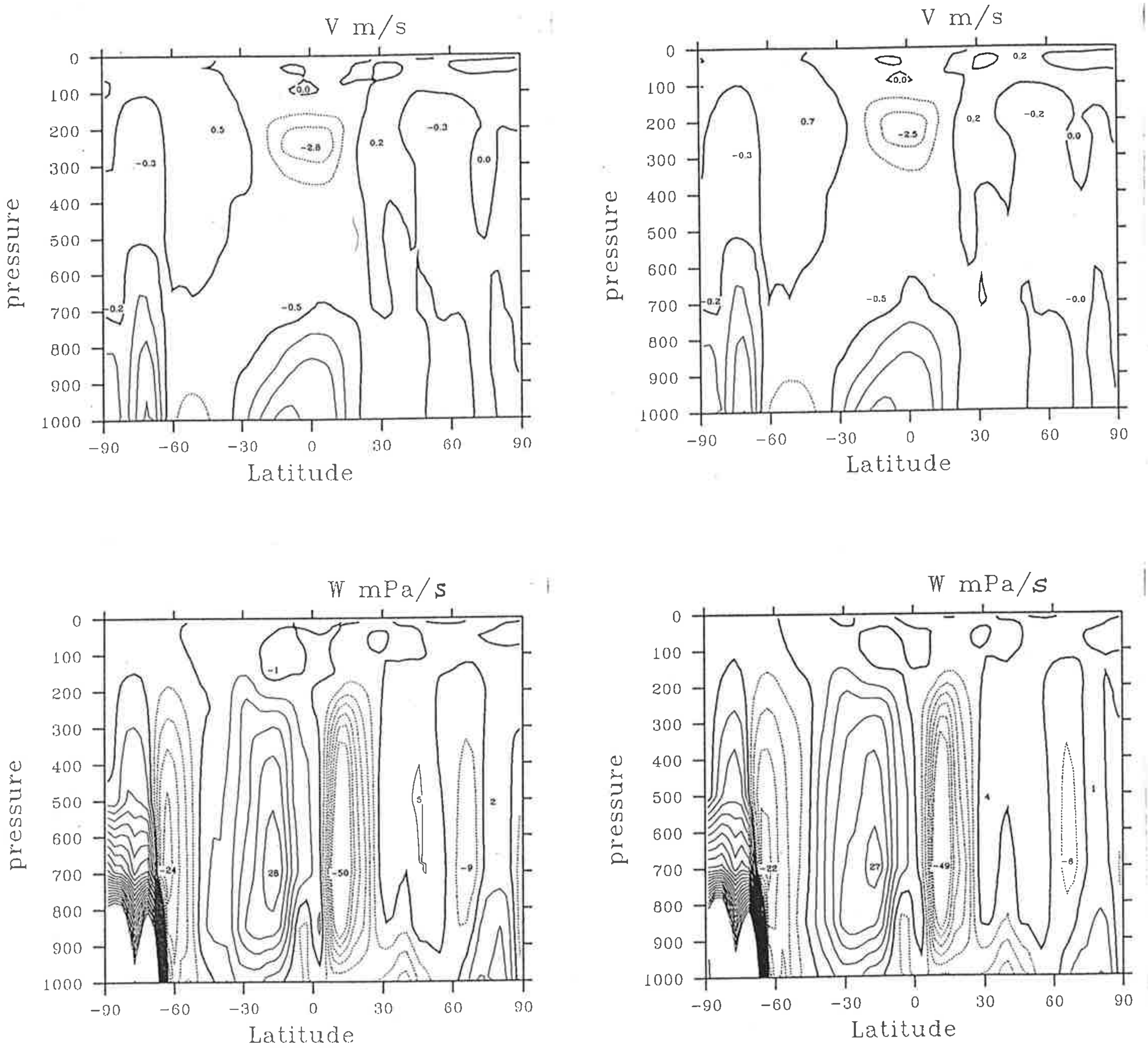


Fig. 5: (b) The same but for August.

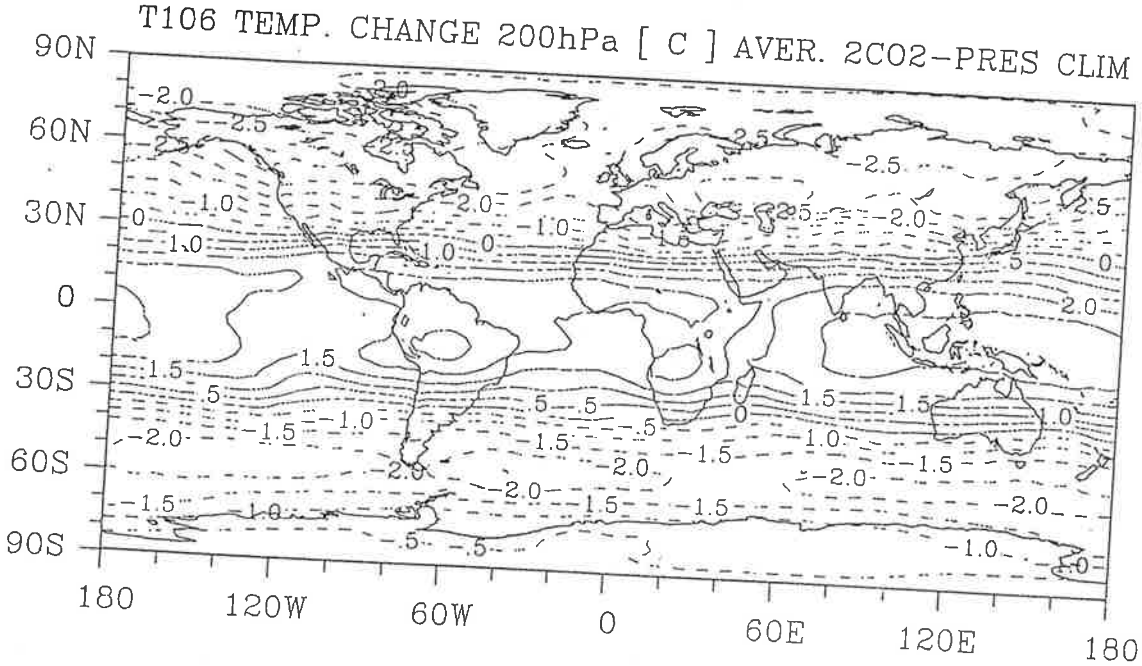


Fig. 6: The temperature change at 200 hPa between the control and the $2CO_2$ simulation.

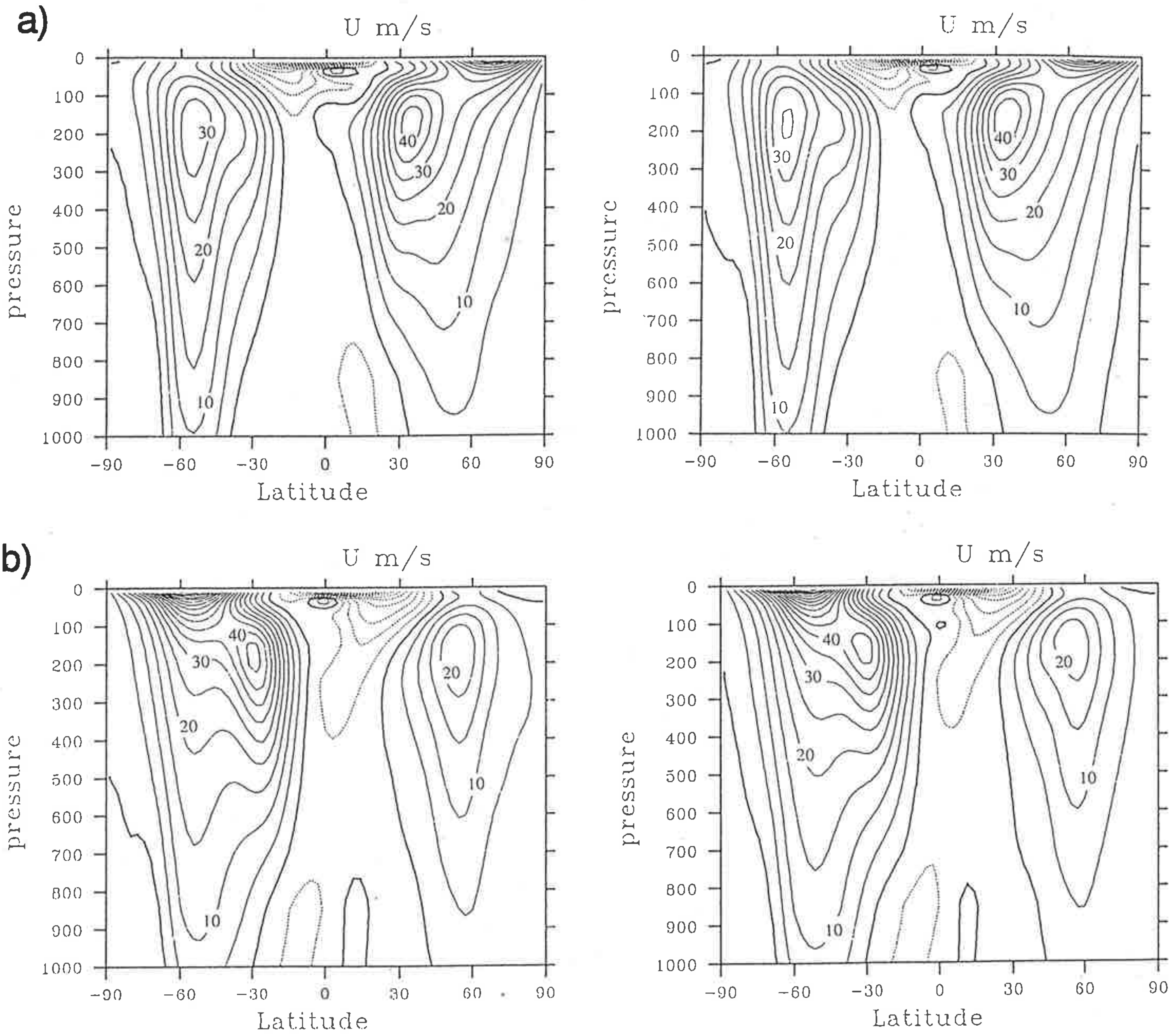


Fig. 7: (a) Zonal wind during February for the control (left) and the $2CO_2$ case (right). (b) The same but for August.

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