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Hurricane-type vortices in a general circulation model

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ABSTRACT

A very high resolution atmospheric general circulation model, T106-L19, has been used for the simulation of hurricanes in a multi-year numerical experiment. Individual storms as well as their geographical and seasonal distribution agree remarkably well with observations. In spite of the fact that only the thermal and dynamical structure of the storms have been used as criteria of their identification, practically all of them occur in areas where the sea surface temperature is higher or equal to 26°C. There are considerable variations from year to year in the number of storms in spite of the fact that there are no interannual variations in the SST pattern. It is found that the number of storms in particular areas appear to depend on the intensity of the Hadley-Walker cell. The result is clearly resolution-dependant. At lower horizonal resolution, T42, for example, the intensity of the storms is significantly reduced and their overall structure is less realistic, including their vertical form and extent.

1. Introduction

Tropical cyclones are by far the most devastating of all natural disasters, both by causing loss of human life as well as giving rise to large economical costs. The tropical storm which afflicted Bangladesh in 1970 killed more than 300,000 people and counts as one of the most terrible natural catastrophies in this century. The economical damages after hurricane Andrew in Florida and Louisiana in August 1992 are estimated to be in the order of 30 billion US dollars.

Detection, prediction and warning of tropical storms are some of the most important tasks of the meteorological services, and major efforts have been spent and are being spent to find ways of further improving this work. Of particular importance is the possibility to use a general purpose forecasting model for such forecasts. Such an opportunity is gradually becoming possible as high general circulation models are able to resolve many of the characteristic features of tropical cyclones. Today, forecasts from the large forecasting centres such as ECMWF and NMC provide crucial guidance in the operational prediction of hurricanes and typhoons (Shun, 1992). It may be expected, as data-assimilation and modelling continue to develop, that tropical storms will be routinely predicted by large scale models in very much the same way as extra-tropical cyclones are predicted today. New types of satellites, such as the ESA earth resource satellites, ERS-1, will here provide additional data for a better initialization of such forecasts.

The possibility to predict tropical storms with a large scale general circulation model also creates a very powerful tool to explore tropical storms in a systematic way, and address questions concerning the fundamental physical processes behind the generation and manifestation of these phenomena and the rôle of them in the general circulation of the atmosphere. The specific question whether tropical storms will be more frequent or more vigorous or both as a result of future increased concentration of greenhouse gases will also require a comprehensive modelling approach.

The first indication that a low resolution GCM could simulate hurricane-type vortices was first demonstrated in an experiment by Manabe et al.

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(1970). A major systematic study was undertaken by Bengtsson et al. (1982) whereby the ensembles of daily (up to 10 days ahead) operational predictions by the ECMWF model for the year 1980 were investigated in order to identify vortices with a structure similar to that of intense tropical cyclones.

The 1980 ECMWF operational model was a grid-point model (JSC, 1980) with an horizontal resolution of 1.875 lat/lon and thus of much higher resolution than the model used by Manabe et al. (1970) and in fact even with a higher resolution than todays atmospheric general circulation models when used for long term climate simulations.

A number of characteristic features were quite realistically reproduced by the ECMWF model, such as the vertical structure of the storm, areas of cyclogenesis, characteristic lifetimes, the motion of the storms as well as the sensitivity to the temperature of the ocean surface. Several unrealistic features were also evident, such as a tendency to simulate/predict too many vortices in the western north Pacific and generally too few elsewhere, particularily in the western north Atlantic. The predicted storm tracks also had a too strong poleward component. There were also considerable difficulties in initialising the vortices. It took generally about a week before the model reproduced a steady number of them.

As subsequently has been found, several of these deficiencies were due to faults in the physical parameterisation of sub-grid scale processes. The GCMs and the global forecasting models 10 years later have overcome several of these deficiencies (Bengtsson, 1991). Of particular importance has been a better parameterization of long wave radiation and deep convection.

Intense tropical storms, hurricanes and typhoons undergo large interannual variations. During the period 1958–1977, (Gray, 1979), the annual number of intense tropical storms varied between 97 in 1971 and 67 in 1977. Even larger variations occur for each hemisphere and in specific ocean basins. In the north-west Atlantic, for example, there were 14 hurricanes in 1971 but only 4 in 1972. Wu and Lau (1992) have studied the relation between ENSO and the frequency of intense tropical storms in different ocean basins. It is suggested by Wu and Lau (1992) that El Niño acts to reduce the number of Atlantic hurricanes while the opposite is true in the cold La Niña phase. Another example of a process which may effect the number of Atlantic storms is the level of soil moisture in the Sahel region, as has been suggested by Gray (1988).

Another question which has been considered recently is whether the anticipated greenhouse warming (IPCC 1990, 1992) may influence the frequency, distribution and intensity of tropical storms. In view of the serious impact of an increase of these phenomena, which in fact may be more damaging than the overall warming itself, Broccoli and Manabe (1990), and Haarsma et al. (1992) have undertaken a series of scenario integrations with the present and a doubled CO_2 concentration, respectively, to investigate whether the suggestions by Emanuel (1986, 1988) hold in a more realistic context. Broccoli's and Manabe's result is inconclusive, and it follows that the result is crucially dependent on the parameterisation of clouds. In the case of fixed or climatologically prescribed clouds, a doubling of CO_2 leads to an *increase* in the number of tropical storms, while in the case of predictive clouds the doubling of CO_2 leads to a *decrease* in the number of storms! Haarsma et al., on the other hand, found a larger number of hurricane type vortices in double CO_2 experiments.

The main purpose of this paper is to explore to what extent a very high resolution climate model using prescribed sea surface temperatures is capable of realistically simulating intense tropical storms with respect to their characteristic structure and evolution, geographical distribution, movement and intensity.

The criteria of identifying the storms will only be based on their typical structure and intensity, and except for the fact that the search is restricted to ocean areas only, there are no conditions imposed on sea surface temperatures, time of the year or the geographical domain.

We will use the notation "hurricane" for the intense tropical vortices generated by the model. We will do so in spite of the fact that the model-simulated hurricanes differ from those of the real atmosphere in some respects. The major difference is one of scale in that the simulated ones extend over a larger area, another is the absence of an eye structure. In a following study we intend to address the problem of scale and internal structure by a very high resolution limited area model nested with the global one. We hypothesize thereby that the development of an eye structure is essentially a matter of increased horizontal resolution down to a few tens of kilometers.

The investigation to be reported here has been concentrated on a 5-year high resolution run using a triangular truncation at wavenumber T106. However, similar studies have been done for two sets of multi-decadal integrations at triangular truncation T42; one set using climatological SSTs and another set using observed SSTs for the years 1979–1992 (repeated twice). In fact, the criteria for selecting the model hurricanes were based on experiments with a T42 resolution.

Following a description of the model in Section 2, we explain in Section 3 the design of the experiment and the criteria used to define the model hurricanes. In Section 4 we analyze the structure of the model-generated hurricanes and in Section 5 the geographical distribution of the generation of hurricanes and their movements. In the final section we discuss the time variability of the model-simulated hurricanes and comment on possible physical processes critical for their development.

In another investigation we intend to study how the frequency, intensity and distribution of hurricanes may change when the high resolution model is driven by SSTs generated by a greenhouse scenario study corresponding to a doubling of the CO_2 concentration.

2. Model description

The present study has been undertaken by the so-called ECHAM3 model (Roeckner et al., 1992). ECHAM3 is the third generation GCM used for global climate modelling investigations in Germany. It is a spectral transform model with triangular truncation. It has evolved from the medium-range forecasting model used at

Table 1. *Specification of the ECHAM3 model*

The ECHAM3-model	
forecast variables:	ζ, D, T_W, q, $\ln p_s$, m (cloud water)
vertical representation:	hybrid coordinate system ($\sigma \rightarrow p$ with increasing height), 19 levels (highest level 10 mb)
horizontal representation:	spectral with triangular truncation at wavenumber 106; non-linear and diabatic terms are calculated on a Gaussian grid (1.1 lat/lon)
time integration:	semi-implicit; leapfrog with time filter. $\Delta t = 12$ min
orography:	mean
radiation:	two-stream approximation; absorbers are CO_2, O_3 aerosols (prescribed) and water vapour, cloud water content (predicted); 4 solar and 6 terrestrial intervals; annual and daily cycle (Hense et al., 1982; Rockel et al., 1991)
surface albedo:	climatological, but dependent on snow
horizontal diffusion:	∇^4 for $n > 30$
vertical diffusion:	at the surface: similarity principle, corrections for weak winds. Ekman layer and free atmosphere: dependent on Richardson number modified by moisture
mountain drag:	gravity wave drag (Miller et al., 1989)
convection:	mass flux scheme (Tiedtke, 1989)
cloud and precipitation:	prognostic equation for cloud water (Roeckner et al., 1991)
surface processes:	5-level heat diffusion scheme, one-layer infiltration/runoff scheme (Dümenil and Todini, 1992)
sea surface temperature:	climatology, averaged 1979–1988

ECMWF. The main aspects of ECHAM3 are summarized in Table 1.

The main part of this study has been undertaken with a high resolution version of ECHAM3 using a triangular truncation at wavenumber T106. Some experiments have also been done at a much lower resolution, T42, normally used in long climate studies (Bengtsson, 1993). The physical parameterization has been developed and validated at T42 resolution. The only modification undertaken to the high resolution run was to change the horizontal diffusion by introducing a ∇^4 smoothing operator for wavenumbers shorter than 30, instead of applying a wavenumber dependant smoothing operator from wavenumber 15, as is done for the T42 model, Roeckner et al. (1992).

The parameterization of sub-grid scale processes is formulated in a simplified parametric form, partly because of insufficient detailed knowledge (e.g., the turbulent transfer and cloud microphysics), and partly because a more accurate treatment would exceed presently available computer resources (e.g., the computation of a radiative transfer). The radiation scheme uses a broad-band formulation of the radiative transfer equations with six spectral intervals in the infrared and four intervals in the solar part of the spectrum (Hense et al., 1982; Rockel et al., 1991). Gaseous absorption due to water vapour, carbon dioxide and ozone are taken into account as well as scattering and absorption due to aerosols and clouds. The cloud optical properties are parameterized in terms of cloud water content, which is an explicit variable of the model.

The vertical turbulent transfer of momentum, heat, water vapour and cloud water is based upon the Monin-Obukhov similarity theory for the surface layer and the eddy diffusivity approach above the surface layer, as in the original ECMWF model (Louis, 1979). The drag and heat transfer coefficients depend on roughness length and Richardson number, and the eddy diffusion coefficients depend on wind stress, mixing length and Richardson number, which has been reformulated in terms of cloud-conservative variables (Brinkop, 1991, 1992).

The effect of orographically excited gravity waves on the momentum budget is parameterized on the basis of linear theory and dimensional considerations (Palmer et al., 1986; Miller et al., 1989). The vertical structure of the momentum flux induced by the gravity waves is calculated from a local Richardson number, which describes the onset of turbulence due to convective instability and the breakdown approaching a critical level.

The parameterization of cumulus convection is based on the concept of mass flux and comprises the effect of deep, shallow and mid-level convection on the budget of heat, water vapour and momentum (Tiedtke, 1989). Cumulus clouds are represented by a bulk model including the effect of entrainment and detrainment on the updraft and downdraft convective mass fluxes. Mixing due to shallow stratocumulus convection is considered as a vertical diffusion process with the eddy diffusion coefficients depending on the cloud water content, cloud fraction and the gradient of relative humidity at the top of the cloud.

Stratiform clouds are predicted per se in accordance with a cloud water equation including sources and sinks due to condensation/evaporation and precipitation formation both by coalescence of cloud droplets and sedimentation of ice crystals (Sundqvist, 1978; Roeckner et al., 1991). Sub-grid scale condensation and cloud formation is taken into account by specifying appropriate thresholds of relative humidity depending on height and static stability.

The land surface model considers the budget of heat and water in the soil, snow over land and the heat budget of permanent land and sea ice (Dümenil and Todini, 1992). The heat transfer equation is solved in a five-layer model assuming vanishing heat flux at the bottom. Vegetation effects such as interception of rain and snow in the canopy and the stomatal control of evapotranspiration are grossly simplified.

No attempt was made to modify the physical parameterization in order to handle processes of importance for the generation and development of hurricanes specifically. Instead the strategy has been to use a general purpose model, since we believe that the generation of hurricane type vortices is inherently determined in models which can handle large scale convective forcing properly, and where the numerical representation and resolution is sufficient. As has been discussed above, already at an equivalent resolution around 500 km such developments occur. However, as will be demonstrated in this study, the realism in the simulation is only becoming evident at much higher resolutions.

3. Design of the experiment

The ECHAM3 model has been used for a large number of experiments using horizontal resolutions ranging from T21–T106. The main purpose of those investigations has been to study the natural variability of climate and to explore the predictability of climate.

The development of well organised tropical vortices is as typical a feature of a GCM as is the development of extra-tropical storms and occurs regularly in the ECHAM model as well as in most other general circulation models. During the peak of the hurricane season, July–October at the Northern Hemisphere and January–March at the Southern Hemisphere, these vortices transport substantial amounts of eddy kinetic energy and moisture polewards during the hurricane season. Gray (1979) has estimated this to be of the order of 20% of the total transport.

A crucial part of the study is the specification of criteria for an automatic determination of hurricane-type vortices in the experiment. At our disposal was the standard archived data record consisting of all the basic quantities at all model levels, together with additional derived parameters, precipitation, fluxes etc. For the experiment these data were stored twice daily.

One of the central objectives was to base the identification of the vortices on dynamical and physical criteria only, thus avoiding empirical conditions on geographical distribution, sea surface temperature or specific time of the year. Since the search was limited to the generation of vortices, we limited the search to ocean areas only, as inspection of a large number of maps did not show any land developments. Furthermore, we only considered storms with a lifetime of at least 36 hours.

Based on the structure of typical tropical vortices taken from a study at T42 resolution, the following criteria were found suitable:

1. Relative vorticity at 850 hPa $> 3.5 \times 10^{-5}\ s^{-1}$.
2. A maximum velocity of 15 ms^{-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 as defined below) 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 $\geqslant 1.5$ days.

The minimum in surface pressure was determined as the centre of the storm. Mean values were calculated within a 7×7 grid point area around the point of minimum pressure.

It was found that the main criteria 3–5 specifying a vertical structure with a warm core and maximum wind at low levels, very efficiently eliminated extra-tropical storms which have a completely different structure. The only differences which happen a few times a year were very intense features at high latitudes in both hemispheres in the winter season.

Broccoli and Manabe (1990) did not use any criteria on the thermal structure and restricted the search for oceanic grid points equatorwards of 30° latitudes. They furthermore limited their search to the six-month "hurricane season", defined as May–October and November–April in the Northern and Southern Hemispheres respectively. The minimum wind speed was set to 17 ms^{-1}. No criteria on the vorticity was used. Wu and Lau (1992), in using the same GFDL model, removed these constraints but introduced additional criteria to eliminate unwanted types of vortices. Tropical continental dry disturbances were, for example, excluded by a criterion on the 950 hPa relative humidity, and extra-tropical baroclinic depressions were removed by an imposed condition on the 200 hPa westerly windspeed. The condition on the windspeed for the vortex was essentially the same as in Broccoli and Manabe (1990).

Finally, Haarsma et al. (1992) used the 11-layer GCM at the UK Met Office coupled to a 50 m mixed layer ocean. They used the same criterion on vorticity as in this study as well as criteria on a warm core, but less stringently than the one used here.

4. Structure of the simulated tropical cyclone

In order to examine the detailed structure and the time evolution of a simulated tropical cyclone, we selected a case from August during the first year of simulation. This is one of the more intense storms simulated during the 5 years, reaching a maximum wind speed of more than 52 ms^{-1}. The

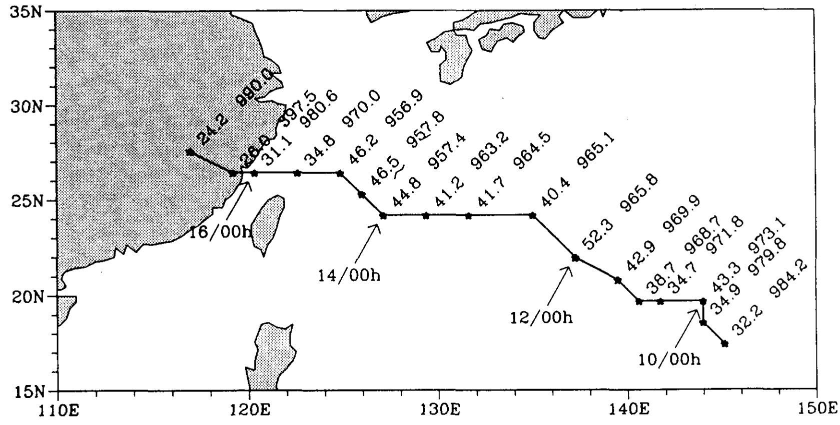

Fig. 1. Simulated track of a tropical cyclone during August of year 1. Above the hurricane track, shown for every 12 h are the windspeed (ms^{-1}) and the surface pressure (hPa) given.

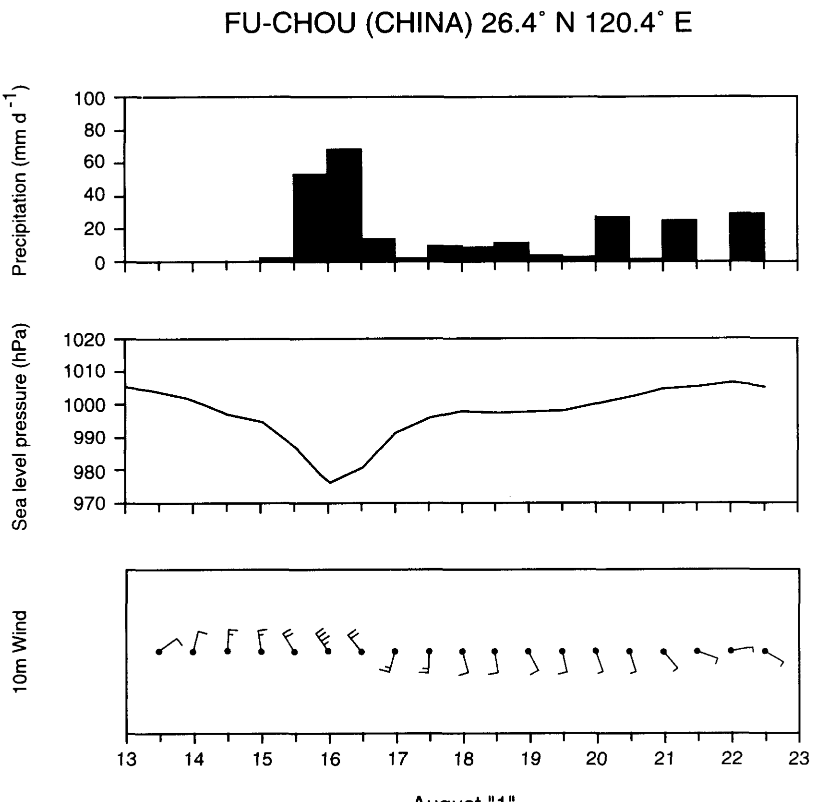

Fig. 2. Meteogram for Fu-Chou (Fukien, China) showing precipitation, surface pressure and 10 m wind for every 12 h from 13 August to 22 August, year 1 of the simulation.

cyclone develops in the area around 15°N, 148°E on 6 August from an easterly wave. This is an area which is a source region for most of the powerful tropical storms on earth. The sea surface temperature in the region of generation is quite high, around 30°C. The cyclone remains all the time over water which is more than 28°C.

During the first days the pressure in the centre of the cyclone falls slowly, but around 8 August a more rapid intensification is taking place. During the course of 8 days the cyclone is moving slowly east-northeast over the China Sea until it finally is hitting land near Fu-Chou at 26.4°N, 120.4°E in the Chinese province of Fukien. Fig. 1 shows the centre pressure of the cyclone and the maximum wind speed. There is generally a steady fall in the central pressure of the hurricane, most pronounced between 9 and 11 August and during 14 August. The maximum wind speed stays above 40 ms^{-1} between 12 and 15 August, reaching a peak of over 52 ms^{-1} on 12 August. At landfall the hurricane collapses quickly.

The realism of the event is portrayed in Fig. 2 showing a meteogram for Fu-Chou 13–18 August during the period when the hurricane passed the city. As comparison, the 5-day prediction for Charleston, South Carolina, of hurricane Hugo, September 1989 by the ECMWF model is shown in Fig. 3. It must be stressed that in both these cases the windspeed interpolated to the specific position had already weakened significantly compared to the windspeed at sea.

The vertical structure of the storm is studied in Figs. 4–6 which show as a function of height and radius: (i) the azimuthal mean of the tangential velocity; (ii) the radial velocity; (iii) the vertical velocity (in Pa/s); (iv) the relative humidity; (v) the vorticity (in 10^{-5}/s); (vi) the temperature anomaly.

We examine the mature stage of the tropical cyclone in Fig. 4 in order to explore the correspondance with observed tropical cyclones as well as with simulated cyclones with a lower resolution version of ECHAM3.

The vertical cross section of the tangential wind compares well with a Pacific composite typhoon (Frank, 1977). The maximum tangential wind occurs at around 850 hPa and is located at 2° latitude distance from the centre, while the observed maximum wind is located at around 1° (Frank, 1977) or 1.5° (Izawa, 1964). The maximum outflow takes place further away from the centre some 10–15° latitude distance at around 100 hPa. The agreement with the composite data from Frank (1977), Fig. 5a, is excellent.

Composite radial velocities have been compiled by Frank (1977) for western Atlantic hurricanes. The agreement with the simulated data is excellent, Fig. 5b. The maximum inflow takes place in the boundary layer around 950 hPa and the maximum outflow just above 200 hPa. The distance from the centre for the inflow maximum is larger for the simulation with about the same ratio as for the tangential wind.

The vertical velocity agrees well with Frank (1977), with upwind motions within some 3° from the centre and with an elongated zone of maximum winds through the whole depth of the troposphere. As in Frank's composite data there is a weak area of sinking motion about 5° from the centre. Similarily the vertical cross section of relative humidity agrees nicely with Frank (1977), and there is even in the simulation a weak indication of

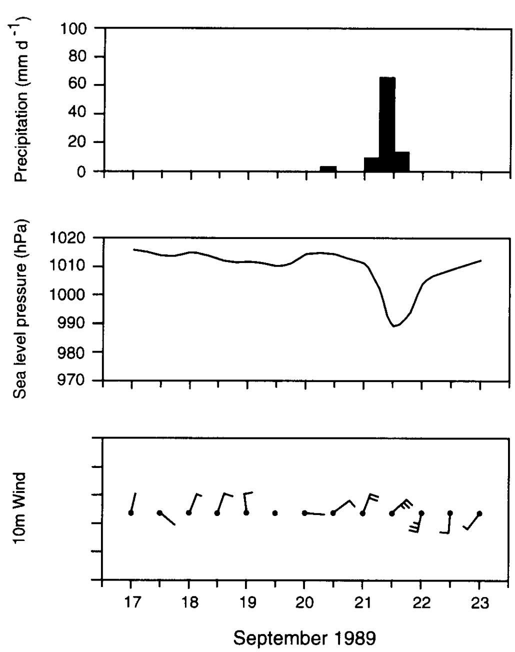

Fig. 3. Meteogram for Charleston (South Carolina, USA) showing precipitation, surface pressure and 10 m wind for every 6 h from 17 September to 23 September 1989, hurricane Hugo, predicted by the ECMWF model from 17 September 1989 12 UTC.

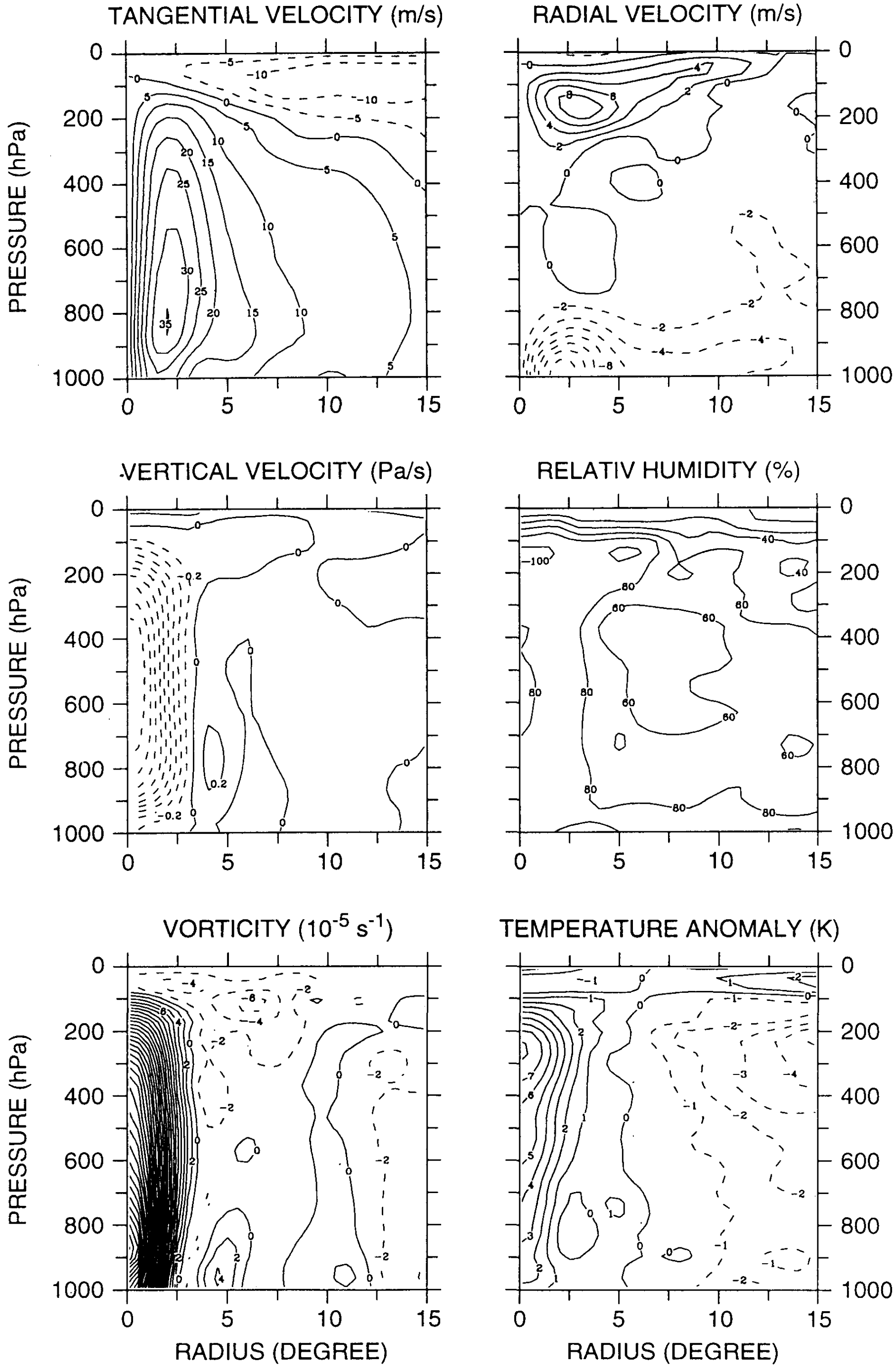

Fig. 4. 2-dimensional cross section of tangential wind (ms^{-1}), radial wind (ms^{-1}), vertical velocity (Pas^{-1}), relative humidity (%), velocity (10^{-5} s^{-1}) and temperature anomaly (K) for the maximum stage of the development at 15 August 12 UTC, year 1.

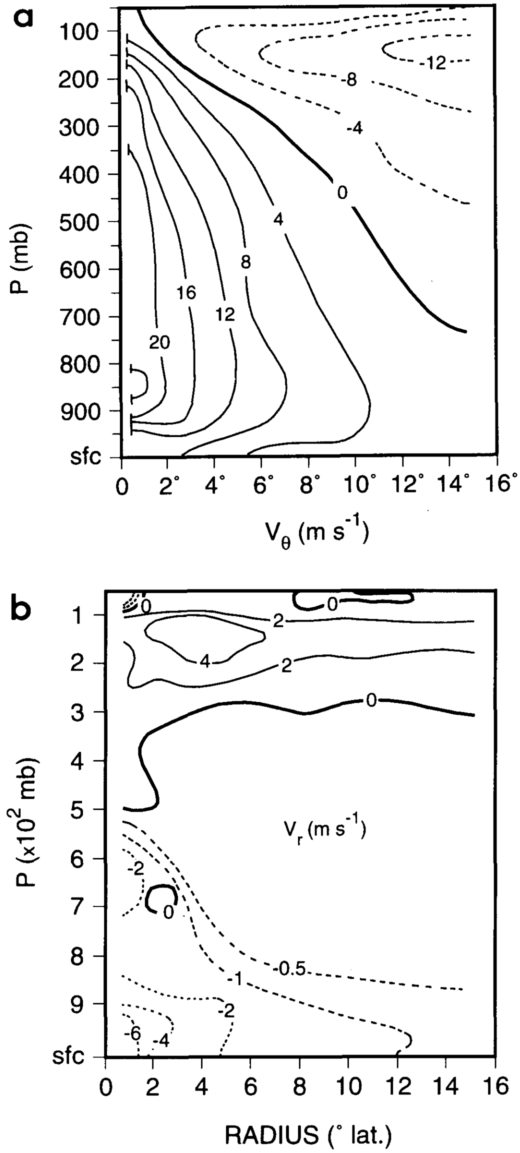

Fig. 5. (a) Two-dimensional cross-section of tangential winds, V_θ for the mean typhoon (central pressure <980 hPa). According to Frank (1977). (b) Two-dimensional cross section of radial winds, V_r for the mean steady-state typhoon. According to Frank (1977).

lower relative humidity (below 80%) at the very centre of the storm.

The vorticity is clearly noted with values well above $10^{-4}\,s^{-1}$ within 2° of the centre. Outside the core of intense vorticity there is an indication of a banded structure of weak bands of positive and negative vorticity through the troposphere. There is a maximum of negative vorticity around 100 hPa around 6° from the centre stretching out through the lower stratosphere on top of the vortex. Finally, the temperature anomaly is reaching a value of over 8°C between 200 and 250 hPa. Observed values from individual intense storms are normally larger. Hawkins and Imbembo (1976) have reported 16°C for hurricane Inez in September 1966. We explored a few other storms as well and found similar characteristic structures.

It may be interesting to compare the structure of the simulated hurricane in the T106 run with another hurricane in T42 run (Fig. 6). There are several similarities in the structure but the low resolution vortices lack the steep, sharp structure of the high-resolution run. They are also much wider in the horizontal direction as a consequence of the coarser resolution. This result is anticipated as one would use successively finer resolution that the simulated features, which would increase in resemblance to the observed ones as is found for example in the study by Dell'Osso and Bengtsson (1985). Also in that case the vertical extension of the simulated storm benefitted from the increased horizontal resolution.

5. Geographical distribution, movement of vortices

According to Gray (1979) there are approximately 80 tropical cyclones with a maximum sustained windspeed of 20–25 ms^{-1} over the globe per year. Fig. 7 shows the tropical storms as simulated by the ECHAM3 T106 model over a period of 5 years, all with maximum sustained windspeed higher than 20 ms^{-1} (see Table 5).

The averaged number of simulated tropical cyclones amounts to 83/year, varying between 91 during the third and fifth year and 72 during the first.

The observed variation over the 20-year period 1958–1978 was a maximum of 97 in 1971 and a minimum of 67 during 1977. The average observed ratio between the number of storms at the Northern Hemisphere to the Southern Hemisphere is 2.2 compared to 2.1 in the simulation.

Table 2 shows the number of simulated Northern Hemisphere cyclogenesis by year and month all

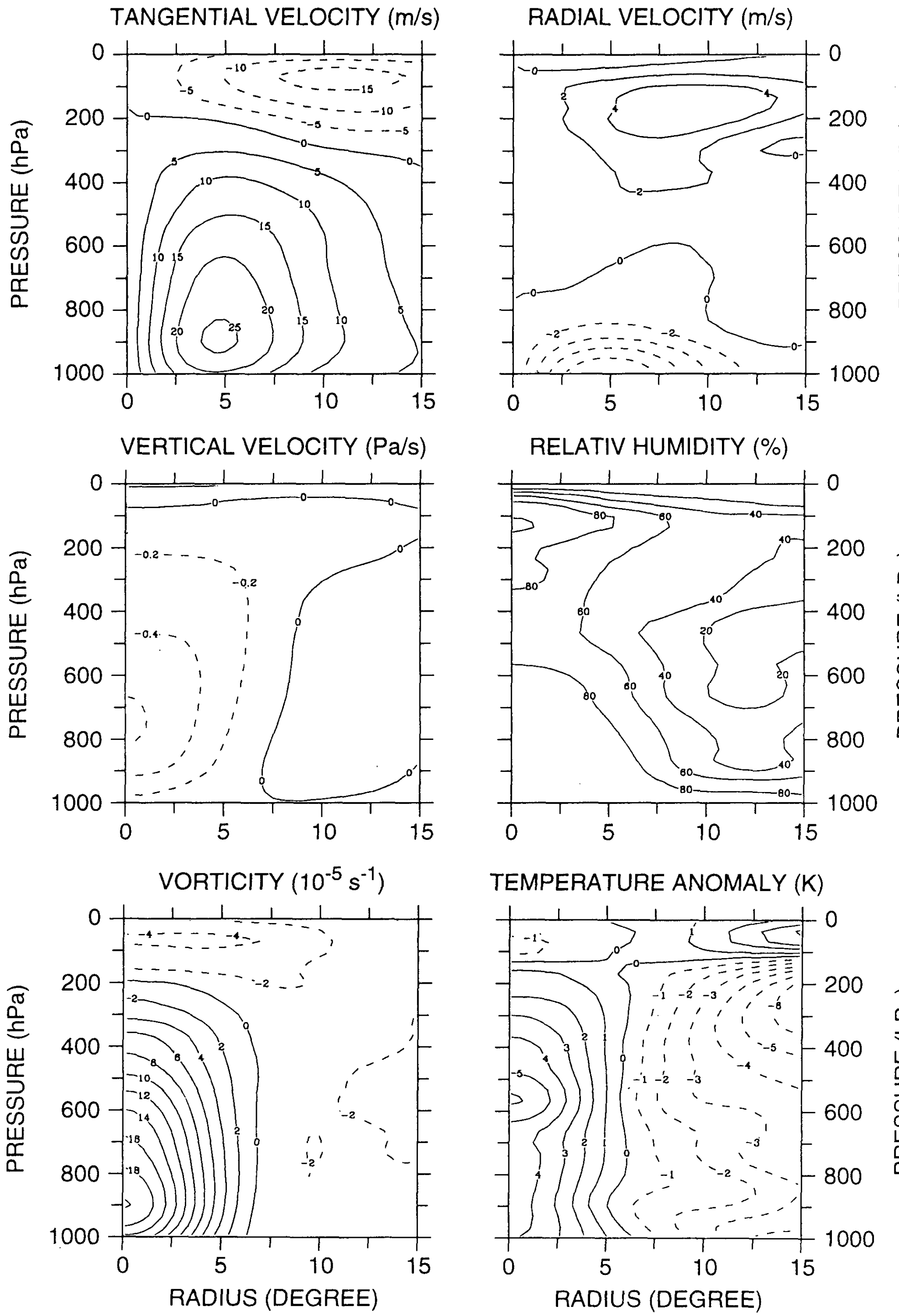

Fig. 6. The same as Fig. 4 but for a T42 resolution.

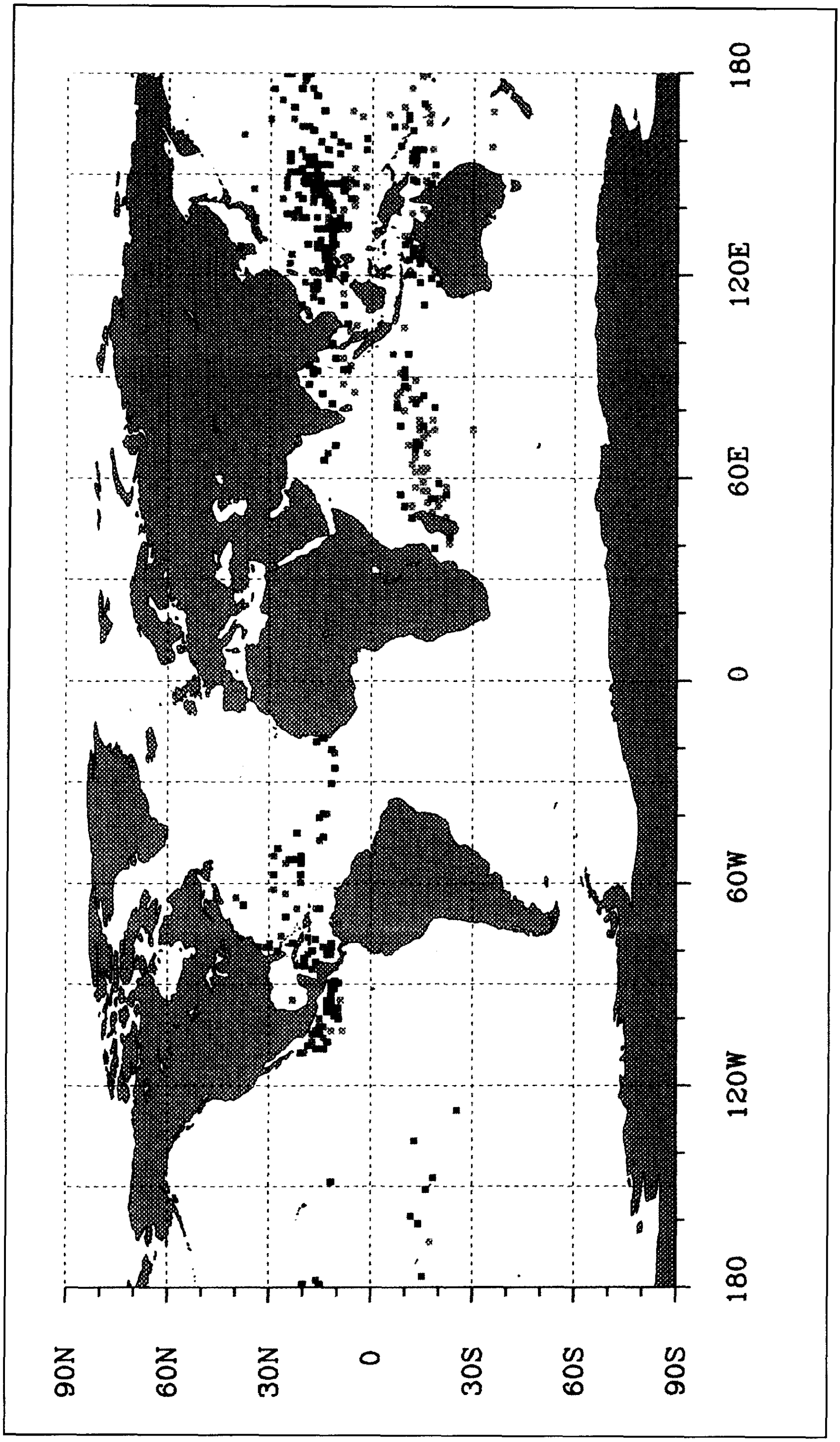

Fig. 7. Cyclone genesis simulation during 5 years. Blue colours during DJF, red colour during MAM, green colour during JJA and black colour during SON.

Table 2. *Frequency of simulated Northern Hemisphere tropical cyclone genesis by year and month*

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total	Range
1	1	2	1	0	3	2	0	10	11	12	4	3	49	
2	1	1	1	2	3	9	4	6	7	11	5	5	55	
3	3	0	3	0	4	8	3	15	14	5	4	4	63	49–63
4	2	2	2	4	3	4	3	5	12	5	6	3	51	
5	4	0	3	1	4	7	6	12	10	5	5	6	63	
total	11	5	10	7	17	30	16	48	54	38	24	21	281	
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 (1958–77)	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 observed averaged frequency (1958–77) of hurricanes according to Gray (1979) is shown on the lowest line. The column to the right shows the range of storms (lowest versus highest number) for the simulated and the observed storms respectively.

Table 3. *The same as Table 2 but for the Southern Hemisphere*

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total	Range
1	7	2	3	5	1	0	0	0	0	0	2	3	23	
2	5	9	5	2	1	0	0	0	0	1	2	3	28	
3	3	6	4	6	2	0	0	0	0	0	3	4	28	23–28
4	7	8	4	2	0	0	0	1	0	1	0	4	27	
5	4	6	7	5	1	0	0	1	0	0	2	2	28	
total	26	31	23	20	5	0	0	2	0	2	9	16	134	
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 (1958–77)	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 4. *Yearly variation of simulated tropical cyclones by ocean basin and year*

Year	NWatl	NEPac	NWpac	NInd.	SInd.	Aust.	S. Pac.	Others	Total
1	10	11	24	1	7	10	4	5	
2	9	7	32	7	13	12	3	0	
3	14	8	37	4	13	8	6	1	
4	11	6	30	4	13	11	3	0	
5	10	7	41	4	18	6	4	1	
total	54	39	164	20	64	47	20	7	415
average range	10.8	7.8	32.8	4.0	12.8	9.4	4.0	1.4	83.0
	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
OBS range	4–14	8–20	17–35	4–9	4–12	5–17	3–10		

For comparison the observed averaged frequency 1958–77 according to Gray (1979) is shown on the lowest line. The specific areas are shown in Fig. 12 and are identical to those used by Gray. Others refer to hurricane developments elsewhere.

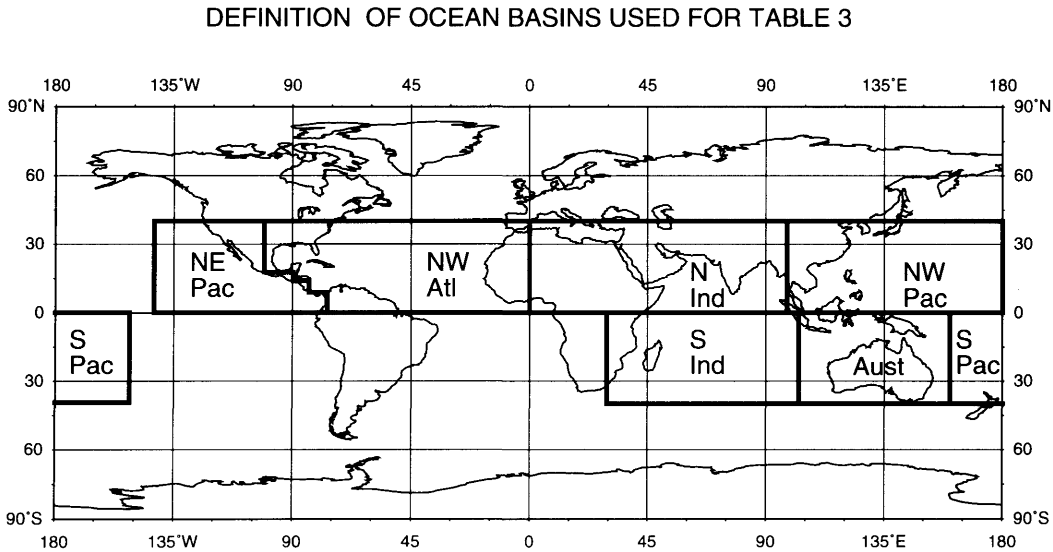

Fig. 8. Specification of ocean basins used in the Table 4. NE Pac = North East Pacific, NW Atl = North West Atlantic, N.Ind = North Indian, NW Pac = North West Pacific, S.Ind = South Indian, Aust = Australia, S Pac = South Pacific.

fulfilling the criteria in Section 3 compared to the observed average distribution during the 20-year period in Gray's study. The agreement is good except that there is a somewhat too high number of simulated storms in November and a peculiar minimum in July.

Table 3 shows the same for the Southern Hemisphere. The agreement with observations here is excellent and falls clearly within the natural variability. The variability from year to year is larger in reality; this is presumably due to the lesser number of years in the simulation and perhaps also to the fact that the sea surface temperature in the simulation is the same from year to year.

Table 4 shows the variation of storms by ocean basins, Fig. 8. The agreement is also here remarkably good and the number falls by and large within the range of variability as reported by Gray. There is an indication of slightly more storms in the North-West Pacific and Southern Indian Ocean and a slightly lower number in the North-East Pacific and Southern Pacific.

In Table 5, finally, we have ordered the storms by their maximum windspeed and by ocean basins. Equivalent observations are presently not known

Table 5. *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	Total
NWAtl.		8	16	14	7	4	3	2	54
NEPac.		8	12	16	2	1	0	0	39
NWPac.		8	32	54	34	20	12	4	164
NInd.		2	8	7	3	0	0	0	20
SInd.		8	20	15	14	6	1	0	64
Aust.		1	13	17	9	6	1	0	47
S.Pac		0	8	6	2	3	1	0	20
others		1	2	2	2	0	0	0	7
total		36	111	131	73	40	18	6	415

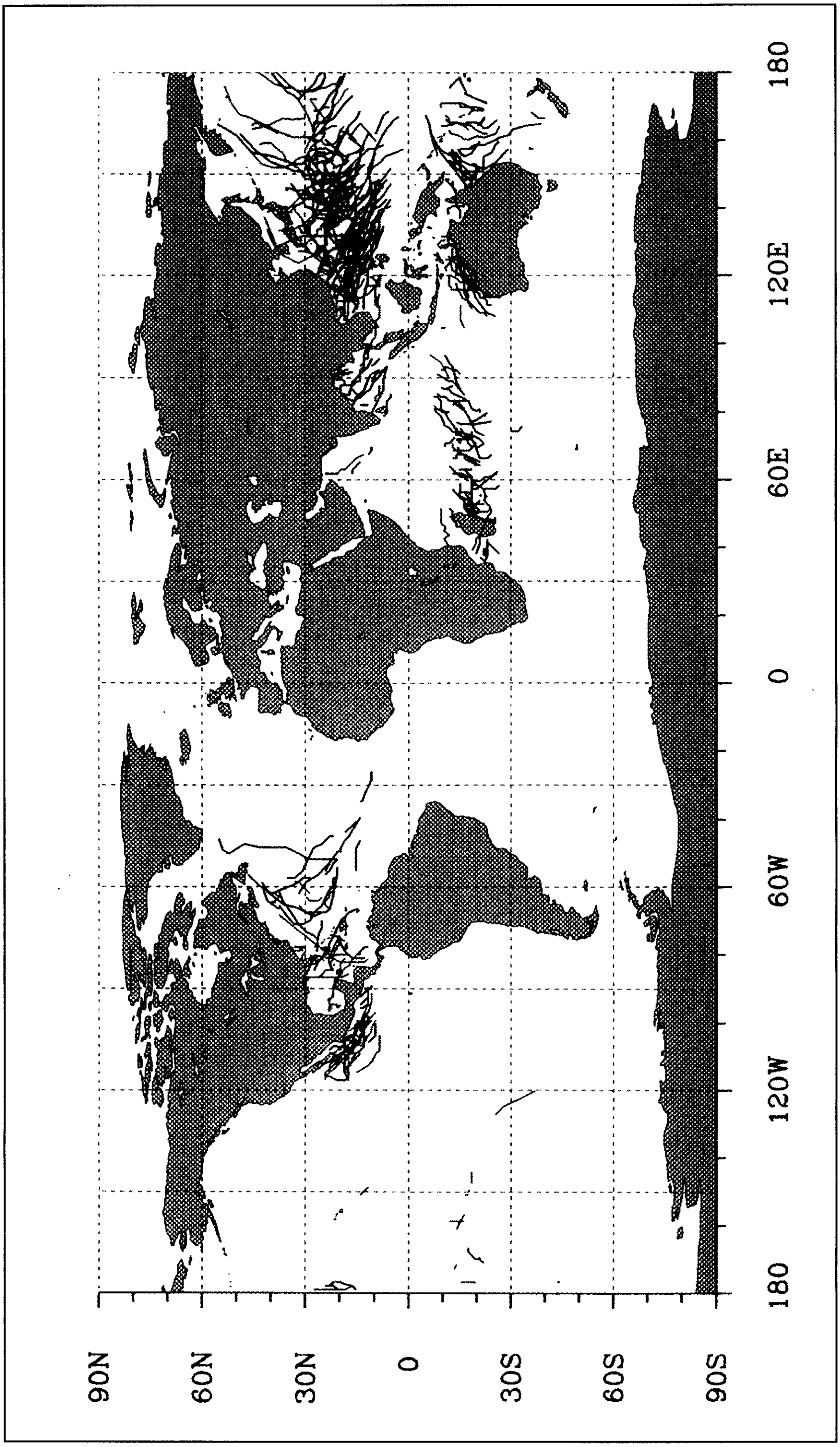

Fig. 9. Simulated cyclone tracks. The tracking is only indicated when the hurricanes satisfied the selection criteria. All tracks for 5 years. Colour notation as in Fig. 7.

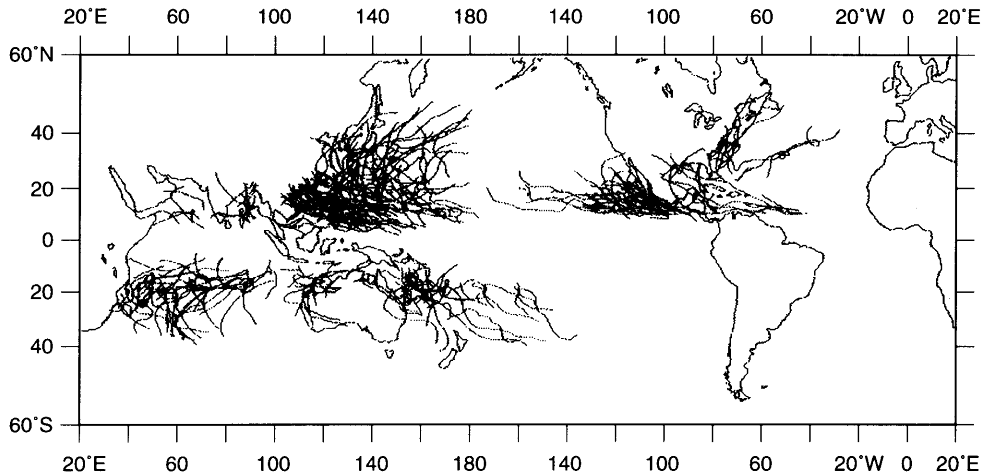

Fig. 10. Observed cyclone tracks over 3 years. According to Gray (1979).

to the authors. It is interesting to note that the North–West Pacific has by far the most powerful storm as well as the largest number of storms. The North–West Atlantic region is particularly interesting, having a comparatively large number of very intense storms, in spite of the fact that the total number of storms is relatively small.

The highest overall windspeed is 53.1 ms^{-1} and the lowest pressure 957 hPa as selected from the archived data for every 12 h. In reality much higher windspeeds and lower minimum pressure are observed. However, these very extreme conditions can only be found over a very small area, not possible to resolve with the present model. Dell'Osso and Bengtsson (1985) and Kurihara and Tuleya (1981) have clearly demonstrated that given an adequate resolution the intensity of the storms appear to converge towards the observed values.

Fig. 9 shows the cyclone tracks for all cyclones having a minimum pressure less than 1000 hPa. Different colours indicate the season. Fig. 10 shows the corresponding observed tracks calculated over 3 years. Finally, there are a few extratropical cyclones which fulfill the criteria given in Section 3. These are all extremely deep, highly occluded and very slowly moving systems which occur at very high latitudes, mostly in the winter season. These events are quite rare, about 3 per year, and none of them meets the hurricane criteria more than 2 days.

6. Possible large-scale mechanisms controlling hurricane genesis

There are several observational aspects with respect to hurricane development which require a more fundamental understanding. Among those are the comparatively rareness of hurricanes and the fact that they are formed, practically without exceptions, over ocean areas where the sea surface temperatures are equal or higher than 26°C. However, this is by no means a sufficient condition, since some areas, such as the tropical part of the Southern Atlantic Ocean, where the SST conditions are fulfilled, do not have any hurricanes. Based on empirical evidence and some general physical reasoning, Gray (1979) defined a set of parameters which in combination and suitably weighted were found to provide a geographical distribution which agreed surprisingly well with the observed generation of hurricanes. There are six parameters; the Coriolis parameter, the relative vorticity, the inverse of the vertical wind shear, the upper ocean thermal energy, the averaged relative humidity in the lower and middle troposphere, and an expression for the moist static stability. The product of the 6 factors then provided a genesis number. It is not our intention here to go into a deeper discussion on Gray's paper, but instead to try to discuss the genesis problem in a more comprehensive way along the lines suggested by Emanuel (1988). Besides we have not been able to practically use Gray's scheme as applied to our GCM runs, due to its overly high sensitivity. Based on our experience we must question the generality of Gray's empirical approach.

Emanuel (1988) has proposed a succinct theory for the maintenance of hurricanes by conceptually seeing hurricanes as mechanisms driven by a large scale Carnot cycle confined by the temperature difference of the ocean surface, T_s and the tropical upper troposphere, T_o. According to Carnot's theorem the total amount of mechanical energy available from a closed circuit through the storm system is the total heat input multiplied by the efficiency factor ε:

$$E = \varepsilon T_s (S_c - S_a) \qquad (1)$$

where ε is

$$\varepsilon = \frac{T_s - T_o}{T_s}. \qquad (2)$$

S is the total entropy per unit mass of air, subscript "$_c$" represents the conditions in the center of the storm and subscript "$_a$" the inflow region which could commence some thousands kilometers away.

A parcel of air travelling between a and c receives total entropy from the oceans, mainly in the form of water vapour, as a consequence of the thermodynamical disequilibrium between the ocean and the atmosphere. The water vapour flux is mainly controlled by the surface windspeed and the stability properties of the planetary boundary layer. The efficiency of the energy supply is determined by the temperature gradient between the surface and the upper troposphere and provides, as Emanuel has demonstrated, an upper bound measure of the maximum intensity of a hurricane.

The large-scale tropical circulation consists of a pattern of Hadley–Walker cells dominated by three major centers of action; the western tropical Pacific, central Africa/western Indian ocean and north western Brazil/central America. These systems are gradually changing in position and intensity by season, they are often significantly modified by tropical SST anomalies such as El Niño, and they also respond on a shorter timescale to extra-tropical circulation forcing.

We will now suggest 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 where the Coriolis force is sufficiently large to provide the required convergence (at least poleward of 5° latitude), and where there is a sufficient supply of heat from the ocean (empirically found when the SST is equal or higher than 26°C). The areas of large scale convergence do change relatively slowly, the vertical wind shear is weak, allowing the storm to develop the required vertical structure. Furthermore, the content of tropospheric water vapour is maintained at a high level due to the steady large scale moisture convergence.

There is observational evidence to support this hypothesis. The first is the absence of hurricanes in the Atlantic Ocean east of Brazil, in spite of the fact that the sea surface temperature is high enough. Another indication is the reduced number of hurricanes in the North West Atlantic during El Niño events. The absence of hurricanes over the Southern Atlantic is due to the predominantly sinking motion enforced by the large scale convection over equatorial Africa and western Brazil. The suppression of hurricanes during El Niño events in the North West Atlantic is also related to the compensating sinking in the area as a consequence of the eastward position of the tropical Pacific convergence area.

We have tested the hypothesis by comparing selected years of the simulation having a maximum or a minimum number of hurricanes respectively during a particular month of the 5 year simulation. Figs. 11, 12 show the result from August year 2 (small number of storms) and August year 3 (large number of storms).

It is interesting to note that the month having the largest number of storms in the North–West Pacific, August year 3 with 10 hurricanes, has a much stronger Hadley–Walker cell, as can be seen from the gradient of the velocity potential, than August year 2 with only 4 storms. It is not possible to know to what extent the large scale circulation is independent of the hurricane vortices. A positive feedback between the two systems of actions appears likely, this may contribute to the comparatively large interannual variability in the number of hurricanes found in this study as well in reality. We studied other pairs of months with maximum or minimum number of storms and found in general a similar tendency, namely that periods of a maximum number of storms had a more intense Hadley–Walker circulation in the actual region.

We have further been trying to obtain some understanding why also in the model simulation 26°C appears to constitute a limit for hurricane development, Fig. 13. The vertical distribution of temperature and moisture over the large scale convergence areas of the tropical oceans are in general such that deep convective activity starts to develop when the ocean surface temperature reaches values around 26°C. As a result the increase in heat

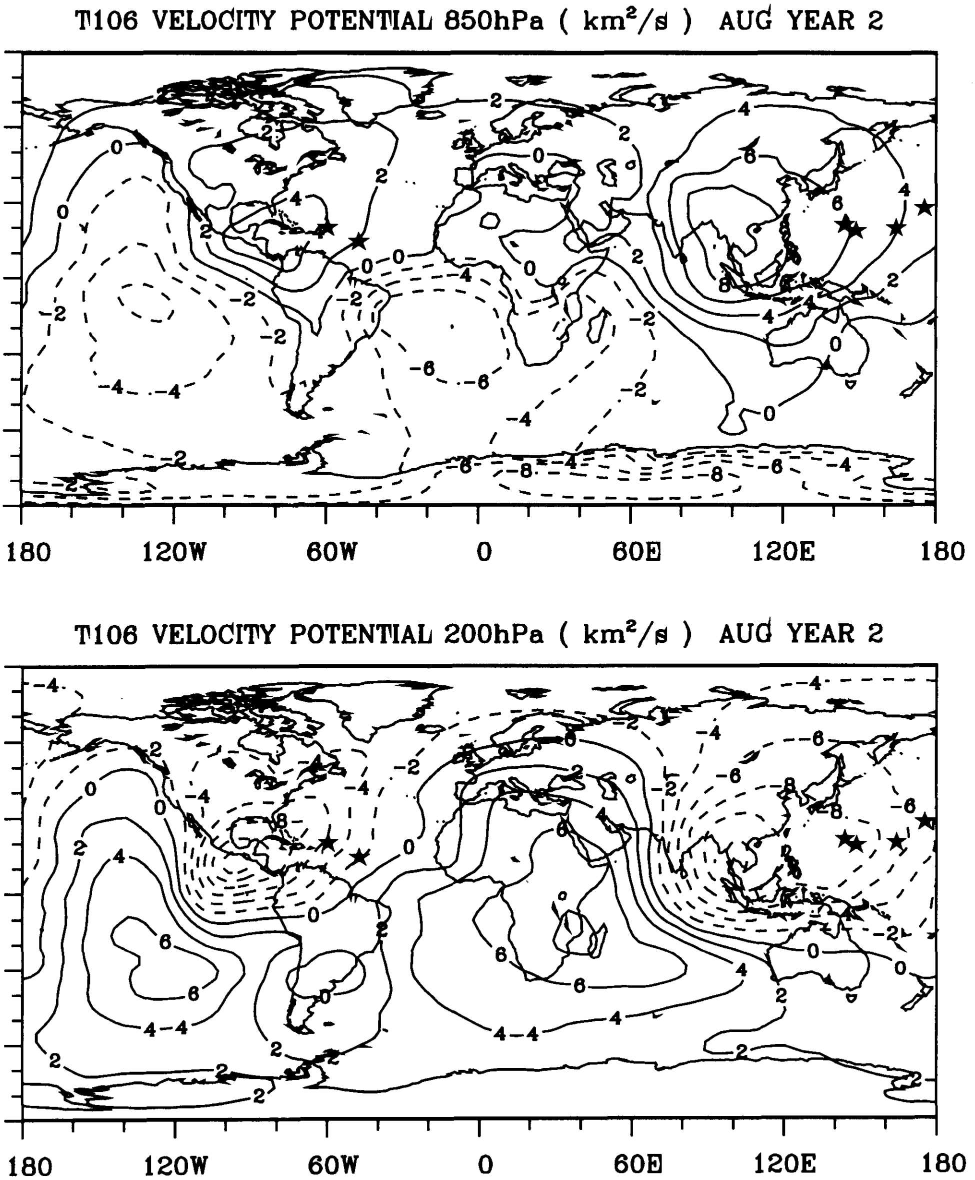

Fig. 11. Velocity potential at 850 and 200 hPa and the number of generated hurricanes in August year 2 (small number of storms).

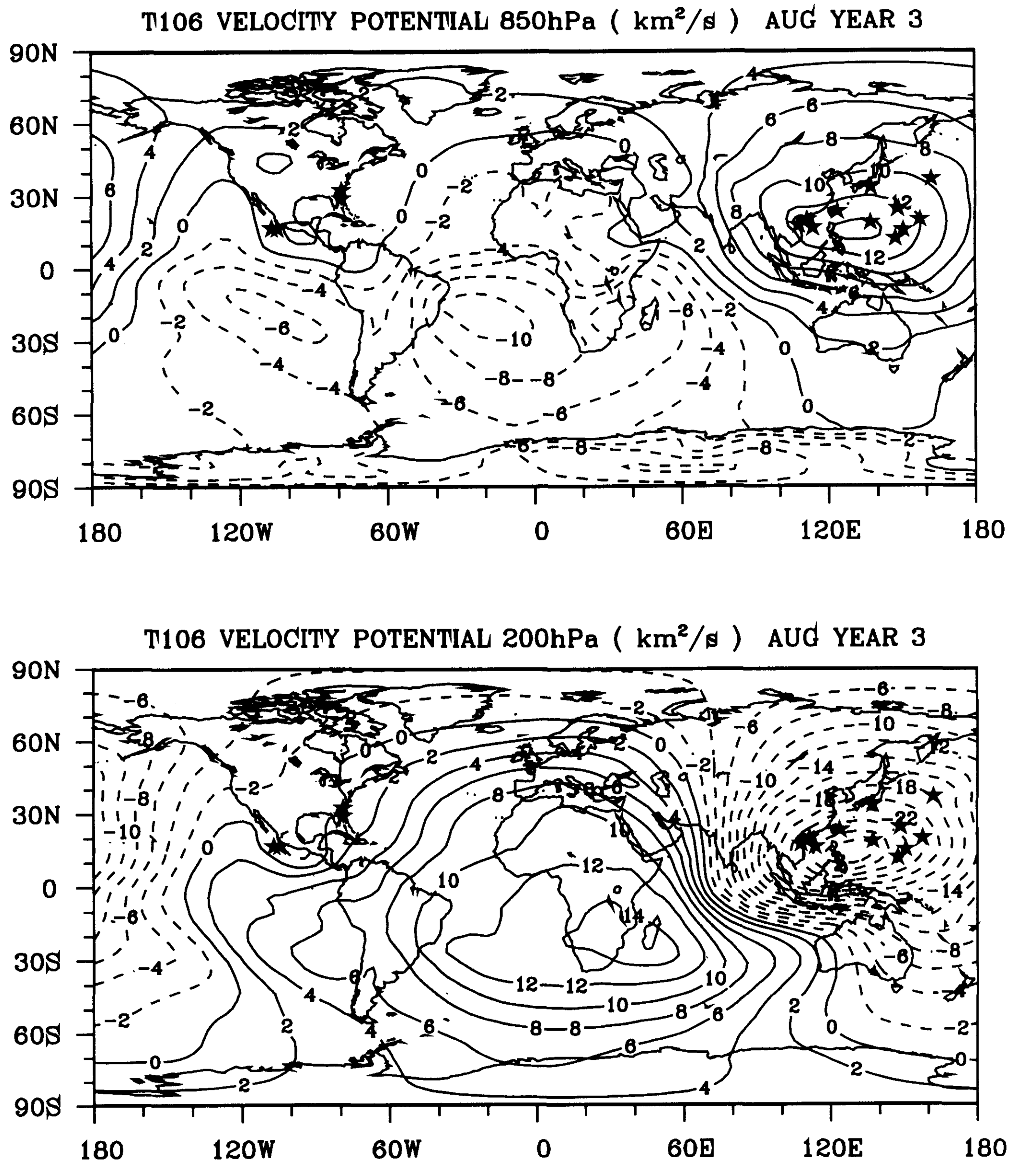

Fig. 12. The same as Fig. 11 but for August year 3 (large number of storms).

absorption by the trapping of longwave radiation in the atmosphere due to the high amounts of water vapour is becoming larger than the increase in the black body radiation from the ocean surface, creating what Ramanathan and Collins (1991) have called a super greenhouse effect. Furthermore, deep convection creates extended cirrus shields causing a sudden steep increase in the longwave cloud forcing providing a heating on the atmosphere below. These processes together with low-level moisture convergence provided by the large scale circulation cooperate in a thermo-

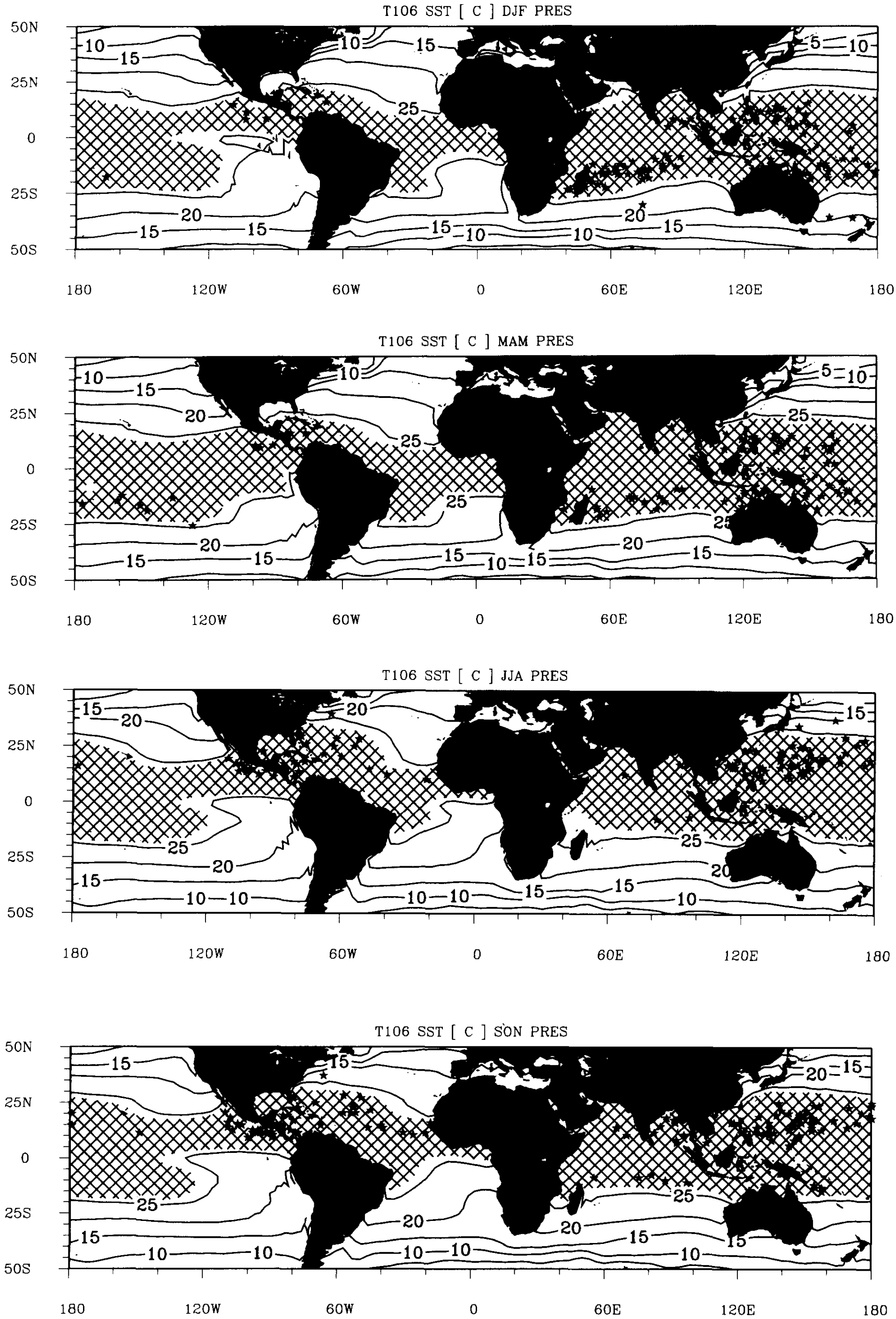

Fig. 13. Simulated hurricane genesis for each season as a function of ocean surface temperature. Note that hardly any storms are generated outside areas where the ocean surface temperature is below 26°C.

dynamic–dynamic feedback loop. Eventually the process is halted by an associated compensational negative shortwave cloud forcing effect from the cirrus shields generated at the top of the convective system creating what Ramanathan and Collins have called a thermostat effect. Roeckner (pers comm) has demonstrated that the ECHAM 3 model used in this experiment simulates the thermostat effect in excellent agreement with ERBE data.

In a separate experiment, we have undertaken a limited study to explore the importance of SST values above 26°C. We repeated thereby the simulation for August year 4 by setting the SST everywhere to a maximum value of 26°C. The integration was restarted on 1 August. It was found that the number of storms in the new experiment was reduced from 15 to 5. A more comprehensive investigation covering a longer integration period would ideally be required, but this falls outside the scope of this study.

7. Conclusions

In the present study, we have demonstrated the capability of a high-resolution general circulation model to realistically simulate hurricanes. The model generated hurricanes have a frequency and distribution which for all ocean basins resemble those observed climatologically. The seasonal distribution is also realistic except for a surprising minimum in July which probably indicate a systematic error of the model. Other aspects as the spring and autum/winter maximum in the North Indian Ocean is well simulated. The interannual variability is less than in the 20 year observational data set reported by Gray (1979), but this is probably due to the shorter experimental time and to the fact that there are no interannual SST variations.

The model simulated hurricanes take place, with a few exceptions, over ocean areas where the temperature is higher or equal to 26°C. There are a few developments at very high latitudes but they are presumably remnants of highly distorted extra-tropical cyclones and not any indications of polar lows. The high latitude storms are also excessively deep and fulfills the hurricane criteria only for less than 2 days.

The lifetime of the hurricanes varies from 1.5 day (prescribed minimum duration) to 12.5 days with a windspeed higher than 15 ms^{-1}. Most of the very intense storms wind maximum windspeed higher than 40 ms^{-1} have lifetimes longer than a week. Furthermore, the onset vortices are generally noticable a long time before the hurricane criteria is satisfied. The particular storms discussed in Section 4 could be noticed as a well defined vortex more than 10 days before the specified hurricane criteria were reached.

The fully developed storms with respect to their three-dimensional windfield, relative humidity, vorticity and temperature distribution agree by and large with observed storms except that the observed ones develop a much finer scale. Furthermore, the horizontal resolution is insufficient to resolve the eye structure. Experiments are being planned with a limited area model having a physical parameterization identical to the global model to investigate what resolution may be required to develop the eye.

Evans (1992) has provided a number of critical comments to the paper by Broccoli and Manabe (1990) and questioned the relevance of using low resolution GCMs as a tool to explore phenomena like tropical hurricanes, which have much smaller scales than can be resolved by low resolution models. We believe that by this study, where we have used a much higher resolution model than in previous studies, we have removed a number of the reservations mentioned by Evans.This experiment, for example, has been able to provide a realistic geographical distribution of the hurricanes as well as a realistic distribution of them during the course of the year. The structure of the storms also agrees reasonably well with observations. We have found a considerable interannual variability in the number of storms without any SST variations. This variability is probably of a chaotic nature, although the integration period is too short to rule out any systematic model drift. However, a 30-year integration with a T42 resolution model has shown a similar variability, which appears to support the concept of a chaotic variability.

Finally, it must be stressed that in an experiment like this it is not really possible to specifically separate between hurricanes and intense tropical depressions. This particular issue will have to be addressed with models having much higher horizontal resolutions than the present one.

The authors plan to explore how the distribution of hurricanes and their intensity may be modified in an atmosphere with a higher concentration of CO_2 and a sea surface temperature calculated by a coupled model at much lower resolution in agreement with the IPCC scenario business as usual. It is the opinion of the authors that a realistic simulation of the present climate as demonstrated here is a necessary condition for such an investigation. A time-slice experiment over 5 years is planned at a time in the integration when the CO_2 concentration has doubled.

The realism of the T106 integration is very encouraging and it is the hope of the authors that more realistic integrations of this kind will be more common as computational possibilities are improving.

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