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Simulation of hurricane-type vortices in a general circulation model

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ABSTRACT

A study of intense hurricane-type vortices in the ECMWF operational model is reported. These vortices develop around day 4 in the forecast and occur in the tropical belt in areas and at times where intense tropical cyclones normally occur. The frequency resembles that observed over most tropical regions with a pronounced maximum in the western North Pacific. The life time of the vortices and their 3-dimensional structure agree in some fundamental way with observations although, because of the resolution, the systems are less intense than the observed ones. The general large-scale conditions for active and inactive cyclone periods are discussed. The model cyclones are sensitive to the sea-surface temperature and do not develop with sea surface temperatures lower than 28–29 °C. The dynamical conditions favouring cyclone development are characterized by intense large-scale divergence in the upper troposphere. Cyclogenesis appears to take place when these conditions are found outside the equatorial zone and over oceans where the water is sufficiently warm.

1. Introduction

The prediction or simulation of hurricane-type vortices by large-scale hemispheric or global general circulation models has to the knowledge of the present authors only been reported once previously in the scientific literature (Manabe et al., 1970). This is not in anyway a surprise, since the horizontal and vertical resolutions which are used in large-scale numerical models cannot satisfactorily describe the small-scale features of these phenomena. However, tropical cyclones have occasionally been observed to have dimensions over 2000 km, in particular in the western North Pacific. See for example the study of the super typhoon Tip (Dunnavan and Diercks, 1980). A numerical model with a resolution of 3° or less would therefore have the potential possibility of reproducing a vortex of this dimension, although it would be impossible to describe the intense circulation around the eye.

This paper discusses and analyses intense vortices in the tropics which have been identified in operational forecasts by the ECMWF model. The ECMWF model (JSC, 1980) is a global model designed for medium and extended range prediction. It has the characteristics of a general circulation model, Fig. 1. ECMWF has on an operational basis carried out 10-day global forecasts 5 times a week from August 1, 1979 and daily from August 1, 1980. The following study is concerned with the period January 1, 1980–December 31, 1980. The numerical model has at times generated vortices with a structure and behaviour resembling intense tropical cyclones. The developments have mostly taken place around days 4 and 5 of the forecasts. Moreover, they have been found in areas and at times where tropical cyclones normally occur and they have shown a similar sensitivity to the sea-surface temperature as has been found in numerical simulations of hurricanes, e.g. Sundqvist (1972), and as we expect to find for tropical cyclones in nature. The life time has been found to be around a week and precipitation rates of 50–100 mm a day are typical in the central part of the

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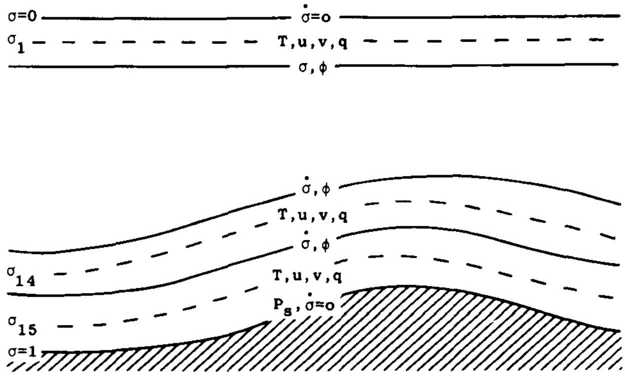
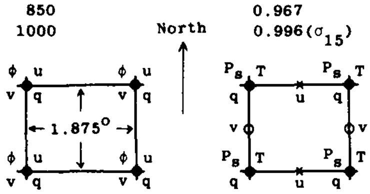
ECMWF 15-LEVEL GRID POINT MODEL

ANALYSIS	PREDICTION
ϕ,u,v,q(for p>300)	T,u,v,q
p(mb)	σ
10	0.025(σ_1)
20	0.077
30	0.132
50	0.193
70	0.260
100	0.334
150	0.415
200	0.500
250	0.589
300	0.678
400	0.765
500	0.845
700	0.914
850	0.967
1000	0.996(σ_{15})





Vertical and horizontal (latitude-longitude) grids and dispositions of variables in the analysis (left) and prediction (right) coordinate systems.

Independent variables	λ, φ, σ, t
Dependent variables	T, u, v, q, p_s
Diagnostic variables	ϕ (geopotential), $\dot{\sigma}$
Integration domain	global
Meshwidth	$\Delta\lambda = \Delta\varphi = 1.875^{\circ}$
Grid	Staggered in the horizontal (Arakawa C-grid). Uniform horizontal (regular lat/lon). Non-uniform vertical spacing of levels (see Figure).
Finite difference scheme	Second order accuracy conserving mass, moisture, and potential enstrophy. Potential enstrophy only for non-divergent flow.
Horizontal diffusion	Linear, fourth order scheme, implicit in east-west.
Time-integration	Leapfrog, semi-implicit (Δt = 15 min) with weak time-filter (ν = 0.05)
Earth surface	Albedo, roughness, soil moisture, snow and ice specified geographically. Albedo, soil moisture and snow time dependent.
Orography	Included, medium smooth.
Physical parameterisation	(i) Boundary eddy fluxes dependent on roughness length and local stability. (Monin-Obukov)
	(ii) Free-atmosphere turbulent fluxes dependent on mixing length and Richardson number.
	(iii) Kuo convection scheme
	(iv) Full interaction between radiation and clouds.
	(v) Full hydrological cycle.
	(vi) Computed land temperature, no diurnal cycle.
	(vii) Climatological sea-surface temperature.

Fig. 1. The ECMWF operational model.

vortices. It is not the basic purpose of this paper to propose that models with a resolution such as the ECMWF-model should be used to predict tropical cyclones, but merely to point to a very interesting behaviour of a high-resolution general circulation model. The fact that vortices of this structure develop is an interesting question in itself and suggests that the tropical cyclones may have an important role in the general circulation. Riehl (1979b) has suggested that tropical cyclones and the equatorial convergence zone can be looked upon as competing modes of the general circulation. Intense tropical cyclones are efficient mechanisms for transporting heat, moisture and momentum between high and low latitudes. Consequently, occurrences of such transports reduce the requirements for exchanges by the convectively forced meridional circulation.

Another question which we try to address in this paper is the large-scale characteristics of active and inactive cyclone episodes. Gray (1979) has recently published a comprehensive review of the formation, structure and likely role of intense vortices in the tropical circulation. Fig. 2, reproduced from Gray (1979) shows the areas of the tropical oceans where hurricanes occur; the density of dots shows their relative frequency. Hurricanes normally occur during the early autumn season, except in the western North Pacific, where they can be found throughout the whole year.

An important constraint in predicting tropical cyclones with numerical models is the scale of the phenomenon. Numerical simulations have been carried out extensively during the last 15 years, e.g. Yamasaki (1968), Ooyama (1969), Sundqvist (1970) as well as more recent studies by Kurihara (1975), Anthes (1977) and Rosenthal (1978).

The dynamical processes necessary for the development and maintenance of the cyclones have been clarified by these numerical experiments, where it has been demonstrated that the forced circulation of the tropical cyclone is driven by the heat released in convective cells. The convective cells are in turn supplied with water vapour produced by the large-scale circulation. Hence there exists an interaction between these two different scales of motion, and when this mutual support is sufficiently pronounced, it results in a large-scale amplification which has been called conditional instability of the second kind, CISK (Charney and Eliassen, 1964). Consequently, a successful simulation of the development of a tropical cyclone must be able to simulate the CISK process. Except for the study by Yamasaki (1975) and Rosenthal (1978), who used a model with a resolution of up to 10 km and where the buoyancy effects from the convective cells were included per se, the effect of the convection has been parameterized. Most modellers have used the parameterization scheme proposed by Kuo, a scheme which was specifically developed for the study of CISK.

The convective parameterization used here in the ECMWF model is based upon Kuo (1974). Hereby a specific parameter, b, is defined which specifies the fraction of moisture which is used for condensation in the cloud and hence used for heating the

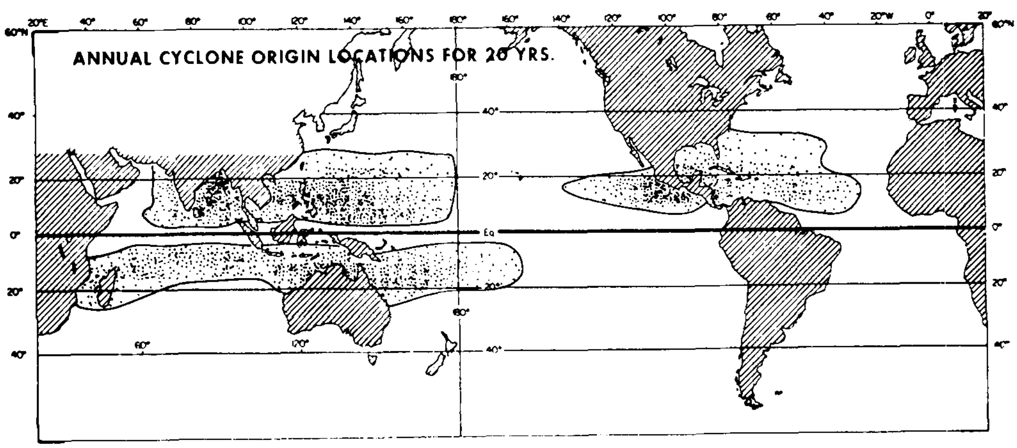


Fig. 2. Areas of tropical cyclone origin (from Gray, 1979).

atmosphere. The remaining part, $1 - b$, is used for moistening the environmental air. The specification of b, which is used in the ECMWF model, follows an approach suggested by Anthes (1977). Hereby b is linearly dependent on the mean relative humidity of the environment such that the moistening is larger in dry air than in moist air. Very little release of latent heat therefore takes place if the atmosphere is dry. Convection can start either from the planetary boundary layer or from any level in the free atmosphere. Evaporation from convective rain is included and follows the proposal by Kessler (1969).

Although modelling efforts have successfully simulated cyclone intensification, they have not considered the question of cyclogenesis. The calculations have started form an initial vortex with a cyclonic vorticity of around 10^{-4} s^{-1} which is more than an order of magnitude larger than the vorticity maximum for an average tropical disturbance. Consequently, no realistic simulation of the transformation of a tropical disturbance to a cyclone has yet been carried out. However, this study, although seriously limited due to the coarse resolution being used, shows that intense tropical cyclones can be generated from an initial state where no indication of any initial disturbance is apparent and where the favourable conditions for cyclogenesis are generated by the large-scale flow. It should be stressed that none of the initial states in this study contained already-developed tropical cyclones, although weak disturbances were observed in several cases.

The ECMWF model has 15 vertical levels which is generally slightly more than has been used in the simulation experiments. The horizontal resolution on the other hand is much too low with a grid distance of around 200 km at 10° N (1.875° lat/lon). However, the grid is staggered and the gradients are all calculated over that distance. For these reasons the model cannot produce cyclones of the scale of a few hundred kilometres and the model-simulated cyclones are therefore of the order of 800–1200 km or 4 to 6 grid points across.

In Sections 2 and 4 we will give a detailed description of the structure of the model tropical cyclones as well as their geographical distribution and frequency throughout the year 1980. They are found to be most frequent in the western North Pacific which may be related to the fact that the size of the cyclones is the largest in this region and consequently easier for the model to simulate.

Fundamental questions extensively discussed by Gray (1979) are the dynamical and thermal conditions for the genesis of tropical cyclones. This study shows clearly, like all others, the strong dependence on the sea-surface temperature. No development takes place in the model when the temperatures are lower than around 28 °C. This value is 1 to 2° too high, and presumably reflects the limited ability of the model to efficiently transport moisture from the boundary layer into the convective systems. In a special sensitivity experiment described in Section 5, it is demonstrated that a reduction of SST to 29 °C or less eliminated the development of an intense vortex over the Pacific ocean. The dynamical condition for hurricane formation is of particular interest since in spite of the fact that there are large ocean areas having temperatures above 28 °C, hurricanes are indeed very rare. By investigating 2 separate episodes, one with intense tropical cyclones and one without during August 1980, it is found that the fundamental difference between the 2 episodes is the intensity of the large-scale divergent flow as well as the position of the area of maximum large-scale upward motion. This aspect will be discussed in Section 3.

It is generally found that the initial state is very crucial for the development of organized tropical disturbances, and the intense cyclones therefore do not develop until around day 4 or 5 in the forecast. A recent improvement in the interpolation procedure in the data assimilation, where analysis increments only are being interpolated from p to σ coordinates, has improved the initial structure of the boundary layer. This has in turn effectively improved the spin-up of the divergent circulation system and has resulted in the appearance of tropical cyclones about 1 day earlier in the forecast.

However, the comparatively long spin-up time indicates that further improvements of the initialization of the model are necessary.

2. Structure and behaviour of a simulated tropical cyclone

In order to examine the detailed structure and the time evolution of a simulated tropical cyclone, a case from 12 GMT July 31, 1980 has been selected. This tropical cyclone is one of the several developments which took place in the operational forecast around this time (successive predictions from August 2–5 all produced tropical cyclones). This simulated cyclone is of medium strength and is considered to be a typical example. No typhoon developments were reported in the real atmosphere at this time and in this particular area. although great activity took place north of this area (typhoon Lex). In Fig. 3, the central pressure time evolution is presented. The incipient disturbance is recognizable at forecast day 4. The deepening of the central pressure is gradual for the first 1.5 days (pre-development stage), and becomes very rapid thereafter, reaching a minimum pressure of 988 mb at day 8.5 (developing stage). The cyclone seems to show signs of decay afterwards. This pattern of central pressure change is very similar to most of the simulation studies (e.g. Madala and Piacsek, 1975). The lowest central pressure of 988 mb is by no means deep, reflecting the influence of coarse grid resolution of the prediction model. Jones (1977) has shown in his 3-dimensional hurricane model, that decreasing the grid resolution results in a weakening of the simulated hurricanes. In his 90 km grid resolution, hurricanes failed to develop.

The track of the simulated tropical cyclone is shown in Fig. 4. It is formed at 3° N corresponding to the area of highest sea-surface temperature. During the pre-development stage it moves westwards, but the northward component increases thereafter. The northward movement is considered partly to be due to the β-effect. Its speed of 4° latitude/day is also reasonable and realistic. The

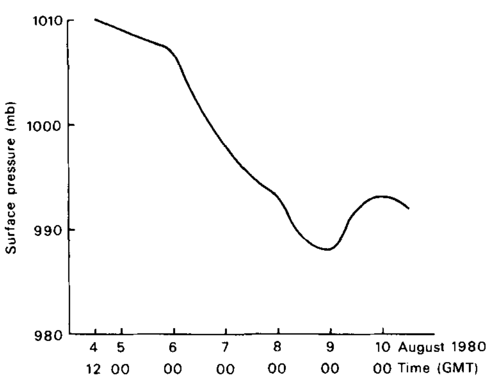


Fig. 3. Centre pressure of tropical cyclone simulated by ECMWF forecast from 12 GMT July 31, 1980. The cyclone originated over the western North Pacific and the centre pressure is given for forecast days 4 to 10 (August 4 to 10, 1980).

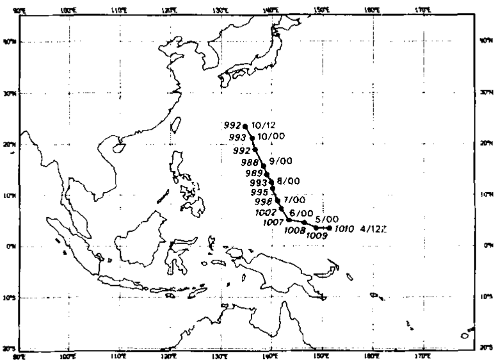


Fig. 4. Track of simulated tropical cyclone from 12 GMT July 31, 1980. Centre pressure is indicated in mb and the tropical cyclone originates on forecast day 4, valid 12 GMT August 4, 1980.

westward component, however, seems to require some comment. It has often been observed that tropical cyclones tend to move with the basic current (steering flow), namely the flow at 500 mb. The estimated basic flow (at 500 mb) in the present experiment is 10–15 m s^{-1} easterlies, which is much larger than the westward component of the cyclone movement of about 3 m s^{-1}. The steering flow for the simulated cyclone can be found in the layer between 1000 mb and 700 mb. The reason for this rather low steering level is not so clear, but is most likely due to the insufficient capacity of the present model to satisfactorily describe deep convection; hence the interaction between the cyclone and the large-scale flow takes place at a lower level in the model than in nature.

The wind field of simulated mature tropical cyclones at 1000 mb and 200 mb is shown in Fig. 5. Axial asymmetry is apparent at 1000 mb indicating strong wind in the north-east quadrant. The asymmetry at the upper troposphere outflow is also evident. There is no indication of spiral band in the precipitation field. Figs. 6–9 show as a function of height and radius: (i) the azimuthal mean of the tangential velocity, (ii) the vertical velocity (in p), (iii) the relative humidity, (iv) the temperature anomaly (calculated from a tropical mean sounding according to Jordan (1958)), (v) the radial velocity and (vi) the relative vorticity, at various stages of the development. We will first examine the structure of mature stage tropical cyclones in Fig. 9, to see the correspondence with observed tropical cyclones as well as with simulated cyclones with higher resolution models. Rather shallow central

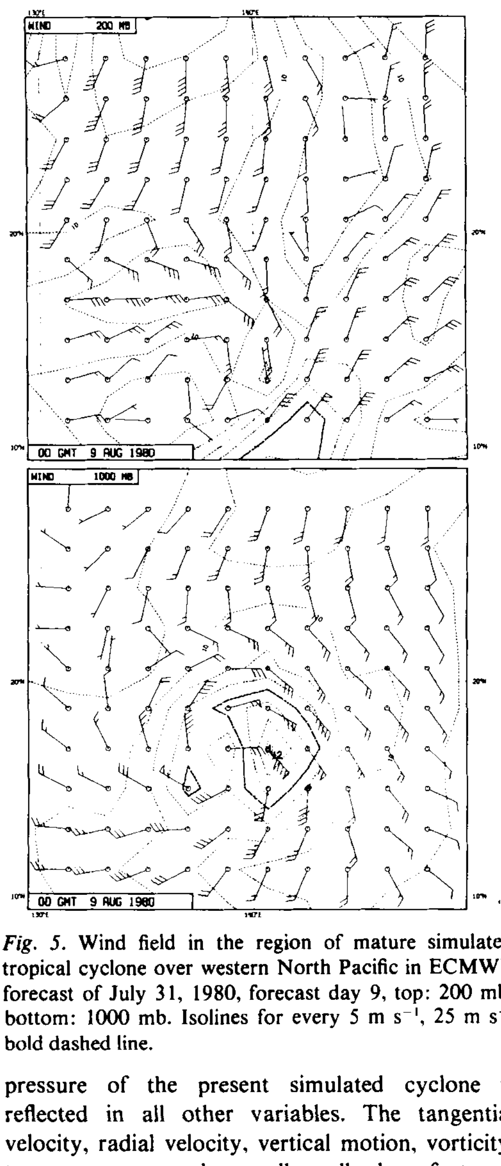


Fig. 5. Wind field in the region of mature simulated tropical cyclone over western North Pacific in ECMWF forecast of July 31, 1980, forecast day 9, top: 200 mb, bottom: 1000 mb. Isolines for every 5 m s^{-1}, 25 m s^{-1} bold dashed line.

pressure of the present simulated cyclone is reflected in all other variables. The tangential velocity, radial velocity, vertical motion, vorticity, temperature anomaly are all smaller by a factor of 2, compared to other simulated or observed intense tropical cyclones. The size of the simulated cyclone is quite large. The maximum tangential wind is located at 3° latitude distance from the centre, while the observed average is located at around 1.5° latitude distance (Izawa, 1964). Similar discrepancies are observed in all other variables, indicating the influence of the grid resolution on the size of the simulated cyclone. Besides these deficiencies, the cyclones seem to have quite a similar structure to those observed.

The time evolution also seems to indicate quite a realistic behaviour. In the pre-development stage (Fig. 6), a fairly deep layer of inflow (1000–500 mb) and outflow (500–100 mb) has already been established. However, the tangential velocity is still small. The associated upward motion is about 0.5 Pascal s^{-1}. The cyclonic vorticity is observed below 500 mb. No indication of anticyclonic circulation in the upper troposphere is noted. High relative humidity and a weak warm core at 9 km are considered to be due to the convective heating. A low-level cold core is also very typical for the weak tropical disturbances, e.g. Reed and Recker (1971). The result in Fig. 6 suggests that it is the large-scale divergence which is creating the onset vortex. This process is so far not supported by composite studies from observations (Gray, 1979; McBride and Zehr, 1981) possibly related to the difficulties in observing the large-scale divergent winds. Another noteworthy structure is the fairly intense cold core in the lower stratosphere. The physical reason for the formation of this cold core is not clear, but a combined effect of over-shooting, evaporation and radiative cooling on top of the cloud is most likely. At the beginning of the development stage (Fig. 7) this cold core becomes most intense (6° colder), and is associated with a warm core (probably caused by subsidence) at 50 mb. Because of this compensation, the surface pressure still falls slowly during the pre-development stage. The formation of stratospheric cooling has been reported in simulation studies by Kurihara and Tuleyev (1974). Observational studies by Koteswaram (1967) confirm the existence of a cold region in the upper troposphere and lower stratosphere, although not so intense as in this case. By this time, the tangential velocity has reached 15 m s^{-1}, the radial inflow and outflow intensify considerably, more so for upper level outflows, resulting in a lowering of the pressure during the following development stage. The vertical velocity at this stage reached 2.8 Pascal s^{-1}. The entire column of the central area of the cyclone now has more than 90% relative humidity, but strong convective heating and the formation of the warm core have not yet started. 24 h later, at the middle of the development stage (Fig. 8), a strong warm core started to develop, corresponding to the rapid fall of the central pressure. This formation of the warm core at the upper troposphere and a gradual downward extension are essential for the

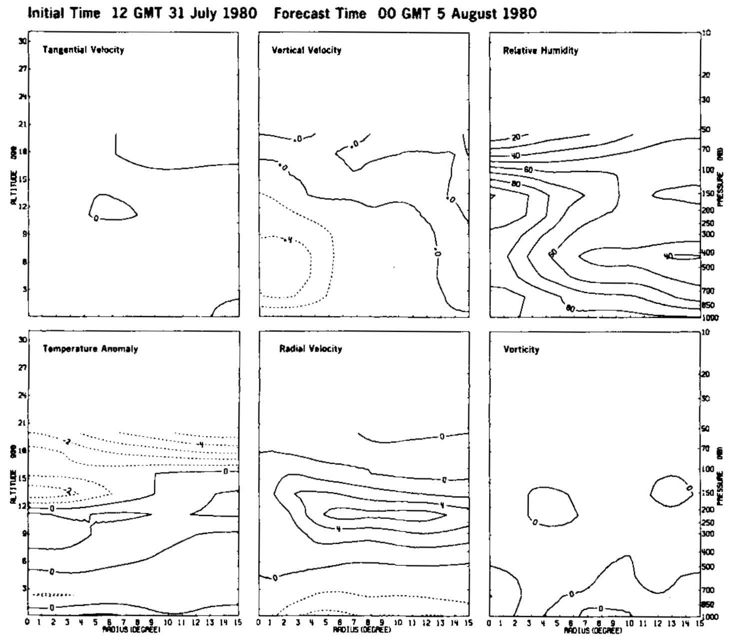


Fig. 6. 2-dimensional cross section of tangential wind (m s^{-1}), vertical velocity (Pascal s^{-1}), relative humidity (%), temperature anomaly (K), radial wind (m s^{-1}), and vorticity (10^{-5} s^{-1}) for pre-development stage of tropical cyclone simulated in ECMWF forecast from 12 GMT July 31, 1980. Forecast time is 4.5 days valid at 00 GMT August 5, 1980.

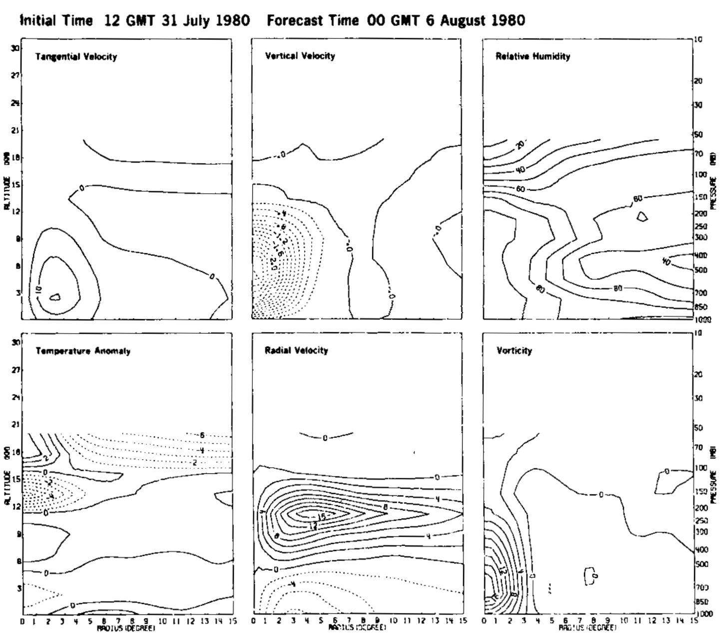


Fig. 7. Same as Fig. 6 for development stage of tropical cyclone. Forecast time is 5.5 days valid at 00 GMT August 6, 1980.

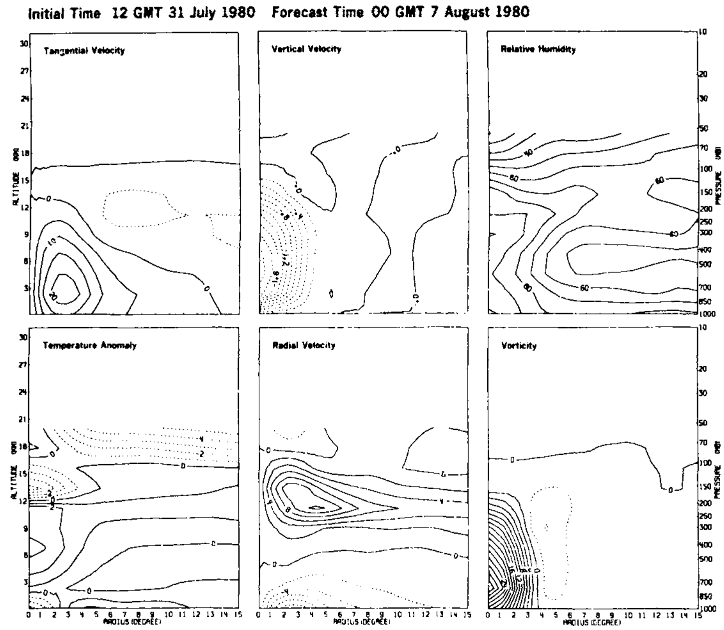


Fig. 8. Same as Fig. 6 for development stage of tropical cyclone. Forecast time is 6.5 days valid 00 GMT August 7, 1980.

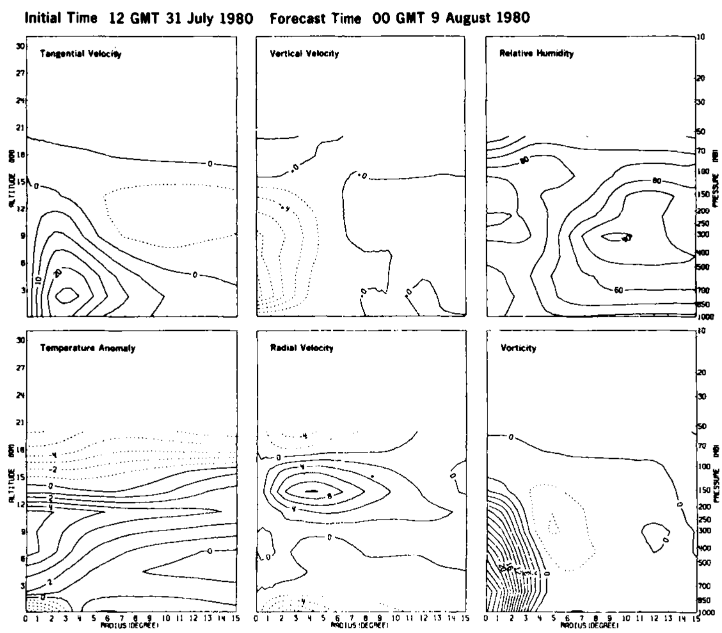


Fig. 9. Same as Fig. 6 for mature stage of tropical cyclone. Forecast time is 8.5 days valid 00 GMT August 9, 1980.

development of an intense tropical cyclone (Yanai, 1964). The cold core at 1000 mb is due to the extrapolation of temperature from the lowest sigma level and is considered to be fictitious. The tangential wind has now increased to 25 m s^{-1}; the vorticity has also increased by 70% in 24 h. The inflow, now concentrated below 700 mb, has been increasing. The outflow, however, has decreased but formed new maxima at a higher altitude closer to the centre. This has caused the stretching of the layer of upward motion from 150 to 100 mb. At the mature stage (Fig. 9), the warm core has intensified further corresponding to the lowest surface pressure. The inflow and outflow have started to decrease. Note that the initial outflow at 200 mb disappeared and shifted to 150 mb. The slight decrease of the vorticity indicates an outward shift of the tangential wind maximum, which is very commonly observed in the real atmosphere.

We have shown that the simulated tropical cyclone is quite realistic in many respects. However, some of the features noted above, such as the upward shift of the outflow level at the mature stage have neither been mentioned in observations nor in simulation studies.

3. Conditions for the onset of a tropical cyclone

One of the major unanswered questions in the study of tropical cyclones is the condition for their development. Very few simulation studies have been performed on this subject since there are so many factors to be considered (horizontal and vertical shear, static stability, moisture distribution, sea-surface temperatures, etc.). Gray (1979) has summarized conditions for the onset of tropical cyclones based on a large number of observations, but they gave essentially climatological conditions.

During the summer of 1980, the operational forecasts showed tropical cyclone development after day 4 for the first few days (August 2–5), but no development occurred during the successive week (August 8–12). We have computed average maps of day 1 forecasts during those 2 periods to compare the difference in the basic field. We have chosen the day 1 field rather than the initial field, in order to prevent the influence of adiabatic nonlinear normal mode initialization, which tends to reduce tropical divergence. Furthermore, on day 1 the disturbance itself had not yet developed and hence there was no influence of the disturbance on the mean flow.

We have compared wind, temperature and moisture fields for both cases and found significant differences in the zonal wind field at 200 mb, and the large-scale divergence at 850 mb and 200 mb over the area of the cylcone development. All other fields, particularly the thermodynamical parameters are very similar in both cases. The vertical shear was also found to be similar.

In Fig. 10 the mean zonal wind and velocity potential at 200 mb for both periods are presented. The mean zonal wind indicates much stronger subtropical jets to the north and south of the area of cyclogenesis (area of highest sea-surface temperature) for the active period. The horizontal wind shear to the south of the area is much larger, suggesting a difference in large-scale dynamical forcing over the area. The velocity potential during the active period also reveals a much stronger centre of velocity potential located over the area of high sea-surface temperature in constrast to the less intense centre of velocity potential located further east during the inactive period. The centre of intense velocity potential was established 3 days before cyclogenesis took place.

This rather simple exercise seems to indicate that in addition to the climatological conditions for the development of tropical cyclones, such as high sea-surface temperature, moist unstable atmosphere, small vertical shear, etc., large-scale dynamical forcing is most important for the onset of a tropical cyclone development.

4. Geographical and seasonal distribution

Since satellite imageries allow a world-wide survey of tropical cyclones, it became obvious that their frequency had previously been considerably underestimated. According to Gray (1979), approximately 80 tropical cyclones with maximum sustained wind of 20–25 m s^{-1} were observed every year over the globe between 1958 and 1978. Around 60% of these reached hurricane intensity. The annual variation is rather small ($\pm 8\%$), although the year-to-year variation in different ocean basins is quite large. A reduction in frequency over one basin tends to coincide with a higher frequency elsewhere (Gray, 1979).

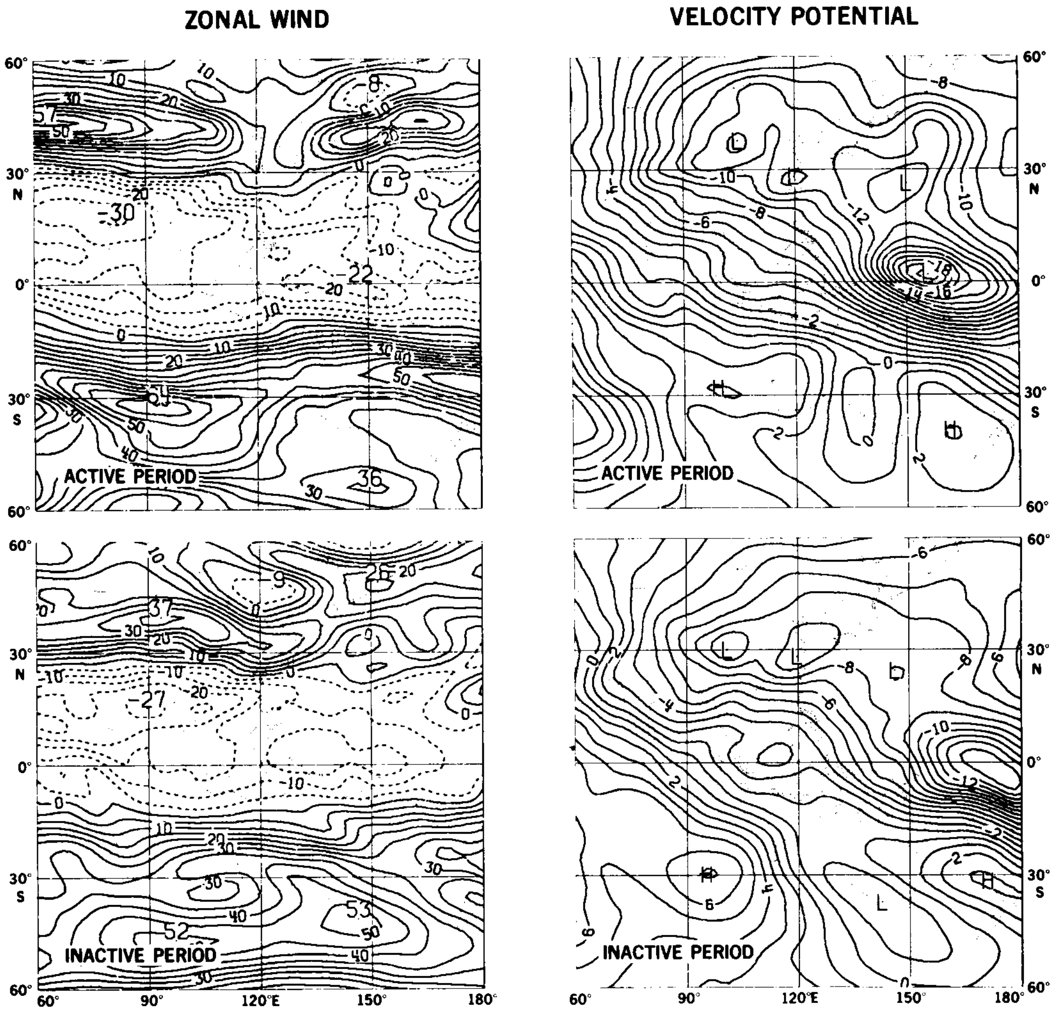


Fig. 10. Zonal wind component at 200 mb in m s^{-1} and velocity potential in 10^6 m^2 s^{-1} averaged over four 24 h ECMWF forecasts from August 2 to 5 (top) and five 24 h forecasts from August 8 to 12, 1980 (bottom). See text for further explanation.

Gray (1979) distinguished between 4 ocean basins in the northern hemisphere and 3 south of the equator. They are indicated in Fig. 2.

Northern Hemisphere: Western North Atlantic
Eastern North Pacific
Western North Pacific
North Indian Ocean (Bay of Bengal and Arabian Sea).

Southern Hemisphere: South Pacific
Australia
South Indian Ocean.

The 8° to 10° latitude belt straddling the equator is virtually devoid of cyclones, although according to Riehl (1979a) incipient tropical cyclones have been encountered within 2° of the equator. Generally, the belt of 5° to 15° latitude is the most favourable for genesis, although this may occur as far north as 35° N; however none have been observed poleward of 22° S.

The hurricane season lasts from November or December to April/May in the southern hemisphere, and from May/June to late autumn north of the equator, with the exception of the monsoon season in July, August and September in the North

Indian Ocean, when very few tropical cyclones are observed. Over the western North Pacific, genesis of tropical storms is possible throughout the year. About 2/3 of all tropical cyclones form north of equator and the highest frequency is observed in the western North Pacific, with nearly 50% of all northern hemisphere tropical cyclones during the 20-year period 1958–1978.

The seasonal frequency and the geographical distribution of the tropical cyclones simulated by the ECMWF model has been determined from archived operational forecasts for the year 1980. The 850 mb wind components were retrieved from ECMWF forecast archives using a 1.5° × 1.5° grid resolution between 30° S and 30° N. The fields are originally stored in the form of coefficients of spherical harmonics. For archiving purposes a triangular truncation at wave number 40 is applied when computing these coefficients. The following criteria have been used to determine a tropical cyclone.

(i) Wind criterion: 850 mb wind fields are scanned for wind speeds of $\geqslant 25.0$ m s^{-1}, which is in accordance with the lower-surface wind limit defining a tropical cyclone. Once a grid point has been found, an area of 7.5° × 7.5° around this point is scanned for higher wind speeds and if such a grid point is found, it is selected.

(ii) Vorticity criterion: once a grid point fulfilling the wind criterion has been found, the same area is scanned for occurrence of relative cyclonic vorticity $\zeta = \zeta_{\rm limit} = 7 \times 10^{-5}$ s^{-1}. This is half way between the observed mean relative vorticity for pre-cyclone disturbances in the early intensifying stage and for intensifying cyclones (Zehr, 1976).

The combination of wind and vorticity criteria

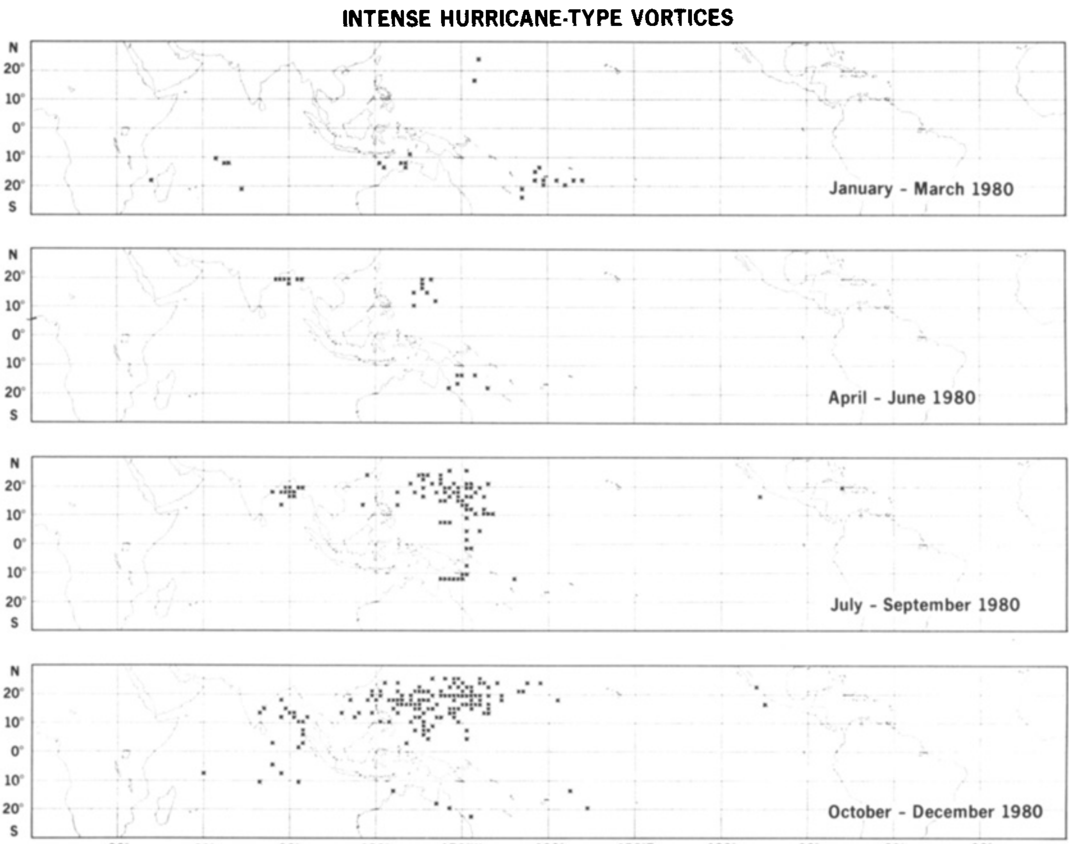


Fig. 11. Frequency of intense hurricane-type vortices simulated in ECMWF operational forecasts in 1980. The figure summarizes the appearance of intense vortices for all 10 days of forecast time. The position of the wind maximum is indicated.

proved to be a successful tool for eliminating high-speed wind fields associated with extra tropical cyclones penetrating towards the tropics into the latitudinal belt of 30° either side of the equator, but some cases with a strong horizontal wind shear especially during the onset of the monsoon over the Arabian Sea in June and July were still included in the statistics. Visual checks were therefore carried out to eliminate all those cases which did not fall into the category dealt with in this paper.

Fig. 11 summarizes the seasonal and geographical distribution of intense tropical vortices simulated in ECMWF forecasts for the months January to March, April to June, July to September and October to December 1980, respectively. One dot represents the position of maximum wind speed found in the area of a tropical cyclone, following the criteria described above. The occurrence of tropical cyclones in Fig. 11 is summarized for all available forecast days from day 1 to day 10. The ECMWF forecast model is found to develop tropical cyclones over all ocean basins as described by Gray (1979), and the density of the dots gives an impression of the relative frequency. Between January and March they are mainly concentrated in the southern hemisphere, while July to December is the high season over the western North Pacific. Only one case was observed over the Caribbean, and over the eastern North Pacific very few tropical cyclones appear in the forecast. Figs. 11 and 12 give a phenomenological comparison between the occurrence of tropical cyclones in the ECMWF model and those observed in 1980. The observed statistics were collected from the different tropical cyclone centres. Only tropical cyclones with central pressure below 980 mbs and/or with maximum sustained winds $\geqslant 25$ m s^{-1} were plotted.

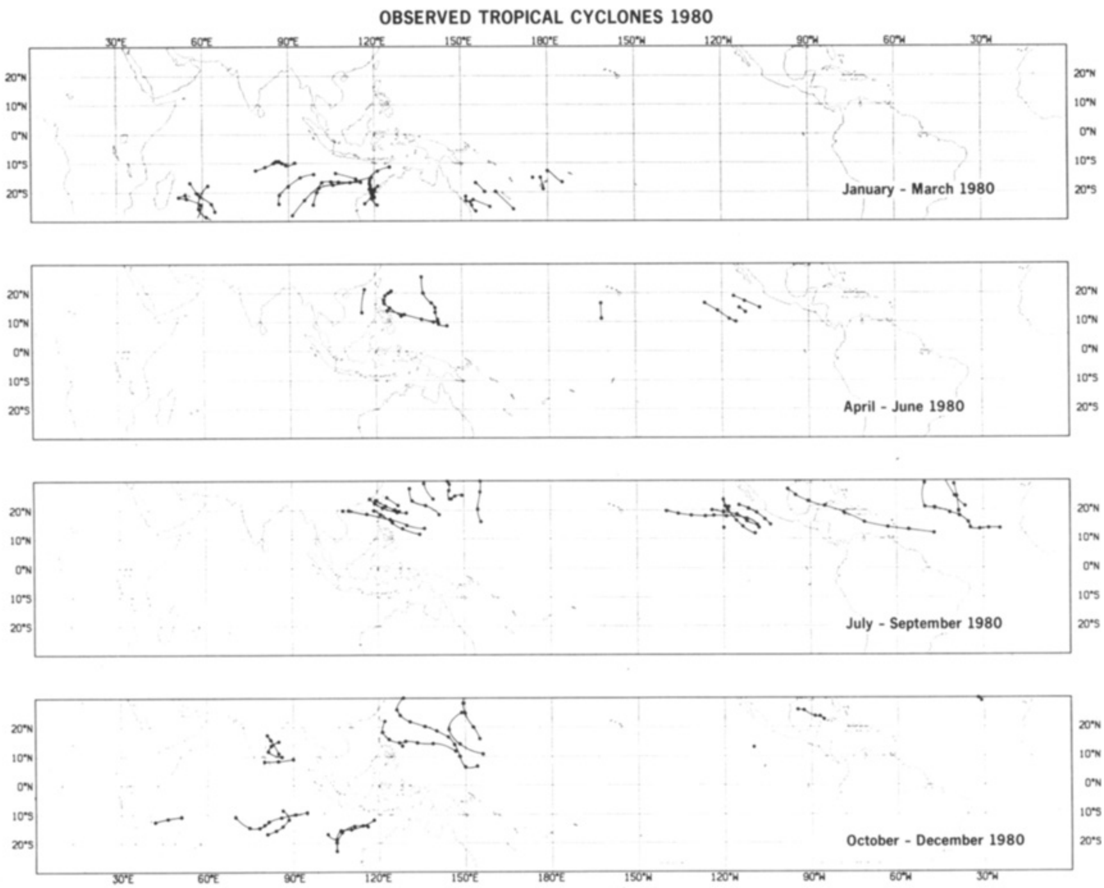


Fig. 12. Tracks of tropical cyclones observed in 1980.

The density of the dots in Fig. 11 and the density of the trajectories plotted in Fig. 12 are a direct measure of the frequency of storms in the model and the atmosphere. Reasonable agreement can be found in the western Pacific and around Australia, while the ECMWF model hardly ever predicts any storms in the western North Atlantic. However, we did not try to distinguish between individual cases, and consequently a tropical cyclone having a life cycle of several days throughout a forecast period will be represented by more than one dot. Moreover, Fig. 11 contains the sum of dots from the ensemble of each forecast day, and consequently in active periods the same cyclone will repeatedly be simulated. The number of dots in Fig. 11 is therefore generally higher than the number of simulated individual vortices.

In Tables 1 to 4 the frequency of simulated tropical cyclones in ECMWF forecasts for each season is listed together with the observed statistics corresponding to the different forecast days, day 1 to day 10. The statistics are given for all the ocean basins defined by Gray (1979) with some simplification over Australia. In winter and spring, Jan–March and April–June, the total number of tropical cyclones simulated by ECMWF forecasts was smaller than observed, while the reverse is true for the last 6 months of 1980. ECMWF became fully operational, running 7 forecasts a week, on August 1, 1980. Before that date only 5 forecasts were produced every week, but that does not fully explain the increasing tendency to develop tropical cyclones in the model. The western North Pacific is obviously the area most favoured by the ECMWF model for simulation of tropical cyclones, which is possibly related to the fact that tropical cyclones are normally of larger dimensions in this region.

We tested the sensitivity of model-simulated tropical cyclones against the wind and vorticity criteria. Given a lower wind limit of 25 m s^{-1}, the

Table 1. *Frequency of tropical cyclones over 7 different ocean basins simulated in ECMWF forecasts between day 1 and day 10, and the number of observed cases, January to March 1980*

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	OBS
1. North Indian Ocean											
2. Western north Pacific									1	1	
3. Eastern north Pacific											
4. Western north Atlantic											
5. South-western Indian Ocean					1	1		1		2	3
6. South-eastern Indian Ocean including north Australia			1	2			1	1	1		9
7. South-western Pacific including eastern Australia	1	1					3	2	2	3	7
TOTAL	1	1	1	2	1	1	4	4	4	6	19

Table 2. *Same as Table 1, but April to June 1980*

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	OBS
1. North Indian Ocean					2	4	1	1	1		
2. Western north Pacific							1	2	2	2	5
3. Eastern north Pacific											3
4. Western north Atlantic											
5. South-western Indian Ocean											
6. South-eastern Indian Ocean including north Australia											
7. South-western Pacific including eastern Australia				1	2	1	1	1			
TOTAL	0	0	0	1	4	5	3	4	3	2	8

Table 3. *Same as Table 1, but July to September 1980*

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	OBS
1. North Indian Ocean				4	7	4	6	2	1	1	
2. Western north Pacific				1	2	3	5	13	17	20	9
3. Eastern north Pacific									1		6
4. Western north Atlantic										1	5
5. South-western Indian Ocean											
6. South-eastern Indian Ocean including north Australia											
7. South-western Pacific including eastern Australia				2	1	1	2	3	3	1	
TOTAL	0	0	0	7	10	8	13	18	22	23	20

Table 4. *Same as Table 1, but October to December 1980*

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	OBS
1. North Indian Ocean					2	3	3	3	3	3	3
2. Western north Pacific			2	9	15	18	25	24	25	26	5
3. Eastern north Pacific									2		1
4. Western north Atlantic											2
5. South-western Indian Ocean										1	1
6. South-eastern Indian Ocean including north Australia								1	1	3	4
7. South-western Pacific including eastern Australia			1	1		1	1	1			
TOTAL	0	0	3	10	17	22	29	29	31	33	16

latter was not very crucial, since 80% of the model vortices exhibited a relative vorticity of over 10^{-4} s^{-1} at their fully developed stage. However, by increasing the limits of the wind speed, the number of model cyclones decreased rapidly. In October to December, Days 7 and 8 in the forecast showed a maximum of cyclone activity. When the wind limit was increased to 28 m s^{-1}, the total number of tropical cyclones dropped to about 60% and with a further increase to 30 and 33 m s^{-1}, the number was reduced to 40% and 25% respectively.

For some selected cases, the tracks of model cyclones are shown in Fig. 13 together with observed tropical cyclones approximately coincidental in time. This result should not be regarded as a verification of tropical cyclones generated by the model; nevertheless it shows that at times when the model has predicted tropical cyclones, such cyclones were actually observed in the same area. In Fig. 14 it is indicated that the model shows some skill in distinguishing between active and inactive periods of tropical cyclone activity over the western North Pacific in July, August and September 1980. The model failed to predict the highly active periods in September 1980. A contributing factor could be that at the time, large positive sea-surface temperature anomalies exceeding 1 °C were observed over the western North Pacific, while ECMWF used climatological sea-surface temperatures. The cyclone tracks in Fig. 13 are in reasonable agreement, but have a general tendency to move poleward too quickly. This is especially the case over the western North Pacific where the cyclones also recurve to become extra-tropical within a few days of forecast time. This tendency of too much northward movement of the disturbance may be related to the overestimation of the size which can result in the larger Rossby effect (Rossby, 1948).

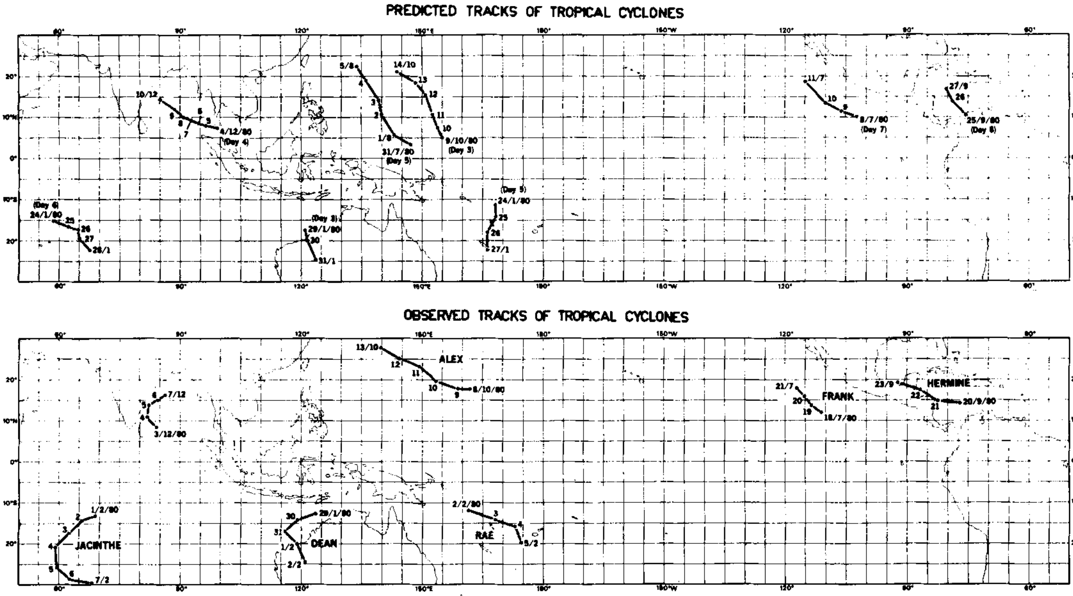


Fig. 13. Tracks of selected, predicted and observed tropical cyclones. Top: simulated–ECMWF forecasts; indicated is the day when the cyclones first emerge as well-defined closed circulation in the forecast, and the verifying dates. Bottom: observed tracks of tropical cyclones, indicating position, date and name.

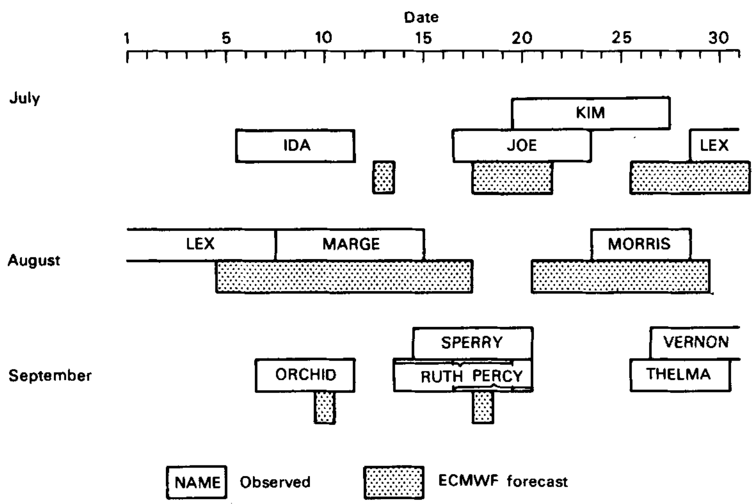


Fig. 14. Observed tropical cyclone activity over the western North Pacific July to September 1980, and corresponding ECMWF forecasts. Indicated is the valid time of the forecasts.

5. Sensitivity to sea-surface temperature

When looking at global and annual averages of rainfall and energy statistics, the importance of tropical cyclones seems to be insignificant. The same budget figures could easily be achieved by replacing the few strong cyclones by a greater number of weak disturbances. This applies to nature as well as model climatology. But, at times, when tropical cyclone activity is high, their feedback to the general circulation is non-negligible. Cloud-band connections between tropical cyclones and the westerlies have been interpreted as visible manifestations of kinetic energy injections into middle latitudes (Erickson and Winston, 1972), and it is suggested that tropical cyclones intruding into the westerlies contribute to the autumnal build-up of the winter circulation. The life span of a model cyclone is normally terminated by the 10-day limit of the forecast provided, although a few extended integrations suggest a life time of around a week. However, so far no obvious connection between the tropics and the westerlies has yet been established. To investigate this and to simultaneously investigate the sensitivity to the sea-surface temperature, an experiment was carried out with the operational ECMWF model (Fig. 15). In the operational forecast from 12 GMT August 5, 1980, an intense tropical cyclone development was predicted over the western North Pacific. The sea-surface temperature, which in this area exceeds 29 °C or even 30 °C, was in the test case reduced to 29.0 °C. This reduction was made for the whole Pacific area between 90° and 180° E. With this modification the forecast was rerun from the original initialized analysis 12 GMT August 5, 1980. The tropical cyclone in the Pacific did not develop, as can be seen from Fig. 15. However, the predicted flow at middle and high latitudes remained virtually unchanged, although some minor differences can be seen on the last day of the forecast. This experiment illustrates the sensitivity of the model to changes in sea-surface temperatures. There are indications that slightly higher temperatures are needed in the model than in the real atmosphere to develop tropical cyclones. It is therefore likely that daily analyses of sea-surface temperature would have an influence on the genesis of tropical cyclones, especially in areas where large sea-

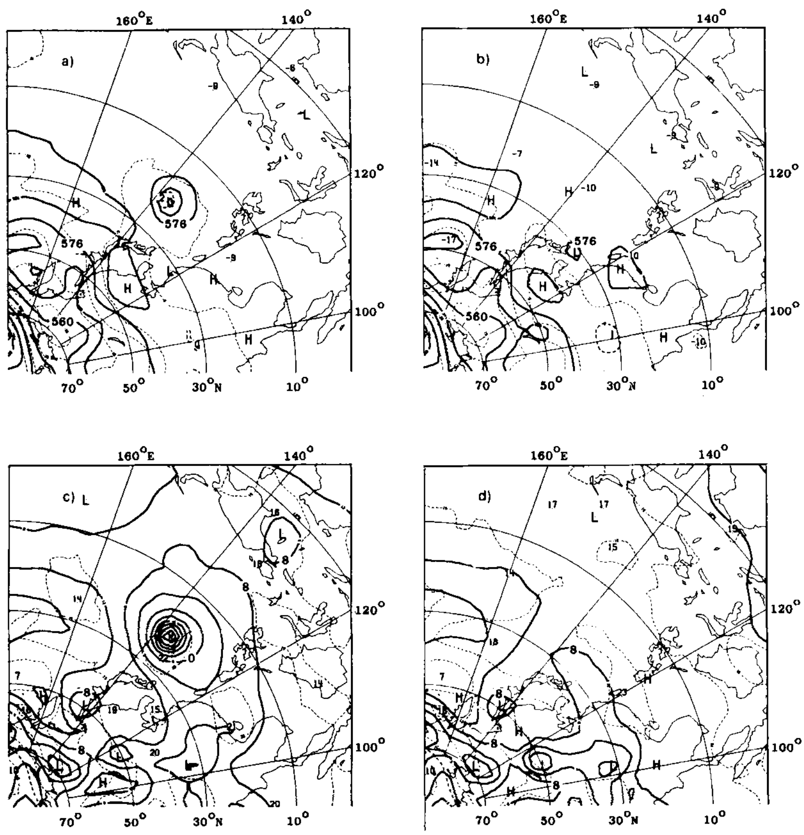


Fig. 15. Day 10 of ECMWF forecast from 12 GMT August 5, 1980, valid at 12 GMT August 15, 1980. Top: 500 mb height. Bottom: 1000 mb height. Left: operational forecast. Right: forecast experiment with sea-surface temperatures reduced to an upper limit of 29 °C over the area shown in the figure.

surface temperature anomalies occur and where the values are between 27–30 °C.

6. Concluding remarks

In the present study we have demonstrated the capability of a high-resolution general circulation model to simulate tropical cyclones. These model-generated cyclones have a frequency and distribution which over many ocean basins resemble those observed climatologically. Their 3-dimensional structures, albeit having some unrealistic features, are in many ways similar to observed tropical cyclones. The serious limitation of the horizontal resolution of the model makes it impossible to describe the small-scale features characteristic of the inner parts of intense tropical vortices. The time scale of the cyclones is of the order of a week, and they have typical poleward directed trajectories; however, the simulated cyclones generally move straighter poleward than the observed cyclones.

The development is very sensitive to the structure of the initial state, and a spin-up time of 4–5 days is normally required. Recent improvements in data assimilation with a more accurate vertical interpolation between σ-surfaces (model coordinates) and pressure surfaces (analysis coordinates) have improved the spin-up time for those vortices by about a day. Further improvements of the spin-up time can be obtained by relaxing the constraint of the adiabatic non-linear normal-mode initialization to avoid the disadvantage of disrupting the vertical structure of the divergent wind of these eddies.

The development of tropical cyclones in the model has been found to be very sensitive to the specified sea-surface temperature. No development takes place when the sea-surface temperature is lower than 28–29 °C and the model cyclones are therefore as in nature normally only observed during the summer and autumn seasons. It has also been demonstrated that the development is prevented from occurring when the sea-surface temperature is reduced below the critical limit.

The large-scale dynamical circulation favouring cyclone development is characterized by an intense large-scale circulation cell with low-level convergence and high-level divergence. Active cyclogenetic episodes are found when the upper large scale divergence is situated away from the equator and over ocean areas with super-critical temperatures. Cyclogenetic episodes simulated by the model are in approximate agreement with observed active periods.

From the standpoint of everyday forecasting, individual cyclones are not well predicted by the model and substantial developmental work is necessary before that will be possible. Used in an indiscriminate way, the development of intense eddies in the forecasts is more a concern than an assistance and can only be used as a crude guide to a potential risk of cyclogenesis. Nevertheless, the present study shows that the large-scale features of tropical cyclones can be simulated with general circulation models having a resolution of the present ECMWF model. However, in order to obtain a successful prediction, a higher horizontal resolution seems necessary as well as an analysis and an initialization scheme which can assimilate the wind and the moisture field accurately enough, and reduce the spin-up time to the order of a day or less. Further improvements of the physical parameterization are also necessary in order to eliminate the intense cooling in the lower stratosphere. It also seems clear, in view of the sensitivity which has been found to the sea-surface temperature, that observed sea-surface temperature values should be used instead of climatological means.

The authors are also anxious to point out that there are several serious deficiencies between the "model hurricanes" and the real ones, and it cannot be ruled out that the vortices simulated in the model can partly be caused by the wrong reason. Great care must be exercised in applying the present results to the real atmosphere. Nevertheless, it is hoped that the present findings will stimulate discussion and further intensify numerical experimentation with higher resolution models.

An important area of further investigation is study of the role of tropical cyclones in the general circulation. To what extent are they required for a simulation of the large-scale features of the general circulation in providing an eddy transport of heat, moisture and momentum polewards? What are the compensating circulation mechanisms which have to be generated in a model which is incapable of simulating tropical cyclones? Questions of this kind need to be formulated and subsequently answered before we can claim to understand the possible large-scale role of tropical cyclones.

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