Atmósfera (1990), **3**, pp. 57-71

Comparison of observed and simulated cyclone frequency distribution as determined by an objective method

HERVE LE TREUT

Laboratoire de Météorologie Dynamique du CNRS, Ecole Normale Supérieure,
24 Rue Lhomond, 75231, Paris Cédex 05, FRANCE

EUGENIA KALNAY

National Meteorological Centre, Washington D. C., 20233, U. S. A.

RESUMEN

En el presente trabajo ha sido elaborado un algoritmo objetivo con el fin de diagnosticar estadísticas de ciclones, ciclogénesis y ciclolisis extratropicales. Nuestro algoritmo utiliza tanto como es posible los mismos criterios empleados en análisis subjetivos y permite una evaluación suplementaria de la calidad del modelo que no es suministrada por los diagnósticos estándar. Ejemplos de aplicaciones posibles a la previsión y a experimentos de simulación son incluidos en el presente artículo.

ABSTRACT

We have designed an objective scheme to diagnose the statistics of extratropical cyclones, cyclogenesis and cyclolysis. It uses as much as possible the same criteria which are used for subjective analyses and allows an evaluation of model performance not captured by standard model diagnostics. Examples of possible applications to forecast and simulation experiments are presented in this paper.

1. Introduction

The spatial distribution as well as the temporal variations (genesis, lysis and seasonal variations) of extratropical cyclones and anticyclones have been described on the basis of very long data sets going back to the beginning of the century. Pettersen (1956) and Klein (1957) have used 40 years of data during the period 1899-1939 to produce statistics over the Northern Hemisphere. More recently Reitan (1974) has used data through the period 1951-1970 in order to study the differences with earlier datasets over North America and the adjacent oceans. In a similar study Zishka and Smith (1980) have produced more complete statistics over the same region for the period 1950-1977. References to other more local studies may be found in those papers. For the Southern Hemisphere, the only available cyclone statistics at a synoptic scale is that of Taljaard (1967), based on the International Geophysical Year (IGY) data of 1958.

These cyclone or anticyclone distributions are part of the climatology that atmospheric general circulation models (AGCMs) should reproduce. Furthermore it is desirable to analyze the sensivity of these fields to the model parameterizations or the prescription of the external boundary conditions. Unfortunately, all past analyses of model outputs in terms of cyclogenesis or cyclolysis have been performed subjectively, a procedure which cannot be done on a routine basis because of the large amount of work involved in the at least twice-daily manual analysis of sea-level pressure maps.

The purpose of the present paper is to show that a simple objective procedure can produce useful results and can serve for the diagnostics of systematic errors within models. A more intricate method, using the technics of non-linear optimization was used by Williamson (1981) to determine various parameters of extratropical disturbances from charts of the deviation to the mean of the 500 mb level (amplitude, location, radius, and ellipsoidal shape of the disturbance). Our method, which is much simpler, tries to match the criteria used in manual analyses, such as the those used by Silberberg and Bosart (1982) to study systematic cyclone errors in the NMC (National Meteorological Center) LFM-II (Limited Area Fined Mesh Model) model, or by Akyildiz (1985) to study the errors in the cyclone development and tracks simulated by the ECMWF (European Center for Medium Range Weather Forecast) operational models. We first describe the procedure in Section 2. It is then applied to the GLA (Goddard Laboratory for Atmospheres) analyses of the two FGGE SOP periods (Special Observing Periods of the First Garp Global Experiment), in Section 3 and to some general circulation model (GCM) experiments, in Section 4.

2. Methodology

The objective method to determine cyclone statistics has been designed following two guiding constraints: to be simple and to generally agree with criteria previously used in manual analysis. At a given time we define the occurrence of a cyclone as the presence of a grid-point with an absolute minimum in the sea-level pressure field, at least 4 mb lower than the average pressure over a small area surrounding it. This is equivalent to choosing a threshold in the Laplacian of the sea-level pressure field. The average pressure is computed as the mean over the closest 20 grid points. A restriction of this average to the 8 or 12 closest points brought only minor changes in the statistics. The results are also not very sensitive to small changes in the amplitude criterion, at least in midlatitudes, because most cyclones exhibit lows much deeper than 4 mb. As a further constrain we require that the cyclones kept in our statistics must be successfully tracked for at least 3 successive 6 or 12-hour intervals.

The tracking of the cyclones is done in the following way: at each time step we define a test area where we check for the presence of a cyclone at the previous time step (6 or 12 hours earlier). This test area, which is a square of 5 grid-points or 600 km (the largest of the two), is chosen to be large enough to avoid counting spurious cases of cyclogenesis. If two or more cyclones are found at the previous time step in the test area, one of them is chosen using a criterion that depends on the wind steering at 500 mb. However this selection procedure is rarely necessary. The cyclones are then tracked keeping in memory their place of origin. Once they have been tracked for more than three successive time steps, a case of cyclogenesis is considered to have taken place at their origin. Conversely, if a cyclone has been tracked for more than three successive time steps and can no longer be detected, it results in a case of cyclolysis.

We checked in detail this method using analyses on a uniform latitude-longitude grid for a number of time steps. It works especially well in mid-latitude regions. Polewards of 60° North or South the grid distortion may introduce some problems. The tropical regions within ±30° are not included in the results because of the shallowness of their pressure systems and in order to avoid the inclusion of too many thermal lows.

When applying our method to determine anticyclone statistics, we change the 4mb criterion on the minimum in pressure into a 2mb maximum pressure, but otherwise use the same scheme. Although the statistics over the occurrence of anticyclone centers are interesting, the very large geographical extension of the atmospheric highs makes the anticyclogenesis and anticyclolysis statistics much less reliable than those for cyclones and they will not be presented here.

3. Application to GLA analysis for the FGGE Special Observing Periods

We have applied our scheme to two series of GLA analyses for the FGGE year (Baker *et al.*, 1983):

1. 50 days of the twice daily analysis for the SOP1 period (beginning on the 5 January 1979).
2. 50 days of the twice daily analysis for the SOP2 period (beginning on the 11 June 1979).

The grid on which the data were discretized is also the grid used by the GLA GCM : it is regular in latitude (with a resolution of 46 points) and in longitude (with a resolution of 72 points).

Figure 1 shows respectively the distributions of cyclone center occurrences, anticyclone center occurrences, cyclogenesis cases and cyclolysis cases, during the SOP1 period. Figure 2 shows the same results for the SOP2 period. In the following subsections we discuss these results separately for the Northern and Southern Hemispheres. They are compared to the above mentionned climatologies. This study shows the general consistency of our results, and is also indicative of some peculiarities of the year 1979.

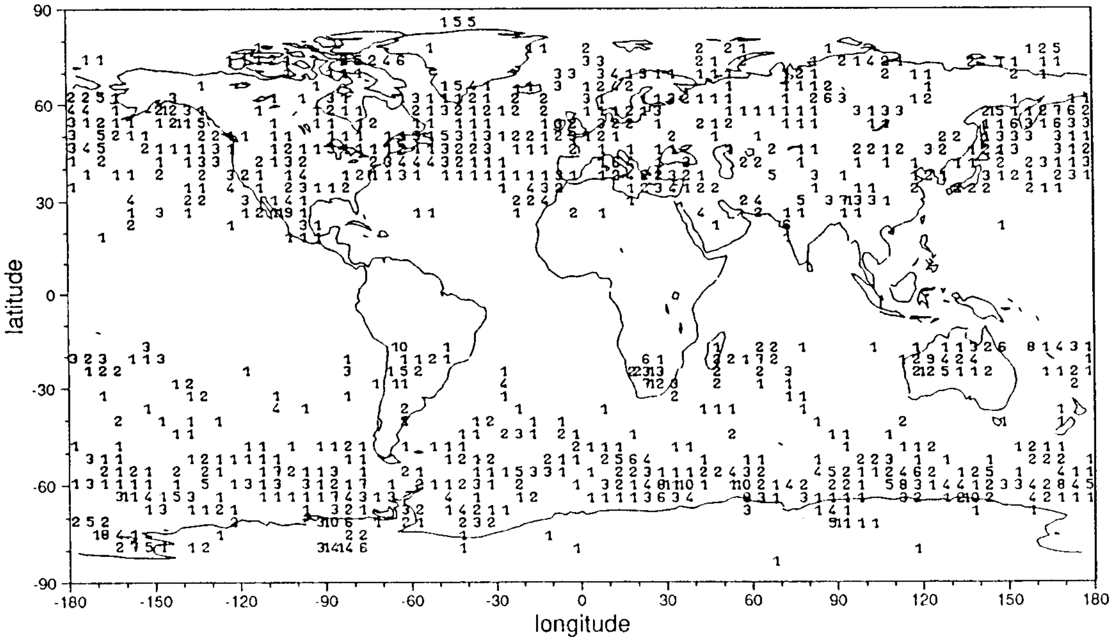

Figure 1.a: Cyclone center occurences for 50 days of the SOP1 GLA FGGE analysis.

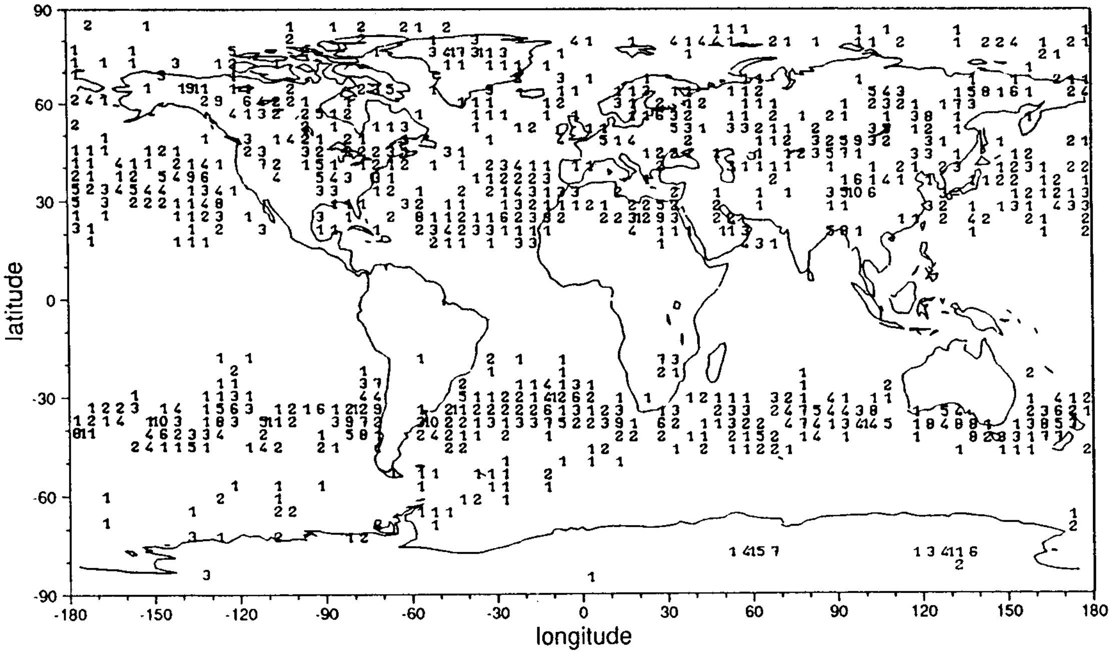

Figure 1.b: Anticyclone center occurences for 50 days of the SOP1 GLA FGGE analysis.

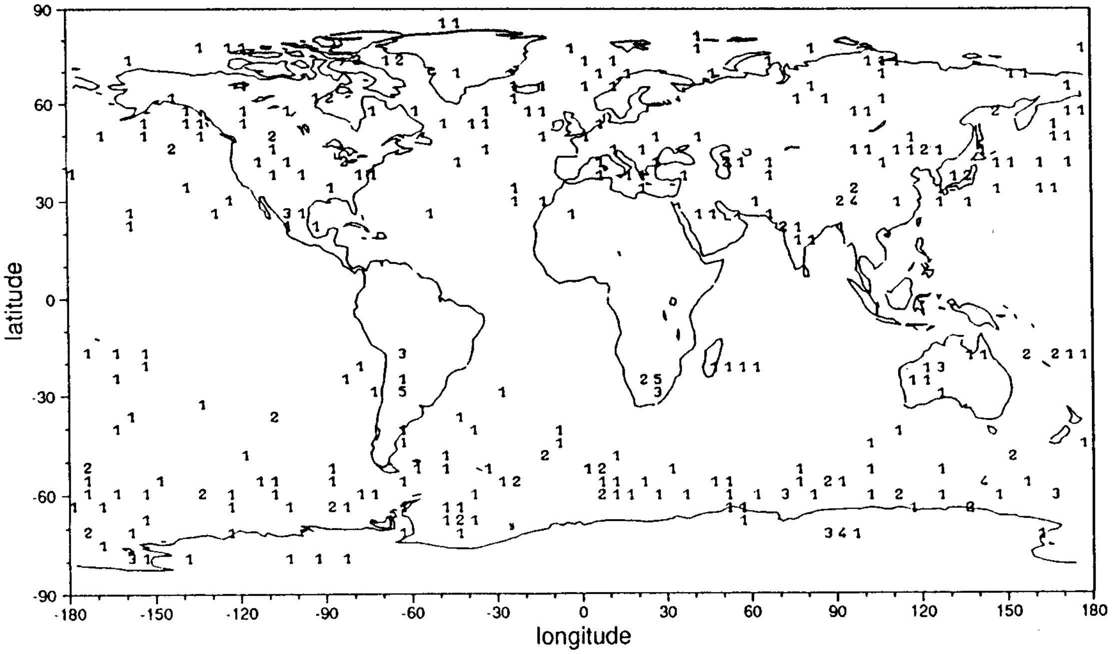

Fig. 1.c: Cyclogenesis cases for 50 days of the SOP1 GLA FGGE analysis.

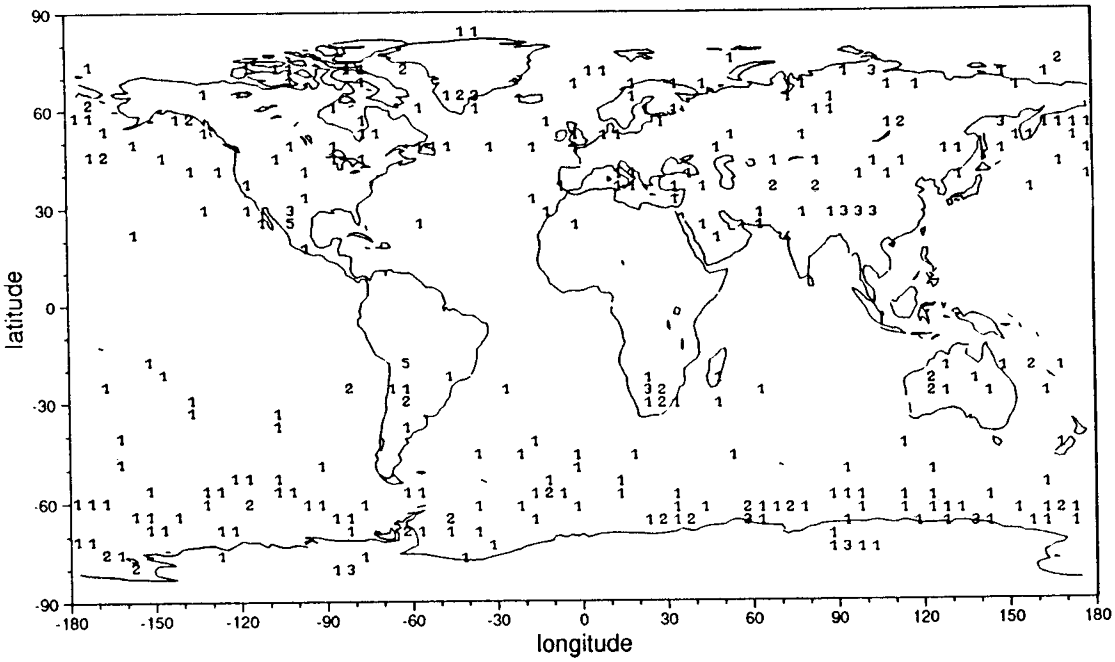

Figure 1.d: Cyclolysis cases for 50 days of the SOP1 GLA FGGE analysis.

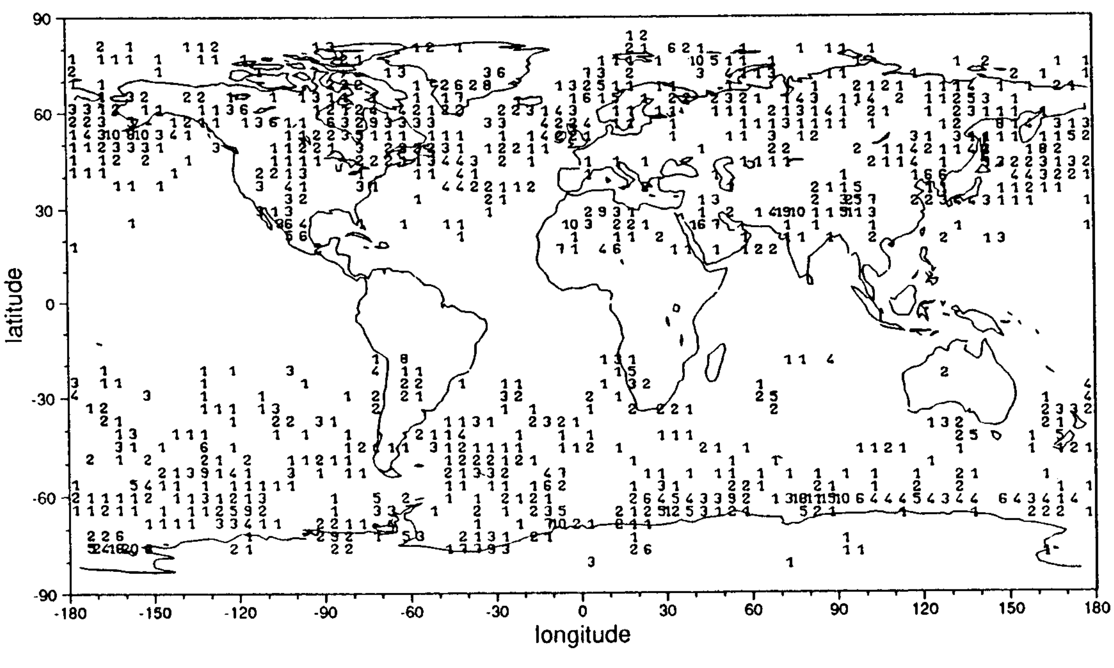

Figure 2.a: Cyclone center occurrences for 50 days of the SOP2 GLA FGGE analysis.

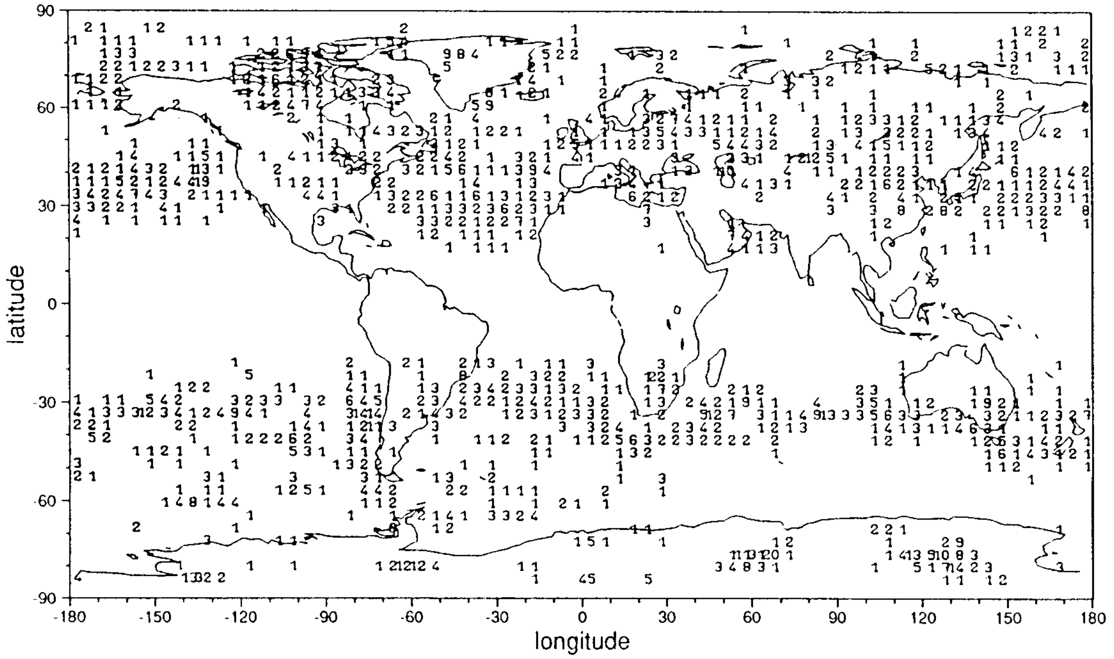

Figure 2.b: Anticylone center occurrences for 50 days of the SOP2 GLA FGGE analysis.

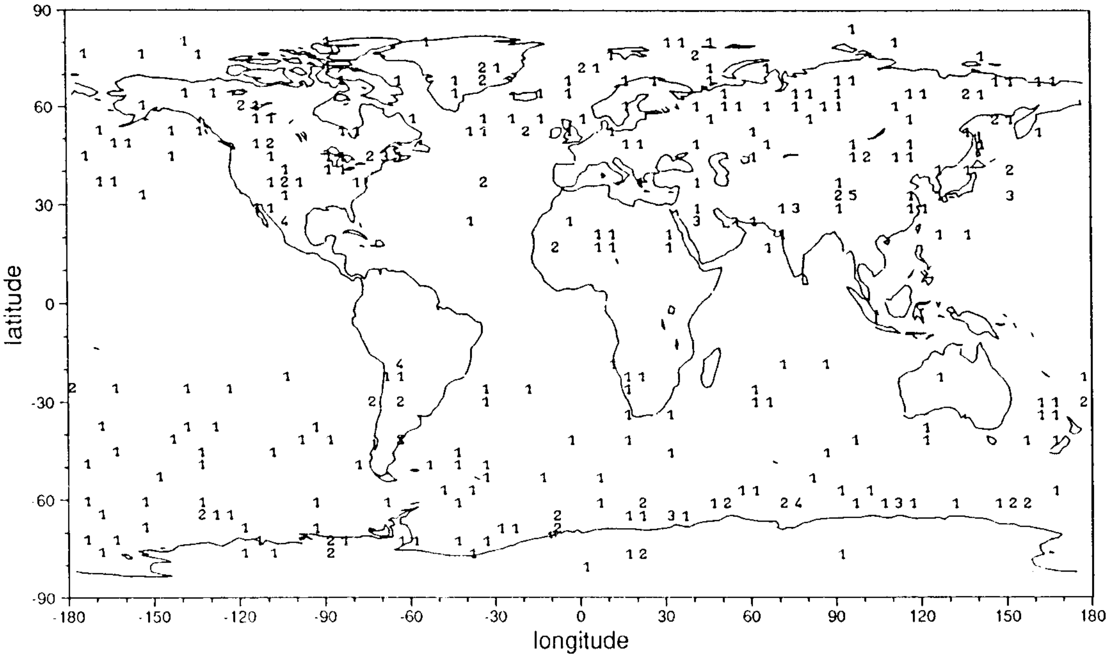

Figure 2.c: Cyclogenesis cases for 50 days of the SCP2 GLA FGGE analysis.

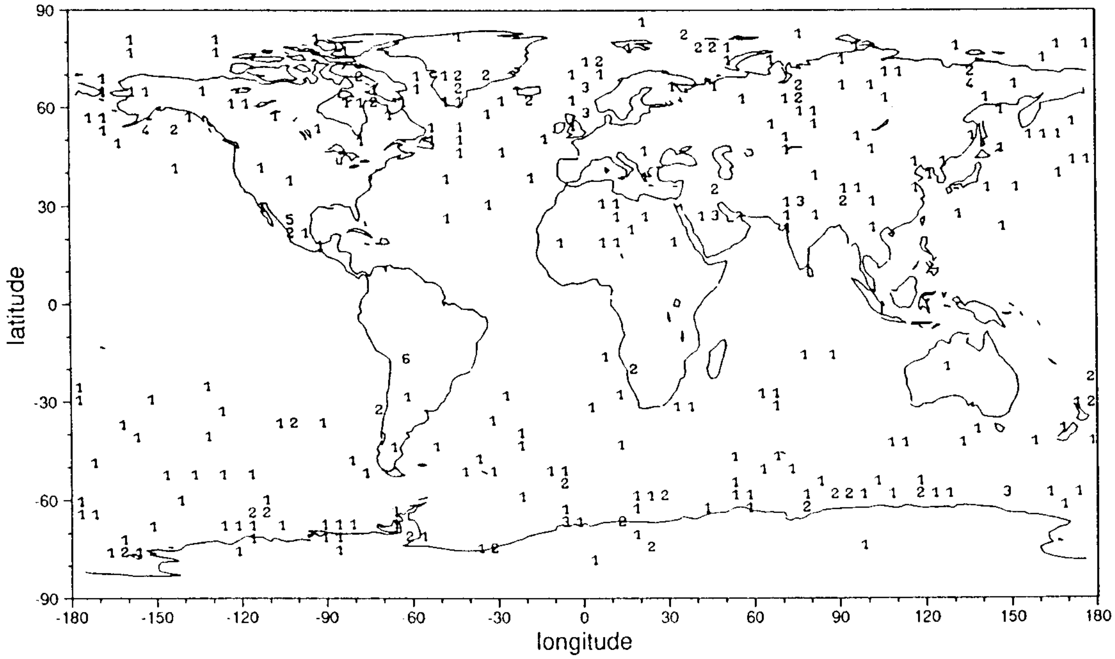

Figure 2.d: Cyclogenesis cases for 50 days of the SOP2 GLA FGGE analysis.

3.1 Northern Hemisphere

The *cyclone center* distribution matches a number of features of Pettersen's and Klein's results. Over North America in winter we find maxima east of the Rockies, in the Great Plains, near the Great Lakes and in the Hudson Bay. Their positions are shifted northward in summer. The lows which appear in Mexico are of thermal origin. Over the Atlantic Ocean the cyclone centers appear in the Gulf Stream area and extend toward Greenland and Northern Europe. In the Mediterranean and the Black Sea there is a strong cyclonic activity in winter which disappears in summer. We may also note a large intensification of the cyclonic activity during summer over Eastern Siberia. The summer lows which appear over Southern China, India or Central Africa have a thermal origin. There are also some discrepancies between our 1979 analysis and the climatology. The main ones are to be found in Asia. This analysis does not show a winter maximum over India or any permanent maximum over the Gulf of Tonkin area; instead we get an abnormal cyclonic activity over Central Siberia.

The broad features of the *anticyclone center* distribution also agree with those of the climatology. We get large anticyclonic zones over the oceans with a slight shift northward during the summer. The distribution is more irregular over the continents. Over North America at the latitudes of the United States we tend to have two maxima: a smaller one in the West upstream of the Rockies and a larger one in the East. Many anticyclones appear over Canada in both periods, however no anticyclones occur West of the Rockies, in qualitative agreement with the climatology (Zishka and Smith, 1980). We may note the large number of anticyclone occurrences in summer over inland waters such as the Great Lakes, the Mediterranean, the Black Sea and the Caspian Sea. In Winter, anticyclones also appear over North Africa. In Asia we get more cases in Eastern Siberia than in Western Siberia, which is in accordance with Pettersen, but the many cases we get over China are a peculiarity of our 1979 analysis.

There are relatively few cases of ***cyclogenesis*** during the 50 days, but they tend to occur in some privileged area. Many of them coincide with the location of the maxima in Pettersen's climatology. Over North America the major zone of cyclonic activity for both seasons is at the east of the Rockies and in the Great Plains. Another maximum appears along the Atlantic Coast in summer. The Northern Atlantic, the North Sea, the Northern Pacific, especially east of Japan and south of Alaska, are also important regions of cyclogenesis and there is a strong winter maximun over the Mediterranean region. Again the major discrepancies between our 1979 analysis and the available climatologies concern Asia, where we find a large number of cyclogenesis cases especially in summer.

The occurrence of cyclogenesis cannot be clearly detected with other model diagnostics. We have compared their distribution to the time-mean sea-level pressure and to the low-pass and band-pass filtered fields computed with the method of Blackmon (1978). The cyclogenesis areas coincide in some cases with maxima of the band-pass filtered sea-level pressure variance, which retains components with figures ranging from about 2 to 5 days, as for example in the Gulf Stream region. But this is not systematic, and in the Great Plains area, as an example, there is cyclogenesis but small values of the band-pass filtered variance of pressure. The cyclogenesis cases are also often located between the mean lows and highs.

The available climatologies for ***cyclolysis*** concern mainly North America (Zishka and Smith, 1980). In our analysis the North Sea as well as the North Pacific, South of Alaska of North of Japan are important areas of cyclolysis. Numerous cyclolysis cases also occur over Central Siberia for both winter and summer. Regions where the seasonal cycle is more apparent are North America and North Atlantic. Over Central America, Africa and Northern India, where the lows have a thermal origin, cyclolysis and cyclogenesis appear in the same locations. Averaged over the whole Northern Hemisphere the mean latitude for cyclolysis is 60.3°N in summer and 55.9°N in winter (against respectively 60.7°N and 57.3°N for cyclogenesis) which represents a significant seasonal variation.

3.2 Southern Hemisphere

The only available analysis for the Southern Hemisphere to compare our results with is, to the best of our knowledge, that of Taljaard (1967) based on observations collected during the International Geophysical Year (IGY). These results - as ours - are based on too short a record to have climatological significance and should be used as a reference only with caution.

There are nevertheless a number of similarities between the two sets of results, especially concerning the distribution of the cyclone centers. In winter (i.e. for the SOP2 period in the Southern Hemisphere) it is maximum at about 65°S, with a number of preferential locations all around Antartica (in the south-east of Argentina, in the south-east of South Africa, and the south-east, south, and south-west of Australia). These regions are identified by Taljaard as cyclonic graveyards and they also turn out to be cyclolysis regions in our study. In summer we find again spotty maxima in the distribution of the occurrence of cyclone centers as well as cyclolysis cases.

The agreement with the climatology also concern the location of the cyclogenesis cases. In winter we find a large maximum over northern Argentina, and many cases in the Western Atlantic and the Eastern Pacific. Another region of large cyclogenesis occurrence is found between Australia and New-Zealand. All these 1979 results qualitatively match those found during the IGY. In summer, cyclogenesis is modified over the continents. It now appears in the eastern part of South Africa rather than in the western part of it, and strong cyclogenesis occurs over western Australia. This is also in accordance with Taljaard's results. Over South America there is a displacement in the cyclogenesis areas, and the lows are now thermal lows that appear repeatedly at the same location.

Besides these similarities between our study and that done for the IGY, there is a discrepancy as regards the meridional distribution of cyclogenesis. Taljaard (1967) found a weak maximum at about 45°S. This is in contrast with our distribution where, in zonal means, we obtain two maxima at about 30°S and 75°S. The large impact of the satellite data on the analysis of this hemisphere has to be mentioned and may explain this discrepancy as much as the differences between the two years and the two methods of analysis. We show in Figure 3 the cyclogenesis cases obtained for both hemispheres using this time the GLA NOSAT (No Satellite data) analysis which uses only conventional data (Halem *et al.,* 1982). If the results for the Northern Hemisphere match well those previously shown, huge differences appear in the Southern Hemisphere, especially over the oceans, and the results are more similar to those of Taljaard.

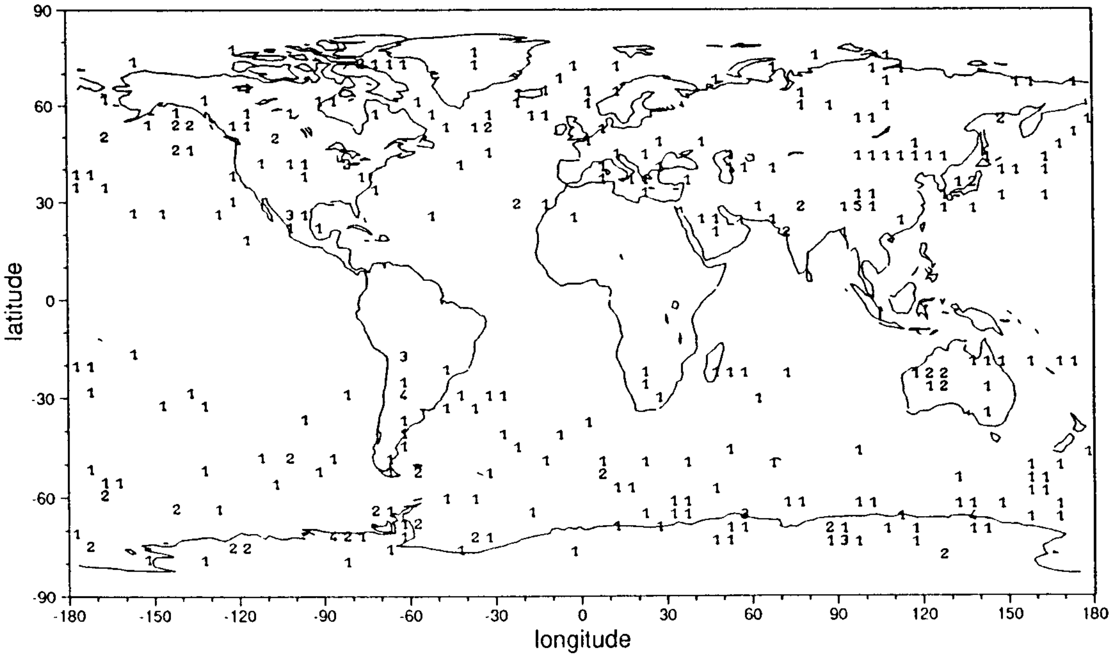

Figure 3: Cyclogenesis cases obtained with the GLA NOSAT analysis for the SOP1 period of the FGGE year.

Our analysis for the distribution of anticyclone centers agrees well with Taljaard's results. In summer (SOP1 period) it mainly shows an oceanic belt between 35° S and 50° S with a southern extension south-east of Argentina. In winter (SOP2 period) anticyclone centers have a wider latitudinal range of occurrence and they are found also over the continents (Argentina, South

Africa, South Australia). South of 60° S the only maxima are found south-west of Chile, in the Pacific. The maximum over Antartica is probably due to the extrapolation to sea-level.

Finally for both Hemispheres the differences between our results for the FGGE year and the existing climatologies, which correspond to other years, seem small enough to be attributed to the internal variability of the atmospheric system rather than to the simplicities of the diagnostic scheme. Possible exception to this are the high latitude regions, where our scheme may loose its accuracy, and areas where conventional data are scarce, such as the Southern Hemisphere, especially south of 50° S.

4. Application to GCM experiments: some examples

The purpose of this section is to discuss briefly examples of applications of our objective method. It must be noted that these are only case studies and that no definitive conclusion concerning the models can be drawn from them without a more systematic analysis.

4.1 Comparison between an ECMWF analysis and a long-term integration the ECMWF GCM

The cyclone tracks derived by our procedure, using an ECMWF analysis going from 10 October 79 to 30 October 79 are shown in Figure 4.a. The analysis is part of the first ECMWF FGGE III-b analysis (Bengtsson *et al.*, 1982). Data are interpolated to the GLA model grid (72 points in longitude and 46 in latitude) and treated in the same fashion as before. We compare it with the results obtained by the same procedure, but using a long-term prediction experiment made with

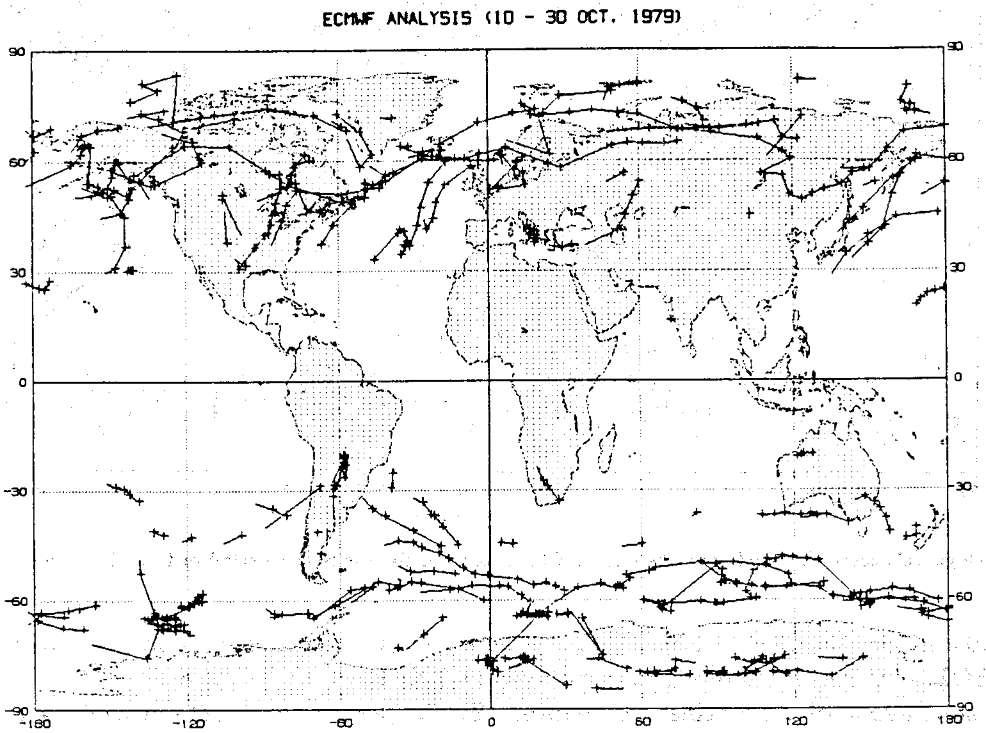

Figure 4.a: Cyclone tracks drawn by the objective procedure for twice daily ECMWF analyses going from 10 October 79 to 30 October 79.

the ECMWFmodel for the same period (Figure 4.b). The version of the model which is used is the T-63 model for which Akyildiz (1985) already studied some systematic errors in the cyclone life cycle and in the cyclone tracks. In the Northern Hemisphere we find, as Akyildiz did, that many tracks over the North-Atlantic Ocean do not have the right northward displacement. In our case the simulated tracks cross Europe, while analyzed tracks do not. It may be related to excessive zonalization of the flow, which has since been improved by the use of a parameterization of the effect of gravity-wave drag induced by orography (Miller and Palmen, 1987).

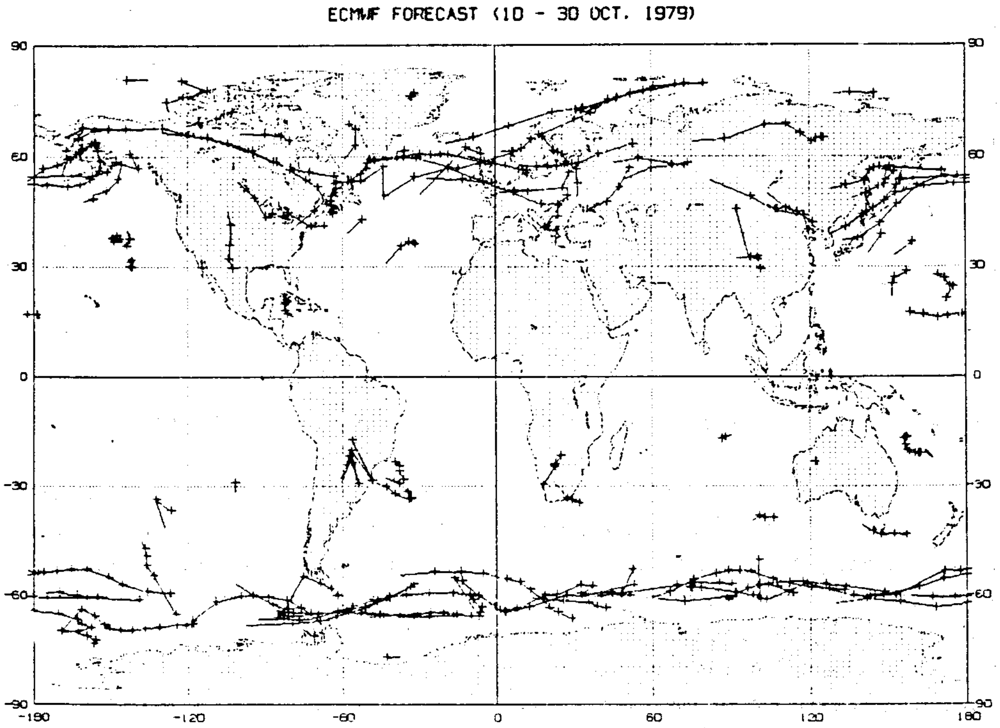

Figure 4.b: Cyclone tracks drawn by the objective procedure for a 20-day integration of the ECMWF model starting on 10 October 1979.

Similar problems, but even more apparent occur, in the Southern Hemisphere. Results of the analysis show a large north-south spread of the cyclone paths, at about 60° S, which the model does not predict. Differences also appear over Antartica, but our procedure is less accurate at very high latitudes. By comparison the tracks generated by the model are much more zonal. These differences between observations and analyses may in part be the result of the dynamical scheme formulation: Akyildiz (1985) indeed showed some differences in the performances of the ECMWF grid-point and spectral T63 models. But the fact that simulated tracks are much more anomalous in the Southern Hemisphere makes it likely that they are also dependent on inaccurate prescriptions of the boundary conditions (sea-surface temperature, sea-ice extent).

4.2 Comparison between a 50 day integration of the LMD GCM and the SOP2 GLA analysis

We show in Figure 5 the cyclogenesis cases deduced from a 50-day experiment made with the Laboratoire de Météorologie Dynamique (LMD) GCM, starting on 11 June 1979. The initial

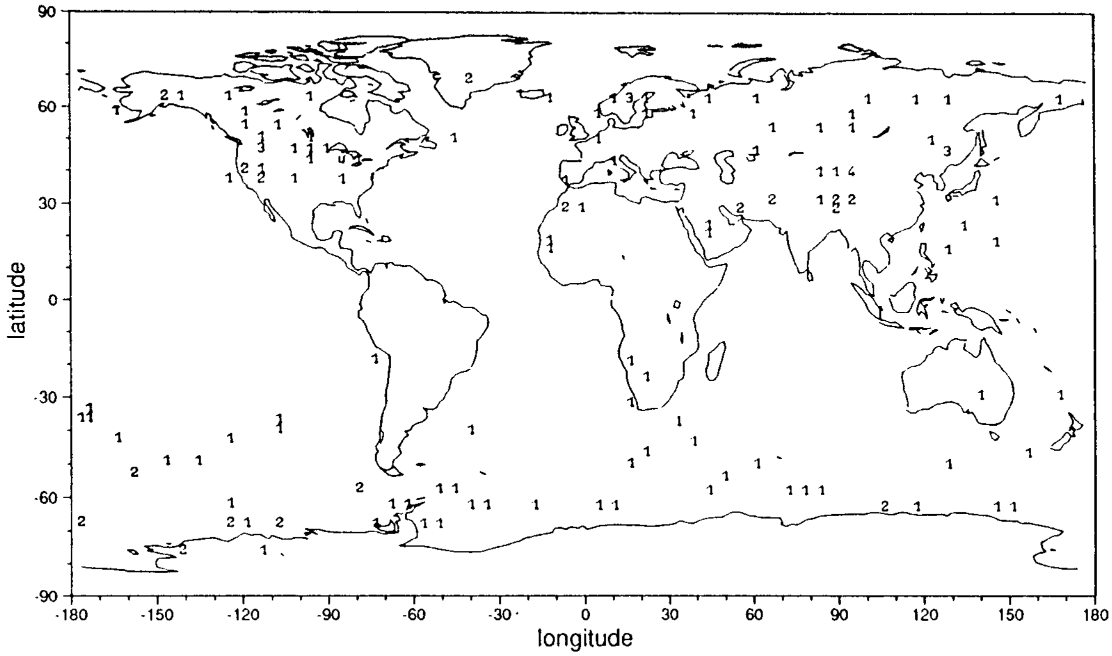

Figure 5: Cyclogenesis cases from a 50-day integration of the LMD GCM starting on 11 July 1979.

data are from the first ECMWF FGGE III-b analysis and were interpolated to the LMD grid. A description of the LMD GCM is available in Sadourny and Laval (1983), and the present experiment has already been described by Le Treut (1984), but we recall here that the model uses a discretization grid which is regular in sine of the latitude (with 50 points of resolution) and longitude (with 64 points of resolution). Its resolution at mid-latitudes is therefore somewhat lower than that of the GLA model and the distorsion of the grid at high latitudes (above 60 degrees) will cause severe problems in our analysis of those regions. By comparing with Figures 2.c we may see that the model reproduces reasonably well the characteristics of cyclogenesis over the Northern Hemisphere continents. On the other hand cyclogenesis is far too weak over the oceans. A large number of such 50-day experiments were made using various cloud cover parameterization or cloud cover prescription and only in a few cases did the cyclone tracks cross the Northern Atlantic. The origin of this problem may be linked with the amplification of the land-sea contrast in the model. In the Southern Hemisphere, the cyclogenesis centers are better distributed over the oceans but fewer than observed. An exception to that is the situation over South America, where no cyclogenesis is simulated in the lee of the Andes. Michaud (1987) showed that the representation of the gravity-wave drag effect in the model leads to a better representation of cyclonic patterns in the Northern Hemisphere winter. But a similar experiment using the gravity-wave drag has not yet been done for the Southern Hemisphere winter.

4.3 Analysis of a series of 5-day forecasts by the GLA GCM for the SOP1 period

We use our method to make a systematic analysis of a series of 10-day forecasts made using the GLA GCM. It is the GLA fourth-order model described by Kalnay-Rivas *et al.* (1977). The starting dates of the forecast are 7, 9, 13, 15, 17, 19, 21, 25, 29 January 1979 and 2 February 1979:

the periods are therefore overlapping. For each of the forecasts, which are sampled with a 6-hour interval, we have stored the cyclogenesis events, ignoring those which would appear within the first day of each integration (Figure 6). These results should therefore be compared with those of Figure 1.c, keeping in mind that Figure 6 represents twice as much data analyzed, because for each 2-day period there are two overlapping forecasts. Analyzed and simulated patterns are close to each other, although there are slightly too few simulated cases, taking into account the preceeding remark. The agreement is quite good over North America, the North Pacific and in the whole Southern Hemisphere, except Antartica. Over Antartica, the precise location of the simulated cyclone centers has no real meaning, due to the grid distortion, but the large number is the result of too low mean surface pressure in the simulations. Finally a clear discrepancy occurs over Asia: cyclogenesis in the model occurs westward of its analyzed location.

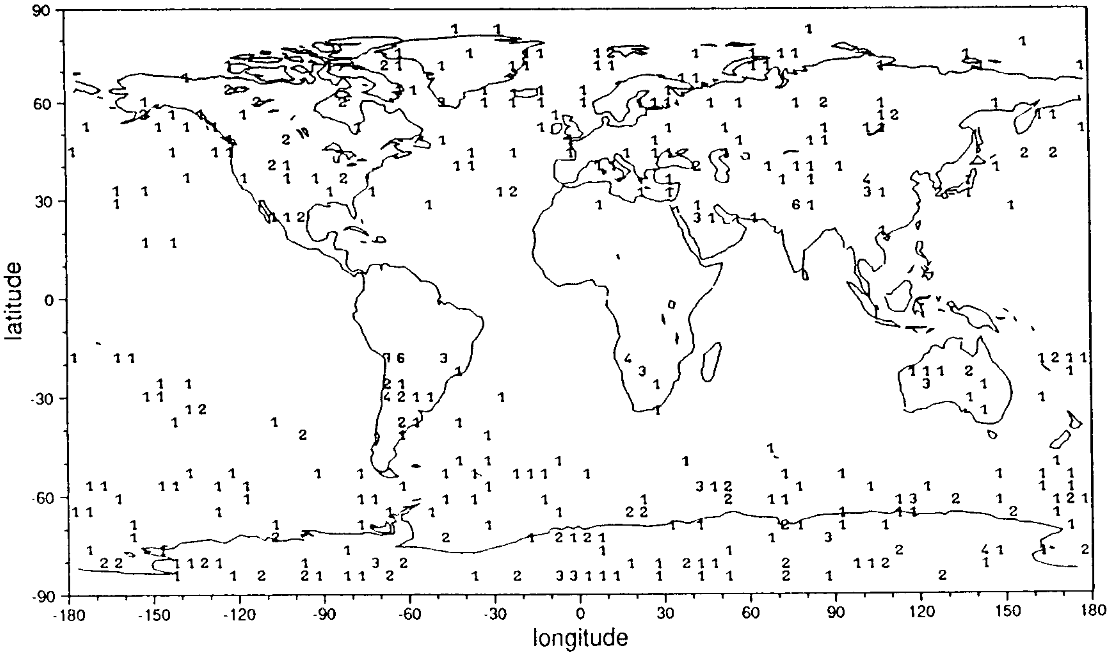

Figure 6: Cyclogenesis cases deduced from a series of overlapping forecasts throughout January 79, made with the GLA GCM.

5. Conclusion

The purpose of this paper is to demonstrate the interest and feasability of a systematic diagnostic study of cyclone tracks and cyclone or anticyclone statistics by objective methods. The simple method used here has been designed to give results as close as possible to those derived from manual analyses. It turns out to be robust enough and not to depend critically on the various thresholds which have to be specified. It has been applied to analyses from the FGGE year and the difference between our results and the existing climatologies is small enough to be attributable to interannual variability or the model coarse resolution. The impact of satellite data assimilation appeared clearly in our results for the Southern Hemisphere. This scheme has also been applied as a diagnostic tool for GCM experiments: it gives an interesting insight in the physics of these models, which is in accordance with the findings of other studies based on manual analyses, and which is not captured with current standard model diagnostics. The simple diagnostics which we propose might be done in a routine manner in operational centers or used for the purpose of GCM sensitivity studies.

Aknowledgements

This work was initiated during a stay HLT made at GLA at the invitation of M. Ghil and benefitted from his comments and support. R. Atlas and the referees are also acknowledged for their useful comments. G. Rabreau (LMD) gave precious help in the design of the plotting routines.

REFERENCES

Akyildiz, V., 1985. Systematic errors in the behaviour of cyclones in the ECMWF operational model. *Tellus.* **37A**. 297-308.

Baker, W. E., 1983. Objective Analysis and Assimilation of Observational Data from FGGE. *Mon. Wea. Rev.*, **111**. 328-342.

Bengtsson, L., M. Kanamitsu, P. Kallberg and S. Uppala, 1982. FGGE 4-dimensional Data Assimilation at ECMWF, *Bull. of the Amer. Meteor. Soc.*, **63**, 29-43.

Blackmon, M. L., 1976. A climatological Spectral Study of the 500mb Geopotential Height of the Northern Hemisphere. *J. Atmos. Sci.* **33**. 1607-1623.

Halem, M., E. Kalnay, W. E. Baker and R. Atlas, 1982. An assessment of the FGGE satellite observing system during SOP-1. *Bull. Amer. Meteor. Soc.* **63**. 407-426.

Kalnay-Rivas, E., A. Bayliss and J. Stroch, 1977. The 4th order GISS model of the global atmosphere. *Beitr. Phys. Atmos.* **50**, 299-311.

Klein, W. H., 1957. Principal tracks and frequencies of cyclones and anticyclones in the Northern Hemisphere. Research Paper n40, U. S. Weather Bureau, Washington D. C., 60 pp.

Le Treut, H., 1984. Sensitivity studies of the GCM simulations to cloudiness specification. Proceedings of the ECMWF workshop on convection in large-scale models, ECMWF, Reading.

Michaud, R., 1987. Sensibilité de Prévisions Météorologiques à longue échéance aux anomalies de température de surface des océans (in french), Thèse d'Etat, Université de Paris VI.

Miller, M. J. and T. N. Palmer, 1987. Orographic wave-drag: its parameterizational influence in general circulation and numerical weather prediction models, 283-333. Proceedings of the Seminar on Observation, theory and modelling of orographic effects, held at ECMWF in September 1986, ECMWF, Reading.

Pettersen, S., 1956. Weather Analysis and Forecasting (2nd edition), Volume 1, McGraw Hills Book Company, N. Y.

Reitan, C. H., 1974. Frequencies of cyclones and cyclogenesis for North America, *Mon. Wea. Rev.,* **102**, 861-868.

Sadourny, R. and K. Laval, 1983. January and July performance of the LMD GCM, in New Perspectives in Climate Modelling, A. Berger, C. Nicolis editors, Elsevier Science Publishers, Amsterdam.

Silberberg and Bosart, 1982. An analysis of systematic errors in the NMC LFM-II model, *Mon. Wea. Rev.*, **110**, 254-256.

Taljaard, J. J., 1967. Developments, distribution and mouvement of cyclones and anticyclones in the southern Hemisphere during the IGY., *J. Appl. Meteor.*, **6**, 973-987.

Williamson, D. L., 1981. Storm track representation and verification, *Tellus*, **33**, 513-530.

Zishka, K. M. and P. J. Smith, 1980. The climatology of cyclones and anticyclones over North America and surrounding environs for January and July, 1950-1977, *Mon. Wea. Rev.*, **108**, 387-401.