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Numerical prediction of atmospheric blocking—A case study

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ABSTRACT

A series of numerical models have been used to investigate the predictability of atmospheric blocking for an episode selected from FGGE Special Observing Period I. Level II-b FGGE data have been used in the experiment. The blocking took place over the North Atlantic region and is a very characteristic example of high winter blocking. It is found that the very high resolution models developed at ECMWF, in a remarkable way manage to predict the blocking event in great detail, even beyond 1 week. Although models with much less resolution manage to predict the blocking phenomenon as such, the actual evolution differs very much from the observed and consequently the practical value is substantially reduced. Wind observations from the geostationary satellites are shown to have a substantial impact on the forecast beyond 5 days, as well as an extension of the integration domain to the whole globe. Quasi-geostrophic baroclinic models and, even more, barotropic models, are totally inadequate to predict blocking except in its initial phase. The prediction experiment illustrates clearly that efforts which have gone into the improvement of numerical prediction models in the last decades have been worth while.

1. Introduction

One of the fundamental questions in dynamical meteorology and one of the basic objectives of GARP, is to determine the predictability of the atmosphere. In the early planning stage and preparation for GARP a number of theoretical and numerical studies were undertaken, indicating that there existed an inherent unpredictability in the atmosphere which, even with the most ideal observing system, would limit useful weather forecasting to 2–3 weeks (Charney et al., 1966; Lorenz, 1968, 1969a, 1969b; Robinson, 1967; Smagorinsky, 1969). In particular it was found that an initial random error increased in time, with a doubling of the error in 3 to 5 days, the error growth being faster for small errors. It was also found that the theoretical error growth was scale dependent with a much higher predictability for the larger scales than for the smaller scales. According to Lorenz (1969b), who carried out a theoretical predictability study for a barotropic model, the predictability for a 20,000 km wave is almost four times larger than a 5000 km wave.

In the numerical experiments summarized by Charney et al. (1966) and Smagorinsky (1969), a random perturbation was added to a prescribed initial state and the forecast from the perturbed initial state was compared with a reference prediction without the error. The predictability was investigated by studying how the two predictions deviated from each other during the course of the integration. The predictability was defined as the time when the two forecasts differed as much as two randomly chosen states.

Assuming the random frequency distribution, it can be shown that the differences between two randomly chosen states have a r.m.s. difference which is $\sqrt{2}$ times larger than the climatic variance (Thompson, 1961). The original definition of predicability has therefore little practical meaning and we will use in this article, as has been suggested by Döös (1970), the term *useful predictability*, which is the time when the prediction error reaches the climatic variance. In the evaluation of a series of 10-day prediction experiments at ECMWF, Hollingsworth et al. (1979) used this definition of useful predictability and found that it agreed quite

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well with an independent subjective evaluation. A corresponding value for the correlation (anomaly correlation) was found to be around 0.6.

Prediction experiments using real data are less favourable than the numerical simulations. Experiments reported by Miyakoda (1972), Druyan et al. (1975) and Hollingsworth et al. (1979) give a value of the useful predictability of 4–6 days, the latest experiment having a slightly better value.

A closer examination of the prediction error from numerical forecasts in general shows several interesting features

(i) The error growth in the beginning of the forecast is substantially higher in the real integrations.
(ii) The predictability for the ultra-long waves, at least for some prediction models, is less than for the medium-scale waves.
(iii) All numerical models known to the author produce systematic errors with a characteristic geographical distribution common for most models.
(iv) There is considerable variation in predictability from day to day and from episode to episode.

The rapid error growth at the beginning of the forecast is most likely caused by an inaccurate specification of the initial state, in particular, phase errors can cause a very rapid growth of the initial error (Bengtsson, 1978).

The high growth rate of the ultra-long waves seems to be a problem mainly for models with an insufficient resolution (either horizontal or vertical) or oversimplified physical parameterization. Lambert and Merilees (1978) have investigated the Canadian spectral operational model and found that in that particular model at that particular time the medium-scale waves were better predicted than the ultra-long waves. There are also indications (Somerville, 1980) that a lateral boundary condition at the equator and an unsatisfactory treatment of the data in the Tropical belt will reduce the predictability of the long waves. We will comment on this particular question later in this investigation. There are indications that the very poor results for the ultra-long waves disappear when more advanced models are being used. The ECMWF model, for instance, clearly predicts the ultra-long waves better than the medium-scale waves.

The systematic errors are related to the errors in the long waves because they have a very large-scale geographical distribution and consequently large-scale systematic errors show up as errors in the long waves. These errors are most noticeable in the winter and a common feature is to predict too high geopotential values in the eastern Atlantic. A similar error distribution can be found in the Pacific.

Perhaps the most puzzling prediction problem is the very large variation of predictability with time. Fig. 1 shows the result of seven integrations carried out at ECMWF (Hollingsworth et al. 1979) with a high resolution global grid point model. The forecasts were all from February 1976 and based upon analyses from NMC, Washington, using data from DST-6. In spite of the fact that for this period we had a homogenous observational data set, the useful predictability varied from less than 5 days to beyond 8 days. Integrations using a different parameterization and high resolution spectral models gave a similar picture and it has been clearly demonstrated that on certain days all forecasts were poor while on other days, in general, all forecasts were good.

The most successful forecast among seven cases investigated at ECMWF was a prediction of a typical blocking pattern. The result of this integration and other successful predictions of blocking is both very interesting and very encouraging. It is interesting because it suggests that a blocking pattern may be regarded as a sort of a quasi-stable equilibrium, as has been suggested by Charney and deVore (1979). Such an equilibrium can be generated by a non-linear interaction between some large-scale components together with a necessary forcing from topography and by non-adiabatic processes. Charney and deVore considered a simple barotropic low-order system with topography and Newtonian forcing. In the real atmosphere the effect of topography and non-adiabatic processes is much more complicated and the energy of the large-scale systems, to a major extent, is obtained through energy transfer from the baroclinic waves. This process can be represented by Newtonian forcing only to a very limited degree. It is unlikely that we will have an equilibrium in the real atmosphere but instead a repetitive characteristic evolution of a certain weather pattern.

Successful forecasting of blocking is of utmost practical importance. The largest deviation from climatology occurs during blocking situations.

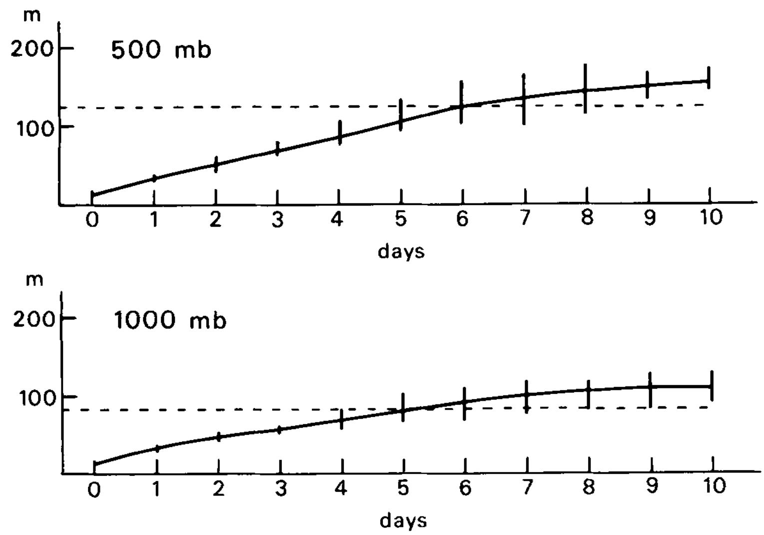

Fig. 1. The thin line shows the ensemble r.m.s. error for the surface and 500 mb as a function of time for seven different forecasts from February 1976. The vertical line shows the variability in the r.m.s. error day by day. The horizontal dashed line is the climatic norm.

With blocking occurring over northern Europe or the northeastern Atlantic in the winter, outbreaks of very cold Arctic air to the south of the block often generates intensive small-scale depressions with strong winds and heavy snow-falls. Such weather events can create serious disruption in society and it is most important that they be predicted as far in advance as possible.

The winter of 1979 was characterized by a very high frequency of blocking in the eastern Atlantic. Associated with the blocking, periods of very cold and unsettled weather with several disastrous snow-storms occurred in northern and central Europe. The purpose of this study is to carry out an investigation of a particular forecast for January 16, 1979, which turned out to be exceptionally accurate for as far as 8 days ahead, and which showed useful predictability for more than 12 days. By a successive simplification of the model we will further try to indicate what the essential conditions are for the prediction of the blocking pattern in this particular case. In the first part of this study we will describe in detail one high resolution integration. In the second part we will present results from simplified models and show how a successive simplification of the models, as well as a reduction of the data being used, gives rise to a deterioration of the forecast.

2. Synoptic description

The weather situation preceding January 16, 1979, is characterized by a well-defined zonal flow over the Atlantic and western Eurasian sector. The zonal flow is successively breaking down and on January 16, 1979, two cut-off lows are created at 40° N, one at 25° W and another one at 25° E. In particular the cut-off low over eastern Europe is very intense. The flow pattern during the following 8 days develops into a typical blocking situation (see Fig. 2).

The ridge over western Europe moves during the first 2 days towards north-northwest under gradual intensification. The axis of the ridge then swings over from a north–south orientation to a west–east and moves slowly into a quasi-stationary position over central Scandinavia where it stays during days 3–5. A very intense cyclone develops west of Spitzbergen on day 3 and moves eastward on the north side of this ridge. This cyclone plays an essential role in intensifying the northern branch of the jet to the north of the high pressure over Scandinavia. Over southern Europe the two cut-off lows have merged into large areas of cyclonic activity, the westerly jet over Northern Africa is also successively intensified.

The 500 mb flow of day 4 shows a characteristic

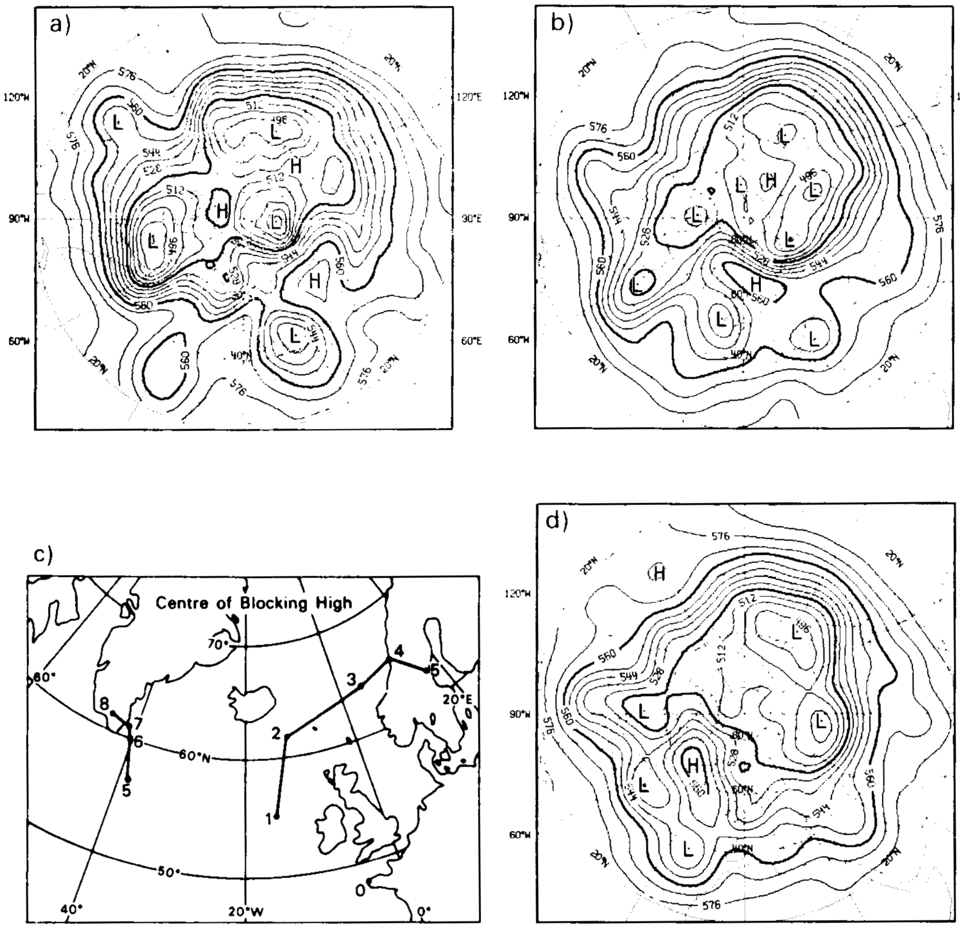

Fig. 2. 500 mb geopotential for January 16, 1979 (a), January 20, 1979 (b), and January 24, 1979 (d). Section (c) shows the centre of the blocking high day by day.

blocking pattern with a split of the jet around 40° W and a blocking pattern over central Scandinavia. The flow pattern from day 3 onwards fulfils the criteria for blocking according to Rex (1950a,b), namely

(a) the basic westerly current is split into two branches,
(b) each branch current is transporting an appreciable mass,
(c) the double jet is extending over at least 45° lon,
(d) a sharp transition from a zonal flow upstream to a meridional type downstream is observed at the current split.

At day 5 the high pressure weakens suddenly over Scandinavia and a new high is established around 40° W. This high pressure constitutes a new blocking cell. This new cell is amplified and drifts slowly towards north-northwest during the next couple of days. There is substantial cyclone activity to the west of this ridge and it is suggested that the northward transport of heat and momentum plays an active role in building up this new high-pressure cell.

3. The initial data

The initial data for this case were obtained from a preliminary data assimilation experiment carried out at ECMWF using level II-b data from January 13–19, 1979. In this experiment, which was part of an early test of the FGGE data collection and processing system, practically all FGGE level II-b data were used.

The data assimilation was carried out by an intermittent 4-dimensional data assimilation system, assimilating data successively every 6 h and regarding observations at 6-h intervals (± 3 h) as synoptic. The analysis was done by a 3-dimensional statistical multivariate scheme (Lorenc et al., 1977). Every analysis was initialized by a nonlinear normal mode technique described by Temperton and Williamson (1979). The prediction model used in the data assimilation was the grid point model of ECMWF (Burridge and Haseler, 1977; Tiedtke et al., 1979). The horizontal resolution was a 1.875° lat/lon staggered grid and the vertical resolution consisted of 15 levels in the vertical. Table 1 shows the vertical levels. The data assimilation started on January 13, 1979, and climatology was used as the first guess for the very first analyses in the series. The data assimilation experiment continued for several days but the prediction experiments, to be described below, have all been done from January 16, 1979. Where not particularly mentioned, the initial data for the different integrations have been interpolated from the initial grid point data.

Table 1. *Vertical resolution used in the experiments*

15-level model		5-level model	
k	σ_k	k	σ_k
1	0.025		
2	0.077	1	0.007
3	0.132		
4	0.193		
5	0.260	2	0.260
6	0.334		
7	0.414		
8	0.500	3	0.500
9	0.588		
10	0.678		
11	0.765	4	0.765
12	0.845		
13	0.914		
14	0.967	5	0.967
15	0.996		

4. Evaluation of the high resolution spectral model

Nine different 8-day prediction experiments have been carried out from the data set described above. Experiments have been made with spectral as well as grid point models. Table 2 specifies the different experiments. Both the grid point model as well as the very high resolution spectral models predict the actual weather events with remarkable accuracy. We will first describe the prediction with the highest spectral resolution. Figs. 3 and 4 show the r.m.s. and correlation coefficient respectively for the whole of the troposphere (1000 mb–200 mb) (verified for each standard level) and for the area to the north of 20° N. The forecast has been verified in total as well as being decomposed in three different zonal wave number groups, ultra-long waves 1–3, medium long waves 4–9 and short waves 10–20.

Table 2. *The table gives relevant information about nine different prediction experiments. Two slightly different data sets have been used where the only difference between data set I and data set II is that in II satellite winds from GOES III (over the Indian Ocean) have been incorporated. It is not expected this will have noticeable influence on the experiments. In II* all satellite data (temperatures and winds) have been excluded during the data assimilation. The two vertical resolutions used are given in Table* 1 *and the two different parameterization schemes EC(a) and EC(b) are presented in Table* 8

Notation	S60	T46	T45	T16	T15	T14	T17	R47	R66
Data set	I	II	II	I	II	I	I	II	II*
Area of integration	global	global	global	global	N.H.	global	global	global	global
Horizontal resolution	P62/58/74	T63	T40	T40	T40	T21	T21	N48	N48
Vertical resolution	15	15	15	15	15	15	5	15	15
Parameterization scheme	EC(b)	EC(b)	EC(b)	EC(a)	EC(b)	EC(b)	EC(a)	EC(b)	EC(b)

P (pentagonal) and T (triangular) represent spectral resolution described in Fig. 12. N represents grid point resolution described in the text.

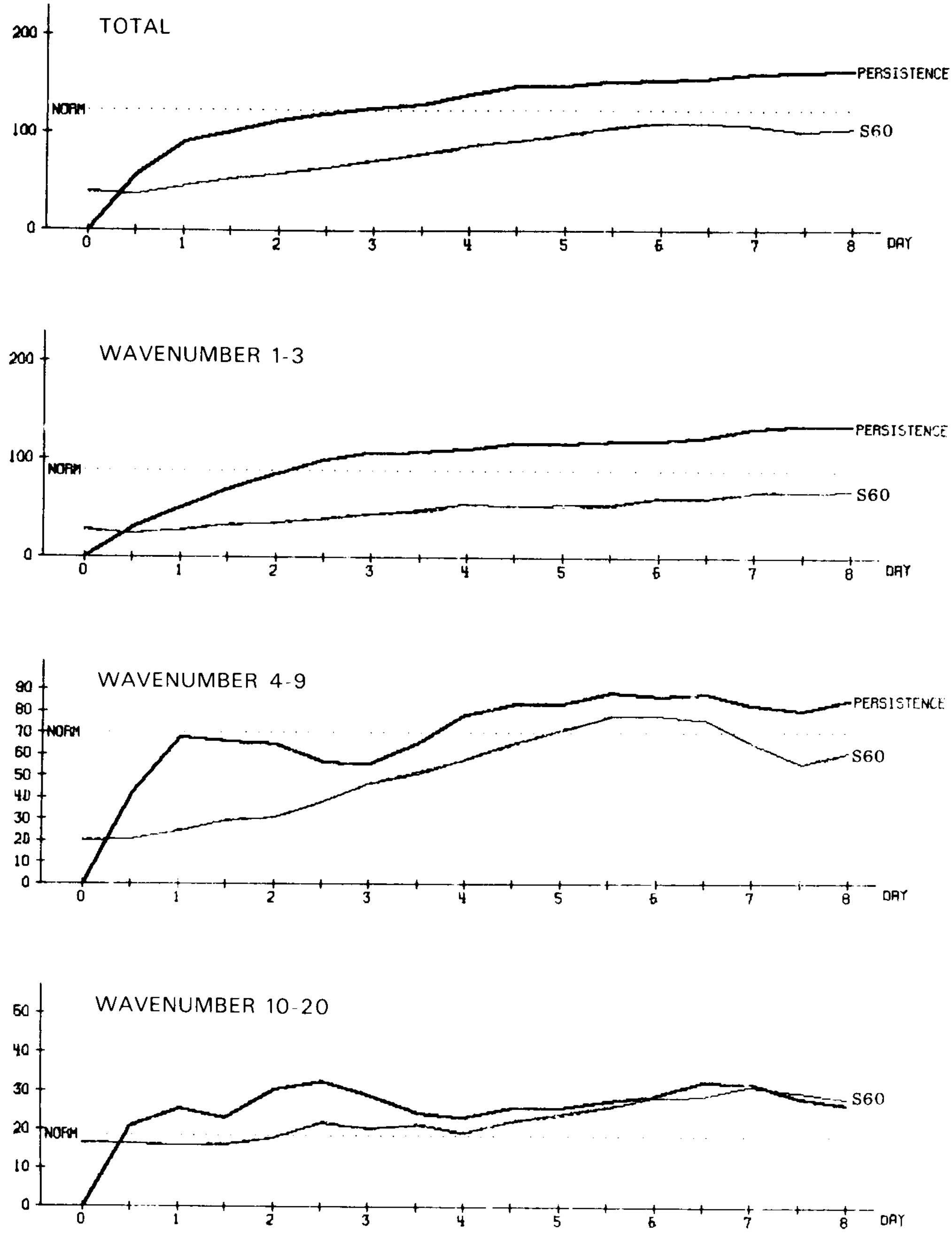

Fig. 3. Mean verification for all standard levels 1000–200 mb and 20.0–82.5 °N. R.m.s. error of height (m).

Verification is done versus NMC's operational analysis and this means that there is initially a r.m.s. difference of around 35 m. This is slightly higher than between two different analyses but the additional increase is most likely caused by vertical interpolation between σ- and p-surfaces and by normal mode initialization. The error growth is approximately linear with a doubling time of 5.5

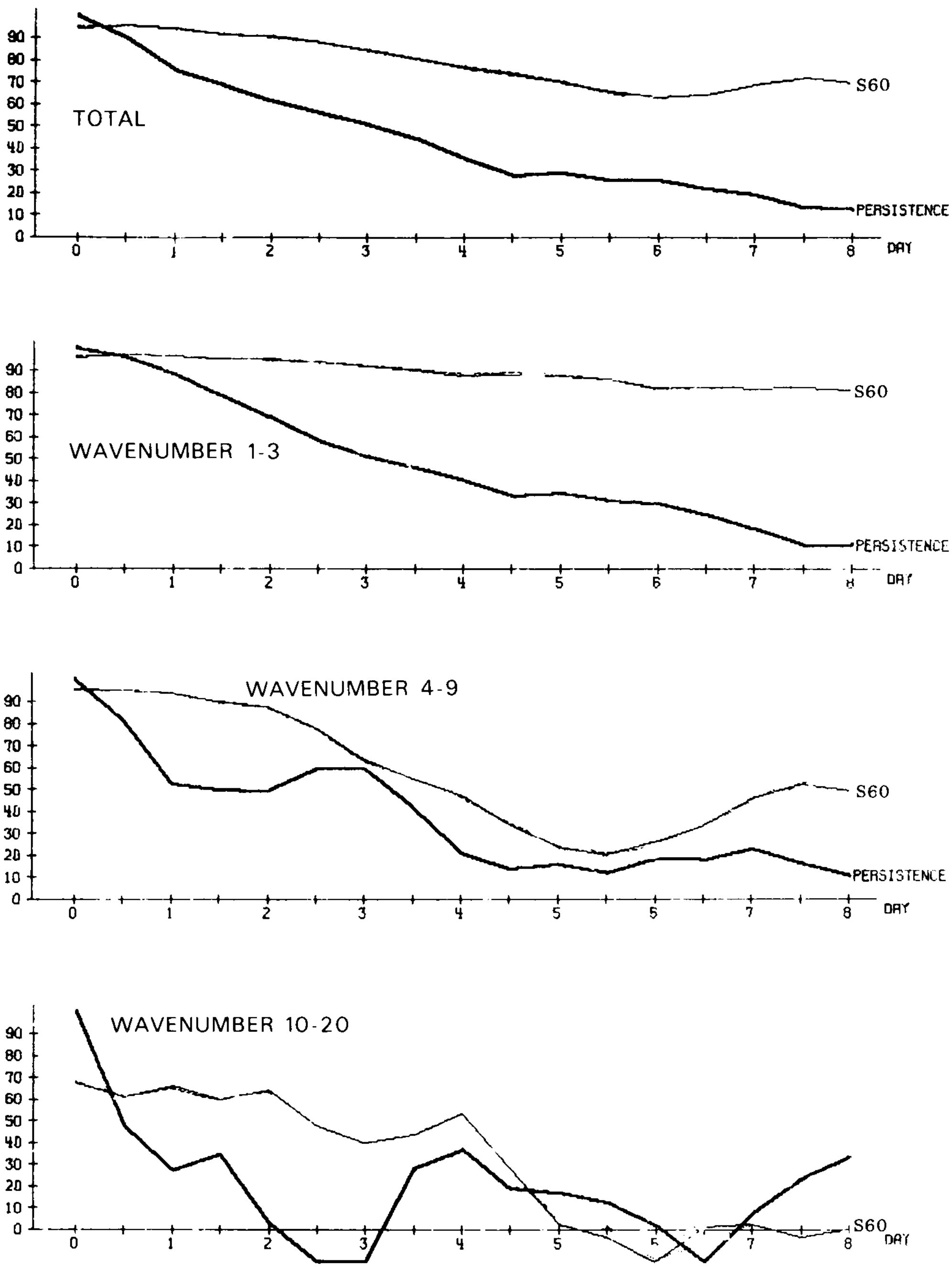

Fig. 4. Mean verification for all standard levels 1000–200 mb and 20.0–82.5 °N. Anomaly correlation of height (%).

days for the total field and almost 7 days for the long waves, assuming an exponential growth gives a very similar doubling time. This particular weather situation is characterized by very large changes. Persistence reaches the norm between 1 or 2 days for all wave components. The large changes which occur during this weather situation are the reason why we obtain the very high correlation figures, as can be seen from Fig. 4. The correlation for the long waves only drops from initially 0.95 to 0.80 after 8 days. The forecasts for 500 mb and corresponding NMC verification are presented in Fig. 5. This figure also shows the trajectory for the blocking high.

From the phenomenological point it is clearly seen that from day 4 onwards we fulfil the definition of a blocking situation. On day 8 the westerlies split into two branches around 70° W and merge again into one branch at around 10° E. This is almost in complete agreement with observations.

4.1. *Diagnostic evaluation*

It is of interest to investigate the changes in the general circulation during a forecast of this kind, and to see to what extent the model can describe the large-scale variation in kinetic and available potential energy and in the transport of momentum and heat.

Here we will only consider the energy diagnostics between the surface and 200 mb and from 20° N to 82.5° N.

There is a general decrease in the kinetic energy and increase in the available potential energy during the 8 days. The reduction in kinetic energy

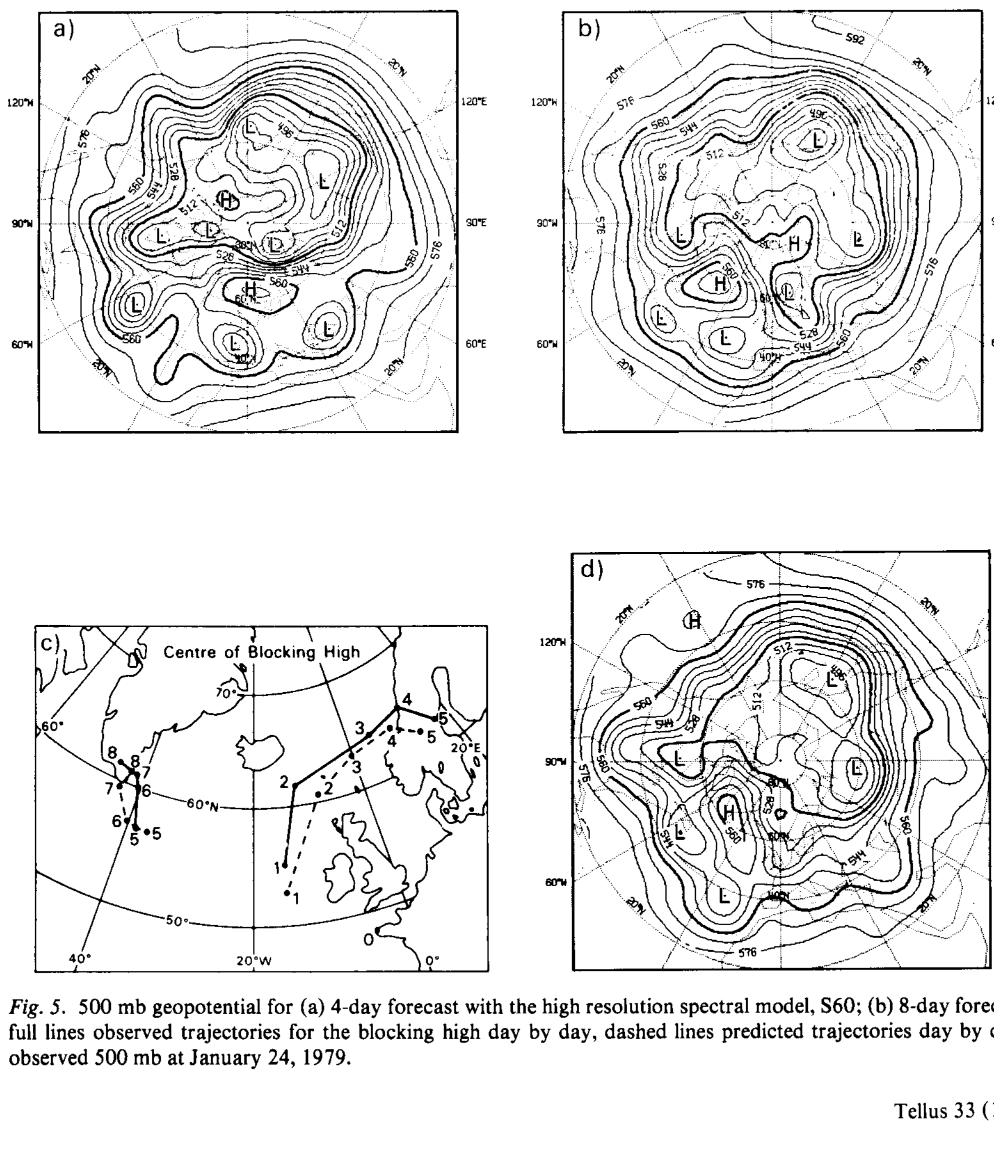

Fig. 5. 500 mb geopotential for (a) 4-day forecast with the high resolution spectral model, S60; (b) 8-day forecast; (c) full lines observed trajectories for the blocking high day by day, dashed lines predicted trajectories day by day; (d) observed 500 mb at January 24, 1979.

falls mainly in the ultra-long waves where the energy drops from 850 to 480 kJ/m^2 and in the medium-range waves where the energy drops from 560 to 430 kJ/m^2. There is a slight increase in the short waves and in the zonal part. The available potential energy increases its zonal part by 400 kJ/m^2 while the medium waves are decreased by 130 kJ/m^2. Neither long waves nor the short waves change significantly. By and large the total energy is therefore approximately conserved over the area.

The high resolution spectral model, S60, predicts these changes rather well, as can be seen from Tables 6 and 7. In general there is a slight loss in kinetic energy, particularly for the short waves. It is also clear that S60 reduces the available potential energy of the ultra-long waves by as much as 200 kJ/m^2, where, in fact, in reality the energy does not drop at all. The underestimation of kinetic energy takes place mainly around the jet stream, whilst there is a slight tendency to an overestimation in the lowest part of the atmosphere.

The transfer of available potential energy between the zonal flow and the long and medium-scale waves, respectively, is well prediced with a mean transfer $A_{zonal} \rightarrow A_{eddy}$ of 1.6–2 $W m^{-2}$ to each of the two groups. The transfer to the short waves is substantially less, 0.2–0.4 $W m^{-2}$.

It is also of interest to see how the model predicts the horizontal fluxes of momentum and heat. The observed and predicted momentum flux is shown in Figs. 6, 7 and 8 for the three groups of wave lengths and as mean values for days 1–4 and days 5–8. During the first 4 days the momentum flux is dominated by the ultra-long waves. There is a strong southward transport of momentum to the north of 55° N and a corresponding northward transport to the south of the same latitude. The model predicts this rather well, although with a slight underestimation of the southward flux. During the second 4-day period of the convergence of momentum moves further to the south to somewhere between 40 and 50° N. At the same time there is a substantial increase in the momentum flux by the medium and short waves. Observe in particular the predicted increase in the momentum transport with the short waves during the second 4-day period. It is interesting to note that the average transport by these waves is predicted for a substantially longer period than are the individual waves (Fig. 3). The model underestimates substantially the momentum flux by the long waves and Fig. 6 highlights two weaknesses of the model, namely

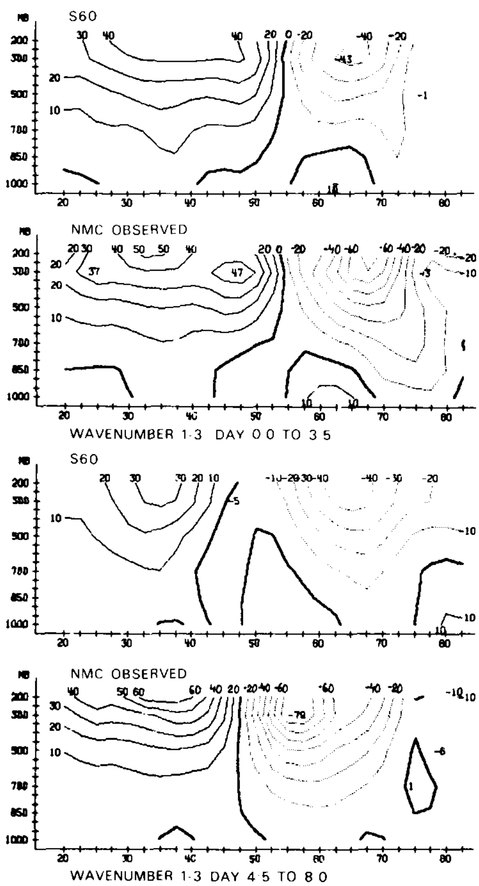

Fig. 6. Vertical cross section of predicted and observed momentum flux calculated from the geostrophic wind. Positive values northward momentum transport, negative values southward momentum transport. Upper part gives the average for the first 4 days and the lower part of the average for the second 4 days. Unit m^2/s^2.

(i) the underestimation of the northward momentum flux from the subtropics, which is very likely connected to an unsatisfactory treatment of the convective processes in the tropics, and

(ii) an underestimation of the amplitude of the long waves with corresponding reduction in the capacity of the transport of momentum.

The prediction of temperature is very satisfactory and clearly better than the momentum

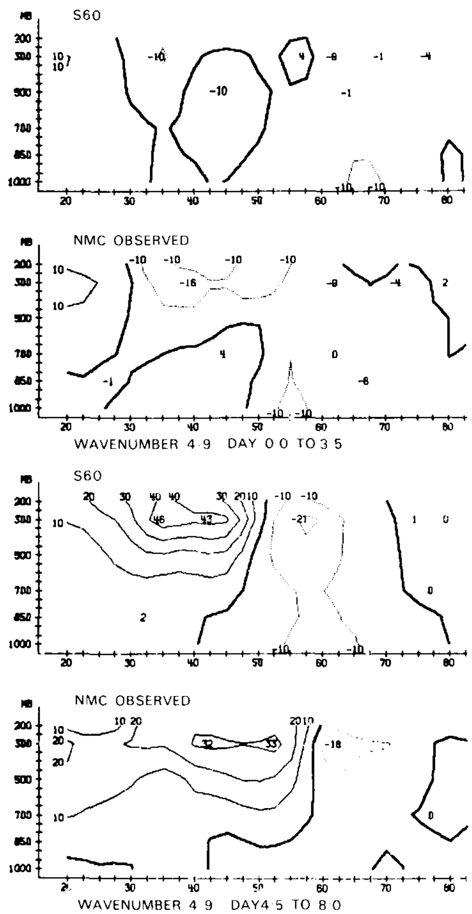

Fig. 7. The same as Fig. 6 but for wave numbers 4–9.

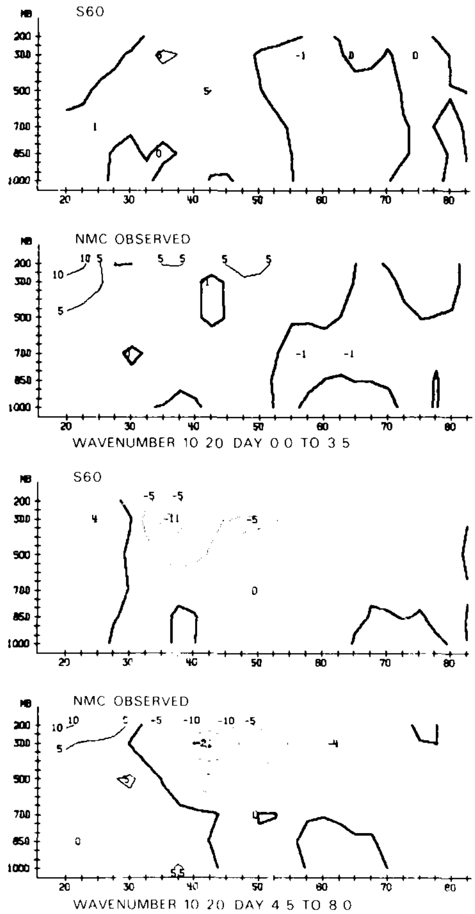

Fig. 8. The same as Fig. 6 but for wave numbers 10–20.

forecasts. Only a slight cooling tendency is obtained reaching a maximum of 2° C in the upper troposphere. Also the horizontal heat fluxes are more satisfactorily predicted (Figs. 9 and 10). Observe the dual maximum in the vertical during the first 4 days. The only substantial difference during the second period is that the long waves have their maximum transport around 8° to the north compared with the observed states. The transport of sensible heat with the short waves is insignificant and is not shown here.

The reason that we have a satisfactory transport of sensible heat with the long waves in spite of an underestimation of the amplitude must be due to the fact that these waves are predicted to have a somewhat larger tilt through the troposphere.

A very detailed evaluation of the phase and amplitude prediction of individual waves and groups of waves shows nothing of particular interest. It is found that the individual components of the largest spherical harmonics are very well predicted and show no tendency to have an erroneous retrograde motion previously observed in many models. Fig. 11 shows the harmonic dials for the wave components $M = 1, N = 1$; $M = 1, N = 3$ and $M = 1, N = 5$.

5. Results from other models

In view of the very high predictability obtained in this particular case, it is scientifically very interesting to use this example for a numerical experimental investigation of predictability. We will

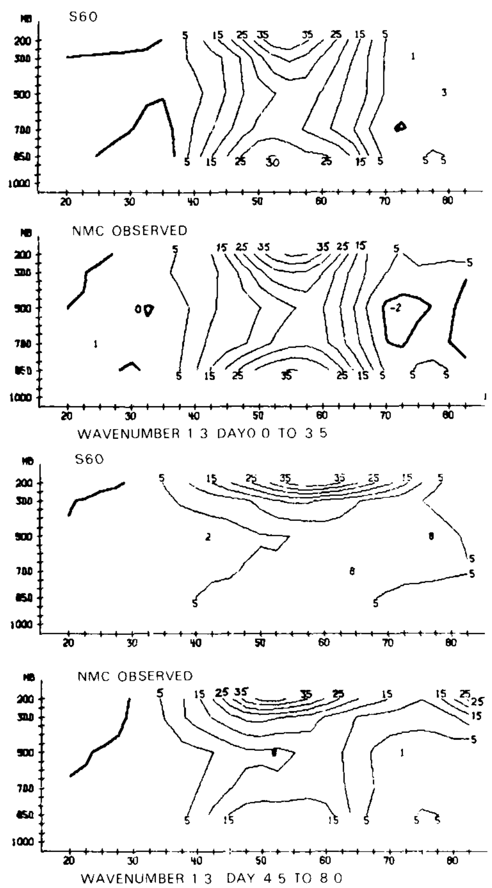

Fig. 9. Vertical cross section of predicted and observed sensible heat flux for wave numbers 1–3 and calculated from the geostrophic wind. Positive values northward transport. Upper part gives the average for the first 4 days and the lower part the average for the second 4 days. Unit °Km/s.

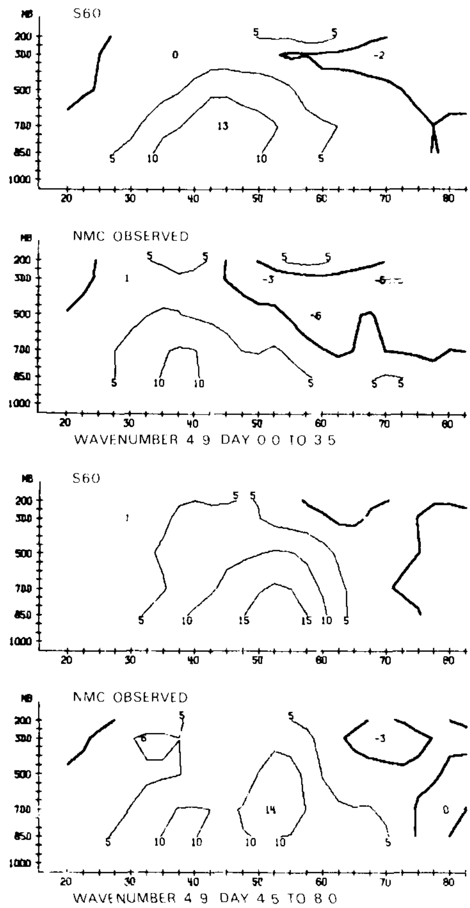

Fig. 10. The same as Fig. 9 but for wave numbers 4–9.

therefore apply the reverse methodology compared to what has been done previously. Instead of investigating successively more accurate numerical calculations or more realistic and sophisticated algorithms for the parametrization of the physical processes, as well as better initial data, we will do the reverse. We will systematically simplify the high resolution model and investigate to what extent this will *reduce predictability* in general and the predictability of the blocking episode in particular.

We will investigate the predictability in this case as a function of

(i) resolution,
(ii) the integration domain,
(iii) the parameterization,
(iv) the intial data.

Finally, we will briefly comment on the predictability of some very simple models. The different experiments are summarized in Table 2.

We have been trying to carry out these experiments in as stringent a manner as possible, but for some practical reason two slightly different data sets have been used (see Table 2). It is not expected that this will have had any influence on the results and it will certainly not affect our conclusions. Two smaller errors in the programs were found after the experiments were finalized.

The satellite temperatures obtained a smaller weight than they should have had (the thickness errors were assumed to be three times as large) and

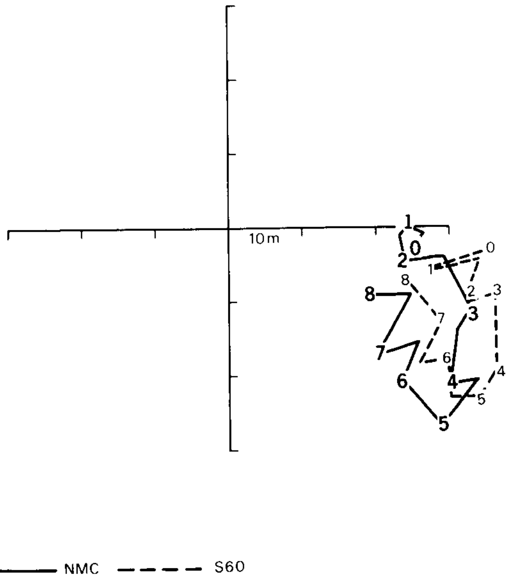

Fig. 11a. Harmonic dial for 500 mb height field spherical harmonic coefficient $M = 1$, $N = 1$. Initial time (day 0), January 16, 1979, unit: 10 m. Numbers are the time in days from the initial time. NMC shows the verified harmonic coefficient.

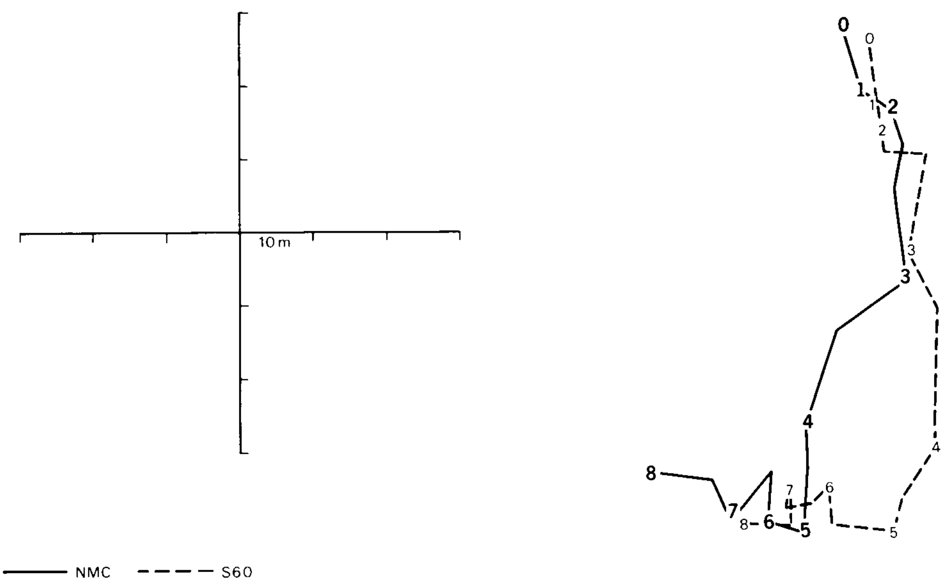

Fig. 11b. The same as Fig. 11a, but for the component $M = 1$, $N = 3$.

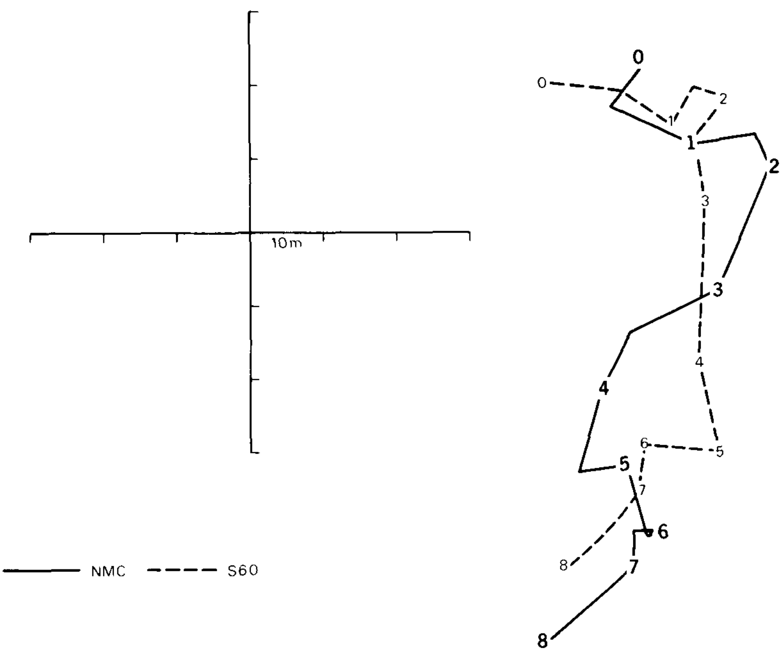

Fig. 11c. The same as Fig. 11a, but for the component $M = 1, N = 5$.

the humidity was slightly underestimated. Since these errors were made in all the experiments, they will not affect our comparisons, except for the experiments with and without satellite data. The major differences in that comparison are therefore caused by the satellite winds.

In evaluating the different experiments we will concentrate on the way the particular blocking phenomenon is being predicted. We will also present some general statistics (r.m.s. and correlation coefficient stratified in different wave number domains).

5.1. *Resolution experiments*

In this sub-section we will describe six different resolution experiments. One, the intergration, is an N48 resolution grid point model (48 grid points between pole and equator), the others are spectral models with different resolutions (Fig. 12).

Tables 3 and 4 show the r.m.s. and the anomaly correlation for every second day for the total field as well as for the long waves. It can be seen that the predictability is being reduced when the resolution is decreased, also that there is very little difference in the accuracy of the three models with the highest resolution. Another interesting observation is the great similarity between the high resolution spectral integration and the grid point integration. This is illustrated in Table 5 which shows that the

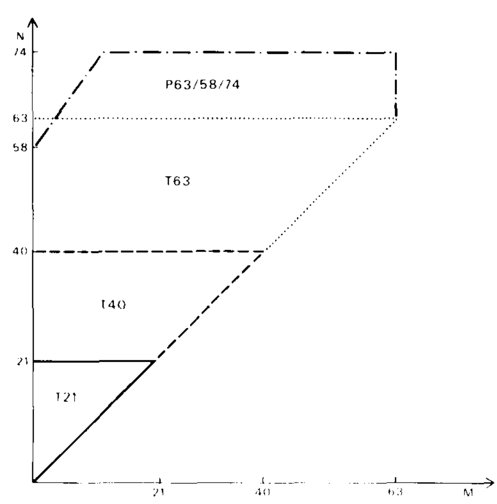

Fig. 12. Five different spectral resolutions. The size of the area is proportional to the number of degrees of freedom for each resolution.

Table 3. *Table gives r.m.s.- error for the height field (1000–200 mb and 20° N–82.5° N) for every second day. Unit m. The error is given for the total field and for the long waves (wave numbers 1–3) separately. The climatological variance (norm) is 89 m for the long waves and 122 m for the total field. Verification has been carried out vs NMC operational analyses. The initial "error" is 33 m for the total field and 22 m for the long waves*

Notation of experiment	Model specification	Day 2		Day 4		Day 6		Day 8	
		Total	1–3	Total	1–3	Total	1–3	Total	1–3
R47	Grid point N48-L15	53	33	75	50	105	50	100	67
S60	Spectral P63/ 58/74-L15	53	33	83	50	111	58	100	67
T46	Spectral T63-L15	53	33	78	50	111	56	100	68
T45	Spectral T40-L15	53	33	78	50	111	56	114	67
T14	Spectral T21-L15	64	42	97	67	111	61	117	78
T17	Spectral T21-L5	78	44	119	78	139	94	164	111

Table 4. *The same as for Table 3, but for the correlation coefficient (anomaly correlation)*

Notation of experiment	Model specification	Day 2		Day 4		Day 6		Day 8	
		Total	1–3	Total	1–3	Total	1–3	Total	1–3
R47	Grid point N48-15	0.91	0.95	0.81	0.89	0.68	0.88	0.70	0.80
S60	Spectral P63/ 58/74-L15	0.93	0.95	0.75	0.88	0.65	0.86	0.69	0.84
T46	Spectral T63-L15	0.91	0.95	0.79	0.89	0.65	0.84	0.69	0.85
T45	Spectral T40-L15	0.91	0.95	0.78	0.89	0.60	0.83	0.53	0.75
T14	Spectral T21-L15	0.85	0.93	0.66	0.78	0.54	0.75	0.44	0.64
T17	Spectral T21-L5	0.84	0.91	0.58	0.66	0.40	0.49	0.35	0.42

Table 5. *Table gives r.m.s.- differences for the total field, wave numbers 1–3 and wave numbers 4–9 for three different intercomparisons (see text). Unit m. All the models have the same vertical resolution. The variance for wavenumbers 4–9 is 70 m. See further Table 3*

Notation of experiment	Day 2			Day 4			Day 6			Day 8		
	Total	1–4	4–9	Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9
N48 vs. T63	17	8	8	33	22	19	55	36	30	78	58	41
T63 vs. T40	19	11	11	50	31	27	81	47	48	97	60	55
P63/58/74 vs. T21	61	39	37	100	71	56	106	64	76	122	82	86

difference between N48 and T63, even after 4 days, is not larger than the initial difference between the ECMWF and NMC analyses. On the other hand the differences between the highest and the lowest spectral resolution grow fast, and from 2 days onward *this difference is greater than the actual r.m.s. error for the high resolution integration.* Consequently the high resolution integration stays closer to reality through the whole 8-day integration than the low resolution to the high resolution.

Tables 6 and 7 show the variation of kinetic energy and available potential energy in time. All models under-predict the kinetic energy, although the error is rather small for the grid point model. The under-prediction of kinetic energy can be seen for all wave components, particularly for the long waves. The values in the tables are spot values, and some small fluctuations affect the results.

The models also underestimate the available potential energy, in particular the available potential energy of the long waves. This underestimation becomes successively worse with reductions in the resolution.

The prediction of the blocking high also shows successive deterioration as resolution is being reduced. However, the prediction of the blocking phenomenon is qualitatively correct for all models in the sense that we predict the initial easterly movement of the block followed by a re-establish-

Table 6. *Table 6 gives the observed and predicted kinetic energy for every second day for the total field and for the long waves (wave numbers 1–3) and medium waves (wave numbers 4–9) separately. The 1000–200 mb and from 20° N–82.5° N. Units 10 kJ m^{-2}*

		Day 0 observed			Day 2			Day 4			Day 6			Day 8		
		Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9
Notation of experiment	Observed NMC	278	85	56	258	65	45	267	59	53	254	56	52	250	48	43
R47	Grid point N48-L15				242	60	40	246	61	37	242	45	47	242	43	40
S60	Spectral P63/58/74-L15				246	60	43	246	59	43	233	50	39	216	39	33
T46	Spectral T63-L15				242	60	43	242	55	44	225	45	37	213	36	30
T45	Spectral T40-L15				233	57	39	233	55	38	213	37	33	217	32	28
T14	Spectral T21-L15				229	58	37	229	53	38	196	32	35	200	28	39

Table 7. *Same as Table 6, but for available potential energy (integrated between 850–200 mb)*

		Day 0 observed			Day 2			Day 4			Day 6			Day 8		
		Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9	Total	1–3	4–9
Notation of experiment	Observed NMC	400	78	32	431	79	28	444	85	24	424	86	23	444	79	21
R47	Grid point N48-L15				400	64	24	405	69	21	417	65	23	444	60	21
S60	Spectral P63/58/74-L15				396	60	20	389	69	21	396	65	16	431	53	18
T46	Spectral T63-L15				396	63	23	389	69	21	403	55	18	424	48	24
T45	Spectral T40-L15				382	61	24	382	66	21	403	59	18	403	48	21
T14	Spectral T21-L15				375	55	23	361	55	22	375	50	18	368	45	21

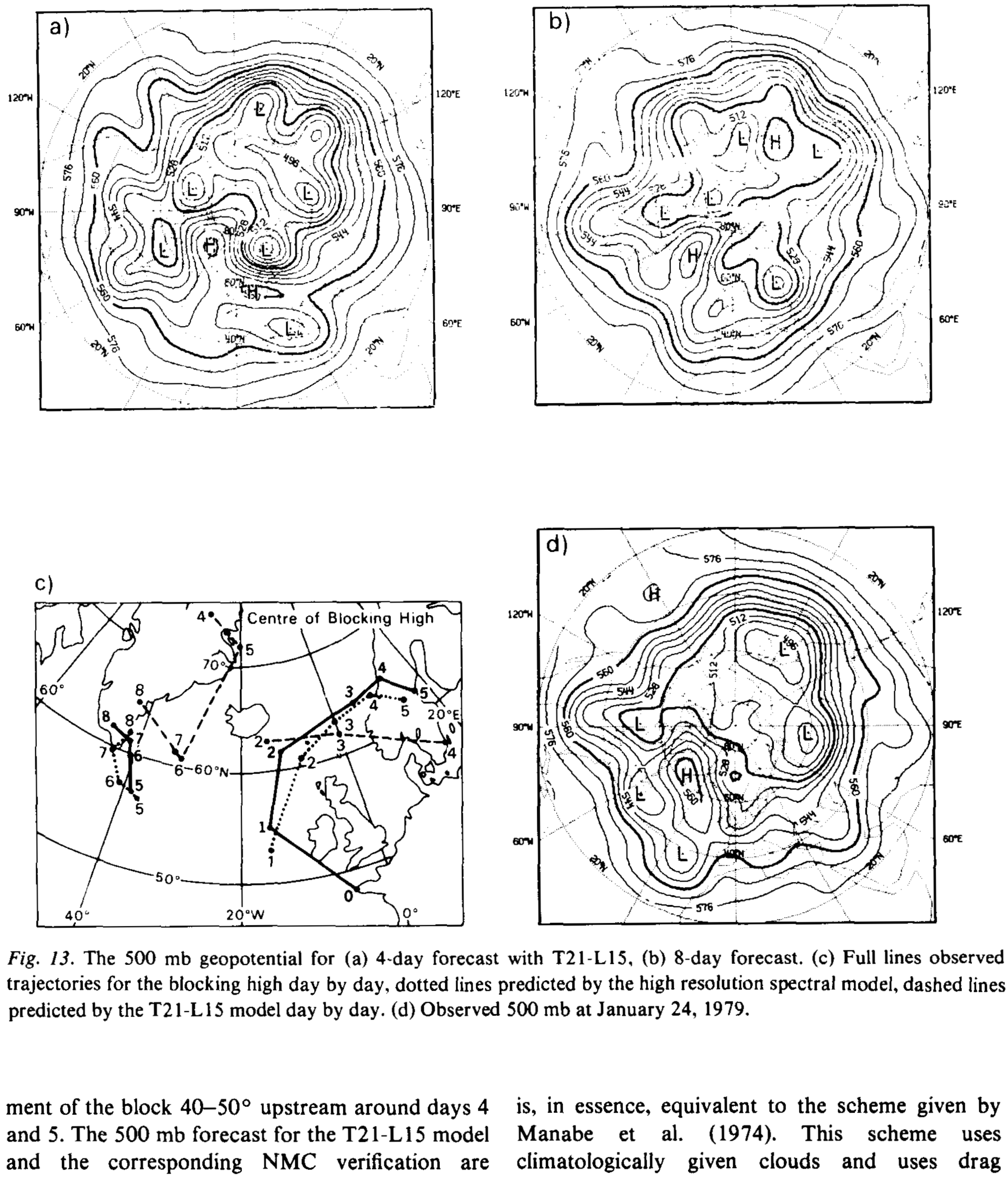

Fig. 13. The 500 mb geopotential for (a) 4-day forecast with T21-L15, (b) 8-day forecast. (c) Full lines observed trajectories for the blocking high day by day, dotted lines predicted by the high resolution spectral model, dashed lines predicted by the T21-L15 model day by day. (d) Observed 500 mb at January 24, 1979.

ment of the block 40–50° upstream around days 4 and 5. The 500 mb forecast for the T21-L15 model and the corresponding NMC verification are presented in Fig. 13. This figure also shows the trajectory for the blocking high.

5.2. *Parameterization experiment*

The parameterization experiment has been done by comparing two different parameterization schemes. These schemes are given in Table 8. The first of the schemes, EC(a), uses a parameterization developed for climate simulations and is, in essence, equivalent to the scheme given by Manabe et al. (1974). This scheme uses climatologically given clouds and uses drag coefficients independent of stability and friction height. The second scheme, EC(b), is the one developed for the ECMWF operational model and described by Tiedtke et al. (1979). Scheme EC(b) has been used for all the other experiments described in this study and is also being used operationally at ECMWF. A more extensive comparison between these two schemes has been published by Hollingsworth et al. (1979).

Table 8. *Survey of the parameterization schemes*

Process (Large-scale condensation)	EC(a) (Condensation if relative humidity exceeds 80%)	EC(b) (Condensation if relative humidity exceeds $U = 0.8 + 0.2e^{-7.0(1-\sigma)}$. Evaporation of rain)
Convection		
Dry convection	Dry convective adjustment	Mixing by vertical diffusion of sensible heat, moisture and momentum
Moist convection	Moist adiabatic adjustment	Deep convection by Kuo convection scheme
Turbulent motion		
Horizontal diffusion	Non-linear, fourth order in space	Non-linear, fourth order in space
Vertical surface	$F_x = C_d(V_n)(X_h - X_s)$ $C_d = \text{const.}$	$F_x = C_d(V_h)(X_h - X_s)$ $C_d = C_d\left(R_i, \frac{h}{z_0}\right)$ (R_i = Richardson number)
Vertical fluxes above surface layer	Vertical diffusion assuming $K = K(z)$	Vertical diffusion assuming $K = K(R_i, l)$ and $l = l(z)$
Radiation	Absorber: Zonal means of H_2O, CO_2, O_3, clouds (specified from climatology at three levels)	Feedback between moisture (clouds) and radiation
Surface values		
T_s Ocean	Prescribed	As in EC(a)
T_s Land	Diagnosed (energy balance equation)	Predicted
Soil moisture	Predicted	As in EC(a)
Snow	Predicted	As in EC(a)

Table 9 summarizes the result from the parameterization experiment. It is found that scheme EC(b) is superior in this case, while in the comparison by Hollingsworth et al. (1979) only a very small improvement could be noticed. The error growth is much faster for EC(a), in particular the long waves have a much faster error growth. Both the kinetic and available potential energy fall off faster with time for this parameterization scheme, particularly the available potential energy. The most likely explanation for this is the use of a climatological distribution of clouds in EC(a) which in a case of blocking will have a more harmful effect because on this occasion we have a very large deviation from climatology.

The prediction of the blocking high is also less favourable, in particular towards the end of the 8-day period where the blocking cell is successively filled out. The model is slowly working towards the more probable climatological state. The 500 mb forecast for the T40-L15 with EC(a) is shown in Fig. 14 together with the corresponding NMC verification. This figure also shows the trajectories for the blocking high.

5.3. *The effect of an equatorial boundary*

The effect of an equatorial wall has been investigated by Miyakoda (1973) and Baumhefner (1972). Arpe et al. (1977) have also carried out a study where the analysis at the southern hemisphere was replaced by climatology. These studies show that there is an observable effect after 3–4 days which quickly grows to a substantial value beyond 7–8 days. The effect of the equatorial wall or of the lack of data at the southern hemisphere spreads in a very complicated way and after 7–8 days the largest errors are found in areas where the meteorological activity is most intense. Even if the previous forecasts differed substantially after 7–8 days, compared to reality their errors were about the same.

In this particular case we have the unique possibility of studying the effect of a meteorological situation were we have found very high predictability. In this situation, since we are using FGGE level III-b data, we have also substantially better data at the southern hemisphere.

Recently Somerville (1980) found that a boun-

Table 9. *R.m.s. (m) and correlation coefficient for the total field (1000–200 mb and 20° N–82.5° N) for every second day for the two parameterization schemes. The error is given for the total field and for the long waves (wave numbers 1–3) separately. The table also gives the corresponding values for predicted kinetic energy and available potential energy. Same units as in Tables 6 and 7*

T40–L15 parameterization EC(a)

	Day 2		Day 4		Day 6		Day 8	
	Total	1–3	Total	1–3	Total	1–3	Total	1–3
R.m.s.	62	38	88	59	121	83	128	93
Correlation coefficient	0.89	0.94	0.71	0.81	0.46	0.62	0.37	0.50
Kinetic energy	240	56	228	44	208	35	212	32
Available potential energy	360	51	347	52	353	52	353	40

T40–L15 parameterization EC(b)

	Day 2		Day 4		Day 6		Day 8	
	Total	1–3	Total	1–3	Total	1–3	Total	1–3
R.m.s.	53	33	78	50	111	56	114	67
Correlation coefficient	0.91	0.95	0.78	0.89	0.60	0.83	0.53	0.75
Kinetic energy	233	57	233	55	213	37	217	32
Available potential energy	382	61	382	66	403	59	403	48

dary at the equator reduces the predictability of the long waves. The long waves are likely to be affected first because of their dimensions and high group velocities. It is also likely that the effect will vary from case to case due to the flow configuration at the boundary. For this particular case the effect was considerable and as can be seen from Table 10 the long waves were already noticeably influenced after 2 days. As can be seen from Fig. 15 the effect on the block is relatively small, although the behaviour at the end of the prediction differs considerably.

5.4. *The effect of initial data*

An alternative data set was obtained from a parallel data assimilation experiment which also started from January 13, 1979, and from climatology. From this assimilation sequence all satellite temperatures as well as satellite winds were eliminated. This case has been studied elsewhere (Bengtsson, 1979) and here we will only summarize the result in Table 11 and Fig. 16. Because a too high error was assigned to the satellite temperatures (4–6°), this impact study essentially measured the impact of satellite winds.

6. Experiments with quasi-geostrophic models

It may be of some interest to carry out some experiments with a few other and much more simple models to see their prediction performance in a case like this. Fig. 17 summarizes the 4-day prediction with a barotropic model (with and without a free upper surface) as well as prediction by a quasi-geostrophic model. The quasi-geostrophic prediction in the operational forecast by the Swedish Meteorological and Hydrological Institute six-layer model is based on operationally received data (for a model description see Moen, 1975). The horizontal resolution for the barotropic models was 381 km and for the quasi-geostrophic model 300 km at 60° N, respectively. The integration domain extends in both cases to 20° N.

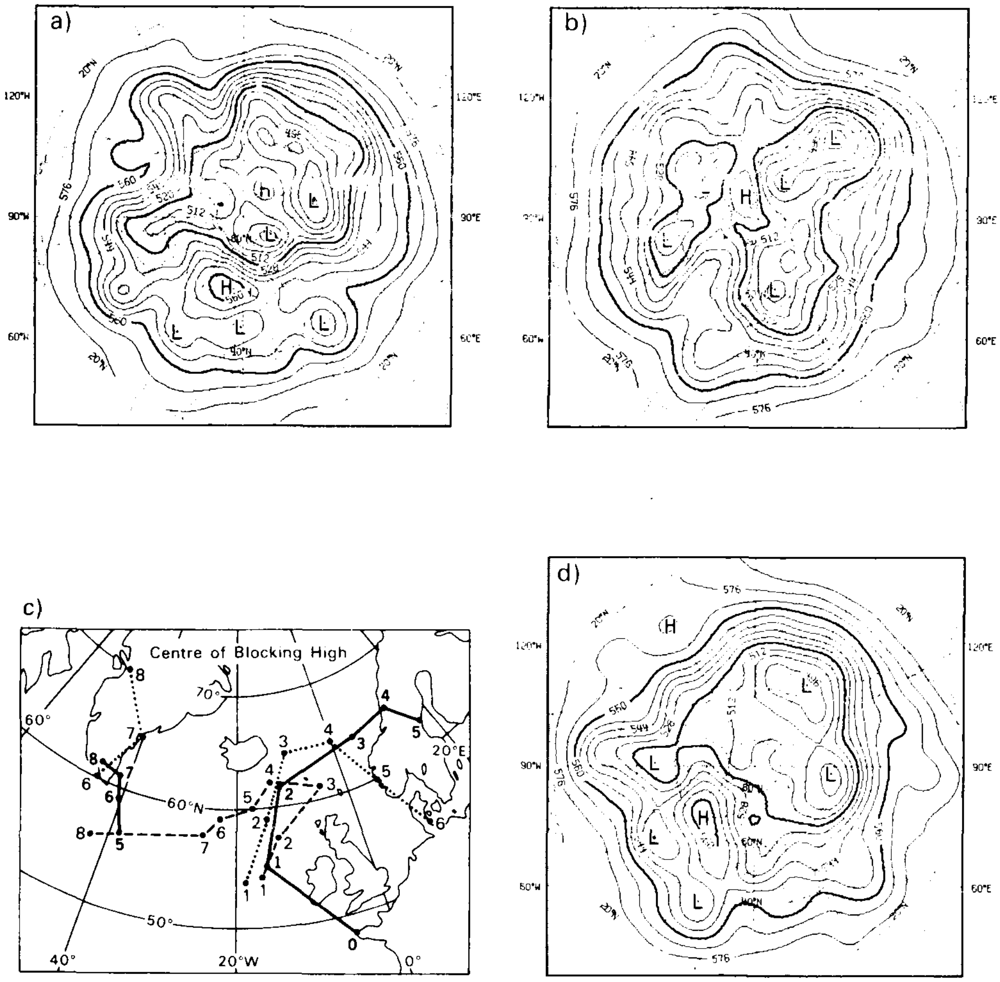

Fig. 14. The 500 mb geopotential for (a) 4-day forecast with EC(a), (b) 8-day forecast with EC(a). (c) Full lines observed trajectory for the blocking high day by day, dotted lines predicted by EC(b), dashed lines predicted by EC(a). (d) Observed 500 mb at 24 January, 1979.

Table 10. *R.m.s. and correlation coefficient for the total field (1000–200 mb and 20° N–82.5° N) for every second day. The error is given for the total field and for the long waves (wave numbers 1–3) separately. Results are given for a global integration (top) and a northern hemispheric integration (bottom)*

Notation of experiment	Model specification	Day 2		Day 4		Day 6		Day 8	
		Total	1–3	Total	1–3	Total	1–3	Total	1–3
T45	T40-L15	53	33	78	50	111	56	114	67
	global	0.91	0.95	0.78	0.89	0.60	0.83	0.53	0.75
T15	T40-L15	61	44	94	67	114	69	117	78
	N.H.	0.89	0.91	0.71	0.78	0.53	0.70	0.53	0.65

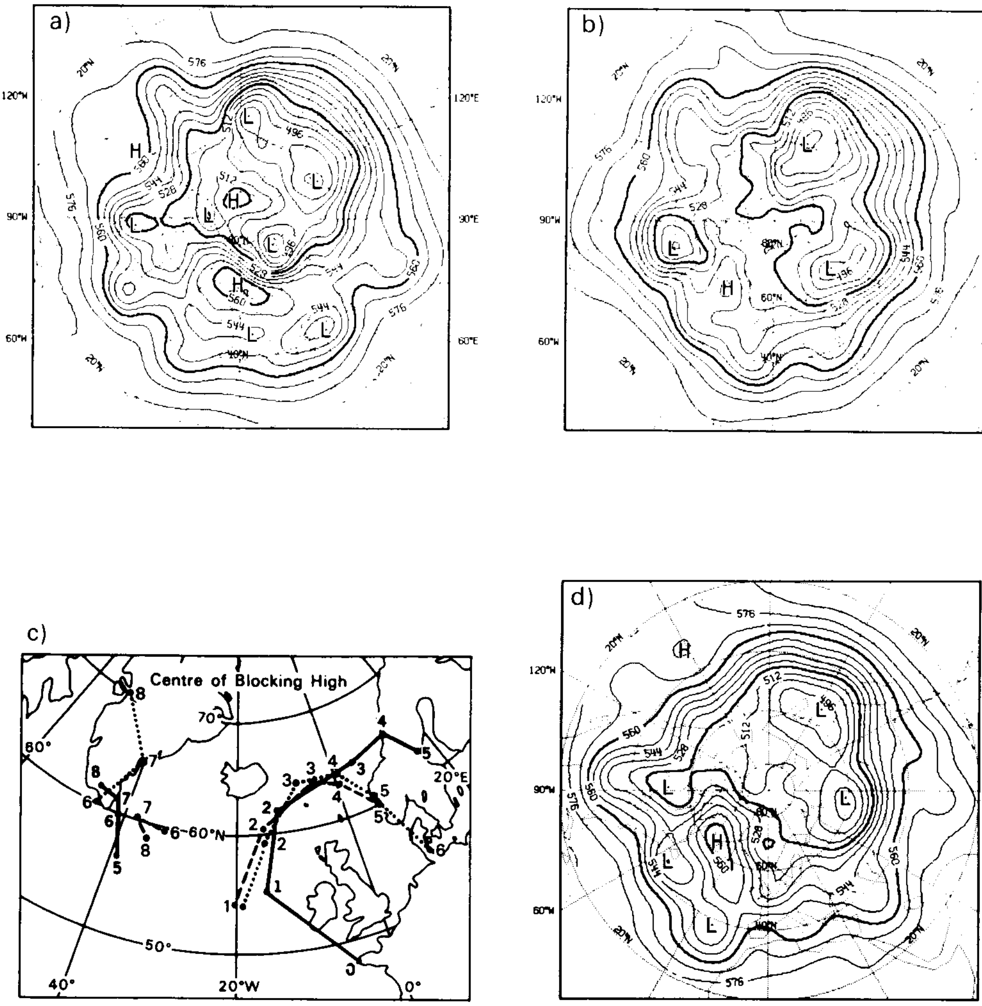

Fig. 15. The 500 mb geopotential for (a) 4-day forecast with hemispheric model, (b) 8-day forecast with hemispheric model. (c) Full lines observed trajectories for the blocking high day by day, dotted lines predicted by the global model, dashed lines predicted by the hemispheric model. (d) Observed 500 mb at January 24, 1979.

Table 11. *R.m.s. error and correlation coefficient. For further explanation see Table 3*

Model specification	Day 2		Day 4		Day 6		Day 8	
	Total	1–3	Total	1–3	Total	1–3	Total	1–3
N48–L15	53	33	75	50	105	50	100	67
SAT	0.91	0.95	0.81	0.89	0.68	0.88	0.70	0.80
N48–L15	59	36	89	64	116	64	117	74
NOSAT	0.89	0.94	0.74	0.83	0.60	0.78	0.58	0.71

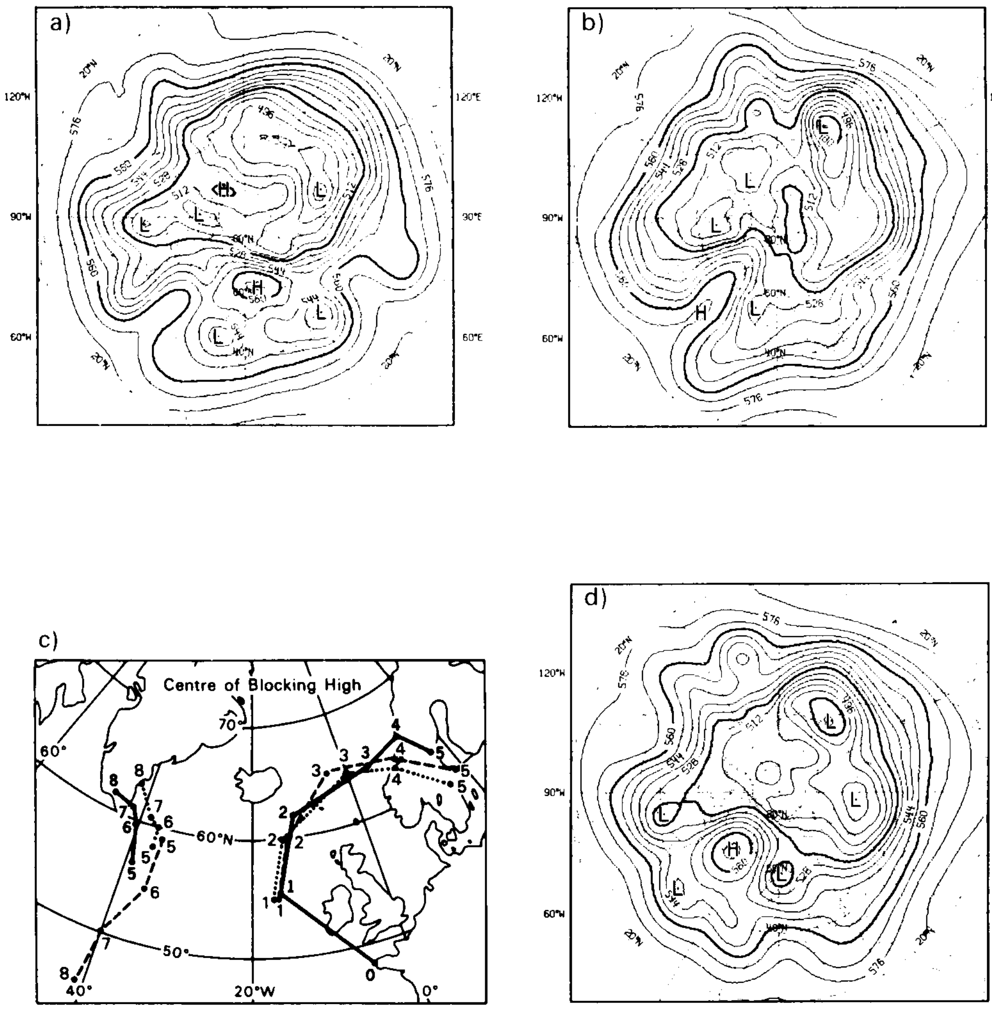

Fig. 16. The 500 mb geopotential for (a) 4-day forecast with the NOSAT model, (b) 8-day forecast with the NOSAT model. (c) Full lines observed trajectories for the blocking high day by day, dotted lines predicted by the SAT model, dashed lines predicted by the NOSAT model. (d) 8-Day forecast with SAT model.

The 500 mb geopotential is given for day 4 together with the trajectories for the blocking high (Fig. 17). It is not very likely that the differences in data would be significant during the first 4 days while the differences between these forecasts and the reference integrations in Section 4 are due to model differences and that different integration domains have been used.

No one would dispute that progress has been made in NWP since the first numerical forecasts were made with the barotropic model some 30 years ago. In spite of the fact that quasi-geostrophic models can still be quite good for short-range forecasts, the effort and work which has gone into the design of high resolution primitive models has certainly been worth while.

7. Conclusion

It is difficult for many reasons to draw firm conclusions for a study which is as limited as this.

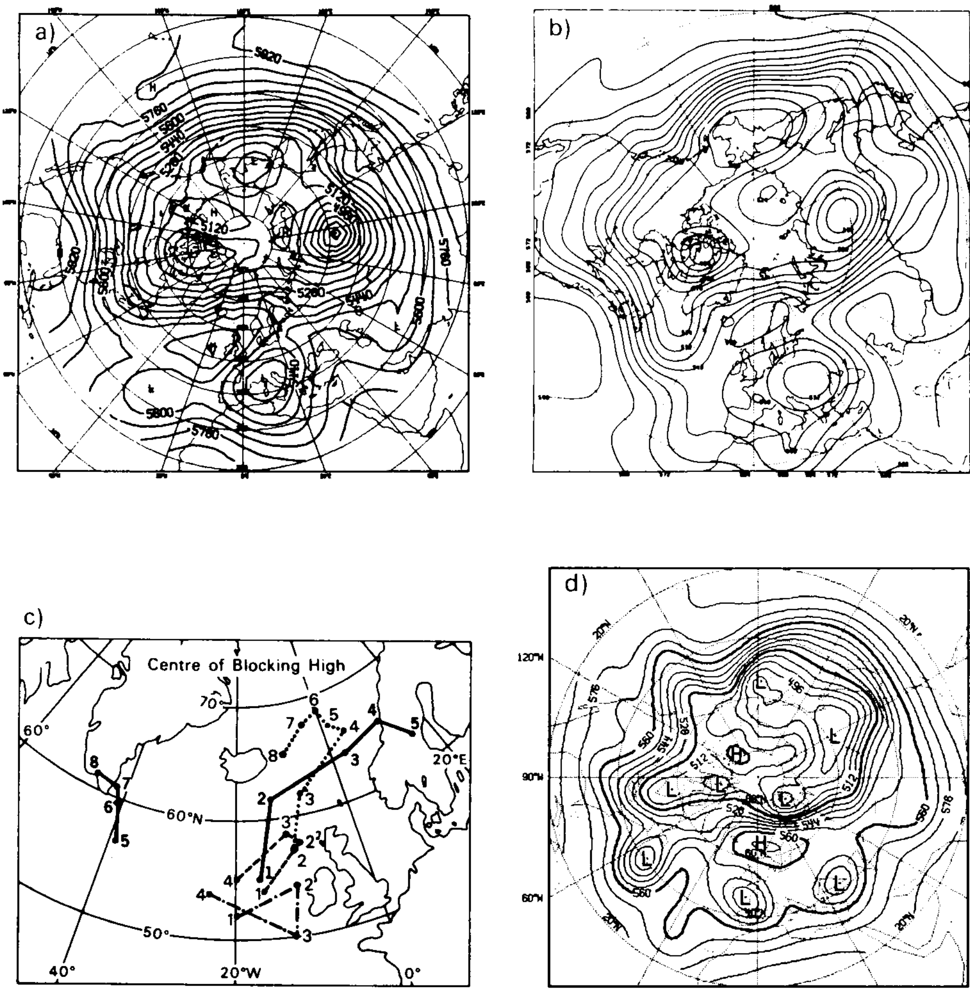

Fig. 17. The 500 mb geopotential for (a) 4-day forecast with the barotropic model (with an upper free surface), (b) 4-day forecast with the Swedish Meterological and Hydrological Institute's six-layer quasi-geostrophic model. (c) Full lines observed trajectories for the blocking high day by day, dotted lines predicted by the baroclinic quasi-geostrophic model, dashed lines predicted by the garotropic model with a free surface, dash-dotted lines predicted by the baroclinic model with a fixed surface. (d) 4-Day forecast with high resolution grid point model. For verification see Fig. 2b.

However, the result of the study is positive in the sense that efforts in improving both the data, parameterization and numerical resolution all have a positive impact on predictability. There is no hesitation either by inspecting results by simpler models that all efforts which have gone into improving numerical weather prediction through the years have been worth while. As far as the prediction of blocking is concerned, the following remarks can be made:

(i) The result of this study further supports the hypothesis that the forecast error growth is generally smaller in a blocking situation than in predominantly zonal circulation.

(ii) We can be cautiously optimistic about the predictability of significant large-scale weather episodes such as blocking on a time scale of 10 days.

(iii) It seems clear, although even very simple systems can produce flow patterns which remind of blocking, that we need a high resolution model with realistic parameterization in order to obtain useful predictability of blocking on a time scale greater than 5 days.

(iv) The results from the resolution experiment suggest that the interaction between travelling small-scale eddies and the quasi-stationary systems are essential for the blocking phenomenon, and models badly describing such interactions can possibly only give a very crude picture about the real phenomenon.

(v) There is no necessary increase in the long waves during blocking, in fact in this particular case the amplitudes of the ultra-long waves were reduced by as much as 40% during the build-up of the blocking pattern.

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ЧИСЛЕННОЕ ПРЕДСКАЗАНИЕ АТМОСФЕРНОГО БЛОКИРОВАНИЯ. АНАЛИЗ КОНКРЕТНОГО СЛУЧАЯ

Для изучения предсказуемости атмосферного блокирования на примере случая, имевшего место во время первого наблюдательного периода ПГЭП, использовался ряд численных моделей. В эксперименте использовались данные ПГЭП уровня 2-б. Блокирование имело место над Северной Атлантикой и является весьма характерным примером нитенсивного зимнего блокирования. Найдено, что модели ECMWF с очень большим разрешением замечательным образом предсказывают процесс блокирования в деталях, даже при заблаговременности более одной недели. Хотя модели с грубым разрешением предсказывают блокирование как таковое, его фактическая эволюция сильно отличается от наблюдаемой и поэтому практическая ценность прогноза существенно снижается. Показано, что наблюдения ветра с геостационарных спутников существенно влияют на прогноз более чем на 5 дней, так же как и расширение области интегрирования до глобальных пределов. Квазигеострофические бароклинные модели и в еще большей степени баротропные совершенно не способны предсказывать блокирование за исключением его начальной стадии. Прогностический эксперимент ясно проиллюстрировал, что усилия по улучшению численных моделей прогноза за последние десятилетия стоили проделанных затрат.