Dynamical Prediction of the Arctic Circulation

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(Manuscript received June 9, 1959)

Abstract

The results of a series of experimental forecasts of the 500 and 1,000 mb flow patterns over the Arctic during January 1956 are discussed. The forecasts were made by integrating graphically the equations of a simple baroclinic mode. A summary of the performance of the model and an analysis of the errors are presented; some characteristics of the Arctic circulation are deduced from these error patterns. In general, the results suggest that the model is capable of producing useful forecasts over the Arctic.

1. Introduction

In a previous article (ESTOQUE, 1957) the writer presented a graphically integrable baroclinic model. The results of 24-hour 500 and 1,000 mb forecasts showed encouraging results over the eastern part of the United States and Canada. Nevertheless, certain systematic errors were apparent, one example of which was a tendency to overpredict anticyclogenesis behind a cyclone. This report presents the result of an application of the model to the specific problem of the arctic circulation.

Dynamical forecasts obtained by either numerical or graphical integration techniques still appear to be inferior, on the average, to those made by ordinary subjective methods. Further experimental forecasts are, therefore, desirable so that the nature of the errors may be determined, and approximate corrective measures introduced. Moreover, if one examines these errors in relation to the assumptions made in deriving the model, one can deduce some characteristics of the actual atmosphere. These two interesting topics will be considered in the light of the results of this series of forecasts for the arctic atmosphere; in addition, the overall performance of the method will be discussed.

2. The experiment

A detailed discussion of the model was presented in the article mentioned in the preceding section. The principal assumptions used in deriving the prediction equations are:

(a) the flow is adiabatic and frictionless;
(b) the geostrophic wind may be used for evaluating vorticity and horizontal advection of vorticity and temperature;
(c) the vertical advection of vorticity and the tilting of vortex filaments are negligible;
(d) the vertical velocity profile is sinusoidal, with a numerical maximum at 500 mb and a zero value at 1,000 mb;

[1] The research was done through support and sponsorship by the Geophysical Research Directorate, Air Force Cambridge Research Center under Contract No. AF 19 (604)—1141 while the author was affiliated with McGill University.

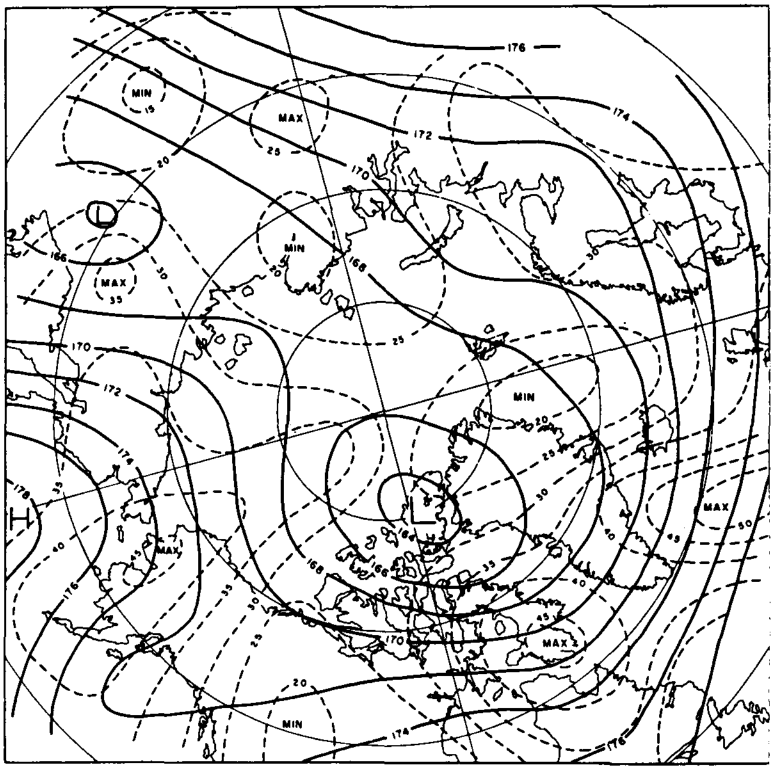

Fig. 1. Average 500 mb contours (solid lines) and root mean square of the 24-hour height changes (dashed lines) for January 1956. Contour heights are in hundreds of feet; height changes are in tens of feet per day.

(e) the absolute vorticity and static stability are constant whenever they appear undifferentiated.

The charts used in the experiment were obtained from routine analyses by the Canadian Meteorological Office at Edmonton, which prepares 500 mb and sea-level pressure charts on a polar stereographic projection. Daily 24-hour forecasts were made, using as initial data the 0300 G.M.T. 500 mb maps and 1,000 mb maps which were constructed by relabeling the 0030 G.M.T. sea-level pressure maps (using a conversion factor of 4 mb = 100 ft). The 500 and the 1,000 mb maps were, therefore, not strictly simultaneous; but, in general, this deficiency is not a major source of error. It must be mentioned that the synoptic analyses were handicapped by the usual paucity of observations. The results obtained here reflect only what is obtainable under the present network of stations. Since the performance of any method is intimately related to the synoptic situations which prevail over the forecast area, this item is discussed in the remainder of this section.

The area under consideration roughly covers the whole region north of 55° N, and the period includes the whole month of January 1956.

The average circulation at 500 and 1,000 mb is shown in Figs. 1 and 2. It may be seen that the sea-level circulation for January 1956 is rather abnormal. The normal circulation for this period of the year is usually characterized by a low pressure center between the southern tip of Greenland and Iceland. In this particular year, however, the corresponding low pressure center is displaced far to the east near the Norwegian coast, implying an eastward shift in cyclonic activity.

The first few days of January were characterized by strong cyclonic developments near the southern tip of Greenland, with cyclones

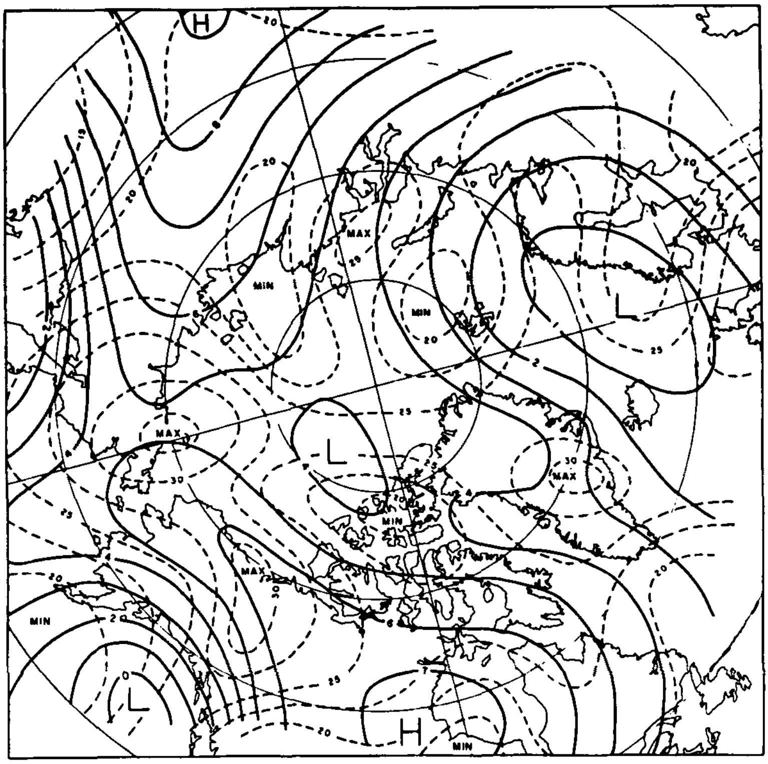

Fig. 2. Average 1,000 mb contours (solid lines) and root mean square of the 24-hour height changes (dashed lines) for January 1956. Contour heights are in hundreds of feet; height changes are in tens of feet per day.

following tracks from Iceland to Spitzbergen. This regime was gradually followed by a build-up of high pressure area over Greenland and a shift of the cyclogenetic area farther to the southeast, with cyclones intensifying and stagnating over the British Isles. The storm tracks moved correspondingly southward, so that cyclones generally followed a course through Great Britain, Sweden and Northern Russia. This situation, which brought in cyclonic circulation throughout Northern Europe, persisted until the last days of the month, after which an extensive anticyclone developed over Finland. This was accompanied by a shift in the cyclogenetic area back to the Greenland-Iceland region.

The Siberian anticyclone was well developed during the first week. However, it gradually weakened and then moved southwestward and Northeastern Siberia came under the influence of cyclonic circulation which prevailed during the second week. During the succeeding week the high pressure area shifted eastward as intense cyclones moved from Scandinavia to Northern Russia. The cyclone tracks subsequently extended farther to the east across Northern Siberia. This situation led to a split in the anticyclonic center, with one of the two centers located north of Siberia.

In the vicinity of the North Pole, major cyclones were observed on January 2nd, 15th and 31st. A high pressure area was centered over the Pole near the end of the second week.

The circulation over North America was characterized by strong and quasi-stationary cyclones over the Gulf of Alaska and well-developed anticyclones over Canada and Alaska throughout most of the period. Occasionally this high-pressure cell became split as Alberta lows moved across Canada and weakened while cyclones moved eastward over the Beaufort Sea.

Table 1. Results of 1 000 and 500 mb forecasts. Correlation (in percent) between initial and verification height, r(IV); between forecast and verification height, r(FV); between forecast and verification height change, r(Δ). Root mean square of observed height change, RMS Δ; root mean square error, RMSE: units in feet.

	1 000 mb					500 mb				
Date Valid	r(IV)	r(FV)	r(Δ)	RMSΔ	RMSE	r(IV)	r(FV)	r(Δ)	RMSΔ	RMSE
2	86	86	53	224	226	74	79	52	426	350
3	81	84	60	252	236	87	93	70	308	228
4	80	70	39	264	314	84	87	44	370	343
5	84	70	49	241	353	88	90	59	333	318
6	70	67	51	302	331	85	89	64	384	310
7	67	75	66	289	269	74	83	63	438	344
8	73	79	67	270	256	82	93	61	331	288
9	60	62	45	333	361	83	87	52	418	360
10	66	54	40	276	348	82	89	33	261	279
11	87	79	54	169	246	93	93	57	225	231
12	86	77	44	186	268	88	91	51	251	231
13	74	76	55	220	228	87	90	50	285	258
14	59	71	56	267	242	83	91	72	323	231
15	88	74	28	177	239	93	93	61	211	217
16	84	74	37	206	260	87	88	43	300	294
17	83	71	21	208	307	74	74	26	371	391
18	87	70	02	215	352	89	87	34	237	255
19	94	83	34	179	282	81	80	54	274	242
20	94	87	15	168	262	82	80	40	263	265
21	91	83	57	181	242	88	92	66	228	183
22	90	84	61	182	289	89	92	64	214	190
23	91	87	62	171	222	90	91	53	210	200
24	87	84	56	193	216	90	92	55	219	200
25	63	78	63	258	255	76	86	66	317	242
26	71	76	59	221	215	82	90	67	283	215
27	72	72	44	209	246	90	89	49	240	237
28	66	75	55	255	261	89	90	41	313	293
29	80	79	52	262	297	89	86	25	366	373
30	74	71	39	272	325	84	85	45	338	323
31	73	79	54	262	257	86	87	40	309	290
Mean	79	76	47	230	273	85	88	52	301	272

3. Results of verification

There seems to be no satisfactory objective measure for specifying the practical usefulness of forecasts. The customary evaluation involves the use of linear correlation coefficients between predicted and observed heights or height changes supplemented by the root mean square errors. Although such measures are useful, there is no substitute for visual inspection in evaluating the significant synoptic features of the forecasts, such as the occurrence of cyclonic or anticyclonic developments and the displacement of motionsystems. Frequently, a forecast which appears, from the low correlation coefficients, to be entirely worthless, is actually of practical value.

For verification purposes, the following quantities have been computed:

(a) Linear space correlations between predicted and observed heights as well as height changes and the root mean square errors for every individual forecast chart.

(b) Time correlations and errors at grid points during the entire period.

(c) Corresponding correlations between initial and verification heights and height changes and the root mean square observed height changes. The latter is a measure the intensity of the synoptic activity.

The results are presented in Table I. It is unfortunate that it is not possible to compare these with conventional forecasts based on the

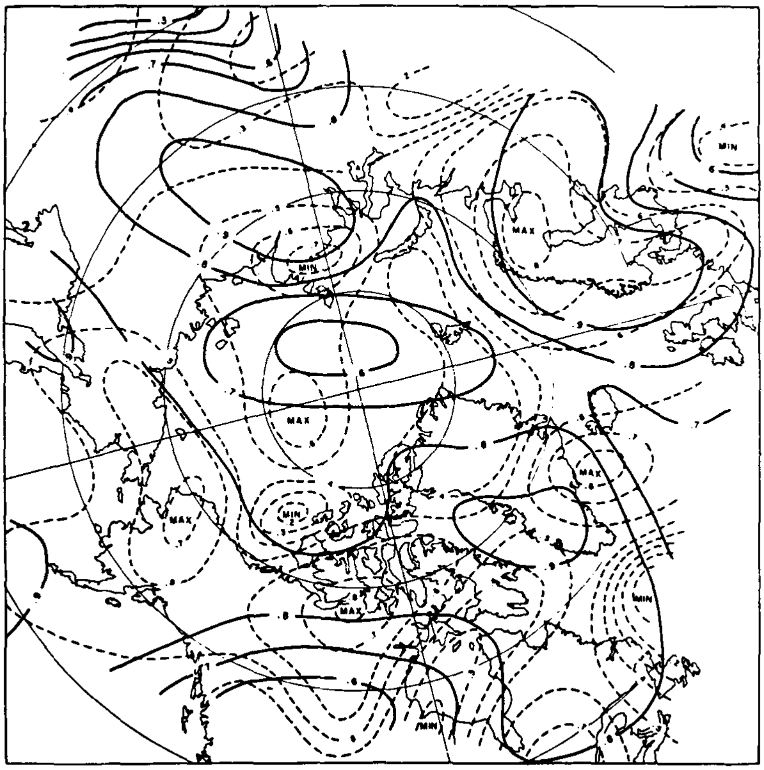

Fig. 3. Geographical distribution of correlation coefficients between observed and predicted heights (solid lines) and height changes (dashed lines) at 500 mb.

same initial data. For comparative purposes, the evaluations of forecasts using the same method, but for different situations, are shown in Table 2. These forecasts, which have been discussed by PETTERSSEN (1957), were made over the United States-Canadian Region.

The verification scores in Table I represent the performance for each individual forecast map over the entire area. As it is often the case, the forecast is actually excellent in some places but very poor over more or less fixed regions, giving an overall mediocre correlation for the verification. This is particularly true for the 1,000 mb forecasts, where the errors are at times excessively large over mountains and warm oceans. In comparing the results over the Arctic with those over United States-Canadian region, one must bear in mind that

Table 2. Comparison of prognosis. M is percentage frequency of cases for which $\mathrm{RMSE} < \mathrm{RMS}\Delta$, N is percentaga for $r(FV) > r(IV)$

Period	Area	r(FV)	r(IV)	RMS	RMSE	M	N	$r(\Delta)$
a: 1 000 mb								
January 1956	Arctic	76	79	230	273	23	42	47
January 1953	U.S.—Canada	62	42	242	215	87	88	63
Jan. 11—Feb. 21, 1956	U.S.—Canada	71	71	178	182	47	43	52
b: 500 mb								
January 1956	Arctic	88	85	301	272	70	75	52
January 1953	U.S.—Canada	72	53	310	239	88	87	65
Jan. 11—Feb. 21, 1956	U.S.—Canada	96	94	230	200	83	80	59

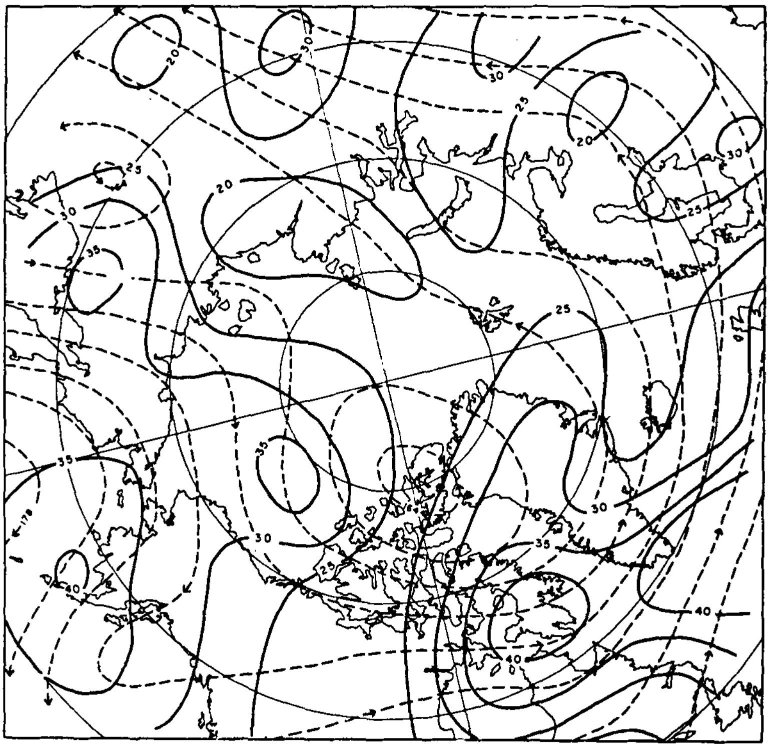

Fig. 4. Geographical distribution of root mean square error of forecast 500 mb heights (solid lines) in tens of feet and the average 500 mb contours (dashed lines). The 500 mb contour interval is 200 feet.

the forecasts are highly sensitive to the regions over which they are made, as well as to the circulation types which prevail over the period. In general, high correlation between forecast and observed changes are associated with low persistence correlation, r(IV). It is believed that the comparatively lower scores over the Arctic are mainly due to the smaller density of observational stations.

Examination of the geographical distribution of the time correlation coefficients and root mean square errors (Figs. 3—6) show the high variability of the accuracy with location. Thus, at 500 mb the best forecasts are obtained over Scandinavia. This is confirmed by the high correlations obtained by the University of Stockholm group. Two other favorable locations are over Northern Canada and southeast of Greenland. Over the Arctic Ocean the results are somewhat less satisfactory due to the sparsity of data on which the analyses are based. The correlation between height changes in this area are about the same as those obtained by the numerical integrations of the Joint Numerical Weather Prediction Unit (1957). Areas of large errors are located in the vicinity of the Gulf of Alaska and south of Greenland. These errors are associated with strong height gradients and large height changes which frequently occurred during the period.

The geographical distribution of the correlation coefficients and errors at 1,000 mb (Figs. 5 and 6) is generally similar to those at 500 mb. It is interesting to note the area of high verification over Southeastern Greenland. A detailed examination of the individual maps revealed that only one major cyclogenesis occurred within this area during the period; the high verification was mainly associated with the motion of well-developed cyclones.

Areas of large errors are also present at 500 mb but are accentuated at 1,000 mb. The areas over the Gulf of Alaska and Western Canada are undoubtedly due to nonadiabatic and

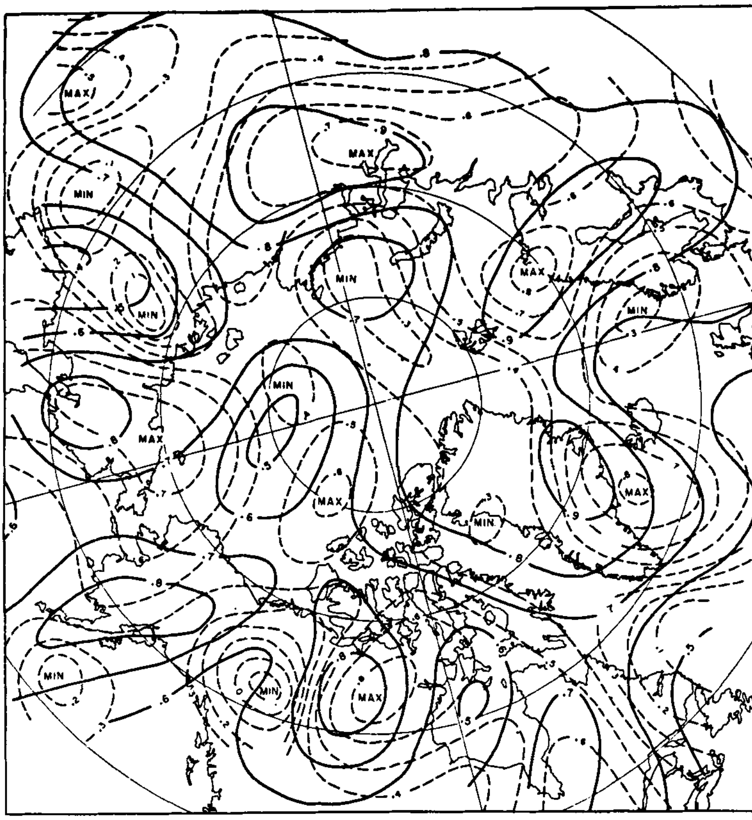

Fig. 5. Geographical distribution of correlation coefficients between observed and predicted heights (solid lines) and height changes (dashed lines) at 1,000 mb.

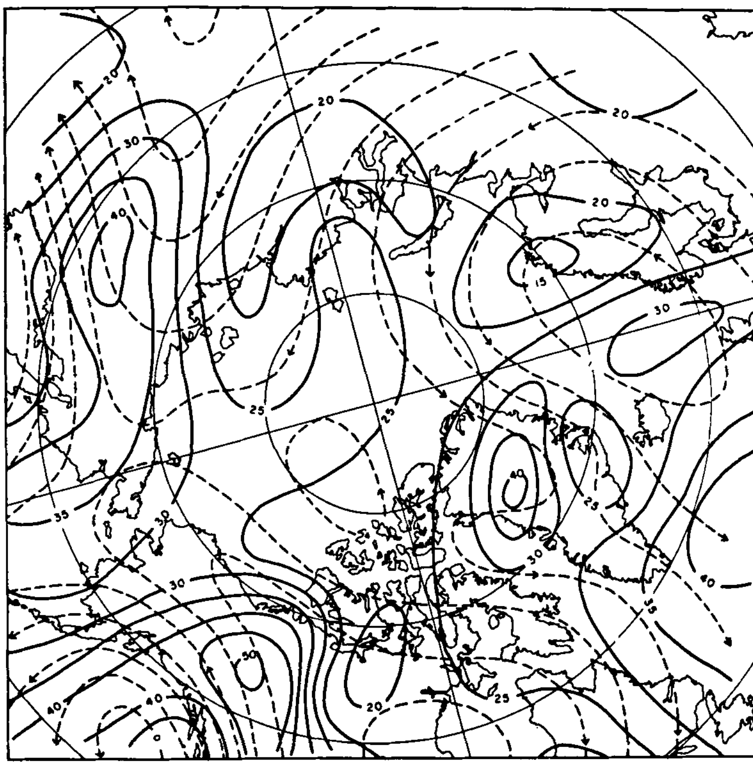

Fig. 6. Geographical distribution of root mean square error of forecast 1,000 mb heights (solid lines) in tens of feet and the average 1,000 mb contours (dashed lines). The 1,000 mb contour interval is 100 feet.

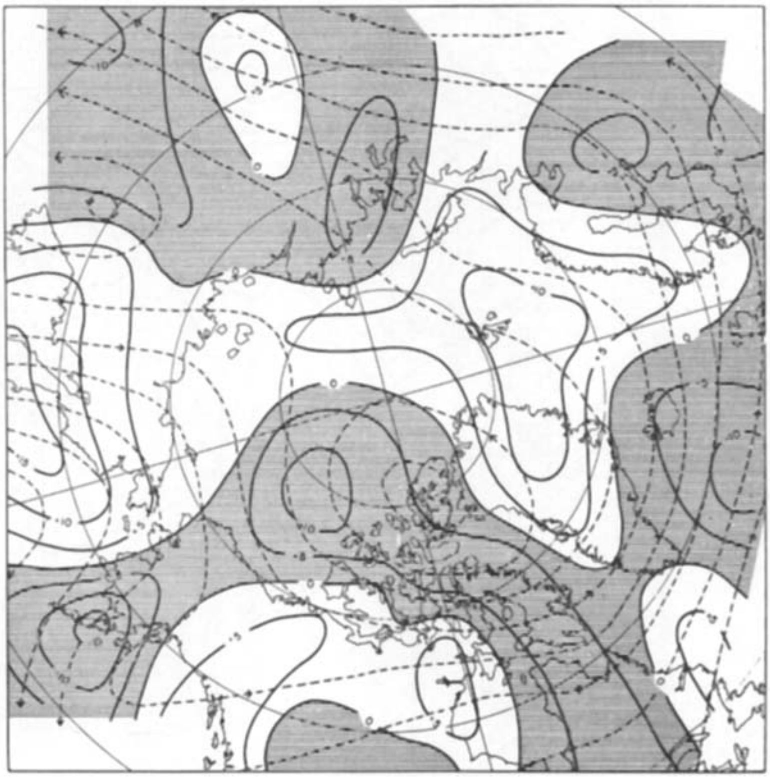

Fig. 7. Geographical distribution of the 500 mb mean algebraic error (solid lines) in tens of feet and the average 500 mb contours (dashed lines). The 500 mb contour interval is 200 feet. Shaded areas indicate regions where predicted heights are too high.

orographic effects, respecitively, while that south of Greenland is mostly due to the former. In addition, there is an area of poor verification over Western Siberia, in which the errors are systematic and associated with a tendency to overforecast the thickness.

4. Algebraic mean error patterns

A careful study of the systematic errors (observed minus forecast) is highly interesting because it reveals weaknesses in the model and suggests necessary modifications which may be made to improve the model. The fundamental equations which have been using in deriving the model are essentially the barotropic nondivergent vorticity equation applied at 500 mb and the thermodynamic energy equation for adiabatic motion. The former is used to predict the heights at 500 mb, and the latter the mean temperature of the 1,000—500 mb layer (or equivalently, its thickness). If the errors due to other sources are assumed to be random, the mean algebraic error field in the 500 mb heights represent the effect of vorticity sources or sinks, and, hence, the mean pattern of convergence and divergence at this level. Similarly, the corresponding thickness error patterns represent the distribution of external heat sources and sinks in the lower troposphere.

The error field for the predicted heights at 500 mb is shown in Fig. 7. Negative values indicate convergence (vorticity sources) while positive values represent divergence (vorticity sinks). It may be seen that the patterns are, to a certain extent, related to the mean flow such that positive values are located east of well-defined trough lines and negative values west. This implies a tendency to forecast the motion of the major waves too fast. On the

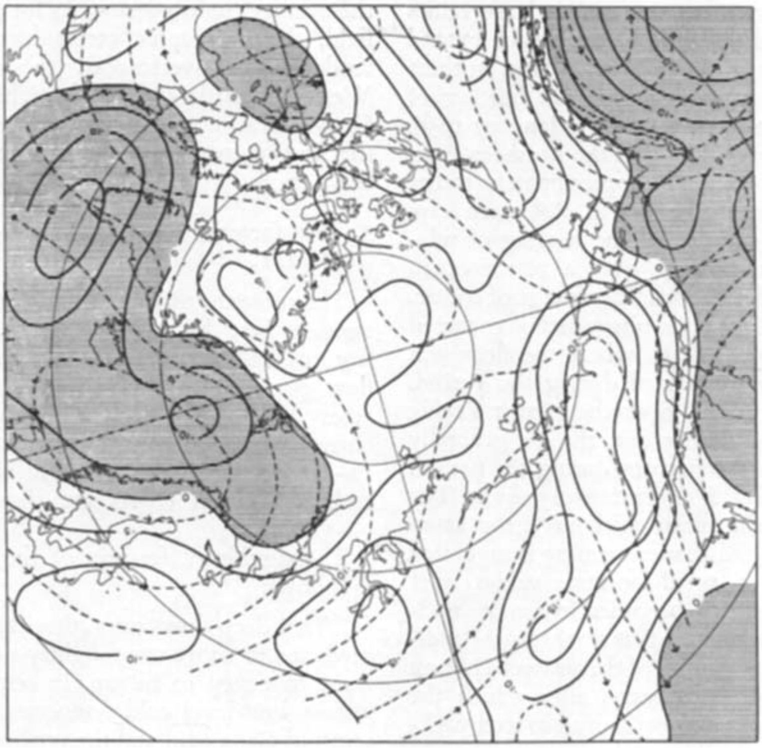

Fig. 8. Geographical distribution of thickness mean algebraic error in tens of feet (solid lines) and the average 1,000 mb contours (dashed lines). The 1,000 mb contour interval is 100 feet. Shaded areas indicate regions where the predicted thicknesses are too low.

basis of the vertical velocity profile adopted in the model, together with the normal vertical distribution of convergence and divergence in relation to trough lines, this error may be remedied by modifying the velocity profile so that the numerical maximum is located at a level lower than 500 mb.

The region characterized by negative values southeast and west of Greenland, north of Alaska, and Eastern Canada indicate places where troughs or cyclones intensified during the forecast period. The large area of positive values extending from Greenland to Scandinavia reflects the tendency for troughs and lows to weaken as they move northeastward after having intensified in the vicinity of Southern Greenland.

There is evidence that errors due to the quasi-geostrophic approximation are often substantial in producing spurious anticyclones. Nevertheless, there is still no basis for assuming that the net effect is so large as to invalidate the preceding inferences about the geographical distribution of vorticity sources and sinks.

The mean error patterns in the thickness (Fig. 8) show some rather striking characteristics. In interpreting these patterns, one may assume that the nonadiabatic heating effect is the primary source of systematic error. There are, however, two other influences which may modify our conclusions. First, the use of the geostrophic wind instead of the actual wind for temperature advection will lead to overestimates of the thickness in regions of strong polar outbreaks. Second, the use of a standard static stability is also a disturbing influence. Finally, the interpretations are only meaningful over fairly flat terrain. The error field, however, indicates that these complicating factors are not of major importance. Considering the positive areas, one can see large values over the North Atlantic Ocean which extend into the Norwegian and Barents Seas. In these regions there is apparently a net heating of the 1,000—500 mb layer during January 1956. It is interesting to note that the northern limit of this zone corresponds approximately to the southern limit of the North Polar ice cap. It is highly suggestive of the heating of relatively cold air flowing over a warm ocean surface. Over the ice pack this effect is, of course, not indicated. The same phenomenon occurred over the Gulf of Alaska where the flow was predominantly southward during the period. On the other hand, over the North Pacific Ocean and the Bering Sea, the air generally had a northward trajectory during the period. Hence the effect is comparatively slight. The sensitivity of the mean thickness error as an indicator of nonadiabatic warming is suggested by the area of small positive values over Hudson Bay which becomes frozen in mid-winter. The studies of BURBIDGE (1951) indicate that slight warming of the air over Hudson Bay may occur in January, after which the Bay becomes covered by snow-covered pack-ice.

The continents and the Arctic Ocean are zones where the thickness is overpredicted on the average; this implies nonadiabatic cooling, presumably by radiation. Near the southern limit of the ice cap and the continental coasts bordering unfrozen seas, the onshore and relatively warmer air is also cooled by the cold ice surface. As stated earlier, the use of geostrophic temperature advection may also introduce the same effect over the continents where the anticyclonic flow is dominant. It is, therefore, possible that the inferred amount of nonadiabatic cooling is somewhat overestimated. Nevertheless, the rates of radiational cooling implied by the error values are of the right order of magnitude (100 ft is approximately equal to about 1.5° C per day). These results show that considerable improvement in the forecasts can be made by incorporating nonadiabatic effects.

The difficulties introduced by orographic influences are of minor importance over the Arctic. Except in Greenland and over the Alaska-Northwestern Canada region, there are no other major mountain barriers. Even over these two regions, the 500 mb errors are, on the average, unimportant. As for the thickness field, the orographic errors have a marked tendency to overforecast the values over Western Canada and Alaska. The effect over Greenland is more difficult to interpret because the flow patterns were more variable during this period.

5. The forecast for January 11—12, 0030 G. M. T.

The ultimate usefulness of a forecast can be assessed best by comparing the significant features of the predicted and the observed flow patterns. In order to illustrate typical errors and to give an idea of the meaning of correlation coefficients, the forecast for January 11—12 is discussed in detail. The initial forecast and verification charts are shown in Figs. 9—11.

The significant features of the forecast are as follows:

(a) The deep low over the British Isles is predicted to move very slightly eastward with some tendency to fill up. In response to the intense low level cold temperature advection south of Greenland and the predicted eastward movement of the 500 mb ridge over the Labrador coast, a rapid 1,000 mb height increase is forecast over a wide area centered south of Greenland. The resulting forecast map shows a high pressure center over the southern tip of Greenland. The forecast concerning the Great Britain low verified rather well, although the filling was more than anticipated. The predicted high pressure center over Southern Greenland failed to materialize, the 1,000 mb height changes having been overpredicted by as much as 600 ft in certain places. About 70 % of this error resulted from an underforecast of the thickness while the remainder, to an overforecast of the height at 500 mb. This excessive building up of an anticyclone is a systematic error which is usually observed wherever southward flowing and relatively cold air streams over a warm ocean surface and is heated from below.

(b) The incipient low pressure center over Hudson Bay is predicted to intensify and move to the southern part of Baffin Island. This is successfully verified at 1,000 mb. It must be mentioned, however, that the corresponding heights at 500 mb were underpredicted. This

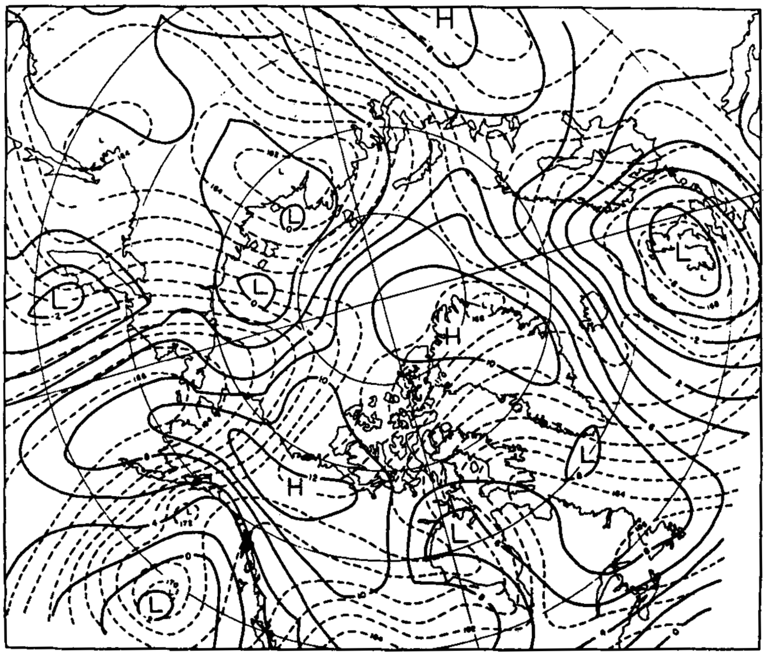

Fig. 9. Initial 1,000 (solid lines) and 500 (dashed lines) mb charts for Jan. 11, 1956. Contour interval is 200 feet.

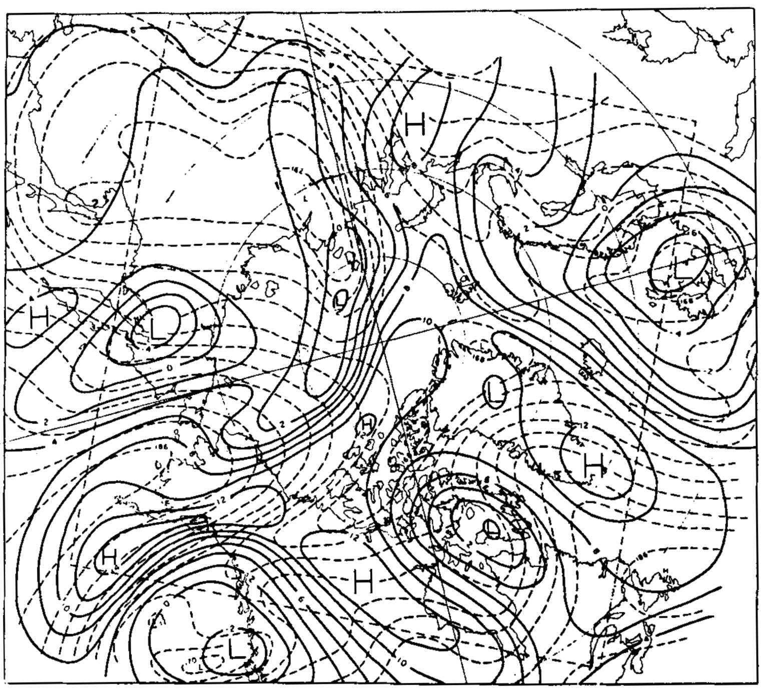

Fig. 10. Predicted 1,000 (solid lines) and 500 (dashed lines) mb charts for Jan. 12, 1956. Contour interval is 200 feet.

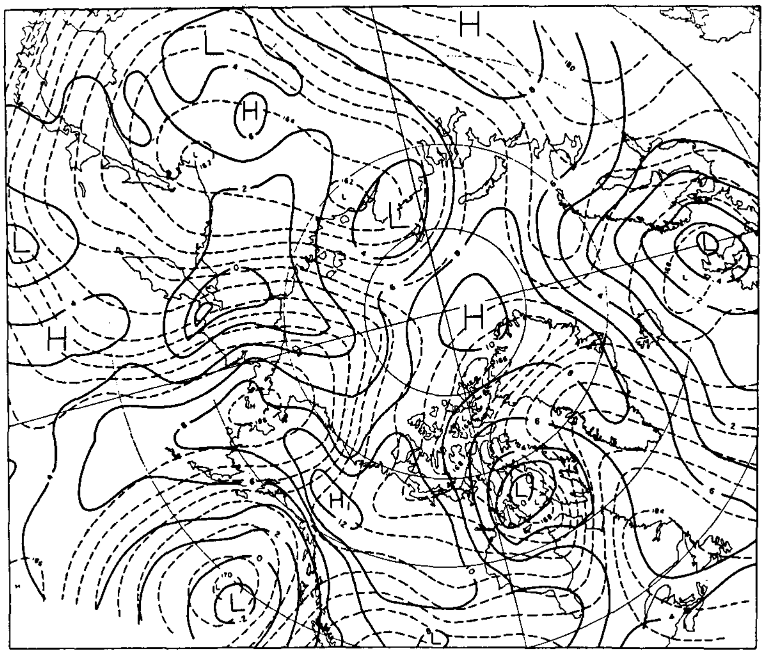

Fig. 11. Verification 1,000 (solid lines) and 500 (dashed lines) mb charts for Jan. 12, 1956. Contour interval is 200 feet.

has been compensated for by an overforecast in the 1,000—500 mb thickness changes to produce a successful 1,000 mb prediction. The overprediction of thickness changes in connection with 1,000 mb cyclogenesis is inherent in the graphical method and conveniently compensates for the inability of the model to predict cyclonic developments at 500 mb.

(c) The 1,000 mb heights are forecast to fall over the Canadian Rockies and the cyclone over the Gulf of Alaska will move eastward to the British Columbia coast. This will be accompanied by a rapid anticyclogenesis to the west-northwest. These forecasts turned out to be very unsatisfactory. The proximity of the boundary may have been a source of error. Nevertheless, the errors in this case are highly typical of all dynamical models. The predicted falls over the mountains failed to materialize. The error is essentially orographic in nature; the common tendency is to move cyclones eastward over the mountains without change in intensity. The spurious anticyclogenesis to the west is again the combined effect of nonadiabatic warming in the lower troposphere and an overforecast of the 500 mb heights.

(d) The low pressure center east of Kamchatka Peninsula is forecast to move directly northward over a distance of about 10 degrees of latitude and intensify. The predicted movement and intensification were somewhat more than observed.

(e) The two-centered low pressure system over the Arctic Basin north of Siberia is forecast to consolidate into an elongated low pressure area and move towards the North Pole. The low did not intensify as expected and the errors in the gradient were very large. Looking back at the initial map, it may be seen that the forecast of strong gradients is due to the initially strong warm advection northeast of the low centers. Nonadiabatic cooling over the region of warm advection, if incorporated in the method, will result in a more realistic 1,000 mb forecast. But the implied rates of cooling appear to be too high. It is not at all clear what the nature of the error is, but a reanalysis of the initial charts may produce an improvement.

6. Concluding comments

The results of this study indicate that the dynamical forecasting problems over the Arctic are not very different from those encountered over middle latitudes. The atmosphere over the Arctic appears to be more amenable to dynamical prediction methods because there are fewer complicating factors. Orographic influence is absent over most of the region. The nonadiabatic effect is relatively uniform, except in the outskirts, so that it is more easily corrected. The prospects for obtaining accurate forecasts are, therefore, very bright. The chief deterrent to the routine use of dynamical prediction methods at present is the paucity of observations. The less accurate forecasts which are now obtainable should improve immensely as soon as an adequate network of stations is established.

Acknowledgements

The writer wishes to thank Professor F. K. Hare and the members of the Arctic Meteorology Research Group for invaluable assistance during the investigation.

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