Cumulative Results of Extended Forecast Experiment. III: Precipitation

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ABSTRACT

A diagnostic analysis and an appraisal of the precipitation calculation by the GFDL (Geophysical Fluid Dynamics Laboratory) 1967 version prediction model are presented, using two-week forecasts of 12 January and 12 July cases. The geographical distribution of predicted rainfall, moisture and snow over the Northern Hemisphere and the contiguous United States was investigated in comparison with climatological maps published by other authors. The agreement of precipitation and dew-point temperature is marginal. The major causes for the deficiencies are 1) a specification of excessive soil moisture over land, 2) probably an improper treatment of moisture diffusion associated with topography, and 3) an inadequate rain generation process in the model. However, the predicted snow distribution over the United States was reasonable.

1. Introduction

The GFDL 1967 version prediction model was applied to a series of two week forecasts for 12 January and 12 July cases taken from 1964–70 data (Miyakoda *et al.*, 1972; 1979—hereafter referred to as Part I and Part II). The cases were independent since only two winter and two summer cases were selected for each year. Since the condensation of water vapor is one of the most complex processes, and the associated precipitation is one of the most difficult elements in weather forecasts, the model's performance for the precipitation simulation will be treated separately here in Part III.

As is usually the case in the general circulation model (GCM), the precipitation in this study was obtained using a physical approach instead of a probabilistic approach. The model includes two types of condensation processes. One is the grid-resolvable-scale process, in which condensation occurs at a specified saturation humidity. The other is the subgrid-scale process, in which the thermodynamics of cumulus clouds is treated as a bulk effect.

In the first type, the process is straightforward. Condensation and the concomitant release of latent heat take place at a grid point *in situ*, if the humidity reaches a specified saturation value. For the second type, the method of "moist convective adjustment" (Manabe *et al.*, 1965) was used, in which the effect of ensembled cumulus clouds is treated within a vertical column of the model's atmosphere instead of at a single grid point. Condensation occurs if the atmosphere is moisture-saturated in any layer of conditional instability. Consequently, the equivalent potential temperature is adjusted instantaneously to a condition of neutral stability, and the moist static energy is conserved during the adjustment. In practice, the second type of process is applied first to moist unstable layers, and thereafter, the first type is carried out for moist stable layers.

In both types of condensation, the saturation humidity was assumed to be 80% everywhere (Miyakoda *et al.*, 1969). A saturation criterion of 100% was not used because it was found that the ensemble average saturation value for the large scale should be somewhat less (Smagorinsky, 1960). The value of 80% was selected empirically. If a 100% criterion were used, precipitation amounts would be considerably underforecast in the early stages of the forecast, although the model's atmosphere would eventually adjust to the imposed condition whatever the criterion is. The algorithms for calculating snowfall will be described later.

The predicted rainfall, snowfall and moisture were averaged over 12 cases. First displayed is the zonal average, then the hemispheric distribution and lastly the distribution over the United States. The comparison of the simulated rainfall with climatology over the United States is particularly useful, since reliable observations were available over this region.

2. Latitudinal distribution of precipitation and humidity

Fig. 1 is the zonal mean precipitation rate for the January and July ensembles. The observations were taken from the climatology of Jaeger (1976) for January and July and also from Schutz and Gates (1971) for December-January-February and June-

July-August. The latter was based on the original data of Lvovitch and Ovtchinnikov (1964).

The distribution has two maxima, one near the equator and one in the middle latitudes. The agreement between the latitudinal positions of the prediction and climatology is not bad, the largest difference occurring in January in the tropics and subtropics. The excess rainfall produced in the model's tropics in January can be attributed to the equatorial boundary imposed in the hemispheric model which blocks the southward flow at the equator. The excess becomes progressively smaller toward higher latitudes.

Overall, the predicted rate of precipitation is higher than the climatology almost without exception at all latitudes. In particular, the excess is large in the extratropics in the summer. Let us assume that these excesses represent an actual model bias. Some possible causes of this overprediction in the present model are (i) the specified value for the availability of soil moisture over land was too large (a uniform value of 0.5 was assumed), and (ii) the 80% saturation criterion may be too low. Besides it is likely that the tropical sea surface temperature specified in the model was somewhat high (U.S. Navy Hydrographic Office, 1944). The evaporation in the model, in fact, is larger in the tropics than observations taken from Budyko (1963).

The water vapor supplied from the earth's surface is normally transported across the equator from the winter to the summer hemisphere (see Oort and Rasmusson, 1971). If the model were global, therefore, the precipitation in July should increase further, causing even a larger discrepancy.

Fig. 2 shows the zonal mean relative humidity distribution produced by the prediction ensembles. Several features are common to both months. The tropics and subtropics are characterized by a shallow layer of very humid air (~75%) near the surface, a dry layer (~20%) centered ~5 km, another humidity maximum (~40%) centered ~13 km, and relatively slowly decreasing values above 13 km. The upper level maximum is in close agreement with the findings of Murgatroyd (1960). In higher latitudes, humidities decrease slowly up to around 8 km, above which they decrease more rapidly.

In the tropics, seasonal changes are reflected in a latitudinal shift of both the 5 km minimum and the 13 km maximum. At higher latitudes, humidities at middle levels (~5 km) increase in January, while those at lower levels decrease. Also present at high latitudes in January is a moisture maximum at around 2 km that is not present in July. Miyakoda and Sirutis (1977), using an 18-level model, found three separate maxima at 1.4, 3.8 and 7.5 km in middle and high latitudes. The difference in this case is likely due to the lower vertical resolution used.

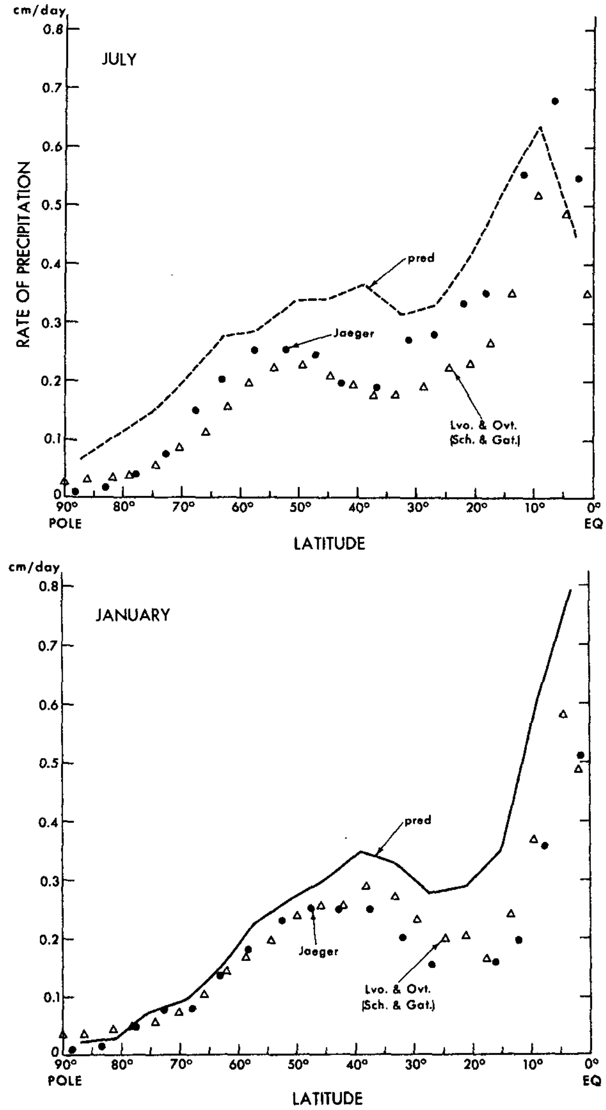

Fig. 1. Latitudinal distributions of the predicted rate of precipitation (PRED) for January and July. Also, plotted are the climatological data by Jaeger (1976) and by Schutz and Gates (1971).

It is very difficult to obtain an accurate humidity analysis. The zonally averaged cross section of humidity for July derived from the National Meteorological Center (NMC) analysis (not shown here) indicates scant resemblance to our prediction except below 5 km north of 50°N, where humidity of about 60–70% is found in a good agreement with the prediction based on the 80% saturation criterion. It is interesting to note that with a 100% saturation criterion, the predicted humidities increased to 70–100% in this region (Miyakoda and Sirutis, 1977), suggesting that the 80% criterion is preferable. However, the optimum value of the criterion may be a function of altitude and latitude. We believe that a saturation criterion near 100% is appropriate for the

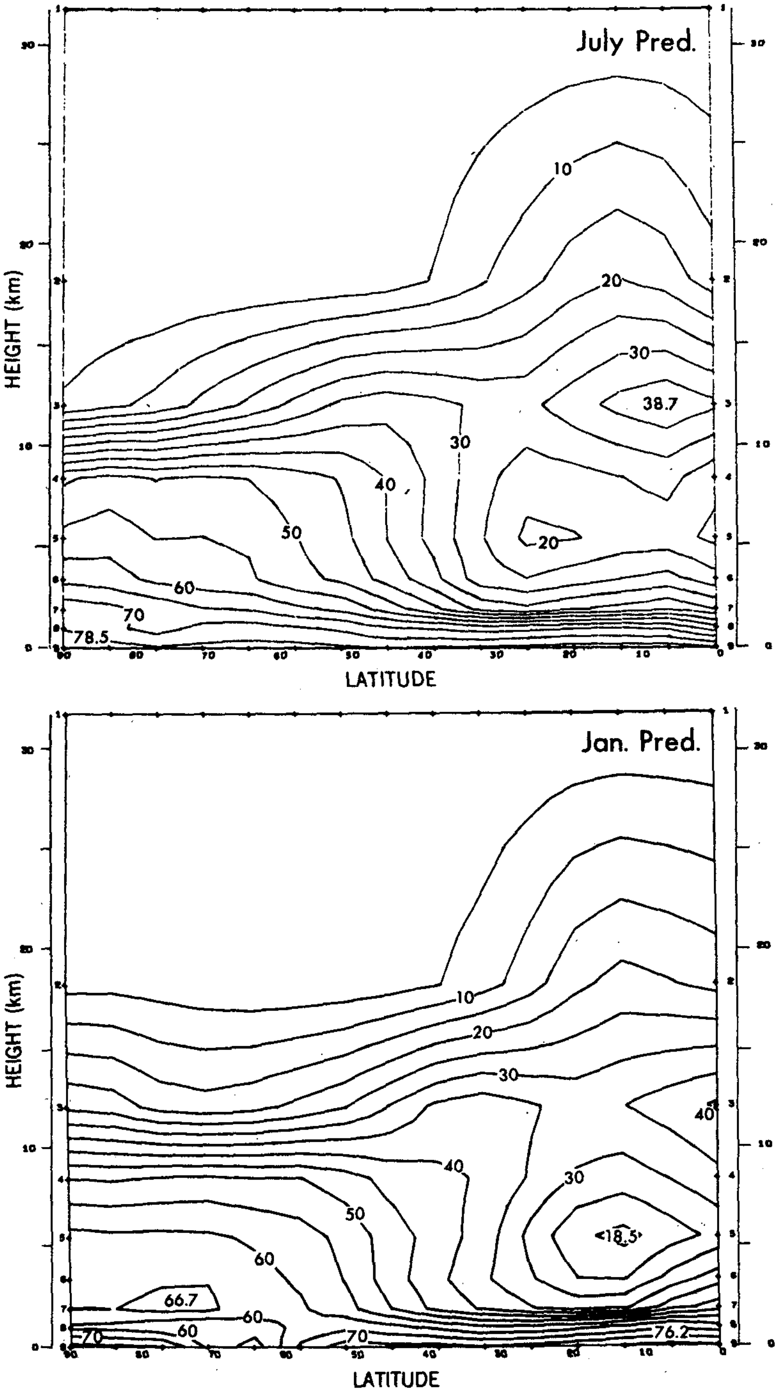

FIG. 2. Latitude-height distributions of predicted humidity for January and July. The ordinate is the geometric height, and the vertical nine levels in the GCM's are marked. The units of the contours are per cent. The maxima and minima are plotted.

planetary boundary layer, decreasing upward. For points at the same level, it would be proper to have a poleward decreasing criterion. As Manabe (personal communication) has pointed out, it is desirable to have a 100% criterion near the earth's surface in order to avoid any discontinuity between the criteria for evaporation and condensation. The European Centre for Medium Range Weather Forecasts (Hollingsworth *et al.*, 1980) uses a height-dependent criterion for condensation, which varies between 100% and 80%.

3. Geographic distribution of precipitation

The precipitation, including both liquid and frozen water, obtained in the prediction was averaged over days 2–14 for each of the 24 cases, with the highly transient first two days excluded.

a. Hemispheric domain

The precipitation distributions derived from the prediction for the January and July ensembles are compared with climatology (Lvovitch and Ovtchinnikov, 1964) for the hemispheric domain in Fig. 3. No smoothing has been applied to the prediction maps. Because of the equatorial boundary, the precipitation near the equator, 15°N, say, may not be valid, although interestingly the tropical convergence zones in the model are not entirely wrong.

The correspondence between the model and climatology is good in terms of the magnitude for maxima and minima, but the agreement between the geographic distribution is noticeable only on the planetary scale. The similitude is somewhat better in January than in July. However, the overall accuracy of prediction is far below the standard of practical requirements.

The outstanding disagreement in January may be the following areas:

1) Over the Sahara desert and Siberia, the prediction produces too much precipitation. This is related to the model's assumption of the availability for soil moisture over land.

2) Over the Atlantic Ocean along the east coast of the United States, a precipitation rate in excess of 250 mm month^{-1} was produced in the prediction, but no such maximum can be found in the USSR climatological atlas.

3) The abundant rainfall over the western Pacific east of the Phillipines is missing in the model.

Discrepancies during July include:

1) The arid zones over the Sahara, Middle East, Gobi and Turkestan deserts were poorly simulated. The failure appears to be mostly due to the excessive soil moisture.

2) Precipitation amounts in excess of 250 mm month^{-1} were erroneously produced over central China. More will be said about this problem later.

3) Heavy rain over eastern India and southeast Asia was not well simulated. The rain corresponds to the monsoon rain at this time of the year (see Staff Members of the Institute of Geophysics and Meteorology, Academia Sinica, 1957; Murakami, 1959; Asakura, 1971).

Thus, the effect of soil moisture on the summer rainfall seems to be particularly large. As was discussed in Part II, this deficiency, in turn, had significant impact on the predicted temperature and flow fields, even on the planetary scale. In this respect, the summer climatic simulation of precipitation with the GFDL GCM of Manabe and Holloway (1975) is better; the model included a hydrological process that handled the soil moisture in a better way. The July simulation of rainfall made by Stone *et al.* (1977), using the GISS GCM (Goddard Institute of Space Studies, Somerville *et al.*, 1974), is also better over the Gobi desert (but an erroneous rainfall occurred over the Sahara desert). The conclusions reached in these papers, however, were based on precipitation averaged over a single month, so that they may not be strictly comparable to the present study. At any rate, it is our impression that, although the simulation of the tropical rain was surprisingly well simulated in the GCM's (see for example, Manabe and Holloway, 1975), the simulation in the extratropics deviates greatly from the climatology.

b. The U.S. region

In order to take a more detailed look at the rain distribution, the predicted precipitation map for the contiguous United States was extracted and compared with the climatology produced by US Environmental Data Service (1968) (Fig. 4). The figure reveals that the predictions are considerably different from the climatology.

In January, areas with abundant rainfall are located in the Mississippi and Ohio Valleys. In the prediction, however, the intense precipitation over the Mississippi Valley is confined to the Gulf tier. Also in error is the heavy precipitation produced by the simulation over the Florida Peninsula, which is contrary to the observed minimum there. It is noted, however, that the intensity of rain over southern Mississippi agrees well with climatology.

In July, the prediction is very poor. The model produced a large amount of rain over the entire United States, while the climatology shows that heavy rain is confined to its eastern half.

A related question arises concerning the deficiency of January rainfall over the Mississippi and Ohio Valleys. One might logically ask whether this is due to an inaccurately predicted flow in the course of two week prediction. In order to examine this point, the predicted rainfall only for the first 5 days, instead of the last 10 days, was accumulated for the 12 cases. The result was very similar to that in Fig. 4, indicating that the predictability decay of flow is not the cause of the poor January precipitation simulation. In the model, rain probably fell too soon over the Gulf of Mexico and at the mouth of the Mississippi,

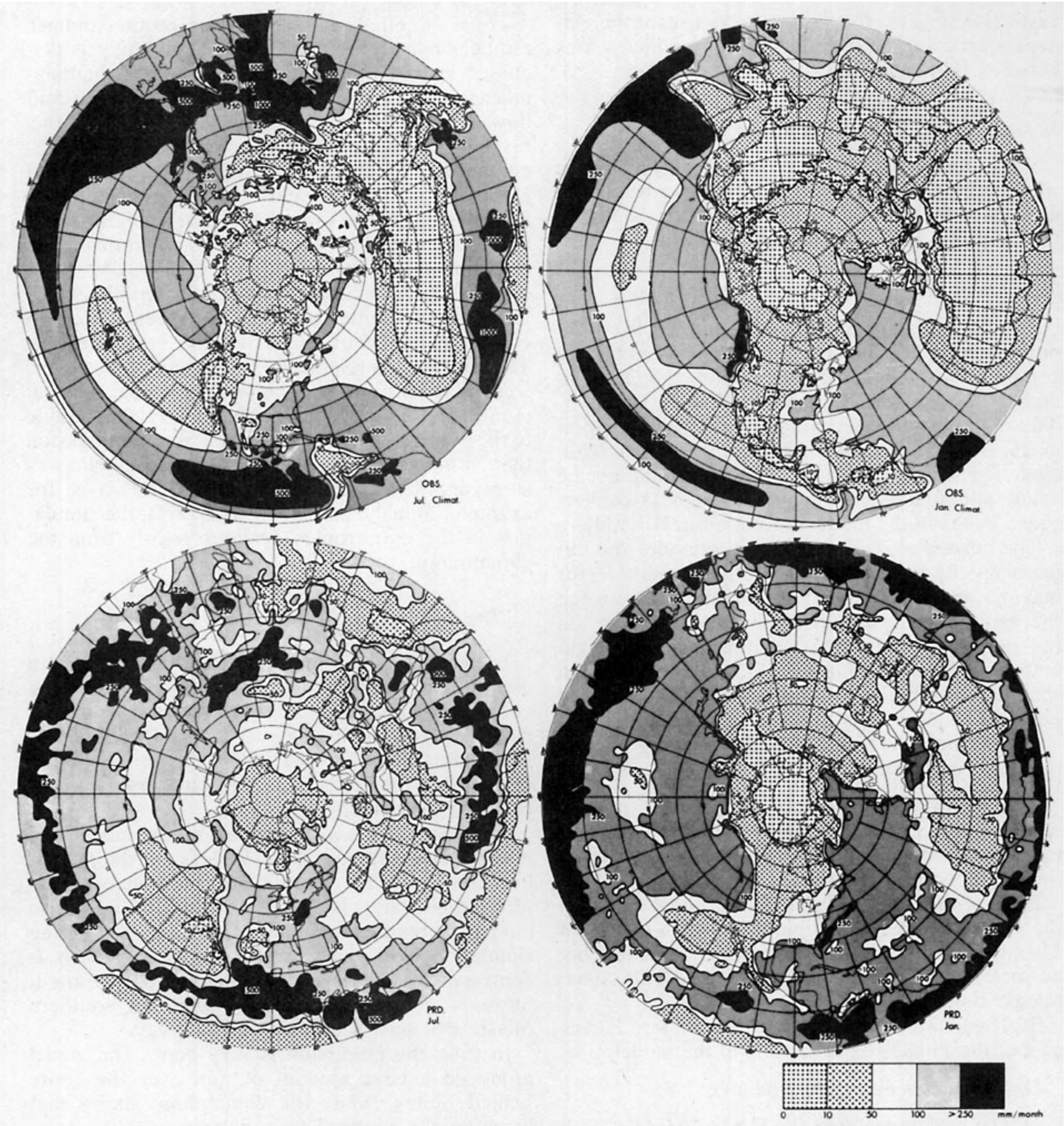

FIG. 3. The rate of precipitation from the prediction (PRD) and from the climatological atlas (OBS) by Lvovitch and Ovtchinnikov (1964). The contours are 500, 250, 100, 50 and 10 mm month^{-1} as shown in the legend.

and consequently water vapor was not carried further inland. Interestingly, a similar bias was also found by Stone *et al.* (1977) and by Manabe and Holloway (1975). The causes for these forecast failures may be related to the mechanism of rain generation in the model or the model's inability of producing a deep cutoff low east of the Rockies, resulting primarily from the model's poor spatial resolution.

Returning to the simulation/climatology comparison in Fig. 4, we note that another major shortcoming in the simulation occurs in the western part of the United States in January. The rain areas were not confined to the west coast but extended excessively inland and too much precipitation was predicted. The inland extension was due to the model's mountains being too smooth and flat (Smagorinsky *et al.*, 1967).

In July, there are two major erroneous areas,

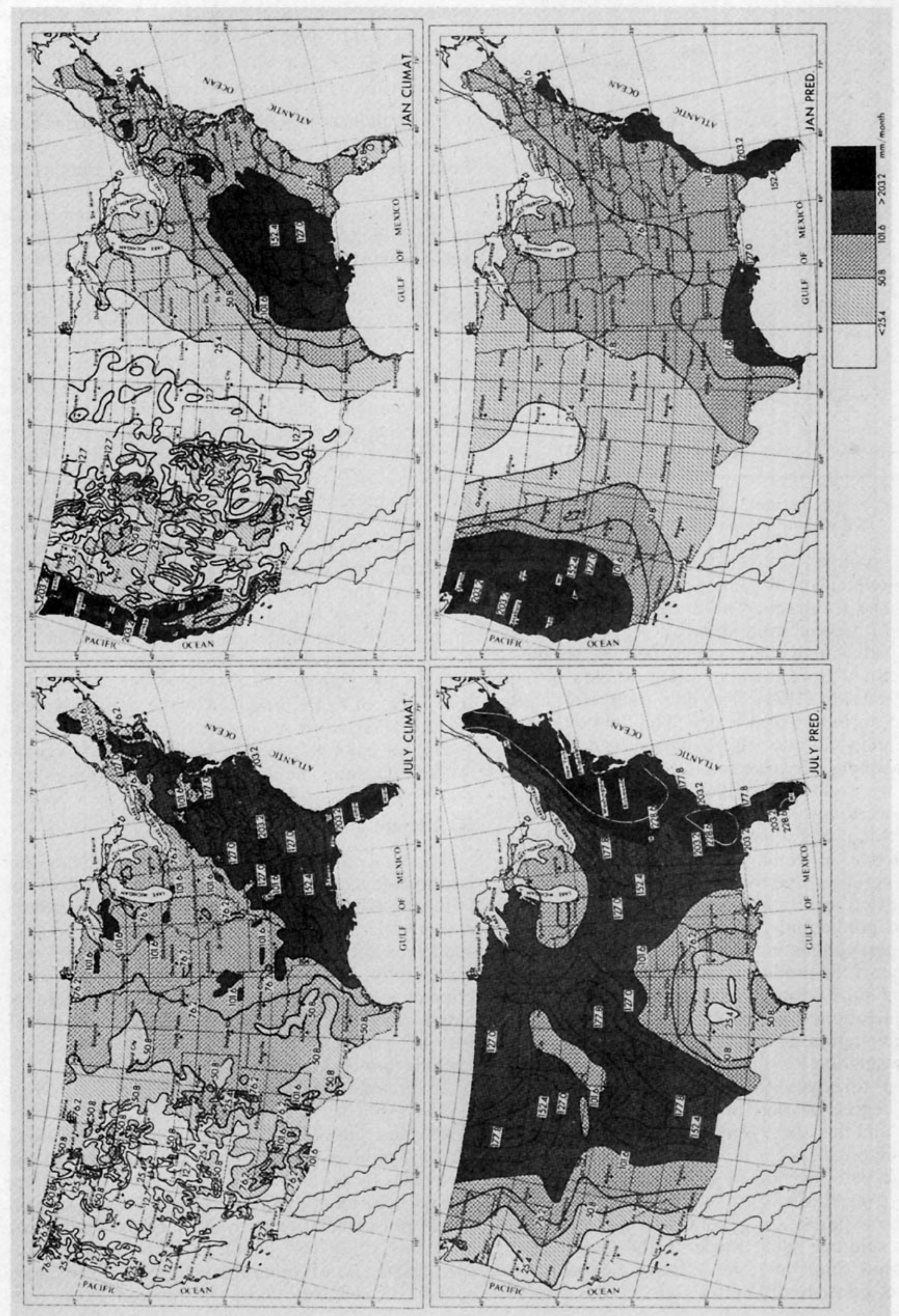

FIG. 4. The rates of precipitation in the prediction (PRED) and the climatology (CLIMAT) for the contiguous United States. The contours are 12.7, 25.4, 50.8, 76.2, 101.6 and 127.0 mm month^{-1}, as shown in the legend.

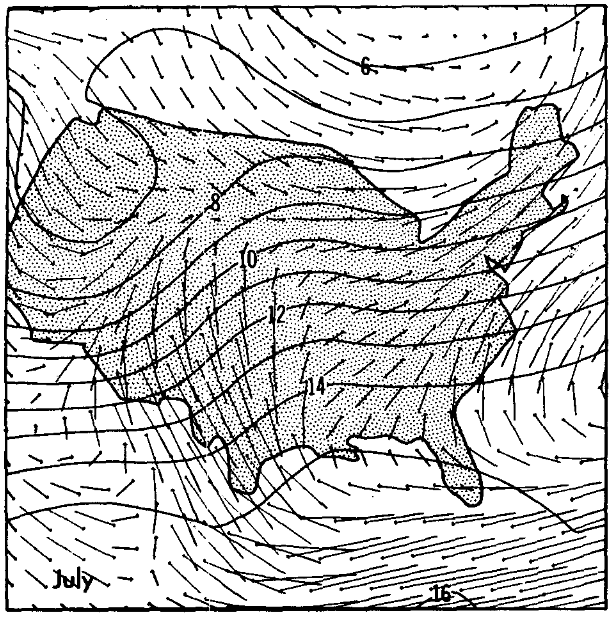

FIG. 5. Wind vectors and the mixing ratio of water vapor in units of g kg^{-1} at the 950 mb level for July.

one in Montana and Wyoming, and the other in New Mexico and Colorado. These areas are associated with two different wind streams. Fig. 5 shows the stream pattern and the moisture field at 950 mb in July obtained from the climatological data of Oort and Rasmusson (1971). The flow over Montana is from the northwest and is dry. The flow over New Mexico and Colorado is from the south and is moist. This reasoning was true for the case of July 1962, treated by Rasmusson (1967). A large maximum of northward flux of water vapor was located over New Mexico, and a small maximum of southward flux was over Wyoming (see Benton and Estoque, 1954). Therefore, the failure of the simulation over New Mexico may be due to a quantitative error in moisture prediction as well as the inadequacy of the cumulus convection parameterization. As will be shown later, the predicted moisture over the mountains was quite wrong. We note that the two global models mentioned earlier did not produce reasonable precipitation distributions in July either.

An evaluation of the skill of short-range precipitation forecasts (Miyakoda, 1975) showed a greater degree of skill in the winter than in the summer and that there is almost no skill in the summer predictions except in small areas in the northeast. The deterioration in skill spreads northward in June over the western United States, and the mountainous areas are generally worse than other areas in summer. New England, the Ohio Valley, Washington State and the Eastern Seaboard are regions of consistently better skill scores, whereas the Florida Peninsula and the coastal areas of Texas are consistently areas of little or no skill.

4. Geographic distribution of dew-point temperature

Fig. 6 depicts the January and July distributions of dew-point temperature T_d at the 850 mb level for both the GCM and climatology (Crutcher and Meserve, 1970).

The simulations apparently bear little resemblance to the climatological fields, even on the planetary scale. Some of the major deficiencies are as follows:

1) The simulated patterns of moisture over the arid regions (Turkestan, the Sahara and Gobi deserts) are particularly poor, especially in July, with values of T_d which are almost uniformly too high;

2) T_d values in the simulation tend to be larger over mountains. This is probably related to the way of handling the diffusion process of water vapor in the vicinity of mountains on the sigma-coordinate (Phillips, 1957) as well as the treatment of roughness over mountainous regions (Sawyer, 1959; Cressman, 1960; Garratt, 1977). The lateral diffusion is calculated on the sigma-coordinate without regard for slope, and as a result, water vapor is easily carried over the top of the mountains. And, since roughness was not increased over the mountains in this particular model, there was nothing in particular to impede the upslope advection of moisture.

3) In the map at the 850 mb level, excessively low values of T_d are produced by the simulation over the dry zones west of continents in the middle latitudes, for example, west of California and over the Atlantic Ocean. The reason for this is not known.

5. Attempt at improvement

Results from the preceding sections indicate that improvements could be made in any or all of the following areas: soil moisture, cumulus parameterization, criterion for moisture saturation, the model's space resolution, lateral diffusion associated with topography, and turbulent transfer in the planetary boundary layer including the mountain roughness length. In this section, we will select only the effect of soil moisture and discuss its impact on evaporation and rainfall.

An interaction atmosphere-ground hydrologic cycle was incorporated first into a GCM by Manabe (1969) and later into the short- to medium-range forecast models. However, the model used in this study was frozen in 1967, and so contained only the simpler treatment of soil moisture. The importance of soil moisture, however, was recognized very soon after this study was begun. An investigation was then started to examine the effect of soil moisture specification. Furthermore, for medium-range fore-

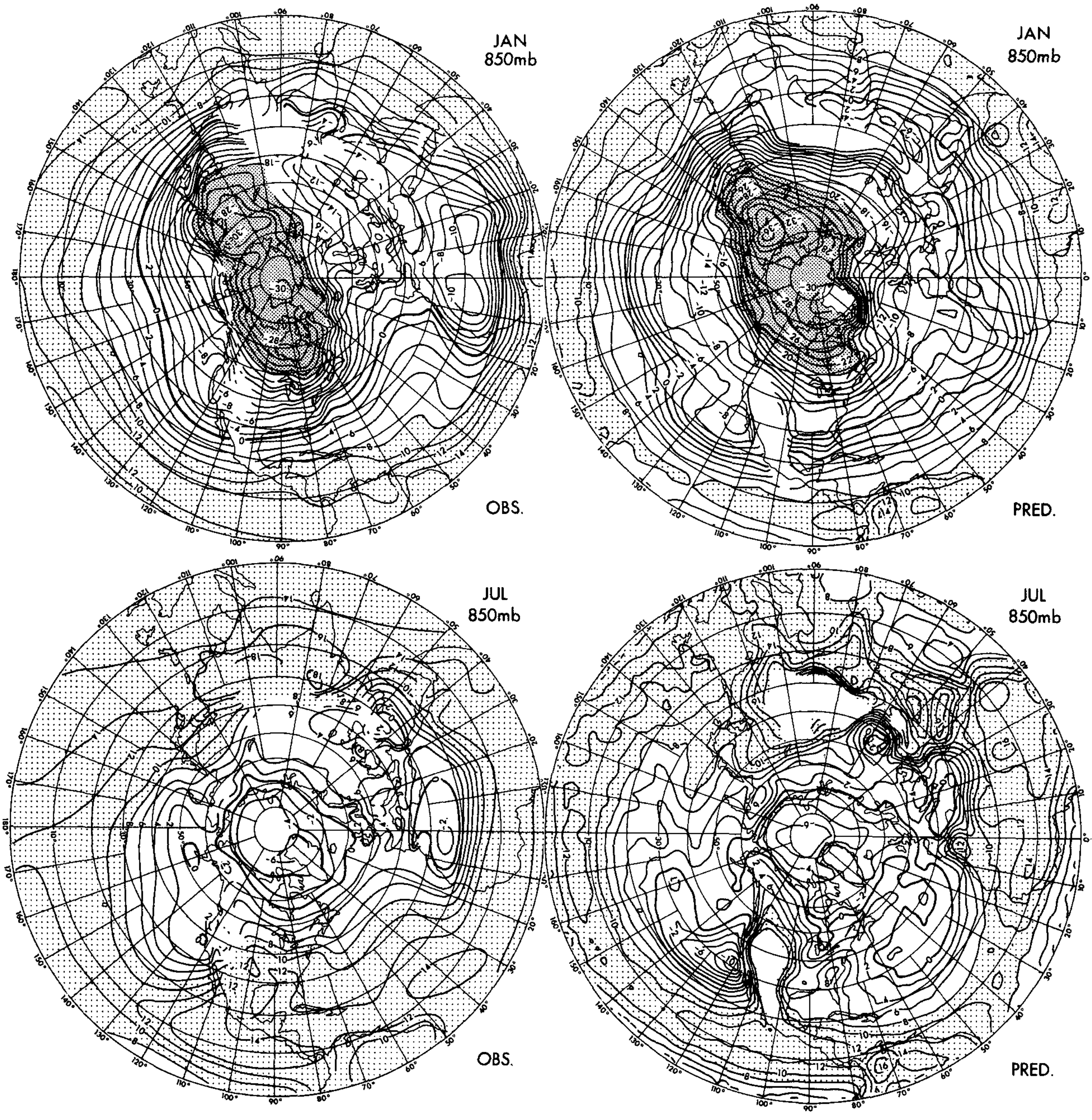

FIG. 6. Dew-point temperatures T_d (°C) in the prediction (PRED) and the observation (OBS) by Crutcher and Meserve (1970). Values are for January and July at the 850 mb level. Regions with $T_d \geqslant 8°C$ are shaded.

casts such as the ones presented here, the examination was more properly restricted to the effect of adequate spatial distribution of soil moisture rather than the incorporation of temporal variation of soil moisture.

A test of the soil moisture effect was performed, and the results were partially described in Part II. Two models were applied to 2-week forecasts for three July cases, i.e. 3 July 1966, 16 July 1968 and 19 July 1969 at 1200 GMT in each case. The 1967 version model was used as the control in which the availability of soil moisture was set to 0.5 everywhere over land. The test runs used the exact same model except that the soil moisture was specified as a spatially variable quantity. The assumed distribution of soil moisture was shown in Part II.

Fig. 7 shows the result of the test, i.e., the rate of precipitation and the rate of evaporation, averaged

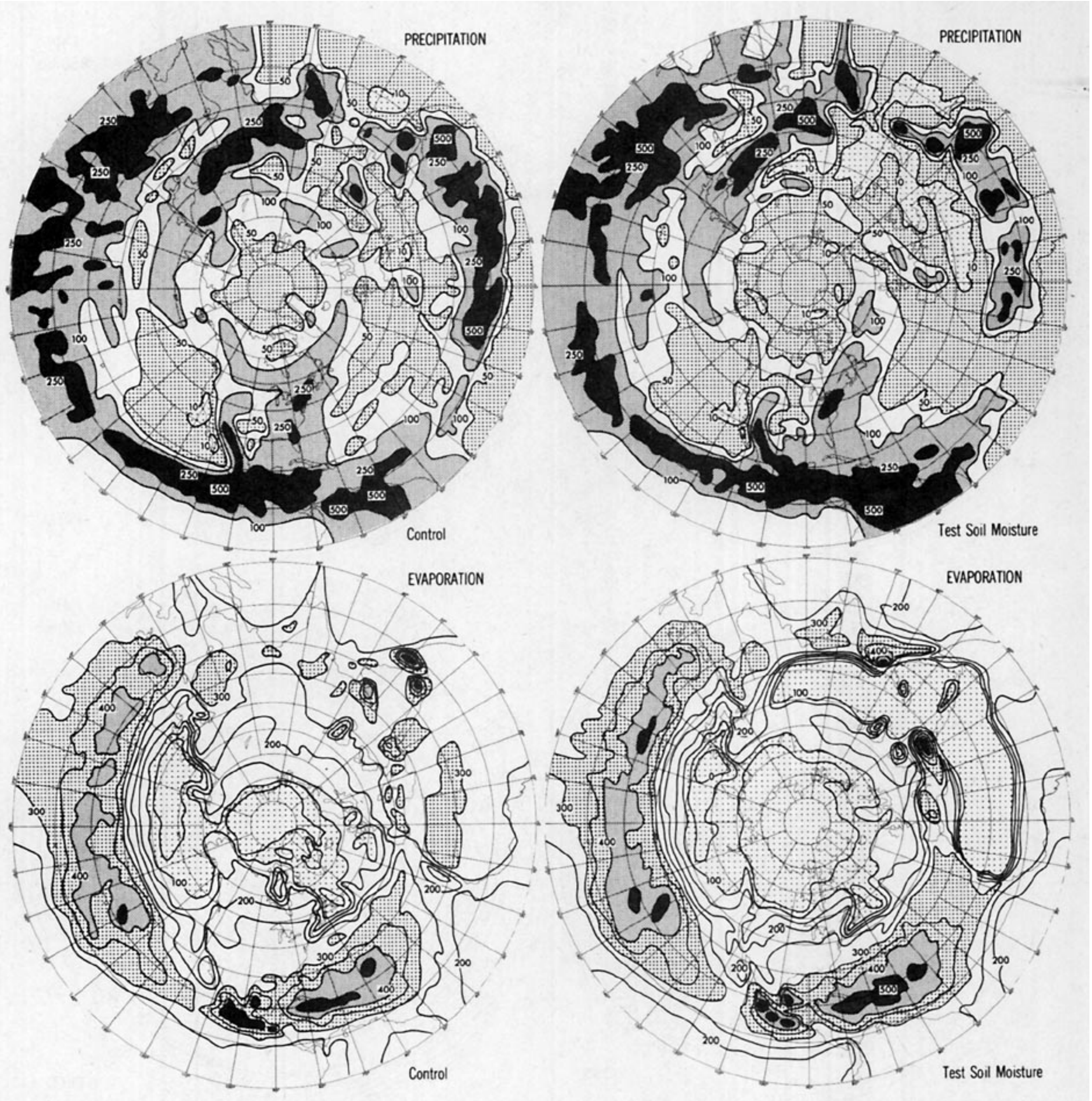

FIG. 7. Comparison of the rates of precipitation (upper) and evaporation (lower) between the control and the test soil moisture experiment. The contour values are 500, 250, 100, 50 and 10 mm month^{-1} for precipitation and every 50 mm month^{-1} for evaporation.

over the last 12 days of each of the two-week forecasts and then taken as an ensemble mean over the three cases. It is immediately obvious that the pattern of evaporation was greatly affected by the alternate specification of soil moisture. A particularly large contrast is seen over the Sahara, Arabian and Gobi deserts. In the control experiment, there was a small region of significant evaporation over the Sahara desert, whereas in the test soil moisture experiment the entire Sahara is an area of minimum evaporation. Thus the evaporation over land has been appreciably reduced in the test case. On the other hand, the evaporation over the sea in the test case has been noticeably increased, as if the deficit of land evaporation was compensated for by oceanic evaporation. It is interesting to note that the rate of evaporation over the Arabian Sea and over the Caspian, Red, and Black seas has been greatly enhanced in the test soil moisture experiment.

Fig. 7 also indicates that the impact on rainfall is indirect and is less obvious than that on evaporation. Yet there is a noticeable effect. If the two maps for the control and the test soil moisture experiments are compared with the July climatology in Fig. 3, it is clear that the test soil moisture case is much closer to the July climatology. The rain over North Africa and central Asia has been considerably reduced in the new case. (see also Mintz, 1981).

However, the reduction in rainfall over the Sahara and Gobi deserts is not as great as expected. Climatologically, the dry region over North Africa is a large and clear-cut area, whereas in the model, the region of <10 mm month^{-1} is smaller and more irregular in shape. Another glaring error occurs over central China (30–40°N, 90–120°E). In the control case, there was heavy rain in this region (>250 mm month^{-1}), which is entirely different from the climatology. This feature persists even in the case of test soil moisture despite the extremely low availability of soil moisture in this region. Some speculations as to the reason for the deficiency were mentioned earlier. In the observational study of Peixoto and Crisi (1965), the water vapor flux over China for summer is restricted to the coastal region, and there is not much convergence of moisture over the inland of China. That is to say, moisture over the mountainous areas in our prediction is too abundant, and this situation may be due to the improper treatment of lateral diffusion and advection of water vapor. A similar problem is seen over the Rockies. The decrease in rainfall over North America in the test case is encouraging. When compared with Fig. 4, we can see that the erroneous rainfall over Montana and Wyoming has been partially eliminated. On the other hand, the enormous rainfall over New Mexico and Colorado has not been rectified, implying that other causes are responsible such as incorrect moisture diffusion. Mintz (1981) discussed the importance of the effect of soil moisture not only on the medium-range forecast but also on the climate variability problem, and summarized the current knowledge on the soil moisture.

6. Snow

a. The method of snow calculation

Extensive studies of snow forecasting have been made outside of the field of numerical weather prediction (e.g., Austin and Bemis, 1950; Penn, 1957; Wagner, 1957). According to these studies, five factors are basically important for snow formation and its fall to the ground: freezing level, melting of snow during its descent, evaporation during its fall through unsaturated air between clouds and the ground, the effect of altitude on the ground surface and continentality. Penn (1957) (see Winston, editor), for example, set his conditions for snow versus rain as follows: 1) a 1000–700 mb thickness of less than 2.8 km (9300 ft); 2) a temperature at 850 mb of less than −2°C; 3) the surface temperature is less than 4°C (39°F); and 4) the height of the freezing level of <360 m (1200 ft).

The criterion in the present study was determined based on the Penn algorithm, though considerably simplified. Snow (or sleet) is assumed to occur under the condition that *within the lowest 2 km, a layer lower than 0°C exists, and that any layer higher than 0°C must not exceed 360 m in thickness.* All of the precipitation at a grid point was considered to be snow, if the condition above was met.

b. Distribution of snow

Fig. 8 shows the hemispheric distribution of snowfall from the model's 12 January cases, as well as the snowline determined by Richter (1960) and by Matson *et al.* (1980), and the permafrost line as determined by Péwé (1969). Richter's snowline is defined as the boundary of an area that is covered by snow for at least two continuous months. The snowline of Matson *et al.* was derived from ten years of satellite data. Although snowfall and snowcover are different parameters, this snowline approximately coincides with the limit of snowfall according to a model study (Manabe and Holloway, 1975).

The agreement between the model snowfall patterns and the region bounded by Richter's or Matson *et al.*'s snowline is generally good except over Western Europe. Over Siberia, northern Greenland and a part of Canada, the model did not have a snowfall rate larger than 10 mm month^{-1} of liquid water. It is interesting to note that non-snow regions correspond roughly to the areas of permafrost.

The predicted rate of increase in snow depth over the United States in January is shown in Fig. 9, and is compared to the observed climatology of snow mass taken from an analysis made by the U.S. Environmental Data Service (1968). In order to estimate the snow depth in the model, the precipitation amount was multiplied by 10.

Comparison of the prediction with the observations leads to the following conclusions: 1) The geographic correspondence as well as the quantitative agreement are surprisingly good; 2) the effect of the Great Lakes on snowfall obviously could not be reproduced in our model, but it would appear in view of the model result, that the heavy snowfall observed near the Great Lakes is not entirely a lake effect; and 3) snowfall in the mountain areas was poorly simulated.

7. Conclusions

1) The hemispheric distributions of predicted precipitation for January and July had little similarity to climatological distributions, particularly for July.

2) The hemispheric distributions of predicted

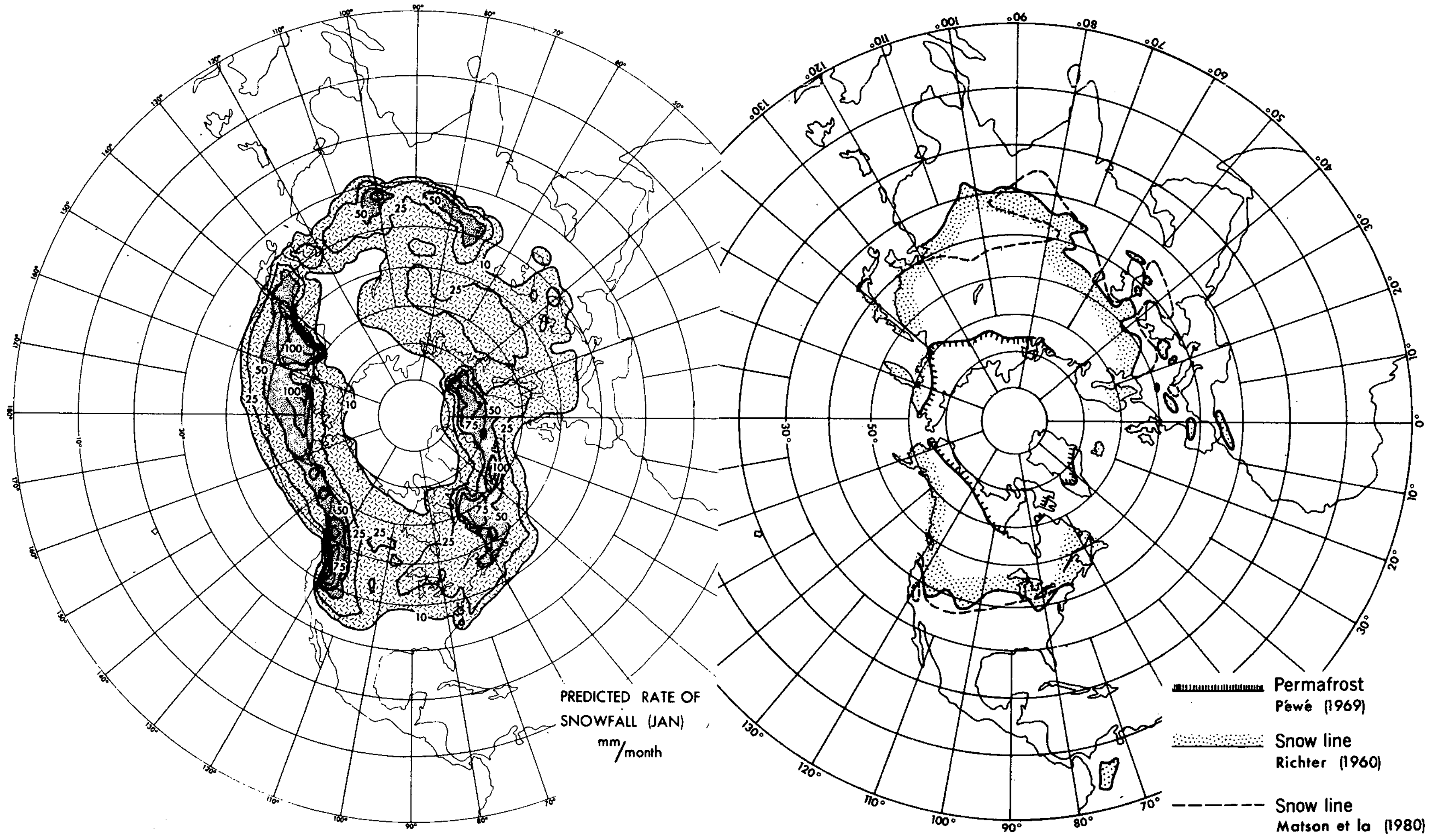

FIG. 8. The rate of snowfall (mm month^{-1} of liquid water) from the model for January (left) and the winter snow line as given by Richter (1960) and January snow line derived by Matson *et al.* (1980) (right).

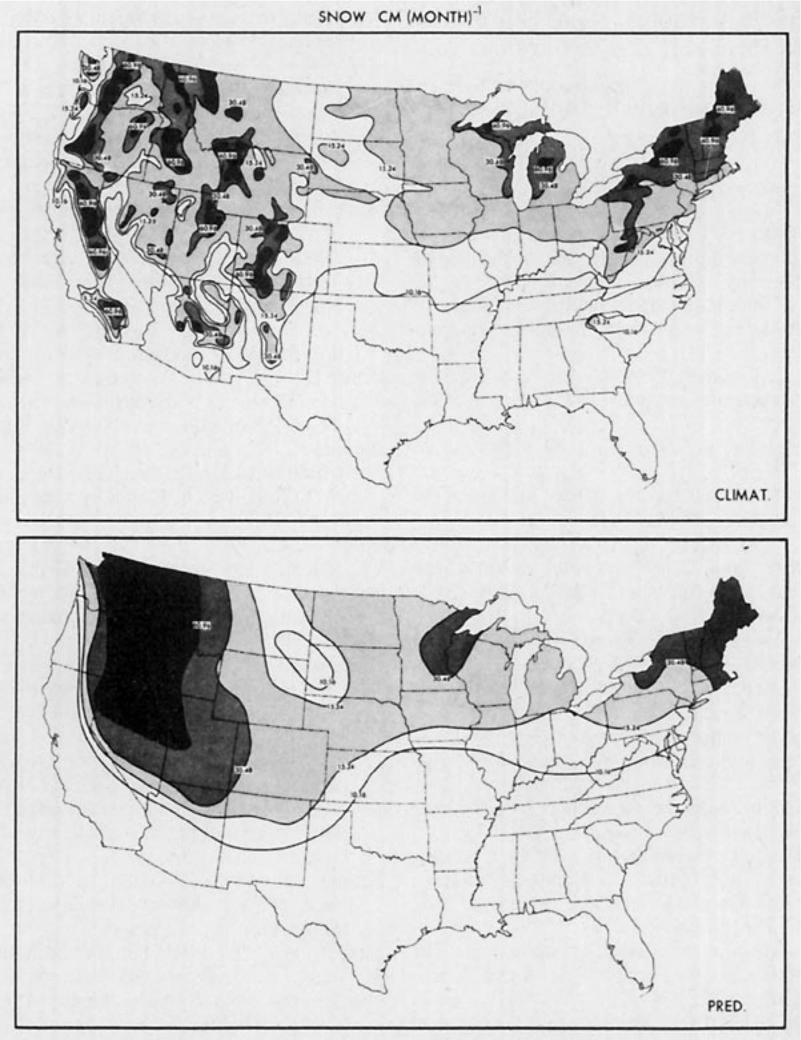

FIG. 9. The climatological rate of snowfall (above) and that given by the prediction (below) in units of cm month^{-1}.

dew-point temperature were also not in good agreement with climatology.

3) Improper soil moisture specification in the prediction is likely to be one of the major causes for the deficiency in the simulation of precipitation, particularly for the deserts of Africa and Asia.

4) Moisture over mountainous areas in the prediction was too high. This is probably due to an inadequate treatment of diffusion over and near mountains. Another possibility is that the surface roughness or the drag over mountains is too small to effectively reduce the low-level advection in the model.

5) The predicted rain distribution over the contiguous United States showed some resemblance to climatology in January but little resemblance in July.

6) The rain pattern over the United States for January shows two major deficiencies. One occurs over the Mississippi and Ohio Valleys, where an area of large amount of rainfall was not well reproduced. In the model, the heavy precipitation was confined to an area along the Gulf coast, and moisture was not carried deeply inland. The second major error occurs over the east coast of the United States crossing a part of the Florida Peninsula, where the model erroneously produced a band of heavy rain.

7) In the rain pattern over the United States for July, the predicted precipitation was widespread, whereas the climatology map shows that rain is mostly confined to the eastern half of the United States. The precipitation in the model was excessively large over Montana, Wyoming, New Mexico, Texas and Colorado. The erroneously high amounts over Montana and Wyoming may be due to the excessive soil moisture, specified in the model. The erroneous rain over New Mexico, Texas and

Colorado may be due to the spurious moisture over the higher elevations, probably due to the same reasons mentioned in 4).

8) The predicted distribution of snow over the United States is reasonable.

REFERENCES

Asakura, T., 1971: Transport and source of water vapor in the Northern Hemisphere and monsoon Asia. *Water Balance of Monsoon Asia,* University of Tokyo Press, 27-51.

Austin, P. M., and A. C. Bemis, 1950: A quantitative study of the "bright band" in radar precipitation echoes. *J. Meteor.*, **7**, 145-151.

Benton, G. S., and M. A. Estoque, 1954: Water vapor transfer over the North American continent. *J. Meteor.*, **11**, 462-477.

Budyko, M. L., 1963: *Atlas of the Heat Balance of the Earth.* Gidrometeorozdat, 69 pp.

Cressman, G. P., 1960: Improved terrain effects in barotropic forecasts. *Mon. Wea. Rev.*, **88**, 327-342.

Crutcher, H. L., and J. M. Meserve, 1970: *Selected Level Heights, Temperatures and Dew Points for the Northern Hemisphere.* Naval Weather Service Command, U.S. Govt. Printing Office, Washington, DC, 29 pp.

Garratt, J. R.,1977: Review of drag coefficients over oceans and continents. *Mon. Wea. Rev.*, **105**, 915-929.

Hollingsworth, A., K. Arpe, M. Tiedtke, M. Capaldo, H. Savijarvi, O. Akesson and J. A. Woods, 1980: The performance of a medium-range forecast model in winter—Impact of physical parameterization. *Mon. Wea. Rev.*, **108**, 1736-1773.

Jaeger, L., 1976: Monatskarten des Niederschlags für die ganze Erde. *Berich. Dtsch. Wetherdienst.*, **18**, No. 139, 38 pp.

Lvovitch, M. I., and S. P. Ovtchinnikov, 1964: *Physical-Geographical Atlas of the World.* Academy of Science, USSR, and Dept. of Geodesy and Cartography, State Geodetic Commission, Moscow.

Manabe, S., 1969: Climate and the ocean circulation: I. The atmospheric circulation and the hydrology of the earth's surface. *Mon. Wea. Rev.*, **97**, 739-774.

——, and J. L. Holloway, Jr., 1975: The seasonal variation of the hydrologic cycle as simulated by a global model of the atmosphere. *J. Geophys. Res.*, **80**, 1617-1649.

——, J. Smagorinsky and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrological cycle. *Mon. Wea. Rev.*, **93**, 769-798.

Matson, M., D. R. Wiesnet, C. P. Berg and E. P. McClain, 1980: New data and new products: The NOAA/NESS continental snow cover data base. *Proc. Fourth Annual Climate Diagnostics Workshop.* Institute for Environmental Studies, University of Wisconsin, 16-18 October 1979. Published by the U.S. Dept. of Commerce, NOAA, 351-364.

Mintz, Y., 1981: The sensitivity of numerically simulated climate to land surface conditions. *Proc. Study Conference on Land Surface Processes in Atmospheric General Circulation Models*, Greenbelt, Maryland [Available from WMO, Geneva, Switzerland.]

Miyakoda, K., 1975: Weather forecasts and the effects of the subgrid scale processes. *Scientific Foundation of Medium Range Weather Forecasts*, Part II, Reading, European Centre for Medium Range Weather Forecasts, 380-593.

——, and J. Sirutis, 1977: Comparative global prediction experiments on parameterized subgrid-scale vertical eddy transports: Description of the parameterizations. *Beitr. Phys. Atmos.*, **50**, 445-488.

——, —— and R. F. Strickler, 1979: Cumulative results of extended forecast experiments II: Model performance for summer cases. *Mon. Wea. Rev.*, **107**, 395-420.

——, ——, —— and I. Shulman, 1972: Cumulative results of extended forecast experiments. I. Model performance for winter cases. *Mon. Wea. Rev.*, **100**, 836-855.

Murakami, T., 1959: The general circulation and water-vapor balance over the Far East during the rainy season. *Geophys. Mag.*, **29**, 131-171.

Murgatroyd, R. J., 1960: Some recent measurements by aircraft of humidity up to 50,000 feet in the tropics, and their relationship to meridional circulation. *Proc. Symposium Atmos Ozone*, Oxford, 20-25 July 1959, *IUGG Monogr.*, No. 3, Paris, 30 pp.

Oort, A. H., and E. M. Rasmusson, 1971: *Atmospheric Circulation Statistics.* NOAA Prof. Pap. No. 5, 323 pp.

Penn, S., 1957: The prediction of snow vs. rain. *Forecasting Guide*, No. 2, J. S. Winston, Ed., U.S. Weather Bureau, 11 pp. [Available from NOAA Library, Rockville, MD.]

Peixoto, J. P., and A. R. Crisi, 1965: Hemispheric humidity conditions during the IGY. Department of Meteorology, MIT. Rep. No. 6, Planetary Circulations Project, Victor P. Starr, Director, 166 pp.

Péwé, T. L., Ed., 1969: *The Periglacial Environment.* McGill, Queen's University Press, 487 pp.

Phillips, N. A., 1957: A coordinate system having some special advantages for numerical forecasting. *J. Meteor.*, **14**, 184-185.

Rasmusson, E. M., 1967: Atmospheric water vapor transport and the water balance of North America: Part I. Characteristics of the water vapor flux field. *Mon. Wea. Rev.*, **95**, 403-426.

Richter, G. D., Ed., 1960: *The Geography of Snow Cover.* Academy of Sciences, USSR, 221 pp.

Sawyer, J. S., 1959: The introduction of the effects of topography into methods of numerical forecasting. *Quart. J. Roy. Meteor. Soc.*, **85**, 31-43.

Schutz, C., and W. L. Gates, 1971: Global climatic data for surface, 800 mb, 400 mb, January. R-915-ARPA, Rand Corp., Santa Monica, 173 pp.

Smagorinsky, J., 1960: On the dynamical prediction of large-scale condensation by numerical methods. *Geophysical Monogr.*, No. 5, Amer. Geophys. Union, 71-78.

——, R. F. Strickler, W. E. Sangster, S. Manabe, J. L. Holloway and G. D. Hembree, 1967: Prediction experiments with a general circulation model. *Proc. Int. Symp. Dynamics of Large Scale Processes in the Atmosphere.* Moscow, 1965, Izdatel stvo "nauka", 70-134.

Somerville, R. C. J., P. H. Stone, M. Halem, J. E. Hansen, J. S. Hogan, L. M. Druyan, G. Russell, A. A. Lacis, W. J. Quirk and J. Tenenbaum, 1974: The GISS model of the global atmosphere. *J. Atmos. Sci.*, **31**, 84-117.

Staff Members of the Section of Synoptic and Dynamic Meteorology, Inst. of Geophysics and Meteorology, Academia Sinica, Peking, 1957: On the general circulation over eastern Asia. *Tellus*, **9**, 432-442.

Stone, P. H., S. Chow and W. J. Quirk, 1977: The July climate and a comparison of the January and July climates simulated by the GISS general circulation model. *Mon. Wea. Rev.*, **105**, 170-194.

U.S. Environmental Data Service, 1968: *Climatic Atlas of the United States.* Environmental Science Service Administration, U.S. Dept. of Commerce, 80 pp.

U.S. Navy Hydrographic Office, 1944: *World Atlas of Sea Surface Temperature.* Washington, DC, H.O. Pub. No. 225, 48 pp.

Wagner, A. J., 1957: Mean temperature from 1000 mb to 500 mb as a predictor of precipitation type. Sci. Rep. No. 2, Contract AF 19(604)-1305, Dept. of Meteorology, MIT, 19 pp.