MONTHLY MEAN SIMULATION EXPERIMENTS WITH A COARSE-MESH GLOBAL ATMOSPHERIC MODEL [1, 2]

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[2] Contribution No. 107, CUNY Institute of Marine and Atmospheric Sciences.

Abstract

Monthly mean simulations of the global atmosphere for October 1976 through February 1977, initialized with data from the beginning of each month, were computed with a new coarse-resolution general circulation model developed at the Goddard Institute for Space Studies. Measured in terms of the monthly mean fields of sea-level pressure, 850 mb temperature, and 500 mb height, the simulation skill of the model, which is still under development, was found to be inadequate, thus far, compared with climatology.

Substitution of observed monthly mean sea-surface temperatures (SSTs) as lower boundary conditions, in place of climatological SSTs, failed to improve the model simulations. While the impact of SST anomalies on the model output is greater at sea level (where anomalously cold and warm water generate higher and lower sea-level pressures, respectively) than at upper levels (where it is negligible), the impact on the monthly mean simulations is not beneficial at any level.

Shifts of one and two days in initialization time produced small, but non-trivial, changes in the model-generated monthly mean synoptic fields. No improvements in the mean simulations resulted from the use of either time-averaged initial data or re-initialization with

time-averaged early model output.

The noise level of the model, as determined from a multiple initial state perturbation experiment, was found to be generally low, but with a noisier response to initial state errors in high latitudes than in the tropics. However, the influence of random initial state errors on the monthly mean simulations is negligible compared with the large-scale simulation errors, indicating both stable model behavior and the need for further model improvement.

Introduction

A new global general circulation model (GCM) with coarse horizontal resolution has recently been developed at the Goddard Institute for Space Studies (GISS) (Hansen, 1978). Designed primarily for climate investigations, the model is currently capable of generating one day of simulation on an 8 x 10 degree latitude-longitude grid in four minutes (on an IBM 360/95 computer), which is an order of magnitude faster than the 4 x 5 degree GISS model (Somerville et al., 1974) from which it was derived.

Diagnostic tests of the new "Climate Model" have been encouraging enough to warrant a preliminary evaluation of its capability as a prediction system. The high speed of the model makes it particularly attractive for long-range forecasting studies. For example, a 30-day forecast can now be executed in two hours. We have, therefore, undertaken to use the model for some monthly mean prediction experiments similar to those carried out with the GISS model (Spar et al., 1976; Spar, 1977 a, b; Spar et al., 1978; Spar and Lutz, 1978). Because these forecast experiments are not conducted in an operational context, they are referred to here as simulations.

Like the GISS model, the climate model is a global, spherical coordinate, primitive equation system, divided vertically into nine dynamically active layers, with top at 10 mb (p_t), bottom at the earth's surface (surface pressure, p_s), and sigma (σ), the vertical pressure coordinate, defined as $(p - p_t)/(p_s - p_t)$. (For radiation, but not dynamical, calculations, three additional levels have been added in the stratosphere above 10 mb.) Horizontally, the coarse-mesh version of the model used in these experiments employs a 24 x 36 gridpoint array symmetrical about the Equator, corresponding to intervals of approximately 8° of latitude by 10° of longitude, and a 12-minute time step. The Arakawa (1972) computational scheme, including "TASU-Matsuno" extrapolation, was used in these calculations, as in the GISS model (Somerville et al., 1974). (For this experiment, the computation time was eight minutes per simulated day. In more recent versions of the model, the running time has been cut in half with the introduction of leapfrog extrapolation and a 15-minute time step.) Because of the large grid size, it is necessary to assign to each gridpoint fractional values of ocean, land, snow, and ice representative of the areas surrounding the point for use in the physical calculations.

Snow cover in the model is computed from the surface air and ground temperature calculations, and surface albedo is variable. Both solar and long-wave radiation calculations make use of a generalization of the "k-distribution method" (Lacis and Hansen, 1974), which includes multiple scattering and takes into account H_2O, CO_2, O_3, O_2, trace gases, and aerosols. Clouds are treated as non-black bodies with albedo dependent on zenith angle. Dry and moist convection in the model are computed by a method based on the spatial variance of static energy and a form of convective adjustment. The model computes precipitation and ground wetness, and sub-surface as well as surface temperatures over land and ice. Sea-surface temperatures are prescribed as boundary conditions.

The purpose of the present study was to determine how accurately the coarse-mesh climate model simulates observed monthly mean states of the atmosphere from given initial and surface boundary conditions. It should be noted, however, that the model has been undergoing continuous development since these experiments were started, and that the results reported here are not necessarily representative of its ultimate performance.

The period selected for this test was the anomalous winter of 1976-1977, which was characterized by unusually cold weather in the eastern United States with abnormally high temperatures in the west. Four groups of experiments were carried out, all based on global data for the period October 1976 through February 1977 provided by the National Center for Atmospheric Research (NCAR) and the National Meteorological Center (NMC), and derived from operational NMC analyses. In the first experiment, initial data for 00 GMT on the first day of each month were used to initialise five month-long forecast runs. At the end of each run, the 12-hourly outputs of the model were averaged to produce a predicted monthly mean state. In this experiment, climatological monthly average sea-surface temperature (SST) and sea-ice fields from the Rand atlas (Alexander and Mobley, 1974) were used as surface boundary conditions. In a second experiment, to measure the impact on the simulations of anomalous ocean temperatures, the five forecast runs were repeated with observed monthly mean SST values derived from satellite radiometer measurements (Brower et al., 1976) used in place of the climatological SSTs.

A third group of experiments was carried out to determine the effect on the monthly mean simulations of a systematic alteration in the initial synoptic pattern, such as might result from a shift in initialization time or the smoothing of initial conditions. Two of the monthly forecast runs (for October 1976 and January 1977) were repeated twice, starting with observed initial data for 00 GMT on the second and third day of each month, respectively, rather than the first. Averages for corresponding periods to the end of the month were then compared in order to assess the sensitivity of the model-generated monthly means to the arbitrary choice of initialization time. In a related experiment, the NMC data were averaged over the first 2½ days of the months to obtain a set of time-averaged initial conditions. The forecast computations were then repeated with these as initial fields to determine whether such smoothing of the initial data would result in more realistic monthly mean simulations than those generated from the "noisier" instantaneous initializations. Another similar experiment was also conducted, in which the model was re-initialized with time-averaged output from the first five days of the original forecast runs before the completion of the monthly simulations.

A fourth set of computations was performed to measure the "noise level" of the model (Chervin and Schneider, 1976 a, b). In this experiment, which closely resembles the random initial state perturbation experiment carried out with the GISS model (Spar et al., 1978), initial conditions for October 1976 were contaminated four times with different random error distributions, resulting in a total of five simulations for that month. The dispersion of the simulations represents the inherent uncertainty, or "noise", of the model-generated monthly mean fields associated with unavoidable random errors in the initial conditions. Such noise level statistics indicate not only the irreducible minimum error of the monthly mean simulations, but also the minimum detectable signal from a prescribed climate change experiment with the model (Chervin and Schneider, 1976 b).

Three quantities were selected for analysis and evaluation: sea-level pressure, 850 mb temperature, and 500 mb height. Simulated and observed monthly mean fields of these variables were computed over the globe, but the main emphasis of the evaluation was placed on the Northern Hemisphere, with particular attention to the quality of the simulations over the North American quadrant during this anomalous winter. The simulation skill of the model was evaluated numerically over seven regions, ranging in size from the United States to the whole globe, in terms of area-weighted root-mean-square (rms) errors and S1 (gradient) skill scores (Teweles and Wobus, 1954).

To provide a standard for evaluation of the model simulations, monthly climatological fields of the three variables, interpolated from data furnished by NCAR[3], were also evaluated as "forecasts" of the five observed monthly mean states. Comparison of the error statistics of the model simulations with those for climatology provides an objective measure of the model's capability of reproducing climatic anomalies.

[3] The NCAR climatology is derived from a variety of sources as described in Crutcher and Meserve (1970) and Jenne et al. (1974).

Basic Simulation Experiment[4]

The model was first initialized with global data interpolated from the operational NMC analyses for 00 GMT on the first day of each of the five months, October 1976 through February 1977. Sea-surface temperatures and sea-ice locations, based on the monthly climatological data of Alexander and Mobley (1974), but interpolated daily, were specified as surface boundary conditions.

The characteristics of the anomalous cold winter of 1976-1977 began to appear over North America during the latter half of September (Taubensee, 1976) in the form of a deep tropospheric trough near the east coast of North America with a strong ridge in the west. As a result of this upper air flow pattern, which persisted through January, record low temperatures developed over the eastern United States, while temperatures were abnormally warm in the west (Wagner, 1977 a; Dickson, 1977 a; Taubensee, 1977; Wagner, 1977 b). In January the wave pattern amplified still further (Wagner, 1977 b), leading to repeated advection of Arctic air southward into the eastern United States, where surface temperatures fell far below normal, notably in the Ohio Valley,

[4] Adapted in part from a master's thesis submitted to the City College by Robert J. Lutz.

producing one of the coldest months on record.

February brought about a modification and eventually a breakdown of this anomalous situation (Dickson, 1977 b). The mean ridge over the Pacific Northwest moved eastward and the wave pattern flattened. Particularly during the last week in February, the mid-tropospheric circulation over North America changed abruptly. The large-amplitude wave pattern, which had dominated the winter season, broke down and gave way to fast westerlies with fast moving storm systems traveling across the country. With westerly flow now dominant, warm air spread quickly across the country and temperatures rose above normal in the eastern United States.

How well the model simulation reproduced the anomalous circulation and temperature fields during the winter of 1976-1977 may be seen in Figures 1, 2, and 3, which show the distribution over the northwest quadrant of the earth of sea-level pressures, 850 mb temperatures, and 500 mb geopotential heights plotted in units of mb - 1000, degrees Celsius, and decameters - 500, respectively. For each month the observed field is shown at the top and the simulation at the bottom of the figure.

In Figures 1, 2, and 3, North America lies in the center of the region, with the North Atlantic Ocean in the right-hand third of the map and the eastern North

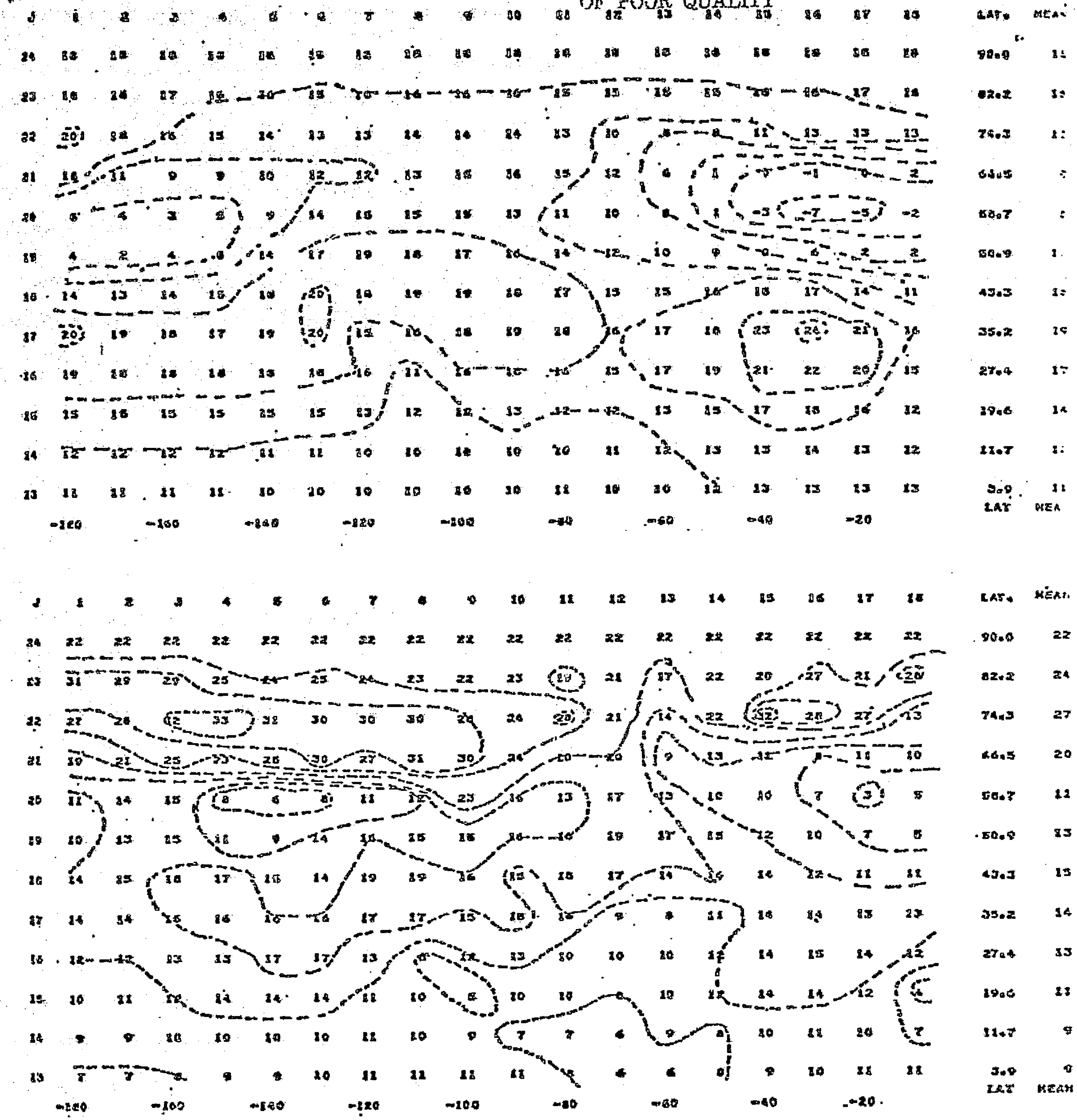


Figure 1. Monthly mean sea-level pressures over the northwest quadrant.
Top: observed; bottom: simulated.
Units: mb - 1000. 4 mb isobars.

(a) October 1976.

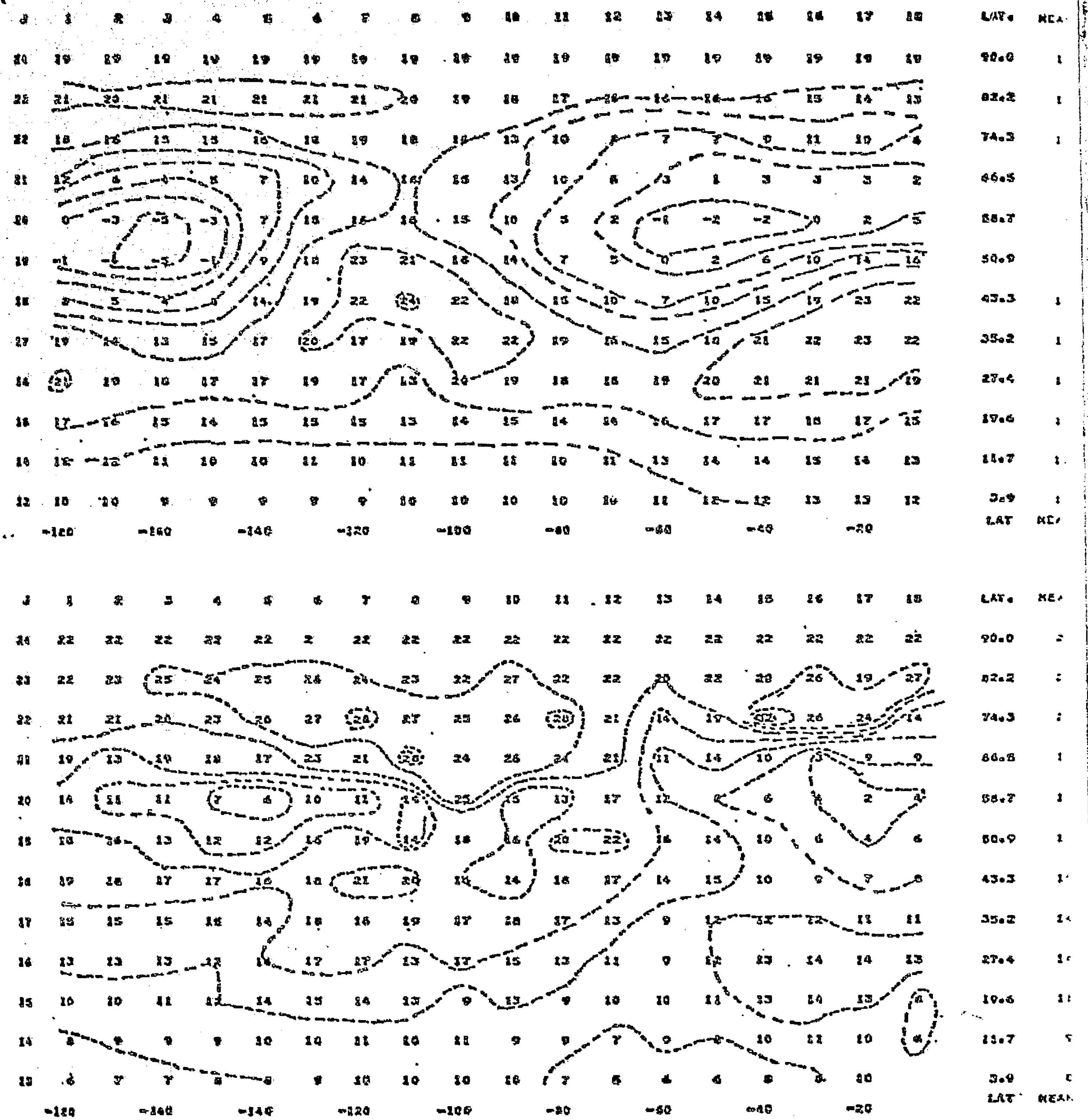


Figure 1. (b) November 1976.

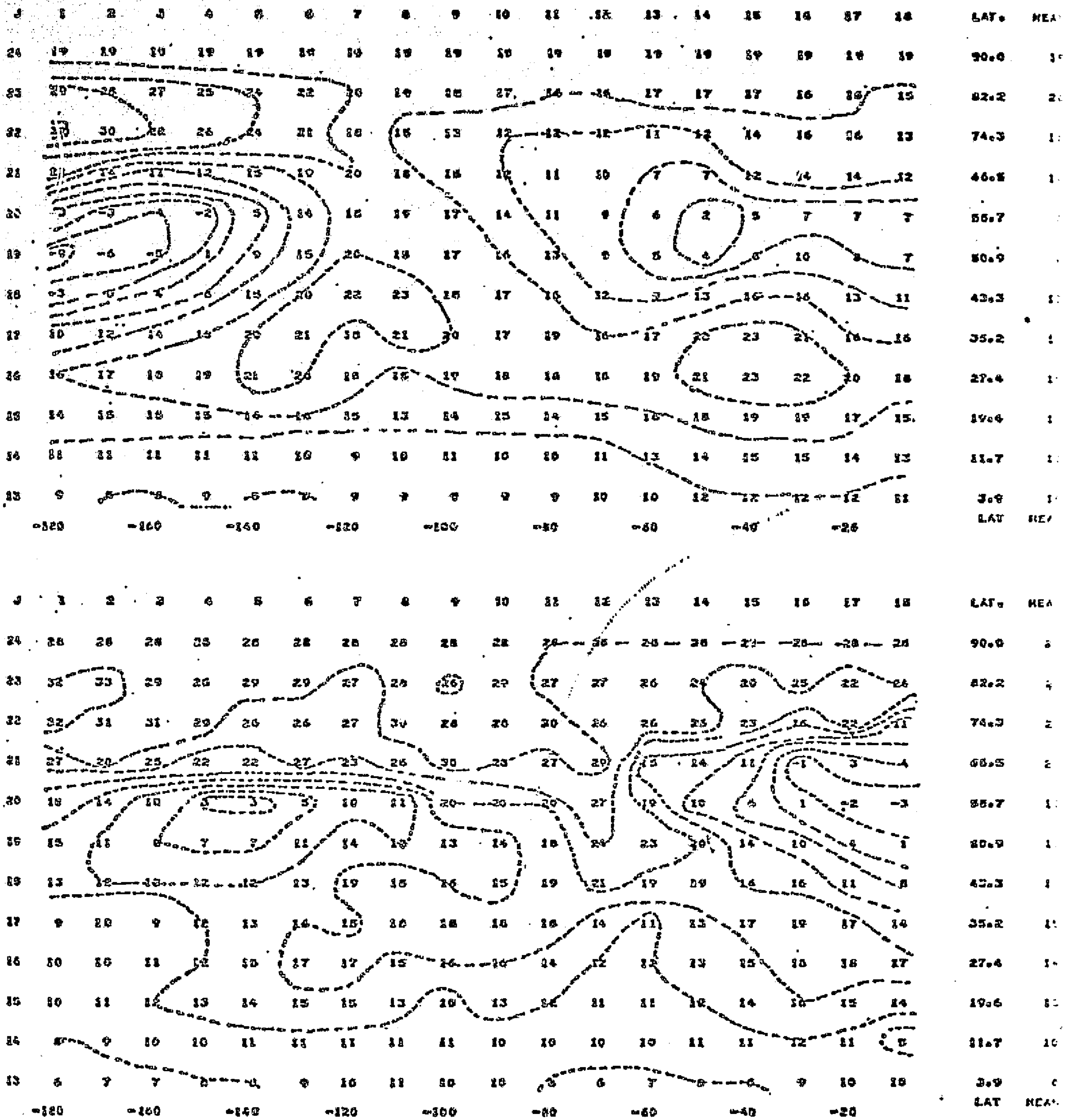
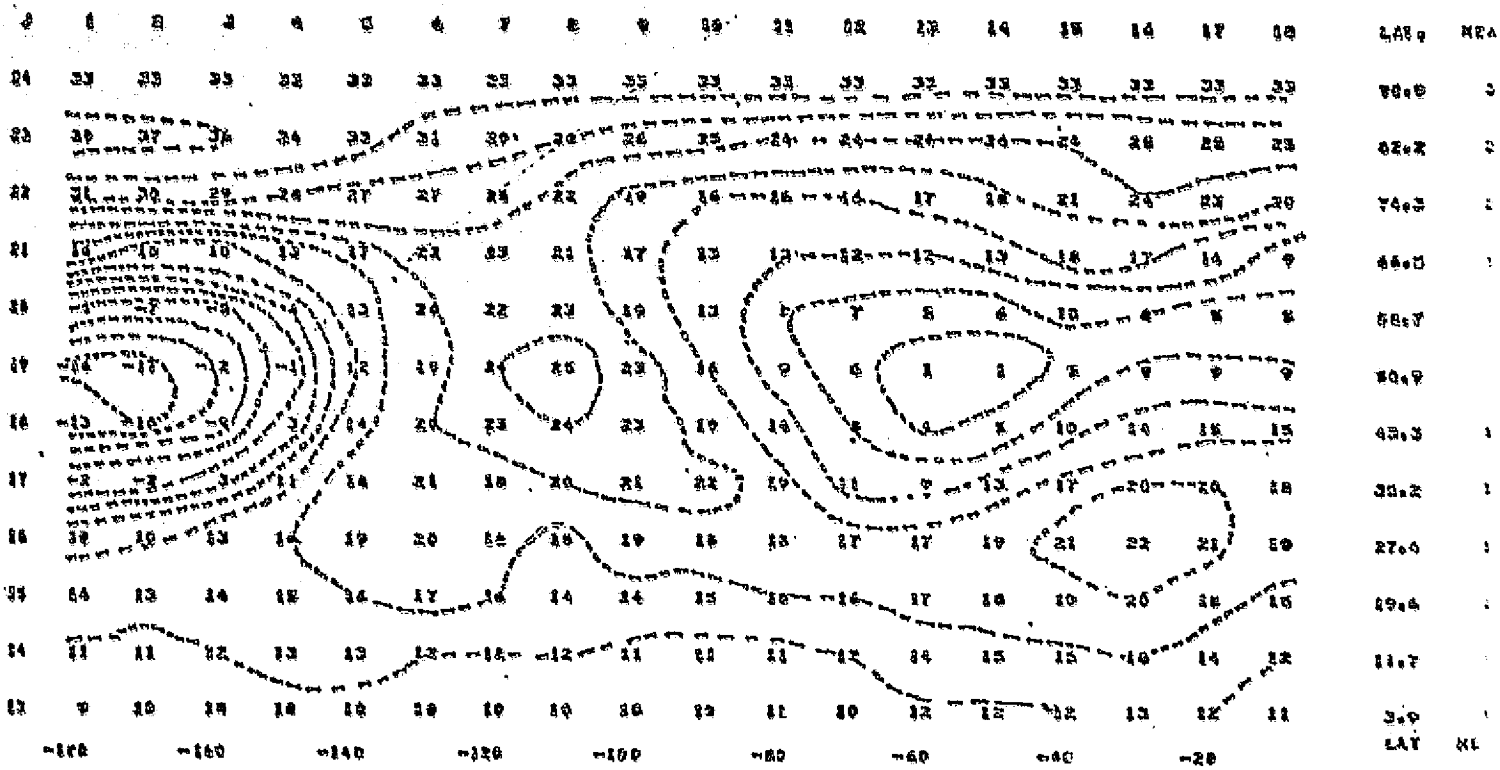


Figure 1. (c) December 1976.



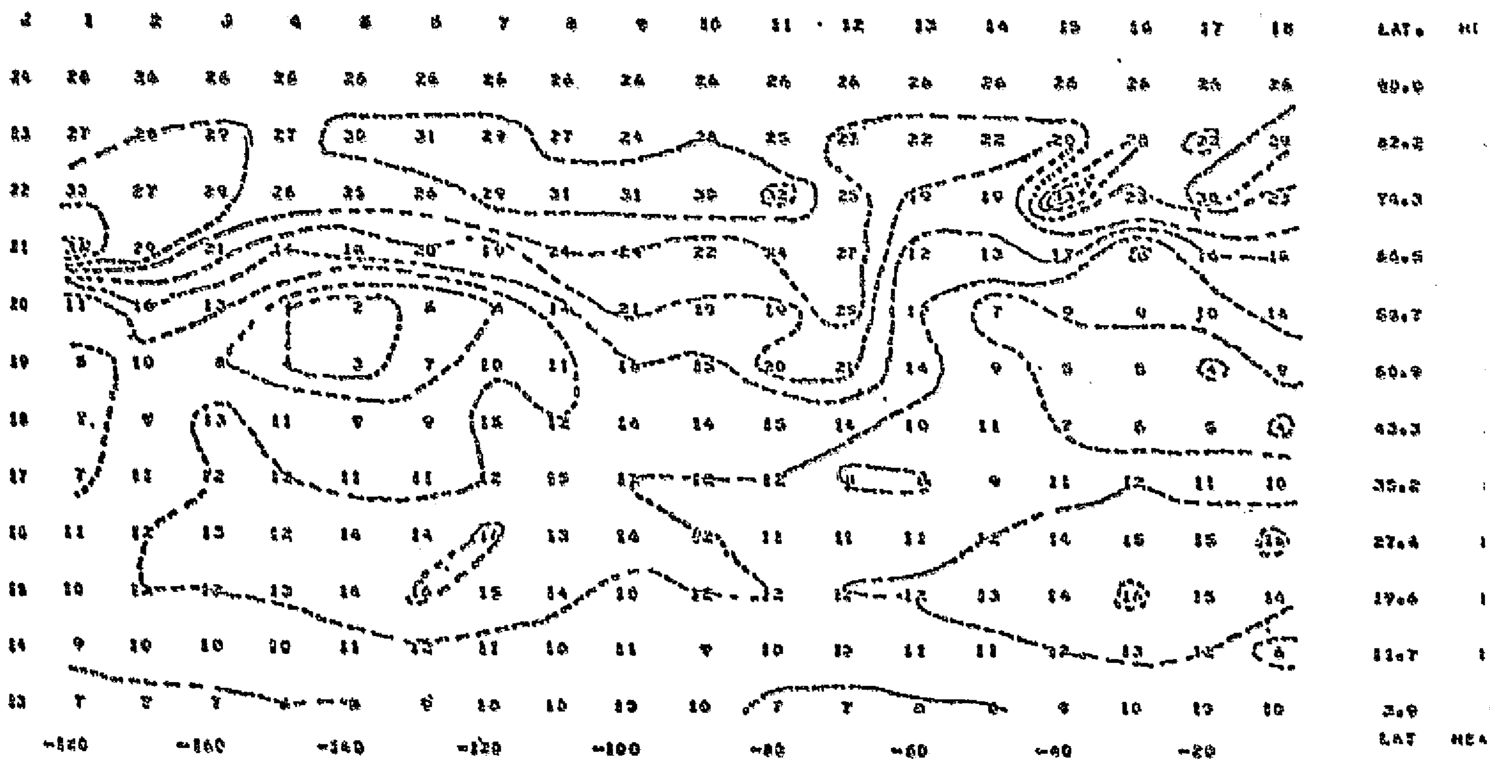


Figure .1. (d) January 1977.

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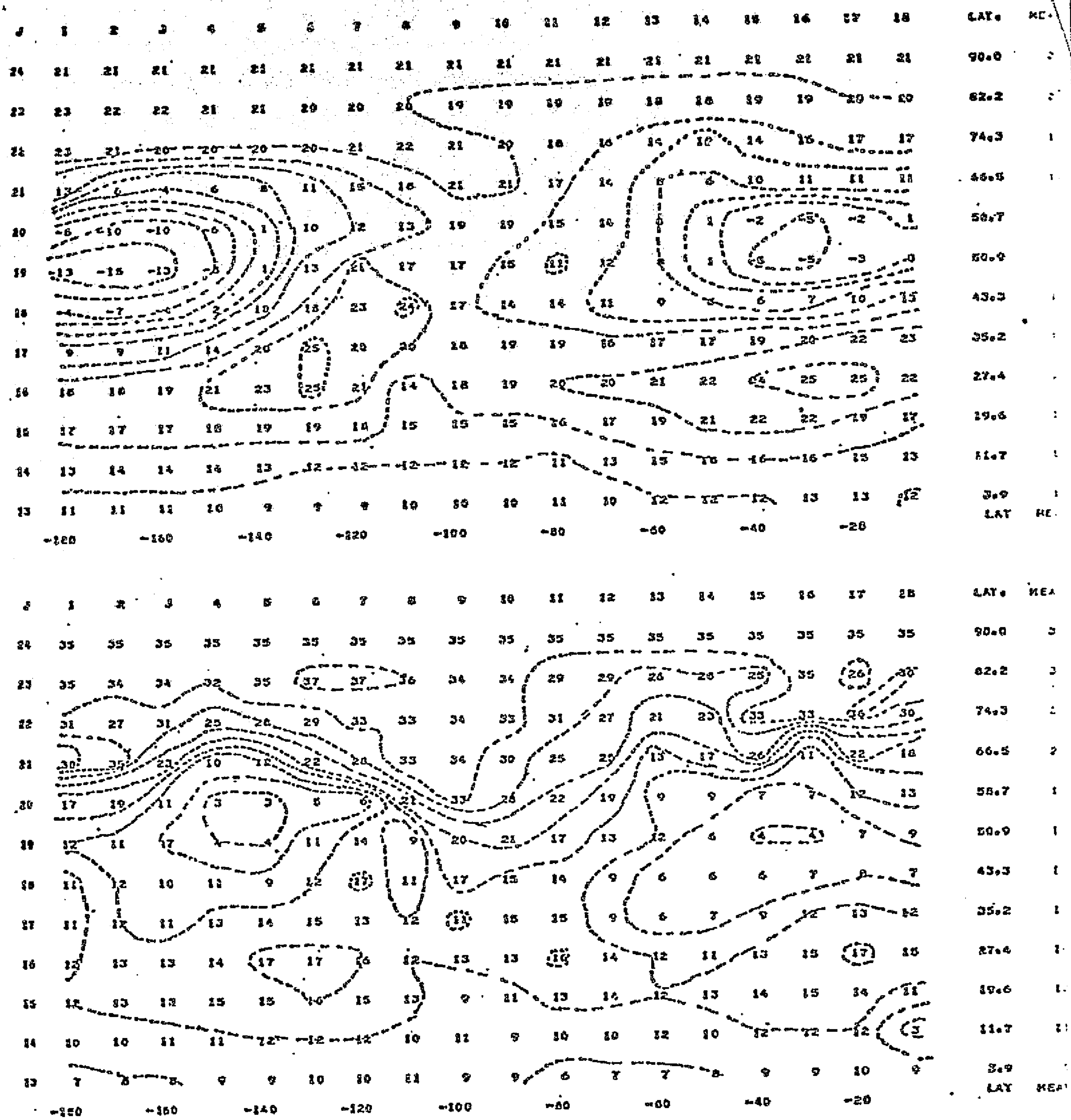


Figure 1. (e) February 1977.

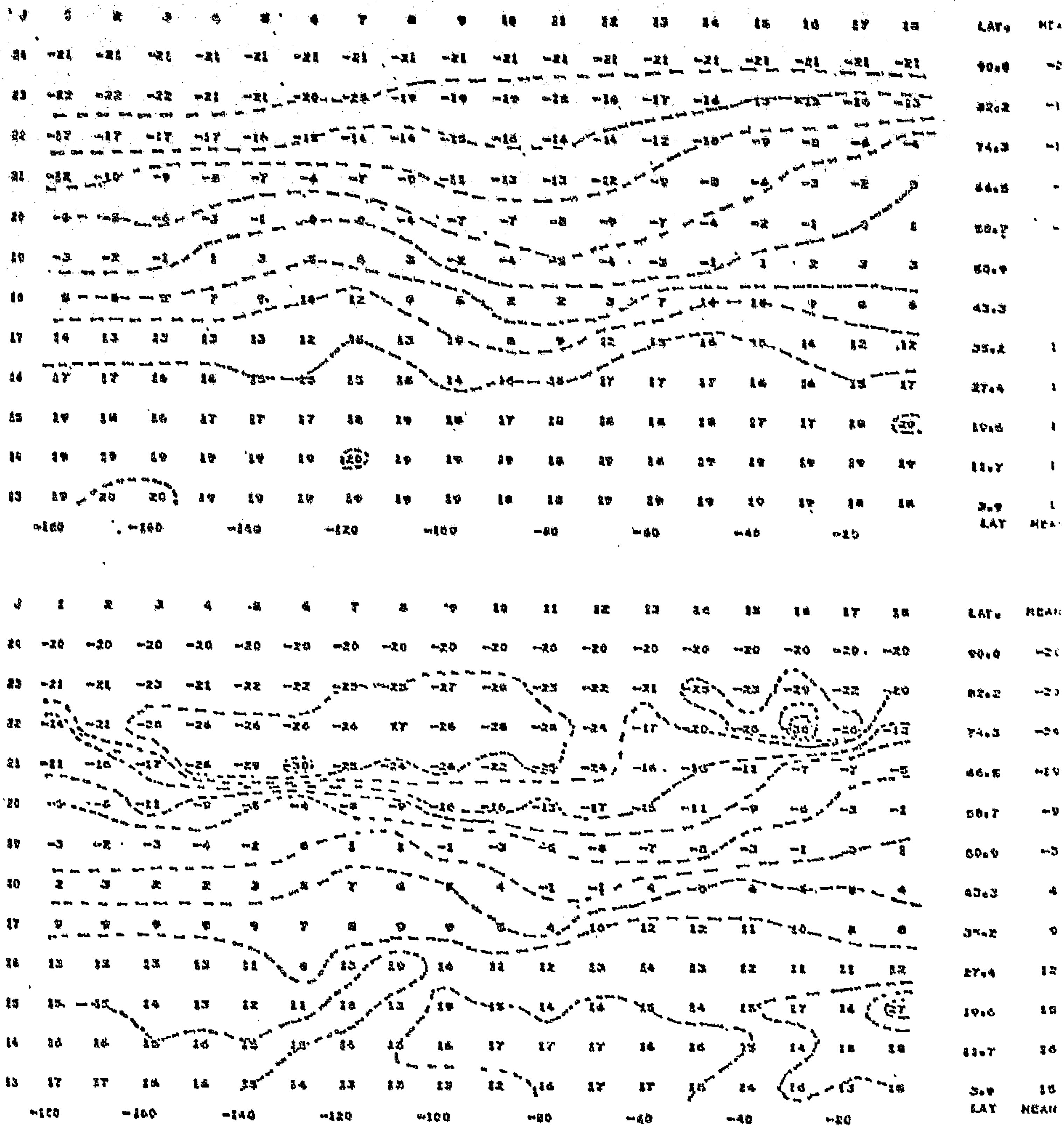
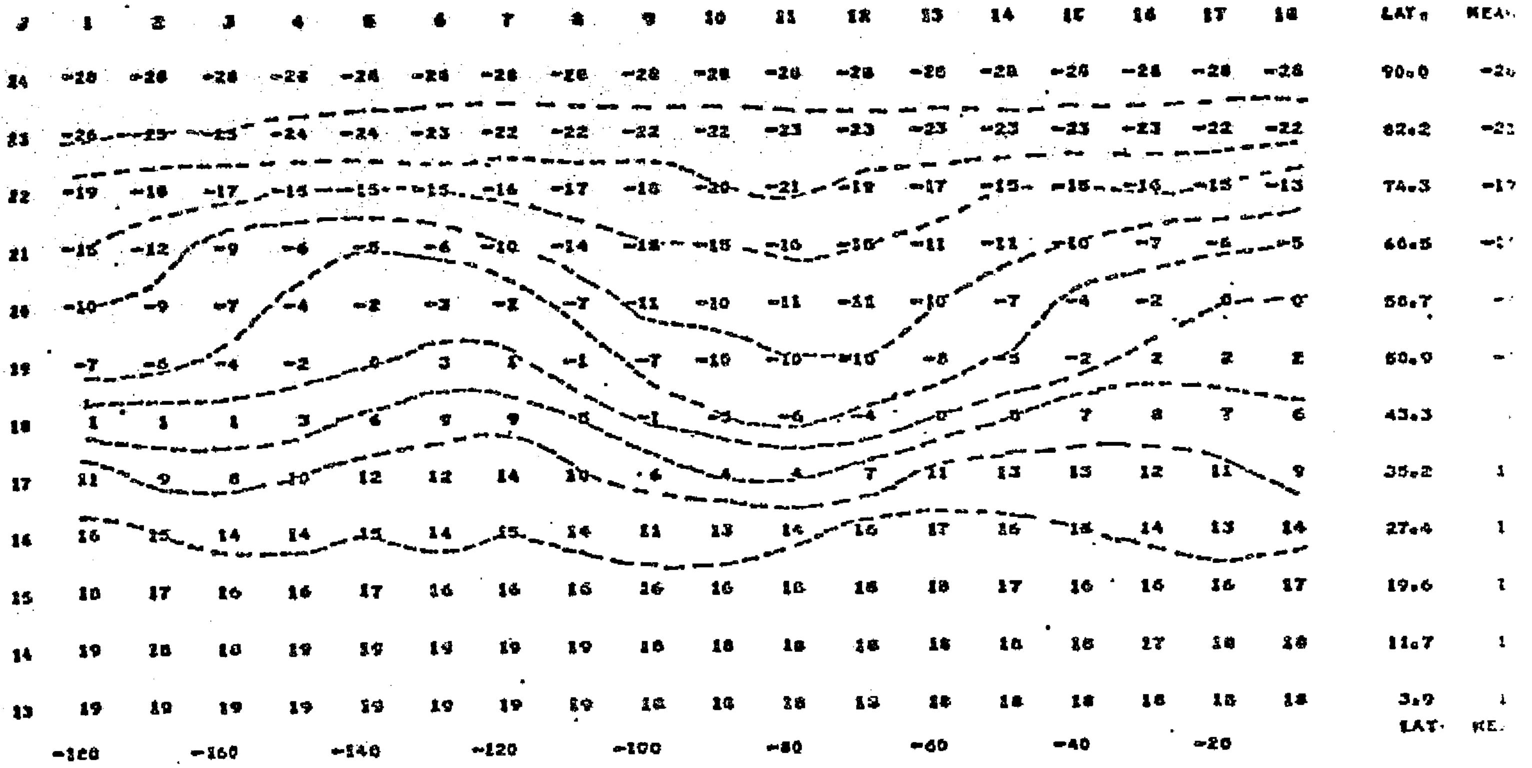


Figure 2. Monthly mean 850 mb temperatures over the northwest quadrant.
Top: observed; bottom: simulated.
Units: degrees C. 5°C isotherms.

(a) October 1976.



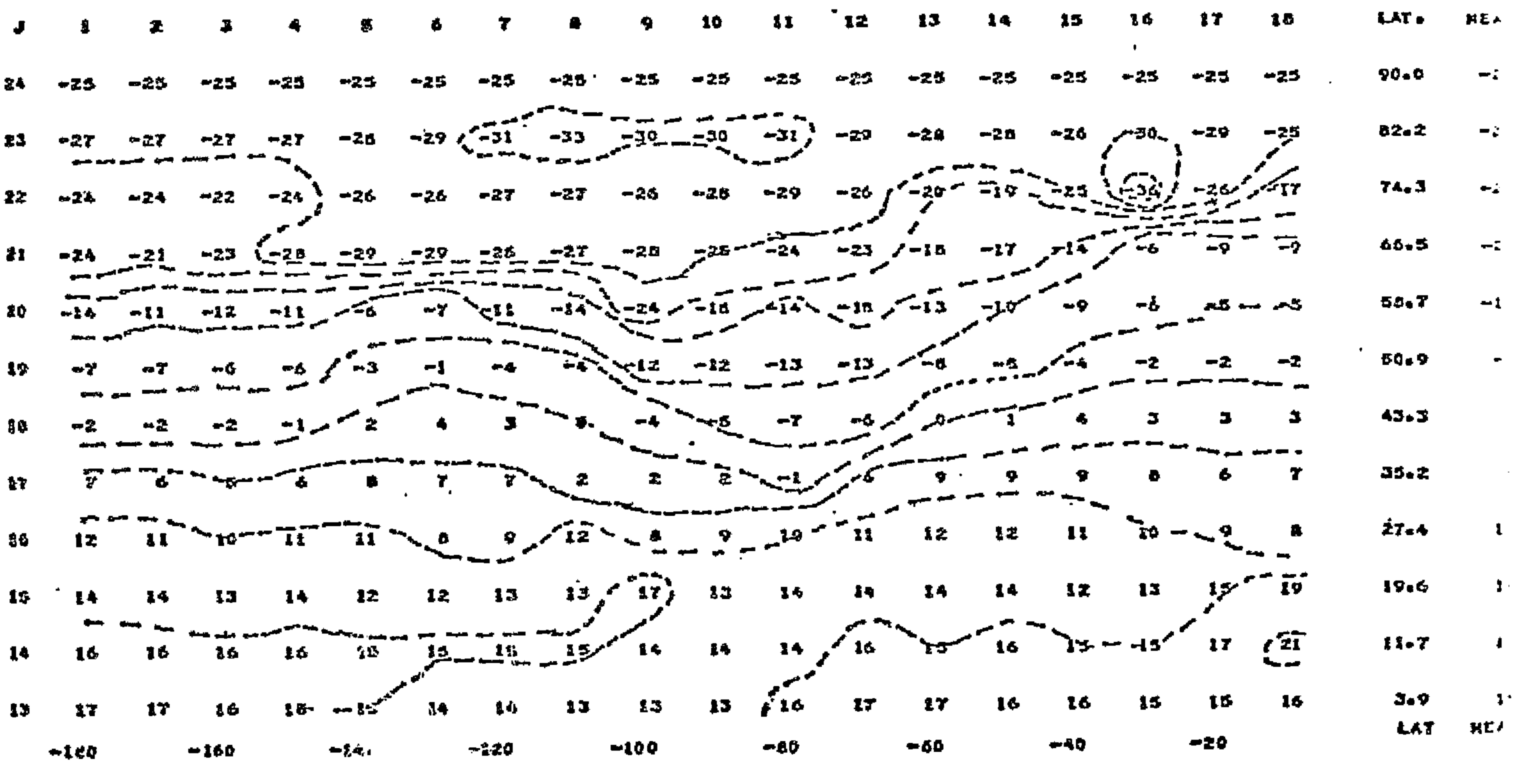


Figure 2. (b) November 1976.

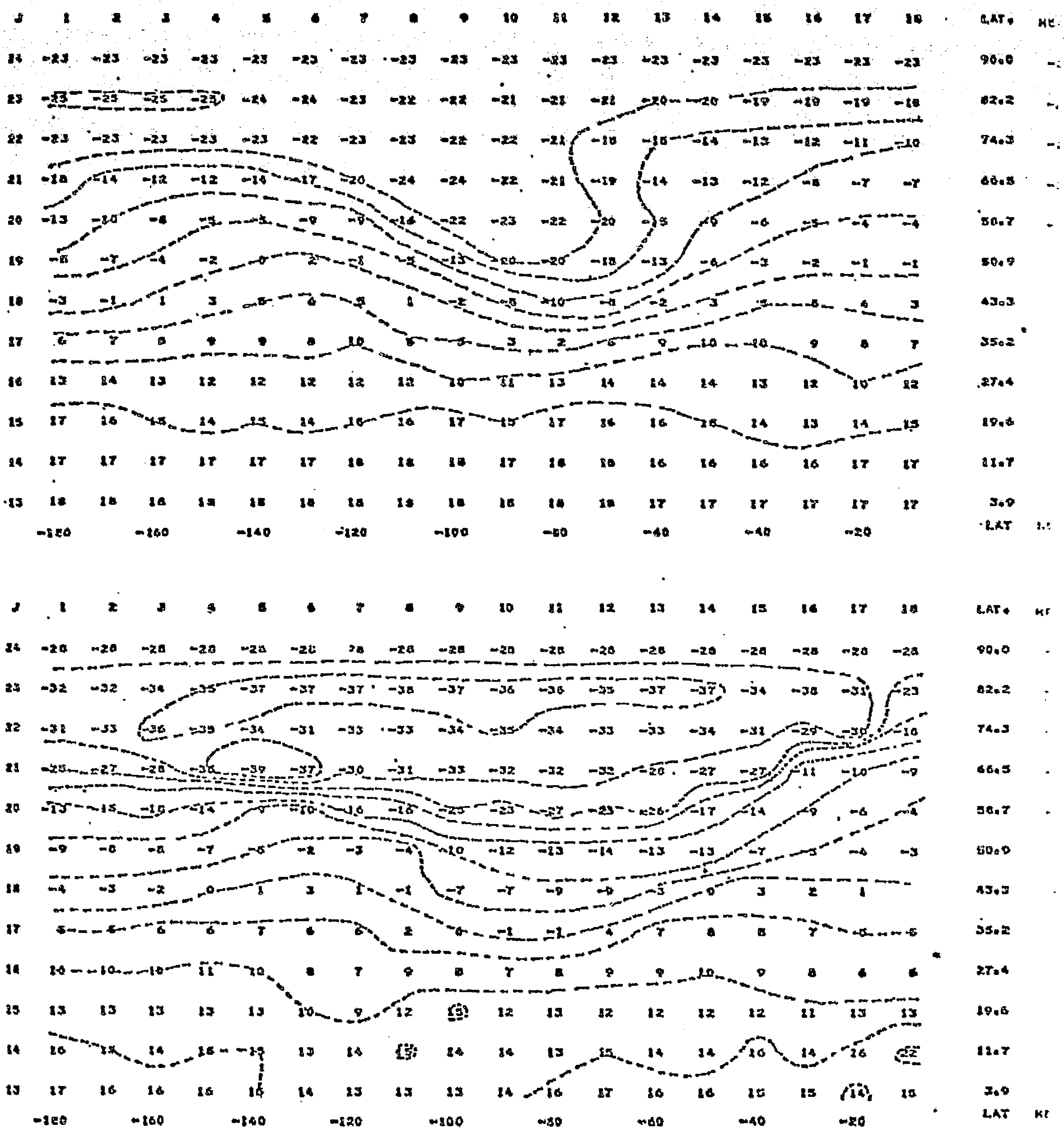
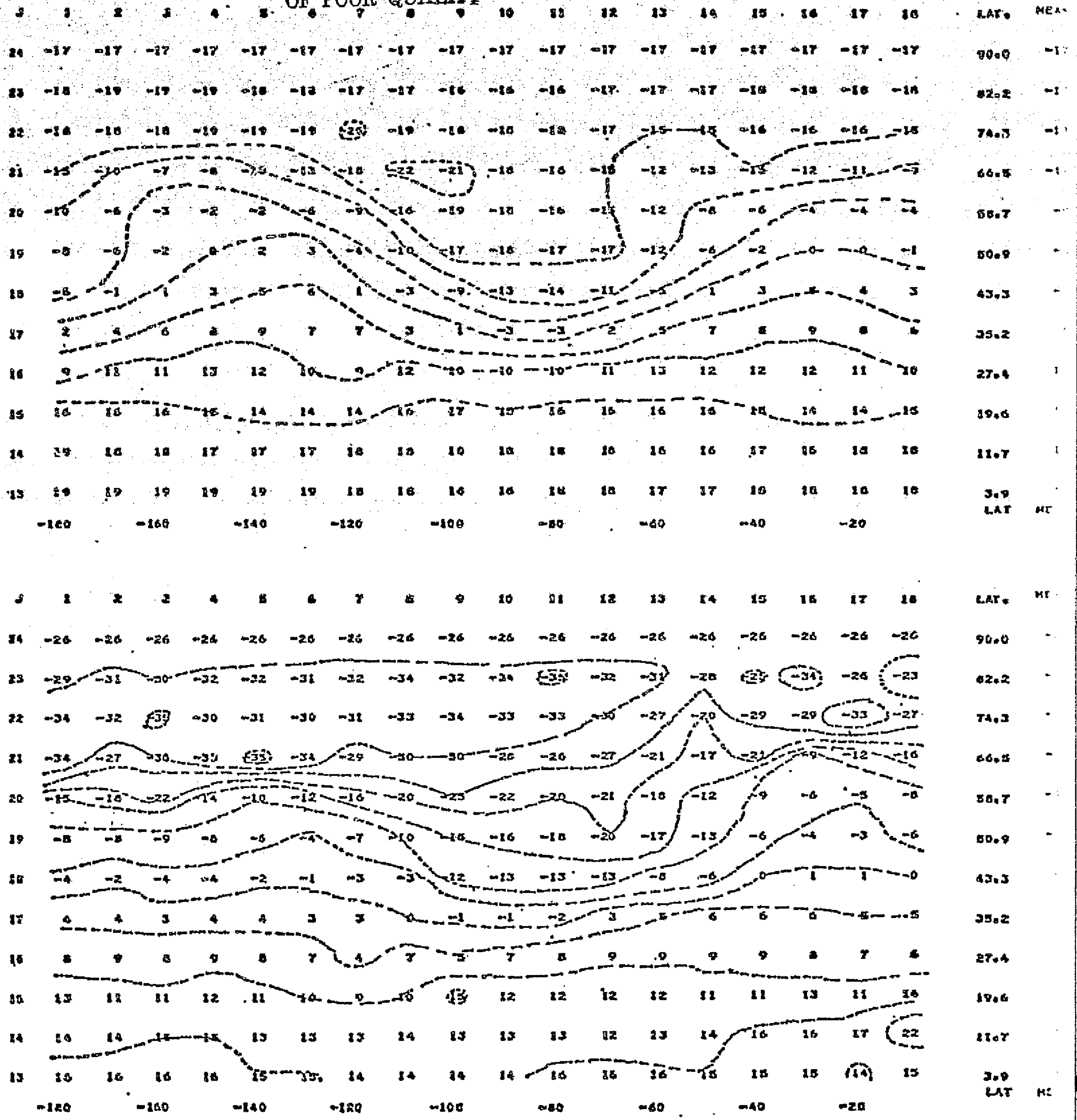


Figure 2. (c) December 1976.



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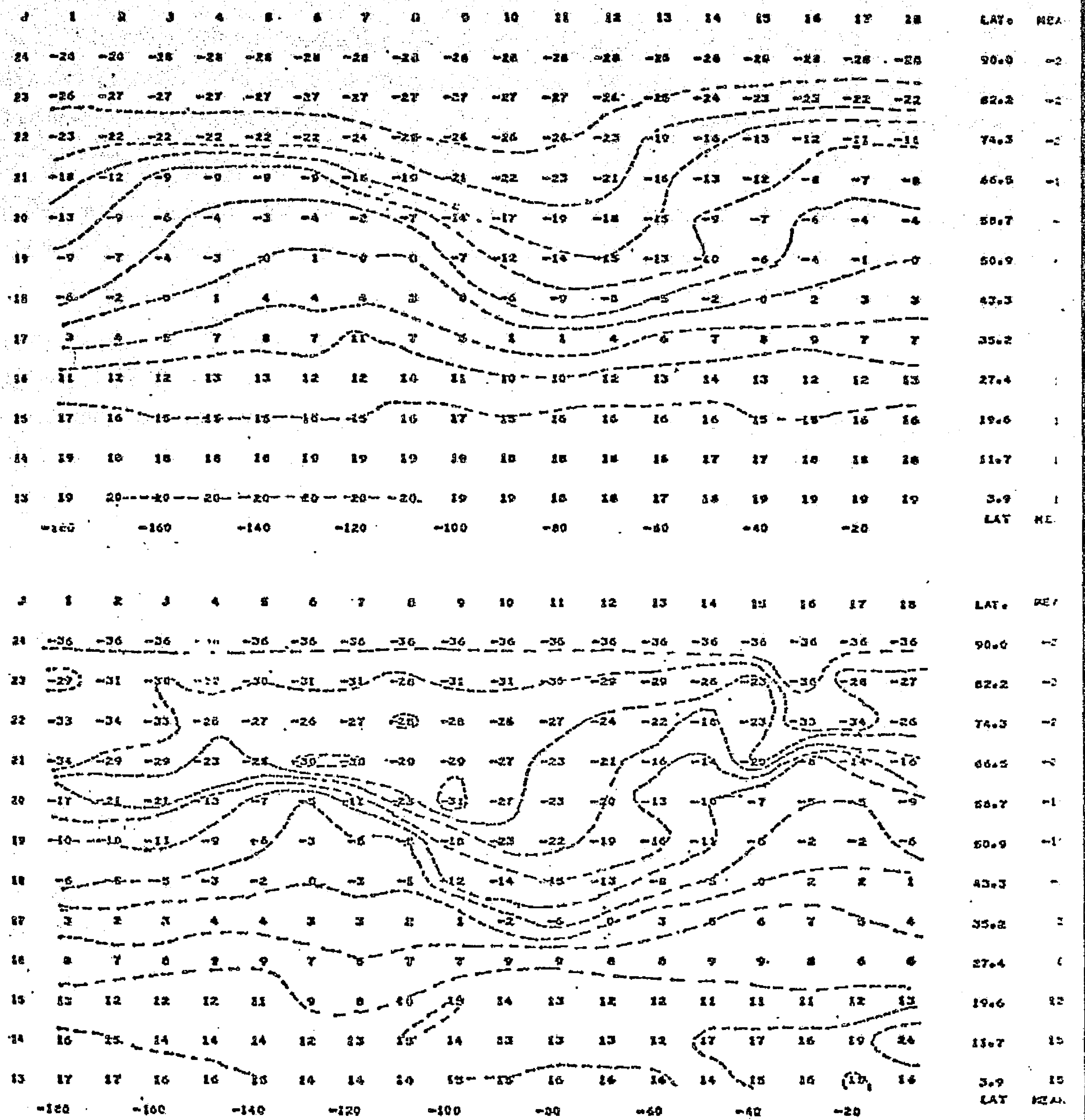

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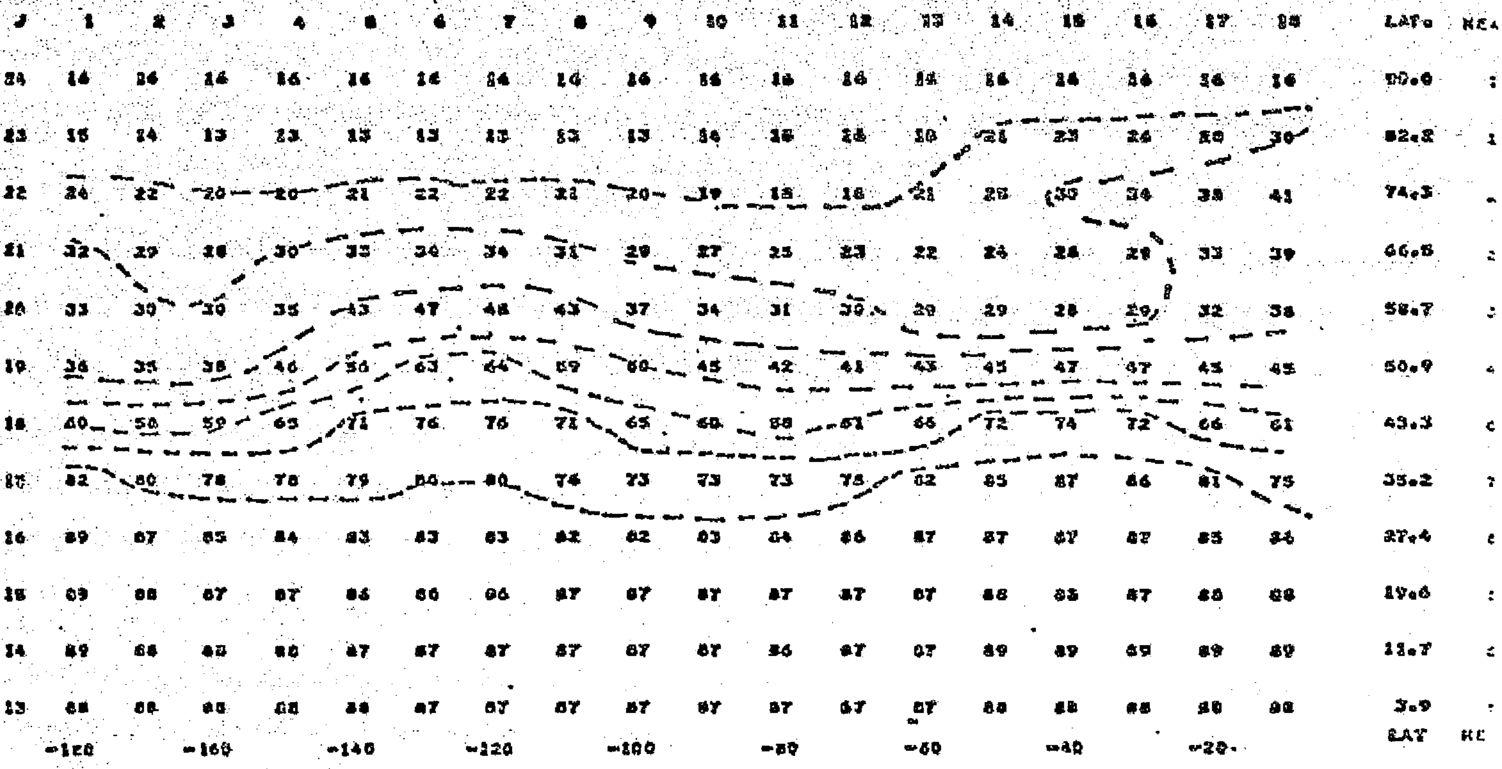

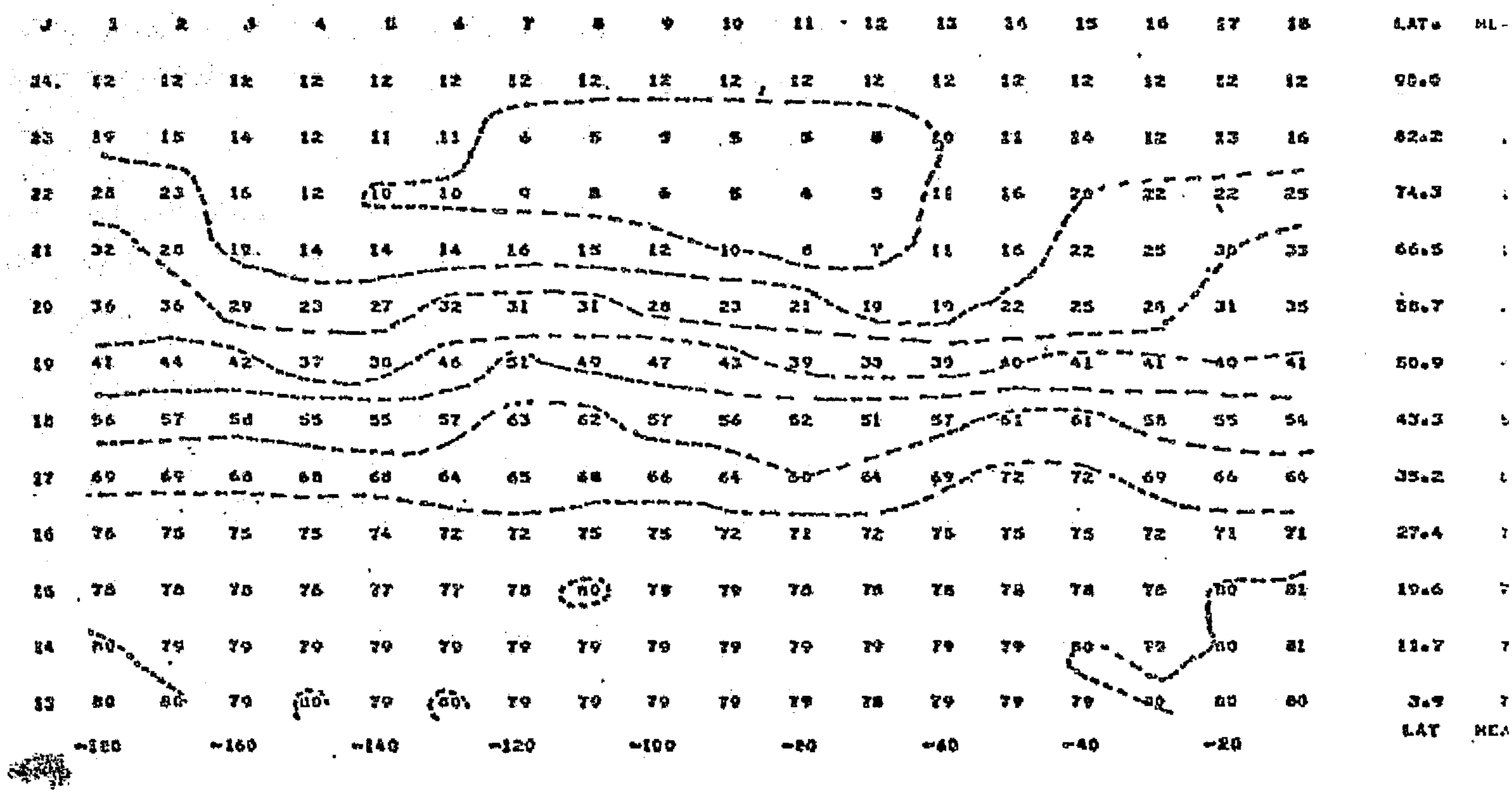

Figure 3. Monthly mean 500 mb geopotential heights over the northwest quadrant. Top: observed; bottom: simulated. Units: decameters - 500. 100 m contours.

(a) October 1976.

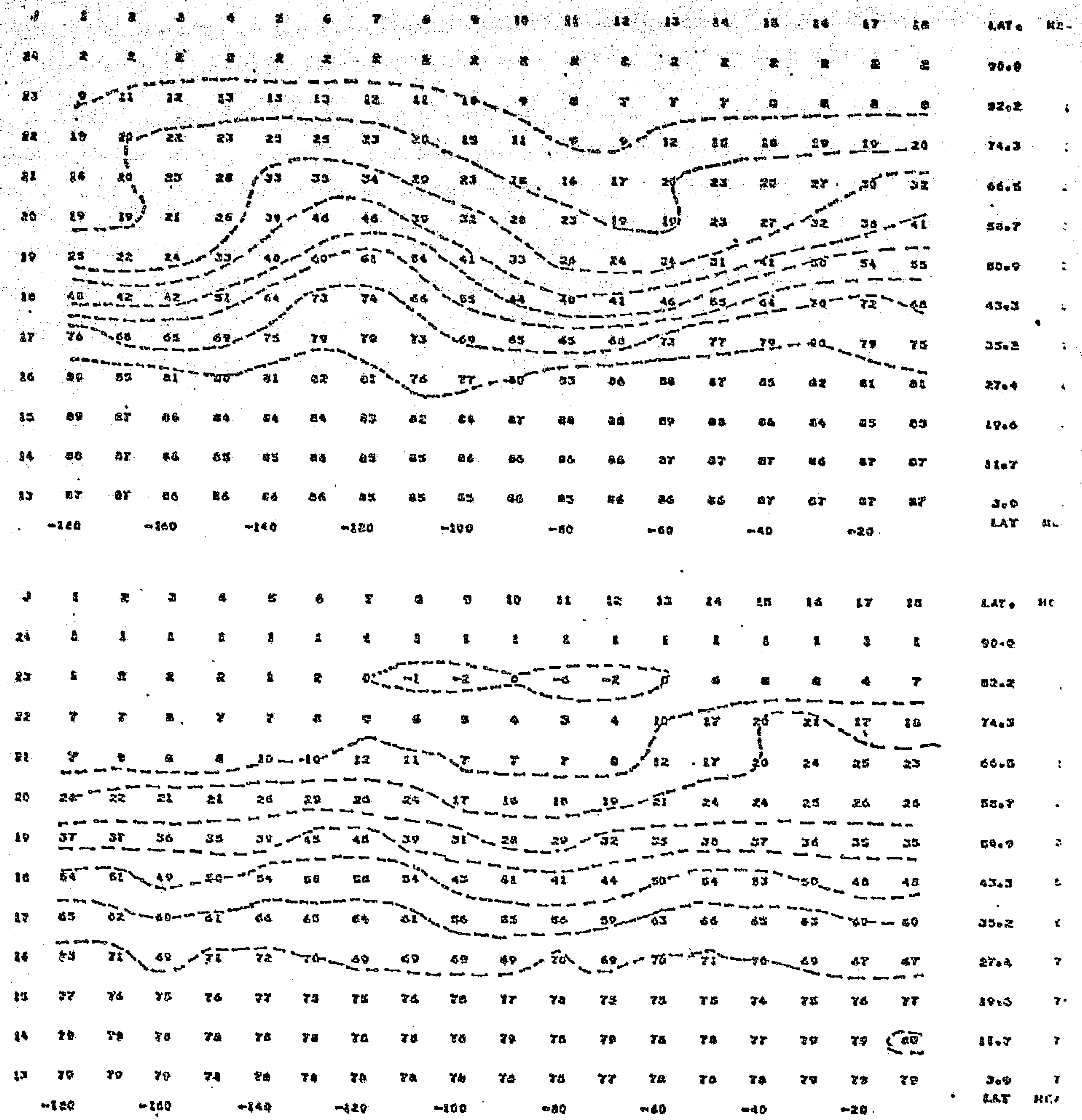

Figure 3. (b) November 1976.

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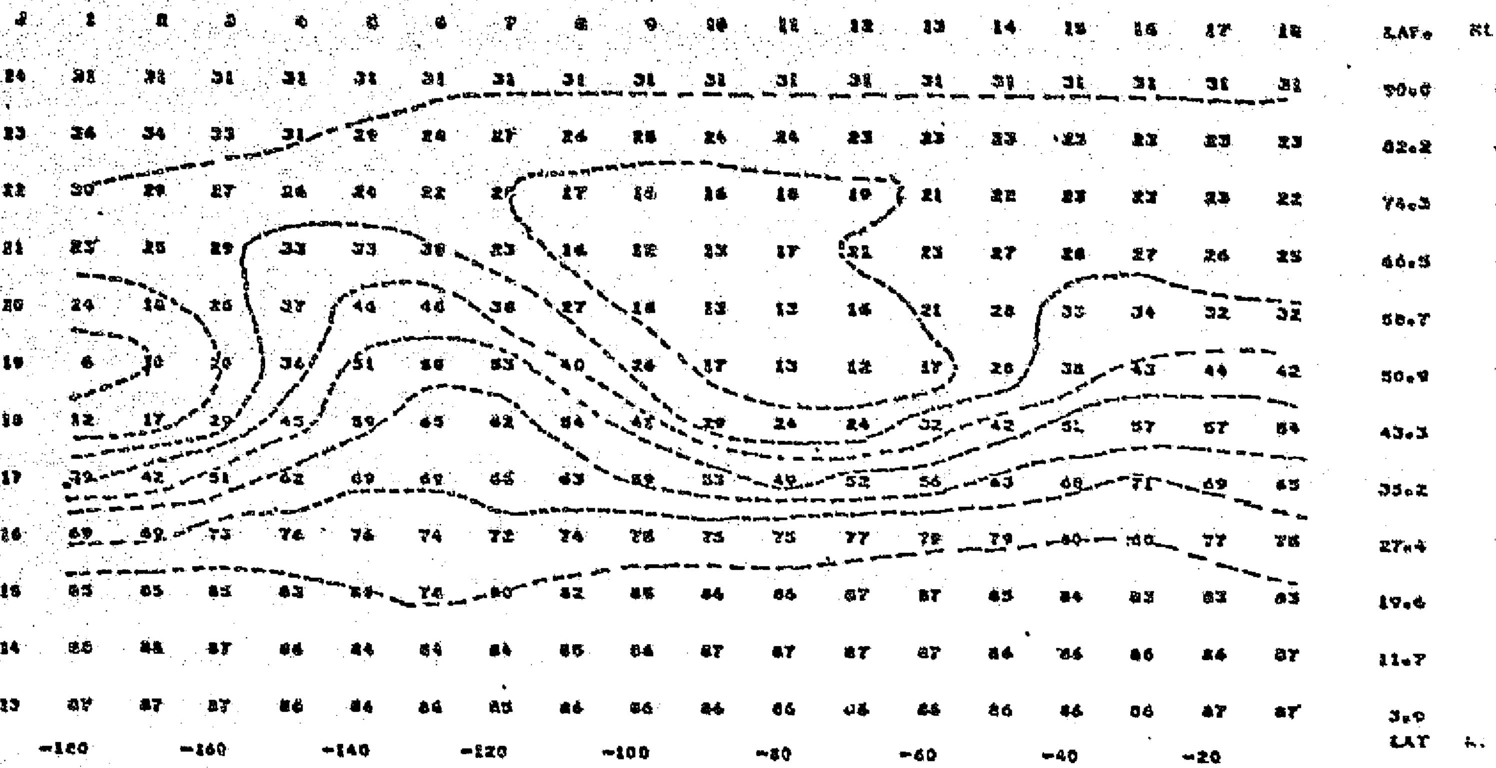
24	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	90.0
23	14	14	13	12	11	10	9	8	8	8	9	10	11	12	13	14	15	15	82.2
22	20	19	17	16	14	12	9	6	5	6	9	12	16	19	23	26	28	28	74.3
21	21	20	20	22	22	21	17	13	7	6	7	10	16	23	29	32	34	33	66.5
20	16	15	19	25	32	37	35	26	14	7	5	8	15	23	29	33	35	33	58.7
19	15	19	26	35	45	53	54	45	29	16	12	15	21	31	36	41	41	40	50.9
18	29	35	42	51	59	66	67	61	49	30	33	35	43	53	60	60	56	54	43.3
17	58	61	65	68	71	72	71	68	64	61	60	65	70	74	76	73	67	66	35.2
16	80	81	80	77	77	77	75	74	76	78	81	83	83	83	81	79	76	77	27.4
15	87	86	85	82	80	80	81	82	84	86	87	86	86	84	82	81	81	83	19.6
14	86	85	84	83	82	83	84	85	85	86	85	85	85	85	84	84	85	86	11.7
13	86	85	85	84	84	84	84	84	85	85	85	86	85	85	85	85	87	86	3.9
	-180		-160		-140		-120		-100		-80		-60		-40		-20		LAT

J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	LAT.
24	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	90.0
23	-2	-3	-5	-7	-8	-7	-9	-10	-11	-10	-10	-8	-7	-4	-1	3	0	5	82.2
22	7	3	0	-2	-2	-2	-5	-4	-7	-9	-8	-8	-6	-1	3	12	11	13	74.3
21	16	8	4	1	3	2	3	4	0	-3	-3	-4	-4	-2	3	9	15	16	66.5
20	27	19	14	12	17	22	19	16	12	8	8	9	9	10	12	16	19	22	58.7
19	33	30	28	29	32	40	42	37	30	26	26	28	30	32	33	35	29	28	50.9
18	41	41	43	46	50	53	55	52	41	37	37	41	47	53	56	55	47	42	43.3
17	54	56	56	59	63	62	61	60	55	51	51	54	59	64	67	67	61	57	35.2
16	66	66	67	69	72	68	65	66	66	65	65	65	65	67	69	70	66	64	27.4
15	74	75	75	74	74	73	72	74	76	76	75	73	72	72	73	72	72	75	19.6
14	77	77	77	77	77	77	77	77	78	78	78	78	77	76	75	76	78	80	11.7
13	79	78	78	78	78	78	78	78	78	78	78	77	78	78	78	78	78	79	3.9
	-180		-160		-140		-120		-100		-80		-60		-40		-20		LAT

Figure 3. (c) December 1976.



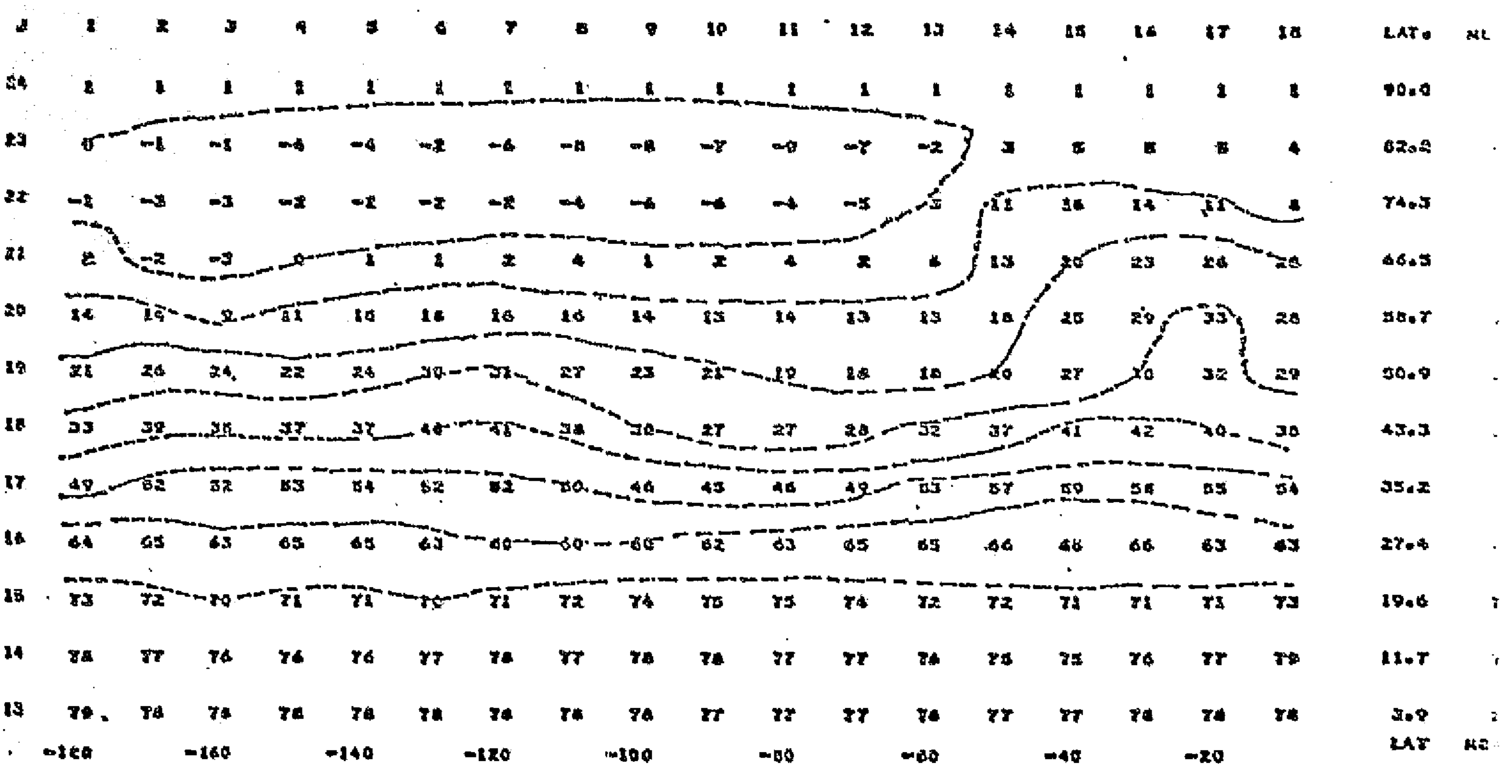


Figure 3. (d) January 1977.

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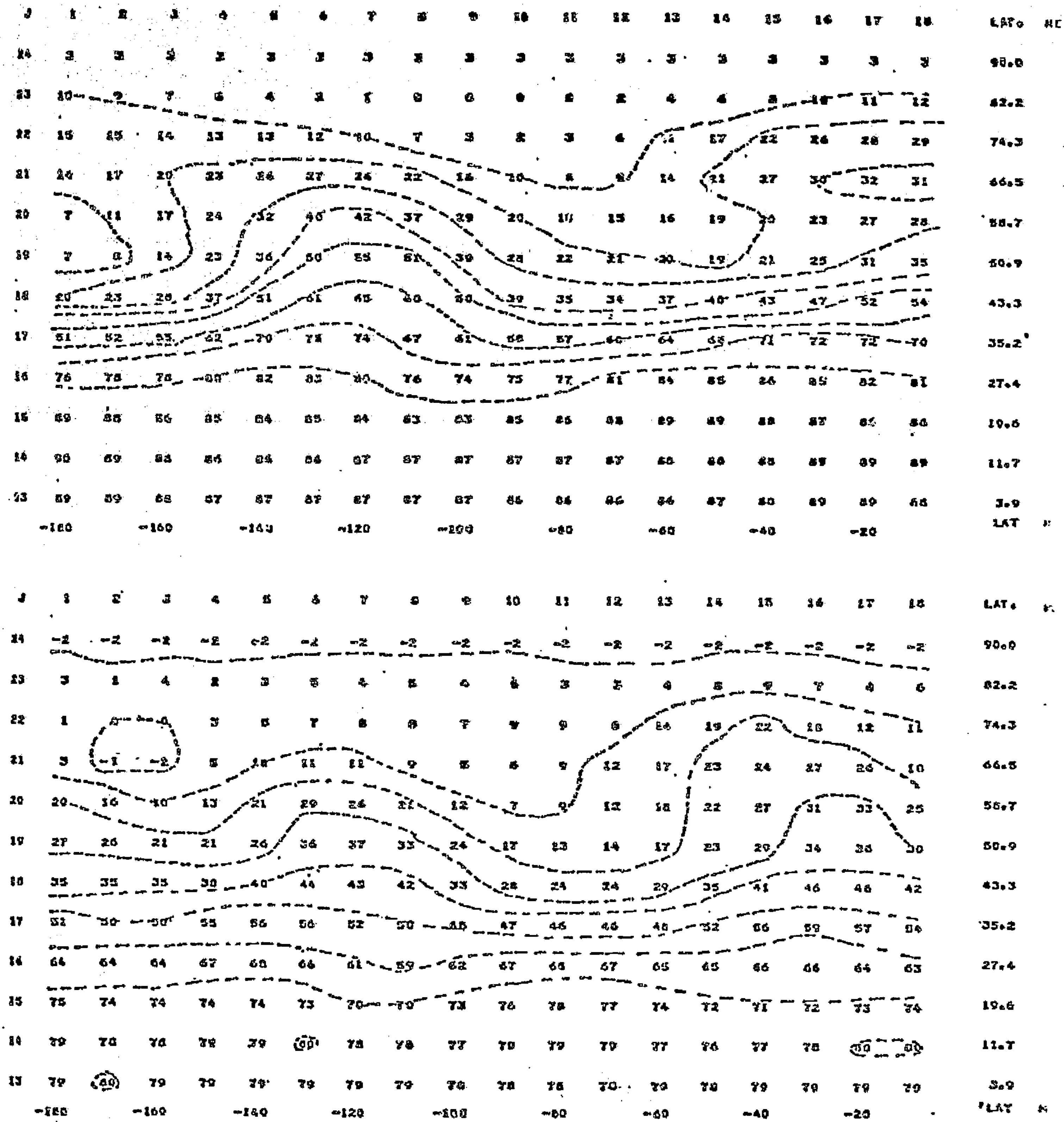

Figure 3. (e) February 1977.

Pacific Ocean on the left. Longitudes are labeled at the bottom of each map, which extends from 10° W on the right to 180° W on the left, the negative numbers denoting west longitude. The latitudes of the gridpoints are shown in the second column on the right of each map in degrees North. (Note that the latitude interval is approximately, but not exactly, eight degrees.) The first column on the right of each map shows the zonal mean value of the variable displayed within the quadrant. (Grid numbers also appear, at the top and in the left column.)

In Figure 1, sea-level isobars have been drawn at an interval of 4 mb. It is apparent from an inspection of the maps that the model fails to simulate adequately the monthly mean sea-level pressure fields. Although the Icelandic and Aleutian lows, as well as the subtropical high pressure cells over the oceans and the North American continental high, are all reflected to some degree in the model simulations, the quantitative agreement between the observed and predicted mean fields must be characterized as poor. Most notable are the failures to simulate the abnormally deep Aleutian lows in January and February, and the strong pressure gradients in the North Atlantic in October, November, January and February. In general, the model-generated monthly mean sea-level pressures are too high in high latitudes and too low in low latitudes.

The 850 mb isotherms in Figure 2 are drawn for an interval of 5° C. It is immediately apparent that the predicted temperatures are generally too low, especially in high latitudes. The cold Arctic may be due to the inadequacy of the eddy transport of sensible heat, a problem that is also present in the GISS model (Stone, et al., 1975). However, the present model simulation is too cold in the tropics as well, which suggests some other defect.

The dominant characteristic of the observed temperature field over the northwest quadrant from October through February was the large contrast between high temperatures over the west coast of North America (e.g., 120° W) and low temperatures in the east (e.g., 80° W), which became most pronounced in December and January and began to ameliorate in February. The model does simulate some aspects of the cold wave in the east, notably in November. However, the December and January simulations are less satisfactory, and in February, when the cold in the east had abated somewhat, the model predicted the most severe conditions. While the model does depict large negative deviations from normal, it fails to simulate the phase opposition between the cold east and warm west, and in February it grossly exaggerates the cold anomaly in the east.

The observed and predicted 500 mb heights, together with manually-drawn 100 m contours, are displayed in Figure 3. The observed fields show the persistent stationary wave pattern (western ridge, eastern trough) mentioned earlier. The positions of the ridge and trough over North America are reasonably well-simulated in the prognostic maps. However, the amplitudes of the mean monthly waves, especially in November, December, and January, are not adequately reproduced, and the predicted flow in those months is much more zonal than the observed. The February 500 mb simulation is much closer to the observed field over North America. In all five months the predicted 500 mb heights are generally too low compared with the observed values, which is consistent with the fact that the troposphere is too cold in the model simulation.

For a quantitative evaluation of the model output, simulation error statistics were computed for seven regions of the earth, ranging in size from the United States to the total globe and defined as follows: (1) United States (27° N to 51° N and 130° W to 70° W): (2) East Pacific and United States (27° N to 51° N and 180° W to 70° W); (3) North America (27° N to 74° N and

130° W to 70° W); (4) Europe (35° N to 74° N and 10° W to 40° E); (5) Tropics (20° N to 20° S over all longitudes); (6) Northern Hemisphere (4° N to 82° N over all longitudes); (7) Globe (82° S to 82° N over all longitudes).

The bias of the model is indicated in Table 1, which lists the area-weighted algebraic mean errors of the monthly mean simulations over the Northern Hemisphere. Also shown, for comparison, are the corresponding values for a "forecast" of climatology. As noted earlier, the simulated sea-level pressures in the Icelandic and Aleutian region were generally too high. However, these local effects are overcompensated by underpredictions elsewhere, with the result that, for the Northern Hemisphere as a whole, the average bias of the sea-level pressure simulations is - 1.6 mb for the five months. The 850 mb temperatures in the simulations are too low everywhere, including the tropics, with an average cold bias of - 3.5° C for the five months over the hemisphere. This result is hydrostatically consistent with the negative bias of the simulated 500 mb heights, which average 93 m less than the observed heights over the Northern Hemisphere for the five-month period. Compared with that of the simulations, the bias of the NCAR climatology in Table 1 is negligible. This indicates not only that the hemispheric mean state was close to normal for the

Table 1. Algebraic mean difference (bias) between monthly mean fields over the Northern Hemisphere for winter 1976-1977. M: Model simulation - observed. C: Climatology - observed.

	October	November	December	January	February	Average
			Sea-level pressure (mb)			
M	- 1.4	- 1.7	- 1.3	- 2.2	- 1.5	- 1.6
C	- 0.2	+ 0.0	- 0.0	- 0.7	- 0.3	- 0.2
			850 mb temperature (°C)			
M	- 3.6	- 3.5	- 3.4	- 3.5	- 3.7	- 3.5
C	- 0.4	- 0.7	- 0.4	- 0.5	- 0.7	- 0.5
			500 mb height (m)			
M	- 94	- 91	- 86	- 100	- 93	- 93
C	+ 4	+ 3	+ 4	+ 2	- 5	+ 2

period (see also, Angell and Korshover, 1978), but also that the model exhibits a negative bias in pressures, temperatures, and geopotential heights relative to climatology as well as to the observed monthly mean fields.

The rms errors and S1 skill scores for the five monthly mean simulations, together with the corresponding scores for the "climatology forecast", are shown for the seven regions defined above in Tables 2 and 3. (The S1 score, a conventional measure of the difference between predicted and observed gradients, is a dimensionless quantity with a range from zero, for a perfect forecast, to a maximum of 200. Based on experience at NMC (Shuman and Hovermale, 1968), it is generally agreed that S1 scores less than 20 indicate virtually perfect synoptic agreement, while scores greater than 70 represent "worthless" forecasts, at least for 500 mb patterns.)

From Tables 2 and 3 it is apparent that the model simulations are, in general, inferior to climatology. Only in the few regions and months indicated by asterisks is the error score of the simulation smaller than that of climatology. The rms errors, expecially of 850 mb temperatures and 500 mb heights, reflect, among other things, the negative bias of the model noted earlier. The large S1 simulation scores for sea-level pressure indicate no skill, even where (as in Europe) they are

Table 2. Root-mean-square (rms) errors of monthly mean model simulations (M) and climatology (C) for winter 1976-1977. (See text for definitions of regions.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	Sea-level pressure (mb)						
1.	United States	M	3.5	5.1	4.5	4.3	6.0
		C	1.6	3.1	2.2	4.0	3.1
2.	E. Pacific - U. S.	M	4.3	7.2	6.8	10.3	8.7
		C	1.9	3.8	3.4	7.1	6.1
3.	North America	M	6.4	7.1	7.4	8.9	7.5
		C	2.0	3.1	2.1	3.8	3.5
4.	Europe	M	5.5*	8.1	4.4*	5.1*	7.3
		C	6.8	2.0	4.7	5.4	4.9
5.	Tropics	M	3.3	3.7	2.8	2.9	4.1
		C	1.5	1.7	1.8	1.2	1.6
6.	Northern Hemisphere	M	5.3	7.2	6.1	7.2	7.8
		C	3.0	2.9	3.5	5.9	4.4
7.	Globe	M	8.5	6.7	7.0	7.4	8.2
		C	3.0	3.2	4.6	4.7	3.7

* denotes simulation values smaller than those for climatology.

Table 2. (Cont'd.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	850 mb temperature (°C)						
1.	United States	M	3.7	4.4	3.8	3.3	6.1
		C	2.7	2.8	2.4	3.2	2.4
2.	E. Pacific - U. S.	M	3.7	4.0	3.4	3.8	5.3
		C	3.2	2.9	2.3	2.8	2.2
3.	North America	M	6.8	6.7	5.9	6.2	7.1
		C	2.4	3.0	2.5	3.9	3.2
4.	Europe	M	5.5	5.1	4.0	5.7	6.6
		C	1.9	1.4	1.7	1.7	2.7
5.	Tropics	M	3.6	3.2	2.9	3.4	3.6
		C	1.8	1.6	1.2	1.4	1.7
6.	Northern Hemisphere	M	5.1	5.2	5.5	5.9	5.4
		C	2.2	2.1	1.9	2.7	2.3
7.	Globe	M	6.8	6.3	6.2	6.5	6.6
		C	2.7	2.1	2.0	2.4	2.2

Table 2. (Cont'd.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	500 mb height (m)						
1.	United States	M	109	115	105	133	149
		C	48	74	57	85	49
2.	E. Pacific - U. S.	M	106	108	102	134	136
		C	46	66	54	101	74
3.	North America	M	119	124	109	146	139
		C	44	71	58	89	51
4.	Europe	M	157	160	115	160	162
		C	62	27	60	58	63
5.	Tropics	M	85	82	78	86	90
		C	16	16	15	17	20
6.	Northern Hemisphere	M	104	114	112	131	119
		C	39	40	43	73	55
7.	Globe	M	102	107	99	114	109
		C	49	47	56	59	44

Table 3. S1 skill scores for monthly mean model simulations (M) and climatology (C) for winter 1976-1977. (See text for definitions of regions.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	Sea-level pressure						
1.	United States	M	95	120	115	156	105
		C	47	77	52	90	94
2.	E. Pacific - U. S.	M	112	140	133	156	139
		C	51	78	51	81	97
3.	North America	M	106	114	115	138	91
		C	58	82	54	93	95
4.	Europe	M	85*	125	85*	90	108*
		C	107	40	101	78	111
5.	Tropics	M	72	69	72	68	70
		C	54	54	57	44	49
6.	Northern Hemisphere	M	95	102	90	89	87
		C	65	53	51	64	62
7.	Globe	M	88	85	89	84	83
		C	53	52	63	56	52

Table 3. (Cont'd.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	850 mb temperature						
1.	United States	M	48	37*	58	36*	44
		C	45	46	32	53	34
2.	E. Pacific - U. S.	M	41*	30*	34	42*	41
		C	45	42	30	49	36
3.	North America	M	65	50	58	53*	61
		C	41	40	40	57	40
4.	Europe	M	61	67	76	93	65
		C	46	34	46	49	39
5.	Tropics	M	75	86	83	98	97
		C	58	64	62	70	67
6.	Northern Hemisphere	M	66	65	67	67	62
		C	49	47	39	51	43
7.	Globe	M	61	61	62	64	61
		C	40	41	37	44	38

Table 3. (Cont'd.)

			Oct.	Nov.	Dec.	Jan.	Feb.
	500 mb height						
1.	United States	M	39*	45*	38	50*	30*
		C	41	54	32	52	36
2.	E. Pacific - U. S.	M	45	51	43	65	43
		C	37	45	31	53	40
3.	North America	M	41	49*	49	65	42
		C	37	53	41	58	37
4.	Europe	M	65	76	54*	71	46*
		C	57	34	66	67	61
5.	Tropics	M	53*	71*	83	72*	102
		C	66	75	72	79	83
6.	Northern Hemisphere	M	52	71	67	67	62
		C	47	42	43	57	48
7.	Globe	M	45	50	52	54	49
		C	38	37	43	45	38

smaller than those for climatology. Over the United States, the S1 simulation scores for the 850 mb temperature and 500 mb height fields are, on the average, slightly smaller than those for climatology (40 vs. 42 and 40 vs. 43, respectively), indicating some skill in the reproduction of those patterns, possibly due to persistence of initial conditions during this anomalous winter. However, there is no evidence of this skill over the Northern Hemisphere, for which the average S1 simulation score for 500 mb heights is an unsatisfactory 64 compared with an average of 47 for climatology.

In general, it must be concluded that, despite the model's realistic simulation of the large-scale meridional structure of the atmosphere, the monthly mean simulations do not adequately reproduce the observed synoptic fields. They are, in fact, inferior to climatology, indicating that, at this stage, the coarse-mesh model is not yet capable of duplicating realistically significant departures from climatology of monthly mean synoptic patterns. This conclusion may be tempered by the fact that climatological SSTs rather than observed sea temperatures were used for the calculations of the vertical fluxes of heat and water vapor over the ocean surface in the simulations above.

Impact of Sea-surface Temperature (SST) Anomalies

Real data experiments with the GISS model (Spar and Atlas, 1975; Spar et al., 1976; Spar and Lutz, 1978) have thus far failed to reveal any consistent beneficial impact of observed SST anomalies on model atmospheric simulations. Nevertheless, the view is widely held (see, e.g., Harnack and Landsberg, 1978) that air-sea interactions play a significant role in the generation of atmospheric anomalies on monthly, seasonal, and even annual time scales, and that persistent SST anomalies may force the atmosphere into anomalous circulation and temperature patterns. In a recent review of the North American abnormal winter of 1976-1977, Namias (1978) has again presented interesting synoptic evidence in support of this concept.

As a further test of the SST hypothesis, the five simulation runs with the climate model were repeated with observed monthly mean SSTs replacing the climatological values. The observed means for each month were computed from daily SSTs, which are derived from satellite radiometer measurements and provided by NOAA[5] on a latitude-longitude grid smaller than 1° square (Brower et al., 1976). For use in the model surface flux calculations,

[5]National Oceanic and Atmospheric Administration.

4-point averages of these fine-mesh monthly mean SSTs were determined for each coarse-mesh model gridpoint.

The mean SST anomaly field for each month is displayed in digital form on the global maps in Figure 4 (a-e), where negative (positive) numbers denote colder (warmer) than normal water, in degrees Celsius. Blank areas on the maps represent the continents. Longitudes are labelled at the top and bottom, negative for west and positive for east, with the Western Hemisphere on the left. Latitudes are indicated in the second column from the right, positive for north and negative for south. The first column on the right lists the zonal mean anomaly for each grid latitude. (Also shown on the maps are the index numbers of the 24 x 36 gridpoint array.)

The coarse-mesh climatological SST fields used for the calculation of the anomalies in Figure 4 (and also in the basic simulation experiment) were computed by averaging the 1° grid data from Alexander and Mobley (1974) over the 8 x 10 degree box surrounding each gridpoint, and are, therefore, somewhat smoother than the observed SST fields. Also, the observed SST tapes were incomplete, with as few as 14 days of data available for the poorest month (February 1977). These factors may have contributed some irregularity to the SST anomaly patterns, although there is no reason to believe that the data presented in Figure

	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24																																					90.0	
23																																					82.2	
22																																					74.3	
21											-2					-2		0	0	0																	66.5	-1
20	-2	-2		-2	-2					-1	0		4	1	0	-1	0	1	1		-1															-1	58.7	0
19	-3	-3	-3	-3	-2	0								1	2	-1	-1	0																-1	-1	-3	50.9	-1
18	1	-1	-1	-2	0	1							1	6	3	0	0			1		2	4	6									2	2	-3	-4	43.0	1
17	2	1	0	-1	0	0						1	1	1	1	1	1	2			2	1										2		1	1	1	35.2	1
16	0	0	0	0	0	0	0			0		1	0	0	0	1	2															0	0	-1	0	1	27.4	0
15	-1	-1	-1	-1	0	0	0	-1			0		0	0	1	1	2						5		2	2		1			0	0	0	0	-1	-1	19.6	0
14	-2	-1	-1	0	-1	-1	-1	-1	-1	1	-1		0	0	-1	0	1								0	1		0		0	0	-2	-2	-2	-2	-2	11.7	-1
13	-1	-1	0	0	0	0	1	0	-1	-2	0			0	0	0	-1	-2	-2					1	1	1	0	2	0	0	-1	-1	-2	-3	-2	-2	3.9	-1
12	-1	-1	0	0	0	1	1	0	0	0						0	-1	-1	-2	-3				0	0	0	0	-1	0	0		0		-2	-2	-1	-3.9	0
11	0	0	0	-1	-1	0	0	0	0	-2	-1					0	0	0	0	-2				0	0	0	0	-1	-1	0	0	1	1	0	-1	0	-11.7	0
10	1	1	0	0	0	0	0	0	0	-2	-1					1	0	0	0	0			2	1	0	0	0	-1	0	0				1	1	0	-19.6	0
9	1	1	1	0	0	0	1	1	1	0	0				0	1	1	1	1	-1			1	1	1	1	1	2	1	1					0	1	-27.4	1
8	1	-1	-1	-1	0	0	0	0	0	0	0			1	0	1	2	2	1	0	0	1	1	0	0	0	1	1	1	2	3	1			0	0	-35.2	0
7	1	1	-1	0	-1	0	1	0	-2	-2	-1		0	1	-1	0	0	0	0	-1	-5	1	-2	-5	2	4	1	0	1	1	1	0	0	0	0		-43.0	0
6	-1	0	1	0	-2	-2	-3	-2	-3	-2	-2		0	-2	-3	-3	-3	-3	-3	-2	-3	-3	-2	-2	-2	-2	-2	0	-1	-2	-2	-1	-3	-1	0	-1	-50.9	-2
5	0	0	-2	-4	-4	-3	-2	0	0	-2	-2	0	-3	-3	-2	-2	0	-2	-2	-3	-2	-2	-2	-2	-2	-3	-2	-2	-3	-2	-2	-2	-2	-3	-3	-1	-58.7	-2
4	-2	-2	-2	-1	0	-1	-2	-2	-2	-2	-3	-2		0	-1	0	-1	0	-1	-1	-1	0	-1			-1								-1	-1	-3	-66.5	-1
3	-1	-1	1	0	0									0	-1	-1																				0	-74.3	0
2																																					-82.2	
1																																					-90.0	
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

Figure 4. Monthly mean sea-surface temperature anomalies (observed - climatology) over the globe in degrees C.

(a) October 1976.

J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				
24																																					90.0	
23																																					82.2	
22																																					74.3	
21											-1					-1		0	0	0																	66.5	0
20	-2	-2		-3	-3					-1	1		4	-1	-1	-1	0	0	1		-1															-1	58.7	-1
19	-3	-3	-3	-3	-3	0								0	3	-2	-2	0																-2	-2	-3	50.9	-2
18	1	-2	-2	-3	-1	1							2	5	4	0	-2			0		3	2	6									2	2	0	-5	43.0	1
17	1	3	2	0	1	1						3	2	2	2	2	1	2			2	2										7		2	2	1	35.2	2
16	1	1	1	0	0	0	1			1		1	2	1	2	2	2															1	-1	1	1	2	27.4	1
15	-1	-1	-1	-1	0	0	0	1			0		1	1	1	2	3						3		2	3		2			-1	0	0	0	-1	-1	19.6	0
14	-2	-2	-2	-1	0	-1	0	0	0	1	0		0	-1	-1	0	2								1	2		0		0	-1	-2	-2	-2	-2	-2	11.7	-1
13	-1	-1	1	0	1	1	1	0	-1	-1	-1			-1	0	0	-1	-2	-2					1	1	1	0	-1	0	-1	-2	-2	-2	-1	-2	-1	3.9	-1
12	1	0	0	1	1	1	1	1	0	1						0	-1	-1	-1	-4				1	1	1	0	0	0	0		-1		-1	-1	0	-3.9	0
11	-1	-1	-1	0	0	0	0	-1	-1	-2	-1					1	0	0	-1	-2				0	0	0	-1	-1	-2	0	0	1	1	0	-1	-1	-11.7	-1
10	1	1	2	1	0	0	0	0	0	0	0					1	0	0	0	0			3	1	1	1	0	-1	0	0				3	1	1	-19.6	1
9	1	1	-1	0	1	1	1	1	1	0	0				0	1	2	2	1	0			2	2	2	2	2	1	1	1					2	1	-27.4	1
8	0	-1	0	0	-1	1	0	-1	0	1	1			1	0	1	3	2	2	0	1	1	1	2	1	1	2	0	1	2	2	1			0	0	-35.2	1
7	1	1	1	0	0	-1	0	0	-1	-1	-1		0	1	0	3	-1	-2	0	-2	-3	-1	-2	-3	4	3	1	-1	0	0	0	1	1	3	0		-43.0	0
6	-1	2	1	2	1	1	0	-1	-1	-1	-1		0	-2	-2	-3	-3	-2	-2	-2	-1	-1	-1	0	-1	-1	-1	0	-2	-3	-1	1	-1	-1	0	-2	-50.9	-1
5	2	1	-1	-2	-2	-2	0	0	0	0	0	0	-3	-2	-3	-1	-2	-3	-2	-2	-2	-2	-2	-3	-3	-2	-3	-3	-2	-2	-2	-1	-1	-2	-2	1	-58.7	-1
4	-2	-3	-2	-2	-2	-2	-1	-2	-2	-3	-3	-2		-1	-1	-1	-1	-1	-1	-1	-1	0	-1			-1								0	-1	-2	-66.5	-1
3	-1	-1	1	0	0									-1	-1	-1																				0	-74.3	-1
2																																					-82.2	
1																																					-90.0	
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

Figure 4. (b) November 1976.

	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24																																					90.0	
23																																					82.2	
22																																					74.3	
21											0					1		-1	0	1																	66.5	0
20	-1	1		-2	-2					1	2		2	-1	0	0	0	0	0		1															-1	58.7	0
19	-3	-2	-2	-2	-2	1								-1	5	-2	0	0																-4	-1	-2	50.9	-1
18	-1	-2	-1	0	2	2							6	10	4	0	-1			1		3	2	6									5	2	1	-5	43.0	2
17	0	1	1	1	1	0						5	2	2	2	3	2	2			2	2										3		2	3	1	35.2	2
16	2	2	0	1	0	-1	1			2		2	3	2	2	2	1															2	0	1	2	1	27.4	1
15	-1	-1	0	0	0	0	1	1			1		1	1	1	1	2						4		1	4		3			0	0	0	0	-1	-1	19.5	1
14	-3	-2	-1	-1	-1	-1	0	0	0	1	0		0	-1	0	0	3								0	2		1		0	0	-1	-2	-2	-2	-2	11.7	0
13	-2	-1	0	0	0	0	1	0	-1	0	-1			-1	-1	-1	-1	-1	-1					0	0	0	0	0	0	-1	-1	-1	-2	-2	-2	-2	3.9	-1
12	0	0	1	1	0	1	1	1	0	0						-1	-1	-1	-2	-3				1	0	1	0	0	0	0		-1		-2	0	1	-3.9	0
11	-1	-1	-1	0	0	0	1	0	0	-1	1					0	0	0	-2	-3				0	0	0	0	0	0	0	0	0	0	0	0	-1	-11.7	0
10	0	0	0	0	0	0	1	0	1	1	1					1	1	0	0	0			2	1	1	1	1	1	0	1				2	1	1	-19.6	1
9	1	-1	-1	-1	1	0	0	2	3	2	1				1	1	3	4	2	1			1	1	2	2	3	3	2	1					2	1	-27.4	1
8	0	0	1	1	0	0	1	1	1	3	2			2	0	1	1	2	1	0	1	0	0	1	1	1	2	2	1	1	2	1			2	0	-35.2	1
7	2	1	1	-1	-1	-1	0	0	0	0	0		0	0	-1	1	-1	-1	0	-2	-3	0	-2	-3	2	3	1	0	1	0	0	1	1	2	1		-43.0	0
6	2	2	1	1	1	1	1	0	0	-1	0		1	-1	-2	-1	0	-1	-1	-1	-1	0	0	0	0	0	-1	1	0	-1	0	1	0	1	2	1	-50.9	0
5	2	1	0	-2	-2	-1	2	2	2	1	2	2	-1	-1	-1	-1	-1	-1	0	-1	0	-1	-1	-1	-2	-2	-2	-1	-2	-1	-2	0	0	-1	-2	2	-58.7	0
4	-2	-2	-2	-2	-2	-2	-1	-2	-2	-2	-2	-2		-1	-1	0	0	0	-1	-1	-2	-2	-2			-2								-1	-2	-1	-66.5	-1
3	0	-1	1	-1	-1									-1	-1	-1																				0	-74.3	-1
2																																					-82.2	
1																																					-90.0	
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

Figure 4. (c) December 1976.

J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-100			-150			-120			-90			-60			-30			0			30			60			90			120			150				
24																																					90.0	
23																																					82.2	
22																																					74.3	
21											0					1		-1	0	0																	66.5	0
20	0	0		-1	-2					-1	2		3	1	-1	-2	0	0	0		1															-1	58.7	0
19	-3	-2	-2	-1	-1	0								-1	6	-2	-1	0																0	-2	-2	50.9	-1
18	-4	-2	-1	-1	0	1							7	11	4	0	-1			2		2	1	6									9	5	2	-6	43.0	2
17	0	0	0	1	1	0						6	2	1	1	2	1	2			1	1										4		3	2	0	35.2	1
16	1	1	1	1	1	0	0			1		2	2	2	2	1	1															2	1	0	1	0	27.4	1
15	-1	0	0	0	0	-1	-1	2			0		0	1	1	1	0						2		1	3		1			0	0	0	0	-1	-1	19.6	0
14	-3	-3	-2	-2	-3	-1	0	-1	0	1	-1		0	-1	-1	-1	3								1	1		0		0	-1	-2	-3	-3	-3	-3	11.7	-1
13	-2	-1	-2	-2	-2	-1	-1	-1	-3	-1	-1			-2	-2	-1	0	-1	-2					1	0	0	1	0	0	0	0	-1	-1	-1	-3	-3	3.9	-1
12	1	-1	-1	0	0	0	0	0	0	-1						-1	-1	-1	-2	-3				1	0	0	-1	-1	0	-1		0		-3	-2	-1	-3.9	-1
11	-3	-1	0	0	0	0	0	-1	0	1	1					0	0	0	-1	0				0	-1	0	-1	-1	-1	0	1	2	1	-1	-2	-2	-11.7	0
10	0	-1	-1	-2	-2	0	0	1	1	0	0					0	0	0	0	0			0	1	1	0	0	0	-1	1				0	-1	-1	-19.6	0
9	0	0	0	0	-2	0	0	1	2	2	1				0	0	1	2	1	0			1	2	2	2	2	2	2	1					0	0	-27.4	1
8	0	1	1	2	1	-1	-2	-2	0	2	3			3	0	1	0	-1	-1	0	1	0	0	0	0	0	0	0	0	2	2	2			0	-1	-35.2	0
7	2	1	1	1	0	-1	-2	0	0	-1	1		2	2	-1	0	-1	1	1	-2	-3	-1	-3	-4	0	1	1	-1	0	0	0	0	0	0	0		-43.0	0
6	0	0	1	0	0	0	1	1	1	-1	-1		0	-1	-2	-1	-1	-1	-1	-2	-2	0	0	-1	-2	-3	-3	-1	0	-1	-1	1	1	1	0	0	-50.9	0
5	1	0	0	-3	-2	-1	2	3	3	2	1	1	-1	-1	0	0	0	1	0	0	0	0	-1	-1	-1	-1	-2	-1	-2	1	-1	1	1	-3	-4	0	-58.7	0
4	-2	-2	-1	0	-1	-1	-1	-1	0	0	-1	-2		-2	1	2	3	2	2	1	-1	-2	-1			-1								-1	-2	-2	-66.5	-1
3	0	-1	0	-1	-1									-2	0	0																				0	-74.3	-1
2																																					-82.2	
1																																					-90.0	
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

Figure 4. (d) January 1977.

	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24																																					90.0	
23																																					82.2	
22																																					74.3	
21											0					0		-3	-1	0																	66.5	-1
20	0	-1		-1	-3					-1	2		3	1	-2	-3	-1	0	0		0															-1	58.7	-1
19	-3	-3	-2	-2	-1	0								-3	6	-2	-1	-1																-1	-2	-2	50.9	-1
18	-5	-3	-3	-1	0	1							4	6	2	0	-1			0		0	1	6									0	1	-2	-5	43.0	1
17	-2	-3	-2	0	1	0						5	1	1	0	2	1	1			1	1										2		0	0	-1	35.2	0
16	-1	0	1	1	0	-1	-1			0		0	1	2	1	1	1															1	-1	-1	0	-1	27.4	0
15	-1	-1	0	-1	-1	-2	-1	1			0		1	1	0	0	0						2		1	2		0			-2	-2	-1	-1	-1	-1	19.6	0
14	-3	-2	-2	-2	-2	-2	0	0	1	2	0		0	-1	-1	0	1								0	1		-1		-4	-1	-2	-2	-3	-5	-4	11.7	-1
13	-3	-3	-3	-2	-2	-1	-1	-1	-2	-1	-2			-2	-1	-1	-1	-2	-1					0	1	1	1	-1	-1	0	1	-2	0	-1	-2	-5	3.9	-1
12	-1	-1	0	0	1	1	0	-1	-2	-2						-1	-1	-1	-1	-3				0	0	0	-1	0	-2	-1		-3		-3	-3	-2	-3.9	-1
11	-3	-1	0	0	1	1	0	0	0	0	0					0	0	0	1	2				-1	0	-1	-1	-2	-1	-1	1	1	-2	-4	-2	-1	-11.7	-1
10	-2	0	-1	0	0	0	0	0	0	0	0					0	0	0	0	-1			1	-1	-1	1	0	-1	-1	2				-2	-2	-2	-19.6	0
9	0	0	0	2	-1	0	1	1	1	1	1				1	1	1	2	2	0			1	0	1	3	4	3	2	1					-1	-1	-27.4	1
8	0	1	1	2	0	-1	-2	0	1	1	1			3	1	-1	-2	-1	1	0	1	0	0	1	0	0	1	1	1	2	2	2			1	0	-35.2	0
7	2	2	2	2	1	-1	0	0	-1	0	1		3	3	0	-2	-2	-1	0	-2	-1	0	0	-4	1	0	-1	-1	0	1	1	1	1	1	0		-43.0	0
6	2	1	2	2	1	1	0	1	0	0	0		2	0	-1	0	0	1	1	1	1	0	0	0	0	-1	-1	0	0	0	0	1	1	1	1	2	-50.9	1
5	3	2	1	-1	-1	1	2	2	2	2	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	2	-58.7	1
4	-2	-1	-1	0	-1	-2	-3	0	-1	0	0	0		1	2	3	2	2	3	2	1	-1	1			1								-2	-2	-2	-66.5	0
3	0	-1	-1	-1	-1									-2	2	1																				0	-74.3	0
2																																					-82.2	
1																																					-90.0	
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

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Figure 4. (e) February 1977.

4 are incorrect. Nevertheless, the SST anomaly fields are relatively smooth, with certain persistent and coherent large-scale patterns discernible in most months. Thus, cold water (negative anomalies greater than 2° C) is found almost every month in the tropical Pacific, in high latitudes of the North Pacific, and in the Gulf of Guinea, while warm water (positive anomalies greater than 2° C) appears mainly in the western North Atlantic and in the Sea of Japan. Over most of the earth during this five-month period, the SST anomalies were not greater than 2° C.

The impact of SST anomalies on the model-generated monthly mean fields may be evaluated by comparing the two parallel simulations, based on climatological and observed SSTs respectively, for each month. The quantitative results of this comparison are shown in Tables 4 and 5 for the Northern Hemisphere only. In Table 4 the rms errors and S1 skill scores are compared for the two simulations, A, computed with the observed (anomalous) SST field, and M (taken from Tables 2 and 3), computed with the climatological SSTs. It is apparent from Table 4 that the use of observed monthly mean SSTs did not result in any improvement in the simulations over the Northern Hemisphere, and in many cases produced even poorer agreement with nature. Similar results (not shown) were found

Table 4. Root-mean-square (rms) errors and S1 skill scores of monthly mean simulations computed with observed sea-surface temperatures (A) compared with errors (from Tables 2 and 3) of simulations computed with climatological SSTs (M). October 1976 through February 1977. Northern Hemisphere.

		1976			1977	
		Oct.	Nov.	Dec.	Jan.	Feb.
rms errors						
Sea-level pressure (mb)	A	5.5	7.4	6.6	7.4	8.2
	M	5.3	7.2	6.1	7.2	7.8
850 mb temperature (°C)	A	5.2	5.3	5.3	6.0	5.6
	M	5.1	5.2	5.5	5.9	5.4
500 mb height (m)	A	105	112	112	135	116
	M	104	114	112	131	119
S1 skill scores						
Sea-level pressure	A	98	104	92	92	93
	M	95	102	90	89	87
850 mb temperature	A	72	69	69	75	68
	M	66	65	67	67	62
500 mb height	A	53	71	70	76	61
	M	52	71	67	67	62

Table 5. Root-mean-square (rms) differences and S1 comparison scores between monthly mean simulations computed with observed (A) versus climatological (M) sea-surface temperatures. October 1976 through February 1977. Northern Hemisphere only.

	1976			1977	
	Oct.	Nov.	Dec.	Jan.	Feb.
rms difference					
Sea-level pressure (mb)	1.6	1.7	2.4	2.0	2.1
850 mb temperature (^{o}C)	1.6	1.5	2.1	1.8	1.7
500 mb height (m)	12	17	24	24	21
S1 comparison score					
Sea-level pressure	35	38	38	41	35
850 mb temperature	28	28	33	31	25
500 mb height	15	18	22	22	20

over all regions analyzed.

The magnitude of the impact of the SST anomalies on the model atmosphere over the Northern Hemisphere is indicated by the rms differences and S1 comparison scores between the A and M simulations, shown in Table 5 for each month. Compared with the simulation errors in Table 4, the impact scores in Table 5 are virtually negligible. The small S1 comparison scores for the 500 mb height field suggest that the impact of the SST anomalies on the model simulations is indeed trivial at that level. However, the influence of anomalous ocean temperatures does appear to be greater at lower levels of the model, and all the impact scores in Table 5 are above the "noise level" of the model, which is discussed below. Over certain smaller regions, the effect of SST anomalies on the sea-level pressure pattern is, in fact, quite large. For example, in January 1977 the S1 comparison score over the United States between simulations A and M is 75 for sea-level pressure, indicating a considerable alteration of that field. On the other hand, the impact S1 score for sea-level pressure over the United States in February 1977 is only 48; and in neither month was the simulation of the sea-level pressure field improved over the United States by the use of observed SSTs.

In general, it appears that, although the use of observed SSTs in place of climatological values had no beneficial effect on the simulations, the model is not insensitive to SST anomalies. The model's response is negligible at upper levels, but not at sea level, where appreciable alterations (not necessarily realistic) of the pressure pattern may be generated both locally and remotely by SST anomalies. The character of the local response is a negative correlation between SST anomaly and sea-level pressure change at the same point; i.e., cold (warm) anomalies generate higher (lower) sea-level pressures. This relation is neither universal nor linear, but it is found with few exceptions. For example, in a sample of 15 warm anomaly and 21 cold anomaly gridpoints with absolute magnitudes greater than 2° C in January 1977, only four of the 36 points did not exhibit this behavior. The mean values of the SST anomaly and the co-located sea-level pressure difference between simulations A and M for the sample were + 5.0° C and − 2.3 mb for the warm anomaly points and − 3.2° C and + 2.2 mb for the cold points. A synoptic effect of the SST anomaly field found in all months studied is a general lowering of pressures in the North Atlantic and an elevation of pressures in the eastern North Pacific, but with no improvement in the quality of the simulations.

The direct, local, thermal effect of the SST anomalies may be seen in the 850 mb temperature differences over the oceans between the A and M simulations. For the sample above of 15 warm and 21 cold anomaly gridpoints in January 1977, all but five points exhibit a positive correlation between the SST anomalies and the 850 mb temperature differences, with mean values + 2.5° C and – 1.1° C at the 850 mb level corresponding to mean SST anomalies of + 5.0° C and – 3.2° C, respectively. The large positive SST anomalies, which generate strong upward heat fluxes from the sea surface, are generally associated with large positive temperature differences between A and M at the 850 mb level, whereas the stabilizing large negative SST anomalies do not produce correspondingly large cooling effects on the model atmosphere. The local decrease (increase) of sea-level pressure over warm (cold) SST anomalies is a hydrostatic consequence of the local thermal effect.

The total reaction of the model atmosphere to SST anomalies is, of course, a complex non-linear combination of local and remote effects, with the latter often dominating. (A more detailed synoptic analysis of the response of the model atmosphere to anomalous ocean temperatures will be presented in a separate publication.)

Response to Changes in Initialization[6]

Model simulations of the atmosphere start with arbitrarily selected initial conditions. For example, it is convenient to initialize a monthly simulation run with data for the first day of a calendar month. Such initial data may be viewed as a random sample taken from the fluctuating state of a system whose characteristic time scale is of the order of days. How sensitive is a long-term mean simulation to this arbitrary choice of initialization? How different would monthly mean simulations be if started with data one or two days earlier, or later? Large differences, indicating an excessive sensitivity to the initial state, could cast serious doubt on the credibility of the model output. An experiment was, therefore, carried out with the climate model to determine its sensitivity to systematic changes in large-scale initial conditions, such as might result from shifts of one or two days in initialization time.

In this experiment, the simulation runs for October 1976 and January 1977 were repeated with the initialization time shifted to 00 GMT on days 2 and 3, respectively. The mean simulation from each run was then compared with the mean for the corresponding period to the end of the

[6] Adapted from a master's thesis submitted to The City College by Robert Klugman.

month (month-minus-one day and month-minus-two days, respectively) generated by the basic simulation run (the "control") from day 1 data. The principal results of this experiment are presented in Table 6, in which are shown the rms differences (D1 and D2) between each "shifted initialization" run and the "control", as well as the rms errors (E1 and E2) of each run, and in Table 7, showing the corresponding S1 comparison and skill scores for the same simulations, for the Northern Hemisphere only.

Comparing E1 and E2 in Tables 6 and 7 with each other and with M (the "control") in Tables 2 and 3, it can be seen, first of all, that shifting initialization time had no significant effect on either the rms errors or S1 skill scores of the monthly mean simulations. Although the verification periods of the three simulations differ by one or two days, their rms errors and S1 skill scores over the Northern Hemisphere are almost the same for corresponding months and variables. (Complete results, not shown, indicate that the same is true for all the regions listed in Tables 2 and 3.)

Of course, the similarity of error scores does not necessarily mean that shifting initialization time had no effect on the simulated synoptic fields. The rms differences and S1 comparison scores (D1 and D2) in Tables 6

Table 6. Root-mean-square (rms) differences between monthly mean simulations initialized on day 2 versus day 1 (D1) and day 3 versus day 1 (D2) compared with corresponding rms errors for day 2 (E1) and day 3 (E2) initializations for October 1976 and January 1977 over the Northern Hemisphere. (See text for details.)

	Sea-level Pressure (mb)		850 mb Temperature (°C)		500 mb Height (m)	
	Oct.'76	Jan.'77	Oct.'76	Jan.'77	Oct.'76	Jan.'77
D1 (difference)	1.4	2.2	1.3	1.6	19	18
E1 (error)	5.1	7.1	4.9	5.8	99	134
D2 (difference)	1.9	3.1	1.8	2.2	25	33
E2 (error)	5.1	7.2	4.8	5.5	95	131

Table 7. S1 comparison scores for monthly mean simulations initialized on day 2 versus day 1 (D1) and day 3 versus day 1 (D2), compared with corresponding S1 skill scores for day 2 (E1) and day 3 (E2) initializations for October 1976 and January 1977 over the Northern Hemisphere. (See text for details.)

	Sea-level Pressure		850 mb Temperature		500 mb Height	
	Oct.'76	Jan.'77	Oct.'76	Jan.'77	Oct.'76	Jan.'77
D1 (comparison)	32	40	23	27	19	19
E1 (skill)	92	87	62	65	50	67
D2 (comparison)	43	51	35	33	25	27
E2 (skill)	91	86	59	64	50	69

and 7 indicate quantitatively the magnitude of this effect. It is apparent that the differences due to shifting initialization time are smaller than the simulation errors. However, the magnitude of the effect is not entirely negligible. Furthermore, it is greater for a two-day (D2) than for a one-day (D1) shift. The effect at the 500 mb level is almost trivial, especially in terms of the S1 comparison scores; but the same is not true of the other two fields. The initialization shift effect is also smaller than the simulation error of climatology (C in Tables 2 and 3). However, the rms difference between 850 mb temperature simulations with a two-day shift in initialization (D2 in Table 6) is only slightly smaller than the corresponding simulation error of climatology (C in Table 2).

In general, shifts of up to two days in initialization time produce small, but not trivial, changes in the monthly mean synoptic fields generated by the climate model. The magnitude of this effect represented by the values of D1 and D2 in Tables 6 and 7 indicates the inherent minimal error of the monthly mean simulations associated with the arbitrary choice of initialization time.

The use of instantaneous initial conditions for the generation of long-term mean simulations raises other questions regarding the role of small-scale and short-lived components in the initial analysis. Do such transient features of the initial state adversely affect the mean simulations, and would the use of a time filter applied to the initial data improve the result?

An experiment was carried out with the October 1976 and January 1977 data in which the five 12-hourly observed fields for the first $2\frac{1}{2}$ days of each month were first averaged arithmetically. The model was then initialized at 00 GMT on day 2 with these time-averaged data and run to the end of the calendar month. The resulting monthly (minus one day) mean simulations were then compared with the observed means for the same periods, with the results shown as $\overline{M}$ in Table 8. Also shown for comparison in the table are the corresponding error statistics, M, for the basic simulation run, from Tables 2 and 3. Although the results are shown only for the Northern Hemisphere in Table 8, they are essentially the same for all the regions listed in Tables 2 and 3.

It is obvious from Table 8 that the use of time-averaged initial conditions did not result in any consistent improvement in the monthly mean simulations. The rms errors and S1 skill scores for $\overline{M}$ are essentially the same as for M, and in some cases slightly worse. (Although they are not shown, the synoptic maps as well as the rms differences and S1 comparison scores for $\overline{M}$ vs. M

Table 8. Root-mean-square (rms) errors and S1 skill scores of monthly mean simulations initialized with time-averaged initial data, $\bar{N}$, compared with those from day 1 initial conditions, M, (from Tables 2 and 3) for October 1976 and January 1977 over the Northern Hemisphere. (See text for details.)

	Oct.'76	Jan.'77	Oct.'76	Jan.'77	Oct.'76	Jan.'77
	Sea-level Pressure		850 mb Temperature		500 mb Height	
rms error	mb		°C		m	
$\bar{N}$	4.9	7.3	4.9	6.0	102	136
M	5.3	7.2	5.1	5.9	104	131
S1 score						
$\bar{N}$	91	89	62	65	53	68
M	95	89	66	67	52	67

also indicate no significant differences between the two simulations.) Thus, no benefit was gained from the use of time-averaged initial data.

The poor quality of monthly mean model simulations is a consequence of the rapid decay of predictability. An experiment was carried out to determine if this decay could be retarded by averaging the output of the first five days of the basic computation, then re-initializing the model at the middle of the five-day period with these time-averaged output data for the remainder of the calculation. Monthly simulations for October 1976 and January 1977 were computed by this method, with the first three days of the mean taken from the basic simulation run and the remainder from the re-initialized output. The verifications of these simulations, together with those of the basic experiment (from Tables 2 and 3), are shown in Table 9 for the Northern Hemisphere. Also shown in the table are the rms differences and S1 comparison scores between the monthly mean simulations computed by the two methods, where M* represents the result of the re-initialization procedure, and M, as before, the basic simulation.

It is apparent from Table 9 that the re-initialization method produced no discernible change in the monthly mean simulations. Not only are the rms errors and S1 skill

Table 9. Root-mean-square (rms) errors and S1 skill scores of monthly mean simulations for October 1976 and January 1977 over the Northern Hemisphere by the re-initialization method, M*, compared with the basic simulation, M. Also shown are rms differences and S1 comparison scores between M* and M. (See text for details.)

	Oct.'76	Jan.'77	Oct.'76	Jan.'77	Oct.'76	Jan.'77
	Sea-level Pressure		850 mb Temperature		500 mb Height	
rms	mb		°C		m	
M* error	5.1	7.4	5.1	6.0	107	135
M error	5.3	7.2	5.1	5.9	104	131
(M* - M) difference	0.9	1.5	0.9	1.3	11	19
S1						
M* skill	93	90	65	66	52	65
M skill	95	89	66	67	52	67
(M* - M) comparison	22	26	16	18	10	14

scores almost identical for the two methods, but the differences between the two simulations, as indicated by the rms differences and S1 comparison scores are practically negligible. (Similar results, not shown, were found for all seven regions.) Thus, neither time-averaging of initial conditions nor re-initialization with time-averages of early model output appears to result in any improvement in the quality of the monthly mean simulations.

Noise Level Estimation[7]

Inherent uncertainties exist in all model simulations due to unavoidable random errors in the initial data. The influence of such errors on long-term atmospheric simulations has been evaluated in "noise level" experiments (e.g., Chervin and Schneider, 1976 a, b; Spar et al., 1978) in which models were run repeatedly with the same synoptic-scale initial conditions, but with the initial analysis contaminated for each simulation by a different small-scale random perturbation field. The dispersion of the resulting simulations represents the noise of the model, which should be weak if it is not to mask signals due to prescribed changes in the model.

A noise level calculation was carried out with the coarse-mesh climate model to determine the inherent uncertainty of the monthly mean simulations. In this experiment, the initial analysis for 00 GMT 1 October 1976 was perturbed four times by means of a random number generator which geographically distributes Gaussian error sets with specified global rms magnitudes. The global rms errors added to the initial data in this experiment were 3 ms^{-1} for the zonal and meridional wind components and 1° C for the temperatures at all nine

[7] Adapted from a master's thesis submitted to The City College by Jesus J. Notario.

sigma levels of the model, and 3 mb for the surface pressures. Four prediction runs from the perturbed initial states were then executed, resulting in a total set of five monthly mean simulations, including the basic simulation which serves as a control.

From a visual comparison of the five fields of sea-level pressure, 850 mb temperature, and 500 mb height (not reproduced), there appear to be no discernible synoptic differences among the simulations. The rms errors and S1 skill scores (not shown) of the four perturbation simulations differ only slightly from those of the control shown in Tables 2 and 3. The similarity of the five fields is indicated quantitatively by the small rms differences and S1 comparison scores between pairs of simulations over the Northern Hemisphere in Table 10, where the results of the first perturbation, P1, are compared with each of the other four runs. Here it can be seen that the averages of the rms differences over the hemisphere are approximately 1 mb, 1° C, and 10 m, respectively, for sea-level pressure, 850 mb temperature, and 500 mb height. These values are less than half as large as those found by Spar et al. (1978) in the corresponding experiment with the 4 x 5 degree GISS model, probably reflecting the influence of the coarser resolution. The averages of the S1 comparison scores in

Table 10. Root-mean-square (rms) differences and S1 comparison scores over the Northern Hemisphere between monthly mean simulations for October 1976. M denotes control simulation. P1, P2, P3, and P4 represent simulations from four different random perturbations of the control initial conditions.

		P1 - M	P1 - P2	P1 - P3	P1 - P4
Sea-level	rms difference (mb)	0.8	1.0	1.1	1.3
Pressure	S1 comparison	23	26	27	29
850 mb	rms difference (^{o}C)	0.9	0.9	0.9	1.0
Temperature	S1 comparison	16	18	17	19
500 mb	rms difference (m)	9.1	9.0	9.4	11.8
Height	S1 comparison	10	10	11	14

Table 10 are approximately 26, 18, and 11 for the three fields, again indicating virtually no differences among the hemispheric patterns due to the initial perturbations. It is apparent from Table 10 that, in genera the influence of random initial state errors on the monthly mean simulations is negligible compared with the simulation errors. Similar results were found for all regions analyzed.

The geographical distribution of model noise level may be represented on global maps of standard deviation of the simulated variables (Chervin and Schneider, 1976 b). These were computed at each gridpoint in the present experiment from the five simulations (with four degrees of freedom) for sea-level pressure, 850 mb temperature, and 500 mb height, and are shown in Figures 5, 6 and 7, respectively, in digital form. Longitudes are labelled at top and bottom, negative for west and positive for east, with the Western Hemisphere on the left. Latitudes are shown in the second column from the right, positive for north and negative for south. Zonal mean values of the standard deviations are tabulated in the first column on the right, and the units on the maps are 10^{-1} mb, 10^{-1} degrees C, and m. (Also shown on the maps are the 24 x 36 gridpoint numbers.)

From the zonal mean standard deviations tabulated

	-180		-150		-120		-90		-60		-30		0		30		60		90		120		150															
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	5	6	5	5	6	6	6	6	6	7	6	6	6	6	6	6	6	6	90.0	6
23	5	11	8	11	11	11	14	14	17	9	18	19	12	13	17	15	16	17	15	16	9	11	7	7	7	5	10	15	9	10	8	7	6	7	6	7	82.2	11
22	11	8	5	8	11	8	17	10	13	17	17	12	8	7	15	27	16	22	17	15	2	12	12	9	7	10	8	10	12	12	22	15	9	9	16	12	74.3	12
21	16	9	7	6	12	7	4	5	10	9	6	9	8	9	8	11	15	30	14	12	15	6	14	17	13	16	13	6	7	12	19	16	5	14	14	13	66.5	11
20	11	8	4	7	10	10	7	4	5	4	3	7	10	6	7	21	25	22	11	11	18	19	12	17	17	13	8	7	6	8	9	18	5	6	9	13	58.7	11
19	8	7	8	7	10	7	6	4	4	5	8	7	9	6	7	13	20	16	10	9	4	7	6	4	6	7	10	5	5	4	11	12	10	7	5	8	50.9	8
18	8	7	8	6	7	4	9	8	8	5	11	8	11	3	6	8	13	6	5	4	10	6	6	5	6	9	5	4	5	5	5	9	8	5	5	6	43.0	7
17	6	7	4	3	3	3	4	16	9	11	10	13	12	8	6	5	10	6	6	5	3	3	5	4	6	6	8	20	12	8	8	4	5	6	6	5	35.2	7
16	3	3	2	3	3	1	5	3	5	6	4	13	3	5	1	4	2	8	7	5	8	6	2	2	6	6	8	9	11	5	2	3	3	1	4	2	27.4	4
15	2	2	2	3	1	2	2	2	6	4	2	3	2	2	2	2	4	9	7	3	7	7	3	6	4	3	15	2	2	2	2	2	3	2	2	2	19.6	3
14	2	3	2	2	1	2	2	1	2	4	5	2	2	1	1	1	2	6	6	10	14	19	3	3	2	2	4	2	4	2	2	2	4	1	2	3	11.7	3
13	2	1	1	1	3	1	3	2	2	1	3	2	1	2	2	2	3	3	2	3	5	3	6	3	3	1	1	1	2	3	2	2	3	1	3	2	3.9	2
12	1	3	3	2	2	2	1	2	1	2	2	4	3	1	1	2	1	3	3	3	5	3	5	3	1	2	2	2	2	2	4	2	0	1	1	2	-3.9	2
11	1	2	1	3	2	3	2	0	3	2	2	2	3	4	3	3	4	2	3	2	9	5	5	2	3	1	1	2	2	1	3	2	4	1	1	2	-11.7	3
10	2	1	2	2	4	4	4	2	4	1	2	14	6	6	5	3	1	3	4	3	16	5	2	4	1	4	2	4	3	4	3	7	6	3	3	2	-19.6	4
9	9	3	4	4	3	5	3	4	3	5	5	14	8	5	7	5	3	3	2	7	10	5	3	3	4	7	4	5	5	7	6	13	9	9	9	9	-27.4	6
8	9	7	3	5	6	5	2	2	3	5	6	10	7	6	8	8	10	5	6	15	8	5	5	4	8	7	6	7	5	8	3	5	9	11	12	14	-35.2	7
7	10	10	3	3	2	5	7	7	7	8	7	7	2	9	9	4	7	3	5	14	12	5	2	8	13	14	13	8	4	6	7	6	8	8	10	13	-43.0	7
6	3	8	5	6	5	4	6	5	5	11	10	10	9	12	8	9	7	7	5	11	10	4	2	6	9	10	7	3	5	6	5	4	6	9	8	5	-50.9	7
5	9	10	8	7	6	6	7	6	2	7	10	5	12	8	10	10	11	8	6	5	8	8	3	5	9	5	5	3	5	5	4	6	7	6	6	8	-59.7	7
4	9	8	9	7	7	7	7	3	6	4	7	17	13	15	13	11	5	5	5	8	10	10	8	11	4	9	6	10	15	13	9	5	10	11	9	10	-66.5	9
3	9	9	9	6	8	8	7	11	14	13	12	20	16	15	15	6	3	10	10	10	7	7	15	7	22	16	16	6	11	15	22	30	14	16	8	10	-74.3	12
2	9	11	8	12	7	13	8	15	17	16	15	12	8	7	11	14	8	7	15	32	15	20	19	14	20	36	15	24	23	8	23	33	11	6	10	8	-82.2	15
1	18	18	18	18	18	18	17	18	18	18	18	18	17	17	18	18	18	18	18	18	18	17	18	18	17	18	17	18	18	18	18	18	18	18	18	18	-90.0	18
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180		-150		-120		-90		-60		-30		0		30		60		90		120		150															

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Figure 5. Standard deviations of five simulations of the global sea-level pressure field for October 1976.

Units: 10^{-1} mb.

	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150					
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	90.0	9
23	7	5	12	7	7	7	6	12	8	16	14	10	9	9	8	6	6	9	8	11	8	23	13	4	10	9	9	14	9	7	5	8	7	5	8	7	82.2	9
22	6	3	14	11	9	6	5	9	13	16	9	9	4	11	20	55	21	16	15	11	5	4	5	6	7	12	1	6	11	4	8	2	5	3	7	6	74.3	10
21	5	10	10	7	13	4	8	9	8	14	9	11	2	8	14	8	10	10	8	9	10	9	4	10	5	12	10	9	7	3	8	5	5	9	15	8	66.5	8
20	4	3	9	3	3	5	8	4	4	3	3	5	7	6	2	6	5	6	8	2	10	13	10	8	6	8	5	2	2	5	7	11	9	7	7	4	58.7	6
19	3	2	4	2	1	3	4	4	5	2	6	3	7	6	6	8	5	4	6	9	7	12	10	6	3	7	10	6	6	7	8	5	13	7	5	3	50.9	6
18	1	2	4	3	3	2	5	4	11	4	12	5	8	5	3	6	3	2	4	3	4	3	5	5	1	6	4	2	3	4	5	6	8	5	1	2	43.0	4
17	3	3	2	1	2	2	2	12	7	7	15	2	5	4	3	2	3	2	4	2	2	1	3	3	2	4	8	15	17	6	5	3	1	1	2	2	35.2	4
16	1	1	1	1	1	3	10	5	3	4	5	2	3	1	2	1	4	12	8	9	11	9	5	7	8	5	10	10	13	4	5	2	0	1	2	1	27.4	5
15	0	1	1	3	1	11	9	1	2	2	4	1	2	1	7	9	12	9	11	9	10	11	2	3	3	6	25	2	1	1	2	2	1	1	4	1	19.6	5
14	1	2	5	1	1	1	1	2	2	2	2	1	2	1	2	3	11	7	4	10	18	27	1	2	17	6	1	2	2	4	2	3	2	1	1	1	11.7	4
13	1	1	2	2	3	3	4	8	6	5	2	1	1	4	4	12	13	3	12	3	2	2	5	3	4	6	4	3	1	3	1	2	1	1	1	3	3.9	4
12	1	1	1	1	2	5	5	10	6	8	3	6	3	5	4	4	8	14	11	6	3	2	1	4	1	2	2	3	2	2	4	2	1	1	1	1	-3.9	4
11	3	2	1	2	2	1	3	7	13	14	11	1	1	1	3	6	6	6	12	6	14	2	2	3	3	3	2	5	11	14	2	2	15	7	3	1	-11.7	5
10	3	3	3	3	3	1	2	4	10	7	6	24	10	3	3	3	7	6	11	10	28	3	2	2	2	4	3	3	4	8	7	12	5	3	2	3	-19.6	6
9	5	3	4	3	3	3	4	4	4	3	3	22	7	5	5	6	6	4	4	2	13	6	2	2	3	2	6	1	2	3	7	23	8	5	2	6	-27.4	5
8	6	4	5	2	2	2	4	4	3	2	3	6	5	8	3	7	4	3	8	5	3	2	4	4	3	5	5	4	4	2	1	7	7	4	4	7	-35.2	4
7	6	8	3	4	5	3	3	3	3	2	2	1	2	8	8	4	6	7	3	5	9	7	4	4	4	5	10	5	7	5	1	4	5	6	1	5	-43.0	5
6	3	3	2	4	3	1	3	4	3	3	2	4	5	3	10	9	4	10	7	9	6	6	6	4	5	6	5	2	4	4	2	3	3	2	5	3	-50.9	4
5	2	3	3	1	3	2	4	6	4	4	1	3	5	2	8	13	11	7	6	6	7	7	7	7	4	5	4	4	2	1	3	2	3	4	3	2	-58.7	5
4	7	7	6	3	2	4	7	6	7	5	6	6	5	6	7	9	6	6	5	7	7	9	9	8	10	5	8	10	16	22	21	17	13	8	8	8	-66.5	8
3	5	7	6	8	9	5	5	7	7	17	15	23	17	2	7	4	4	5	7	55	33	26	39	32	39	17	42	42	28	44	55	18	16	23	7	6	-74.3	19
2	4	1	4	2	4	7	8	14	19	21	26	16	6	2	14	8	12	15	21	20	31	21	27	62	28	58	55	34	42	30	51	27	12	12	9	4	-82.2	20
1	19	19	19	19	19	18	19	19	19	19	19	19	19	19	19	19	18	19	18	19	19	19	19	19	19	19	18	19	19	19	19	18	19	19	19	19	-90.0	19
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-50			-30			0			30			60			90			120			150				

Figure 6. Standard deviations of five simulations of the global 850 mb temperature field for October 1976.

Units: 10^{-1} degrees C.

	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
24	9	10	10	10	10	9	10	9	9	9	10	10	9	9	9	9	9	9	10	9	10	10	9	9	10	9	9	9	9	9	9	10	10	9	9	10	90.0	9
23	3	8	12	10	12	7	6	6	6	6	10	10	17	12	12	6	15	11	14	10	13	10	9	7	4	10	8	8	8	7	11	8	13	6	11	9	82.2	9
22	5	8	15	12	9	6	7	2	7	9	7	8	8	6	9	13	16	15	15	14	12	7	7	2	9	7	10	7	10	7	6	5	10	11	9	6	74.3	9
21	8	7	10	11	9	7	10	9	8	11	9	11	9	13	6	13	17	9	13	15	11	16	13	7	7	8	9	8	8	4	4	4	5	17	21	18	66.5	10
20	15	7	10	14	9	9	10	8	3	4	4	7	7	10	5	13	14	8	13	9	2	13	19	14	9	8	5	3	6	5	7	3	14	19	24	21	58.7	10
19	9	8	7	12	7	6	7	7	7	5	6	5	5	8	5	21	19	8	5	7	7	14	16	13	6	8	10	9	9	9	8	4	12	18	17	15	50.9	9
18	8	5	4	8	3	5	8	5	11	7	12	9	10	14	2	16	15	8	4	4	4	7	11	9	4	6	7	5	3	4	8	5	5	9	7	8	43.0	7
17	8	4	2	3	3	4	4	4	8	8	18	9	5	8	1	9	8	6	6	7	3	2	4	7	5	5	3	4	2	4	7	7	6	5	5	6	35.2	6
16	4	2	3	1	3	5	9	4	3	7	8	5	5	5	4	4	2	6	6	5	1	6	4	7	4	5	3	4	4	4	7	6	3	5	4	4	27.4	4
15	2	2	2	5	3	3	2	3	1	5	3	2	4	2	4	4	3	7	2	4	4	4	2	3	2	2	2	4	2	2	2	2	2	2	3	2	19.6	3
14	2	1	1	1	1	2	1	2	1	2	2	2	1	2	2	2	1	2	1	2	3	2	1	3	3	4	1	1	1	2	2	3	3	2	1	1	11.7	2
13	2	1	1	0	1	1	1	1	1	2	1	2	1	1	1	1	1	2	2	2	3	1	2	2	2	1	1	1	1	2	1	2	2	1	2	2	3.9	1
12	2	2	1	1	1	1	1	1	1	2	2	2	1	1	1	1	1	2	1	1	4	1	2	2	1	1	2	1	1	2	2	2	1	1	2	2	-3.9	1
11	2	2	1	2	3	3	4	3	4	5	3	1	1	2	2	3	4	4	3	4	4	2	3	3	3	2	3	4	2	1	3	1	2	1	3	3	-11.7	3
10	4	3	3	4	6	4	3	5	3	8	6	5	4	2	3	7	7	6	6	5	5	2	3	4	4	3	4	5	5	8	9	9	7	3	3	7	-19.6	5
9	9	4	6	3	5	5	8	9	7	8	7	10	3	4	6	11	10	5	8	9	8	7	6	5	7	4	4	4	7	5	9	16	11	12	8	6	-27.4	7
8	8	5	8	7	4	3	3	6	6	2	5	8	8	10	13	8	6	4	14	13	6	5	5	9	7	6	6	7	7	8	3	7	9	11	15	7	-35.2	7
7	9	12	14	11	11	9	8	7	6	6	7	6	5	10	19	9	5	16	6	7	12	15	10	9	10	7	8	15	14	12	10	9	12	12	12	7	-43.0	10
6	10	14	12	12	10	9	9	9	9	11	8	10	6	5	15	18	15	16	15	12	15	17	14	12	12	12	9	4	8	8	3	2	6	3	5	7	-50.9	10
5	11	12	11	9	8	6	4	7	8	11	10	7	7	10	8	18	19	12	5	9	10	10	12	14	15	11	11	8	9	7	6	6	5	7	9	10	-58.7	9
4	11	11	9	6	7	9	10	9	12	15	16	16	11	13	11	14	13	11	13	12	9	8	10	10	10	5	9	10	10	9	11	13	13	10	11	11	-66.5	11
3	7	7	10	10	11	11	12	11	12	14	18	20	18	14	12	9	7	4	8	10	6	7	9	9	5	4	11	13	12	11	9	10	11	8	9	6	-74.3	10
2	6	8	9	10	9	9	5	8	9	13	13	15	11	13	9	12	6	10	8	7	9	9	13	10	11	8	5	6	6	6	7	8	6	4	5	4	-82.2	9
1	6	6	6	6	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	-90.0	6
J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	LAT	MEAN
	-180			-150			-120			-90			-60			-30			0			30			60			90			120			150				

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Figure 7. Standard deviations of five simulations of the global 500 mb geopotential height field for October 1976.

Units: meters.

in Figures 5, 6 and 7, it is apparent that, in general, the noise level is negligibly small near the Equator (with zonal mean standard deviations of 0.2 mb, 0.4° C, and 1 m) and greatest in high latitudes. The largest point standard deviations of sea-level pressure are found in the Antarctic (3.6 mb) and near Iceland (3.0 mb), with maximum zonal means of 1.8 mb near the South Pole and 1.2 mb at 74° N. For the 850 mb temperature simulations, the largest point standard deviations are found again in the Antarctic (6.2° C) and also over Greenland (5.5° C), with maximum zonal means of 2.0° C at 82° S and 1.0° C at 74° N. At the 500 mb level, maximum point standard deviations appear in the Antarctic (20 m), South Atlantic (19 m), North Atlantic (21 m), and over eastern Siberia (24 m), with maximum zonal means of about 10 m north of 51° N and south of 42° S.

The increase in noise level from low values in the tropics to higher values in high latitudes is consistent with the results of Chervin and Schneider (1976 b) with the NCAR model and Spar et al. (1978) with the GISS model. However, there is considerable zonal variation of the standard deviations as well in Figures 5, 6 and 7, even in the sub-tropics, where larger values generally appear over the continents (Australia, Africa, South America) than over the oceans. This is particularly true of the

850 mb temperatures, indicating the apparently greater sensitivity of the model temperature calculations to initial conditions over land than over water. The noise level also appears greater over the Antarctic and Greenland ice, possibly reflecting modeling defects associated with topography as well as the physics of the ice surface.

In general, it may be concluded that, while the influence of random initial state errors on the monthly mean simulations appears to be insignificant when compared with the large-scale simulation errors, the geographical distribution of noise level, particularly its variation with latitude, should be considered, as suggested by Chervin and Schneider (1976 b), in the evaluation of any climate change experiments with the model. However, the relatively trivial influence of random initial state errors compared with the simulation errors indicates both stable behavior of the model and the need for further model improvement.

Conclusions

Monthly mean simulations computed from initial data at the beginning of each of the five months, October 1976 through February 1977, with a coarse-resolution climate model developed by Hansen and his colleagues at GISS have revealed certain limitations of the model as a long-range prediction system, despite its realistic simulation of large-scale meridional structure. However, as the model is still in the process of development and modification, any conclusions regarding its performance should be considered only tentative.

The model simulations exhibit a cold bias in the 850 mb temperatures at all latitudes, with a corresponding negative bias in the geopotential heights of the 500 mb surface, relative to climatology as well as to the observed monthly mean state. For most of the regions and months analyzed, the rms errors and S1 skill scores of the monthly simulations of sea-level pressure, 850 mb temperature, and 500 mb height are larger than the corresponding values for climatology, indicating that, at this stage, the model does not realistically simulate anomalous monthly mean synoptic patterns from given initial conditions.

When observed monthly average sea-surface temperatures (SSTs) are substituted for the climatological

SSTs used in the first simulations, the results are not improved. At upper levels, represented by the 500 mb surface, the impact of SST anomalies on the model simulations is found to be negligible. Lower levels of the model atmosphere, on the other hand, are more sensitive to alterations in ocean temperatures. Thus, for example, higher (lower) sea-level pressures are generated locally by the model over cold (warm) SST anomalies, and more complex remote effects on the sea-level pressure field are found also. However, the impact of the SST data on the monthly mean simulations of sea-level pressure, 850 mb temperature, and 500 mb height fields is, in general, not beneficial, and the results of the experiment lend no support to the hypothesis that SST anomalies are responsible for atmospheric anomalies. Admittedly, this result may be more indicative of model deficiencies than of the behavior of the real atmosphere.

Small changes in the monthly mean synoptic patterns generated by the model are found to result from shifts of one and two days in the initial data, indicating an inherent minimal error level associated with the arbitrary choice of initialization time. The monthly mean simulations are not improved by the use of either time-averaged initial data, smoothed over a 2½-day period, or re-initialization, before completion of the monthly run, with time-averaged model output smoothed over the first five forecast days.

The noise level of the coarse-mesh model, as determined from a multiple random perturbation experiment, appears to be even lower than that of the 4 x 5 degree GISS model. At this stage, the general effect of random initial state errors on the monthly mean simulations is negligible compared with the large-scale simulation errors, indicating stable behavior of the model but also a need for model improvement. Average rms differences between perturbed simulations over the Northern Hemisphere are only about 1 mb, 1° C, and 1 m for sea-level pressure, 850 mb temperature, and 500 mb height, respectively. However, the global distribution of the noise level, represented by maps of the standard deviations of the five simulations generated in the perturbation experiment, reveals marked spatial differences, with minimum values in the tropics and maxima in high latitudes, as well as zonal variations which suggest greater sensitivity to initial errors over land and ice than over open ocean.

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Figures

1. Monthly mean sea-level pressures over the northwest quadrant. Top: observed; bottom: simulated. Units: mb - 1000. 4 mb isobars. (a) October 1976 through (e) February 1977.

2. Monthly mean 850 mb temperatures over the northwest quadrant. Top: observed; bottom: simulated. Units: degrees C. 5^{o} C isotherms. (a) October 1976 through (e) February 1977.

3. Monthly mean 500 mb geopotential heights over the northwest quadrant. Top: observed; bottom: simulated. Units: decameters - 500. 100 m contours. (a) October 1976 through (e) February 1977.

4. Monthly mean sea-surface temperature anomalies (observed - climatology) over the globe in degrees C. (a) October 1976 through (e) February 1977.

5. Standard deviations of five simulations of the global sea-level pressure field for October 1976. Units: 10^{-1} mb.

6. Standard deviations of five simulations of the global 850 mb temperature field for October 1976. Units: 10^{-1} degrees C.

7. Standard deviations of five simulations of the global 500 mb geopotential height field for October 1976. Units: m.