FURTHER STUDIES ON ATMOSPHERIC GENERAL CIRCULATION AND TRANSPORT OF RADIOACTIVE DEBRIS

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ABSTRACT

This paper is a continuation of a previous publication (Mahlman, 1966) which attempted to explain the physical bases for large-scale seasonal and short-term radioactive fallout fluctuations. The previous paper demonstrated that the seasonal fallout variation depends directly upon the stratospheric circulation and that the spring fallout peak is attributable to increased eddy fluxes of debris following the major breakdown of the polar night vortex.

In this paper an analysis is performed on a "minor breakdown" of the stratospheric circulation which occurred during a period of general intensification of the polar vortex (15 November to 15 December 1958). Computation of the v'w' covariances showed that this period is favorable for northward and downward transport of radioactive debris, but far less so than the period following the January 1958 major breakdown of the polar night circulation.

The mean meridional circulation was computed for the chosen time period using a thermodynamic method. For this period the mean cell is always <u>direct</u>, but changes direction when the mean north-south temperature gradient reverses from positive to negative. A calculation is also performed on the mean circulation relative to a polar vortex oriented coordinate system. For this system the mean cell is <u>indirect</u>. In the previous paper the latitudinal mean cell was computed to be <u>indirect</u> prior to the major polar night vortex breakdown while relative to the circulation coordinate, the mean cell was thermodynamically <u>direct</u>. These opposite results suggest that the mechanisms for maintaining the zonal mean circulation and the polar vortex differ considerably between the onset and termination of the stratospheric polar night circulation. Also, this implies that the debris transport characteristics of the lower stratosphere depend explicitly on circulation type and season.

I. INTRODUCTION

At the time of the first tests of thermonuclear weapons in the atmosphere, scientists believed that no significant surface fallout would result since such weapons contain enough thermal energy to inject most of the debris into the stable layers of the lower stratosphere. The assumption was that the debris would remain indefinitely in the stratosphere since the high static stability of the region acts to inhibit the vertical transport processes responsible for carrying it downward. It soon became evident, however, that significant amounts of radioactive debris were being transported downward from the stratosphere. This was verified through radiochemical and physical measurement of large surface fallout intensity variations many months after weapons testing had terminated. In view of the fact that the mean tropospheric residence half-time of a radioactive particle is about one month (Stewart, Crooks, and Fisher, 1955), the inference that the surface increases were of stratospheric origin was justified.

Even though the initial fallout measurements were very sporadic, within a relatively short time it became apparent that the atmospheric circulation acts to produce some surprising surface fallout characteristics over time periods following such thermonuclear weapons testing (for references, see Mahlman, 1966). These measurements revealed that very large local surface increases in fallout intensity can be documented for several years after cessation of nuclear testing. Furthermore, there existed a pronounced peak of fallout intensity in mid-latitudes, and a well-defined peak of radioactivity was present in the spring of each year.

The radiochemical measurements strongly suggested a very efficient mechanism for transporting stratospheric air into the troposphere. At that time, however, no atmospheric model was capable of explaining the phenomenon. Although substantiating local radiochemical measurements were not available at that time, Reed and Sanders (1953) and Reed (1955) showed that stratospheric air can enter the troposphere in the intense frontal zones below the core of the jet stream. This process was substantiated in greater detail by subsequent investigators (Endlich and McLean, 1957; Danielsen, 1959a, b, 1964a, b; Danielsen, Bergman, and Paulson, 1962; Reed and Danielsen, 1959; Staley, 1960, 1962; Reiter, 1963a, b, 1964; Reiter and Mahlman, 1964, 1965a, b; Mahlman, 1964a, 1965b).

Some of these investigators (Staley, 1962; Danielsen, Bergman, and Paulson, 1962; Danielsen, 1964b) also were able to show through flight measurements that higher values of fallout intensity are associated with this frontal zone.

Staley (1960, 1962) demonstrated that the intrusion of air from the stratosphere into the troposphere is associated with high level cyclones. This hypothesis was corroborated with a case study by the author (Mahlman, 1964a, 1965b). These studies revealed that the descent of stratospheric air occurs in association with very pronounced cyclogenesis at tropopause level. This dependence of the sinking process upon cyclogenesis was also noted by Danielsen (1964a). The cyclogenetic mechanism was further substantiated by Reiter and Mahlman (1964, 1965a, b) through case study analyses. Also, it was hypothesized that the amount of mass in each descent is proportional to the intensity of cyclogenesis at tropopause level.

As a means of testing the above cyclogenetic hypothesis, a lengthy statistical analysis was performed on the 300 mb meteorological data and the Public Health Service surface fallout data during the test moratorium years 1963 and 1964 (Mahlman, 1964b, c, 1965a, 1966). This analyses showed quite conclusively that both the shorter-period fallout variations and the mid-latitude peak can be readily explained by the relative time frequency of strong cyclogenesis and the fact that the region of maximum cyclonic activity occurs in the optimum position for producing a mid-latitude maximum in downward transport of debris.

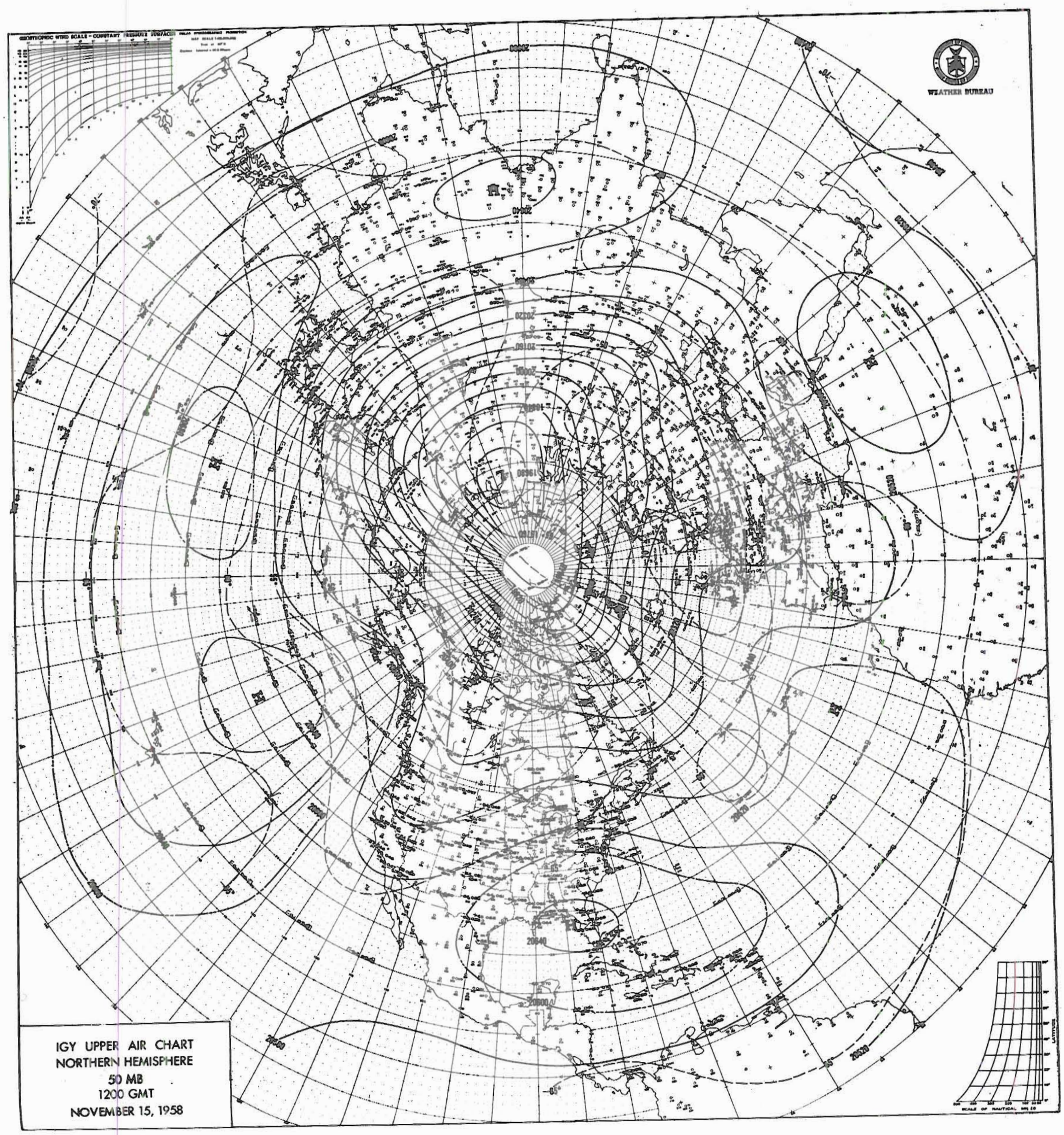


FIG. 1. Continued.

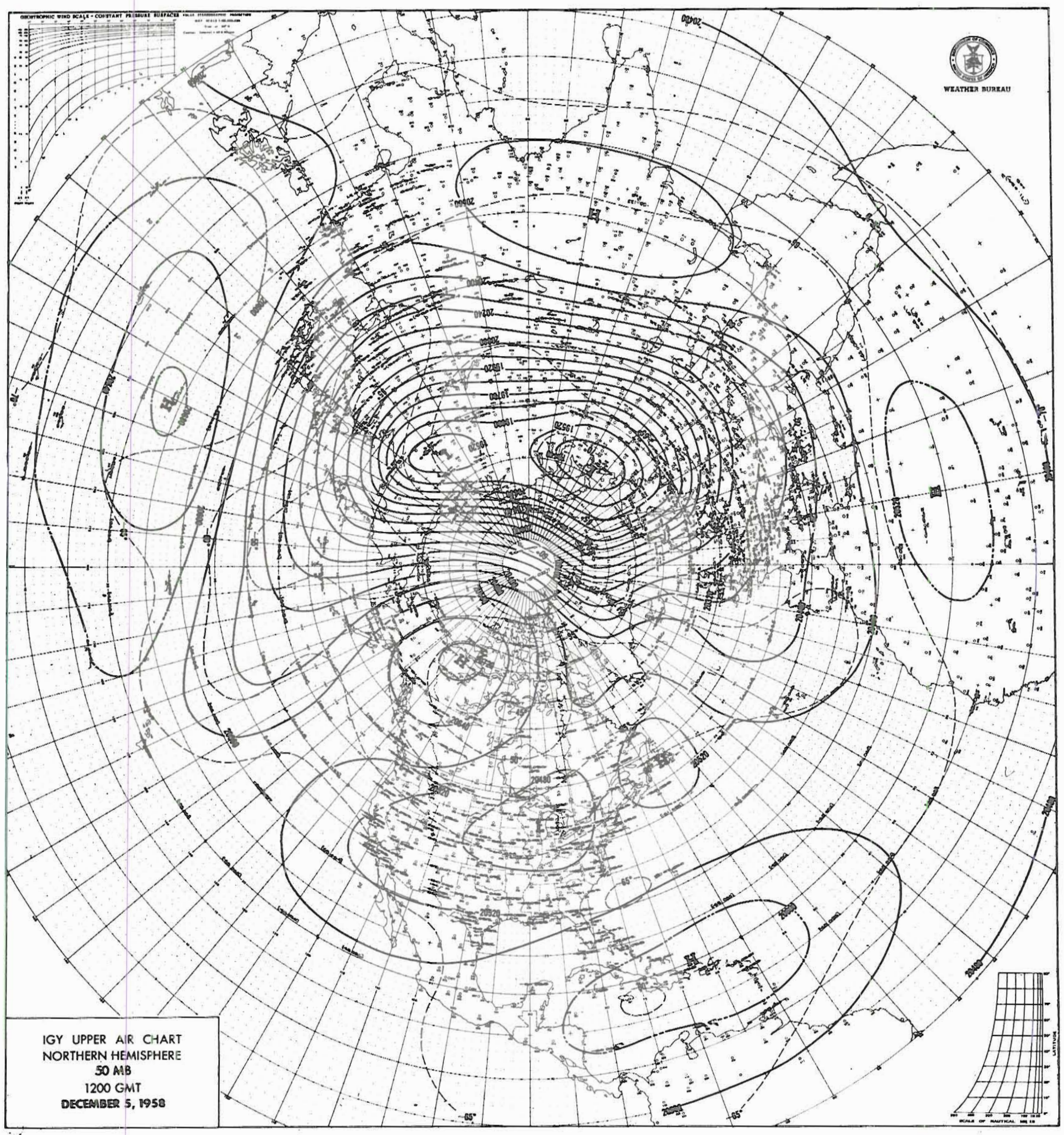


FIG. 1. Continued.

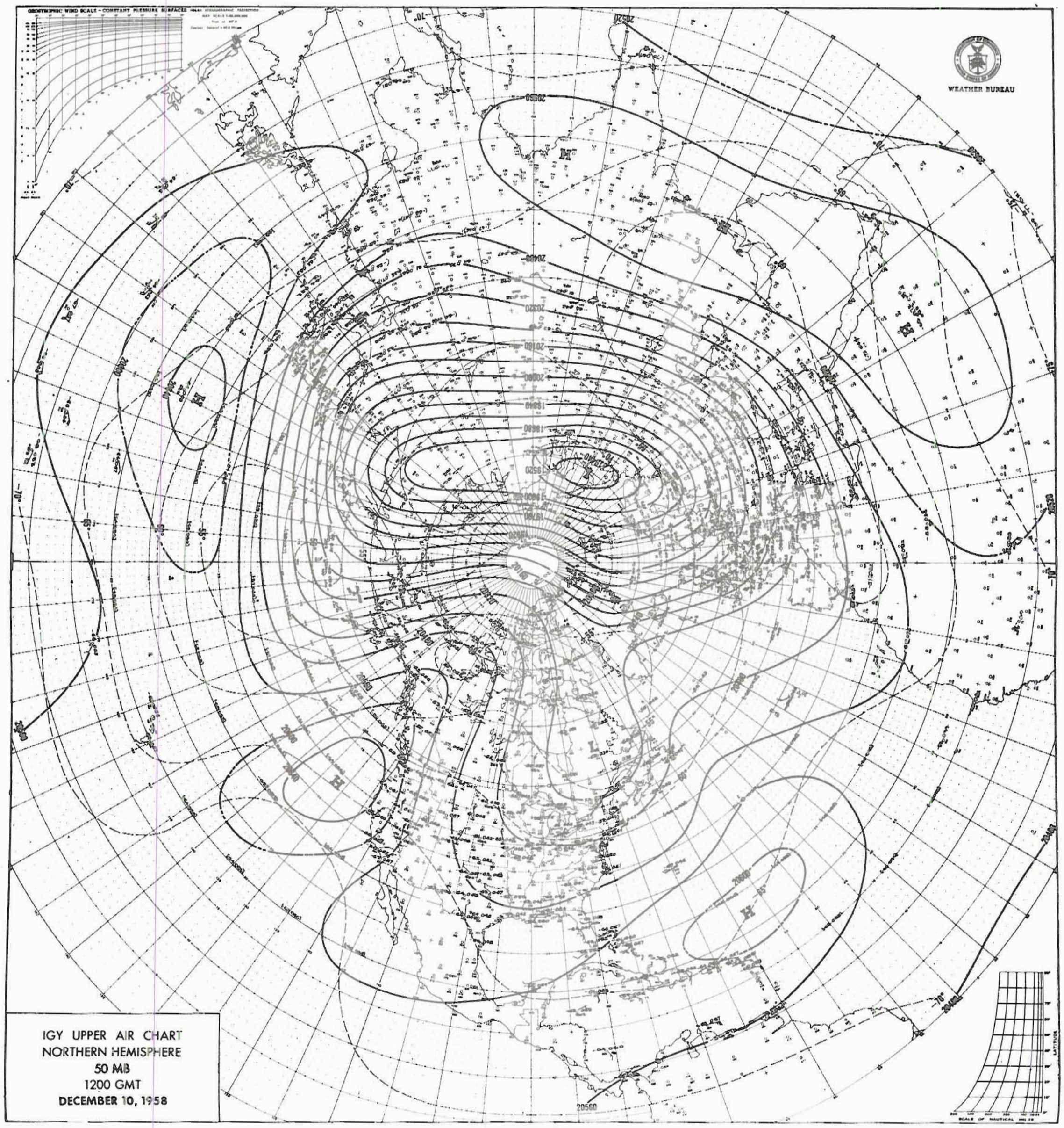


FIG. 1. Continued.

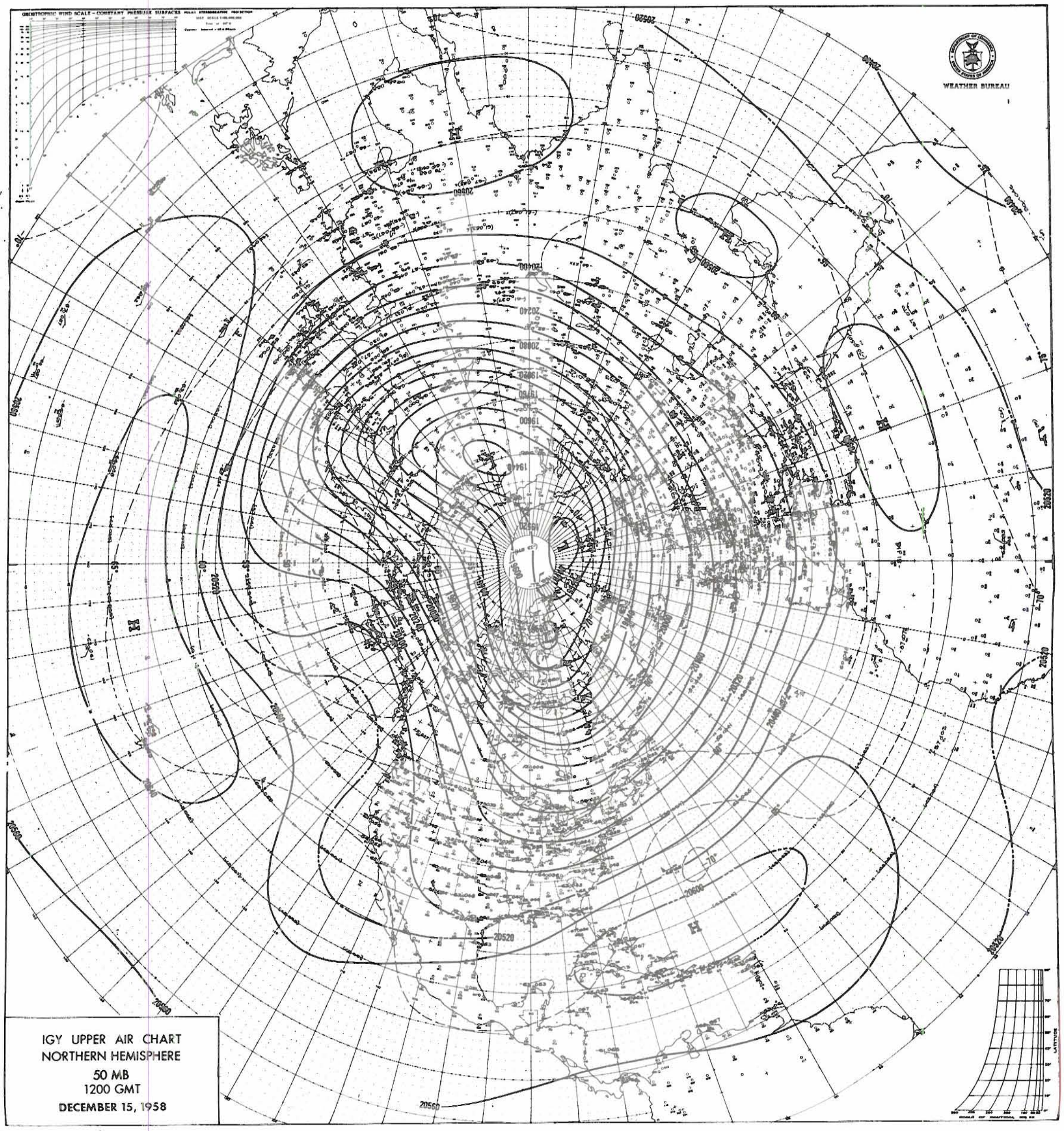


FIG. 1. Continued.

II. EDDY TRANSPORT PROCESSES IN THE LOWER STRATOSPHERE --15 NOVEMBER—15 DECEMBER 1958

As a general rule the fall and wintertime circulation of the polar stratosphere is one of westerlies increasing in intensity as the winter season progresses. As this circulation intensifies there is a pronounced tendency for the flow to become more zonal--creating an intensely cold polar vortex. As noted by previous investigators, the intensification during the fall and early winter is not a gradual process but is marked by irregular interruptions of the circulation buildup (Lee and Godson, 1957; Godson and Lee, 1958; Hare, 1960; Boville, Wilson and Hare, 1961). In many winters the vortex begins to deform into a one, two, or three wave pattern leading to what is commonly referred to as the "sudden warming" phenomenon. The synoptic characteristics of such "sudden warmings" have been outlined in some detail by previous authors (Teweles, 1958; Teweles and Finger, 1958; Craig and Hering, 1959; Craig and Lateef, 1962; Palmer, 1959; Hare, 1960; Conover, 1961; Belmont, 1962; Miers, 1963; Morris and Miers, 1964). This warming process acts to destroy the mean latitudinal temperature gradient and most of the kinetic energy in the lower stratosphere. Since this sudden warming phenomenon often occurs in mid-winter, many times the westerlies will re-intensify. When the solar radiation returns to polar latitudes, the westerly regime completely disappears and the summertime easterlies set in.

In the previous paper (Mahlman, 1966) an extensive analysis was performed on the eddy transport processes in the lower stratosphere encompassing a period before, during, and after the stratospheric polar vortex breakdown of January—February 1958. This work showed rather clearly that favorable conditions for northward and downward debris transport at higher latitudes ($\overline{v'w'} = -$) were present in the lower and middle stratosphere <u>after</u> the breakdown of the polar night vortex. This transport is in qualitative agreement with the time of occurrence of the spring surface fallout peak. These calculations also agree with those of Molla and Loisel (1962) which indicate favorable $\overline{v'w'}$ values in the 100-50 mb layer for January and April 1958. These computations can, of course, be only indicative of the probable sense of the transports until synoptic measurements of trace substances become available on a more or less routine basis. The now discontinued ozonesonde network (Hering, 1964) was an excellent step in this direction.

As noted in the Introduction, these results indicated that a more thorough knowledge of the dynamics of the stratospheric circulation is necessary before a complete understanding of the fallout problem can be claimed. In order to proceed toward this goal, the period 15 November to 15 December 1958 was selected for analysis using the U. S. Weather Bureau (1963) stratospheric maps for the IGY period.

This period was characterized by an intensifying winter stratospheric circulation which was interrupted by large perturbations forming at higher latitudes (see Fig. 1). Fig. 2 shows a time series of cyclone index (Mahlman, 1966) at 50 mb, 60°N in which the index changes from high to low and back to high values again during the time period. As implied by Fig. 2, toward the end of the period the flow becomes increasing zonal. The period 10-15 December was dominated by a "sudden cooling" in the highest latitudes (see Fig. 3) due to an increasing zonal symmetry of the polar vortex and a damping of the disturbances which originally produced the cyclone index decrease. The hemispheric circulation was dominated by an eccentric polar vortex and a well-developed Aleutian anticyclone. According to Boville (1960), this Aleutian high developed in October 1958 in an almost barotropic stratosphere as a result of pronounced cyclogenesis in the troposphere. This high continues to dominate the flow until about 10 December.

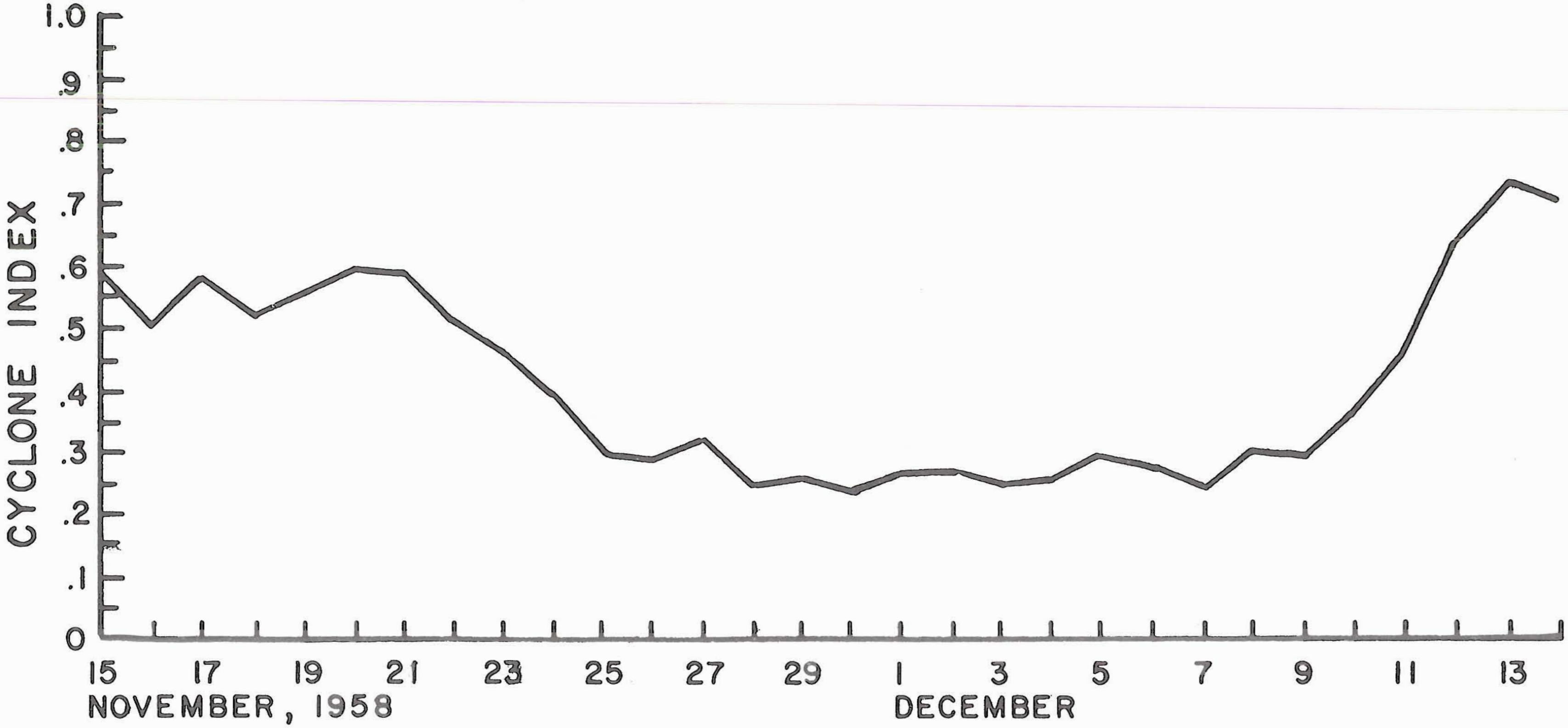


FIG. 2. Time series of cyclone index (Mahlman, 1966) at 50 mb, 60°N for the period 15 November—15 December 1958.

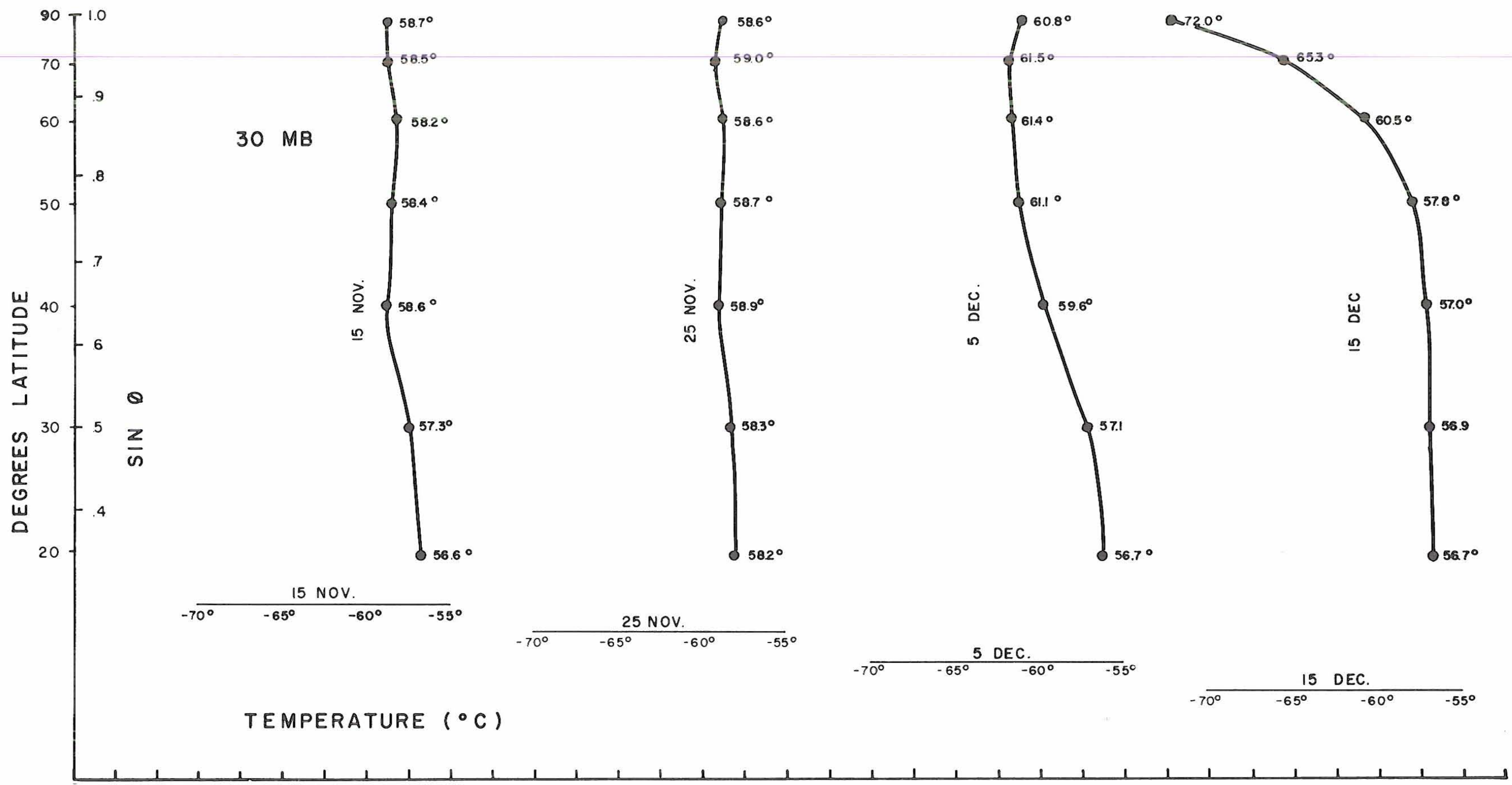


FIG. 3c. Same as Fig. 3a except at 40 mb.

Since this selected case study is during a period of buildup of the polar night vortex, it is of interest to determine the transport properties of the lower stratosphere during this time and compare the results with those obtained previously for the breakdown period. Such computations should provide some insight into the reasons for the differences in surface fallout intensity between the winter and spring seasons. The determination of these transport properties demands a knowledge of the u, v, w, and T fields, where u is the zonal wind component and T is the temperature.

In most previous studies of the stratosphere (Jensen, 1961; Murakami, 1962; Dickenson, 1962; Oort, 1962; Molla and Loisel, 1962; Miller, 1966) the computations of u, v, w, and T were taken from the original station data. Mean values over the hemisphere were then obtained by computing an arithmetic average of all stations located within a given latitude belt. This approach is straightforward because the computations can then be computerized directly in terms of the original station data. One difficulty that has always been recognized by the above investigators is that such an averaging procedure can yield inaccuracies due to the unequal weighting of station data. This effect becomes particularly serious in cases where most of the effect of a given quantity may depend upon the contribution from a limited longitudinal region. Another shortcoming of the single station method is that the computed vertical motion depends upon the validity of the thermal wind approximation in relating the measured detailed vertical wind shear from the sounding to the larger scale horizontal temperature gradients. In some cases the effect may be to seriously overestimate the magnitude of the time averaged vertical motion field.

As a means of avoiding the difficulties pointed out above, all values of u, v, w, and T were calculated at 100 and 50 mb and at intervals of 10° longitude at the respective latitudes 40°, 50°, 60° and 70° North. At 80°N the data coverage is poor and the latitudinal circumference is relatively small. Below 40°N the data coverage is also inadequate due to the larger percentage of ocean area. Also, the circulation disturbances in higher latitudes are usually not present south of 40°N.

In obtaining the horizontal wind components, actual winds were used whenever possible, but geostrophic winds were computed when no wind measurements were available. Because the vertical wind component (w) must be derived, considerable uncertainty is present when one attempts to find accurate w fields. Since the static stability in the stratosphere is quite high and the radiative heat changes are somewhat simpler in higher latitudes at this time of year, the thermodynamic method for computing vertical velocity was chosen to be the most desirable. By solving the thermodynamic equation for w, one obtains

$$w = \frac{1}{\frac{g}{c_p} + \frac{\partial T}{\partial z}} \left[\frac{1}{c_p} \frac{dh}{dt} - \frac{\partial T}{\partial t_z} - \vec{V}_2 \cdot \nabla T_2 \right] \tag{1}$$

where g is the acceleration of gravity, c_p the specific heat of air at constant pressure, h the heat per unit mass, $\vec{V}_2$ the horizontal vector wind, ∇ the horizontal del operator, z the height, and t is the time. The subscript z denotes differentiation on a constant height surface. This equation is somewhat ambiguous the way it is to be used here because the temperature derivatives are to be computed relative to the pressure surface rather than the z surface. In the stratosphere, however, this approximation is quite valid since the vertical temperature gradients are very small in these regions. The validity of this approximation may be readily seen by writing the transformation equations for the temperature derivatives in Eq. (1) from z to pressure coordinates,

$$\frac{\partial T}{\partial t_z} = \frac{\partial T}{\partial t_p} - \frac{\partial T}{\partial z} \frac{\partial z}{\partial t_p} \tag{2a}$$

$$V_s \frac{\partial T}{\partial s_z} = V_s \frac{\partial T}{\partial s_p} - V_s \frac{\partial T}{\partial z} \frac{\partial z}{\partial s_p} , \qquad (2b)$$

where $V_s \frac{\partial T}{\partial s}$ is the advection $(V_2 \cdot \nabla T)$ expressed in natural coordinates and the subscripts z and p denote height and pressure coordinates, respectively. Characteristic orders of magnitudes of the various terms are: $\frac{\partial T}{\partial t_p} \sim V_s \frac{\partial T}{\partial s_p} \sim 2^{o}C/day$; $\frac{\partial T}{\partial z} \sim 10^{-3} deg\, m^{-1}$; $\frac{\partial z}{\partial t_p}(max) \sim 50 m/day$; $\frac{\partial z}{\partial n_p}(max)$ (slope of p surface normal to wind) $\sim .2 \times 10^{-3}$; $\frac{\partial z}{\partial s_p}(max) \sim .02 \times 10^{-3}$; $V_s(max) \sim 50 m/sec$. Substituting these numerical approximations into the transformation equations (2a and 2b) gives

$$\frac{\partial T}{\partial t_z} \simeq 2 \text{ deg/day} + (< .05 \text{ deg/day})$$

$$V_s \frac{\partial T}{\partial s_z} \simeq 2 \text{ deg/day} + (< .1 \text{ deg/day}) .$$

Therefore, one may with complete justification write

$$\frac{\partial T}{\partial t_z} = \frac{\partial T}{\partial t_p} \text{ and } V_s \frac{\partial T}{\partial s_z} = V_s \frac{\partial T}{\partial s_p} ,$$

and calculate the horizontal derivatives on pressure surfaces.

Computing w instead of $\omega \left(\frac{dp}{dt}\right)$ is advantageous because the amount of adiabatic heating of the parcel due to compression is then given explicitly in terms of the computed value of w. The diabatic heating term was assumed to be a constant value of -1 deg/day in accordance with the computations of Ohring (1958), Davis (1963), and Kennedy (1964). The local time derivative of the temperature is obtained by taking an average of the 24-hour local temperature change on each side of the given observation time. As implied above, the temperature advection, the eddy correlation coefficients, eddy covariances, means, and products of means of all combinations of u, v, w, and T were computed from 15 November to 15 December 1958 at 100 and 50 mb for latitudes 40°, 50°, 60°, and 70°N. The results of all these computations are included in Table I. The tabulated mean values of v given in Table I probably have no physical significance, since the actual values of $\overline{v}$ computed indirectly from the mean cell values in Chapter III are more than two orders of magnitude smaller than the mean absolute value of v. The chief merit in calculating $\overline{v}$ directly is that large values point out probable errors in the initial wind tabulations.

In order to reveal the probable debris transport properties of the lower stratosphere during this period, the eddy correlation coefficients of v'w' ($r_{v'w'} = \overline{v'w'} / \sqrt{\overline{v'^2}} \sqrt{\overline{w'^2}}$) calculated for this period are plotted for the various latitudes and levels as a function of time in Fig. 4. Fig. 4 shows that the v'w' correlation is generally negative in the lower latitudes (40° and 50°N), indicating a general tendency for northward and downward transport of trace substances. In higher latitudes (60° and 70°N) the v'w' correlation is slightly negative during the first 15 days and then becomes positive thereafter. This change of sign is consistent with the reversal of the northward temperature gradient from positive to negative at about this time (thus partially reflecting a change in slope of the mean isentropic surfaces from negative to positive).

In view of the presence of these negative v'w' correlations, one might inquire why there is no appreciable lower stratospheric buildup of fallout intensity in the fall months compared to that observed in late winter and spring. A possible answer to this difficulty may be found in comparing the v'w' covariance data given in Table I with that presented in Appendix A of the earlier paper (Mahlman, 1966).

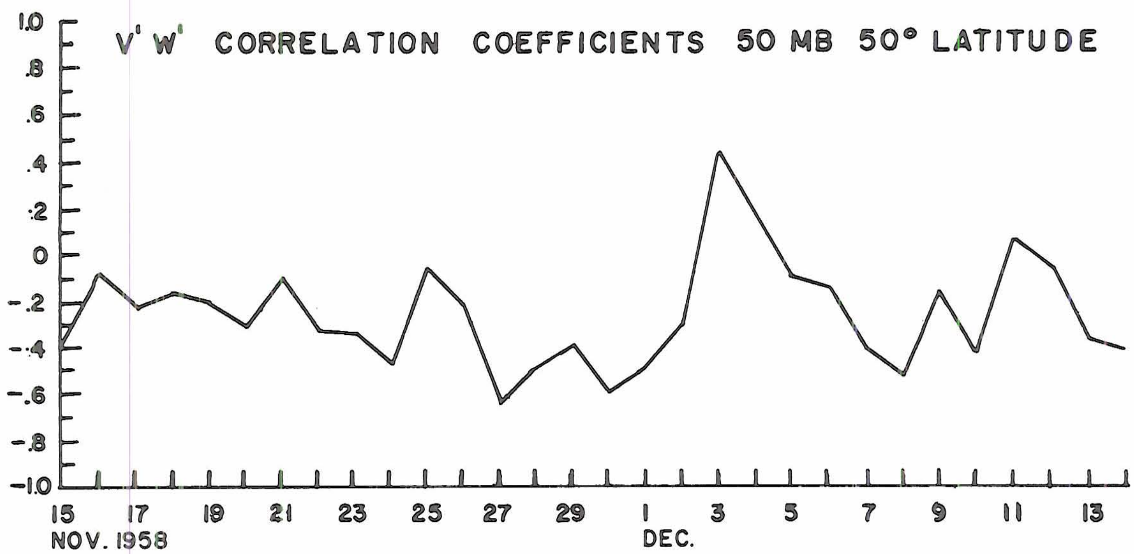
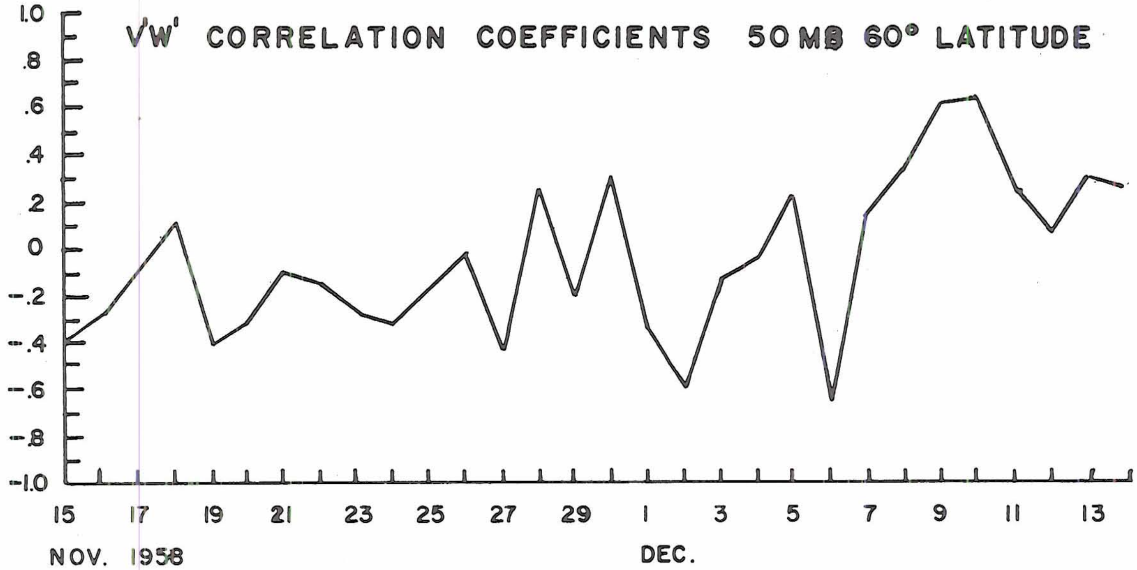


FIG. 4. v'w' eddy correlation coefficients for indicated levels and latitudes from 15 November to 15 December 1958.



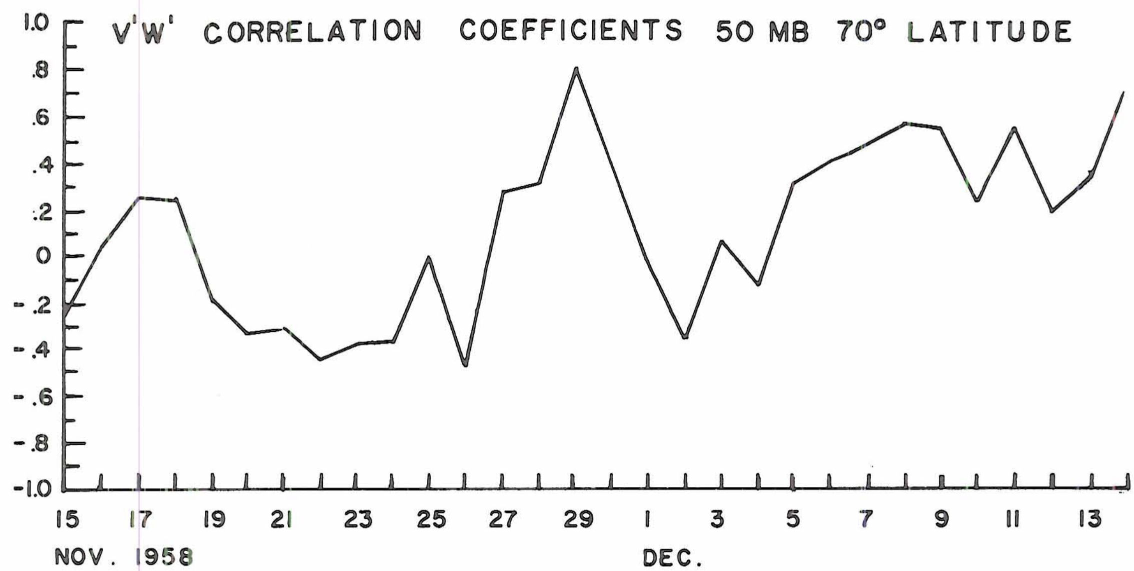
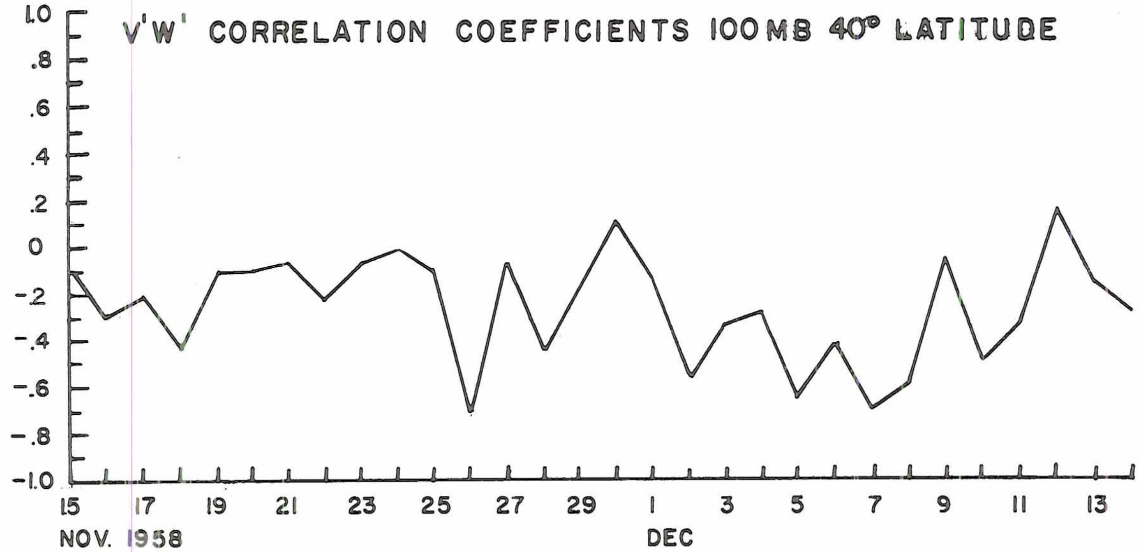


FIG. 4. Continued.



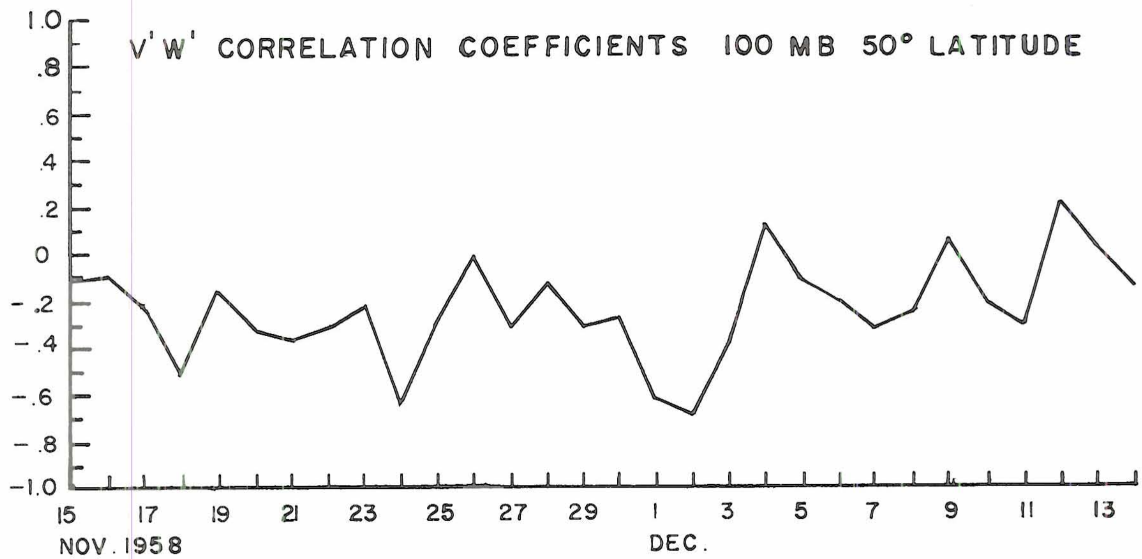
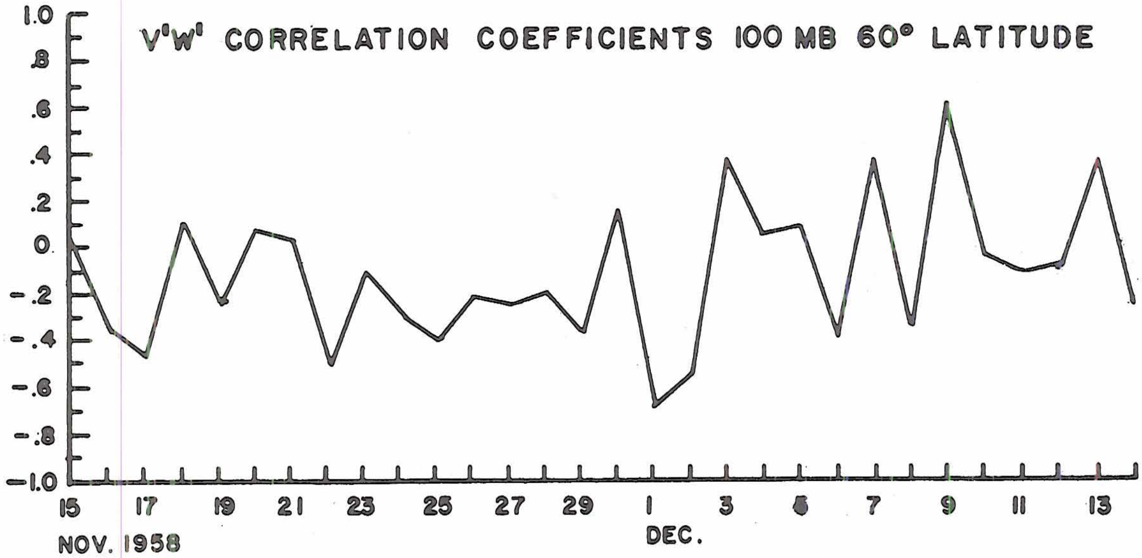


FIG. 4. Continued.



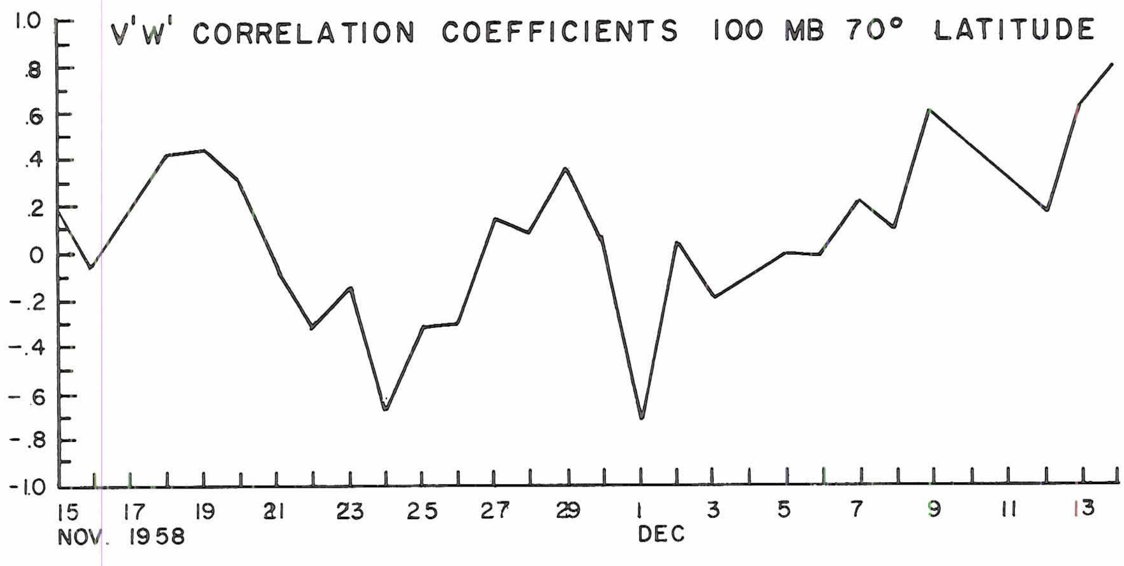


FIG. 4. Continued.

LEVEL 50 MB. LATITUDE 40 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1.386	-.993	-.400	94.263	-1.080	-.850
NOV 16	7.316	11.888	-.498	99.930	-4.139	-1.133
NOV 17	19.322	14.049	-.518	92.538	-4.394	-1.899
NOV 18	15.634	8.980	-.376	64.044	-3.224	-2.645
NOV 19	.534	8.452	-.461	66.121	-2.089	-1.806
NOV 20	.426	-4.839	-.024	33.312	-.819	.452
NOV 21	-.748	.243	-.268	84.378	-2.459	.029
NOV 22	-.366	4.101	-.135	50.961	-1.516	-.812
NOV 23	2.328	3.399	-.108	82.559	-2.923	-.921
NOV 24	-4.813	6.317	-.079	101.130	-2.034	-1.420
NOV 25	-2.171	9.682	-.157	131.733	-2.445	-1.989
NOV 26	-5.176	8.698	-.023	106.991	-4.154	-3.293
NOV 27	-5.889	13.548	-.295	103.821	-3.459	-2.310
NOV 28	-3.016	11.486	-.235	101.170	-6.772	-1.471
NOV 29	4.811	4.121	-.407	101.661	-4.760	-2.043
NOV 30	7.144	9.430	-.362	122.298	-3.742	-2.644
DEC 1	11.095	4.703	-.099	123.795	-1.081	-1.844
DEC 2	-3.483	-.858	-.018	128.995	-1.286	-1.364
DEC 3	13.364	5.488	.131	124.082	-1.127	-.802
DEC 4	7.316	2.731	.078	86.389	-1.442	-.562
DEC 5	5.466	1.730	-.188	47.515	-1.671	-.253
DEC 6	7.899	-.545	-.299	114.418	-3.478	-1.214
DEC 7	35.558	11.356	-.433	61.702	-5.053	-1.661
DEC 8	19.203	11.048	-.164	87.118	-2.122	-.340
DEC 9	31.330	14.674	-.047	86.534	-1.624	.198
DEC 10	33.145	15.081	-.427	110.307	-3.632	-2.329
DEC 11	42.786	27.039	-.583	95.868	-3.078	-3.183
DEC 12	18.923	16.933	-.352	90.831	-1.289	-.462
DEC 13	12.324	10.867	-.274	82.666	-1.430	-.483
DEC 14	6.832	7.341	-.258	80.021	-2.129	-2.080
DEC 15	-26.288	46.101	-.661	17.583	-1.393	-.881

LEVEL 50 MB. LATITUDE 40 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-.039	-.034	-.581	.580	-.284	-.273
NOV 16	.122	.279	-.438	.431	-.669	-.257
NOV 17	.358	.311	-.535	.387	-.857	-.442
NOV 18	.351	.203	-.355	.293	-.616	-.508
NOV 19	.010	.195	-.471	.298	-.418	-.466
NOV 20	.011	-.222	-.041	.206	-.186	.184
NOV 21	-.014	.008	-.305	.352	-.341	.008
NOV 22	-.007	.139	-.280	.295	-.538	-.485
NOV 23	.040	.159	-.150	.472	-.494	-.421
NOV 24	-.074	.180	-.103	.384	-.351	-.455
NOV 25	-.036	.271	-.169	.535	-.382	-.519
NOV 26	-.081	.211	-.018	.360	-.440	-.538
NOV 27	-.110	.496	-.293	.450	-.408	-.531
NOV 28	-.044	.360	-.231	.318	-.669	-.313
NOV 29	.085	.184	-.435	.404	-.454	-.490
NOV 30	.195	.424	-.466	.592	-.519	-.605
DEC 1	.234	.170	-.160	.457	-.179	-.523
DEC 2	-.071	-.034	-.037	.579	-.297	-.614
DEC 3	.235	.221	.217	.472	-.176	-.287
DEC 4	.171	.114	.170	.297	-.260	-.180
DEC 5	.121	.087	-.301	.176	-.199	-.068
DEC 6	.142	-.021	-.384	.410	-.415	-.311
DEC 7	.498	.424	-.408	.219	-.454	-.397
DEC 8	.318	.500	-.397	.352	-.460	-.201
DEC 9	.624	.533	-.095	.376	-.394	.087
DEC 10	.608	.494	-.395	.536	-.498	-.571
DEC 11	.661	.599	-.341	.417	-.354	-.524
DEC 12	.409	.549	-.414	.561	-.289	-.15[illegible]
DEC 13	.361	.459	-.511	.694	-.531	-.25[illegible]
DEC 14	.192	.315	-.339	.539	-.439	-.654
DEC 15	-.090	.305	-.155	.143	-.401	-.49[illegible]

LEVEL 50 MB. LATITUDE 40 PRODUCT OF (U,V,W,T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1337.142	.806	8.822	-.298	-3.268	.002
NOV 16	-1338.554	30.301	12.503	-11.214	-4.628	.105
NOV 17	-1368.047	95.464	10.408	-36.077	-3.933	.274
NOV 18	-1498.344	21.627	13.419	-9.026	-5.601	.081
NOV 19	-1585.596	42.867	11.328	-18.690	-4.939	.134
NOV 20	-1407.520	34.309	9.123	-13.278	-3.531	.086
NOV 21	-1340.665	5.896	9.048	-2.180	-3.345	.015
NOV 22	-1245.646	-6.232	5.956	2.131	-2.036	.010
NOV 23	-1497.606	67.923	6.590	-27.945	-2.711	.123
NOV 24	-1448.343	41.764	7.256	-16.241	-2.822	.081
NOV 25	-1498.157	-11.001	12.100	4.458	-4.903	-.036
NOV 26	-1702.606	-9.137	15.303	4.250	-7.118	-.038
NOV 27	-1703.880	-2.221	11.075	1.044	-5.208	-.007
NOV 28	-1893.300	17.774	14.225	-9.019	-7.218	.068
NOV 29	-1944.540	101.557	12.378	-53.510	-6.522	.341
NOV 30	-1687.623	1.601	10.431	-.723	-4.709	.004
DEC 1	-1934.468	14.066	5.295	-7.111	-2.677	.019
DEC 2	-1701.830	-23.884	8.503	10.555	-3.758	-.053
DEC 3	-1796.951	38.396	12.571	-18.046	-5.908	.126
DEC 4	-1785.071	18.362	10.313	-8.737	-4.907	.050
DEC 5	-1646.996	-11.151	10.166	4.976	-4.537	-.031
DEC 6	-1839.029	-12.894	7.155	6.449	-3.579	-.025
DEC 7	-2032.219	-5.579	10.874	3.075	-5.993	-.016
DEC 8	-2064.072	-25.890	8.821	14.735	-5.020	-.063
DEC 9	-2033.016	4.772	8.053	-2.683	-4.526	.011
DEC 10	-1771.522	28.394	10.721	-14.011	-5.290	.085
DEC 11	-1783.987	-9.053	11.613	4.588	-5.885	-.030
DEC 12	-1575.515	62.737	10.404	-27.558	-4.570	.182
DEC 13	-1533.400	-38.274	11.297	16.640	-4.911	-.123
DEC 14	-1790.625	-5.280	11.116	2.666	-5.612	-.017
DEC 15	-1687.257	-16.183	11.539	8.613	-6.141	-.059

LEVEL 50 MB. LATITUDE 40 MEANS OF T, U, V, AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-60.083	22.255	-.013	-.147
NOV 16	-60.139	22.258	-.504	-.208
NOV 17	-60.167	22.738	-1.587	-.173
NOV 18	-59.917	25.007	-.361	-.224
NOV 19	-60.306	26.293	-.711	-.188
NOV 20	-60.306	23.340	-.569	-.151
NOV 21	-60.222	22.262	-.098	-.150
NOV 22	-60.361	20.637	.103	-.099
NOV 23	-60.333	24.822	-1.126	-.109
NOV 24	-61.028	23.733	-.684	-.119
NOV 25	-60.806	24.638	.181	-.199
NOV 26	-60.500	28.142	.151	-.253
NOV 27	-60.194	28.306	.037	-.184
NOV 28	-61.083	30.995	-.291	-.233
NOV 29	-60.750	32.009	-1.672	-.204
NOV 30	-61.139	27.603	-.026	-.171
DEC 1	-61.861	31.271	-.227	-.086
DEC 2	-62.056	27.424	.385	-.137
DEC 3	-61.833	29.061	-.621	-.203
DEC 4	-61.250	29.144	-.300	-.168
DEC 5	-60.750	27.111	.184	-.167
DEC 6	-60.639	30.328	.213	-.118
DEC 7	-60.722	33.467	.092	-.179
DEC 8	-60.222	34.274	.430	-.146
DEC 9	-60.139	33.805	-.079	-.134
DEC 10	-59.917	29.566	-.474	-.179
DEC 11	-59.333	30.067	.153	-.196
DEC 12	-59.889	26.307	-1.048	-.174
DEC 13	-59.389	25.820	.644	-.190
DEC 14	-59.556	30.066	.089	-.187
DEC 15	-56.306	29.966	.287	-.205

TABLE I. Covariances, eddy correlation coefficients, mean products, and means of u, v, w, and T from 15 November to 15 December 1958 at indicated levels and latitudes.

LEVEL 50 MB. LATITUDE 50 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	12.191	25.929	-.115	74.146	-7.108	-2.020
NOV 16	46.743	35.574	.129	82.621	-5.231	-.350
NOV 17	46.031	43.439	.134	132.042	-6.547	-1.218
NOV 18	35.454	37.575	.155	27.451	-3.675	-.929
NOV 19	8.742	31.230	-.296	31.703	-2.554	-1.118
NOV 20	-17.452	17.921	-.170	16.775	-4.467	-1.389
NOV 21	-23.783	27.808	-.121	40.398	-6.402	-.524
NOV 22	-16.690	35.984	-.166	49.941	-3.846	-1.112
NOV 23	-2.731	50.221	.323	89.452	-6.771	-1.597
NOV 24	.100	46.721	.407	77.111	-4.573	-2.498
NOV 25	17.982	49.572	1.119	182.564	-4.830	-.282
NOV 26	23.836	47.445	.422	214.642	-4.352	-1.056
NOV 27	-27.199	39.228	-.252	211.428	-7.344	-4.435
NOV 28	-54.860	45.131	-.693	155.207	-6.685	-4.909
NOV 29	-10.026	38.097	-.348	172.692	-7.503	-3.600
NOV 30	-24.559	36.722	-.462	57.392	-5.315	-3.519
DEC 1	-17.123	28.611	-.375	35.268	-4.061	-3.312
DEC 2	-37.859	18.440	.207	20.220	-3.346	-1.846
DEC 3	-16.436	23.859	.541	130.445	.246	3.446
DEC 4	-40.232	29.436	.160	30.824	6.212	1.986
DEC 5	-59.224	21.078	-.154	-28.466	-3.358	-.593
DEC 6	-84.865	27.805	.108	-91.754	-4.058	-.738
DEC 7	-79.035	31.069	.021	-73.874	-5.392	-2.966
DEC 8	-51.294	38.864	-.182	-4.560	-2.237	-3.146
DEC 9	-62.181	30.628	-.086	19.362	-.744	-.916
DEC 10	-27.841	31.746	-.129	108.320	-7.168	-3.795
DEC 11	-14.583	37.141	-.675	43.631	-4.058	.709
DEC 12	-38.695	28.679	-.772	117.428	.751	-.315
DEC 13	-23.217	31.225	-.424	48.615	-2.133	-1.283
DEC 14	-26.219	20.763	.044	17.088	-3.343	-1.317
DEC 15	-121.560	111.488	-.176	-94.283	-3.169	-1.688

LEVEL 50 MB. LATITUDE 50 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	.116	.384	-.036	.428	-.857	-.378
NOV 16	.395	.496	.049	.402	-.689	-.076
NOV 17	.353	.562	.047	.493	-.662	-.208
NOV 18	.391	.476	.073	.110	-.549	-.159
NOV 19	.089	.409	-.126	.139	-.363	-.203
NOV 20	-.178	.281	-.077	.082	-.629	-.301
NOV 21	-.211	.342	-.041	.169	-.746	-.085
NOV 22	-.158	.497	-.086	.260	-.748	-.315
NOV 23	-.020	.623	.118	.385	-.857	-.339
NOV 24	.001	.549	.137	.361	-.616	-.462
NOV 25	.103	.531	.389	.479	-.411	-.045
NOV 26	.155	.510	.221	.536	-.529	-.212
NOV 27	-.177	.461	-.088	.562	-.577	-.630
NOV 28	-.345	.463	-.177	.369	-.306	-.475
NOV 29	-.072	.456	-.115	.398	-.479	-.382
NOV 30	-.230	.571	-.230	.180	-.532	-.585
DEC 1	-.185	.425	-.229	.090	-.424	-.475
DEC 2	-.419	.319	.133	.056	-.342	-.295
DEC 3	-.184	.442	.341	.304	.020	.453
DEC 4	-.397	.504	.078	.062	.359	.199
DEC 5	-.560	.421	-.085	-.070	-.228	-.085
DEC 6	-.721	.515	.084	-.184	-.342	-.135
DEC 7	-.666	.493	.010	-.167	-.385	-.399
DEC 8	-.564	.588	-.110	-.014	-.270	-.523
DEC 9	-.587	.513	-.053	.049	-.069	-.151
DEC 10	-.324	.535	-.063	.288	-.551	-.422
DEC 11	-.151	.519	-.231	.131	-.298	.070
DEC 12	-.359	.406	-.297	.461	.080	-.051
DEC 13	-.324	.583	-.268	.303	-.451	-.362
DEC 14	-.438	.506	.038	.102	-.710	-.4(8
DEC 15	-.375	.475	-.026	-.389	-.453	-.333

LEVEL 50 MB. LATITUDE 50 PRODUCT OF (U,V,W,T) BAR

DAY	TU	TV	TW	UV	TW	VW
NOV 15	-1399.305	45.548	14.577	-18.518	-5.927	.193
NOV 16	-1236.655	20.323	16.491	-7.152	-5.804	.095
NOV 17	-1389.740	-4.557	19.437	1.857	-7.923	-.026
NOV 18	-1181.065	101.260	11.608	-35.722	-4.095	.351
NOV 19	-1369.280	113.959	6.955	-46.519	-2.839	.236
NOV 20	-1306.556	31.040	15.184	-11.695	-5.721	.136
NOV 21	-1244.833	29.814	18.675	-10.783	-6.754	.162
NOV 22	-1222.976	74.955	14.825	-27.094	-5.359	.328
NOV 23	-1475.845	128.952	20.237	-55.716	-8.744	.764
NOV 24	-1305.226	113.958	17.830	-43.339	-6.781	.592
NOV 25	-1615.731	61.047	18.335	-28.959	-8.698	.329
NOV 26	-1545.183	31.914	16.383	-14.973	-7.687	.159
NOV 27	-1302.799	107.438	14.257	-42.213	-5.602	.462
NOV 28	-1238.696	110.256	13.621	-40.328	-4.982	.443
NOV 29	-1455.296	44.575	19.600	-19.488	-8.569	.262
NOV 30	-1414.966	113.923	10.251	-47.735	-4.295	.346
DEC 11	-1656.977	57.417	12.647	-27.126	-5.975	.207
DEC 2	-1768.196	67.635	11.036	-32.915	-5.371	.205
DEC 3	-1600.847	-31.984	15.857	.14.249	-7.064	-.141
DEC 4	-1383.807	55.066	14.073	-21.645	-5.532	.220
DEC 5	-1400.535	35.377	17.106	-14.234	-6.883	.174
DEC 6	-1611.066	109.749	10.574	-50.461	-4.862	.331
DEC 7	-1508.223	3.852	13.912	-1.655	-5.977	.015
DEC 8	-1453.042	-26.272	10.933	11.039	-4.594	-.083
DEC 9	-1889.583	5.122	8.792	-2.754	-4.728	.013
DEC 10	-1924.813	107.423	16.597	-59.849	-9.247	.516
DEC 11	-1893.187	88.523	9.808	-48.693	-5.395	.252
DEC 12	-1601.851	53.673	7.807	-25.631	-3.728	.125
DEC 13	-1618.340	68.057	10.156	-33.506	-5.000	.210
DEC 14	-1703.911	101.633	13.542	-52.990	-7.061	.421
DEC 15	-1573.104	168.908	9.935	-90.099	-5.299	.569

LEVEL 50 MB. LATITUDE 50 MEANS OF T, U, V, AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-58.667	23.852	-.776	-.248
NOV 16	-59.278	20.862	-.343	-.278
NOV 17	-58.389	23.801	.078	-.333
NOV 18	-57.861	20.412	-1.750	-.201
NOV 19	-57.917	23.642	-1.968	-.120
NOV 20	-58.889	22.187	-.527	-.258
NOV 21	-58.667	21.219	-.508	-.318
NOV 22	-58.167	21.025	-1.289	-.255
NOV 23	-58.444	25.252	-2.206	-.346
NOV 24	-58.583	22.280	-1.945	-.304
NOV 25	-58.361	27.685	-1.046	-.314
NOV 26	-57.389	26.925	-.556	-.285
NOV 27	-57.583	22.625	-1.866	-.248
NOV 28	-58.194	21.285	-1.895	-.234
NOV 29	-57.694	25.224	-.773	-.340
NOV 30	-58.111	24.349	-1.960	-.176
DEC 1	-59.222	27.979	-.970	-.214
DEC 2	-60.278	29.334	-1.122	-.183
DEC 3	-59.944	26.706	.534	-.265
DEC 4	-59.333	23.323	-.928	-.237
DEC 5	-59.000	23.738	-.600	-.290
DEC 6	-59.194	27.217	-1.854	-.179
DEC 7	-59.250	25.455	-.065	-.235
DEC 8	-58.806	24.709	.447	-.186
DEC 9	-59.278	31.877	-.086	-.148
DEC 10	-58.778	32.747	-1.828	-.282
DEC 11	-58.667	32.270	-1.509	-.167
DEC 12	-57.917	27.658	-.927	-.135
DEC 13	-57.333	28.227	-1.187	-.177
DEC 14	-57.167	29.806	-1.778	-.237
DEC 15	-54.306	28.968	-3.110	-.183

TABLE I. Continued.

LEVEL 50 MB. LATITUDE 70 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	18.633	64.750	-.756	1.148	1.116	-1.675
NOV 16	-47.374	77.097	-.381	-54.686	.451	.284
NOV 17	.427	73.240	.602	15.049	1.821	2.015
NOV 18	25.385	72.538	-.815	97.990	2.169	2.314
NOV 19	-21.531	96.884	-1.371	31.897	1.614	-2.331
NOV 20	-4.657	101.008	-.358	42.883	-.517	-3.217
NOV 21	-9.229	63.614	-.069	-30.719	-.821	-3.273
NOV 22	-18.628	86.808	-.568	-102.205	.861	-4.464
NOV 23	11.600	121.767	-1.278	-56.115	1.851	-3.935
NOV 24	23.487	104.486	-.710	-24.856	.005	-3.200
NOV 25	48.025	73.639	-.488	17.611	.866	-.079
NOV 26	43.809	69.024	-.455	157.832	.194	-4.465
NOV 27	45.876	64.636	-.475	96.480	1.009	3.883
NOV 28	55.852	96.206	-1.110	109.039	2.318	5.003
NOV 29	-33.884	116.029	.892	-195.606	-1.640	17.204
NOV 30	-28.310	58.440	.416	-410.777	1.167	7.601
DEC 1	2.338	83.268	-1.539	110.509	-1.258	-.272
DEC 2	-4.215	129.301	-1.174	227.367	-2.410	-6.836
DEC 3	52.053	44.337	-.382	59.067	2.409	.850
DEC 4	-5.798	2.264	-.239	-190.888	.296	-.892
DEC 5	33.862	4.730	-.645	-452.889	-2.351	4.120
DEC 6	33.638	-10.195	-.680	-318.257	-2.463	5.464
DEC 7	20.789	-27.107	.372	-263.755	-2.436	5.516
DEC 8	27.849	-8.824	-.226	-298.678	-3.574	5.883
DEC 9	42.772	-17.509	.032	-352.698	-1.846	5.013
DEC 10	27.935	-19.660	.231	-76.958	.321	1.043
DEC 11	3.876	-39.609	.567	-29.942	-.647	5.310
DEC 12	26.362	-18.773	.705	-1.063	1.433	1.111
DEC 13	18.497	-8.032	.488	-93.104	.395	2.207
DEC 14	29.348	14.108	-.085	-136.922	-2.566	3.610
DEC 15	27.852	139.428	-.161	-272.707	4.107	-3.765

LEVEL 50 MB. LATITUDE 70 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	.252	.359	-.247	.007	.385	-.237
NOV 16	-.440	.352	-.206	-.177	.173	.054
NOV 17	.007	.381	.163	.111	.704	.260
NOV 18	.269	.373	-.195	.465	.481	.248
NOV 19	-.211	.380	-.223	.149	.313	-.181
NOV 20	-.079	.457	-.073	.363	-.198	-.328
NOV 21	-.124	.283	-.015	-.175	-.233	-.308
NOV 22	-.279	.369	-.149	-.578	.302	-.443
NOV 23	.165	.500	-.378	-.259	.615	-.377
NOV 24	.417	.439	-.270	-.131	.002	-.361
NOV 25	.607	.347	-.228	.054	.265	-.009
NOV 26	.548	.324	-.230	.415	.055	-.475
NOV 27	.539	.330	-.166	.234	.167	.280
NOV 28	.522	.335	-.302	.235	.391	.315
NOV 29	-.269	.347	.180	-.360	-.205	.808
NOV 30	-.172	.182	.099	-.587	.127	.425
DEC 1	.031	.269	-.342	.341	-.267	-.014
DEC 2	-.043	.361	-.222	.647	-.465	-.359
DEC 3	.446	.170	-.098	.151	.411	.065
DEC 4	-.079	.011	-.148	-.632	.131	-.134
DEC 5	.247	.020	-.225	-.692	-.304	.302
DEC 6	.345	-.045	-.234	-.695	-.415	.399
DEC 7	.221	-.124	.138	-.639	-.479	.466
DEC 8	.275	-.043	-.086	-.734	-.681	.555
DEC 9	.394	-.092	.015	-.746	-.344	.534
DEC 10	.300	-.110	.172	-.227	.126	.212
DEC 11	.068	-.234	.226	-.133	-.195	.535
DEC 12	.769	-.210	.416	-.008	.582	.173
DEC 13	.520	-.173	.384	-.478	.074	.318
DEC 14	.554	.222	-.084	-.499	-.586	.687
DEC 15	.046	.244	-.017	-.626	.567	-.555

LEVEL 50 MB. LATITUDE 70 PRODUCT OF (U,V,W,T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1142.228	-34.584	-9.564	12.135	3.356	.102
NOV 16	-1260.445	99.962	-11.733	-39.392	4.624	-.367
NOV 17	-1149.715	-11.438	-8.380	3.939	2.886	.029
NOV 18	-1216.374	80.832	-.889	-30.861	.339	-.023
NOV 19	-1280.545	-42.257	6.098	17.221	-2.485	-.082
NOV 20	-1253.809	77.643	-3.988	-31.923	1.640	-.102
NOV 21	-1175.389	46.683	-7.006	-17.672	2.652	-.105
NOV 22	-671.079	-27.599	-8.085	5.790	1.696	.070
NOV 23	-272.394	33.102	-10.949	-2.825	.934	-.114
NOV 24	-392.726	-85.662	-6.449	10.539	.793	.173
NOV 25	-208.468	-64.286	-12.591	4.223	.827	.255
NOV 26	-320.827	48.591	-8.716	-4.752	.852	-.129
NOV 27	-259.410	-41.080	-13.265	3.280	1.059	.168
NOV 28	-189.384	-38.530	-15.474	2.308	.927	.189
NOV 29	3.657	-102.201	-19.426	-.114	-.022	.604
NOV 30	170.599	-257.113	-5.189	-13.474	-.272	.410
DEC 1	640.754	-72.126	-14.809	-14.449	-2.967	.334
DEC 2	28.115	-145.761	-9.299	-1.230	-.078	.407
DEC 3	193.365	-66.449	-17.176	-3.894	-1.006	.346
DEC 4	81.033	-141.650	-3.256	-3.380	-.078	.136
DEC 5	85.586	24.395	-7.021	.599	-.172	-.049
DEC 6	160.943	13.110	-12.846	.590	-.579	-.047
DEC 7	148.882	-109.800	-11.709	-4.575	-.488	.360
DEC 8	122.301	46.819	-5.151	1.570	-.173	-.066
DEC 9	238.121	-37.814	-6.925	-2.433	-.446	.071
DEC 10	-101.962	110.744	-.874	-3.007	.024	-.026
DEC 11	-1201.587	61.784	-5.650	-18.738	1.714	-.088
DEC 12	-2140.090	56.416	-1.838	-30.313	.988	-.026
DEC 13	-2612.719	144.133	-18.924	-90.675	11.905	-.657
DEC 14	-2600.239	-.700	1.271	.420	-.764	-.000
DEC 15	-1677.363	-58.540	16.543	29.699	-8.393	-.293

LEVEL 50 MB. LATITUDE 70 MEANS OF T, U, V AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-57.056	20.020	.606	.168
NOV 16	-56.556	22.287	-1.768	.207
NOV 17	-57.778	19.899	.198	.145
NOV 18	-56.444	21.550	-1.432	.016
NOV 19	-56.056	22.844	.754	-.109
NOV 20	-55.222	22.705	-1.406	.072
NOV 21	-55.722	21.094	-.838	.126
NOV 22	-56.556	11.866	.488	.143
NOV 23	-56.500	4.821	-.586	.194
NOV 24	-56.500	6.951	1.516	.114
NOV 25	-56.333	3.701	1.141	.224
NOV 26	-57.278	5.601	-.848	.152
NOV 27	-57.000	4.551	.721	.233
NOV 28	-56.222	3.368	.685	.275
NOV 29	-57.333	-.064	1.783	.339
NOV 30	-57.056	-2.990	4.506	.091
DEC 1	-56.556	-11.330	1.275	.262
DEC 2	-57.722	-.487	2.525	.161
DEC 3	-57.444	-3.366	1.157	.299
DEC 4	-58.278	-1.390	2.431	.056
DEC 5	-59.056	-1.449	-.413	.119
DEC 6	-59.778	-2.692	-.219	.215
DEC 7	-59.778	-2.491	1.837	.196
DEC 8	-60.389	-2.025	-.775	.085
DEC 9	-60.833	-3.914	.622	.114
DEC 10	-61.278	1.664	-1.807	.014
DEC 11	-62.944	19.090	-.982	.090
DEC 12	-63.111	33.910	-.894	.029
DEC 13	-64.444	40.542	-2.237	.294
DEC 14	-65.778	39.531	.011	-.019
DEC 15	-57.500	29.172	1.018	-.288

TABLE I. Continued.

LEVEL 100 MB. LATITUDE 40 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	30.624	12.113	-.276	164.023	-2.156	-.461
NOV 16	17.333	28.789	-.783	205.310	-5.207	-2.887
NOV 17	12.965	14.465	-.790	163.457	-2.813	-1.972
NOV 18	33.771	30.475	-1.028	175.473	-6.528	-5.765
NOV 19	39.370	24.250	.843	182.242	3.449	-1.026
NOV 20	2.911	-3.724	.152	57.122	-1.189	-.343
NOV 21	13.949	6.048	-.310	67.540	-1.756	-.256
NOV 22	10.101	10.554	-.115	84.183	.884	-1.167
NOV 23	7.807	-2.229	.032	114.549	-3.478	-.422
NOV 24	14.488	1.851	-.131	72.955	-4.532	-.023
NOV 25	29.210	19.771	-.807	77.691	-4.627	-.926
NOV 26	16.950	3.324	-.435	50.972	-1.745	-9.474
NOV 27	21.380	20.175	-.594	90.348	-2.611	-.717
NOV 28	26.065	6.909	-.793	230.542	-7.029	-4.950
NOV 29	17.086	14.749	-1.021	129.910	-10.262	-2.079
NOV 30	11.728	8.025	-.435	169.544	-4.496	.643
DEC 1	24.575	1.741	.026	213.992	-1.455	-.820
DEC 2	5.199	5.338	-.388	212.394	1.672	-4.721
DEC 3	-18.718	1.504	.425	300.665	-8.928	-4.999
DEC 4	-6.090	5.240	-.381	137.400	-6.445	-2.263
DEC 5	-.873	1.835	-.003	197.802	-4.443	-3.932
DEC 6	2.497	-.208	-.240	78.173	-2.670	-2.286
DEC 7	36.795	1.022	-.374	83.427	-4.916	-3.831
DEC 8	28.641	9.788	.060	142.114	-2.575	-4.840
DEC 9	47.171	5.653	-.990	107.519	-10.097	-.885
DEC 10	64.357	21.902	-1.017	234.038	-6.371	-4.866
DEC 11	54.561	18.596	-1.382	174.887	-4.394	-3.833
DEC 12	46.488	16.793	-.105	127.199	-1.273	1.029
DEC 13	10.804	3.172	-.006	53.129	1.637	-1.009
DEC 14	7.050	-2.634	.129	126.892	-4.944	-2.228
DEC 15	42.543	38.581	-.024	225.248	-9.749	-2.165

LEVEL 100 MB. LATITUDE 40 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	.409	.190	-.287	.359	-.314	-.079
NOV 16	.173	.310	-.421	.393	-.498	-.298
NOV 17	.151	.152	-.376	.426	-.332	-.210
NOV 18	.450	.342	-.380	.478	-.585	-.435
NOV 19	.611	.390	.430	.578	.347	-.107
NOV 20	.080	-.116	.244	.277	-.297	-.097
NOV 21	.209	.125	-.360	.207	-.303	-.061
NOV 22	.178	.230	-.116	.281	.137	-.224
NOV 23	.138	-.068	.032	.353	-.346	-.073
NOV 24	.248	.063	-.120	.277	-.463	-.005
NOV 25	.369	.356	-.414	.232	-.394	-.113
NOV 26	.293	.058	-.257	.114	-.132	-.725
NOV 27	.350	.359	-.396	.213	-.231	-.069
NOV 28	.337	.122	-.454	.478	-.471	-.454
NOV 29	.161	.277	-.350	.297	-.429	-.173
NOV 30	.155	.160	-.378	.413	-.478	.103
DEC 1	.273	.027	.028	.386	-.177	-.139
DEC 2	.053	.093	-.320	.317	.119	-.573
DEC 3	-.162	.018	.187	.402	-.450	-.340
DEC 4	-.085	.117	-.354	.266	-.520	-.291
DEC 5	-.010	.040	-.003	.380	-.389	-.664
DEC 6	.024	-.005	-.234	.144	-.193	-.430
DEC 7	.290	.017	-.272	.167	-.419	-.708
DEC 8	.322	.166	.044	.272	-.212	-.598
DEC 9	.532	.082	-.285	.310	-.575	-.065
DEC 10	.684	.303	-.517	.506	-.506	-.503
DEC 11	.553	.172	-.544	.399	-.426	-.340
DEC 12	.421	.175	-.056	.304	-.157	.145
DEC 13	.234	.067	-.005	.225	.300	-.180
DEC 14	.094	-.054	.081	.362	-.433	-.299
DEC 15	.076	.149	-.002	.592	-.487	-.234

LEVEL 100 MB. LATITUDE 40 PRODUCT OF (U, V, W, T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-2241.536	69.102	12.724	-41.476	-7.637	.235
NOV 16	-2298.901	-69.386	7.563	42.635	-4.647	-.140
NOV 17	-2515.359	85.564	8.297	-56.801	-5.508	.187
NOV 18	-2463.529	-47.215	21.163	31.033	-13.909	-.267
NOV 19	-2488.258	87.658	-5.711	-58.246	3.795	-.134
NOV 20	-2603.816	62.737	5.371	-42.649	-3.651	.088
NOV 21	-2405.881	-10.816	6.892	6.751	-4.302	-.019
NOV 22	-2463.176	51.765	7.739	-33.409	-4.995	.105
NOV 23	-2805.346	82.709	16.160	-60.850	-11.889	.351
NOV 24	-2881.083	77.783	13.110	-59.465	-10.022	.271
NOV 25	-2647.130	-61.472	9.985	44.173	-7.175	-.167
NOV 26	-2867.014	39.809	12.266	-29.771	-9.173	.127
NOV 27	-2710.451	-153.479	12.044	110.685	-8.686	-.492
NOV 28	-2933.726	36.053	19.021	-27.639	-14.582	.179
NOV 29	-3096.618	21.427	18.057	-17.495	-14.744	.102
NOV 30	-3010.515	.572	5.190	-.451	-4.090	.001
DEC 1	-3028.372	43.871	2.064	-33.326	-1.568	.023
DEC 2	-3160.474	-41.055	7.831	32.720	-6.241	-.081
DEC 3	-3472.516	-190.350	16.586	164.935	-14.372	-.788
DEC 4	-3077.923	-3.886	12.617	3.114	-10.112	-.013
DEC 5	-2953.057	48.611	7.803	-37.178	-5.968	.098
DEC 6	-3427.508	17.635	5.811	-16.039	-5.285	.027
DEC 7	-3177.213	-19.765	11.803	16.336	-9.756	-.061
DEC 8	-3339.868	28.372	9.836	-25.559	-8.861	.075
DEC 9	-3505.032	36.970	8.618	-34.920	-8.140	.086
DEC 10	-3301.810	4.886	8.514	-4.223	-7.360	.011
DEC 11	-2882.091	-75.678	13.417	58.456	-10.364	-.272
DEC 12	-2971.651	-84.205	10.232	68.238	-8.292	-.235
DEC 13	-2835.256	66.833	.560	-51.344	-.430	.010
DEC 14	-3091.001	14.396	15.001	-11.904	-12.405	.058
DEC 15	-3285.135	-79.974	12.824	80.236	-12.866	-.313

LEVEL 100 MB. LATITUDE 40 MEANS OF T, U, V, AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-61.111	36.680	-1.131	-.208
NOV 16	-51.167	37.584	1.134	-.124
NOV 17	-61.556	40.863	-1.390	-.135
NOV 18	-61.222	40.239	.771	-.346
NOV 19	-61.194	40.662	-1.432	.093
NOV 20	-61.889	42.072	-1.014	-.087
NOV 21	-62.083	38.752	.174	-.111
NOV 22	-61.778	39.872	-.838	-.125
NOV 23	-61.750	45.431	-1.339	-.262
NOV 24	-61.389	46.932	-1.267	-.214
NOV 25	-60.694	43.614	1.013	-.165
NOV 26	-61.917	46.304	-.643	-.198
NOV 27	-61.306	44.212	2.504	-.196
NOV 28	-61.861	47.424	-.583	-.307
NOV 29	-61.583	50.283	-.348	-.293
NOV 30	-61.806	48.709	-.009	-.084
DEC 1	-63.139	47.964	-.695	-.033
DEC 2	-62.972	50.188	.652	-.124
DEC 3	-63.306	54.853	3.007	-.262
DEC 4	-61.972	49.666	.063	-.204
DEC 5	-62.139	47.523	-.782	-.126
DEC 6	-61.389	55.833	-.287	-.095
DEC 7	-62.000	51.245	.319	-.190
DEC 8	-60.889	54.852	-.466	-.162
DEC 9	-60.917	57.538	-.607	-.141
DEC 10	-61.806	53.423	-.079	-.138
DEC 11	-61.083	47.183	1.239	-.220
DEC 12	-60.556	49.073	1.391	-.169
DEC 13	-60.750	46.671	-1.100	-.009
DEC 14	-61.139	50.557	-.235	-.245
DEC 15	-57.222	57.410	1.398	-.224

TABLE I. Continued.

LEVEL 100 MB. LATITUDE 50 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	48.562	27.821	.014	124.440	-1.812	-.986
NOV 16	87.742	30.549	-.530	171.921	-2.159	-.718
NOV 17	57.593	25.725	.422	90.296	1.033	-1.715
NOV 18	52.723	18.983	.003	36.547	-3.120	-3.084
NOV 19	48.467	33.395	.013	-20.722	.558	-1.140
NOV 20	14.999	14.319	-.448	43.108	-1.070	-1.305
NOV 21	10.909	29.419	-.538	-9.740	-.789	-1.841
NOV 22	17.871	14.808	.126	-17.216	-1.055	-1.506
NOV 23	29.296	21.132	-.209	12.310	-2.064	-1.423
NOV 24	22.768	38.134	-.562	58.795	-2.995	-4.188
NOV 25	7.201	13.841	.387	-11.431	-3.756	-1.713
NOV 26	27.135	27.141	.009	13.406	-4.178	-.043
NOV 27	22.250	31.776	.025	107.503	-4.148	-2.797
NOV 28	8.752	30.320	-.952	32.612	-.431	-.993
NOV 29	-9.092	60.148	-.050	107.420	-4.055	-4.136
NOV 30	-21.730	45.563	-.383	18.628	.161	-2.446
DEC 1	-3.672	30.762	-.101	106.358	-1.463	-5.299
DEC 2	-9.586	13.392	.231	1.429	.237	-8.523
DEC 3	-10.982	15.626	.231	59.255	-.846	-3.010
DEC 4	-31.754	19.466	.672	-11.445	-2.584	1.104
DEC 5	-25.906	19.440	.502	10.485	-.083	-.819
DEC 6	-68.947	36.789	-.374	-71.994	-3.681	-2.599
DEC 7	-75.785	29.751	-.093	-90.171	-6.327	-4.990
DEC 8	-44.115	53.153	.093	-31.992	-.070	-2.413
DEC 9	-30.382	47.134	.029	-29.536	-2.480	.618
DEC 10	-51.548	33.152	-.232	-46.322	.105	-1.584
DEC 11	-19.426	11.883	-.030	-11.276	.400	-3.099
DEC 12	-32.453	17.109	-.071	7.217	.651	1.709
DEC 13	-46.366	22.804	-.458	-62.847	-2.489	.196
DEC 14	-23.284	36.655	.136	-73.093	-3.287	-1.082
DEC 15	-58.506	88.608	-1.957	-155.536	-1.465	2.471

LEVEL 100 MB. LATITUDE 50 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	.482	.325	..006	.354	-.177	-.113
NOV 16	.679	.388	-.195	.451	-.164	-.090
NOV 17	.494	.276	.189	.211	.101	-.210
NOV 18	.471	.224	.002	.101	-.388	-.507
NOV 19	.604	.439	.006	-.083	.074	-.159
NOV 20	.240	.289	-.303	.251	-.209	-.322
NOV 21	.153	.446	-.241	-.059	-.141	-.357
NOV 22	.222	.207	.063	-.087	-.192	-.308
NOV 23	.286	.277	-.077	.049	-.227	-.211
NOV 24	.256	.519	-.186	.299	-.371	-.627
NOV 25	.072	.166	.152	-.046	-.497	-.273
NOV 26	.255	.259	.003	.039	-.378	-.004
NOV 27	.178	.313	.008	.297	-.368	-.306
NOV 28	.077	.293	-.290	.108	-.045	-.114
NOV 29	-.079	.511	-.012	.298	-.308	-.307
NOV 30	-.261	.444	-.118	.078	.021	-.262
DEC 1	-.041	.298	-.050	.277	-.196	-.617
DEC 2	-.131	.140	.097	.004	.025	-.690
DEC 3	-.139	.208	.141	.157	-.103	-.384
DEC 4	-.279	.228	.268	-.029	-.226	.129
DEC 5	-.340	.258	.268	.036	-.012	-.115
DEC 6	-.492	.344	-.105	-.144	-.222	-.205
DEC 7	-.629	.285	-.021	-.220	-.356	-.325
DEC 8	-.577	.478	.042	-.098	-.011	-.252
DEC 9	-.441	.492	.012	-.111	-.371	.066
DEC 10	-.705	.355	-.139	-.139	.018	-.206
DEC 11	-.411	.112	-.015	-.047	.092	-.316
DEC 12	-.614	.226	-.032	.039	.122	.224
DEC 13	-.667	.356	-.253	-.235	-.328	.028
DEC 14	-.360	.548	.088	-.227	-.442	-.141
DEC 15	-.278	.275	-.269	-.705	-.294	.324

LEVEL 100 MB. LATITUDE 50 PRODUCT OF (U, V, W, T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1619.811	25.830	10.169	-12.655	-4.982	.079
NOV 16	-1865.038	-5.298	10.083	2.969	-5.650	-.016
NOV 17	-1774.056	43.823	8.857	-23.582	-4.766	.118
NOV 18	-1768.333	-98.141	9.986	54.526	-5.548	-.308
NOV 19	-1691.530	26.932	4.956	-14.746	-2.714	.043
NOV 20	-1553.317	4.253	9.993	-2.111	-4.960	.014
NOV 21	-1610.367	6.273	10.193	-3.196	-5.193	.020
NOV 22	-1722.162	-10.112	10.333	5.450	-5.569	-.033
NOV 23	-1899.597	-42.571	12.510	26.019	-7.646	-.171
NOV 24	-1960.351	4.940	12.826	-3.028	-7.861	.020
NOV 25	-1828.058	-97.095	15.373	55.547	-8.795	-.467
NOV 26	-1861.716	-35.642	16.978	20.889	-9.950	-.190
NOV 27	-1655.959	15.770	12.655	-8.642	-6.934	.066
NOV 28	-1898.677	-118.562	9.550	71.712	-5.776	-.361
NOV 29	-1674.723	-41.468	10.961	22.278	-5.888	-.146
NOV 30	-1653.629	-17.098	7.195	8.901	-3.745	-.039
DEC 1	-1756.402	46.386	7.554	-24.642	-4.013	.106
DEC 2	-1888.942	31.258	14.149	-17.928	-8.115	.134
DEC 3	-1786.919	3.663	12.032	-2.050	-6.735	.014
DEC 4	-1738.634	-48.903	9.017	26.195	-4.830	-.136
DEC 5	-1685.744	-25.785	8.214	13.249	-4.221	-.065
DEC 6	-1967.553	-17.428	14.462	10.637	-8.827	-.078
DEC 7	-1885.305	-82.491	9.256	47.542	-5.335	-.233
DEC 8	-1723.533	-29.052	15.504	15.307	-8.168	-.138
DEC 9	-1807.840	.910	10.567	-.522	-6.056	.003
DEC 10	-2047.284	-44.316	1.071	28.171	-.681	-.015
DEC 11	-1971.543	10.434	8.394	-6.307	-5.074	.027
DEC 12	-1819.217	-33.728	8.559	19.663	-4.990	-.093
DEC 13	-2049.936	-9.851	8.822	6.536	-5.854	-.028
DEC 14	-2233.937	23.215	14.075	-16.888	-10.238	.106
DEC 15	-1870.049	23.116	7.290	-15.535	-4.900	.061

LEVEL 100 MB. LATITUDE 50 MEANS OF T, U, V, AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-57.500	28.171	-.449	-.177
NOV 16	-57.694	32.326	.092	-.175
NOV 17	-57.417	30.898	-.763	-.154
NOV 18	-56.417	31.344	1.740	-.177
NOV 19	-55.583	30.432	-.485	-.089
NOV 20	-55.944	27.765	-.076	-.179
NOV 21	-56.222	28.643	-.112	-.181
NOV 22	-56.528	30.466	.179	-.183
NOV 23	-55.750	34.073	.764	-.224
NOV 24	-56.556	34.662	-.087	-.227
NOV 25	-56.528	32.339	1.718	-.272
NOV 26	-56.361	33.032	.632	-.301
NOV 27	-54.972	30.124	-.287	-.230
NOV 28	-56.928	33.888	2.116	-.170
NOV 29	-55.833	29.995	.743	-.196
NOV 30	-56.361	29.340	.303	-.128
DEC 1	-57.500	30.546	-.807	-.131
DEC 2	-57.389	32.915	-.545	-.247
DEC 3	-56.500	31.627	-.065	-.213
DEC 4	-56.972	30.517	.858	-.158
DEC 5	-57.278	29.431	.450	-.143
DEC 6	-56.778	34.654	.307	-.255
DEC 7	-57.194	32.963	1.442	-.162
DEC 8	-57.194	30.135	.508	-.271
DEC 9	-56.167	32.187	-.016	-.188
DEC 10	-56.750	36.075	.781	-.019
DEC 11	-57.111	34.521	-.183	-.147
DEC 12	-55.861	32.567	.604	-.153
DEC 13	-55.583	36.880	.177	-.159
DEC 14	-55.417	40.312	-.419	-.254
DEC 15	-52.750	35.451	-.438	-.138

TABLE I. Continued.

LEVEL 100 MB. LATITUDE 60 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	16.649	52.824	.096	57.725	-.709	.336
NOV 16	3.477	45.950	.178	49.870	-1.313	-1.881
NOV 17	28.399	46.860	-.231	12.916	-1.072	-2.655
NOV 18	16.746	43.827	.186	3.028	-2.688	1.010
NOV 19	26.137	27.987	.086	-56.814	-.061	-1.024
NOV 20	20.491	44.909	.015	36.613	-.186	.439
NOV 21	-3.533	46.523	-.029	-18.588	-1.670	.235
NOV 22	-3.066	43.002	-.227	-42.609	-.760	-1.465
NOV 23	-7.858	70.291	.877	-10.268	-1.660	-.449
NOV 24	-21.263	56.897	-.062	4.023	-1.410	-1.905
NOV 25	-40.262	54.632	.003	-7.152	-2.975	-2.870
NOV 26	-44.639	53.736	.468	-32.788	-1.104	-1.034
NOV 27	-68.327	78.563	-.249	22.386	.745	-1.580
NOV 28	-53.218	68.114	.828	46.470	-1.537	-1.134
NOV 29	-81.383	62.717	-.287	-20.661	1.033	-3.299
NOV 30	-73.540	44.609	.611	-77.500	-1.080	1.411
DEC 1	-88.615	54.067	-.680	-62.525	-.194	-6.279
DEC 2	-37.533	38.968	-.250	107.663	-.435	-3.188
DEC 3	-34.881	37.179	.763	-10.769	-.786	1.976
DEC 4	-60.774	7.114	-.383	-169.991	1.159	.361
DEC 5	-91.399	7.263	-.322	-80.056	3.113	.539
DEC 6	-108.347	31.374	-.449	-298.123	5.958	-5.008
DEC 7	-85.170	24.804	-.717	-274.961	3.010	3.704
DEC 8	-88.835	19.483	.075	-295.983	4.849	-3.199
DEC 9	-106.214	23.725	-.241	-194.318	1.965	3.971
DEC 10	-42.588	-3.913	-.021	-54.820	.190	-.263
DEC 11	-69.497	6.889	.096	-23.857	3.359	-.926
DEC 12	-86.624	5.275	.306	-57.084	-.142	-.538
DEC 13	-57.404	20.647	.703	-123.309	-1.488	2.426
DEC 14	-18.028	30.596	-.034	-163.642	1.900	-1.981
DEC 15	-42.198	70.252	-.353	-193.768	2.081	-2.076

LEVEL 100 MB. LATITUDE 60 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	.325	.380	.040	.454	-.324	.057
NOV 16	.072	.367	.078	.395	-.566	-.313
NOV 17	.434	.390	-.089	.084	-.324	-.437
NOV 18	.228	.367	.060	.016	-.556	.128
NOV 19	.318	.270	.044	-.306	-.017	-.231
NOV 20	.408	.405	.007	.341	-.087	.093
NOV 21	-.045	.406	-.012	-.120	-.489	.047
NOV 22	-.037	.435	-.144	-.275	-.307	-.495
NOV 23	-.081	.498	.315	-.052	-.429	-.080
NOV 24	-.354	.421	-.019	.031	-.446	-.268
NOV 25	-.376	.403	.001	-.026	-.501	-.382
NOV 26	-.377	.344	.283	-.088	-.280	-.199
NOV 27	-.514	.474	-.106	.057	.134	-.228
NOV 28	-.503	.400	.377	.154	-.395	-.181
NOV 29	-.759	.358	-.104	-.057	.182	-.357
NOV 30	-.789	.345	.238	-.261	-.183	.173
DEC 1	-.748	.361	-.261	-.146	-.026	-.666
DEC 2	-.383	.237	-.158	.295	-.123	-.539
DEC 3	-.346	.237	.473	-.034	-.238	.384
DEC 4	-.574	.053	-.224	-.452	.243	.059
DEC 5	-.718	.054	-.173	-.201	.567	.092
DEC 6	-.714	.229	-.131	-.513	.409	-.380
DEC 7	-.465	.197	-.221	-.495	.211	.376
DEC 8	-.592	.158	.030	-.543	.431	-.346
DEC 9	-.644	.241	-.115	-.384	.181	.615
DEC 10	-.515	-.036	-.012	-.175	.036	-.039
DEC 11	-.711	.063	.042	-.070	.474	-.116
DEC 12	-.760	.077	.100	-.237	-.013	-.083
DEC 13	-.869	.362	.341	-.585	-.196	.369
DEC 14	-.445	.544	-.025	-.809	.392	-.294
DEC 15	-.186	.208	-.052	-.832	.445	-.299

LEVEL 100 MB. LATITUDE 60 PRODUCT OF (U, V, W, T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1230.324	15.937	8.612	-6.340	-3.426	.044
NOV 16	-1265.907	-47.490	4.334	19.556	-1.785	-.067
NOV 17	-1444.085	1.867	12.572	-.876	-5.900	.008
NOV 18	-1313.624	46.496	13.897	-20.881	-6.241	.221
NOV 19	-1049.714	-1.966	10.427	.717	-3.804	-.007
NOV 20	-1024.705	15.672	6.540	-5.576	-2.327	.036
NOV 21	-1175.964	10.729	9.426	-4.300	-3.778	.034
NOV 22	-1097.959	-36.218	12.928	13.807	-4.929	-.163
NOV 23	-1056.455	-43.501	15.108	15.583	-5.412	-.223
NOV 24	-1296.374	-9.341	7.235	4.110	-3.184	-.023
NOV 25	-1058.917	-16.985	6.338	6.031	-2.251	-.036
NOV 26	-1112.708	24.355	10.659	-9.013	-3.945	.086
NOV 27	-944.797	25.518	5.374	-8.226	-1.732	.047
NOV 28	-903.234	44.015	6.108	-13.522	-1.876	.091
NOV 29	-751.444	85.882	4.463	-22.041	-1.145	.131
NOV 30	-756.461	101.708	-1.132	-26.009	.289	-.039
DEC 1	-1130.093	26.922	2.726	-10.327	-1.046	.025
DEC 2	-982.363	4.166	9.974	-1.399	-3.350	.014
DEC 3	-1006.094	-86.476	3.222	29.024	-1.081	-.093
DEC 4	-912.360	27.331	-8.386	-8.260	2.534	-.076
DEC 5	-965.450	-34.350	-6.679	10.745	2.089	.074
DEC 6	-932.504	34.468	.343	-10.168	-.101	.004
DEC 7	-729.260	-16.355	-13.283	3.822	3.104	.070
DEC 8	-720.675	-9.406	.008	2.160	-.002	-.000
DEC 9	-1167.139	32.327	-7.450	-11.785	2.716	-.075
DEC 10	-935.273	26.540	-6.146	-7.860	1.820	-.052
DEC 11	-1119.981	-19.220	1.806	6.803	-.639	-.011
DEC 12	-1516.370	77.982	-2.915	-37.857	1.415	-.073
DEC 13	-1625.492	14.047	-1.738	-7.435	.920	-.008
DEC 14	-1542.572	58.409	-3.846	-28.845	1.899	-.072
DEC 15	-1416.074	.136	2.615	-.067	-1.287	.000

LEVEL 100 MB. LATITUDE 60 MEANS OF T, U, V AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-55.611	22.124	-.287	-.155
NOV 16	-55.444	22.832	.857	-.078
NOV 17	-55.472	26.033	-.034	-.227
NOV 18	-54.083	24.289	-.860	-.257
NOV 19	-53.639	19.570	.037	-.194
NOV 20	-53.667	19.094	-.292	-.122
NOV 21	-54.167	21.710	-.198	-.174
NOV 22	-53.667	20.459	.675	-.241
NOV 23	-54.306	19.454	.801	-.278
NOV 24	-54.278	23.884	.172	-.133
NOV 25	-54.611	19.390	.311	-.116
NOV 26	-54.833	20.293	-.444	-.194
NOV 27	-54.139	17.451	-.471	-.099
NOV 28	-54.222	16.658	-.812	-.113
NOV 29	-54.111	13.887	-1.587	-.082
NOV 30	-54.389	13.908	-1.870	-.021
DEC 1	-54.278	20.821	-.496	-.050
DEC 2	-54.083	18.164	-.077	-.184
DEC 3	-54.750	18.376	1.579	-.059
DEC 4	-54.944	16.605	-.497	.153
DEC 5	-55.556	17.378	.618	.120
DEC 6	-56.222	16.586	-.613	-.006
DEC 7	-55.861	13.055	.293	.238
DEC 8	-56.028	12.863	.168	-.000
DEC 9	-56.583	20.627	-.571	.132
DEC 10	-56.194	16.644	-.472	.109
DEC 11	-56.250	19.911	.342	-.032
DEC 12	-55.889	27.132	-1.395	.052
DEC 13	-55.417	29.332	-.253	.031
DEC 14	-55.889	27.601	-1.045	.069
DEC 15	-53.639	26.400	-.003	-.049

TABLE I. Continued.

LEVEL 100 MB. LATITUDE 70 COVARIANCE

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-8.527	41.865	-.560	-5.022	2.605	1.105
NOV 16	-3.398	39.016	-.351	-33.401	1.289	-.275
NOV 17	19.007	36.594	.252	-5.815	.808	1.148
NOV 18	2.099	37.584	.108	-26.980	1.085	2.431
NOV 19	-19.346	49.114	.381	-20.811	.380	4.001
NOV 20	-9.402	33.372	-.143	-18.325	1.582	1.872
NOV 21	-5.272	54.254	-.528	-55.887	1.636	-.451
NOV 22	-21.485	71.094	-1.243	-25.986	.916	-2.418
NOV 23	-13.426	80.843	-1.952	-74.779	-.234	-.868
NOV 24	-12.135	68.998	-.847	-45.393	-.095	-3.198
NOV 25	8.100	39.417	-.318	3.502	1.263	-1.809
NOV 26	-5.941	40.827	-.319	-27.244	-.196	-2.029
NOV 27	10.415	37.422	-.434	-11.559	1.537	1.223
NOV 28	18.363	81.226	-.163	46.092	.998	.353
NOV 29	-37.958	39.119	.320	-108.545	.755	3.152
NOV 30	-21.026	29.471	-.211	-76.104	.883	.039
DEC 1	-26.130	32.487	-.916	31.342	.812	-6.608
DEC 2	5.359	76.568	-.323	79.336	.615	.156
DEC 3	8.760	23.596	-.225	-6.224	1.075	-1.412
DEC 4	-1.979	-30.911	.369	-143.811	2.335	-.848
DEC 5	-12.137	-19.552	.154	-101.240	.758	-.080
DEC 6	7.970	-29.481	-.227	-136.377	.120	-.073
DEC 7	-7.365	-27.365	-.396	-288.214	.115	1.259
DEC 8	16.096	-47.705	-.037	-389.977	.116	.433
DEC 9	-.813	-19.617	.072	-143.243	-.338	2.064
DEC 10	4.700	-23.535	-.134	56.403	.556	1.770
DEC 11	-16.840	-53.590	-.406	28.205	.752	1.127
DEC 12	25.304	-44.428	.159	-135.062	.035	.519
DEC 13	24.940	-28.904	-.135	-172.711	-1.535	3.627
DEC 14	22.358	-15.422	-.516	-200.455	-3.830	5.514
DEC 15	-31.513	66.513	-2.527	-216.938	.500	.458

LEVEL 100 MB. LATITUDE 70 EDDY CORRELATION COEFFICIENTS

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-.092	.397	-.276	-.020	.551	.205
NOV 16	-.051	.392	-.258	-.165	.467	-.067
NOV 17	.332	.325	.129	-.033	.262	.189
NOV 18	.035	.363	.059	-.140	.319	.415
NOV 19	-.346	.423	.105	-.146	.086	.435
NOV 20	-.129	.316	-.057	-.100	.362	.296
NOV 21	-.089	.435	-.228	-.361	.570	-.075
NOV 22	-.445	.499	-.434	-.205	.359	-.321
NOV 23	-.165	.461	-.782	-.391	-.086	-.148
NOV 24	-.191	.479	-.479	-.273	-.047	-.691
NOV 25	.121	.268	-.174	.018	.512	-.333
NOV 26	-.087	.242	-.172	-.117	-.077	-.321
NOV 27	.145	.237	-.189	-.041	.370	.134
NOV 28	.297	.435	-.097	.194	.465	.055
NOV 29	-.426	.208	.124	-.336	.170	.336
NOV 30	-.339	.176	-.119	-.347	.381	.006
DEC 1	-.435	.186	-.349	.152	.263	-.735
DEC 2	.058	.348	-.222	.233	.272	.029
DEC 3	.121	.121	-.126	-.023	.437	-.213
DEC 4	-.024	-.226	.187	-.483	.545	-.117
DEC 5	-.215	-.131	.132	-.367	.350	-.014
DEC 6	.173	-.254	-.314	-.605	.085	-.021
DEC 7	-.084	-.194	-.267	-.771	.029	.199
DEC 8	.154	-.352	-.022	-.867	.021	.062
DEC 9	-.014	-.168	.083	-.612	-.195	.574
DEC 10	.093	-.230	-.133	.279	.279	.438
DEC 11	-.358	-.499	-.351	.177	.439	.288
DEC 12	.541	-.596	.136	-.829	.014	.127
DEC 13	.486	-.577	-.092	-.806	-.246	.596
DEC 14	.528	-.452	-.426	-.805	-.433	.774
DEC 15	-.070	.114	-.310	-.631	.104	.073

LEVEL 100 MB. LATITUDE 70 PRODUCT OF (U,V,W,T) BAR

DAY	TU	TV	TW	UV	UW	VW
NOV 15	-1128.838	18.116	-4.078	-6.899	1.553	-.025
NOV 16	-1311.435	39.367	-.192	-17.741	.087	-.003
NOV 17	-1084.603	-21.361	.368	7.978	-.138	-.003
NOV 18	-1078.349	15.764	-4.884	-5.818	1.802	-.026
NOV 19	-1118.638	3.723	.894	-1.394	-.335	.001
NOV 20	-1355.113	-1.946	2.844	.933	-1.364	-.002
NOV 21	-1216.582	19.190	-5.179	-8.073	2.179	-.034
NOV 22	-1059.877	106.093	1.231	-38.881	-.451	.045
NOV 23	-358.368	-73.746	-4.940	9.195	.616	.127
NOV 24	-536.440	-19.847	-3.804	3.712	.712	.026
NOV 25	-523.176	-18.950	-5.940	3.435	1.077	.039
NOV 26	-500.299	18.597	-3.002	-3.088	.498	-.019
NOV 27	-258.470	46.115	-.032	-4.029	.003	-.001
NOV 28	-325.506	128.381	-3.508	-14.127	.386	-.152
NOV 29	-276.047	9.866	-8.358	-.946	.801	-.029
NOV 30	-72.198	-8.510	-1.817	.214	.046	.005
DEC 1	-86.425	56.335	.381	-1.708	-.012	.008
DEC 2	-240.920	35.784	4.929	-3.012	-.415	.062
DEC 3	-187.921	-26.836	.408	1.807	-.027	-.004
DEC 4	-166.958	25.992	-6.931	-1.545	.412	-.064
DEC 5	74.804	-116.229	-11.192	-2.886	-.278	.432
DEC 6	146.241	-46.502	-3.061	-2.195	-.144	.046
DEC 7	-1.731	47.843	-8.380	-.026	.005	-.127
DEC 8	35.525	9.196	-7.623	.104	-.086	-.022
DEC 9	281.951	-49.616	3.402	-4.314	.296	-.052
DEC 10	54.985	-12.085	5.088	-.212	.089	-.020
DEC 11	-812.593	70.690	-7.621	-16.913	1.823	-.159
DEC 12	-1117.735	20.730	1.441	-6.631	-.461	.009
DEC 13	-1424.932	-23.678	-3.946	9.692	1.615	.027
DEC 14	-1140.000	-28.454	8.675	9.180	-2.799	-.070
DEC 15	-854.323	27.401	.285	-8.264	-.086	.003

LEVEL 100 MB. LATITUDE 70 MEANS OF T, U, V, AND W

DAY	TBAR	UBAR	VBAR	WBAR
NOV 15	-54.444	20.734	-.333	.075
NOV 16	-53.944	24.311	-.730	.004
NOV 17	-53.889	20.127	.396	-.007
NOV 18	-54.056	19.949	-.292	.090
NOV 19	-54.667	20.463	-.068	-.016
NOV 20	-53.167	25.488	.037	-.053
NOV 21	-53.778	22.622	-.357	.096
NOV 22	-53.778	19.708	-1.973	-.023
NOV 23	-53.611	6.685	1.376	.092
NOV 24	-53.556	10.017	.371	.071
NOV 25	-53.722	9.739	.353	.111
NOV 26	-54.889	9.115	-.339	.055
NOV 27	-54.389	4.752	-.848	.001
NOV 28	-54.389	5.985	-2.360	.064
NOV 29	-53.667	5.144	-.184	.156
NOV 30	-53.611	1.347	.159	.034
DEC 1	-53.389	1.619	-1.055	-.007
DEC 2	-53.500	4.503	-.669	-.092
DEC 3	-52.833	3.557	.508	-.008
DEC 4	-53.000	3.150	-.490	.131
DEC 5	-54.889	-1.363	2.118	.204
DEC 6	-55.667	-2.627	.835	.055
DEC 7	-56.278	.031	-.850	.149
DEC 8	-56.000	-.634	-.164	.136
DEC 9	-56.944	-4.951	.871	-.060
DEC 10	-55.944	-.983	.216	-.091
DEC 11	-58.278	13.943	-1.213	.131
DEC 12	-59.111	18.909	-.351	-.024
DEC 13	-59.000	24.151	.401	.067
DEC 14	-59.444	19.178	.479	-.146
DEC 15	-53.222	16.052	-.515	-.005

TABLE I. Continued.

Such a comparison quickly reveals that a consistent difference exists between the negative v'w' covariances for the two cases. After the polar night vortex breakdown of January 1958, characteristic magnitudes of the negative v'w' covariances are about 10 kt km day^{-1}. For the present case, however, where the polar night vortex is in its formative stage, the characteristic magnitude is approximately 2 kt km day^{-1}. Thus, it appears probable that the northward eddy debris transport characteristics differ by about a factor of five for the two cases under comparison.

The above hypothesis cannot be verified or disproven until such computations are made continuously through the various seasonal transitions in the lower stratosphere. A complete examination of the mechanisms of trace substance transport in these regions cannot be performed until measurements of such substances are available at approximately the same density as the radiosonde network. If such data were available, the flux calculations could be made directly in terms of the trace substance distributions.

The computations of the T'v' covariance given in Table I show persistent positive values at the lower two latitudes throughout the computation period. As may be seen in Fig. 2 this implies that the eddies are acting to transport heat against the mean temperature gradient. This observation is in agreement with results obtained by previous investigators (Priestly, 1949; White, 1954; Piexoto, 1960; Murakami, 1962; Peng, 1963; Mahlman, 1966). At the two higher latitudes, the T'v' covariances are initially positive, but decrease to zero and then to negative values shortly after 1 December. This sudden reversal in sign of T'v' covariance occurs at the same time as the pronounced cooling in the northernmost latitudes seen in Fig. 3. It remains to be seen what constitutes the physical cause for this rapid reversal in the sign of the northward eddy heat flux.

The measurement of T'u' covariances given in Table I shows some very interesting results. At $40^{\circ}N$ the T'u' covariance is a small positive value for the entire computation period. At 50° and $60^{\circ}N$ for both levels $\overline{T'u'}$ is initially positive, decreasing to large negative values toward the end of the period. However, at $70^{\circ}N$ the opposite effect is noted--initially small negative values increasing to moderate positive values toward the end of the period. At first glance such apparently contradictory behavior is very perplexing. The reason that $\overline{T'u'}$ can be strongly negative at one latitude and be simultaneously positive at an adjacent latitude may be seen in Fig. 5. This figure is a schematic representation of the large scale flow conditions at 50 mb and is approximately representative of the circulation pattern between 1 and 10 December 1958. The plus, zero, and minus signs tabulated at discrete intervals along the 60° and $70^{\circ}N$ latitude circles indicate the algebraic sign of the T'u' product at each point inferred qualitatively from the streamline and temperature patterns. This figure clearly demonstrates that large negative and positive values of $\overline{T'u'}$ are expected at 60° and $70^{\circ}N$, respectively, for such an asymmetric polar vortex. This is in agreement with the observed differences in $\overline{T'u'}$ at these two latitudes.

The u'v' covariances given in Table I show that the northward eddy momentum transport is consistently positive throughout the time period at the lower two latitudes. At the higher latitudes $\overline{u'v'}$ is initially positive but decreases to strongly negative values over the approximate period 5-10 December. In general, while the u'v' covariances are decreasing, the mean zonal speed $\overline{u}$ is also decreasing. However, when $\overline{u}$ begins to increase again, $\overline{u'v'}$ is still negative. This suggests that the increase in zonal momentum toward the end of the computation period cannot be explained by the northward eddy flux, but is probably due to an upward flux of momentum through the tropopause.

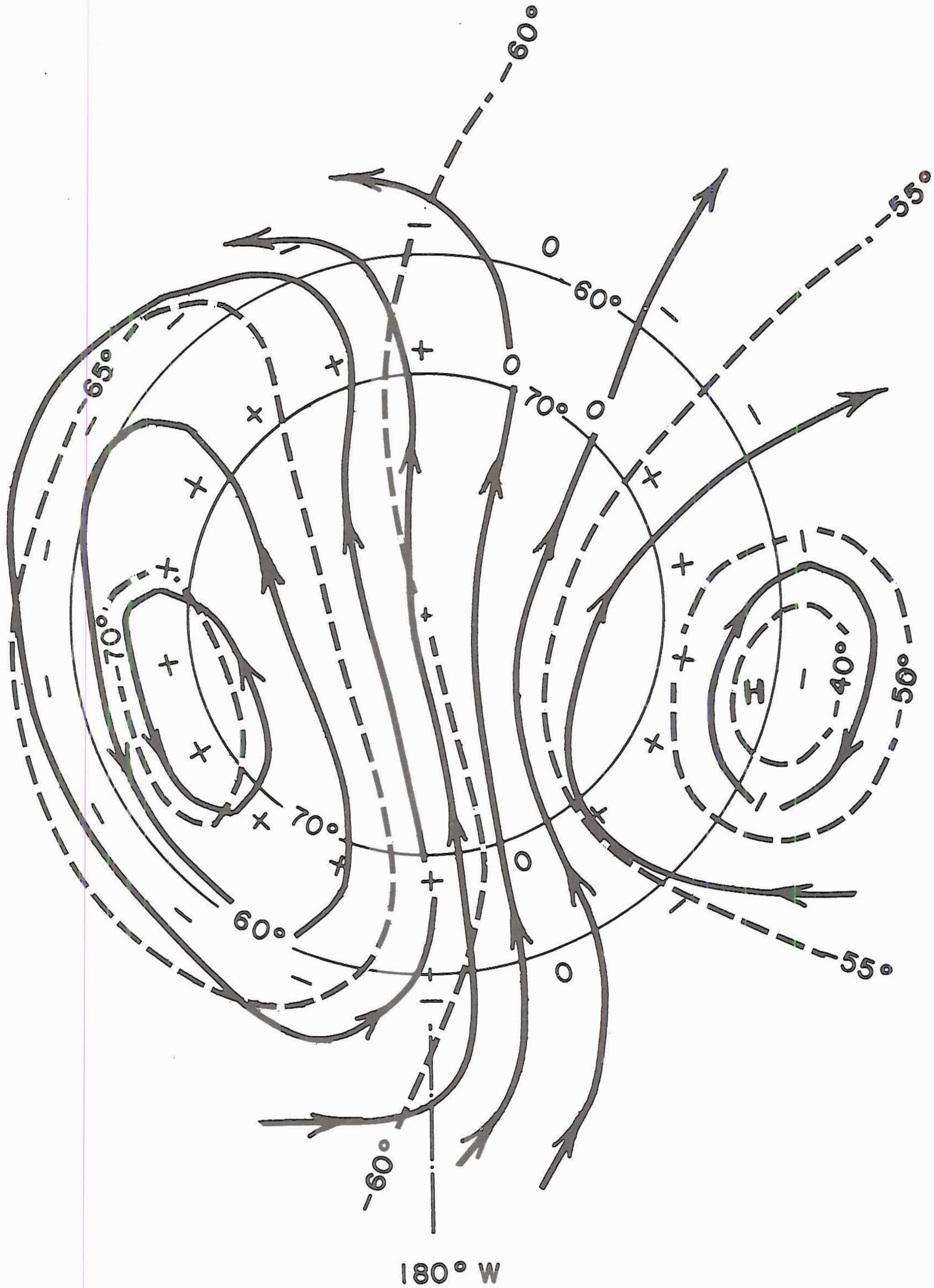


FIG. 5. Schematic diagram of typical 50 mb circulation over the pole from 1—10 December 1958. The +, 0, and - signs indicate the algebraic sign of the local T'u' product and demonstrate how T'u' can be strongly positive at one latitude and be just as strongly negative at an adjacent latitude.

Table I also gives the $\overline{T'w'}$ covariances and show consistently small but negative values at $40^{\circ}N$. At 50° and $60^{\circ}N$ the values are negligibly small while at $70^{\circ}N$ they become negative again. This qualitatively indicates a buildup of eddy available potential energy in the highest and lowest latitudes under consideration. In most cases, however, the $\overline{T'w'}$ values are too small to allow a great deal of confidence in them.

The $\overline{u'w'}$ covariances are negative at $40^{\circ}N$ for the entire computation period. At 50° and $60^{\circ}N$, however, they are initially negative, but increase to small positive values toward the end of the period. On the other hand, $\overline{u'w'}$ at $70^{\circ}N$ is positive at the onset and becomes negative by 12 December.

Of all the eddy transport quantities, the most pronounced is that of the $\overline{T'v'}$ covariance. As will be shown in the next two chapters, the large variation of this quantity has a definite modifying effect on the thermodynamics of the polar stratosphere.

III. MEAN MERIDIONAL CIRCULATIONS IN THE STRATOSPHERE DURING THE COMPUTATION PERIOD

In the previous section detailed measurements of the stratospheric eddy fluxes during the period 15 November to 15 December 1958 were presented. This section will contain results of computations of stratospheric mean meridional circulations deduced indirectly from the results of the tabulations in Chapter II.

The possible presence of mean meridional circulations in the stratosphere is of great interest not only because of its importance to the transport of trace substances, but from a dynamical point of view as well. Brewer (1949) hypothesized the existence of a potential energy consuming direct meridional cell in the stratosphere. In view of the discovery of an indirect cell in the mid-latitude troposphere, however, it was realized that such a cell might also characterize some regions of the stratosphere as well.

Because a mean meridional cell usually is present as a small residual on a nearly geostrophic circulation in the earth's atmosphere, detection of such a cell by direct techniques often proves to be very difficult. However, the data taken during the International Geophysical Year have proven to be of sufficient accuracy to provide consistent computational results. Many studies have been undertaken using these data, most prominently by the members of the Planetary Circulations Project at the Massachusetts Institute of Technology. Members of this project have attempted to solve the stratospheric meridional cell problem by employing two distinct approaches. Oort (1962) made direct measurements by averaging over longitude the time mean v components at individual stations. His results showed a net equatorward motion at 100 mb in lower latitudes and a net poleward motion at polar latitudes and that a well-pronounced <u>indirect</u> cell apparently exists in the polar night stratosphere. The second approach employed by the MIT group and others is based on deductions of the meridional circulation from momentum budget calculations (Palmén, 1955; Kuo, 1956; Palmén, Riehl, and Vuorela, 1958; Haurwitz, 1961; Dickenson, 1962; Miyakoda, 1963; Gilman, 1963, 1964; Newell and Miller, 1964). The computations of Dickenson (1962), Miyakoda (1963) and Newell and Miller (1964) all point to the existence of an indirect cell in the polar night stratosphere.

Other investigators have employed a thermodynamic approach (Jensen, 1961; Murgatroyd and Singleton, 1961; Teweles, 1963; Mahlman, 1966). Jensen (1961) and Teweles (1963) computed adiabatic vertical motions at single points and then averaged these values around latitude circles. These computations pointed to the existence of an indirect cell in the polar night stratosphere. Murgatroyd and Singleton (1961) used a heat flux model in which the effect of eddy heat transport was neglected. Their computation for the high latitude winter stratosphere indicated a direct circulation. Mahlman (1966) employed a method conceptually similar to that of Murgatroyd and Singleton, but the effect of eddy heat transport was included. The results showed that the eddy heat flux gave by far the largest contribution to the mean vertical motion and that rising motion was present over the polar regions for the entire computation period. The computed mean meridional circulation was indirect before and during the breakdown of the polar vortex and direct afterward. This is in accordance with the reversal of the meridional temperature gradient after the breakdown.

Earlier investigators on the problem of trace substance transport in the lower stratosphere concluded that a direct circulation with sinking over the pole was necessary to reconcile the circulation with the observed sense of these transports (Brewer, 1949; Goldie, 1950; Dobson, 1956; Stewart et al., 1957; Palmer, 1959).

On the basis of the quantitative mean cell computations given above and previous papers by Newell (1961, 1963a, b, 1964) and by the author (Mahlman, 1966), it appears reasonable to hypothesize at this time that the majority of the northward and downward debris transport is attributable to the effects of eddies. The intent of the following mean cell computation, along with the eddy transport calculations of Chapter II, is to test the applicability of this hypothesis during the chosen period of intensification of the polar night circulation. Such computations for similar and for differing conditions are necessary in order to check the original hypotheses and to understand the effect of differing seasonal, thermodynamical, and dynamical conditions on such mean circulations. Also, because any indirect calculation of a mean meridional cell must depend upon the accuracy of a number of terms, there is always some uncertainty as to the validity of the computational results.

Computational Scheme for the Mean Meridional Cell

The expression for the vertical motion, obtained by solving the thermodynamic equation for w, is given by Eq. (1). However, as argued previously, the $\frac{\partial T}{\partial t}$ and $\vec{V}_2 \cdot \nabla T$ terms in Eq. (1) are to be measured on pressure surfaces.

By expanding $\vec{V}_2 \cdot \nabla T$ in Eq. (1) and averaging over the area north of a given latitude circle (indicated by ~) one obtains

$$\widetilde{w\left(\frac{\partial T}{\partial z} + \frac{g}{c_p}\right)} = \widetilde{\frac{1}{c_p}\frac{dh}{dt}} - \widetilde{\frac{\partial T}{\partial t}} - \widetilde{\nabla \cdot \vec{V}_2 T} + \widetilde{T\nabla \cdot \vec{V}} \ . \qquad (4)$$

One may define the following averages applicable to this problem

$$T = \overline{T} + T' = \widetilde{T} + T^*$$

$$v = \overline{v} + v'$$

$$w = \widetilde{w} + w^*$$

$$\nabla \cdot \vec{V}_2 = \widetilde{\nabla \cdot \vec{V}_2} + (\nabla \cdot \vec{V}_2)^* \ ,$$

where the " $\overline{\quad}$ " represents an average around a latitudinal circle, the " ' " is a point deviation from this average, " $\sim$ " represents the area average, and " * " is the point deviation from this area average.

By using the divergence theorem, the third term on the right-hand side of Eq. (4) can be expressed in terms of a line integral along the boundary in the form

$$- \widetilde{\nabla \cdot \vec{V}_2 T} = \frac{1}{A} \oint_{\phi} T v \, dx \qquad (6)$$

where A is the total area enclosed by the latitude circle ϕ , and x is the distance around the earth at latitude ϕ . Applying the definitions $v = \bar{v} + v'$ and $T = \bar{T} + T'$ and substituting in Eq. (6) gives

$$- \widetilde{\nabla \cdot \vec{V}_2 T} = \frac{1}{A} \oint_{\phi} T v \, dx = \frac{1}{A} \oint_{\phi} T'v' \, dx + \frac{1}{A} \oint_{\phi} \bar{T}\bar{v} \, dx \qquad (7)$$

since the closed integrals around a latitude circle of the cross products $\bar{v}T'$ and $v'\bar{T}$ must vanish identically. Now by substituting Eq. (7) into Eq. (4), expanding all terms in Eq. (4) in terms of the area averages given in Eq. (5) and dropping terms which vanish identically, Eq. (4) yields

$$\tilde{w} \left(\frac{\partial \tilde{T}}{\partial z} + \frac{g}{c_p}\right) + \widetilde{w^* \frac{\partial T^*}{\partial z}} = \widetilde{\frac{1}{c_p} \frac{dh}{dt}} - \frac{\partial \tilde{T}}{\partial t} + \frac{1}{A} \oint_{\phi} T'v' \, dx + \frac{1}{A} \oint_{\phi} \bar{T}\bar{v} \, dx$$

$$+ \tilde{T} \widetilde{(\nabla \cdot \vec{V}_2)} + \widetilde{T^* (\nabla \cdot \vec{V}_2)^*} \qquad (8)$$

Now, if it is assumed that $(\nabla \cdot \vec{V}_2)^* = - \frac{\partial w^*}{\partial z}$ and the $\widetilde{\nabla \cdot \vec{V}_2}$ term is written in line integral form similar to Eq. (6), Eq. (8) becomes

$$\tilde{w}\left(\frac{\partial \tilde{T}}{\partial z} + \frac{g}{c_p}\right) = \widetilde{\frac{1}{c_p}\frac{dh}{dt}} - \frac{\partial \tilde{T}}{\partial t} + \frac{1}{A}\oint_{\phi} T'v'\,dx + \frac{1}{A}\oint_{\phi} \bar{T}\bar{v}\,dx - \frac{\tilde{T}}{A}\oint_{\phi} v\,dx$$
$$- \widetilde{w^* \frac{\partial T^*}{\partial z}} - \widetilde{T^* \frac{\partial w^*}{\partial z}} \ . \qquad (9)$$

Finally, by expressing the fourth and fifth terms on the right side of Eq. (8) in integrated form and combining the last two terms, one obtains the equation for the vertical component of the mean meridional circulation

$$\tilde{w} = \frac{1}{\frac{\partial \tilde{T}}{\partial z} + \frac{g}{c_p}}\left[\widetilde{\frac{1}{c_p}\frac{dh}{dt}} - \frac{\partial \tilde{T}}{\partial t} + \frac{1}{A}\oint_{\phi} T'v'\,dx + \frac{\bar{v}x}{A}\left(\bar{T} - \tilde{T}\right) - \frac{\partial}{\partial z}\left(\widetilde{w^*T^*}\right)\right] \qquad (10)$$

Eq. (10) is now in a very convenient form because once this equation is multiplied by $\frac{\partial \tilde{T}}{\partial z} + \frac{g}{c_p}$, each term has physical significance in terms of the heat budget of the area under consideration. The term on the left represents the temperature change due to a mean rising or sinking motion over the area. The $\widetilde{\frac{1}{c_p}\frac{dh}{dt}}$ term is the contribution due to non-adiabatic heating effects. $\frac{\partial \tilde{T}}{\partial t}$ is the observed temperature change, and $\frac{1}{A}\oint_{\phi} v'T'\,dx$ is the horizontal eddy flux. The $\frac{\bar{v}x}{A}(\bar{T} - \tilde{T})$ represents the heating in the area due to a mean horizontal inflow (or outflow) when the boundary temperature differs from the internal temperature. Finally, $\frac{\partial}{\partial z}(\widetilde{w^*T^*})$ gives the heating due to an upward (or downward) eddy heat flux.

Computation of the Mean Cell

Eq. (10) derived above will now be used to calculate the sense and magnitude of the mean cell for the chosen period. The first, fourth, and fifth terms on the right-hand side of Eq. (10) are all difficult to evaluate to a satisfactory degree of accuracy. However, the first term can be estimated with some reliability. On the basis of the works by Ohring (1958), Davis (1963), and Kennedy (1964), a mean $\widetilde{\frac{1}{c_p}\frac{dh}{dt}}$ of $-1\,^{\circ}C$/day was assumed for the entire polar cap.

The second term in Eq. (9) was evaluated by plotting successive charts of mean temperature ($\overline{T}$) with respect to sine of latitude (Fig. 2) and by determining graphically the mean temperature change north of the chosen latitude for five-day increments.

The third term ($\frac{1}{A} \oint_{\phi} T'v'\,dx$) was determined by taking five-day weighted averages of $\overline{T'v'}$ and substituting this result into the integrated form of term three, $\frac{x}{A} \overline{T'v'}_{\phi}$. This procedure was repeated for each latitude and at 100 and 50 mb, respectively.

The fourth term ($\frac{\overline{v}x}{A} (\overline{T} - \tilde{T})$) cannot be evaluated directly because $\overline{v}$ depends upon a prior knowledge of the mean meridional circulation. However, it can be determined iteratively by solving for $\tilde{w}$ without this term included, using the calculated $\tilde{w}$ to get an estimate of $\overline{v}$, and then making a new calculation including the term, etc. Because of the relatively small contribution of this term, very few iterations are necessary. In the case under investigation here, this procedure is unnecessary because $\overline{T} - \tilde{T}$ is negligibly small in higher latitudes (except for the period 10-15 December) (see Fig. 2).

Finally, the fifth term ($\frac{\partial}{\partial z} (\widetilde{w^*T^*})$) is probably quite small in the stratosphere, due to the nearly isothermal temperature distribution in the vertical. It can be directly computed provided that sufficiently detailed vertical motion fields are available. This is probably not the case. However, the previous report (Mahlman, 1966) showed that consistent vertical motion fields could be determined for the synoptic and planetary scales. Efforts to evaluate this term have indicated that its probable magnitude is less than 0.1 °C per day. Consequently, for this calculation the term will be neglected.

In its present form Eq. (10) only computes the mean cell north of a given latitude circle. However, one can evaluate $\tilde{w}$ for intermediate latitude bands by solving the expressions (Mahlman, 1966)

$$\frac{A^*_{40^\circ-50^\circ}}{A^*_{40^\circ-90^\circ}} \tilde{w}_{40^\circ-50^\circ} + \frac{A^*_{50^\circ-90^\circ}}{A^*_{40^\circ-90^\circ}} \tilde{w}_{50^\circ-90^\circ} = \tilde{w}_{40^\circ-90^\circ} \quad (11a)$$

$$\frac{A^*_{50^\circ-60^\circ}}{A^*_{50^\circ-90^\circ}}\,\tilde{w}_{50^\circ-60^\circ} + \frac{A^*_{60^\circ-90^\circ}}{A^*_{50^\circ-90^\circ}}\,\tilde{w}_{60^\circ-90^\circ} = \tilde{w}_{50^\circ-90^\circ} \qquad (11b)$$

$$\frac{A^*_{60^\circ-70^\circ}}{A^*_{60^\circ-90^\circ}}\,\tilde{w}_{60^\circ-90^\circ} + \frac{A^*_{70^\circ-90^\circ}}{A^*_{60^\circ-90^\circ}}\,\tilde{w}_{70^\circ-90^\circ} = \tilde{w}_{60^\circ-90^\circ} \qquad (11c)$$

for $\tilde{w}_{40^\circ-50^\circ}$, $\tilde{w}_{50^\circ-60^\circ}$, and $\tilde{w}_{60^\circ-70^\circ}$, respectively. Here A* is the area enclosed between the latitudes indicated by the respective subscripts.

The results of these calculations are given in Fig. 6. They are given for each five-day period so that consistency of results can be checked, and also so that the relation of the mean cell to the circulation buildup toward the end of the period can be investigated. The zonal mean w values from Table I (averaged over five-day periods) are also included in Fig. 6 as a consistency check. The two types of computations of mean vertical motion are seen to be in excellent agreement. Fig. 6 shows rather strikingly that a mean rising motion is present over the pole until about 5 December. Furthermore, strong descending motion is present at 100 and 50 mb in mid-latitudes. In view of the mean temperature profiles given in Fig. 3, this is a direct circulation. From 5-15 December, however, a marked change takes place in the mean cell structure. For this period descending motion is found over the pole with strong ascending motion between 60° and 70°N. Beginning on 5 December the north-south mean temperature gradient reverses in higher latitudes (Fig. 3). In view of this fact, the northernmost branch of the mean cell is still direct. On the other hand, the descending current at 50°N is now in the warmest air, and thus is an indirect circulation.

The basis for this rather peculiar behavior presently is not well understood. Through a comparison with the previous study (Mahlman, 1966), one might hypothesize that the 5-15 December mean cell

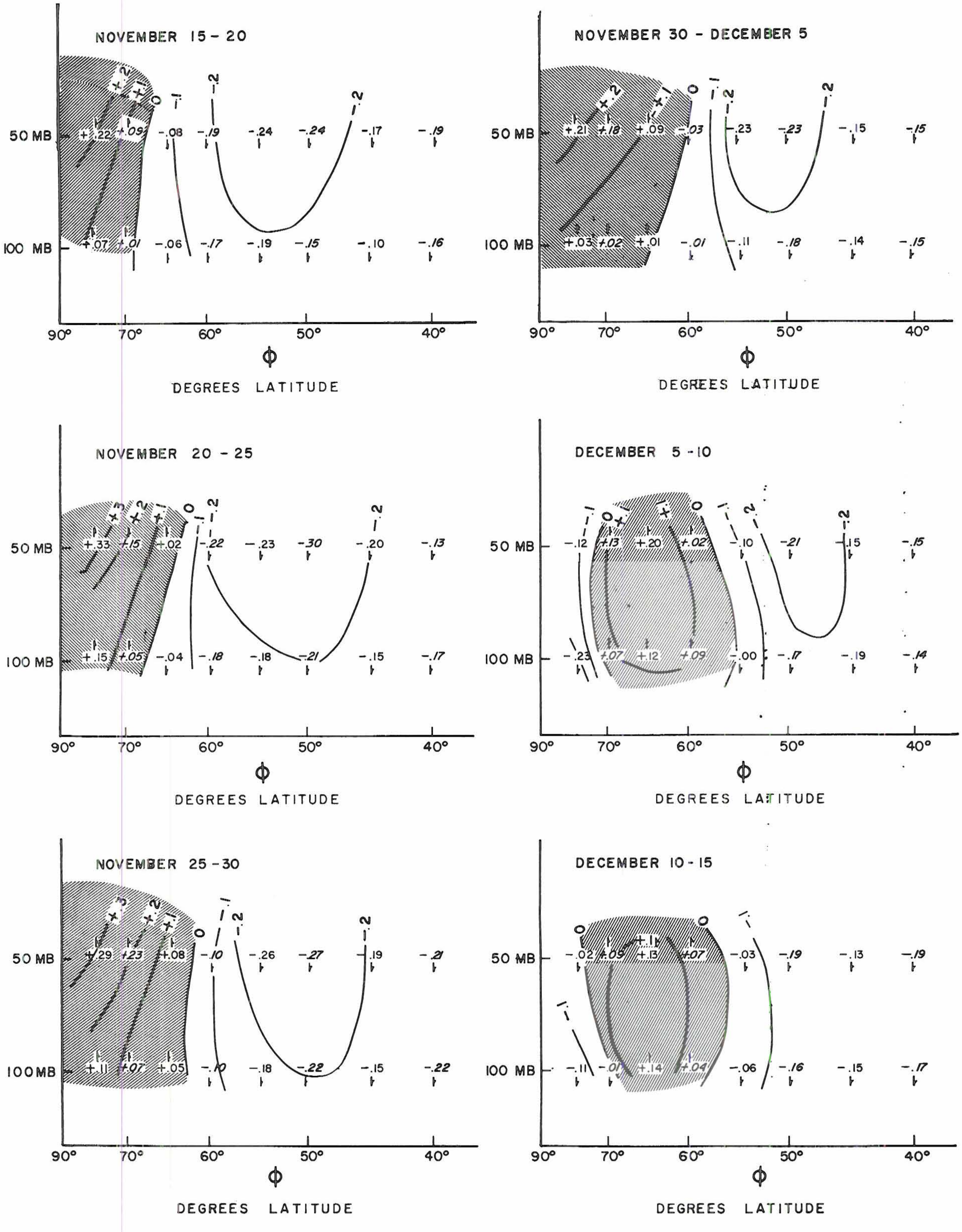


FIG. 6. Area averaged vertical motion ($\tilde{w}$) in km day^{-1} computed from Eqs. 10, 11a, 11b, and 11c for successive five-day periods from 15 November to 15 December 1958. The zonal mean vertical motion ($\overline{w}$) values are entered in italics and show the high degree of consistency between the two computational approaches.

configuration represents a shorter period transition between the direct circulation of the fall regime (increasing T northward in high latitudes) and the indirect circulation of the winter regime. The 100 and 50 mb synoptic charts provide some corroborating evidence for this. From 5-13 December the mean descending motion over the pole can be seen to be due synoptically to strong cold air advection over the pole at the edge of the asymmetric polar vortex. This may be readily seen on the 10 December 50 mb chart in Fig. 1. By 15 December the cold air advection over the pole has vanished on the 50 mb chart. Probably at this time the descending current vanishes also, thus giving the <u>indirect</u> wintertime mean circulation computed previously. In view of the very large number of tabulations required (31,680 separate hand tabulations for this study) it was not possible to further extend the analysis at all levels and latitudes. However, a limited computation was performed at 50 mb, 70^{o}N for 20-25 December and showed that ascending motion was present over the pole during this later period, in agreement with the above hypothesis.

Thus, it appears from the point of view of transport of trace substances that the mean meridional cell characteristics in the polar stratosphere are probably similar from the onset of westerlies through the breakdown of the polar vortex. That is, rising motions are present over the polar cap with sinking motion in mid-latitudes. The exception to this rule occurs during the brief period when the latitudinal temperature gradient reverses from positive to negative.

From a thermodynamical and energetical point of view, however, the mean meridional cell characteristics are highly variable through the fall and winter months. At the onset of the westerlies and through the temperature gradient reversal to the wintertime regime, the polar mean cell is a <u>direct</u> circulation. During the polar night when the circulation is particularly intense, the mean cell is <u>indirect</u>. Finally, after the breakdown of the polar vortex occurs, the mean circulation again becomes direct.

Before these tentative conclusions may be regarded as a satisfactory picture of the polar stratosphere, detailed studies over longer time periods must be performed.

Mean Cell Relative to the Polar Vortex

As pointed out in the previous paper (Mahlman, 1966), the mean circulation relative to a coordinate system oriented along a line of maximum circulation can be appreciably different from that of a mean cell measured with respect to latitude. In the previous case the circulation was characterized by an elongated bipolar vortex (predominately wave number two). The analysis revealed that the mean circulation was direct in the curvilinear system and indirect when measured with respect to the latitudinal frame. In view of this apparent paradox, it is of interest to prepare such a comparison for the present study. In the case analyzed here the polar vortex is displaced a considerable distance from the pole (see Fig. 1), but is far more symmetric relative to its center than in the previous case. Accordingly, the line of maximum circulation is also more symmetric relative to the vortex center. (The line of maximum circulation is defined as the height contour at which the highest average wind speed occurs.) Because of this a mean cell computation relative to this center lends not only insight into the transport processes, but also provides information on the mechanisms acting to maintain the thermal structure of the vortex itself.

To perform this computation of the mean cell relative to the polar vortex, initially the height contour of maximum circulation intensity was noted on the 50 mb surface. By interpolating from analyses of the vertical motion fields used in determining the transport properties in Chapter II, w values were noted at discrete intervals along parallel lines located at $+10^{\circ}$, $+5^{\circ}$, 0°, -5°, and -10° latitude distant from the height contour of maximum circulation intensity. This process was repeated at 100 mb utilizing the same contour employed at 50 mb. By using the same maximum circulation contour at both levels, continuity with height was assured. The mean w for each day at the given distances $+10^{\circ}$, $+5^{\circ}$, 0°, -5°, and -10° latitude from the chosen contour was determined by summing the individual w tabulations. These daily values were averaged over the period 15 November to 15 December 1958 to determine a single mean cell relative to the polar vortex oriented coordinate system.

The results of this calculation are presented in Fig. 7. This figure shows rather remarkably that sinking motion is present over the entire region of the intense circulation around the cold polar vortex. However, the most intense mean sinking is to the outside of the polar vortex. In view of the cold vortex center, this circulation is <u>indirect</u>, thus acting to intensify the mean negative temperature gradient of the vortex. This result is opposite to the sense of the computed <u>direct</u> latitudinal mean cell for the same time period. Fig. 7 indicates that the mean temperature gradient in the vortex will probably intensify as time progresses. This is in agreement with the observed change.

In the previous paper on the "sudden warming" phenomenon (Mahlman, 1966), the mean cell relative to the maximum circulation contour was measured to be <u>direct</u> while the mean meridional cell was <u>indirect</u> over the time period. In view of the completely opposite results obtained in the two cases, it appears that the thermodynamical and dynamical processes in the polar stratosphere differ considerably at the beginning and at the end of the strong polar night circulation. Implications of this will be discussed in the next chapter.

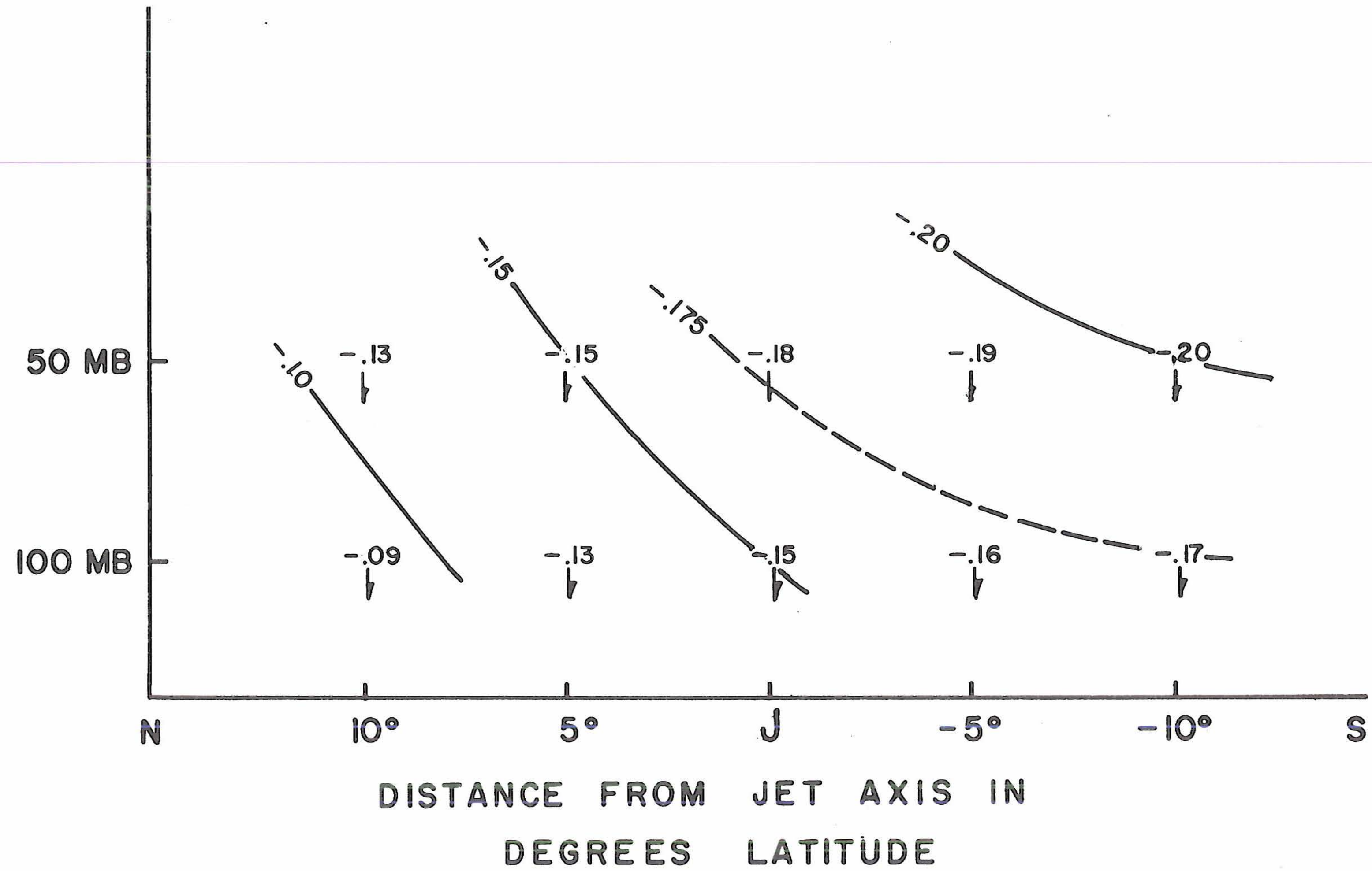


FIG. 7. Time composite at 50 and 100 mb from 15 November to 15 December 1958 of mean vertical motion (km day^{-1}) with respect to coordinate system oriented along line of maximum circulation intensity around the polar night vortex. Note presence of sinking motion over entire area.

IV. CAUSES OF THE "MINOR BREAKDOWN" AND COMPARISON WITH A MAJOR BREAKDOWN

As may be seen in Fig. 1, the period 15 November to 15 December was characterized by a significant interruption of the buildup of the winter stratospheric circulation. The first disturbance in the period was noted in the lower stratosphere over western Europe on 16 November. On about 22 November a cyclone formed in north central Canada and remained there until it weakened on 9 December and finally disappeared on 13 December. The disappearance of this disturbance is associated with a marked intensification of the polar night vortex.

Comparison with a Major Breakdown

In many respects the case analyzed here is qualitatively similar to a major breakdown of the polar night vortex. As shown by Reed (1962), Reed, Wolfe, and Nishimoto (1963), Miyakoda (1963), and by Muench (1964) the major polar vortex breakdown is associated with a significant transfer of energy from the zonal current and wave number 1 to higher wave numbers. The "minor breakdown" case investigated here exhibits similar characteristics. Furthermore, the time period required for the "minor breakdown" is roughly the same as for a major breakdown.

However, the dominant feature of the major breakdown is what has usually been termed the "sudden warming" phenomenon. At the time of the breakdown very large local warmings are observed. This warming aspect is also strong enough on the planetary scale to produce a complete reversal of the hemispheric mean north-south temperature gradient within a period of about five days (Mahlman, 1966). However, for the "minor breakdown" case under investigation no significant warming was observed on the planetary scale (Fig. 3).

Another significant difference between the two types of breakdowns is that the major breakdown marks the end of the strong polar night circulation, while the circulation becomes even more intense following the "minor breakdown". Also, the total kinetic energy of the flow decreased drastically in the major breakdown case (Miyakoda, 1963; Sekiguchi, 1963; Muench, 1964; Murakami, 1965), while for this case the total kinetic energy increased over the polar cap from the beginning to the end of the chosen period (Boville, 1962).

Other noticeable differences are that in the "minor breakdown" case the structure of the polar vortex itself remains relatively unaffected. These major differences rather strongly suggest that the controlling dynamics of the two phenomena are completely different. It thus appears that a study of these differences may prove to be instrumental in developing a more adequate knowledge of the dynamics of the winter stratosphere, and indirectly, a fuller understanding of the trace substance transport problem.

In the previous paper (Mahlman, 1966) a linear stability analysis was performed for a combined barotropic-baroclinic model circulation similar to the polar night vortex. This analysis showed that a necessary condition for instability is that the meridional gradient of mean potential vorticity must vanish on isentropic (θ) surfaces ($\frac{\partial \overline{P}}{\partial y_\theta} = \frac{\partial}{\partial y}\left[\frac{-\partial \overline{\theta}}{\partial p}(f - \frac{\partial \overline{u}}{\partial y_\theta})\right] = 0$). This result was similar to those obtained in previous analyses by Charney and Stern (1962) and by Pedlosky (1964a, b). Evaluation of this criterion revealed that the necessary condition for instability was satisfied prior to the January 1958 polar night vortex breakdown. This analysis also showed that the radiational properties of the Arctic polar night stratosphere led to eventual fulfillment of this instability condition. However, since the above is only a necessary condition for instability, there is no guarantee that the flow will break down when the meridional gradient of the zonal mean potential vorticity vanishes. However, if the meridional potential vorticity gradient is everywhere positive, the flow is absolutely stable and can not break down.

In view of the above results obtained for the major breakdown case, it is of interest to measure the stability criterion for the "minor breakdown" phenomenon and compare the results with the previous case. This was accomplished in crude fashion by computing the static stability between 100 and 50 mb and averaging the horizontal shear of the mean wind at the two levels to obtain the potential vorticity. The approximation is valid for this period since the inclination of the mean θ surface relative to the mean p surface is very small and the shear of the zonal mean wind is small relative to the Coriolis parameter. The results of this calculation are given in Fig. 8. This figure suggests that relative to geographic latitude, the circulation is absolutely stable up until 15 December. At that time the meridional gradient of $\overline{P}$ vanishes in high latitudes, thus fulfilling the necessary condition for instability. At the time of the "minor breakdown" seen in Fig. 2, however, the sufficient condition for stability is satisfied. Consequently, it would appear that the "minor breakdown" cannot be readily explained as an instability phenomenon.

In view of the rather large displacement of the polar vortex from the geographical pole (Fig. 1), the calculation of $\overline{P}$ was repeated, but this time relative to the polar vortex oriented coordinate system introduced in the last section of Chapter III. Fig. 9 gives the results of this calculation and shows that on 15 November the necessary condition for instability is satisfied. The 25 November profile shows that the originally negative $\overline{P}$ gradient within the polar vortex has nearly vanished. This measurement is in agreement with the onset time of the "minor breakdown" beginning on 21 November (Fig. 2). By 5 December the negative $\overline{P}$ gradient is re-established and becomes even more intense by 15 December.

These $\overline{P}$ profiles relative to the polar vortex (Fig. 9) are considerably different than the latitudinal $\overline{P}$ profiles of Fig. 8. The results relative to the polar vortex (Fig. 9) imply that the minor breakdown may be due to an instability phenomenon while Fig. 8 suggests that this is not the case.

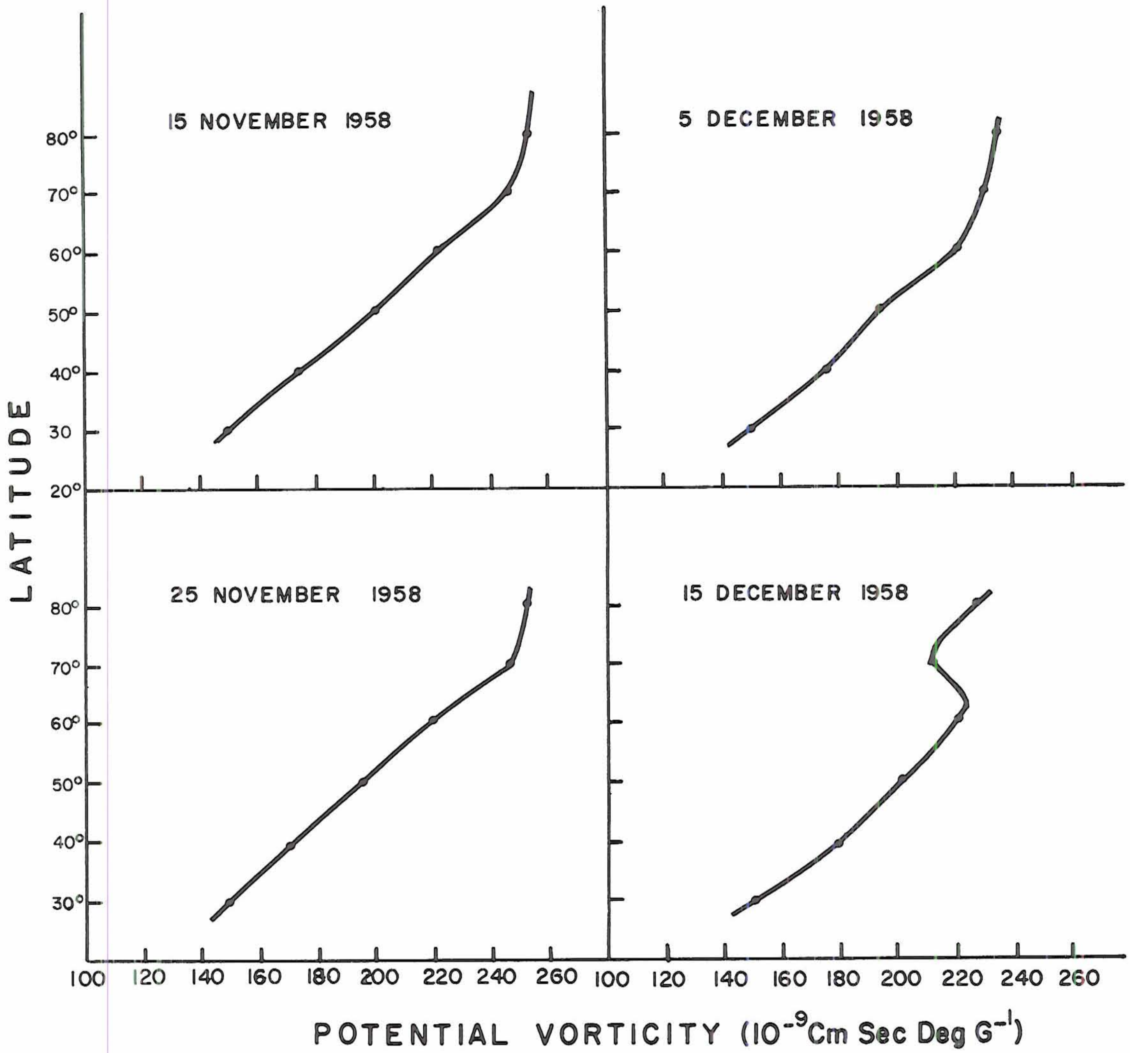


FIG. 8. Zonal mean potential vorticity (10^{-9} cm sec deg g^{-1}) at 75 mb plotted with respect to latitude for indicated dates.

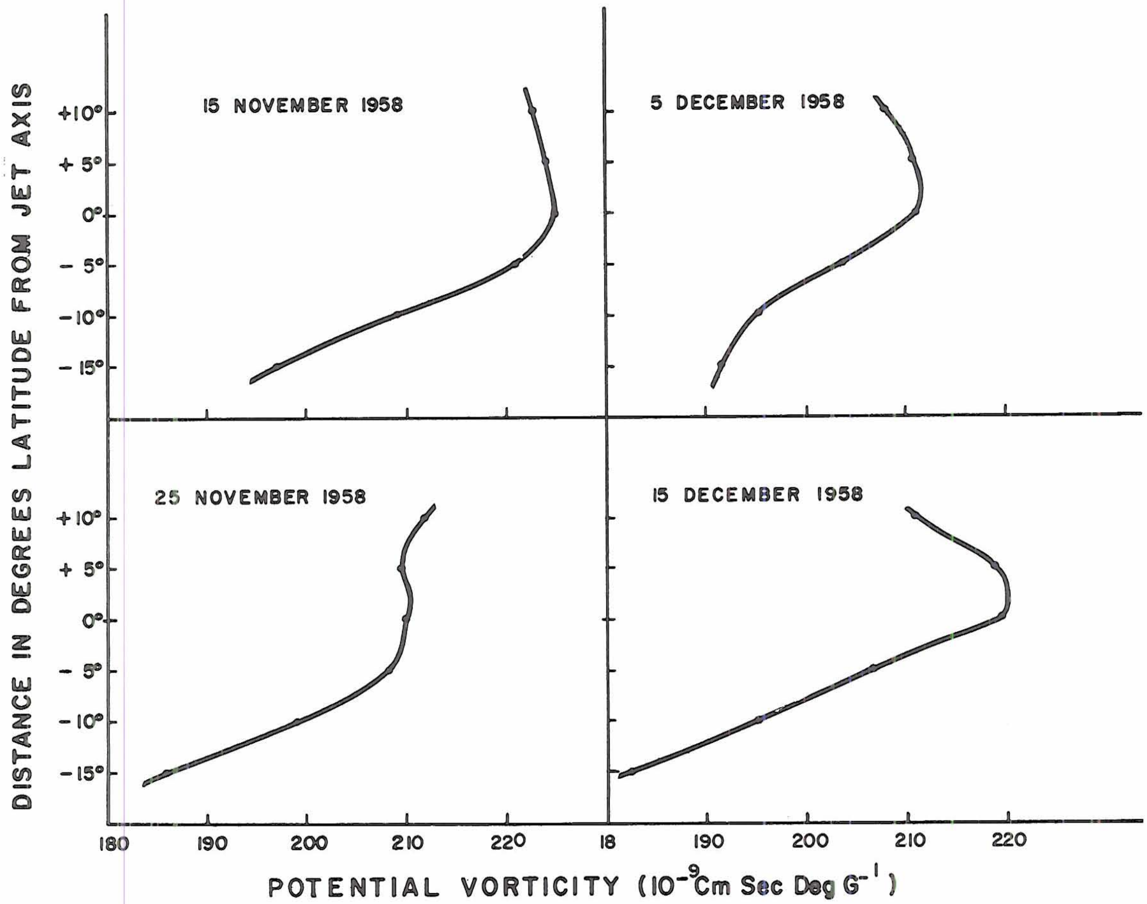


FIG. 9. Mean potential vorticity at 75 mb with respect to line of maximum circulation intensity around polar vortex. Values are plotted as a function of distance from this line for indicated dates.

In view of the modeling assumptions employed in developing the theory, it would appear that the $\overline{P}$ profile relative to the polar vortex itself is probably more relevant. It still must be emphasized, however, that fulfillment of this instability condition does not guarantee that disturbances will amplify. This points to the need for finding mathematically sufficient conditions for instability for the combined barotropic-baroclinic problem.

Synoptic Considerations

As noted by Miyakoda (1963) the major breakdown of January 1958 was associated with an extremely pronounced blocking anticyclone in the North Atlantic region. Also, Muench (1964) measured a large increase in the upward energy flux into the stratosphere just prior to the breakdown. This suggests that the apparent onset of instability in this major breakdown depended directly upon an upward energy flux from the troposphere. At first this appears to contradict observations by previous investigators that the onset of the breakdown initiates at higher elevations and propogates downward. However, the visible response to such tropospheric forcing may be initially seen at the higher levels. It is thus of interest to determine whether or not similar such evidence is present for this "minor breakdown" case.

The first stratospheric flow disturbance in this present case has already begun by 15 November (Fig. 1) in the form of a warm trough over western Canada and a developing cold ridge over western Europe. The 300 mb charts for the same period show that western Canada and the United States were dominated by formation of an intense tropospheric cold cyclone while western Europe was experiencing strong blocking action. With the onset of the "minor breakdown" on 22 November a warm stratospheric low formed in north central Canada and became well-pronounced by 25 November (Fig. 1). This disturbance was associated with formation of a 300 mb blocking anticyclone over Alaska and a very large cyclone over north central Canada. As a consequence of this the qualitative evidence for a tropospheric forcing of the "minor breakdown" appears to be strong. Substantiating evidence for this hypothesis may be seen in the 25 November chart in Fig. 1 which shows that the low over Canada has a warm core while the core of the polar vortex is cold. This indicates that the Canadian low will weaken with increasing height while the polar vortex will intensify.

This hypothesis of tropospheric forcing of the "minor breakdown" is easier to reconcile physically than for the major breakdown, since prior to the establishment of the strong polar night circulation, the stratospheric waves strongly resemble those of the upper troposphere. The above hypothesis needs to be tested quantitatively before it can be accepted with complete confidence. This would involve careful computation of the vertical energy fluxes at the tropopause and their effects on the energy budget of the stratosphere in a manner similar to that performed by Muench (1964) but for times of the year other than the period of a major breakdown.

V. SUMMARY

A period encompassing a "minor breakdown" of the winter stratospheric circulation was investigated for its thermodynamic, dynamic, and radioactivity transport characteristics. Computation of eddy transport quantities revealed that such a "minor breakdown" of the stratospheric circulation is favorable for northward and downward transport of debris, but by about a factor of five less than for a period following a major breakdown of the polar night vortex.

The sense and magnitude of the mean meridional circulation period was obtained by employing a heat budget method. This mean cell was found to be thermodynamically direct in the polar regions over the entire time period. However, the sense of the mean cell reverses after 5 December 1958 at the same time that the north-south temperature gradient reverses. A computation is also performed on the sense and magnitude of the mean cell relative to a polar vortex oriented coordinate system. This reveals that the mean circulation in this system is thermodynamically indirect. The difference in the sense of the mean cells between these two coordinate systems suggests that the mechanisms for maintaining the polar vortex and zonal mean circulations differ considerably.

Finally, the factors acting to initiate the "minor breakdown" are reviewed. By calculating the stability criterion derived previously (Mahlman, 1966), the flow relative to a geographical coordinate system is absolutely stable. However, when the stability criterion is evaluated relative to the polar vortex, the necessary condition for instability is satisfied. In view of the suggestion that the polar vortex oriented coordinate system is the more logical one relative to the theoretical modeling assumptions, it appears that the "minor breakdown" may be an instability phenomenon. Synoptic evidence is presented which suggests that tropospheric forcing may provide the energy source for this "minor breakdown".

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