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LARGE SCALE ATMOSPHERIC TRANSPORT PROCESSES OF RADIOACTIVE DEBRIS

by

ELMAR R. REITER

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

**Final Report
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**DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
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PROCESSES OF RADIOACTIVE DEBRIS

Summary of Research Conducted Between
1 December 1963 and 31 January 1967

by
Elmar R. Reiter
Principal Investigator

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Final Report Under Contract
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With U. S. Atomic Energy Commission

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

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ABSTRACT

During the contract period from 1 December 1963 to 31 January 1967, transport processes carrying radioactive debris from the stratosphere to the troposphere were investigated by means of individual case studies, by statistical techniques considering relatively long periods of time, and by a study of the behavior of the stratospheric polar night vortex during a "break-down" period. This report contains a summary of conclusions which the investigators arrived at, and have published, in previous reports.

I. INTRODUCTION

Nuclear debris released into the atmosphere by testing atomic weapons will be subject to the effects of air motions which may disperse the radioactive material over wide areas. Particle size and scale of atmospheric motions play an important role in the deposition of debris on the ground. Large particles will fall out in the vicinity of the test site, the fallout distribution depending essentially on the height to which the particles have been carried by the nuclear blast, their sinking velocity, and the vertical wind profile over the test site (U. S. Weather Bureau, 1955).

Atmospheric diffusion properties, manifest through small-scale (turbulent) wind fluctuations, affect the spread of nuclear debris at all levels, and over any distance. When operating over relatively long time (and/or space) intervals, they result in a more or less uniform distribution of small-sized particles with no measurable sinking velocity of their own, to a degree where nuclear debris concentration may be regarded as a quasi-conservative air mass property.

The research covered by this report was not concerned with small-scale transport processes. Hence, fallout patterns in the immediate vicinity of a nuclear test site, and atmospheric diffusion and turbulence effects were not explored. The investigations were limited to transport processes of synoptic scale and mesoscale, the latter encompassing systems of at least the size of convective clouds or of stable laminae, i. e., tens of kilometers in horizontal diameter, or hundreds of meters in vertical extent. Diffusion processes, while still superimposed upon the scales of motion under consideration, had to be regarded as "noise" rendering the quasi-conservative parameters of large-scale atmospheric motions non-conservative by mixing with adjacent air masses during time intervals of synoptic scale (order of magnitude of one day).

In dealing with debris transport within the atmospheric scales under consideration, one may distinguish between dry and wet fallout processes, depending on the absence or occurrence of precipitation at the time the fallout was measured. An even stricter separation would be according to measurement technique: radioactivity measured by air filters or in precipitated water. From a meteorological point of view such refinement brings about considerable complications, because "dry" debris collected by air filters could have been advected in a dry transport process, or could have come from evaporating rain (Facy, 1962).

The present studies were not concerned with cloud-physical aspects of debris collection by precipitation, nor did they encompass estimates on the relative efficiencies of wet and dry removal of radioactive aerosols. The main emphasis, even in those fallout cases where precipitation was observed, rested with a description of the large-scale transport phenomena that provided suitable aerosol concentrations on which washout processes became effective.

In summary, the following transport conditions were studied in detail:

- (1) Dry fallout transport from the stratosphere to the ground through the jet stream;
- (2) Dry and wet transport, by import of debris from the stratosphere into the lower troposphere, and subsequent removal by precipitation;
- (3) Transport of stratospheric air into the troposphere through the jet stream, without radioactive fallout at the surface. The latter problem was considered by tracing a discrete intrusion of stratospheric air into the troposphere, as well as by studying the flow processes near the "tropopause gap" over a large area and during a period of several days;
- (4) Wet removal of stratospheric debris through high-reaching thunderstorms penetrating the tropopause.

Whereas the investigations mentioned above were dealing with isolated cases, mainly using trajectory analysis techniques in establishing the debris transport processes, considerable attention was devoted as well to the statistical behavior of radioactive fallout in a second group of separate studies. These were concerned with:

(5) Statistical correlation between radioactive fallout over the United States and cyclogenesis at tropopause level, the latter measured by a "cyclone index";

(6) Transport processes in the stratosphere, their time variation, and their connection with the observed spring maximum of radioactive fallout;

(7) The dynamics of the stratospheric polar vortex of winter, and its instability.

These investigations provide insight into the mechanisms governing large-scale radioactive debris transport in the atmosphere.

II. DRY FALLOUT TRANSPORT FROM THE STRATOSPHERE TO THE GROUND

1. Case Description: Two periods of radioactive fallout over the continental United States were investigated. During the first period from 17 to 21 September 1961, heavy fallout was reported by the Public Health Service monitoring system over the eastern and southeastern United States. Peak counts of 24-hour samples exceeded $800 \mu\text{C per m}^3$ of dry air (Machta et al., 1962; Reiter, 1963a, b). The second case described the processes leading to fallout over Nevada in excess of $20 \mu\text{C per m}^3$ of air (Mahlman, 1964a, 1965a). In both cases the debris could be traced backwards along isentropic trajectories to a stratospheric source. The radioactive contaminant moved through the "tropopause gap" associated with the jet stream.

2. The Controversy: In the case of September 1961, Penn and Martell (1963) contended that a large part of the fallout observed over the southeastern United States came from an underground nuclear experiment, conducted in Nevada on 15 September 1961. Their main argument leading to this conclusion was that the debris appeared to be highly fractionated as is usually observed with nuclear detonations in which the fireball touches the ground. However, the radiochemical evidence itself in this case was not without controversy, making a Nevada source unlikely (Lockhart, 1964), and meteorological conditions seem to exclude a source within the United States (Reiter, 1964).

3. The Evidence: On 14 and 15 September Anderson (1962) reported unusual peaks in the scintillation counts observed by gamma-sondes over Flin Flon, Canada. These sondes were launched to measure secondary cosmic radiation. An example of the "unusual" balloon flight of 14 September is shown in Fig. 1.

The radioactive debris observed by Anderson was contained in a shallow layer near the 303°K isentropic surface. Trajectories on this surface, constructed backwards in time, reveal that the debris has been traveling with a strong jet stream, crossing the jet axis from the cyclonic towards the anticyclonic side on 13 September over the northern coast of Canada (Fig. 2). This trajectory behavior made a Soviet nuclear experiment, conducted on 10 September 1966, over Novaya Zemlya, a likely source of the debris, as has also been pointed out by Machta et al. (1962).

In view of the quasi-conservative nature of potential vorticity of air parcels containing the radioactive debris, a traversing of the jet axis is possible only if the parcels remain within a stable layer that emerges from the "jet stream front". This is shown schematically in Fig. 3. Neither strong accelerations nor decelerations are required during such transports of stratospheric or tropopause-level air into the troposphere.

The further progress of the contaminated air southeastward from Flin Flon is shown by a "three-dimensional" trajectory in Fig. 4. As may be seen from this diagram, the air containing radioactive debris descended from approximately 600 mb near Flin Flon to nearly 900 mb over the eastern seaboard. Here it was well within reach of the turbulent mixing layer near the ground.

As the anticyclonic curvature of the trajectory before it reached the ground indicates, the contaminated air was drawn into a strong anticyclone which was associated with a cold outbreak sweeping over the southeastern United States.

4. Characteristics of Dry Transport: The two case studies have the following in common: Radioactive debris traveled from tropopause level to the ground within three to four days. The fallout region at the ground was well defined and showed abnormally high radioactivity concentrations in the absence of any precipitation. (In the case of March 1963 the debris was more than 100 days old. The absolute levels of radioactivity during the moratorium of nuclear testing had decreased considerably. Therefore, the case studied by Mahlman (1964a, 1965a) is less "spectacular" than the September 1961 case.)

In both instances the main sinking motion occurred along a southward oriented air trajectory, flowing into a well-developed trough. As the contaminated air follows the west side of this trough, it reaches mid-tropospheric levels. The high values of potential vorticity associated with the air that carried the debris indicate the stratospheric origin of the air mass.

In the middle troposphere the contaminated air leaves the influence region of the upper trough. It enters an anticyclonic circulation system associated with the cold air that has been imported by the upper trough

and advances behind a more or less intense cold front. These cold anticyclones are characterized by the presence of "subsidence inversions" which, in the light of these trajectory studies, seem to be intrusions of stratospheric or tropopause air.

It should be pointed out that the stratospheric air mass which enters into this anticyclonic circulation emerges from the jet stream flow as a separate and well-defined branch. It has been shown that such a "splitting" of the jet stream may be expected whenever the flow crosses a "barrier", such as a mountain range or a cold dome (Reiter, 1965). Cold outbreaks, associated with strong cyclones, therefore, give rise to such splits in the jet stream.

The divergent flow associated with these cold anticyclones lowers the stable layer containing the radioactive debris still further. Clear skies and diurnal heating favor the development of an adiabatic mixing layer at least during the mid-day hours. As soon as these mixing processes reach the level of the stable contaminated layer, radioactivity is carried to the ground.

Intense cold outbreaks associated with relatively deep cyclones are rather frequent events over the central and eastern United States. Intrusions of stratospheric air into the low troposphere, therefore, have to be expected quite frequently in these regions. As long as the contaminated air remains in the eastern portions of the cold anticyclone, descending motions are dominant and the fallout processes should be entirely "dry".

III. DRY AND WET TRANSPORT PROCESSES

1. Case Description: Reiter and Mahlman (1964, 1965c) have studied a case of radioactive fallout which occurred over the southern United States between 24 and 27 November 1962. Fig. 5 shows the typical fallout pattern which prevailed throughout the period. Peak values of radioactivity in dry air were in excess of $320 \mu\mu\text{C per m}^3$. The age of the

debris in the region of heavy fallout was less than 15 days. This suggests a Soviet nuclear device as the main fallout source, presumably the test on 17 November 1962 over Semipalatinsk, USSR (Mahlman and Davis, 1964). The shaded regions in Fig. 5 indicate precipitation during the 24-hour period that ended at 0600 Greenwich Time, 25 November, as reported in the Daily Weather Maps of the U. S. Weather Bureau. As may be seen from this diagram, part of the fallout region experienced rain. There were several stations, however, which observed radioactive fallout without a trace of precipitation.

2. Characteristics of Transport Processes: The large-scale tropospheric transport processes of this case bear close resemblance to those described in the previous section. Stratospheric air was descending through the "tropopause gap" underneath a powerful jet stream. As this air reached mid-tropospheric levels within the stable layer in which it traveled, it became incorporated in a cold anticyclone which moved slowly eastward. A new frontal system followed in its wake. Vertical motions along this frontal system were responsible for the observed precipitation.

The developing anticyclonic vortex which allowed the radioactive debris to move southward in a well-defined jet stream branch is shown in Figs. 6 and 7. Along the western edge of the anticyclone a low-level jet stream was quite prominent on 23 November. The southerly flow associated with this low-level jet imported moist air masses from the Gulf of Mexico, thus separating very distinctly moist rising from dry descending air. Fig. 8 shows as an example the moisture distribution on the 295°K isentropic surface. As may be seen from the cross section shown in Fig. 9, this isentropic surface is characteristic of the stratospheric air descending in the stable layer underneath the jet stream.

Trajectories along the isentropic surface 295°K are shown in Fig. 10. The forward edge of the advancing stratospheric air is indicated by hatched bands. Computations on the actual amounts of mass involved in the sinking process from the stratosphere to the troposphere were somewhat complicated by the fact that the stable layer shown in Fig. 9 and presumably carrying the radioactive debris over the eastern United States became superimposed upon another stable layer of similar potential temperatures. After eliminating the mass contained in this second layer, it was estimated that 0.64×10^{12} metric tons of air split off the main jet stream and settled in the middle and low troposphere.

From this study, as well as from the ones described in the previous section, it appeared that stratospheric air may reach the earth's surface within a few days, provided that the air shows potential temperatures between approximately 295 and 305°K . Stratospheric air with potential temperatures significantly higher than these values will require the action of diabatic cooling and mixing processes before it reaches the ground. If these processes are caused by radiation and mixing only, as may be assumed in the absence of precipitation, considerably more time will be required for stratospheric fallout to reach the ground than was observed in the cases described so far. If the sinking air mass shows significantly lower potential temperatures than the ones given above, this air most likely will be of upper tropospheric origin, hence will not contain stratospheric debris.

Between 24 and 28 November 1962 several stations of the monitoring network reported considerable radioactivity in rainwater. Austin, Texas, for instance, measured $21,000\mu\text{C/liter}$ on 27 November. Other stations, such as Jackson, Mississippi, measured radioactivity in dry air only. No precipitation was reported there, nor by several other stations of the network. The atmospheric processes responsible for this peculiar fallout distribution may be estimated from Fig. 11:

A tongue of dry air spreading along and above the 295°K isentropic surface is blocked by a relatively deep layer of moist air. From the trajectory studies we may assume that the dry tongue contains stratospheric air and radioactive debris. Convective motions and precipitation associated with the frontal system mentioned earlier, and contained within the deep moist layer, are destroying the stable layer. The stratospheric air and its radioactive debris are mixed with low-level tropospheric air. The debris is subsequently washed out by rain.

Over those stations which measured dry fallout in the absence of precipitation, the stable layer containing dry stratospheric air may easily be identified aloft. The range of diurnal heating of surface air suggests that this dry layer is brought within reach of convective mixing motions, which prevail during daytime in an adiabatic layer near the ground. The conditions over Jackson, Mississippi, are shown as an example in Fig. 12.

In contrast to the cases of radioactive fallout discussed in the previous section, the present case occurred along the southern and western rim of an anticyclone. The descending motions within the anticyclone, which helped to move the debris from tropopause level into the lower troposphere, no longer prevail in this region. Rising motions and precipitation contribute to the destruction of the stable layer of stratospheric air and to the removal of debris by washout processes.

IV. TRANSPORT OF STRATOSPHERIC AIR INTO THE TROPOSPHERE THROUGH THE JET STREAM, WITHOUT RADIOACTIVE FALLOUT AT THE SURFACE

1. Case Description: Reiter and Mahlman (1965a) traced an intrusion of stratospheric air into the troposphere by means of isentropic analysis. The stratospheric air, as in the previous cases, was

contained within a stable layer which, between 18 and 19 April 1963, emerged from the "jet stream front" and subsided to low tropospheric levels, without causing any noticeable increase in the radioactivity of surface air. The intrusion of stratospheric air occurred in a south-westerly jet stream mainly over Colorado and Kansas. The time at which the intrusion process developed was characterized by chinook winds immediately to the east of the Continental Divide.

2. Characteristic Features of Intrusion: The potential temperature characteristic of the stable layer containing stratospheric air was 310°K . This is slightly higher than the temperatures specified earlier for intrusions of contaminated stratospheric air which have been observed to reach the ground. The present study, thus, confirms the estimates made earlier.

The mass involved in the intrusion was estimated to be 0.25×10^{12} metric tons which is somewhat less than the air masses involved in the fallout cases described above. Of this, a small stable layer which separated from the main layer over Dodge City, dipping down to low levels, contained only an insignificant fraction of extruded mass--less than 10 per cent.

The trajectories within the layer of air subsiding from the stratosphere curved cyclonically, whereas in previous studies of stratospheric intrusions reaching the ground the air motions followed an anticyclonic curvature and descended quickly into the lower troposphere.

The cyclone-index change (see Mahlman, 1965b) between 18 and 21 April, associated with the present intrusion, was only 2.0 compared with an estimated threshold value of 2.5 for cases of subsiding stratospheric air which lead to radioactive fallout at the ground. This implies that the cyclogenesis associated with the present case was not intense enough to bring about a rapid descent of stratospheric air to the ground.

Although a deep adiabatic layer of dry air, containing the chinook winds mentioned above, continuously "tapped" the stable layer of stratospheric air, no measurable increase of radioactivity was observed near the ground. This may have been due to the diluting effects of mixing processes acting over a deep layer, but also to the depleted stratospheric reservoir and to the rather uniform "background" of the spring maximum of radioactive fallout.

The role of flow patterns in the upper troposphere and lower stratosphere in the time-history of an intrusion of stratospheric air has been studied in another investigation of the same case (Reiter, Glasser, and Mahlman, 1966). It was found--in agreement with Danielsen (1959)--that the "tropopause" has to be re-defined if air mass transfers between stratosphere and troposphere should be estimated with any degree of reliability. The definition of a tropopause, as currently used by the U. S. Weather Bureau, offers a convenient reference level in single-station analysis. When considering area distributions of tropopause levels and their changes with time, this definition leaves much to be desired because it generates erratic fluctuations of tropopause levels which introduce a certain element of error into mass transfer calculations.

It was decided, therefore, to use as an additional criterion in the definition of the tropopause intercept of an isentropic surface, the separation line between high and low values of potential vorticity. A value of $20 \times 10^{-9} \text{ g}^{-1} \text{ cm} \cdot \text{sec} \cdot \text{deg}$ seemed to offer a suitable value in most cases for such a re-definition of the tropopause.

A preliminary investigation, utilizing trajectory computations on isentropic surfaces, revealed that major intrusions of stratospheric air into the troposphere are well defined in space and time. The quantitative estimates of such mass transfers, made during earlier studies, therefore, seem to characterize quite well the main events of such

mass flow. "Continuous seepage" of stratospheric or tropospheric air through the tropopause gap seems to play a rather minor role in such mass exchange processes.

During this preliminary study, the following bodies of air could be identified:

- (a) Stratospheric air that remains in the stratosphere;
- (b) Tropospheric air that remains in the troposphere;
- (c) Stratospheric air that intrudes into the troposphere;
- (d) "Undecided" stratospheric or tropospheric air that remains in the tropopause gap during the period and over the area under investigation;

(e) There possibly is tropospheric air that intrudes into the stratosphere. (Trajectories for the latter were difficult to trace since, in the present case, they are leading into the data-sparse region north of the United States-Canadian border.)

It appears highly desirable to extend this study over longer periods of time, covering various stages of circulation patterns, and over wider areas. In such an investigation one might be able to compare the mass flow from the stratosphere with the flow into the stratosphere, associated with jet stream systems. It would be interesting to see whether or not the former exceeded the latter by a significant amount. If so, is the tropopause gap near the jet streams a preferred outflow region of stratospheric air, and is the replenishment of stratospheric air accomplished to a large extent by meridional circulations in the "Hadley" cell which imports air at high levels from the tropics? A detailed trajectory study might be able to give reasonable estimates which could be verified by more sophisticated tracer or constant-balloon experiments.

V. WET REMOVAL OF STRATOSPHERIC DEBRIS BY HIGH-REACHING THUNDERSTORMS

1. Case Description: Heavy Iodine-131 fallout was observed in milk from the Wichita, Kansas, milkshed on 13 May 1962 and during subsequent sampling periods (Table I, Reiter and Mahlman, 1965b). Several other stations reported stronger-than-normal radioactivity in milk around the same time period, but the Wichita and Kansas City milksheds showed the greatest abundance of contamination of all reporting stations from the Midwest (Table II). As may be seen from Fig. 13, a number of thunderstorms were reported in the region prior to the period of observed fallout in milk, with radar echoes from altitudes in excess of 50,000 ft.

2. The Controversy: Martell (1964, 1965) and his co-investigators (Martell, Shedlovsky, and Watkins, 1965; Penn and Martell, 1963) contend that in cases of high I-131 concentrations in radioactive fallout over the contiguous United States, vented nuclear shots at the Nevada test site constitute a major--or at least an important--debris source. Their argument is mainly based on radiochemical evidence. I-131 has a half-life of only 8 days, and due to its volatile nature, fractionation of radioactive material escaping from an underground test would tend to increase the relative concentrations of this constituent of the debris.

Other investigators (Machta et al., 1962, 1964; List, Telegadas, and Ferber, 1964; Reiter and Mahlman, 1965b) oppose Martell's conclusions on the grounds of meteorological and conflicting radiochemical evidence. By means of quasi-isentropic trajectories, which offer a high degree of reliability (Danielsen, 1961), air motions may be traced backward from the fallout area. Only if the rate of horizontal transport in the atmosphere between source region and deposition area agrees with the time and distance between nuclear test and fallout observation, and

if plausible vertical transport mechanisms--upward over the test site, and downward over the fallout site--can be found, may valid conclusions be drawn as to the nuclear test event responsible for the observed fallout.

3. The Evidence: The Paca shot of 7 May 1962, which Martell held responsible for the radioactive fallout observed in milk from the Wichita and Kansas City milksheds, was a contained test, i. e., no radioactive gases were observed escaping the test site at detonation time (Hardy, Rivera, and Collins, 1964). Post-shot drilling operations were conducted within 24 hours of shot time, but again no radioactivity was observed escaping off-site.

Measurements of radioactivity in dry air reported by the U. S. Department of Health, Education, and Welfare Radiation Surveillance Network indicate only a small--almost negligible--increase in radioactivity in the Wichita-Kansas City region during the period in question. Analyses of precipitation samples, on the other hand, show a sizeable increase in radioactivity and a shift in debris age from >100 days to only 34-40 days. These facts render the present fallout case quite different from the one described in the previous section, which showed remarkable fallout increases both in dry air and in rain water.

It may be concluded that the fallout in milk was caused by "wet" deposition of radioactivity, and not by dry debris settling on the ground. According to Martell (1964) and List, Telegadas and Ferber (1964), it takes from two to four days from the time the fallout reaches the ground to the completion of the radioactivity transfer into milk.

Air samples from the stratosphere, collected by the Defense Atomic Support Agency, Project Star Dust, along a cross section running close to the line Brownsville, Texas;--Great Falls, Montana, revealed the presence of "hot" debris clouds near the levels 50,000 ft and 60,000 ft (Fig. 14). Forward trajectories (Fig. 15) on the 400°K

isentropic surface, starting from the times and places at which the lower one of these two debris clouds was intercepted by sampling aircraft, indicate that strong concentrations of radioactive aerosols were present near the 50,000 ft level in the region where thunderstorms occurred on 9 May (Fig. 13). Since a number of convective cloud tops penetrated beyond this level, it is reasonable to assume that a wash-out mechanism transported debris from the stratosphere directly to the ground.

Trajectory studies make it quite unlikely that a Nevada debris source had contributed to the fallout observed in Wichita and Kansas City milk on 13 May and shortly thereafter. (Later occurrences of radioactive fallout, as reported in Table I, have not been investigated in detail, since none of the Nevada tests conducted during May 1962 produced enough radioactive release to be able to cause a significant contribution to the observed fallout.) On the other hand, the Christmas Island test series of April and May 1966 may very well be held responsible for the high concentrations of radioactive debris measured by Project Star Dust in the stratosphere. Westerly winds observed at the 100 mb surface near Christmas Island on 4 May 1962, for instance, were feeding directly into a southwesterly jet stream over the western Pacific. This flow aloft could, without doubt, transport nuclear debris over the contiguous United States in a matter of a few days.

4. Characteristics of "Wet" Transport: The direct effect of radioactive debris on nucleation and scavenging mechanisms near the top of a cumulonimbus cloud can only be speculated on. More detailed measurements will have to be conducted in order to establish the efficiency of a Cb-cloud top, after penetration through the tropopause, in removing radioactive aerosols from the stratosphere. From the high fallout rates observed in rain water at the ground one may conclude that entrainment flow into a cumulonimbus cloud still is quite strong even at levels of 50,000 ft.

If cloud penetration depth into the stratosphere may serve as an indicator of "wet" removal of stratospheric debris, we may assume that occasions of such a radioactivity transport are by no means rare. According to statistical data compiled by Long (1966), a large number of thunderstorms penetrate the tropopause by more than 5,000 ft, especially over the midwestern United States. There may be some doubt as to the reliability of cloud height measurements by radar (Jordan, 1962), especially when these observations have been taken over great distances and with uncalibrated radar sets. Aircraft calibration flights conducted in 1961 were able to reduce the elevation angle errors to 0.5 degrees or less for a number of radar sites. This would produce an error in cloud height of $\pm 5,000$ ft at a distance of 100 n. mi.

In Long's statistical study only penetrations of the tropopause by more than 5,000 ft were counted as such, and only clouds within a radius of less than 100 n. mi. were considered. Table III clearly indicates the high frequency of tropopause penetrations over the midwestern states. The seasonal distribution of penetrations, shown in Fig. 16, suggests that wet removal of stratospheric debris by high-reaching thunderstorms may be quite effective over the middle west as well as over the south-central United States, where penetrations are frequent during spring. It is during this season that radioactive debris concentrations reach a maximum in the lower stratosphere.

Considering, furthermore, Fig. 17, which shows the diurnal variation of tropopause penetrations by thunderstorms in the Kansas City region, we may classify the case of radioactive washout, observed on 13 May 1962, as typical for the central United States.

VI. STATISTICAL CORRELATION BETWEEN RADIOACTIVE FALLOUT AND CYCLOGENESIS AT TROPOPAUSE LEVEL

1. Definition of "Index": In several studies Mahlman (1964b, 1965b, c, 1966) has pointed out the correlation between intrusions of

radioactively contaminated stratospheric air into the lower troposphere and cyclogenesis at jet stream level. Several such intrusions have been analyzed in detail in the case studies described in the previous sections. In order to test the validity of this correlation on a statistical basis, the following "cyclone index" describing the state of upper flow patterns was devised:

$$C = 1 - (1/90) \left[\frac{\sum_{i=1}^n (\theta - 270^\circ)^2}{n} \right]^{\frac{1}{2}} \quad (1)$$

C assumes the value 1.0 for purely zonal flow, and 0.0 for purely meridional flow. n is the number of measurements made along a latitude circle, and θ is given from

$$\alpha = \theta - 270^\circ \quad (2)$$

where α is defined by

$$\left| dy/dx \right| = \tan \alpha \quad (3)$$

x and y give the location of a point on an isobar--assuming quasi-geostrophic flow conditions--in a Cartesian coordinate system with the x-axis parallel to latitude circles.

2. Application of the Cyclone Index: Since nuclear testing in the atmosphere tends to produce sharp peaks in the time history of radioactive fallout, the period following the last atmospheric test in December 1962 was chosen for the investigation. In order to study the full statistical importance of stratospheric-tropospheric mass exchange, the 300 mb level was chosen for the index calculations. The computations were performed for the latitude band 45 to 55°N and for the sector between 70°W and 180°W which was held to be

representative for the belt of cyclone activity influencing the North American continent.

Index values were calculated at 24-hour intervals for the period January 1963 to December 1964, and an objective smoothing technique was applied in order to filter out computational noise. The results of these computations are shown in Fig. 18. The vertical lines in this diagram indicate the connection between fallout increases observed at the ground within five days after a rapid decrease of the cyclone index.

As may be seen from this diagram, not every decrease in cyclone index is followed by a fallout maximum. Apparently the rapidity of the index decrease--yielding a certain measure of the intensity of cyclogenesis--provides a better correlation. In order to test this, the parameter

$$100(C_1 - C_2)/\Delta t \quad (4)$$

was computed. C_1 and C_2 are the values of the cyclone index at the beginning and at the end of a period of index decrease. Δt is the length of this period in days.

In Table IV all pairs of values for this parameter obtained from Fig. 18 and the associated fallout increases--if any--within five days have been arranged systematically. It appears that whenever this parameter exceeded the value of 2.5, the decrease in cyclone index was followed by a peak in radioactive fallout. Thus, the cyclone index may be used as a tool in forecasting the average fallout level for a large area such as the contiguous United States.

The significance of the time lag between maximum values of the parameter $100(C_1 - C_2)/\Delta t$ and the occurrence of fallout maxima is shown in Fig. 19. A drastic peak in radioactive fallout at the surface

may be expected five days after the date at which the center of the period of index change occurred. Approximately 17 days after this date below-normal levels of surface radioactivity are encountered on the average.

VII. TRANSPORT PROCESSES IN THE STRATOSPHERE AND THE SPRING MAXIMUM OF RADIOACTIVE FALLOUT

(by J. D. Mahlman)

On the basis of work on transport of radioactive debris in the troposphere and the exchange of mass between the stratosphere and troposphere it was deduced that the spring fallout peak must depend upon the physical transport characteristics of the lower stratosphere (Mahlman, 1966). The existence of a spring fallout peak must thus depend upon a build-up of debris in the lower stratosphere at higher latitudes during the latter part of the winter to produce the observed depositions. This necessitates that in some manner the stratospheric circulation must effect a northward and downward transport of radioactive debris during this period.

As a means of examining this basic premise, a two-month period (January-February 1958) was selected which encompassed a well-documented example of a polar night vortex breakdown. The physical characteristics of the circulation during this period were examined by computing u , v , w , and T values at 36 equispaced grid points at 50° , 60° , and 70° N latitude. From this information the eddy covariances of all possible combinations of u , v , w , and T were computed. Particular emphasis was placed upon the $\overline{v'w'}$ correlation which measures the northward and downward transport accomplished by the large-scale eddies. Fig. 20 shows that prior to the period of polar night vortex breakdown ($\approx$ 25 January) the $\overline{v'w'}$ correlation is slightly positive, increasing to highly positive values just before the stratospheric

warming onset. After the warming has taken place the $v'w'$ correlation becomes highly negative (northward and downward eddy transport) and remains consistently so for about one month. Thus, it can be concluded that the vortex breakdown results in a dynamically favorable condition for build-up of radioactive debris in the high latitude portions of the lower stratosphere.

The effect of eddy transport of radioactive debris would be modified by the existence of a mean meridional cell in these regions, depending upon its direction and intensity. The direction and magnitude of this cell was computed with the aid of the above data by employing a heat flux method. This computation showed that the sense of this cell is indirect and acts to transport debris up and away from the polar regions at this time (Fig. 21). It may be seen from Fig. 21 that the cell operates even more strongly in the indirect sense during the polar vortex breakdown period. The evaluation of the various terms in the heat equation revealed conclusively that the magnitude of the mean warming during the breakdown period is almost entirely controlled by the eddy temperature flux acting at that time.

As a means of checking the results obtained in geophysical model experiments, the mean vertical motion was computed with respect to a coordinate system oriented along a line of maximum circulation intensity. This result showed that the circulation is direct when viewed from such a reference frame (Fig. 22). It consequently appears that the build-up of debris in the late winter is a very complicated interaction of mean and eddy transport mechanisms.

As an initial step toward a more complete understanding of the dynamical input into shorter term processes acting in these regions and their dependence upon elevation, the cyclone index at tropopause level was compared statistically with the vertical motion field at 100 mb.

The analysis revealed that a direct relationship exists between the magnitude of the two quantities and suggests that vertical stratospheric transport is inhibited during periods of maximum stratospheric-tropospheric mass exchange. Also, detailed trajectory computations were performed showing that a pronounced descending motion is associated with northward air motion following the polar vortex breakdown. It also was demonstrated that a strong change of trajectory direction with height exists in winter stratosphere and this process, when coupled with smaller scale vertical diffusion processes, may act to transport significant amounts of ozone out of the region of maximum production.

It is concluded from the above that the spring maximum of radioactive fallout is produced by a very complex interaction of the physical mechanisms presented. A satisfactory model which fully explains the fallout distributions in terms of these characteristics must necessarily depend upon more detailed quantitative evaluation of the relative contribution of each process. This, consequently, will depend upon an increase in our knowledge of the dynamics of the stratospheric circulation and its interaction with the troposphere.

VIII. DYNAMICAL BEHAVIOR OF THE POLAR NIGHT VORTEX (by J. D. Mahlman)

In the previous section it was argued that physical processes acting in the stratosphere during the period of the polar night vortex breakdown are highly significant in terms of producing a spring maximum of radioactive fallout at the surface of the earth. Because of the dependence of transport properties upon the behavior of the polar night circulation, it is imperative that a satisfactory dynamical explanation of the breakdown be achieved before an understanding of the fallout problem can be claimed.

Since the polar night circulation is altered from a nearly symmetric vortex to large-scale eddies when the breakdown occurs, it is reasonable to hypothesize that the phenomenon results from a release of flow instability at the time of breakdown. In a preliminary attempt to isolate the relevant dynamical aspects of this vortex from an instability viewpoint, a linear model was constructed which simultaneously incorporated the effects of lateral and vertical wind shear (Mahlman, 1966). The model employed isentropic coordinates with the well-known quasi-geostrophic approximation and included the effects of compressibility. The results showed that the meridional potential vorticity gradient must vanish as a necessary condition for instability.

To compare this result with that obtained by Kuo (1949), meridional profiles of absolute vorticity and potential vorticity were plotted as a function of latitude for each month from July 1957 to February 1958. The absolute vorticity criterion of Kuo is never satisfied but the potential vorticity gradient changes sign beginning in late October. This is in agreement with the observation of "minor breakdowns" beginning in the late fall months. It also suggests that the effects of compressibility are dynamically important in the stratosphere.

In the calculation of the latitudinal gradient of potential vorticity ($\frac{\partial P}{\partial y_\theta} = \frac{\partial}{\partial y_\theta} \left[- \frac{\partial \theta}{\partial p} (\zeta_a) \right]$ where θ is potential temperature, p the pressure, and ζ_a the absolute vorticity) it became evident that the influence of variations in $-\frac{\partial \theta}{\partial p}$ was much more significant than the contribution of the shearing terms in this region. In the Northern Hemisphere polar night stratosphere it is observed that cooling of the polar cap causes the temperature to decrease more rapidly with height in higher latitudes as the winter season progresses. This results in a negative meridional gradient of $-\frac{\partial \theta}{\partial p}$ which, if strong enough, offsets the increase in the Coriolis parameter and the shearing effect and acts to produce zeros in the $\partial P / \partial y_\theta$ field.

As a possible means of explaining the marked differences in stability of the Northern and Southern Hemispheric stratospheric vortices, the $-\frac{\partial\theta}{\partial p}$ field was computed as a function of latitude for the respective regions (Fig. 23). This figure shows that the stratospheric thermal stability characteristics for the two hemispheres are significantly different. The latitudinal gradient of $-\frac{\partial\theta}{\partial p}$ is very pronounced in the Arctic but almost zero in the Antarctic stratosphere. Consequently, even though the Antarctic vortex is extremely cold, it is predicted from this theory to be more stable than the Arctic winter-time circulation.

Although these hemispheric differences provide supporting evidence in favor of the theory outlined by Mahlman (1966), more thorough tests are needed before the relevant features of the vortex breakdowns can be explained. This awaits better and more plentiful data in these regions, and also a systematic preparation of this data, as done by the U. S. Weather Bureau during the IGY period.

IX. CONCLUSIONS AND OUTLOOK

The case studies of radioactive debris transport through the tropopause gap described in Sections II to IV are mainly dealing with the polar front jet stream. It appears that only jet streams which are associated with a frontal zone extending throughout the depth of the troposphere can accomplish the transport of debris from tropopause level to the ground in a period of a few days. (This consideration should include the "Arctic front jet stream", which has characteristics very similar to those of the polar front jet. Its role and efficiency in debris transport is not well established, however, because the polar latitudes have too sparse an aerological network.)

It may be assumed that the subtropical jet stream, and its associated tropopause gap, performs a function in stratospheric-

tropospheric mass exchange similar to, but probably weaker than, that of the PFJ. Since potential temperatures in the jet stream front of the STJ are considerably higher than in the equivalent layer of the PFJ, diabatic processes have to become active before stratospheric air intruding through the tropopause gap of the STJ may reach the ground. Again, the aerological network in the subtropical regions is sparse. Therefore no detailed trajectory analyses are available at this time which would permit an estimate of the efficiency of the STJ in vertical transport processes.

Most of the studies on radioactive fallout have been conducted over the North American continent because of the superior quality of data available from there. A climatologically preferred trough position, caused by the orographic barrier of the Rocky Mountains, may bias our conclusions on jet stream structure and transport processes, if they are obtained exclusively from this region.

In order to estimate more accurately on a global basis the magnitude of stratospheric-tropospheric mass exchange it would be desirable to study, at least for a limited period of time, global jet stream patterns at tropopause level and associated transport processes as revealed by isentropic trajectory analyses. In such a study all jet stream systems mentioned above should be taken into account. In addition, the role of the tropical easterly jet stream of summer, which is found over southern Asia and central Africa, should be assessed. Its seasonal occurrence may have an important influence on the seasonal fluctuations of the debris burden in the lower stratosphere.

Except for a preliminary study briefly described in Section IV, all cases considered so far dealt with outflow of stratospheric air into the troposphere. The problem of return flow of tropospheric air into the stratosphere, with the exception of the crude estimate just mentioned, have not been dealt with in detail. The convenient assumption of adiabatic flow can no longer be maintained in the ascending air motions that

bring tropospheric air back into the stratosphere. At this time we do not know whether or not the same jet streams are as efficient in replenishing air in the stratosphere, as they seem to be in removing it. From Palmén's (1954) schematic view of the "wheels" of the general circulation one might conceive the possibility that tropospheric air is imported into the stratosphere by the Hadley cell at low latitudes. The presence of this cell stresses the importance of mean meridional motions. The present case studies of stratospheric air intrusions into the troposphere, on the other hand, are associated with cyclogenesis, hence with eddy motions. It would be of considerable interest to estimate the relative importance of these two modes of transport across the tropopause at different latitudes.

From the foregoing it appears that the general circulation of the atmosphere as a whole should be viewed with respect to its efficiency in transporting quasi-conservative air mass properties, such as debris content. This not only concerns the breakdown into mean meridional versus eddy transport processes, but the latter should be regarded as a function of planetary wave number domain. Wiin-Nielsen et al. (1963, 1964) and others (see Reiter, 1963) have made successful attempts at giving quantitative estimates of the spectrum of large-scale eddy motions in the atmosphere. These results should be interpreted in terms of, and compared with independent data on, vertical mass transport through the tropopause region.

Similar studies would be desirable for the middle and upper stratosphere. In Section VII the encouraging results arrived at by Mahlman (1966) were described briefly. Similar studies should be carried out for other periods of time, in which the polar night vortex exhibits a different behavior. The stratospheric transport processes during summer and autumn should be incorporated into such detailed treatment.

The three-dimensional flow behavior near jet streams has been diagnosed successfully in a number of case studies. This does not mean, however, that these flow processes are yet fully understood. Numerical baroclinic jet stream models which would treat adequately the inflow and outflow characteristics of air motions into and from the stratosphere have yet to be developed. Since such flow behavior is intimately linked with energy transformations in the jet stream region, more refined forecasting procedures of cyclogenesis and cyclolysis will result from such developments.

The studies described in this report were conducted with the use of data stemming from "classical" observation tools, such as the radiosonde and rawinsonde network. Measurements of radioactive fallout, conducted by various agencies, were used in establishing the validity of atmospheric transport calculations. With the development of additional tools, such as long-lived constant-density balloons, improved balloon tracking capabilities, artificial tracer aerosols, refined sampling techniques, etc., large and small-scale transport processes in the atmosphere may be measured directly and checked against theoretical results.

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Milk sampling station	Date May 1962	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Little Rock, Ark.								30									<10	40				
Denver, Colo.				<10							45							<10				
Des Moines, Iowa				<10							300							60				75
Wichita, Kans.						670			660					215		165					250	
Louisville, Ky.	<10								20							30						
Minneapolis, Minn.				<10								280							170			
Kansas City, Mo.			45									605							150			
St. Louis, Mo.		15								80					50			<10				75
Syracuse, N. Y.				<10																		
Cincinnati, Ohio				<10							50							20				
Chattanooga, Tenn.				<10					30							<10						
Charleston, W. Va.				<10								40						50				

TABLE I. Iodine-131 concentrations in pasteurized milk (pc/liter) for indicated stations (after U. S. Public Health Service).

Wichita		Kansas City	
Date	Amount	Date	Amount
6 May	< 10	4 May	< 10
13 May	670	11 May	40
15 May	660	18 May	600
20 May	215	25 May	150
23 May	160	29 May	590
27 May	250	1 June	780
29 May	340	5 June	450
3 June	160		

TABLE II. Iodine-131 (pc/liter) in samples of pasteurized milk from Wichita, Kansas, and St. Louis, Missouri, milkshed areas (after List, Telegadas, and Ferber, 1964).

Penetration amount (1000 ft)	MSY	MKC	NYC	AMA	TPA	CVG	MSO	BRO	ILM	SAC
25		1		0						
24		2		0						
23		3		0						
22	1	6		0						
21	3	7		0						
20	5	9		1						
19	7	12		2						
18	8	13		3						
17	11	18		3						
16	14	22	1	4				1		
15	18	24	2	4		0		1		
14	23	30	3	6	1	0		1		
13	29	39	4	7	1	1		2		
12	39	49	5	8	1	1		3		
11	48	60	9	10	2	2	0	3		
10	59	73	14	14	4	4	1	4		1
9	73	87	17	18	6	8	3	5	1	1
8	93	102	21	22	10	9	5	6	2	2
7	115	117	27	27	16	15	7	8	2	3
6	144	134	35	33	26	26	12	9	3	4
5	172	153	44	41	36	33	15	10	5	6

TABLE III. Average number of thunderstorms above certain tropopause penetration levels, 1961 through 1964: 0 designates 1 or 2 total thunderstorms above a penetration level (Long, 1966).

Table IV: Values of $100 (C_1 - C_2)/\Delta t$ computed from index drops in Fig. 18.¹ Calculated values are arranged in ascending order of $100 (C_1 - C_2)/\Delta t$. The word "fallout" signifies that a fallout increase occurred within five days after the index decrease and a "none" denotes that no subsequent increase was observed.

Value of $100 (C_1 - C_2)$ Δt	Fallout Occurrence	Value of $100 (C_1 - C_2)$ Δt	Fallout Occurrence
0.6	None	3.0	Fallout
1.1	None	3.2	Fallout
1.3	None	3.5	Fallout
1.3	None	3.5	Fallout
1.3	Fallout	3.5	Fallout
1.4	None	3.6	Fallout
1.5	None	3.6	Fallout
1.6	None	3.7	Fallout
1.7	None	3.7	Fallout
1.8	None	3.9	Fallout
2.0	None	4.0	Fallout
2.0	None	4.0	Fallout
2.0	Fallout	4.0	Fallout
2.3	None	4.0	Fallout
2.3	None	4.2	Fallout
2.4	Fallout	4.4	Fallout
2.5	None	4.5	Fallout
2.6	Fallout	4.6	Fallout
2.6	Fallout	4.6	Fallout
2.7	Fallout	5.1	Fallout
2.7	Fallout	5.1	Fallout
2.7	Fallout	5.4	Fallout
2.8	Fallout	5.7	Fallout
2.8	Fallout	5.7	Fallout
2.9	Fallout	6.3	Fallout
2.9	Fallout	6.4	Fallout
3.0	Fallout	7.8	Fallout
3.0	Fallout

FIG. 1. Scintillation counts per second (ordinate) as a function of pressure (mb) for balloon flight of 14 September 1961, 22 GCT, released from Flin Flon. Canada.

FIG. 2. Isentropic trajectory along the 303°K surface, 13 September 1961, 00 GCT to 15 September, 00 GCT. Numbers to the left of the trajectory give the Montgomery stream function value (10^7 erg g^{-1}), to the right the observation time.

FIG. 3. Schematic trajectory of a debris-carrying air particle (irregularly shaded arrow) in a three-dimensional view of a relative coordinate system which moves with the jet maximum. Isentropic surfaces are indicated by thin lines; surfaces of constant wind velocity, boundaries of the frontal zone and tropopause are marked by heavy lines. The debris in the case outlined here travels at a speed of approximately 60 knots relative to the earth's surface, or circa 40 knots relative to the moving jet-stream system. By the time the debris reaches the anticyclonic side of the jet stream after strong sinking, it will decelerate. It is still contained within a stable layer which now has the appearance of a subsidence inversion rather than of a strongly baroclinic frontal zone.

FIG. 4. Trajectories of the boundaries of the fallout region (irregularly shaded) observed on 18 September, 12 GCT. The hatched region on top of the northernmost trajectory gives a three-dimensional view of this trajectory: its vertical extent indicates the movement of the particle along the vertical p -coordinate, the height of the hatched region being proportional to the pressure difference against the 900 mb level; the numbers plotted are Greenwich Central Time (date and time), pressures (mb) and isentropic stream function values (10^7 erg g^{-1}). Small marks along the plane trajectories indicate six-hour displacements.

FIG. 5. Distribution of radioactive fallout, 25 November 1962, over the continental United States. Values are given in $\mu\text{curie per m}^3$ of dry air, as measured by the U. S. Public Health Service Radiation Surveillance network. Average collection time in the central United States is 1500 GCT; filters are exposed for 24 hours. Lines labelled < 15 and marked by a shaded band enclose areas with debris age less than 15 days. Lightly shaded regions indicate precipitation during 24-hour period ending 0600 GCT as reported in the "Daily Weather Maps" of the U. S. Weather Bureau.

FIG. 6. Isotachs (mps) of isentropic surface 295°K , 23 November 1962, 00 GCT. Surface frontal systems have been entered. Regions with speeds less than 10 mps and more than 30 mps are marked by different shading. Intersection of isentropic surface with ground is indicated by heavy line. Jet axes are shown by heavy lines with arrows. 295°K isentropic surface not present at stations marked "G".

FIG. 7. Same as Fig. 6 except for 23 November, 12 GCT.

FIG. 8. Relative humidity (per cent) on isentropic surface 295°K , 24 November 1962, 00 GCT. Frontal systems are entered into the diagram. Areas with relative humidities in excess of 80 per cent and those with "motorboating" reports are marked by different shading. Stations in "motorboating" region are prefixed by letter "A" and give maximum possible humidity under such conditions. Inter-section of isentropic surface with ground marked in Figs. 6 and 7.

FIG. 9. Cross section through the atmosphere from Green Bay (GRB), Wisconsin, to Oklahoma City (OKC), Oklahoma, 22 November 1962, 12 GCT. Heavy full and broken lines: Isotachs (mps, vertical numbers); thin lines: potential temperature (K), slanting numbers). Vertical hatching indicates stable layers. Heavy dots mark the coded tropopause levels.

FIG. 10. Trajectories on 295°K isentropic surface; from 22 November 1962, 12 GCT, to 23 November, 00 GCT: full lines with arrows; from 23 November, 00 GCT to 12 GCT: broken lines with arrows. Numerical values of Montgomery stream function (units $10^7 \text{ cm}^2 \text{ sec}^{-2}$) and of pressure (mb) are given at starting and terminal points of trajectories: vertical figures for the first two map times; slanting figures for 23 November, 00 GCT. The centers of the hatched bands indicate the probable boundaries of tropopause air.

FIG. 11. Cross sections through the atmosphere from Denver (DEN), Colorado, and Dodge City (DDC), Kansas, to Burrwood (BRJ), Louisiana, for 24 November, 12 GCT. Heavy lines: isotachs (mps, vertical numbers); thin lines: relative humidities (per cent, slanting numbers); areas with "motorboating" reports and with humidities exceeding 80 per cent are marked by different shading. Dotted lines indicate potential temperatures of 290°K , 295°K , and 300°K .

FIG. 12. Temperature soundings at Jackson, Mississippi, on 24 November, 1962, 00 and 12 GCT, and on 25 November 00 GCT, plotted on a tephigram. Soundings have been shifted by 20° C along the temperature coordinate for successive observation times. Relative humidities are plotted along soundings (maximum humidities possible with "motorboating" are prefixed with letter "A"). Standard pressure levels along sounding are indicated by short lines and are labelled with small slanting numbers. The adiabat through the observed surface temperature maximum is assumed to determine the depth of the adiabatic mixing layer (marked by hatching).

FIG. 13. Area of thunderstorm echoes (dotted line) reported by Wichita radar, 9 May 01 GCT (8 May 7 p.m. CST) to 9 May 08 GCT (9 May 2 a.m. CST). Location of each echo $\geq 50,000$ ft is shown by an X, altitude (thousands of ft) and time of occurrence (CST) are indicated (after List, Telegadas, and Ferber, 1964).

FIG. 14. Cross section through the atmosphere along Project Star Dust flight track, 8 May 1962. Potential temperatures ($^{\circ}$ K, solid lines) and isotachs (mps, dashed lines) analyzed from 8 May 12 GCT data of Brownsville, San Antonio, Amarillo (Texas), Denver (Colorado), Lander (Wyoming), and Great Falls (Montana). Radioactivity data are given in disintegrations per minute per standard cubic foot, as measured by Project Star Dust Flight, 8 May, approximately 15 to 18 GCT. Values are averaged over flight legs indicated by horizontal lines.

FIG. 16. Average monthly number of tropopause penetrations by thunderstorms, 1961 through 1964 (Long, 1966).

FIG. 17. Diurnal distribution of penetration, Kansas City. The figures given are the total number for the hour for the period 1961 through 1964 (Long, 1966).

FIG. 18. Time series of comparison between cyclone index and shorter period fallout fluctuations. Upper part of diagram is smoothed cyclone index series. In the lower part: thin connected lines are five-day mean age-adjusted gross beta activities: heavy smooth line gives mean monthly fallout values. Vertical lines from cyclone index show the high percentage of fallout increases within five days after rapid cyclone index decreases. Numbers across top of figure are values of $100(C_1 - C_2)/\Delta t$ computed during each cyclone index decrease. Numbers above heavy bars are greater than critical value of 2.5 and numbers below thin bars are below 2.5 (Mahlman, 1965b).

FIG. 19. Time distribution of excess of positive values of fallout change from an even distribution of plus and minus values from sample of 32 occurrences of $100 (C_1 - C_2) / \Delta t > 2.5$ taken from Fig. 18. Time = 0 days was taken to be the center point of the critical cyclone index decreases. Solid line represents smoothing of points by 1-2-1 weighting method (Mahlman, 1965b).

FIG. 20. $\overline{v'w'}$ correlation coefficients for 50 mb, 60° latitude from 1 January to 28 February 1958. Note presence of very large negative values after onset of the polar night vortex breakdown (Mahlman, 1966).

FIG. 21. Area averaged vertical motion ($\bar{w}$) in km day^{-1} for indicated periods before, during, and after polar night vortex breakdown of January-February 1958. Hatching denotes area of rising motion (Mahlman, 1966).

FIG. 22. Time composite of adiabatically computed mean vertical motion (km day^{-1}) with respect to coordinate system oriented along line of maximum circulation intensity at 50 mb. Composite is for the period 10-27 January 1958. Hatching denotes area of rising motion ($\bar{w} = +$) (Mahlman, 1966).

FIG. 23. Comparison between latitudinal profiles of $-\frac{\partial\theta}{\partial p}$ for Arctic and Antarctic winter stratospheres (Mahlman, 1966).

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- Reiter, E. R. , 1964a: Comments on paper by S. Penn and E. A. Martell, "An analysis of the radioactive fallout over North America in late September 1961". Journal of Geophysical Research, 69, 786-788.
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