Statistical Characteristics of Three-Dimensional Particle Movement in the NCAR General Circulation Model

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ABSTRACT

An analysis of the three-dimensional, large-scale movement of air particles for the winter months with the NCAR general circulation model indicates that the horizontal movement of particles in the upper troposphere is greatly affected by wave motion in mid- and high latitudes, by the field of horizontal convergence and divergence, and by mean meridional circulation in the tropics. The mean center of mass of particles in both hemispheres generally moves toward respective poles and the mean square of the meridional component of the particle distances generally decreases with increasing time, indicating the effect of horizontal convergence on particle movement near the subtropics. The vertical movement of the particles is affected by upward motion near the thermal equator and downward motion near the subtropical region in the Northern and Southern Hemispheres. The vertical dispersion is most intense in the tropics and decreases toward the poles. There are two maxima of particle accumulation, one occurring near 15°N, the other near 30°S, and a minimum accumulation of particles appears near the thermal equator, indicating the effects of the divergence field and meridional circulation between the thermal equator and the subtropics.

The mean squares of zonal, meridional and vertical components of the distance for clusters of particles released at the equator and 45°N appear to consist of two components, a monotonically increasing component due essentially to the effect of turbulent diffusion, and a periodic component due primarily to the horizontal velocity convergence and divergence of mean motion.

1. Introduction

Studies of particle movement in fluid are fundamental to the understanding of the mechanism for fluid motion and the prediction of particle dispersion. For large-scale atmospheric motion, analyses of particle movement have been confined mostly to surfaces of constant pressure (Kao, 1962, 1965, 1974; Kao and Bullock, 1964; Kao and Al-Gain, 1968; Murgatroyd, 1969). This is because isobaric surfaces generally have been used as reference surfaces for large-scale weather maps and experimental balloon flights. Investigations of particle movement of global scale with three-dimensional models and isentropic analysis (Danielsen, 1961; Barnum and Diercks, 1969) have been attempted, but have not been made extensively. The objective of this study is to analyze the statistical characteristics of three-dimensional large-scale particle movement with the General Circulation Model (GCM) of the National Center for Atmospheric Research (NCAR).

To gain an insight into the nature of the large-scale Lagrangian motion in the atmosphere, an experiment is programmed to study motions of marked fluid particles, initially released from a set of geographically evenly-distributed grid points separated by 5° latitude and 5° longitude. To examine the characteristics of the relative dispersion between particles by three-dimensional large-scale motion in the atmosphere, a second experiment is programmed to investigate the movement of clusters of marked fluid particles in the NCAR General Circulation Model.

The analysis in this study indicates that large-scale three-dimensional movement of particles is affected by meridional circulation, large-scale wave motion, the field of convergence and divergence, and large-scale turbulent diffusion.

2. Data source and procedures

The wind data used in this study were extracted from an NCAR stratospheric model for Day 60, 0000 GMT, through Day 81, 0000 GMT, which corresponds to January of a year. In this model, a spheri-

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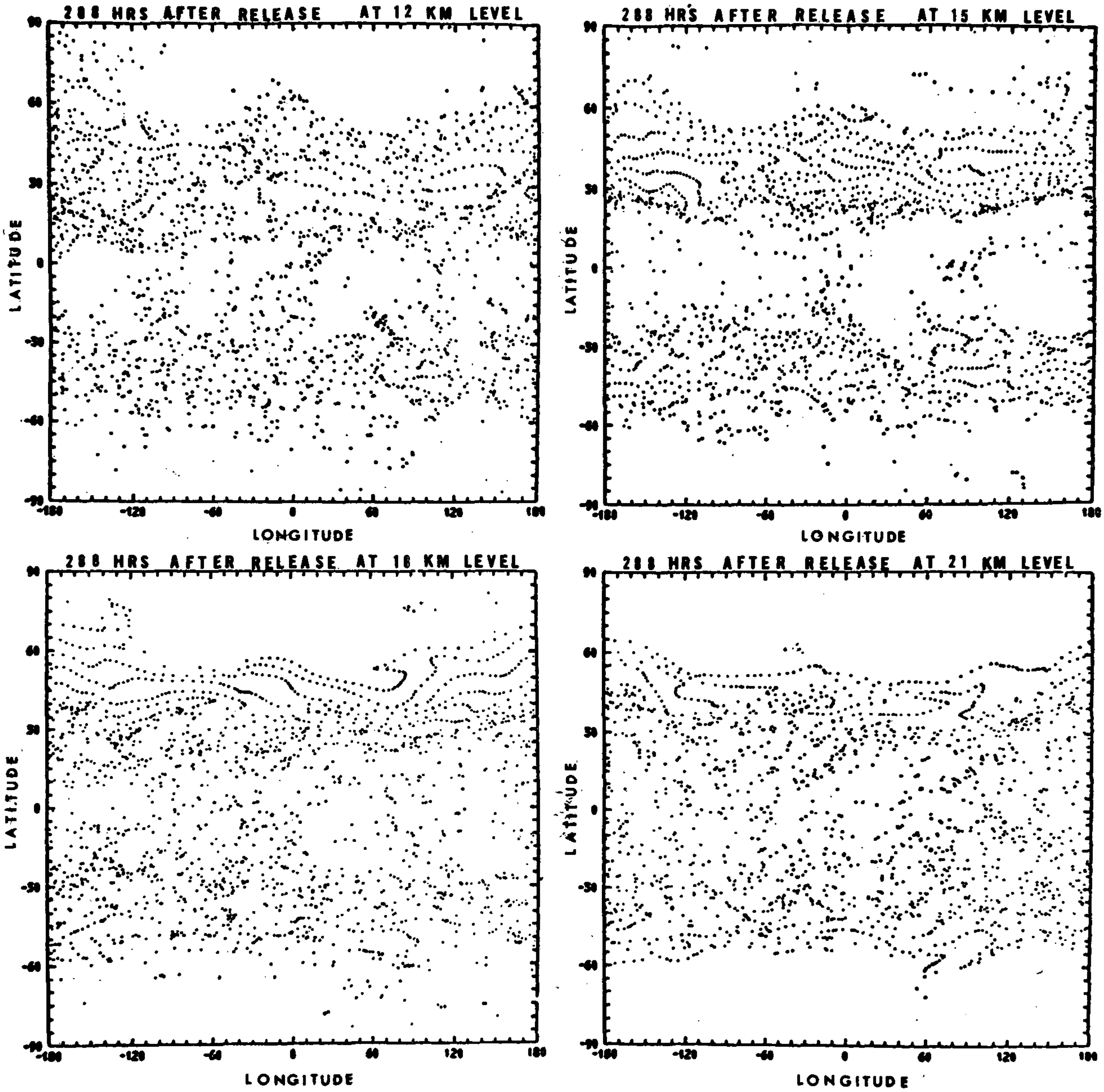

FIG. 1. The longitude-latitude distribution of marked particles at 12, 15, 18 and 21 km 288 h after release.

cal polar coordinate system is used with the horizontal grid point every 5° of longitude and latitude except near the poles, and the atmosphere between the earth's surface and 36 km is divided into 12 layers with a vertical increment of 3 km (Kasahara *et al.*, 1973).

In the first experiment, marked fluid particles were initially released from all grid points at 12, 15 and 18 km between 60°S and 60°N, and at 21 km between 55°S and 55°N. These particles were traced at 2 h time steps up to 288 h.

In the second experiment, clusters of marked fluid particles—each cluster consists of 25 particles forming three concentric circles of radii 130, 260 and 390 km with one particle in the center and eight locations equally spaced on each circle—were released one after another at 12 h intervals from Day 60, 0000 GMT, through Day 70, 0000 GMT. Each cluster was traced for 10 days. To eliminate bias caused by topographic effects, these clusters were released at four locations (100°E, 170°W, 80°W and 10°E) at the equator and 45°N.

The computation of the particle trajectories involved the interpolation of the velocity field every 2 h from 0000, 1200 and 2400 GMT maps and the trajectories of the particles were constructed at 2 h time steps.

3. Statistical characteristics of the movement of particles initially released at latitudinally evenly-spaced grid points

To analyze the characteristics of the large-scale horizontal movement, a geographically evenly-spaced distribution of particles is shown in Fig. 1 at four levels (12, 15, 18 and 21 km) 288 h after release. These figures indicate that large regions void of particles are found near the equator and in the lower latitudes, which coincide with regions of horizontal divergence of the centers of warm highs above the continents. During the time period of interest, the centers of the warm highs are located at the thermal equator in the Southern Hemisphere. The field of divergence in the tropics appears to be most pronounced at 15 km.

A large concentration of particles forms in the subtropical latitudes of both hemispheres, particularly pronounced at 15 km. It is interesting that the mean jet stream cores at 15 km occur near 25°N and 35°S (Kasahara *et al.*, 1973). It appears that meridional convergence occurring near the jet core tends to accumulate particles near these latitudinal circles.

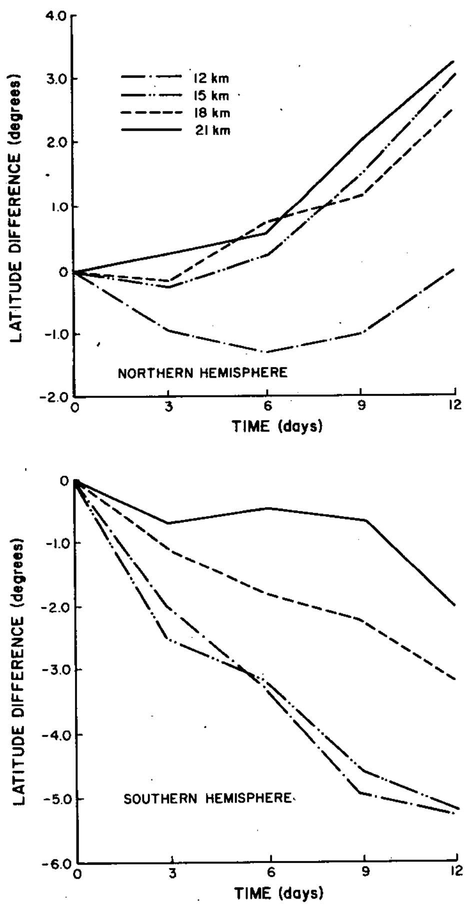

FIG. 2. The latitudinal position of the center of mass of the marked air particles relative to their initial position.

Particle distribution at mid- and high latitudes is generally affected by the synoptic flow patterns; i.e., the poleward movement of the particles is associated with high pressure ridges and centers, whereas the equatorward movement is associated with the low pressure troughs and centers. It is also found that in mid- and high latitudes more particles are clustered in pre-trough than in post-trough regions, indicating the effect of horizontal convergence in pre-trough regions and horizontal divergence in post-trough regions. Near the equator the movement of particles appears to be greatly affected by meridional divergence of the mean flow, a consequence of the Hadley cells north and south of the equator. Since no particles were initiated north of 60°N and south of 60°S, particles appearing in these belts 288 h after release must have been affected by meridional motion.

The position of the center of mass of the particles in each hemisphere relative to their initial position in the horizontal plane is plotted in Fig. 2 as a function of the latitude. It is seen that the centers of mass of particles in each hemisphere generally shift toward the respective pole, except that in the upper troposphere (12 km) in the Northern Hemisphere the center of mass moved toward the equator during the first six days and then toward the North Pole. The latitudinal position of the centers of mass will eventually reach a quasi-stationary latitude. Our experiments performed over a period of 12 days are not long enough to reach the stationary state. Mesinger (1965), however, found by using NMC data that a long-term steady state was reached at the 300 mb level about 15 days after the particles were released.

As a measure of the change in particle distance the ratio of the meridional standard deviations of the particle positions to their initial value as a function of time in the Northern and Southern Hemispheres at 12, 15, 18 and 21 km is shown in Table 1. With the exception of the somewhat irregular characteristic of the standard deviation at 12 km in the Northern Hemisphere, the ratio generally decreases with increasing time, indicating that the field of horizontal

TABLE 1. The ratio of the meridional standard deviations of the particle positions to their initial values.

	Level (km)	Day 0	3	6	9	12
Northern Hemisphere	12	1	1.006	0.967	0.950	0.983
	15	1	0.959	0.918	0.889	0.840
	18	1	0.967	0.916	0.887	0.870
	21	1	0.976	0.922	0.892	0.873
Southern Hemisphere	12	1	0.956	0.923	0.923	0.870
	15	1	0.961	0.923	0.914	0.881
	18	1	0.964	0.933	0.914	0.895
	21	1	1.018	0.943	0.937	0.922

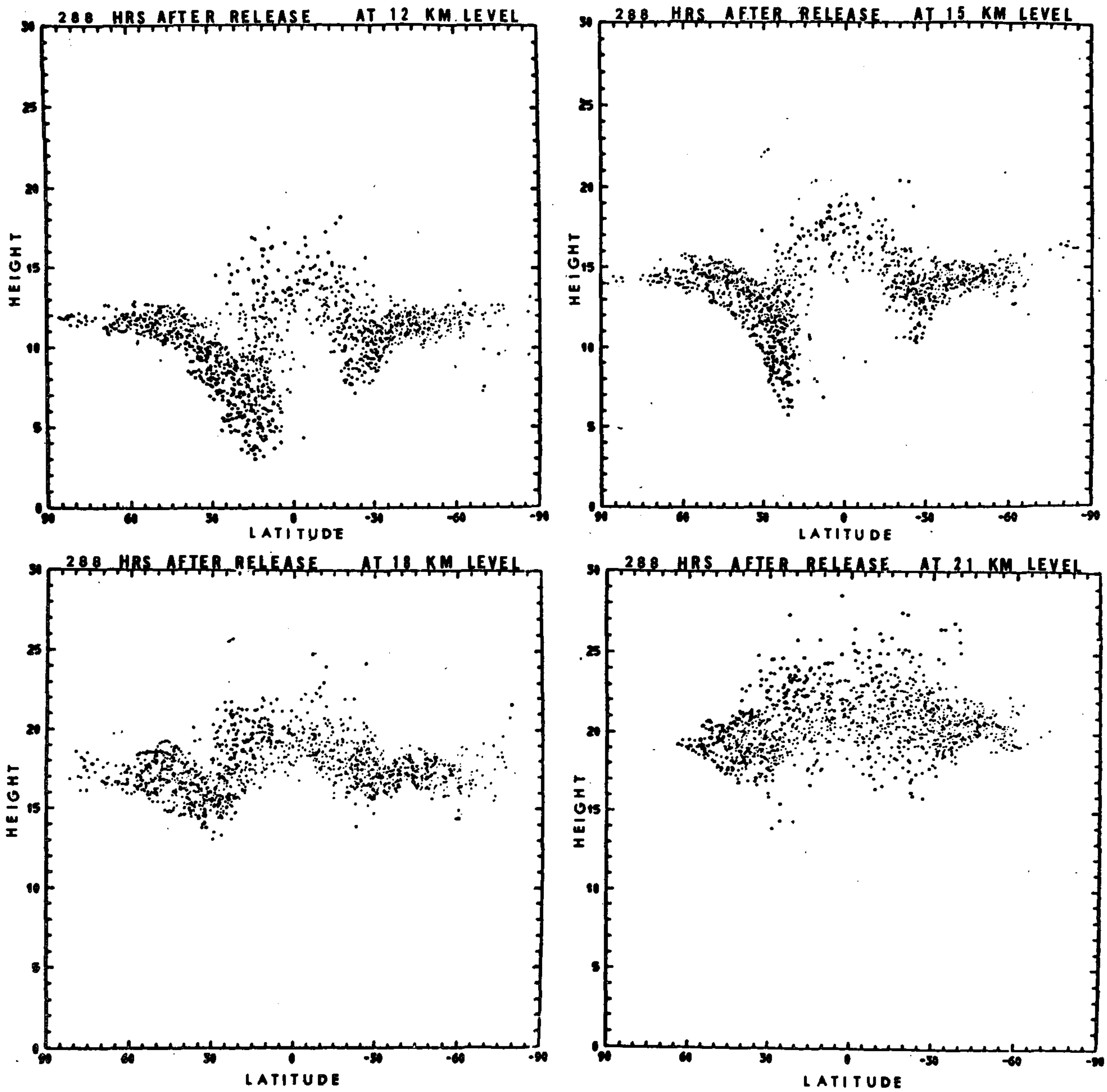

FIG. 3. The latitude-height distribution of the marked air particles 288 h after release at 12, 15, 18 and 21 km.

convergence in the atmosphere generally plays an important role in the movement of particles in the atmosphere. Table 1 also indicates that the ratio of the meridional standard deviation of particle positions generally increases with increasing height, indicating that the intensity of the horizontal convergence generally decreases with increasing height.

The distributions of particles projected on the meridional plane as a function of height and latitude 288 h after release at 12, 15, 18 and 21 km are shown in Fig. 3. This figure indicates that in the upper troposphere pronounced vertical dispersions of particles occur near 10°N and 20°S, and that at the thermal equator particle distribution is greatly affected by upward motion, whereas in subtropical regions (15°N and 25°S) particle distribution is affected by downward motion. The rate of vertical dispersion decreases toward higher latitudes. This is a result of weaker meridional circulations outside the tropics.

The distribution of particle-number contained in a $\pm 2.5°$ latitude-wide column, as a function of latitude, for particles 288 h after release at 12, 15, 18 and 21 km is shown in Fig. 4. Fig. 4 also shows that two maxima of particle accumulation in the upper troposphere occur near 40°N and 40°S and a minimum occurs near the equator, indicating the effect of horizontal

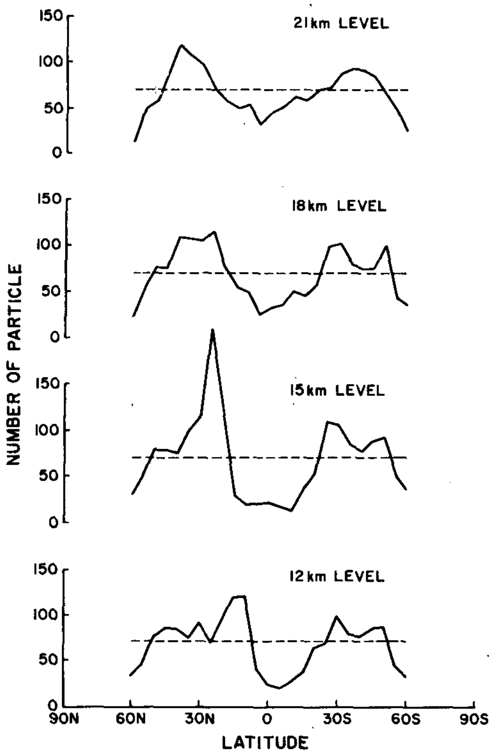

FIG. 4. The distributions of particle-number as a function of latitude at 12, 15, 18 and 21 km.

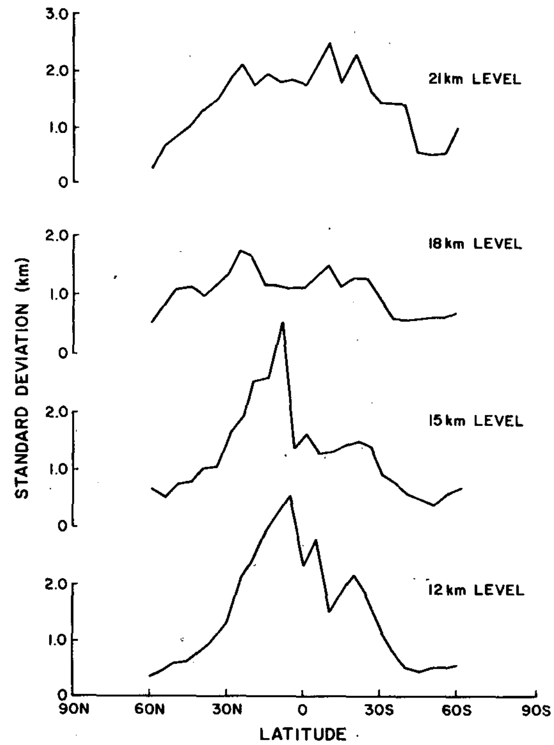

FIG. 6. The latitudinal distribution of the standard deviation of particle positions at 12, 15, 18 and 21 km.

convergence near 40°N and 40°S, and the effect of horizontal divergence near the equator.

The latitudinal distribution of the mean height of the center of mass of particles 288 h after release at various levels is shown in Fig. 5. Except in the tropics, the mean height of the center of mass at each level is lower than at the level of initial release. In the upper troposphere, two minima of the mean height of the center of mass occur near 30°N and 30°S. The low centers of mass poleward of 60°N and 60°S may not be representative since no particles were released in those regions.

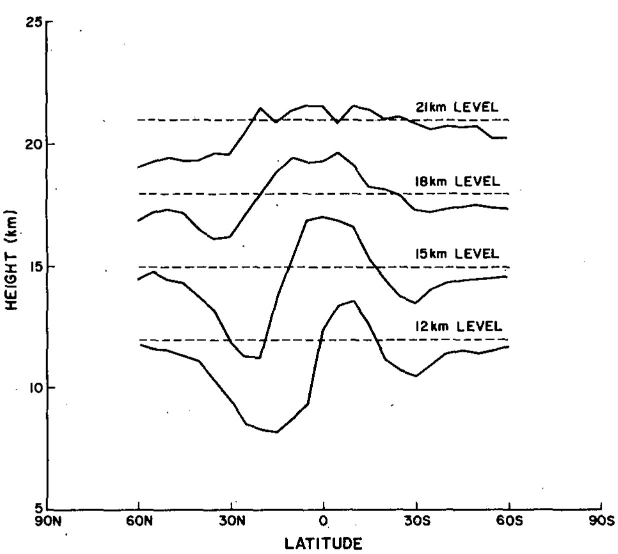

FIG. 5. The mean heights of the center of mass at 12, 15, 18 and 21 km.

The latitudinal distribution of the standard deviations of the particle position along the vertical for particles 288 h after release at 12, 15, 18 and 21 km is shown in Fig. 6. This figure shows that in the upper troposphere there is only one maximum of standard deviation occurring near 10°N. However, in the stratosphere several maxima appear. The standard deviation generally increases with increasing time, indicating a rather steady vertical dispersion of particles in the model atmosphere.

4. Statistical characteristics of relative movement of particles released in clusters

To analyze the characteristics of the relative movement of particles from a instantaneous source, clusters of marked air particles—each cluster consists of 25 particles forming three concentric circles of radii 130, 260 and 390 km with one particle in the center and eight at locations equally spaced on each circle—were released one after another at 12 h intervals from Day 60, 0000 GMT, through Day 70, 0000 GMT. To avoid the immediate effect of the tropopause in the model, clusters of particles were released at 12

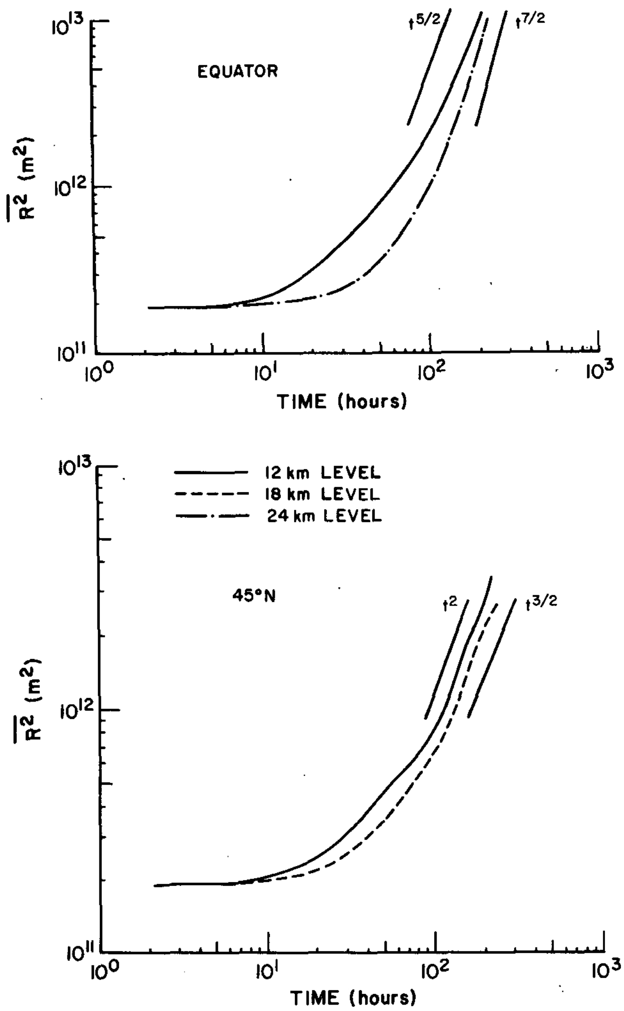

FIG. 7. The mean squares of the three-dimensional particle distance at 12, 18 and 24 km.

and 18 km at 45°N, and at 12 and 24 km at the equator (the model tropopause is about 4.5 km higher than that of the real atmosphere in this particular period). The trajectories of these particles are determined at 2 h intervals, and ensemble mean squares of the zonal, meridional and vertical components, and of the three-dimensional particle distance were computed.

Since motion in the atmosphere is essentially three-dimensional, we first present the distributions of the mean square of the three-dimensional particle distance for clusters of particles released at 45°N at the equator in Fig. 7. It is seen in this figure that for diffusion times >100 h the mean square particle distance is approximately proportional to $t^{3/2}$ to t^2 at 45°N and to $t^{5/2}$ to $t^{7/2}$ at the equator, the exponent also varying with altitude; these values generally agree with the mean square of the horizontal component of the particle distance computed with NMC data (Kao, 1974). Since the mean square of the vertical component of the particle distance is generally much smaller than that of the horizontal, it can be considered horizontal. Fig. 7 indicates that for diffusion times >100 h the distributions of the mean square of the three-dimensional particle distance may be approximately fitted by a power law.

To analyze the zonal, meridional and vertical components of the relative motion between particles, the distributions of the mean squares of the zonal, meridional and vertical components of the particle distance for particles released at the equator and 45°N are plotted in the top two diagrams in Figs. 8, 9 and 10, respectively. These figures indicate that the mean squares of the zonal, meridional and vertical components of the particle distance consist essentially of two components, one monotonically increasing with increasing time, and the other periodic in time. Since turbulent diffusion can only contribute to the monotonically increasing part of the mean square particle distance, the periodic part of the mean square particle distance represents the contribution of the horizontal

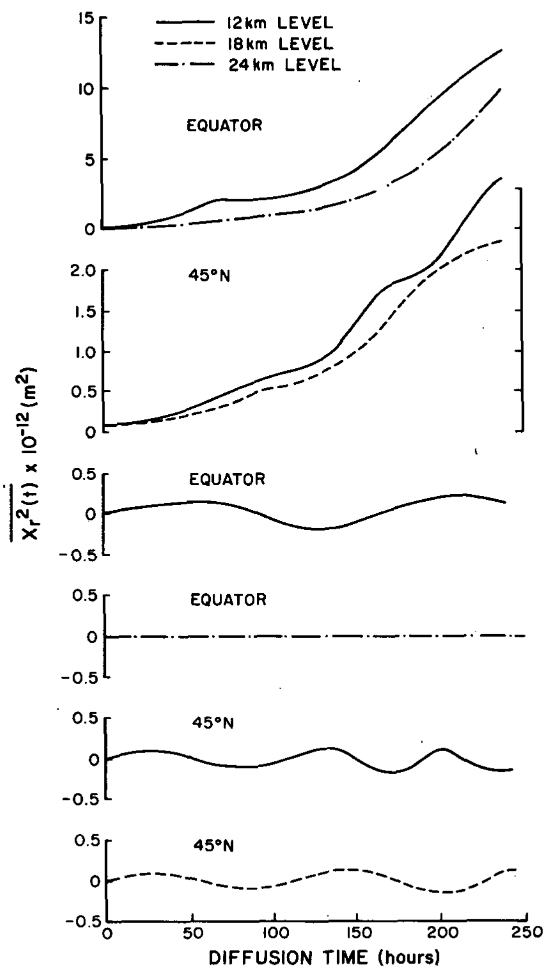

FIG. 8. The mean squares of the zonal component of the relative distance of particles (top two diagrams) and the values after subtracting those due to turbulent diffusion (lower four diagrams).

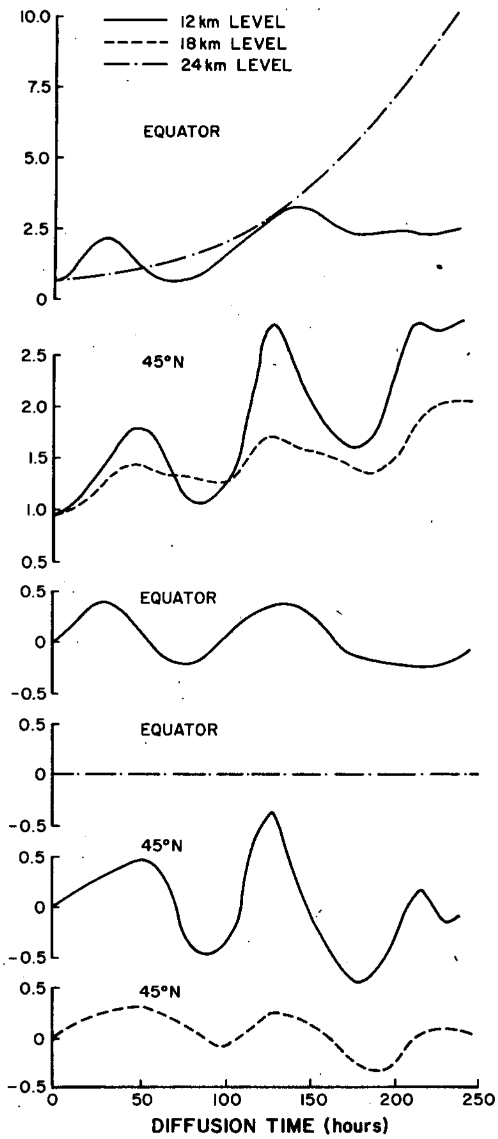

FIG. 9. As in Fig. 8 except for the meridional component.

velocity convergence and divergence of the mean motion, occurring at different parts of atmospheric waves.

To separate the monotonically increasing and the periodic parts of the mean square particle distance, we approximate the former by a power law. The results so estimated appear similar to the distributions of the mean square of the three-dimensional particle distance as shown in Fig. 8. The periodic part of the mean square particle distance is obtained by subtracting the monotonically increasing part from the mean square particle distance. The periodic part of the zonal, meridional and vertical components of the mean square particle distance so computed is plotted in the lower four diagrams of Figs. 8, 9 and 10, respectively. These diagrams indicate that the horizontal velocity convergence and divergence of the Lagrangian mean motion have a predominant period of 5–6 days, which seems to be associated with the large-scale wave motion in the atmosphere. These figures also indicate that the horizontal velocity convergence and divergence of the mean motion appear to be more regular in the tropics than in mid-latitudes.

It is interesting that the periodic part of the mean square particle distance also appears in the mean square particle distance of the zonal and meridional components computed from the particle trajectories determined with NMC (National Meteorological Center) data (Kao and Al-Gain, 1968), and from balloon trajectories of the EOLE experiments (Morel and Larcheveque, 1974); however, the magnitude appears smaller.

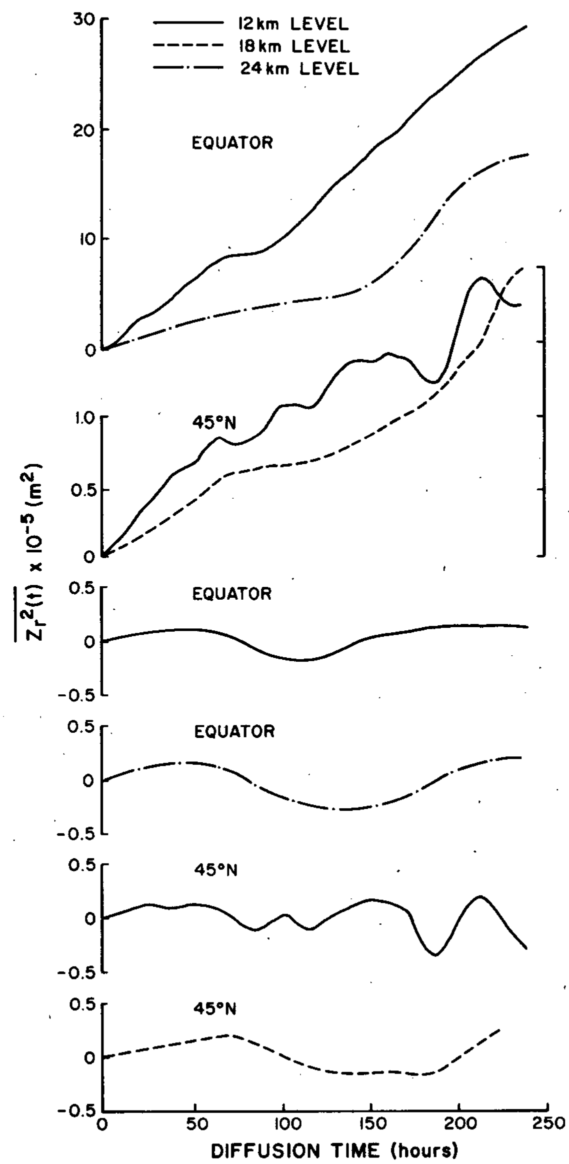

FIG. 10. As in Fig. 9 except for the vertical component.

To estimate the effect of turbulent diffusion on the mean square particle distance, the mean squares of the zonal, meridional and vertical components of the particle distance were plotted on log-log diagrams and approximated by

$$\overline{X_{ri}^2}(t)=A_i t^{a_i}+\sum_j B_{ij}\cos\left(\frac{2\pi}{T_{ij}}t\right),$$

where $i=x,y,z$.

For diffusion times >100 h, the values of a_i have been estimated in Table 2. The entries in the table indicate that, except at 24 km near the equator, $a_x>a_z>a_y$. Since the values of a_x, a_y, a_z are positive for diffusion times >100 h, the mean squares of the x, y and z components of particle distance are dominated by the monotonically increasing component of the mechanism.

TABLE 2. Values of a_i determined from the NCAR General Circulation Model.

	Equator		45°N	
	12 km	24 km	12 km	18 km
a_x	3.3	4.0	3.3	3.3
a_y	1.0	2.8	0.8	0.2
a_z	1.6	2.6	1.6	0.5

5. Summary

An analysis of the three-dimensional large-scale movement of air particles for the winter months with the NCAR general circulation model indicates that the horizontal movement of particles in the upper troposphere is greatly affected by wave motion in mid- and high latitudes, by the field of horizontal convergence and divergence, and by mean meridional circulation in the tropics. The mean center of mass of particles in both hemispheres generally moves toward respective poles, and the mean square of the meridional component of the particle distances generally decreases with increasing time, indicating the effect of horizontal convergence on the particle movement near the subtropics. The vertical movement of particles is affected by upward motion near the thermal equator and downward motion near the subtropical region in the Northern and Southern Hemispheres. The vertical dispersion is most intense near the thermal equator and decreases toward the poles. There are two maxima of particle accumulation, one near 15°N, the other near 30°S, and a minimum accumulation of particles appears near the thermal equator, indicating the effect of the divergence field and the meridional circulation between the thermal equator and the subtropics.

The mean squares of the zonal, meridional and vertical components of the distance for clusters of particles released at the equator and 45°N appear to consists of two components, a monotonically increasing component due essentially to the effect of turbulent diffusion, and a periodic component due primarily to horizontal velocity convergence and divergence of the mean motion.

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