Vertical Motions within the Indian Tropical Middle Atmosphere

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ABSTRACT

Computations of vertical motions in the middle atmosphere over the Indian tropical region have been made based on the thermodynamic equation with the geostrophic approximation. The authors have used the once weekly rocketsonde temperature and wind data for the tropical station Thumba India, (8°32′N, 76°52′E) for the four summers (1972, 1973, 1975 and 1976) and two winters (1971 and 1972) which are also years of varying monsoon activity.

In the tropical middle atmosphere, downward motion (subsidence) is the dominant feature when the motion field is considered in a longer time scale. The trend of fluctuations in vertical motion suggests wave structures in the tropical middle atmosphere. The magnitude of the extreme values of the vertical motion in the stratosphere over the high latitudes is larger, by a factor of 2 or more, than those obtained over the low latitudes (tropics). Whereas the magnitude of the vertical motion in high latitudes is associated with stratospheric warmings during winter, the values relating to low latitudes are computed at 3 h intervals during March.

1. Introduction

The couplings between the mesosphere and stratosphere and between the stratosphere and troposphere form an essential part of the synthesis of middle atmospheric processes. These couplings are often manifestations of the vertical motions in the different regions. For example, much of the variance of total ozone is due to vertical motion in the baroclinic waves of the polar night westerly vortex affecting layers from 150 to above 25 mb (London, 1963). Advection and vertical motion are generally closely linked and augment each other in producing ozone fluctuations (Kulkarni, 1963). A knowledge of the vertical motions is essential for the understanding of the meridional circulation and for evaluating vertical and horizontal transport processes; it is also useful for explaining local sudden warmings. An excellent review on vertical motions in association with stratospheric warmings over the high latitudes of the Northern Hemisphere has been given recently by McInturff (1978). Computations of vertical motion in the stratosphere of middle and high latitudes during winter have been well documented (see for example; Craig and Lateef, 1962; Finger and Teweles, 1964; Quiroz, 1969; Newson, 1974). The magnitude of vertical motions in high latitudes during summer is seldom reported. Considering the reduced temporal variability in stratospheric temperatures and winds during summer at high latitudes, it is expected that the magnitude of the vertical motion would be less in summer than in winter when the stratosphere undergoes dramatic changes.

Earlier studies (e.g., Craig and Lateef, 1962; Quiroz, 1969) involved computation of vertical motions in the winter stratosphere at high latitudes using the thermodynamic equation with the geostrophic assumption. Two of the present authors (Mukherjee and Ramana Murty, 1973), adopting the same procedure, have computed the vertical motion in the stratosphere and mesosphere over the tropical station Thumba, for the winter of 1970–71, using once weekly rocketsonde data. Recently, Weisman and Olivero (1979) have computed vertical motions in the tropical stratosphere and mesosphere using rocketsonde temperature and wind data, generated at 3 h intervals by the Tropical Diurnal Experiment of March 1974 within the Western Hemisphere Meteorological Rocket Network. They have used a generalized thermal wind expression which includes an ageostrophic contribution. By scale analysis they have shown this to be non-negligible for their computation (rocket soundings at 3 h intervals). The present authors have used the thermal wind derivation based on the geostrophic assumption. Using characteristic scale analysis, they found that the contribution by the ageostrophic part is negligible when computations of the vertical motion are based on once weekly observations. Nevertheless, the results obtained in the present study would be useful in the understanding of the physical processes in the tropical middle atmosphere, such as interactions among vertical motions, wave disturbances and monsoon activity.

2. Data and analysis

Weekly M-100 rocketsonde temperature and wind data for Thumba for the four summers (June–August) of 1972, 1973, 1975 and 1976 and two winters (December) of 1971 and 1972 have been used for com-

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putation of vertical motion. The rocketsonde data for 1974 were not available as there were no flights in that year. Observations for four summers and two winters have been taken here to be more illustrative than definitive. The temperature sensor used in the M-100 rocketsonde is a tungsten-rhenium wire 40 μm in diameter. The probable mean square error in determining the atmospheric temperature with this sensor is 3°C at 40 km, 5°C at 50 km and 7–10°C at 60–80 km (Mukherjee and Ramana Murty, 1972; Mukherjee *et al.*, 1979). The sources of wind error in the M-100 rocket soundings are due to 1) the radar tracking error, 2) fall velocity and 3) acceleration of the parachute. The radar tracking error also takes into account the wind speed error which depends on the speed itself. The parachute is tracked by Meteor/Meteorite radar and the accuracy of the range tracking is 60 m that of the angular tracking (azimuth and elevation) is 7.2 min. The root-mean-square (rms) error in wind speed and direction at various altitude levels are given in Table 1. The raw data are smoothed in order to reduce the effect of random errors existing in the radar data and telemetry measurements received for processing.

In the international comparison of rocketsondes at Wallop Island (37°51′N, 75°29′W) in March 1972 and at the French Guiana Space Center (5°12′N, 52°25′W) in September 1973, it was found that the temperature measured with M-100 rockets differed from the USA/UK rocketsonde temperature by 8–18°C at 55 km and above. Comparisons among wind observations indicated increasingly large incompatibility in zonal winds above 40 km obtained by M-100 rockets as compared to those obtained by USA, UK and France (Finger *et al.*, 1975). This discrepancy will not vitiate the present computations, as they all relate to measurements by M-100 rockets from a single station only. But this fact, however, does not preclude the possibility of errors in the computation of vertical motion which may arise out of the errors in measurements of wind speed and direction. The rms errors in wind speed and direction of two arbitrarily chosen altitudes, one in the middle stratosphere and the other in the upper stratosphere, all-owing for worst conditions, are considered; their effect on the advection term and therefore on the vertical motion is then computed and examined.

3. Computational procedure

The vertical motions have been computed at 1 km intervals in the height range of 20–55 km for 1971 (winter), 1972 (both summer and winter) and 1973 (summer) and in the height range of 20–60 km for the summers 1975 and 1976. The thermodynamic equation, derived from the first law of thermodynamics and the hydrostatic approximation (Panofsky, 1946; Haltiner and Martin, 1957), has been adopted as

$$\frac{\partial T}{\partial t} = \frac{1}{c_p}\frac{\partial H}{dt} - w(\Gamma - \gamma) - \mathbf{V}\cdot\nabla_H T, \qquad (1)$$

where

$\dfrac{\partial T}{\partial t}$	local change of temperature
$\dfrac{1}{c_p}\dfrac{\partial H}{dt}$	diabatic heating or cooling
w	vertical motion (positive upward)
Γ	dry adiabatic lapse rate ($g\vert c_p$)
γ	environmental lapse rate ($-\partial T/\partial z$)
$\mathbf{V}$	wind velocity vector
$\mathbf{V}\cdot\nabla_H T$	horizontal thermal advection.

TABLE 1. Root-mean-square error in wind speed and direction for M-100 rocket data published in *World Data Centre B Bulletins.*

Altitude region (km)	Wind speed (m s^{-1})	Wind direction (deg)
Below 40	5	10
40–50	11	22
60–80	10	15

In the stratosphere ($\Gamma - \gamma$) is always positive. The diabatic terms used for the region above 30 km (up to which wind data are available) are based on Fig. 10 of Kuhn and London (1969) who have considered the radiative cooling caused by 15 μ CO_2, 9.6 μ O_3 and 80 μ H_2O bands. In the work of Kuhn and London, the values of the diabatic term are available for altitudes above 30 km only. Therefore, for diabatic terms below 30 km, the authors have approximated the cooling rates caused by 15 μ CO_2 which is based on Fig. 2a of Murgatroyd and Goody (1958) and fixed the value of −1°C per day during both summer and winter. The authors' computation has shown that any error resulting from such an approximation will not greatly affect the overall results.

The diabatic term is negligible for high latitudes in comparison with the local change of temperature. Several studies (Craig and Lateef, 1962; Hirota and Sato, 1969; Quiroz, 1969) have emphasized the difficulty of accurate evaluation of the advection term. In the absence of horizontal grid-point data in the middle atmosphere, the customary method of overcoming this difficulty is to use the geostrophic thermal wind relation to express the horizontal advection of temperature in terms of the vertical shear of the geostrophic wind. For the computation of the advection term utilizing data for a single station one must assume the geostrophic approximation, although this assumption may not strictly hold over tropical regions. Under the geostrophic assumption, a transformation, which is realized through the thermal wind equation (Kays and Craig, 1965), has been used for the computation of the horizontal thermal advection. Using the thermal wind equation one can obtain the following expression for the advection term

$$\mathbf{V}\cdot\nabla_H T = -\frac{fT}{g}V^2\frac{\partial\theta}{\partial z}, \qquad (2)$$

where

f Coriolis parameter
T mean temperature
g gravity field strength
V magnitude of mean velocity
$\frac{\partial\theta}{\partial z}$ change of wind direction in two consecutive layers of 1 km height difference.

It has been reported that use of the "Omega equation" has yielded results which are similar to those given by the simpler equation used here (McInturff, 1978). Eq. (2) involves the geostrophic approximation and is approximate because constant height rather than constant pressure data are used. Only a small percental error in the computed vertical motion would arise from the use of constant height data, in view of the thermal wind computations at constant height rather than constant pressure (Quiroz, 1969).

For the computation of the advection term following Eq. (2), the mean velocity vector and the mean temperature for two consecutive layers are first worked out and then substituted into the formula to get the result. The value of the Coriolis parameter at 8°N has been taken into account. If we rearrange the thermodynamic equation given in (1), the vertical motion w is written as

$$w = \frac{1}{(\Gamma - \gamma)}\left[-\frac{\partial T}{\partial t} - \mathbf{V}\cdot\nabla_H T + \frac{1}{c_p}\frac{\partial H}{dt}\right], \quad (3)$$

where the advection term is given by Eq. (2). The computations of the vertical motion indicate that the diabatic term in Eq. (3) is small compared to the other two terms. If, in addition, the advection term is neglected, the local warmings imply downward motion and coolings imply upward motion. The accuracy in the computation of the vertical motion has been restricted since there are no launchings at intervals closer than a week.

The results of computation have shown that the magnitude of the advection term, compared to the other two terms, cannot be neglected at lower latitudes. The sign of the advection term is sensitive to the change of wind direction from one layer to the other and it is desirable to take into account the correct direction of the wind. Hence, our computations would give only a fair estimate of the field of vertical motion in the stratosphere and mesosphere. In the case of steady flow, that is, when the wind is not changing in direction with height, the contribution by the advection term would be nil. Such a situation would result in near zero vertical motion, as the contributions of the other two terms in (3) are small.

Using Eq. (3), the vertical motions have been computed for the height range of 20–60 km at 1 km intervals. The computed vertical motions have been subjected to three-point (2 km) smoothing in the vertical, using a 1–2–1 filter, to remove the irregular fluctuations in the motion field.

Tables 2A, B and C give the smoothed values of the vertical motions for the summers of 1972 and 1973, 1975 and 1976 and for the winters of 1971 and 1972. The standard deviations (SD) of the vertical motions obtained at each level from 20 to 60 km are also worked out for each year. For brevity, only the values at intervals of 5 km of both vertical motions and standard deviations are shown in the tables.

4. Results

a. *Estimation of error in vertical motion*

Estimation of the vertical motion by use of the thermal wind relationship for approximating the advection term in the thermodynamic equation is highly sensitive to error in vertical wind shear. Hence, it is necessary to examine the error in the advection term as a function of height, allowing for worst conditions, and to estimate its effect on the vertical motion. To examine this feature, we have chosen the case of 23 July 1975 as an illustration. Also, we have chosen the vertical motions for two specific heights, 36.5 and 46.5 km, to demonstrate the variability in the advection term and hence on the vertical motion at those levels due to error in the wind speed and direction.

The value of vertical motion at 36.5 km, i.e., 0.42 cm $\mathrm{s^{-1}}$, has varied from 0.61 to 0.25 cm $\mathrm{s^{-1}}$ for the extreme values of errors considered. The percentage variation suggested by the vertical motion has, therefore, ranged from +46 to −41 cm $\mathrm{s^{-1}}$ at this level (middle stratosphere). At 46.5 km (upper stratosphere) it has ranged from +65 to −53 cm $\mathrm{s^{-1}}$. Another example of the error analysis for the sounding for 29 November 1972 (Table 2C) containing $w = -6.7$ cm $\mathrm{s^{-1}}$ at 46.5 km has been included in the paper and in Table 3, as a further illustration. In this case, the percentage variation in vertical motion at 46.5 km ranged from −43 to +22 cm $\mathrm{s^{-1}}$.

The values for error-free vertical motion given for 23 July 1975 at 36.5 km (+0.42) and 46.5 km (+1.12) and for 29 November 1972 at 46.5 km (−6.98) in Table 3, will not agree with the values in Table 2B (−0.3 at 36.5 km and +0.9 at 46.5 km) and Table 2C (−6.7 at 46.5 km) since the error analyses are applied to the vertical motion before 1–2–1 smoothing is performed. The values given in Table 3 are unsmoothed values, while Tables 2A, 2B and 2C give only smoothed values of vertical motion.

b. *Vertical motions during summer*

Tables 2A and 2B show the vertical motions at 5 km intervals with their standard deviations for four summers—1972, 1973, 1975 and 1976. As temperature data are not available for 7 and 21 June, 19 July (from 41 km) and 24 August for the year 1972 and for 9 July and 13 August for the year 1975, they are obtained by simple linear interpolation. The values of vertical motions vary from −21.9 cm $\mathrm{s^{-1}}$ (at 48.5 km on 7

TABLE 2A. Values of vertical motion (cm s^{-1}) during summer monsoon (June–August) for 1972 and 1973.

	Height (km)							
Date	21.5	26.5	31.5	36.5	41.5	46.5	51.5	56.5
1972								
7 Jun	+0.0	−0.1	−0.3	−0.3	−0.6	−3.6	−15.0	—
14	−0.1	−0.2	−0.3	−0.3	−1.0	+1.4	−2.0	—
21	−0.1	−0.1	−0.3	−0.2	+0.7	+3.6	−5.3	—
28	+0.0	−0.5	−0.3	−0.5	−2.3	−0.2	+0.2	—
5 Jul	−0.1	−0.0	−0.2	−0.0	+0.7	+10.8	−3.6	—
12	−0.0	−0.3	−0.4	+0.2	+0.5	−2.1	+0.8	—
19	−0.1	+0.0	−0.2	−0.2	−0.6	+0.2	−0.1	—
2 Aug	−0.0	−0.1	−0.3	+0.5	−0.8	+3.8	−2.9	—
9	−0.1	+1.0	−0.7	+0.0	−1.0	+0.3	−2.0	—
16	−0.1	−0.5	+0.1	−0.5	−0.2	−0.8	−0.4	—
24	−0.1	−0.4	−0.3	−0.2	−0.4	−1.4	−1.4	—
30	−0.1	−0.8	−0.8	−0.1	−0.4	−0.8	−5.5	—
8 Sep	−0.2	+0.9	−1.2	−0.7	+1.0	−1.4	−0.9	—
SD (cm s^{-1})	0.06	0.51	0.33	0.31	0.90	3.67	3.06	—
1973								
6 Jun	−0.1	+0.3	−0.1	−0.4	−0.2	+0.0	+1.1	+2.2
14	−0.1	−0.3	+1.3	−1.6	−0.3	−0.3	−2.5	—
20	−0.1	+0.2	−3.8	−0.5	−1.9	−1.0	−3.7	—
27	−0.2	−1.2	+1.0	−3.5	−6.4	−0.1	−1.6	—
4 Jul	+0.1	−0.6	−1.1	−0.0	−5.3	+10.1	−1.2	—
11	+0.1	+0.2	+0.5	−1.1	+0.6	+0.0	+2.2	—
18	−0.2	−0.8	+0.9	+0.5	−0.3	−2.7	−3.1	—
25	−0.2	+0.6	−0.5	+0.9	−2.0	+0.1	−0.5	—
1 Aug	−0.1	−1.5	+0.9	−1.7	+0.6	−1.0	−2.0	—
8	−0.0	+0.6	−1.4	−0.7	−0.3	+6.1	−6.2	—
16	−0.2	−0.1	−0.9	−0.2	−3.4	−3.8	−3.7	—
22	+0.1	−0.3	+0.2	+1.4	+2.6	−0.5	+4.1	—
29	−0.1	−0.2	−1.2	+2.2	+0.6	+1.7	−2.3	—
5 Sep	−0.1	−0.9	—	—	—	−2.7	−2.8	—
SD (cm s^{-1})	0.11	0.65	1.40	1.47	2.54	3.63	2.64	—

June) to +10.8 cm s^{-1} (at 46.5 km on 5 July) in 1972, from −10.2 cm s^{-1} (at 54.5 km on 14 June) to +13.6 cm s^{-1} (at 44.5 km on 4 July) in 1973, from −2.3 cm s^{-1} (at 52.5 km on 2 July) to +0.9 cm s^{-1} (at 46.5 km on 23 July) in 1975, and from −4.7 cm s^{-1} (at 59.5 km on 4 August) to +2.1 cm s^{-1} (at 30.5 km on 11 August) in 1976. Only two values, 10.8 cm s^{-1} at 46.5 km on 5 July 1972 and 0.9 cm s^{-1} at 46.5 km on 23 July 1975, are noticeable in the tables (Tables 2A and 2B), as the values given therein refer to 5 km intervals only.

The magnitude of the upward and the downward motions are large in 1972 and 1973 compared to those in 1975 and 1976. In 1975 and 1976, downward motions are prevalent in the stratosphere and the lower mesosphere, but this is not so in 1972 and 1973. Both upward and downward motions are noticed in these two years. Also, the extreme values of the vertical motion are one order of magnitude higher in 1972 and 1973 than in 1975 and 1976. The values of the variances (square of SD) in the motion field are more in 1972 and 1973 than in 1975 and 1976. The values of the vertical motion in all the years considered are about one order of magnitude higher in the upper stratosphere and the lower mesosphere than in the lower and middle stratosphere.

c. *Vertical motion during winter*

Table 2C gives the vertical motions at 5 km intervals with their standard deviations for two winters, 1971 and 1972. The values vary from −3.1 cm s^{-1} (at 41.5 km on 8 December) to +2.5 cm s^{-1} (at 47.5 km on 1 December) in 1971 and from −7.1 cm s^{-1} (at 47.5 km on 29 November) to +1.3 cm s^{-1} (at 44.5 km on 6 December) in 1972. Only the value −3.1 cm s^{-1} at 41.5 km on 8 December in 1971 is significant in the table.

It is seen from Table 2C that the downward motion is dominant in 1972; but it is not so in 1971. The downward motion is intense in 1972 and upward motion is intense in 1971. The values of the vertical motions and the variances are larger in the upper stratosphere and the lower mesosphere than in the lower and the middle stratosphere, as observed during summer.

TABLE 2B. Values of vertical motion (cm s^{-1}) during summer monsoon (June–August) for 1975 and 1976.

	Height (km)							
Date	21.5	26.5	31.5	36.5	41.5	46.5	51.5	56.5
1975								
4 Jun	−0.0	+0.0	−0.0	−0.1	−0.2	−0.9	−1.3	−1.2
11	+0.0	−0.2	−0.2	+0.1	−0.4	+0.2	−0.5	−1.1
18	−0.2	−0.1	−0.1	−0.3	−0.9	−0.1	−0.7	−0.7
25	−0.1	−0.1	+0.0	−0.4	−0.3	−1.0	−0.3	−0.7
2 Jul	−0.0	−0.0	−0.6	+0.6	−0.6	−0.0	−2.2	−1.8
9	−0.1	−0.1	−0.4	−0.1	−0.5	−0.9	−1.0	−1.0
16	−0.1	−0.4	−0.1	−1.0	−0.6	−0.8	−1.6	−1.7
23	−0.1	−0.1	−0.1	−0.3	−2.2	+0.9	−0.9	−0.9
30	+0.0	−0.1	+0.1	−0.4	−0.4	−2.8	−1.4	−1.1
6 Aug	−0.1	−0.0	−0.1	−0.6	−0.5	−0.7	−1.1	−0.9
13	−0.1	−0.2	−0.0	−0.4	−0.3	−0.5	−1.4	−1.3
20	−0.1	−0.1	−0.2	+0.2	−0.3	−1.6	−0.7	−1.5
27	−0.1	−0.1	−0.5	−0.5	−0.8	+0.5	−0.2	−0.2
3 Sep	−0.0	+0.1	−0.2	+0.1	−1.0	−0.4	−1.0	−0.7
SD (cm s^{-1})	0.06	0.12	0.20	0.33	0.51	0.92	0.54	0.43
1976								
2 Jun	−0.1	−0.2	−0.1	+0.1	−0.4	+1.0	−1.1	−0.6
9	−0.1	−0.1	+0.2	−1.6	−0.0	+0.2	−0.7	−0.8
16	−0.0	−0.2	+0.0	−0.2	−0.8	−0.7	−0.9	−0.8
23	−0.1	−1.0	+0.2	−0.6	−0.3	−0.8	−1.0	−1.0
30	−0.1	−0.2	−0.1	+0.1	−0.5	−0.7	−0.8	−1.3
7 Jul	−0.1	+0.5	−0.4	−0.3	−0.3	−0.9	−0.9	−0.7
14	−0.1	+0.0	−0.4	−0.2	−0.7	−0.2	−1.6	−1.1
21	−0.1	+0.1	+0.5	−0.3	−1.5	−1.5	−0.9	−1.1
28	−0.0	−0.3	−0.9	−0.1	−0.5	−0.5	−1.2	−0.2
4 Aug	−0.1	+0.0	+0.0	+0.4	−0.4	−0.8	−1.5	−1.4
11	−0.1	+0.2	+0.5	−1.2	−0.5	−0.9	−0.6	−0.9
18	−0.1	−0.0	+0.4	−0.4	−0.6	−0.7	−0.8	−1.3
25	−0.0	+0.1	−0.6	−0.6	−0.2	−0.9	−0.8	−0.9
1 Sep	+0.0	−0.3	−0.5	−0.1	−0.2	−0.4	−0.1	−1.0
SD (cm s^{-1})	0.05	0.34	0.43	0.52	0.36	0.59	0.37	0.32

TABLE 2C. Values of vertical motion (cm s^{-1}) during winter (December) for 1971 and 1972.

	Height (km)							
Date	21.5	26.5	31.5	36.5	41.5	46.5	51.5	56.5
1971								
1 Dec	−0.0	+0.0	+0.1	−0.2	−0.3	+2.2	+0.1	—
8	−0.1	−0.1	−0.5	+0.5	−3.1	−1.0	−0.1	—
15	−0.1	−0.1	+0.0	−0.1	−0.5	−1.9	−1.0	—
22	−0.1	−0.3	−0.2	−0.3	−0.5	+0.2	+0.6	—
29	−0.1	−0.2	−0.4	−0.3	−0.4	−1.5	−1.4	—
SD (cm s^{-1})	0.04	0.11	0.25	0.33	1.20	1.65	0.82	—
1972								
29 Nov	−0.3	+0.0	−0.1	−0.5	−0.8	−6.7	−2.4	—
6 Dec	−0.2	−0.1	−0.1	−0.2	−0.2	−0.5	−3.5	—
13	+0.0	+0.1	−0.2	−0.2	−0.9	−0.4	−0.7	—
20	−0.2	−0.1	−0.2	+0.3	−0.5	−0.7	−0.8	—
27	−0.2	−0.0	−0.2	−0.3	−0.5	−0.4	−0.9	—
SD (cm s^{-1})	0.11	0.08	0.05	0.29	0.28	2.78	1.24	—

TABLE 3. Error estimation for advection term and vertical motion.

		Error in wind			
Date	Height (km)	Speed (m s^{-1})	Direction (deg)	Advection term [$\times 10^4$ (°C s^{-1})]	Vertical motion (cm s^{-1})
23 Jul 1975	36.5	—	—	−0.93	+0.42
		+5	+10	−1.16	+0.61
		−5	−10	−0.73	+0.25
	46.5	—	—	−1.91	+1.12
		+11	+22	−2.79	+1.86
		−11	−22	−1.19	+0.53
29 Nov 1972	46.5	—	—	+4.83	−6.98
		+11	+22	+8.42	−9.97
		−11	−22	+3.01	−5.46

d. Vertical motions in high and low latitudes

Table 4 gives a comparative study of the order of magnitudes of the extreme values of the vertical motion in the middle atmosphere for high- and low-latitude stations. Since the high-latitude values are given for 25 mb (~25 km), 10 mb (~30 km) and 2 mb (~40 km), the low-latitude value for these three levels only are considered.

The values of the vertical motion over the high latitudes are larger, by a factor of 2 or more, than those over the low latitudes.

The mean values of the vertical motion at 30 km obtained in the present study from the weekly rocketsonde data for Thumba during June–August (−0.28 cm s^{-1} in 1972 and −0.07 cm s^{-1} in 1975) compare fairly well with the diurnal mean values obtained by Weisman and Olivero (1979) (−0.00 cm s^{-1} to +0.70 cm s^{-1}) insofar as the order of magnitude is concerned.

5. Discussion

The results of the computation of the vertical motions using once weekly rocketsonde data for four summers (1972, 1973, 1975 and 1976) and two winters (1971 and 1972) have shown that the downward motions (subsidences) are dominant features in the middle

TABLE 4. Magnitude of extreme values of vertical motion in the high-latitude and low-latitude (tropical) middle atmosphere.

Magnitude and height of vertical motion	Geographic area	Time resolution of observational data	Reference
	A. *High latitudes*		
1. 8 cm s^{-1} (25 mb ~ 25 km)	United States, Canada and adjacent North Atlantic region	Based on twice daily observations	Craig and Lateef (1962)
*2. A few mm s^{-1} to a few cm s^{-1}	Northern America	Four-hour intervals	Kays and Craig (1965)
3. 8 cm s^{-1} (10 mb ~ 30 km)	Northern America	Daily 10 mb synoptic charts	Finger and Teweles (1964)
4. 60 cm s^{-1} (40 km)	Heiss Island (81°N) (Single station analysis)	2–6 days	Quiroz (1969)
5. 9.4 cm s^{-1} (2 mb ~ 40 km)	Northern America	Weekly synoptic analysis	Miller (1970)
	B. *Low latitudes*		
1. No data (25 km) 3.1 cm s^{-1} (30 km) 4.4 cm s^{-1} (40 km)	Kourou (5.1°N)	Observations taken at 3 h intervals	Weisman and Olivero (1979)
2. No data (25 km) 0.9 cm s^{-1} (30 km) 1.8 cm s^{-1} (40 km)	Fort Sherman (9.3°N)		
3. 3.0 cm s^{-1} (25 km) 2.1 cm s^{-1} (30 km) 5.9 cm s^{-1} (40 km)	Ascension Island (8.0°S)		
4. No data (25 km) 1.5 cm s^{-1} (30 km) 2.7 cm s^{-1} (40 km)	Antigua (17.2°N)		
5. No data (25 km) 2.0 cm s^{-1} (30 km) 2.7 cm s^{-1} (40 km)	Natal (5.9°S)		

* Values of vertical motion mentioned are averages only and not extreme values.

atmosphere over the Indian tropical region. Only during the summers of 1972 and 1973 have both upward and downward motions persisted. The fluctuations noticed in the vertical motions during these two years, in the region of the upper stratosphere and the lower mesosphere, are due to the effect of the strong meridional component observed in the wind field in those years, at that level. The values of the variances, particularly in the upper stratosphere and mesosphere, are larger during the summers of 1972 and 1973 than during the other summer and winter years.

The study has shown that the vertical motion in stratospheric–mesospheric region is larger over the high latitudes than over the tropics (Table 4). The values over the high latitudes are based on the synoptic-scale analysis [except for the one computed by Quiroz (1969)] and they were associated with stratospheric warmings during winter. On the other hand, the computations of Weisman and Olivero (1979) are based on the analysis of single stations, located in the Western Hemisphere tropics, at 3 h intervals for the month of March. Higher values of vertical motion reported over high latitudes are due to stronger perturbations in the temperature field and greater values of the Coriolis parameter.

The values of vertical motions computed in the present study for Thumba are lower than those reported by Weisman and Olivero (1979) for the tropical stations of the Western Hemisphere. This disagreement could be attributed to the effects of differences in the time interval between two consecutive launchings at Thumba (7 days) and the tropical stations in the Western Hemisphere (3 h). The contributions of local change of temperature, diabatic terms due to low-latitude tidal effects and the nonnegligible contribution of the ageostrophic term are the factors which are considered responsible for the disagreement.

The amplitudes of the vertical motions increase with height. They are one order of magnitude larger in the upper stratosphere and the lower mesosphere than in the lower and the middle stratosphere. As a result of their computations using a 3 h time scale, Weisman and Olivero (1979) infer vertical propagation of internal gravity waves in the stratosphere and mesosphere over low latitudes.

6. Conclusions

The study of the vertical motion during the four summers of 1972, 1973, 1975 and 1976 and the two winters of 1971 and 1972 using the once weekly rocketsonde temperature and wind data for a single station, Thumba, has shown the following features:

- Downward motion (subsidence) is prevalent in the tropical middle atmosphere.
- The values of variance of the vertical motion are larger in the upper stratosphere and the lower mesosphere in 1972 and 1973.
- The magnitude of the extreme values of the vertical motion in the stratosphere over high latitudes (obtained during periods associated with conditions of stratospheric warming) is larger, by a factor of 2 or more, than those over the low latitudes (obtained at 3 h intervals). This is attributed to large temperature changes and large contributions from the advection term at high latitudes during the period of warming.

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