Monthly Mean Values of the Mesospheric Wind Field over Poker Flat, Alaska

B. B. BALSLEY AND A. C. RIDDLE[1]
Aeronomy Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80303

(Manuscript received 17 June 1983, in final form 14 May 1984)

ABSTRACT

Monthly-averaged horizontal and vertical mesospheric wind fields have been measured using the Poker Flat Radar at 65°N latitude during 15 months in 1980–81. The horizontal wind fields are reasonably consistent with previous observations and with some of the current theoretical models that take into account enhanced turbulence and eddy transport observed at mesospheric heights. However, the observed vertical wind field has a quasi-sinusoidal seasonal variation with peak values of 25 cm s^{-1} both downward near summer solstice and upward near winter solstice and is inconsistent with current models of mean circulation in the meridional plane. Because there are no other comparable vertical wind observations, the possibility of error in the vertical wind measurements was carefully considered and rejected. We conclude that the actual mean circulation is more complex than that implied by current models. Possible complicating factors include nonuniform zonal flow, multicellular meridional structure and an enhanced vertical Stokes drift that would arise from strong eddy activity.

1. Introduction

Various experimental techniques used over the past few years to monitor the horizontal wind in the mesosphere have yielded a reasonably consistent, albeit complex picture of the worldwide mesospheric circulation. Ground based radar techniques have contributed an appreciable portion of these data. For details of separate radar techniques, the reader is referred to Vincent *et al.* (1977) for the partial reflection drift technique, Roper and Salah (1978) and associated papers for the meteor radar method, and Balsley and Gage (1980) for the MST Radar technique.

The purpose of this paper is to present monthly-averaged values of the mesospheric wind field for the fifteen month period May 1980–July 1981 obtained by the Poker Flat MST Radar (65°N) (Balsley *et al.*, 1980). In addition to both zonal and meridional results, we present measurements of the vertical wind values during the same period. This latter data set is unique, since no other technique has the requisite accuracy to measure the relatively small ($\sim$ cm s^{-1}) values of the mean vertical wind in the presence of a much larger ($\sim$ tens of m s^{-1}) horizontal wind.

2. Discussion of the data base

Data for the present study were obtained directly from the data set that has been gathered almost continuously since March 1979. The data consist of Doppler spectra of the radar returns obtained every few minutes from each $\sim$2 km height range in the lower ($\leqslant$30 km) and upper ($\geqslant$50 km) atmosphere (see Carter *et al.*, 1980 for details on the data base). Note that a spectrum is obtained at each height range whether or not an actual echo is present; echo/no-echo analysis is determined later.

The wind field is derived from the Doppler shift of echoes returned simultaneously on two oblique orthogonal antenna beams directed 15° away from vertical, and a third vertically-directed beam (cf. Carter and Balsley, 1982). As discussed below, the monthly mean wind is obtained directly from the monthly mean values of these high time resolution data.

MST radar echoes in the mesosphere arise from two separate processes (Balsley and Gage, 1980). The first involves the action of small-scale atmospheric turbulence operating on an existing vertical gradient of electron density. Turbulence is thought to arise from the breakdown of upward propagating gravity waves and tides. These "turbulence" echoes occur primarily during daytime, since the requisite electron density is strongly reduced at night. The second echoing process makes use of short-lived ionization trails deposited by meteoric particles. Meteor echoes typically occur in the height range 92 ± 12 km and are present throughout the day and night (Avery *et al.*, 1983).

Characteristics of, and a possible causal mechanism for, the mesospheric turbulence echoes at Poker Flat have been discussed by Ecklund and Balsley (1981) and Balsley *et al.* (1983). Basically, the echoes have a pronounced seasonal character: Summer echoes (i.e., those echoes that occur between May and August) are strong, relatively continuous, and exhibit a narrow vertical profile centered at 86 ± 2 km; winter echoes (echoes between September and April) are considerably weaker, sporadic, and are smoothly distributed between 55 and 80 km.

[1] Present affiliation: CIRES, University of Colorado, Boulder, CO 80309.

For the present study we use both meteor echoes and turbulence echoes in order to obtain the most complete picture of the annual variability of the monthly-averaged wind field over a reasonably extensive height range. Results below about 75 km have not been included in our analysis. This is due primarily to the fact that echoes below this height are predominantly non-meteoric, wintertime echoes that have a pronounced diurnal occurrence character. Because of this, long-term averages of the wind at these altitudes would be heavily biased by the strong mesospheric tides present in the wind field (Carter and Balsley, 1982). Above 75 km, however, the diurnal continuity of the data is much better, since the summer echoes are relatively continuous and since meteor echoes are not sunlight dependent (although they do have a diurnal dependence). In order to further reduce the effects of diurnal tides and other short term periodic variations on the non uniform echo occurrence, the data used in this study were first averaged over one-hour periods. These one-hour averages were then averaged into monthly mean values.

3. On the accuracy of the MST technique for measuring the wind field

It is well established that the MST radar technique gives a very accurate representation of the tropospheric and stratospheric wind field (cf. Balsley and Gage, 1980 and references cited therein). There appears to be little doubt that the same accuracy can be ascribed to the mesospheric results, although concurrent *in-situ* comparisons with other techniques (e.g., smoke trails, radar-tracked falling spheres, or satellite wind determinations) have yet to be reported. Above about 90 km, however, there is a possibility that radar-deduced wind measurements could, under some conditions, be in error. This is because the presence of relatively large magnetospheric electric fields that extend down to these heights, combined with the fact that the electron "gas" becomes increasingly decoupled from the neutral atmosphere with increasing height, indicates that under strong electric field conditions the observed drifts could contain components of both the neutral flow and the ionized motion. The effect of electric fields on the radar wind observations has been examined theoretically by Reid (1983), who finds that such effects can indeed be important under relatively "disturbed" conditions at high latitudes. Studies of the modulation of the mesospheric and lower-ionospheric drifts during disturbed conditions have been reported by Balsley *et al.* (1982) and by Luhmann *et al.* (1983). Inasmuch as we are concerned with monthly averaged values of atmospheric motions, however, such effects should be strongly reduced for at least two reasons: 1) any effects due to diurnal or semidiurnal electric field variations will be smoothed out in monthly averages of the relatively continuous hourly-averaged values, and 2) the occasional larger aperiodic effects (time scales ~ hours) arising from enhanced magnetospheric activity will be greatly diminished when averaged together with the remaining non-active periods for a given month.

4. A short comparison between winds derived from meteor and turbulence echoes

Earlier studies of the wind field above 50 km at Poker Flat used either meteor echoes (Avery *et al.*, 1983) or a combination of mainly meteor echoes and a few turbulence echoes (Nastrom *et al.*, 1982; Carter and Balsley, 1982). A brief comparison between the two techniques made by Avery *et al.* (1983) shows that under most conditions both yield the same results. One exception to this statement occurs during periods of strong turbulence echoes, when our existing algorithms preclude the selection of meteor echoes. Since strong winds appear to correlate with strong turbulence (Nastrom *et al.*, 1981; Smith *et al.*, 1983),

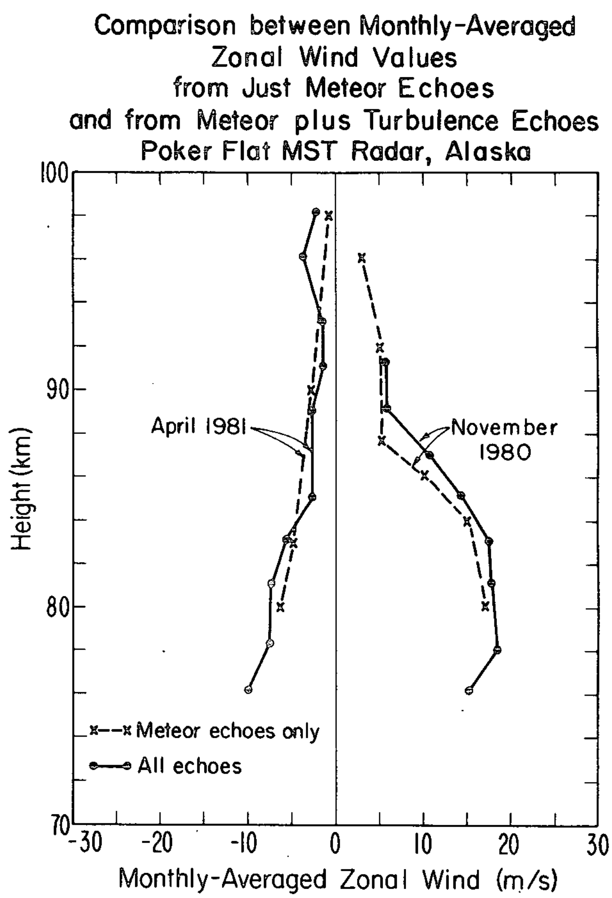

FIG. 1. Monthly-averaged zonal wind profiles for November 1980 and April 1981 obtained by averaging one-hour averaged values (see text) using turbulence and meteor echoes (solid curves), and using only meteor echoes (dashed curves). Meteor data from S. K. Avery (private communication, 1983).

the meteor-only echo analysis during periods of intense turbulence is therefore biased toward lower wind values. Indeed, preliminary analysis shows a minimum in turbulence echo strength of the mesospheric echoes during minimum wind periods. The present study cannot be affected by this feature, however, since no attempt is made to distinguish between meteor and turbulence echoes, and since both are combined into a single data set.

Additional evidence showing the close correspondence between meteor echo- and turbulence echo-derived winds is presented in Figs. 1 and 2. In Fig. 1, monthly average profiles of the zonal wind for November 1980 and April 1981 obtained using hourly means of both meteor and turbulence echoes are compared with profiles obtained for the same period using only meteor echoes (meteor echo winds have been obtained from S. Avery, private communication, 1983). In Fig. 2, a profile derived from an harmonic analysis of both meteor and turbulence echoes (Nastrom *et al.,* 1982) is compared with our current analysis technique for the same period. The close correspondence of these sets of curves in Figs. 1 and 2 attests to the validity of our subsequent results.

5. Data presentation

a. Horizontal winds

Monthly mean values of the *zonal* wind field between 76 and 109 km are plotted in Fig. 3. Each curve represents the average value of the wind at

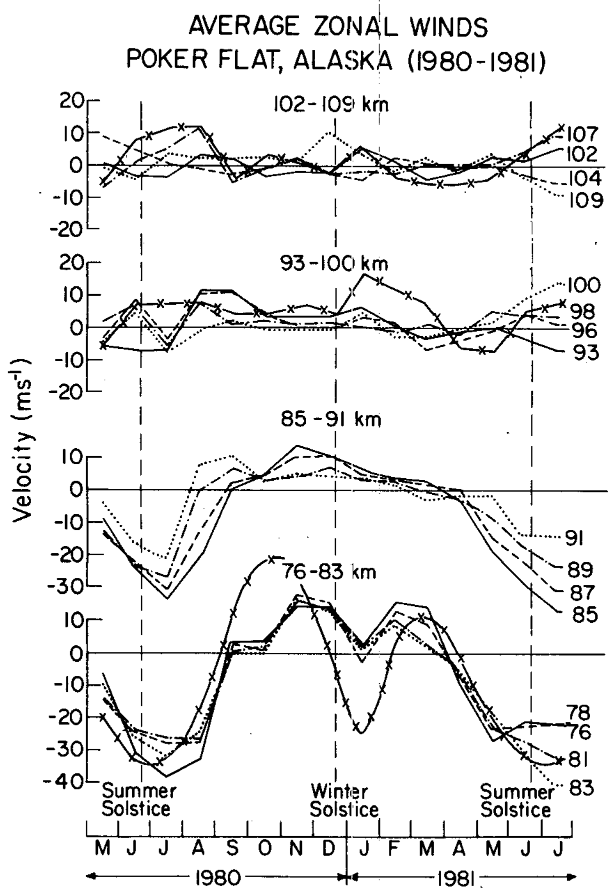

FIG. 3. Monthly-averaged zonal winds between 76 and 109 km obtained by averaging one-hour averaged wind values using both meteor and turbulence echoes. Additional curves (crosses) are shown for reference from Belmont *et al.* (1975) for 65 km, 70°N in the bottom panel, and from Gregory *et al.* (1981) for the same approximate height ranges at 52°N for 1978–79 in the top two panels.

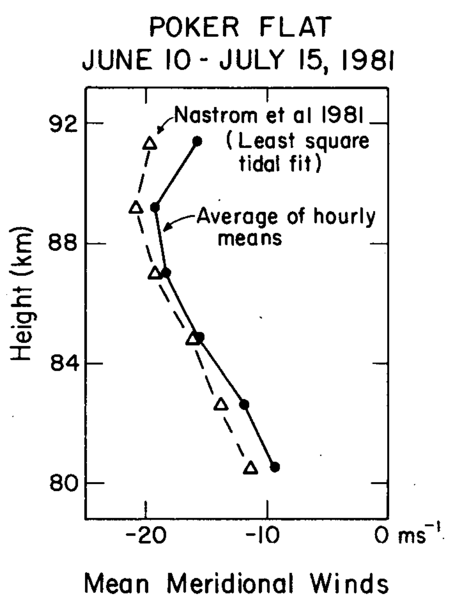

FIG. 2. Comparison between mean meridional wind profiles obtained by 1) Nastrom *et al.* (1982) using monthly values extracted from a least squares tidal fitting process and by 2) the method of monthly averaging one-hour average velocity values used in the present analyses.

the indicated height, ±1 km. The curves have been grouped into four separate sets to facilitate comparison.

Perhaps the two most distinct features in this figure are the pronounced annual variability of the zonal wind field below 91 km and the "notch" in this quasi-sinusoidal curve during January. An eleven-year monthly mean curve obtained from MRN rocket data (Belmont *et al.,* 1975) for 65 km at 70°N has been superimposed on the lowest curve set for comparison. Note that the MST-derived curve and the curve from Belmont *et al.* (1975) are quite similar in both shape and magnitude, and that the January notch is even more pronounced in the rocket data.

In the 85–91 km set, although the general shape of the zonal wind curve is similar to that in the lower height range, the magnitude has decreased and the notch is not present. Also, in contrast to the constancy of the 76–83 km set, the 85–91 km set exhibits a smooth vertical gradient in the zonal wind field.

Relative to the two lower data sets, the upper two sets (93–100 km and 102–109 km) exhibit sharply reduced magnitudes for all seasons. Any tendency for an annual variation is all but lost in random month to month variations. This is particularly true in the upper curve set, where the variability of the monthly mean on any given month is clearly greater than the comparable variability, for example, in the lowest curve set. This variability could be due either to an actual variability in the wind field, or to the fact that the larger echo rates at the lower heights result in a reduced statistical variability of the measured values. However, comparable curves obtained at Saskatoon (52°N) by the partial reflection drift technique (Gregory *et al.*, 1981) for 1978–79 show the same general features, in spite of the ~13° latitude difference.

The *meridional* wind is shown in somewhat less detail in Fig. 4. In this case the available data have been condensed into two height-averaged curves (75–92 km, and 94–109 km). Equivalently-averaged values of the zonal wind (dashed curves) are also plotted. One feature of the meridional wind in Fig. 4 is again a quasi-sinusoidal annual variability. The meridional wind amplitude is somewhat less in the higher height range, although the difference is not at all as obvious as it is for the zonal wind. Note that the average meridional wind between 75 and 92 km around the June solstice is equatorward at about 10 m s^{-1} as described by Nastrom *et al.* (1982), and that the winter-solstitial wind is poleward at about 5 m sec^{-1}. These values are considerably larger than those predicted by early zonally-averaged models but are reasonably in line with values reported by Groves (1980). The consequences of such large values of meridional flow in terms of turbulent energy deposition at mesospheric heights has been discussed by a number of investigators (e.g., Lindzen, 1981; Nastrom *et al.*, 1982; Ebel *et al.*, 1983).

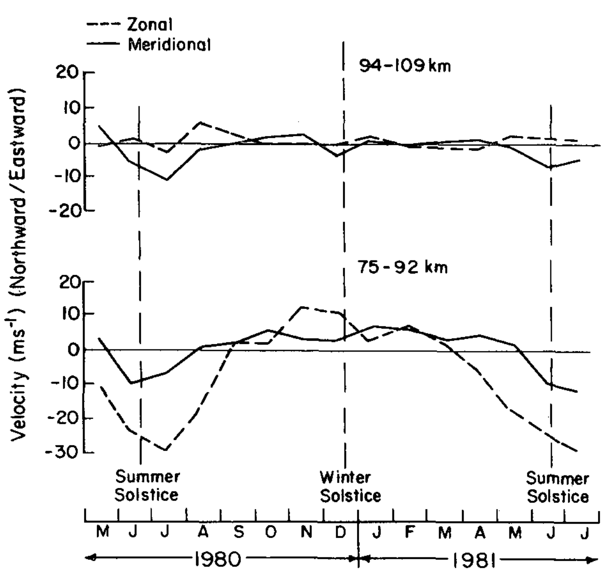

FIG. 4. Monthly-averaged zonal (dashed) and meridional (solid) winds for height ranges 75–92 km and 94–109 km for the period May 1980 to July 1981.

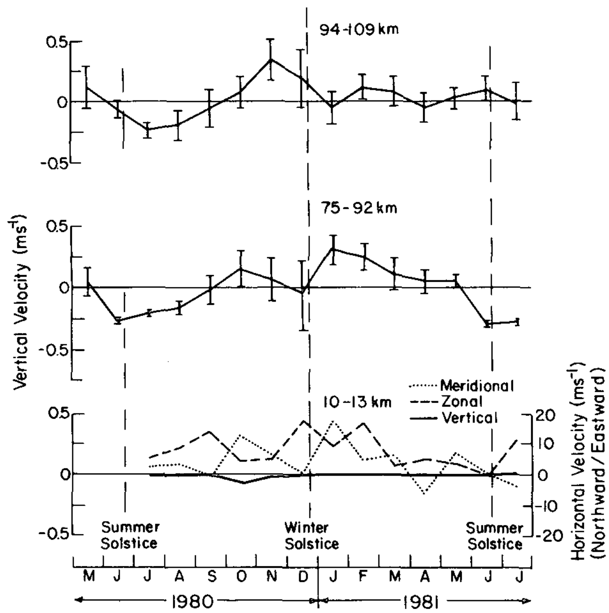

FIG. 5. Monthly-averaged vertical winds for the same period as Fig. 4. The upper two curves are for the same height ranges as Fig. 4; the bottom curves depict monthly-averaged zonal (dashed curve), meridional (dotted curve), and vertical (solid curve) winds between 10 and 13 km. Note that the zonal and meridional winds are scaled on the left side. The small values of vertical winds observed between 10 and 13 km and the relatively large horizontal wind values in the same height range attest to the fact that the vertical antenna beam is directed very close to vertical. A similar comparison at mesospheric heights (i.e., compare Fig. 4 and the top panels of Fig. 5) shows that the observed vertical winds cannot be due to a tilted vertical antenna beam, since much larger values of vertical wind in the mesosphere occur with the same magnitude of horizontal wind as seen between 10 and 13 km.

b. Vertical winds

Monthly mean values of the vertical wind for the height ranges 72–92 km and 94–109 km are shown by the upper two curves in Fig. 5. Note that the velocity scales for these curves (±0.5 m s^{-1}) are some 50 times *smaller* than those shown earlier for the horizontal winds. Error bars denote the standard deviation of the hourly mean values used in computing the monthly means.

Although these vertical curves are somewhat "noisy," they exhibit a similar quasi-sinusoidal annual variability seen in the horizontal wind fields in Figs.

3 and 4. Maximum values for the vertical wind fields, however, are only about ±25 cm s^{-1}. *In general, the vertical wind can be described as having a quasi-sinusoidal annual shape with a maximum upward flow occurring near the winter solstice and maximum downward flow occurring near the summer solstice.* Although the limited accuracy of the data set attested by the magnitude of the error bars precludes a more detailed analysis, it appears possible that this quasi-sinusoidal picture could be shifted a few weeks later at higher altitudes (94–109 km).

In view of their potential importance for understanding mesospheric circulation patterns, it is important to establish the accuracy of these (vertical) observations. Specifically, because of the relatively small vertical velocities, a number of possible observational errors could seriously affect the measurement accuracy. Possible error sources are described and discussed below:

1) *Is the vertical antenna directed exactly vertically?* If the vertical beam were inclined at a slight angle (δ), then the observed vertical winds would be contaminated by a component of the horizontal wind v, equal to $v \sin\delta$. Since $v \gg w$, this could be a serious effect even for slight departures from vertical. Observationally, however, an identical argument must be advanced for all altitudes, and since the bottom set of curves in Fig. 5 shows no such effect in the vertical wind field at 10–13 km (even though the 10–13 km horizontal wind magnitude is comparable to the mesospheric horizontal wind magnitude), we can conclude that the mesospheric vertical winds do not arise as a result of a "nonvertical" vertical antenna beam.

2) *Does preferential scattering from tilted atmospheric structure affect the observations?* Enhanced echoes at near-vertical incidence in the atmosphere are well known (Röttger and Liu, 1978; Green and Gage, 1980). Similar effects in the mesosphere have been reported by Fukao *et al.* (1979) and by Hocking (1979). For finite beam-width antennas, one possible result of scattering from almost-but-not-exactly horizontally stratified structures would be that the echoes would arrive from slightly off-vertical angles within the antenna beam and would therefore possess a contaminating component of horizontal velocity that could affect the vertical observations. Similar arguments can be advanced for the contaminating effects of upward propagating gravity waves with tilted phase fronts (Gage *et al.*, 1981). However, while it is conceivable that anisotropic scattering from such tilted structures could be a problem in the lower region (≤92 km), it cannot occur at the higher heights, since essentially all of the echoes at the higher heights arise from meteor echoes which have no such anisotropy. Therefore, insofar as both the upper and lower height ranges exhibit the same general annual characteristics, we conclude that anisotropic effects are not responsible for the observed vertical motions.

3) *Can the ambient electric field produce the observed vertical motions?* The effect of *in-situ* electric fields on the observed mesospheric motions has been discussed in a previous section in terms of the total wind field and the effect has been minimized in terms of monthly-averaged wind values. Moreover, the apparent phase change of the annual variation between the two heights, if true, precludes the magnetospheric electric field as a source of the observed drifts, since the electric field variability must be in phase at both heights. Also the fact that the magnitude of the vertical drifts are comparable over at least a 20 km height range argues against electric field control, since Reid (1983) has shown that the electric field effects should increase sharply with increasing height. On the basis of the above arguments, we conclude that the observed mean motions are not due to electric field effects.

4) *Could the antenna beam be "bent" by non-vertical ionospheric gradients?* The possibility exists that a vertically-propagating 50 MHz pulse could be slightly refracted by off-vertical electron density gradients in the upper mesosphere and lower ionosphere. Such ray "bending" could contaminate the observations by returning a small component of the larger horizontal wind in a manner similar to that described in 1) above. This effect, moreover, would only occur above ~60 km so that the very small vertical winds observed in the troposphere–stratosphere (Fig. 4) can not be used as an argument against raybending. However, estimates of the magnitude of such an effect using unreasonably large values of electron density gradients and tilts show that 1) the maximum anticipated raybending is much too small to account for the observed values and 2) such an effect, if present, should increase strongly with height. We therefore conclude that raybending is not a viable explanation for the observed vertical drifts.

5) *Could magneto-ionic mode splitting explain the observed vertical drifts?* Even in the absence of non-vertical ionization gradients, the ray path can be "bent" by magneto-ionic effects. Such a process would again result in contamination of the vertical wind data by horizontal wind components. This effect at 50 MHz, however, can be shown to be much too small under even the most stringent conditions. This fact, coupled with the fact that such effects should increase with height, allows us to discard magneto-ionic splitting as a possible source of error.

6) *Can the effects of a time rate of change of electron density be construed as vertical motions?* Under some conditions, a loss or gain of local electron density could conceivably result in an apparent motion of the 3 m refractive index structure responsible for the MST echoes. While the process might be considered a factor in some short term effects, it is clearly

unrealistic to invoke it as a long-term-average drift-producing mechanism, since the required long term loss or gain of electrons is inconceivable. Furthermore, the quasi-sinusoidal seasonal drift motion due to an electron production/loss process is unrealistic.

Thus, on the basis of the above discussions, it is reasonable to conclude that the observed long term vertical motions do not arise from any of the postulated processes. In the absence of any other process, we conclude that the observed vertical motions are indeed a measurement of the monthly-averaged vertical wind field.

6. Brief comparison of the Poker Flat results with existing models and observations

The monthly-averaged *zonal* wind field in the mesosphere and lower thermosphere measured by the Poker Flat MST radar and presented here is reasonably consistent with other observations at comparable latitudes (e.g., Belmont *et al.,* 1975) and is not inconsistent with existing numerical models of mesospheric circulation (e.g., Schoeberl and Strobel, 1978; Apruzese *et al.,* 1982). The observed *meridional* wind field exhibits the enhanced wind values observed by other techniques at high latitudes (cf. Groves 1980; Nastrom *et al.,* 1982) and obtained from current model studies (e.g., Ebel *et al.,* 1983) using modified parametric values for frictional damping, eddy diffusivity and dissipation.

On the other hand, as discussed in the following section, the observed monthly-averaged mean *vertical* wind, is essentially opposite to that deduced for the zonally-averaged, Lagrangian mean pole-to-pole circulation cell, with the observed downward motions maximizing near the summer solstice and the maximum upward motions occurring near winter solstice. Moreover, the $\sim$25 cm s^{-1} maximum observed values are at least an order of magnitude larger than anything yet proposed.

7. Discussion of the vertical wind component

The generally accepted zero-order picture of zonally-averaged mean meridional flow in the mesosphere at the solstices (see, for example, Leovy, 1964) is one in which strong solar heating of (primarily) stratospheric ozone in summer leads to an upwelling into higher (mesospheric) heights, with a consequent meridional flow away from the summer polar region to the winter polar region and a concomitant subsidence in the winter hemisphere. This general pattern is consistent with the postulated adiabatic cooling/heating of the regions near the summer/winter polar mesopause. For example, adiabatic cooling arising from an upward wind is thought to lead to the extremely low temperature ($\sim$140 K) observed at the summer mesopause at high latitudes. Noctilucent clouds (NLC), which occur near the summer mesopause at high latitudes are also thought to be causally related to both a cold mesopause and an enhanced upward wind (Reid, 1975; Turco *et al.,* 1982).

Contrasting this relatively simple picture of mesospheric meridional-plane circulation and its consequences, with the large seasonally-reversed vertical flow at 65°N shows three major discrepancies:

1) Upward (downward) atmospheric motions in the winter (summer) arctic mesosphere are inconsistent with current models of a single-cell, pole-to-pole, mean circulation pattern.

2) The observed velocities are also inconsistent with adiabatic heating (cooling) of the winter (summer) arctic mesosphere.

3) The average downward summer velocities (about tens of cm s^{-1}) observed over Poker Flat are also inconsistent with the occurrence of noctilucent clouds.

While the above discrepancies might suggest that the observations are in question, the discussions given in the Data Presentation give equally strong support that the radar results are correct. Clearly further work is required to resolve this apparent enigma. Toward this end it is worthwhile to point out a number of factors that could enter into the final solution:

1) The vertical motions observed over Poker Flat may not be representative of the zonally-averaged vertical motions deduced from model calculations. Stated another way, the Poker Flat observations might be modulated by "local" orography or by a large-scale stationary wave pattern, so that the Alaskan circulation pattern may not be the same as that at other longitudes.

2) Although the actual pole-to-pole circulation may be zonally symmetric, it could be much more complex than the currently accepted single cell circulation discussed above. Indeed, a multicell circulation with a "polar cell" north of, say, 65° is attractive and could account for many of the discrepancies listed above (e.g., a summertime polar cell would provide enhanced NLC near the pole as well as the adiabatic cooling required to produce the cooled arctic mesosphere and the downward motions observed at Poker Flat). The idea of multicellular circulation has been discussed by Cunnold *et al.* (1975) and by Portnyagin and Solovyova (1982).

3) The (reasonably rare) occurrences of NLC above Poker Flat in summer may correspond to sporadic periods of upward flow even though the *average* summertime flow at 65°N is downward. This possibility is particularly intriguing in light of NLC observations by Donahue *et al.* (1972), who find the greatest occurrence of NLC near the summer pole, although they are invisible from the ground at very high latitudes. Donahue *et al.* point out that "NLC

observed occasionally during summer twilights at high latitudes are mere *ragged extensions* to lower latitudes of a persistent phenomenon which develops over the geographic pole during summer".

4) In comparing atmospheric motions obtained from theory, models, and observations, it is important to take into account whether the results are given in terms of Eulerian or Lagrangian motions. Both the magnitude and, in some cases, the direction of flow depend on whether the flow is expressed in an Eulerian or a Lagrangian framework. Eulerian motion is that motion associated with the motion observed at a fixed point in space, while Lagrangian motion describes the motion of a collection of air parcels. Lagrangian motion is defined in terms of Eulerian motion plus a "Stokes" motion (an eddy-induced particle motion), and is important in studying passive additives (e.g., scalar quantities such as ozone, water vapor, radioactive tracers, etc.). Eulerian flow, on the other hand, is that flow observed by a measuring system in a fixed reference frame (i.e., a radar system). An understanding of these concepts has had considerable importance in the troposphere and stratosphere in understanding the one-cell (Lagrangian) meridional circulation deduced by Brewer and Dobson to explain the latitudinal distribution of ozone and water vapor and the concurrent multicell meridional shown to comprise the Hadley and Ferrel cells. (Excellent discussions of these subjects can be found in Wallace (1978) and Matsuno (1983).)

8. Conclusions

The fifteen-month monthly-averaged *horizontal* mesospheric wind field measurements obtained using the Poker Flat Radar at 65°N latitude are reasonably consistent with other observations as well as with current theoretical models that take into account the enhanced turbulence and eddy transport observed at mesospheric heights. In contrast, the observed *vertical* wind field (a quasi-sinusoidal seasonal variation with a 25 cm s^{-1} downward maximum near the summer solstice and a 25 cm s^{-1} upward maximum near the winter solstice) is inconsistent with the current idea of mean circulation in the meridional plane, and indicates that the actual flow is much more complex (e.g., the actual flow is either zonally nonuniform, meridionally multicellular, or complicated by an appreciable Stokes drift arising from strong eddy activity).

Acknowledgments. The authors are indebted to a number of colleagues. For initial discussions of the observed vertical motions and of their consequences we are indebted to G. D. Nastrom, G. C. Reid, K. S. Gage, S. A. Avery, W. L. Ecklund, D. A. Carter, and T. E. VanZandt. D. Fritts, R. Garcia, G. Thomas, J. Holton, R. Lindzen, J. Mahlman, M. Schoberl, and D. Strobel also contributed a number of useful suggestions. We appreciate in particular many helpful discussions with R. Walterscheid on Eulerian and Lagrangian circulation concepts. The above research was supported in part by the Atmospheric Research Section of the National Science Foundation.

REFERENCES

Apruzeze, J. P., M. R. Schoeberl and D. F. Strobel, 1982: Parameterization of IR cooling in middle atmosphere dynamics model I. Effects on the zonally averaged circulation. *J. Geophys. Res.*, **87**, 8951–8966.

Avery, S. K., A. C. Riddle and B. B. Balsley, 1983: The Poker Flat, Alaska MST radar as a meteor radar. *Radio Sci.*, **18**, 1021–1027.

Balsley, B. B., and K. S. Gage, 1980: The MST radar technique: Potential for middle atmospheric studies. *Pure and Appl. Geophys.*, **118**, 452–493.

——, W. L. Ecklund, D. A. Carter and P. E. Johnston, 1980: The MST radar at Poker Flat, Alaska. *Radio Sci.*, **15**, 213–223.

——, D. A. Carter and W. L. Ecklund, 1982: On the relationship between auroral electrojet intensity and the wind field near the mesopause. *Geophys. Res. Lett.*, **9**, 219–222.

——, W. L. Ecklund and D. C. Fritts, 1983: VHF echoes from the high-latitude mesosphere and lower thermosphere: Observations and interpretations. *J. Atmos. Sci.*, **40**, 2452–2466.

Belmont, A. W., D. G. Dartt and G. D. Nastrom, 1975: Variations of stratospheric zonal winds, 20–65 km, 1961–1971. *J. Appl. Meteor.*, **14**, 585–594.

Carter, D. A., and B. B. Balsley, 1982: The summer wind field between 80 and 93 km observed by the MST radar at Poker Flat, Alaska (65°N). *J. Atmos. Sci.*, **39**, 2905–2915.

——, —— and W. L. Ecklund, 1980: The Poker Flat MST radar: Signal analysis and data processing techniques with examples. *Proc. 19th Conf. on Radar Meteorology*, Miami Beach, Amer. Meteor. Soc., 563–567.

Cunnold, D., F. Alyea, N. Phillips and R. Prinn, 1975: A three-dimensional dynamical-chemical model of atmospheric ozone. *J. Atmos. Sci.*, **32**, 170–194.

Donahue, T. M., B. Guenther and J. E. Blamont, 1972: Noctilucent clouds in daytime: Circumpolar particulate layers near the summer mesopause. *J. Atmos. Sci.*, **29**, 1206–1209.

Ebel, A., H. J. Jakobs and P. Speth, 1983: Turbulent heating and cooling of the mesopause region and their parameterization. *Ann. Geophys.*, **1**, 358–370.

Ecklund, W. L., and B. B. Balsley, 1981: Long term observations of the Arctic mesosphere with the MST radar at Poker Flat, Alaska. *J. Geophys. Res.*, **86**, 7775–7780.

Fukao, S., T. Sato, R. M. Harper and S. Kato, 1979: Radio wave scattering from the tropical mesosphere observed with the Jicamarca radar. *Radio Sci.*, **15**, 447–457.

Gage, K. S., D. A. Carter and W. L. Ecklund, 1981: The effect of gravity waves on specular echoes observed by the Poker Flat MST radar. *Geophys. Res. Lett.*, **8**, 599–602.

Green, J. L., and K. S. Gage, 1980: Observations of stable layers in the troposphere and stratosphere using VHF radar. *Radio Sci.*, **15**, 395–405.

Gregory, J. B., C. E. Meek and A. H. Manson, 1981: Mean zonal and meridional wind profiles for the mesosphere and lower thermosphere at 52°N, L = 4.4, during solar maximum. *Atmos.-Ocean*, **19**, 24–34.

Groves, G. V., 1980: Seasonal and diurnal variations of middle atmosphere winds. *Phil. Trans. Roy. Soc. London.*, **A296**, 19–40.

Hocking, W. K., 1979: Angular and temporal characteristics of partial reflections from the D-region of the ionosphere. *J. Geophys. Res.*, **84**, 845–851.

Leovy, C., 1964: Simple models of thermally driven mesospheric circulation. *J. Atmos. Sci.*, **21**, 327–341.
Lindzen, R. S., 1981: Turbulence and stress owing to gravity wave and tidal breakdown. *J. Geophys. Res.*, **86**, 9707–9714.
Luhmann, J. G., R. M. Johnson, M. J. Baron, B. B. Balsley and A. C. Riddle, 1983: Observations of the high latitude ionosphere with the Poker Flat MST radar: Analyses using simultaneous Chatanika radar measurements. *J. Geophys. Res.*, **88**, 10 239–10 245.
Matsuno, T., 1983: Circulation and waves in the middle atmosphere in winter. *Space Sci. Rev.*, **34**, 387–396.
Nastrom, G. D., B. B. Balsley and D. A. Carter, 1982: Mean meridional winds in the mid and high latitude summer mesosphere. *Geophys. Res. Lett.*, **9**, 139–142.
Portnyagin, Yu, I., and T. V. Solovyova, 1982: On regular vertical movements in mesopause–lower thermosphere region. *J. Geomagn. and Aeron.*, **22**, 225–232.
Reid, G. C., 1975: Ice clouds at the summer polar mesopause. *J. Atmos. Sci.*, **32**, 523–535.
——, 1983: The influence of electric fields on radar measurements of winds in the upper mesosphere. *Radio Sci.*, **18**, 1028–1034.
Roper, R. G., and J. E. Salah, 1978: Preliminary results from the URSI/IAGA cooperative tidal observations program. *J. Atmos. Terr. Phys.*, **40**, 879–886.
Röttger, J., and C. H. Liu, 1978: Partial reflection and scattering of VHF radar signals from the clear atmosphere. *Geophys. Res. Lett.*, **5**, 357–360.
Schoeberl, M. R., and D. F. Strobel, 1978: The zonally averaged circulation of the middle atmosphere. *J. Atmos. Sci.*, **15**, 577–591.
Smith, S. A., G. J. Romick and K. Jayaweera, 1983: Poker Flat MST radar observations of shear induced turbulence. *J. Geophys. Res.*, **88**, 5265–5271.
Turco, R. P., O. B. Toon, R. C. Whitten, R. G. Keesee and D. Hollenbach, 1982: Noctilucent clouds: Simulation studies of their genesis, properties and global influences. *Planet. Space Sci.*, **30**, 1147–1181.
Vincent, R. A., T. J. Stubbs, P. H. O. Pearson, K. H. Lloyd and C. H. Low, 1977: A comparison of partial reflection drifts with winds determined by rocket techniques. *J. Atmos. Terr. Phys.*, **39**, 813–821.
Wallace, J. M., 1978: Trajectory slopes, counter gradient heat fluxes and mixing by lower stratospheric waves. *J. Atmos. Sci.*, **35**, 554–558.