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Comparison of Satellite-Derived Dynamical Quantities for the Stratosphere of the Southern Hemisphere

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PREFACE

The workshop proceedings presented in this report are the result of a coordinated effort to intercompare data from different sounding systems for the middle atmosphere in the Southern Hemisphere and to evaluate the impact of base-level analyses on meteorological fields. This effort originated as Pre-MAP Project 1 (PMP-1) led by Professor K. Labitzke, Free University of Berlin, under the auspices of the Middle Atmosphere Program (MAP). The workshop reported here was held in Williamsburg on April 14-17, 1986 and formed part of the MAP-sponsored MASH project on the dynamics of the middle atmosphere in the Southern Hemisphere. The members of the PMP-1 working group generously contributed many hours in producing material for this and previous reports in the hope of providing guidance to users of data in studies of middle atmosphere dynamics and transport. Their assistance is gratefully acknowledged. Financial support for the Williamsburg workshop was arranged by Dr. D. M. Butler through the NASA Upper Atmosphere Research Program.

Alan O'Neill

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*Middle Atmosphere in the Southern Hemisphere

COMPARISON OF SATELLITE-DERIVED DYNAMICAL QUANTITIES FOR THE STRATOSPHERE OF THE SOUTHERN HEMISPHERE

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1. INTRODUCTION

Over the past 10 to 15 years, radiometric measurements from polar orbiting satellites have furnished a wealth of information on the global structure of the middle atmospheric circulation. These data have formed the basis for climatological studies and dynamical investigations. Information on smaller scale structures than can be resolved by satellites is being supplied by radar and lidar measurements. These activities have been paralleled by increasing efforts to model aspects of the observed circulation using both simplified (mechanistic) models and complex numerical models of the general circulation.

The main focus of these studies has been on the circulation of the Northern Hemisphere; the Southern Hemisphere has not been ignored, but until recently, advances have been comparatively few and far between. Reasons for this imbalance include: (1) impetus to studies of the Northern Hemisphere resulting from much better coverage by radio/rocketsonde network, (2) the quality of operational analyses of the Southern Hemisphere upper troposphere (used to tie on satellite thickness analyses) has been comparatively poor owing to large data-sparse regions, and (3) attention has inevitably been concentrated on one of the most dramatic manifestations of dynamical processes in the middle atmosphere - the major midwinter warming of the Northern Hemisphere.

In recent years, the routine production of global tropospheric analyses by data assimilation into numerical forecast models has helped to improve the quality of analyses for the Southern Hemisphere (satellite measurements have contributed to this improvement). The situation is not entirely satisfactory, but independent analyses (such as those made by the Meteorological Office, Bracknell, United Kingdom, and the National Meteorological Center, Washington, D.C.) are in reasonable accord.

It has also been realized that the middle atmosphere of the Southern Hemisphere, despite the absence of major midwinter warmings, is far from quiescent. Very intense, dynamically induced warmings occur in late winter; the intense polar-night vortex may be the seat of instabilities which affect the circulation on a large scale; traveling waves are often clearly seen in the more zonally symmetric circulation of the Southern Hemisphere.

Because middle atmosphere circulations of the two hemispheres show marked differences, dynamical meteorologists have the opportunity to study what are, in effect, two different atmospheres. The elucidation of dynamical mechanisms is bound to be furthered by intercomparison. In particular, the tropospheric circulations are different in the two hemispheres, enabling connections of the troposphere with the middle atmosphere to be established more firmly.

At the Middle Atmosphere Program (MAP) in Kyoto (November 23 and 25, 1984), proposals were solicited for new MAP projects. One suggestion was for a study of the dynamics of the Middle Atmosphere in the Southern Hemisphere (MASH), and this has since received the formal approval of the MAP Steering Committee. The MASH project involves a concerted study of the dynamics of the middle atmosphere in the

Southern Hemisphere, with emphasis on interhemispheric differences and connections with the troposphere. The study will be based on observational data and simulations with numerical models. Parallel studies of radiation, transport, and photochemistry will also be encouraged. The uses of observational data will include:

(a) Intercomparison of observations and analyses obtained by different means. This will be a coordinated study along the lines documented in MAP Handbook 12 for the Northern Hemisphere (contemporaneous satellite data from the LIMS, SAMS and TOVS instruments are available).

(b) Climatological studies of the middle atmospheric circulation. These will focus on the time-mean structure and variances of the circulation together with their seasonal evolution, the structure and temporal variability of large-scale eddies, and the morphology of gravity waves.

(c) Diagnostic and associated theoretical studies will address the evolution of the circulation on both short and seasonal time scales. Topics here will include wave-mean flow interactions and the importance of wave breaking in the Southern Hemisphere (particularly for the dynamics of final warmings), the possible role of instabilities in the strong westerly vortex, the origin of the large-amplitude planetary waves which develop particularly in early and late winter (e.g., whether developments like blocking in the Northern Hemisphere occur in the troposphere), and the effect of gravity waves on the middle atmosphere.

These investigations will be complemented by studies with numerical models of various levels of sophistication. Broad headings for this work are

(1) experiments with mechanistic models to test dynamical hypotheses, e.g., to determine the influence of the troposphere on the middle atmosphere during final warmings, and

(2) longer integrations with numerical models to explore the mechanisms behind the seasonal evolution of the circulation.

Features that such models would need to reproduce in the Southern Hemisphere include:

(a) the tendency for large amplitude waves to develop in early and late winter

(b) the reversed temperature gradient at high latitudes in the upper stratosphere which appears by midwinter

(c) the poleward and downward movement of zonal mean winds during the final warming

(d) the traveling wave 2 which contributes much of the variance in the stratosphere.

A series of workshops was held in 1982-1984 which made intercomparisons of Northern Hemisphere stratospheric analyses from several satellite systems (PMP-1 Working Group). The topics considered by these workshops included intercomparison of temperature analyses/ measurements from satellites and in situ systems, and assessing the accuracy of derived quantities used in studies of stratospheric dynamics (Rodgers, 1984b; Grose and Rodgers, 1986).

The first MASH workshop was held in Adelaide on May 18-19, 1987, and proceedings of this meeting will be published in a special issue of PAGEOPH (Vol. 130, 1989). It highlighted some of the inadequacies in our present understanding of the middle atmosphere of the Southern Hemisphere. Three broad areas (among many) requiring much more work are 3-D modeling, troposphere-middle atmosphere coupling, and interhemispheric coupling.

This report summarizes the proceedings from a pre-MASH planning workshop on the intercomparison of Southern Hemisphere observations, analyses and derived dynamical quantities held in Williamsburg, Virginia during April 1986. The aims of this workshop were primarily twofold:

(1) comparison of Southern Hemisphere dynamical quantities derived from various satellite data archives (e.g. from limb scanners and nadir sounders)

(2) assessing the impact of different base-level height information on such derived quantities.

These tasks are viewed as especially important in the Southern Hemisphere because of the paucity of conventional measurements.

A further strong impetus for the MASH program comes from the recent discovery of the springtime ozone hole over Antarctica. Insight gained from validation studies such as the one reported here will contribute to an improved understanding of the role of meteorology in the development and evolution of the hole, in its interannual variability, and in its interhemispheric differences.

The dynamical quantities examined in this workshop included geopotential height, zonal wind, potential vorticity, eddy heat and momentum fluxes, and Eliassen-Palm fluxes. The time periods and data sources constituting the MASH comparisons are summarized in Table 1 on page 19. Table 1 also includes a list of acronyms which are used throughout the text.

2. ANALYSES

The primary objective of the MASH workshop was to compare different Southern Hemisphere satellite-derived quantities and to examine the impact of different operational base-level analyses on these derived quantities. Although the satellite-derived quantities are largely based on satellite temperature (thickness) data, for certain dynamical quantities (e.g., potential vorticity maps) the base-level height analysis may contribute significant information throughout the lower-middle stratosphere. This section includes a discussion of the base-level analyses followed by details of the stratospheric satellite instruments and related analyses of temperature, thickness, and geopotential height.

2.1. Base-Level and Tropospheric Analyses

The MASH workshop utilized Southern Hemisphere geopotential height analyses provided by meteorological centers in Reading, Washington, and Bracknell (ECMWF, NMC, and UKMO respectively). These analyses are used for the base-level information at 50 or 100 mb in deriving heights throughout the stratosphere. The three meteorological centers employ broadly similar methods in producing the gridded height analyses. For example, they are produced operationally (i.e. constrained by data cut-off times), use synoptic (radiosonde) and asynoptic (i.e. aircraft, satellite-inferred) upper-air reports, and incorporate background (so-called first-guess) information such as a numerical forecast and/or climatology in the absence of current data.

Substantial improvements have occurred in tropospheric global data assimilation, objective analysis procedures, and short-term forecast accuracy since 1979 (Bengtsson and Shukla, 1988), and increasing use has been made of asynoptic meteorological information, e.g. aircraft and satellite data. Nevertheless, difficulties associated with delayed reports and relatively sparse data coverage exist in the Southern Hemisphere. Moreover, differences in quality control and analysis methodology, such as the treatment of isolated, but quite accurate, synoptic reports and the application of spatial smoothing, exist between the three meteorological centers which will influence the accuracy of the archived gridded height analyses. As a result, the Southern Hemisphere tropospheric height analyses are generally regarded as poorer quality compared with Northern Hemisphere analyses (Hollingsworth et al., 1985; Lambert, 1988; Trenberth and Olson, 1988).

The ECMWF and NMC Southern Hemisphere objective analysis procedures have undergone several major changes since their inception in 1978; these are discussed by Trenberth and Olson (1988, and references therein). For example, in May 1980 initialization (removal of unwanted high-frequency components) was applied to the NMC global analyses, and a global spectral forecast model was introduced. (Prior to May 1980, initialization was not applied, and a grid-point numerical forecast model was used.) These changes are known to have resulted in a substantial reduction in noise levels in the NMC final analyses and forecasts (Jenne, private communication, 1984). Further improvements have been made subsequently. The UKMO operational height analysis procedures for the troposphere and lower stratosphere (e.g. 100 mb) have been documented and intercompared with ECMWF and NMC global analyses by Hollingsworth et al. (1985).

2.2. Satellite Analyses

Southern Hemisphere satellite analyses considered in the MASH workshop consist of archived temperature or thickness analyses for SAMS, LIMS, and TOVS (HIRS + MSU + SSU).

The SAMS and LIMS measurements were made on the Nimbus 7 satellite, while the TOVS measurements/retrievals are from the Tiros-N and NOAA* series of operational polar orbiting satellites. SAMS and LIMS data may be viewed as a research product, whereas TOVS was primarily for operational meteorological requirements, with stratospheric channels included mainly to improve the accuracy of the operational tropospheric temperature soundings.

The limb-scanning SAMS experiments provided temperature retrievals from 15-100 km with a vertical resolution of ~ 8 km using a sequential estimator procedure (Rodgers et al., 1984). The temperature analyses are gridded at a 2.5° latitude interval from 50°S to 70°N from December 1978 to June 1983. Details of the SAMS instrument and validation of temperatures are discussed by Wale and Peskett (1984) and Barnett and Corney (1984), respectively. Geopotential heights have been obtained using climatological height analyses for the lower stratosphere (Barnett and Corney, 1985).

The LIMS instrument is a limb-scanning radiometer with a vertical resolution of ~ 3 km for the temperature measurements. The LIMS experiment, temperature retrieval and validation are discussed by Gille and Russell (1984), Gille et al. (1984a,b), Remsberg (1986), and Miles et al. (1987). The temperature retrievals were mapped to 1200 UTC using a Kalman filter procedure (Remsberg et al., 1989†) at 4° latitude increments from 64°S to 84°N and at 18 pressure levels from 100 to 0.05 mb, for the period October 25, 1978 - May 28, 1979. Geopotential heights for the LIMS experiment were calculated with 50 mb height base-level analyses from the stratospheric analysis branch at NMC (see below).

The TOVS observing system consists of the HIRS, MSU, and SSU multi-channel radiometers which view at both sides of nadir (i.e. side-scanning) (Smith et al., 1979; Pick and Brownscombe, 1981; Clough et al., 1985). The TOVS stratospheric temperature sounding capability consists of 9 channels:

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*National Oceanic and Atmospheric Administration.

†Submitted to J. Atmos. Ocean. Tech, 1989. (Not yet available.) Description of the Nimbus 7 LIMS MAP archive tape product for middle atmosphere studies.

(a) four HIRS channels located in the lower-middle stratosphere with a vertical resolution of ~ 10-15 km

(b) two MSU channels with a vertical resolution of ~ 10 km located near the 90 and 300 mb levels (for nadir viewing)

(c) three SSU channels centered near the 15, 5, and 1.5 mb levels (for nadir viewing). (Note that prior to June 1979, the top SSU channel was inoperative.)

Statistical tests have established that the vertical resolution of the overlapping (nadir-viewing) SSU channels is ~ 10 km (Clough et al., 1985). Side-scanning normal to the suborbital track results in near-global meridional sampling (~ 87°N - 87°S) and longitudinal resolution superior to that achieved by the limb-scanning instruments.

The TOVS radiance information is operationally processed by the National Environmental Satellite Data and Information Service (NESDIS) in Washington, D.C. The accuracy (precision and systematic biases) of HIRS, MSU, and SSU radiance measurements and TOVS temperature retrievals for stratospheric levels (100 mb and higher) has been discussed by Phillips et al. (1979), Smith et al. (1979), Schlatter (1981), Pick and Brownscombe (1981), Geller et al. (1983), Nash and Brownscombe (1983), Schmidlin (1984), Gelman et al. (1986), and Nash and Forrester (1986).

In addition to tropospheric analysis/forecast applications, TOVS information is also used for middle atmosphere research efforts at NMC and UKMO to produce daily global analyses of thickness, temperature, and geopotential height at "standard" pressure levels throughout the stratosphere. Although both stratospheric groups at UKMO and NMC have access to the same TOVS radiance measurements (i.e. from NESDIS), the subsequent production of gridded analyses is somewhat different at these two centers.

The UKMO stratospheric group directly converts TOVS radiances into deep layer-mean thicknesses using a regression procedure applied to a radiosonde/rocketsonde temperature (thickness) climatology for the 100-20, 100-10, 100-5, 100-2, and 100-1 mb layers (Pick and Brownscombe, 1981; and Clough et al., 1985). TOVS stratospheric thickness profiles are then interpolated onto a global 5° × 5° grid, and spatial smoothing is applied, retaining twelve Fourier wave components in latitude and longitude. Temperatures at specific pressure levels are then obtained through interpolation of the TOVS thickness information. The UKMO geopotential height data used in the MASH workshop consists of stratospheric geopotential heights for the 100, 50, 20, 10, 5, 2, and 1 mb levels. Note, however, the 100 and 50 mb height fields are strictly operational analyses, whereas those from 20 to 1 mb are obtained by stacking the TOVS thicknesses on the operational 100 mb height field. The UKMO 100 to 50 mb operational height analyses were obtained from ECMWF during 1979, NMC during 1980-83, and UKMO since 1984.

The stratospheric analysis group at NMC has produced global analyses of temperature and geopotential height since September 1978

(Geller et al., 1983; Gelman et al., 1986). The selection of data for the analyses changed about once per year. Prior to October 17, 1980, NMC used both radiosonde and satellite temperature data (VTPR or TOVS) in the Southern Hemisphere 70-10 mb region, and SSU thicknesses only for the 5-0.4 mb region. (For the period September 24, 1978 to February 23, 1979, NMC used radiances from the NOAA-5 VTPR instrument.) Since October 17, 1980, however, NMC has used only TOVS data from the various NOAA satellites for all Southern Hemisphere analysis levels (i.e. 70-0.4 mb).

The NMC stratospheric analysis differs from UKMO in that NMC uses retrievals produced by NESDIS. The NESDIS temperature retrieval method directly retrieves temperature at 40 pressure levels and uses collocated satellite and in situ data which are updated weekly for the 1000 - 10 mb region (Phillips et al., 1979); above the 10 mb level, however, an historical temperature sample is used because of less frequent in situ data. The NESDIS retrievals are provided to NMC as layer-mean temperature profiles. The operational NMC 100 mb height analyses are used as a base for deriving heights at 70, 50, 30, 10, 5, 2, 1, and 0.4 mb. Temperatures at these pressure levels are obtained from linear interpolation of adjacent layer mean temperatures. The NMC stratospheric temperature and height analyses are gridded using a modified Cressman interpolation procedure (Finger et al., 1965).

3. RESULTS

The scope of the MASH workshop primarily involved a comparison of derived quantities that are of direct relevance to studies of middle atmosphere dynamics. Whereas temperature or thickness analyses represent the basic satellite information, derived quantities are inferred only after considerable manipulation of the data. The initial step in deriving virtually all dynamical quantities for the middle atmosphere consists of hydrostatic integration of satellite temperature profiles above a lower stratosphere base-level geopotential height analysis. Horizontal winds may then be estimated geostrophically through differentiation of the satellite-derived geopotential height distribution. Nonlinear quantities such as eddy fluxes of heat and momentum, and the Eliassen-Palm flux divergence may be derived through multiple differentiation of the horizontal wind fields with respect to latitude, longitude, and altitude. The derivation of dynamical quantities from satellite analyses will therefore tend to amplify noise which may be present in the satellite temperature information and the base-level height analyses.

The comparisons presented in this report are for selected dates which are representative of the larger body of data examined during the workshop. After a brief discussion of temperature differences, the intercomparison of dynamical quantities derived from analyses during 1979 is described in Section 3.1. The impact of different base-level height information on derived quantities is addressed in Section 3.2.

Comparison of different satellite temperature analyses in the Southern Hemisphere for January and May 1979 corroborated the findings obtained from previous Northern Hemisphere MAP workshops (Rodgers, 1984a,b; Grose and Rodgers, 1986). That is, differences between NMC and UKMO zonal-mean cross sections were less than ± 5 K; SAMS-LIMS differences of ± 5 K exhibited a vertical "wavy" structure; UKMO was colder than LIMS in the upper stratosphere by ~ 7 K in January 1979 and ~ 15-20 K in May 1979; and LIMS and SAMS have less zonal structure than NMC and UKMO. (The UKMO upper stratosphere cold bias apparently is related to the failure of the SSU 1.5 mb channel.) Readers are referred to these MAP documents for a detailed account of the temperature comparisons and, additionally, to complementary results in which temperature information (radiances or retrieved profiles) from SAMS, LIMS, MSU, and SSU (TOVS) have been intercompared between satellites or with in situ measurements:

(a) SAMS: Barnett and Corney (1984, 1985), Delisi and Dunkerton (1988)

(b) LIMS: Gille et al. (1984a,b), Hitchman and Leovy (1986), Remsberg (1986), Hitchman et al. (1987), Miles et al. (1987), Delisi and Dunkerton (1988), and Grose et al. (1988)

(c) MSU: Yu et al. (1983), Newman and Stanford (1983)

(d) SSU(TOVS): Pick and Brownscombe (1981), Geller et al. (1983), Nash and Brownscombe (1983), Barnett and Corney (1984), Schmidlin (1984), Gelman et al. (1986), and Nash and Forester (1986)

(e) NMC: Newman and Randel (1988) have compared NMC 100 and 30 mb monthly mean temperature analyses for October and November 1979-1986 with monthly mean radiosonde measurements over Antarctica from 1957-1984.

3.1. Quantities Derived from Archived Satellite Analyses During 1979

The comparison of dynamical quantities derived from archived satellite analyses is discussed for January and May, 1979. This time period was examined because of the availability of the Nimbus 7 LIMS and SAMS data as well as the commencement of Southern Hemisphere stratospheric analyses by NMC and UKMO. In this section we compare (a) zonal wind cross sections between these four data sets, and (b) Eliassen-Palm fluxes and isentropic maps of potential vorticity derived from LIMS and UKMO. May 1979 is the more dynamically active month, so we expect a higher signal-to-noise ratio then. We shall place most attention, therefore, on the May comparison (also see Grose and O'Neill, 1989).

Zonal Wind. Meridional cross sections of zonal geostrophic wind for LIMS, NMC, SAMS, and UKMO on January 26, 1979 and May 19, 1979 are shown in Figures 1 and 2, respectively. Note that the SAMS thicknesses have not been smoothed in latitude, and the SAMS winds are extrapolated north of 12°S. The four wind cross sections for January 26 contain broadly similar features, with stratospheric easterlies above the mid-latitude upper tropospheric westerlies. Maximum easterly flow occurs in the lower mesosphere, where LIMS and SAMS show fair agreement in wind speeds at 0.1 mb in middle latitudes (-65 to -80 m/s) and in subtropical latitudes (0 to 10 m/s). In the upper stratosphere (near 1 mb) UKMO and LIMS show evidence of a secondary jet maximum near 20°S, which is not present in the SAMS analysis. The NMC wind field exhibits more latitudinal structure in contrast to LIMS, SAMS and UKMO. For example, at 30 mb the NMC field shows quite large variations in latitude, whereas the UKMO analysis exhibits a more gradual variation. In contrast to the strong easterly flow indicated in the LIMS, SAMS, and UKMO cross sections at 1 mb and 20°S (-45 to -55 m/s), the NMC analysis shows speeds approaching -20 m/s. In higher southern latitudes (e.g. 60°S) differences of about 10 m/s are found between the NMC wind speed and the LIMS and UKMO analyses near the 1 mb level.

The LIMS and SAMS zonal wind cross sections for May 19, 1979 show good agreement in the location and strength of the westerly jet core in the subtropical lower mesosphere, with maximum speeds approaching or exceeding 110 m/s. the LIMS, NMC, and UKMO fields show a jet core axis which tilts poleward with decreasing altitude near 50° - 60°S in the lower-middle stratosphere. The SAMS analysis does not contain this feature to the same extent. In the tropical lower mesosphere, LIMS and SAMS differ by about 50 m/s (e.g. at 10°S, 0.1 mb). In the subtropical upper stratosphere (20° - 30°S), NMC winds are about 20-30 m/s weaker than for LIMS, SAMS, and UKMO. In the lower stratosphere at 10° - 15°S, the LIMS wind analysis indicates values ~ -20 m/s in contrast to values near zero for SAMS and UKMO. Noticeable differences in vertical wind shear occur between the four analyses in the 10-30 mb layer in subtropical and middle latitudes. The LIMS and SAMS winds at the 50 mb level differ by about 10 m/s at 10°S and also near 45°S, suggesting significant differences in zonal wind at the base-level for the two sets of analyses.

These winds are geostrophic estimates, and it is of interest to evaluate to what extent these derived values from satellite data agree with in situ radiosonde and rocketsonde wind speeds obtained from tracking moving instrument packages. Comparison of LIMS and rocketsonde zonal wind speeds at Ascension Island (~ 8°S) during January and May 1979 (Fig. 3a) indicates favorable agreement, with LIMS capturing the strong variations with altitude associated with the quasi-biennial and semiannual oscillation. (Note that the LIMS winds used for the rocket comparison are based on a temperature retrieval procedure somewhat different than utilized for the archived LIMS data - see Hitchman and Leovy, 1986.) The equatorial rocket-LIMS differences were found to be similar to those at mid-latitude stations and support the use of satellite geostrophic winds even at low latitudes (also see Smith and Bailey, 1985 and Grose et al., 1988). A similar comparison between UKMO winds and rocket measurements by Hirota et al. (1983) suggests that although UKMO winds exhibit less vertical structure than individual rocket profiles on a daily basis, agreement is better if time-mean profiles are compared (Figure 3b).

The wind comparisons for January 26 and May 19, 1979 indicate that NMC fields contain more latitudinal "noise" than LIMS, SAMS, and UKMO. Similar differences were found for other dates during 1979 both in meridional sections and on horizontal maps of zonal wind. Although base-level differences may explain part of these differences, it is more probable that latitudinal dependence related to the basic temperature data and/or application of smoothing may be responsible for this difference.

It should be noted, however, that the 1979 comparisons are for analyses produced during the initial phase of Southern Hemisphere analysis at NMC and UKMO, and the quality of these analyses has improved since then. Nevertheless, the percentage differences identified locally are not insignificant since they imply large differences in vertical and meridional shears, which are of considerable importance in evaluating dynamical quantities such as the refractive index. For certain purposes, it may be advantageous to apply temporal or spatial smoothing to the satellite data (e.g. weekly averages) and the base-level height analyses (e.g., Hitchman and Leovy, 1986).

Potential Vorticity. The evaluation of potential vorticity (PV) is made for May 24, 1979 during a period of enhanced planetary wave activity. The comparison consists of LIMS and UKMO PV fields on the 500 K and 850 K isentropic surfaces (near 70 and 10 mb, respectively). PV is a highly differentiated quantity and errors in PV are thus liable to be large. (See Grose (1984, LIMS) and Clough et al. (1985, TOVS) for details of the PV calculation.)

A contemporaneous set of maps of ozone and nitric acid mixing ratios are available from the LIMS experiment (e.g., Leovy et al., 1985) and are included for the May 24, 1979 PV comparison. Because these trace gases have photochemical lifetimes which are longer than the time scale for large-amplitude dynamical motions, they represent passive tracers which can be used with the PV analyses to infer quasi-conservative large-scale mixing of stratospheric air parcels in the lower-middle stratosphere.

The distribution of the modulus of PV on the 500 K and 850 K surfaces is shown in Figure 4, along with the LIMS analyses of nitric acid and ozone for the 500 K and 850 K surfaces. Although the LIMS and UKMO PV fields exhibit broadly similar features, noticeable localized differences are evident. The 500 K comparison indicates three tongues of high PV (4-5 PV units at 60°S) near 70° - 90°E, 150°W, and 30°W which are correlated with three maxima in the nitric acid analysis. A noteworthy feature seen in the LIMS and UKMO PV fields is a reversal in the meridional gradient of PV which occurs in the 110°E - 170°E sector associated with an equatorward displacement of high PV. This change in meridional gradient is also suggested in the 500 K nitric acid field. However, a similar reversal which occurs in the mid-latitude LIMS PV and nitric acid near 70°W has no counterpart in the UKMO field. In subtropical latitudes (e.g. at 30°S), ripples occur in the UKMO field, such as those near 40°W, which are possibly related to artifacts of the methods of observation and derivation of the gridded fields (e.g., Clough et al., 1985).

Several of the features observed at 500 K are evident at the 850 K level. For example, LIMS and UKMO show a tongue of high PV near 150°W which is more intense in the UKMO analysis (8 PV units vs. 6 for LIMS).

Near 30°W LIMS indicates a broad tongue of high PV, whereas the UKMO field indicates a shorter wavelength tongue of high PV near 10°W. Moreover, the UKMO analysis in this region shows a stronger meridional PV gradient. The low-latitude ripple pattern seen at 500 K is also evident at 850 K, e.g. near 40°W in UKMO. The 850 K PV fields are similar to the LIMS ozone distribution in several respects. For example, the ozone map indicates a tongue of low mixing ratio near 160°W with strong meridional gradients, while a region of weak meridional gradient is present in low latitudes near 110°E.

Although the LIMS and UKMO PV analyses at 500 K and 850 K exhibit qualitative similarities, the UKMO fields generally contain more longitudinal structure than do the LIMS maps. Some of this structure could be real, being on a scale that could be revealed by the good longitudinal resolution afforded by side-scanning on the TOVS instruments. Because of these local differences in PV distribution, potential users should exercise caution for quantitative applications. However, the larger-scale patterns involving distinct trough/ridge features and meridional extrusions of PV do seem to be captured in a fairly reasonable manner in light of the broad agreement with the trace constituent fields. This is particularly true for processes that are dominated by large scales of motion in a deep layer of the atmosphere.

Eliassen-Palm Flux. Meridional cross sections, from LIMS and UKMO data, of the (quasi-geostrophic) Eliassen-Palm flux divergence on May 19, 1979 are shown in Figure 5 (a scaled form of this quantity is actually plotted as explained in the caption). In the stratosphere, the two terms that constitute this divergence (see Eq. (2.2) in Dunkerton et al., 1981) are frequently large and of opposite sign, so the divergence is prone to large errors. Indeed, on the day shown, there is no apparent qualitative, let alone quantitative, agreement between the two fields. The LIMS field has convergence over a broad latitudinal band at middle latitudes, whereas the UKMO has divergence. It is likely that the UKMO field is the more suspect of the two, for it shows little continuity from one day to the next around the chosen day; the continuity of the LIMS field is better.

The serious discrepancies noted here between fields of Eliassen-Palm flux divergence are probably attributable to the poorer than normal vertical resolution of the UKMO analyses in the first half of 1979. Afterwards, UKMO analyses should generally be of much better quality (as found by Grose and Rodgers, 1986) because of better instrument performance and additional data from the HIRS-2 and MSU radiometers. Even so, the vertical resolution of the best possible analyses from these instruments is poorer than from LIMS. As most of the longitudinal variance in the stratosphere is in the longest zonal waves, which LIMS analyses should be able to resolve, side-scanning in the TOVS instruments does not prove to be a significant advantage for the calculation of Eliassen-Palm flux divergence, but it can be for calculations of synoptic maps of PV.

3.2. Impact of Base Level on Derived Quantities

In principle, basic retrieved fields from satellites need be no less accurate in the Southern Hemisphere than they are in the Northern Hemisphere. Indeed the spatially uniform quality of the measurements is one of the main advantages of using satellite data in diagnostic studies. To calculate many quantities of dynamical interest, however, a field of geopotential height at a base level (usually in the lower stratosphere) is also needed. Herein lies the main shortcoming of derived quantities for the Southern Hemisphere: conventional observations of the troposphere and lower stratosphere (e.g., from radiosondes) are sparse. It is not our purpose here to judge the reliability of base-level analyses made available by different meteorological centers but to illustrate the differences in derived quantities (eddy flux, zonal wind, potential vorticity, and divergence of the Eliassen-Palm flux) that are produced in the stratosphere when satellite thickness data from one source - in this case the UKMO analyses - are used in conjunction with various base-level analyses of geopotential height at 100 mb.

The impact of different base level analyses is discussed for two periods: (1) June and September, 1981 and (2) September, 1985 Table 1. In the 1981 comparison (Section 3.2.1), UKMO satellite data are combined with ECMWF and NMC 100 mb base-level height analyses to obtain heights at 50, 20, 10, 5, 2, and 1 mb. Temperatures at each level were derived hydrostatically from the height analyses and geostrophic winds were then calculated. The 1981 comparison investigated the impact on eddy statistics such as the stationary and transient eddy height variances and eddy fluxes of heat and momentum. The 1985 comparison uses the same approach as for 1981, but includes the base-level height analyses from UKMO and considers the impact on zonal wind, potential vorticity, and Eliassen-Palm flux divergence.

3.2.1. 1981 Eddy Statistics

The impact of the different base height analyses for June and September 1981 has been considered by comparing monthly mean fields and daily transient eddy statistics obtained using the ECMWF and NMC base analyses. This comparison was made using horizontal maps at the 100 and 10 mb levels (not shown) and latitude-pressure cross sections of the zonal mean (also see Karoly, 1989). Results are discussed separately for stationary and transient eddy features.

Stationary Eddies. Any differences between the ECMWF and NMC height analyses at the 100 mb level occur with the same amplitude at all stratospheric levels. The typical maximum regional differences in the monthly mean height maps were ~ 100 m. Differences in the zonal and monthly mean height fields were smaller, except at high latitudes poleward of 65°S, where the differences in the zonal mean height fields were ~ 100 m (not shown).

Regional differences in the mean height field in middle latitudes lead to differences in stationary wave amplitudes and fluxes of heat and momentum. The stationary wave amplitudes are larger in the thickness data in September than in June so that differences in the stationary wave amplitudes due to the different base analyses are more apparent in June than in September. Stationary wave diagnostics for June 1981 are shown in Figures 6, 7, and 8 for the NMC and ECMWF base analyses. The rms zonal variations of height show that the ECMWF analyses have larger amplitude stationary waves. The stationary eddy meridional fluxes of momentum and heat are qualitatively similar in structure for both base analyses. However, quantitative differences in momentum flux, in particular, are large at 60°S, with 30% stronger poleward transport for the ECMWF base analyses.

Transient Eddies. Since transient eddy statistics are quadratic, the differences due to the base analyses do not occur with the same amplitude at all levels, but the major differences are similar at all levels. Regional differences (not shown) in amplitude of the transient eddy kinetic energy or height variance are relatively larger than for the stationary eddy fields, but there is reasonable qualitative agreement for the regions of large amplitude transient eddy activity. The horizontal fields from the ECMWF base analyses seem to be more spatially coherent, whereas those from the NMC base analyses have more short-length-scale spatial structure.

For the transient eddy statistics, there is good qualitative agreement for the two base analyses for June and September. The zonal mean daily standard deviation of height for September 1981 is shown in Figure 9 with the fields obtained using the NMC and ECMWF base analyses and the difference, NMC-ECMWF, on the right. This eddy statistic is very similar for the two analyses, except for large differences which occur at high latitudes, poleward of 70°S. For the horizontal maps of the transient eddy meridional fluxes of momentum and heat there are large regional differences at 100 mb (not shown). In terms of the zonal-mean pattern, large differences also occur at high latitudes, poleward of 70°S, for the meridional eddy fluxes (Figs. 10 and 11), whereas differences of 10% in the momentum transport occur in middle latitudes.

Overall, there is qualitative agreement between stationary and transient eddy statistics derived using the two base analyses for the two months, but quantitative differences exist, particularly at high latitudes, which would be very important for budget studies or other derived statistics in the middle-upper stratosphere. Similar differences between ECMWF and NMC high-latitude analyses in the Southern Hemisphere lower stratosphere have been documented by Randel et al. (1987), Lambert (1988), and Newman and Randel (1988).

3.2.2. 1985 Derived Quantities

The 1985 base-level impact is evaluated for the ECMWF, NMC, and UKMO base height information combined with the UKMO (TOVS) thickness analyses. Comparisons are presented for zonal mean wind, potential vorticity, and the Eliassen-Palm flux divergence.

Zonal Wind. Three meridional cross sections of zonal-mean wind on September 8, 1985 are shown in Figure 12 for ECMWF, NMC, and UKMO base-level analyses. These fields include values for the troposphere using operational heights from the three centers. (Note that the NMC heights at 50 mb for the September 1985 comparison are the operational product rather than the stratospheric analysis series (i.e. from 70 - 0.4 mb). The three wind analyses show a westerly jet in the middle-upper stratosphere which is centered near 55°S and 35 km with maximum speeds in excess of 80 m/s. At low and middle latitudes there is good agreement between the fields. At high latitudes, however, the three fields differ by up to 10-15 m/s at 100 mb, the impact of which is noticeable up to the upper stratosphere (e.g., at 80°S). These findings are typical for September 1985.

Potential Vorticity. Three synoptic maps of PV on the 850 K surface on September 24, 1985 are shown in Figure 13 derived using the ECMWF, NMC, and UKMO base-level height information. The fields are generally in good agreement. This result is only to be expected since derivatives of the UKMO thickness field (a field the three maps have in common) contribute most to the value of PV. Differences in detail do occur, however, such as the presence of a tongue of high PV near 60°S, 20°E in the NMC and UKMO analyses, which does not appear in the ECMWF analysis. Conversely, at 60°S, 30°W the ECMWF field contains a tongue of high PV which is absent in the NMC and UKMO analyses.

At low latitudes horizontal gradients of the thickness field become small, and those of the geopotential height field at the base level contribute proportionally more to the value of PV. Moreover, gradients of PV are small at low latitudes, so a small difference between base-level analyses can make a big difference to an isopleth's position. Thus, although the tongue of locally high PV near 180°E appears on all three maps, it extends further westward for the ECMWF base. Similar differences were found at the 500 K surface (not shown).

Eliassen-Palm Flux. Three meridional cross sections of the Eliassen-Palm flux divergence which are derived using the ECMWF, NMC, and UKMO base data are shown in Figure 14. Although the three fields all have divergence in the stratosphere at high latitudes and convergence at middle and sub-polar latitudes, there are significant differences. At high latitudes in the upper stratosphere (e.g., at 80°S), divergence with the ECMWF base is half as large as that with the others. A region of flux divergence exists in the NMC analysis at 55°S, 40 km which is not shown in the ECMWF and UKMO fields. Notice also that there are significant differences at high latitudes in the troposphere.

4. CONCLUSIONS

Overall, examination of the basic meteorological fields (temperatures, winds) derived from measurements by different satellites leads to similar conclusions to those reached in the PMP-1 comparison of data for the Northern Hemisphere. While there is usually qualitative agreement between the different sets of fields, substantial quantitative differences are evident, particularly in high latitudes. Differences in vertical and longitudinal resolution between the limb- and nadir-viewing experiments result in quantitative differences in fields of derived winds, potential vorticity and Eliassen-Palm flux divergence.

There are several techniques that may be used to evaluate the reliability of the information contained in the measurements:

(1) Independent data sets (derived from different instruments and base-level analyses) should, ideally, be used in parallel and studied for consistency.

(2) The temporal continuity of derived fields is often useful in highlighting problems with the data.

(3) Consistency between zonal-mean meridional velocities inferred separately from zonally averaged momentum and thermodynamic equations provides a powerful constant (assuming unknown friction can be neglected).

(4) The conservation of potential vorticity over a period of a week or so in the middle stratosphere is an important objective check on the reliability of the analyses.

(5) A good correlation over short periods between some quasi-conservative chemical species (whose concentrations are measured directly) and potential vorticity (a highly derived quantity) is persuasive evidence that the data have at least qualitative value.

It is clear from our study that the fidelity of the base-level analysis is of great importance in calculating derived quantities for the middle atmosphere, especially in the Southern Hemisphere. We have demonstrated this relationship by using a single set of satellite data (from TOVS) with base-level analyses obtained from three meteorological centers (ECMWF, NMC, and UKMO). The Eliassen-Palm flux divergence is particularly sensitive to the base-level analysis (though it can also be sensitive to the instrument used), as is the potential vorticity at low latitudes where horizontal gradients are weak.

Some effort is needed to improve base-level analyses in the Southern Hemisphere. There appear to be particular problems at high latitudes where conventional observations are sparse and infrequent, and spurious features may influence diagnostics throughout the stratosphere. Significant uncertainties in operational analyses of geopotential height over Antarctica have been identified by Hollingsworth et al. (1985), Lambert (1988), and Trenberth and Olson (1988) for tropospheric levels, and similar discrepancies have been observed in the present comparison at 100 mb. Possible reasons for poor quality analyses in this region include sparse radiosonde coverage, steep Antarctic topography, and difficulties in adequately assimilating upper-air reports from isolated stations (e.g., at the South Pole). It is known, for example, that NMC received radiosonde reports from the

South Pole station for only two days in the month of September 1985. Such telecommunication problems should be resolved.

The steep Antarctic topography may produce errors in the forecast model first-guess fields and, furthermore, will generate gravity wave activity which may produce sampling problems in the radiosonde observations.

Clearly, care should be taken in removing spurious features from the reference-level analyses in the polar region and ensuring that the operational centers have access to all Antarctic radiosonde station data. Further comparison of radiosonde heights with the final operational analyses should be made specifically for the reference-level (e.g., 100 mb). A comparative appraisal of the procedures used to construct the different base-level analyses for the Southern Hemisphere would be of value to Middle Atmosphere researchers. For example, investigation of which station data is incorporated into the base analyses could be made along with evaluating differences in analysis procedures in data-void regions. Such a task may require the use of a data assimilation model and is beyond the scope of the average user of the data; those who produce the analyses are best placed to assess and improve them.

On the basis of the experience gained from the PMP-1 and Williamsburg workshops, we feel it prudent to advise caution in drawing inferences, particularly quantitative ones, from meteorological fields derived from satellite data. Such counsel is certainly apt for the Southern Hemisphere, where coverage of data from sources other than satellite is limited.

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Table 1. MASH INTERCOMPARISON TOPICS AND DATA SOURCES.

Quantities Derived From Archived Satellite Analyses	
Date	January, May 1979
Satellite Analyses	LIMS, NMC, SAMS, UKMO
Base-Level Analyses	NMC, CIRA'85, ECMWF
Derived Quantities	U, PV, EPFD

Base-Level Impact on Derived Quantities		
Date	June, September 1981	September 1985
Satellite Analyses	UKMO	UKMO
Base-Level Analyses	ECMWF, NMC	ECMWF, NMC, UKMO
Derived Quantities	Z, VT, UV	U, PV, EPFD

Derived Quantities

EPFD - Eliassen-Palm Flux Divergence
PV - Potential Vorticity
U - Zonal Wind
UV - Eddy Momentum Flux
VT - Eddy Heat Flux
Z - Geopotential Height

Base-Level Height Sources

CIRA - COSPAR Reference Atmosphere (MAP Handbook, Volume 16)
ECMWF - European Center for Medium Range Weather Forecasts, Reading
NMC - National Meteorological Center, Washington
UKMO - United Kingdom Meteorological Office, Bracknell

Satellite Stratospheric Temperature/Thickness Data and Analyses

HIRS - High Resolution Infrared Sounder
LIMS - Limb Infrared Monitor of the Stratosphere
MSU - Microwave Sounding Unit
NESDIS - National Environmental Satellite Data and Information Service
NMC - National Meteorological Center
SAMS - Stratospheric and Mesospheric Sounder
SSU - Stratospheric Sounding Unit
TOVS - TIROS-N Operational Vertical Sounder (HIRS + MSU + SSU)
UKMO - United Kingdom Meteorological Office (Thickness Retrievals)
VTPR - Vertical Temperature Profile Radiometer

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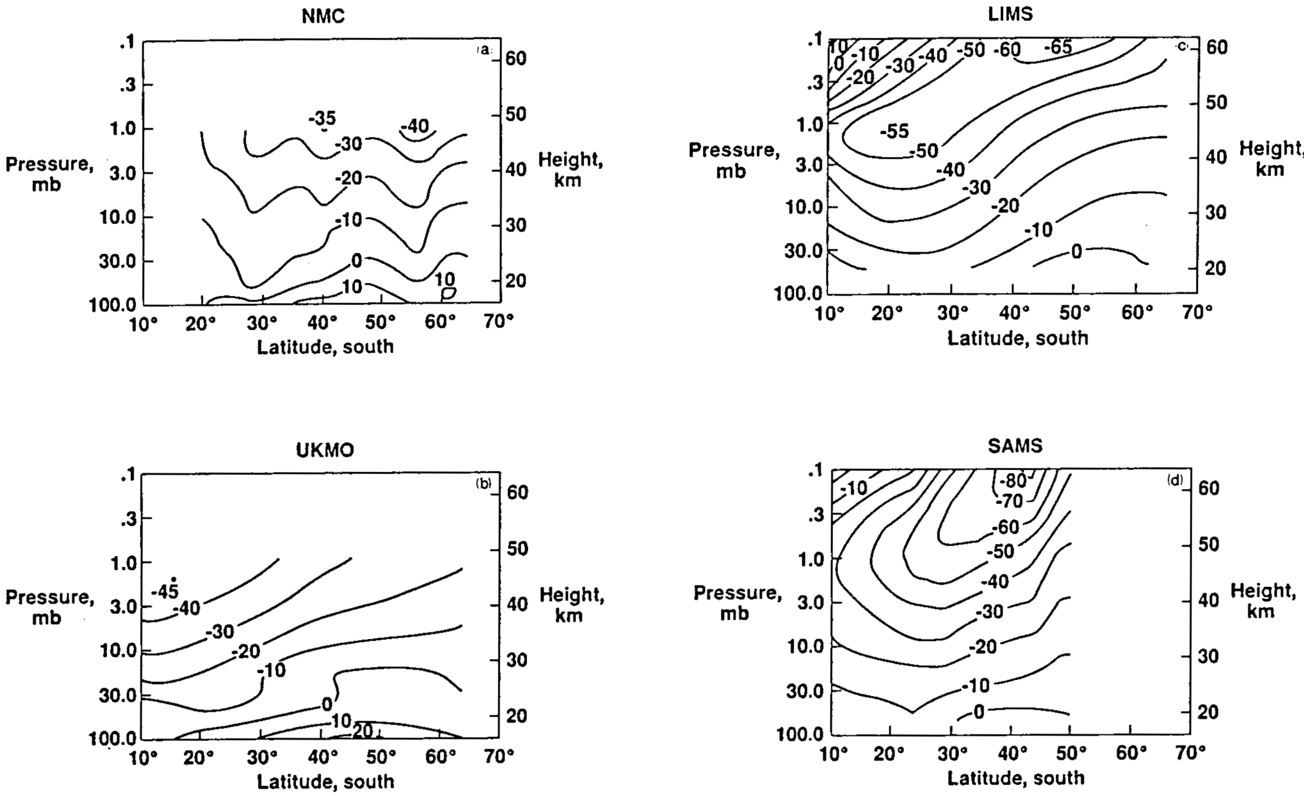

Figure 1. Zonal-mean geostrophic wind (m s^{-1}) for the Southern Hemisphere on January 26, 1979 from (a) NMC, (b) UKMO, (c) LIMS, and (d) SAMS.

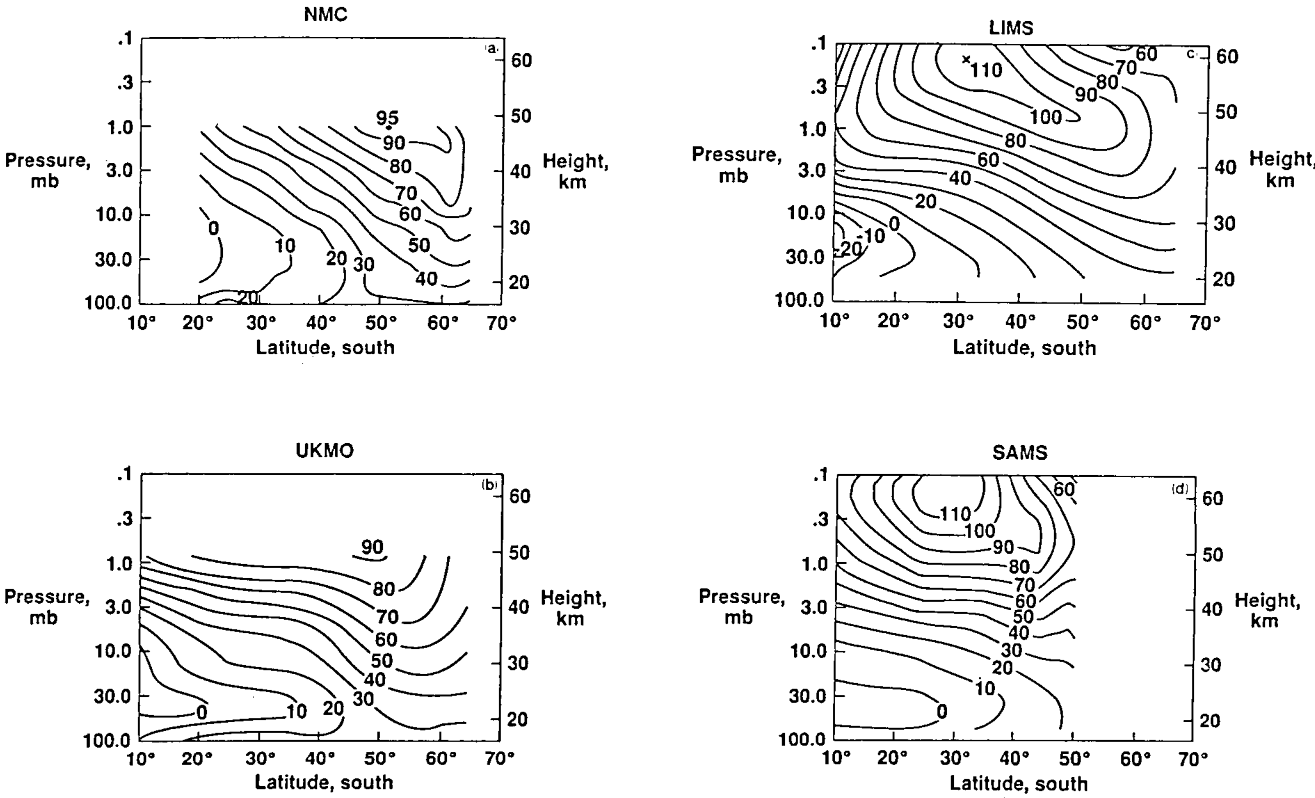

Figure 2. As in Figure 1, but for May 19, 1979.

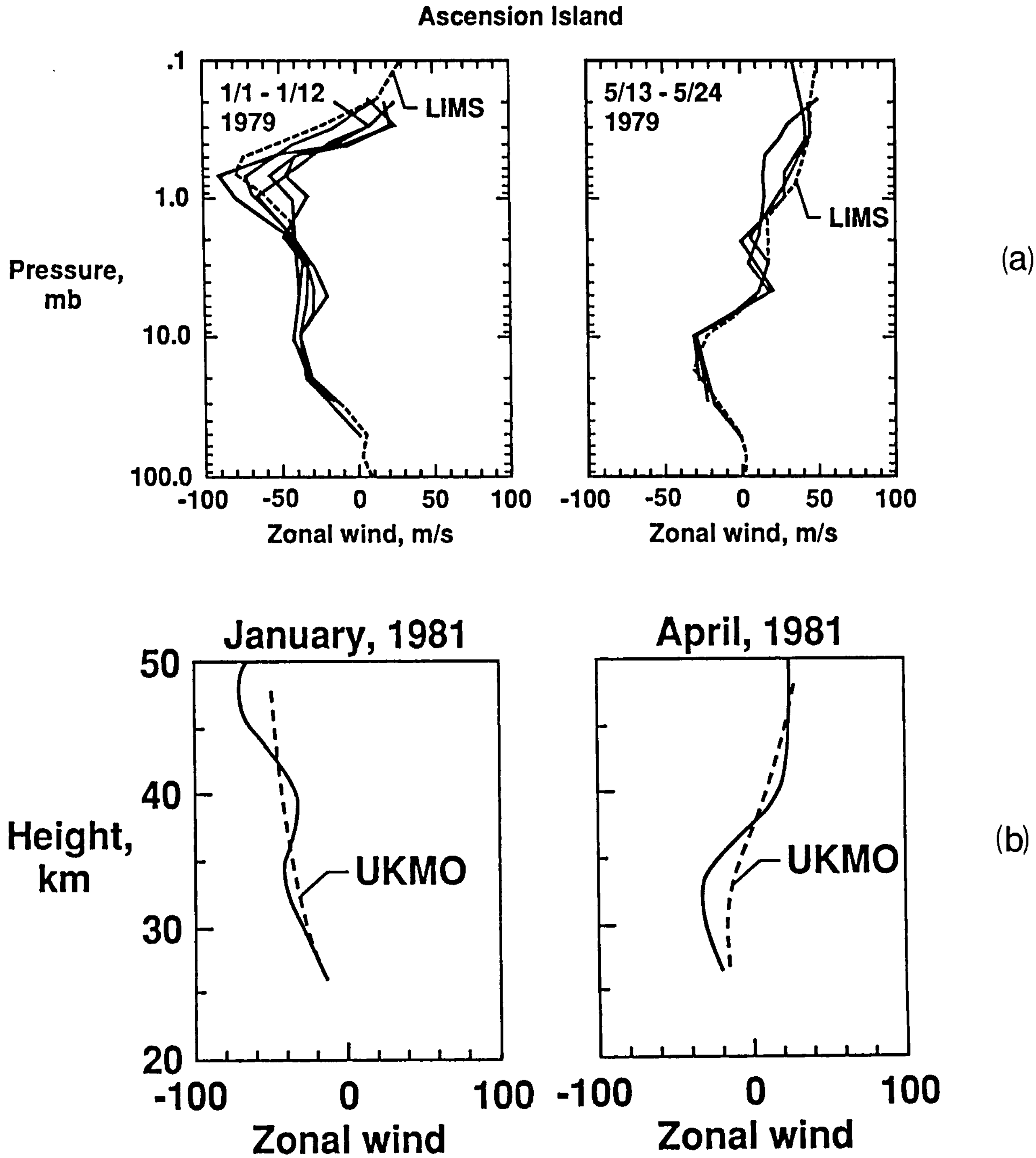

Figure 3. (a) Twelve-day mean LIMS geostrophic (dashed) and individual rocket profiles (solid) of zonal wind at Ascension Island during January 1-12, 1979, and May 13-24, 1979. (b) Monthly mean UKMO geostrophic (dashed) and rocket (solid) zonal wind at Ascension Island during January and April 1981. Units: m s^{-1}.

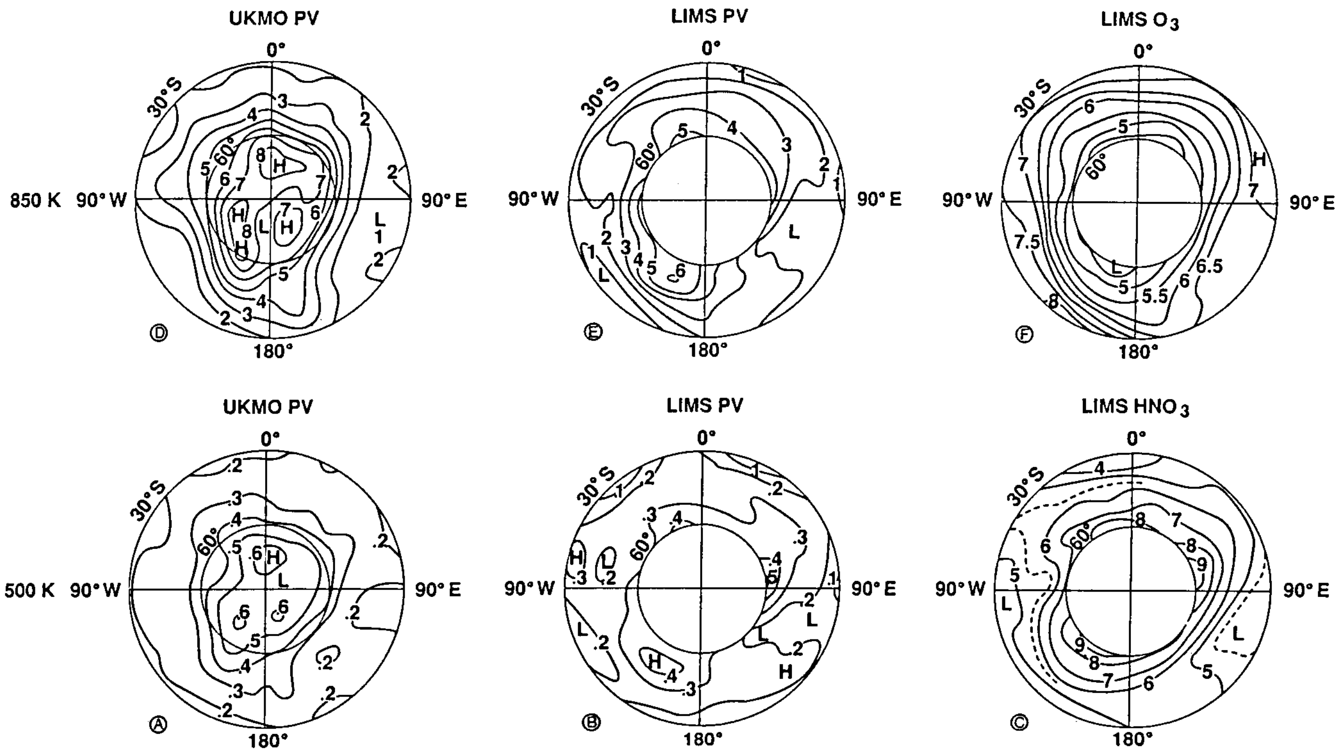

Figure 4. (a,d) UKMO and (b,e) LIMS maps of the modulus of Ertel's potential vorticity on the 500 K and 850 K isentropic surface for the Southern Hemisphere on May 24, 1979 (units: 10^{-4} K m^2 kg^{-1} s^{-1}). (c) 500 K nitric acid mixing ratio (ppbv) and (f) 850 K ozone mixing ratio (ppmv) from LIMS on the same day.

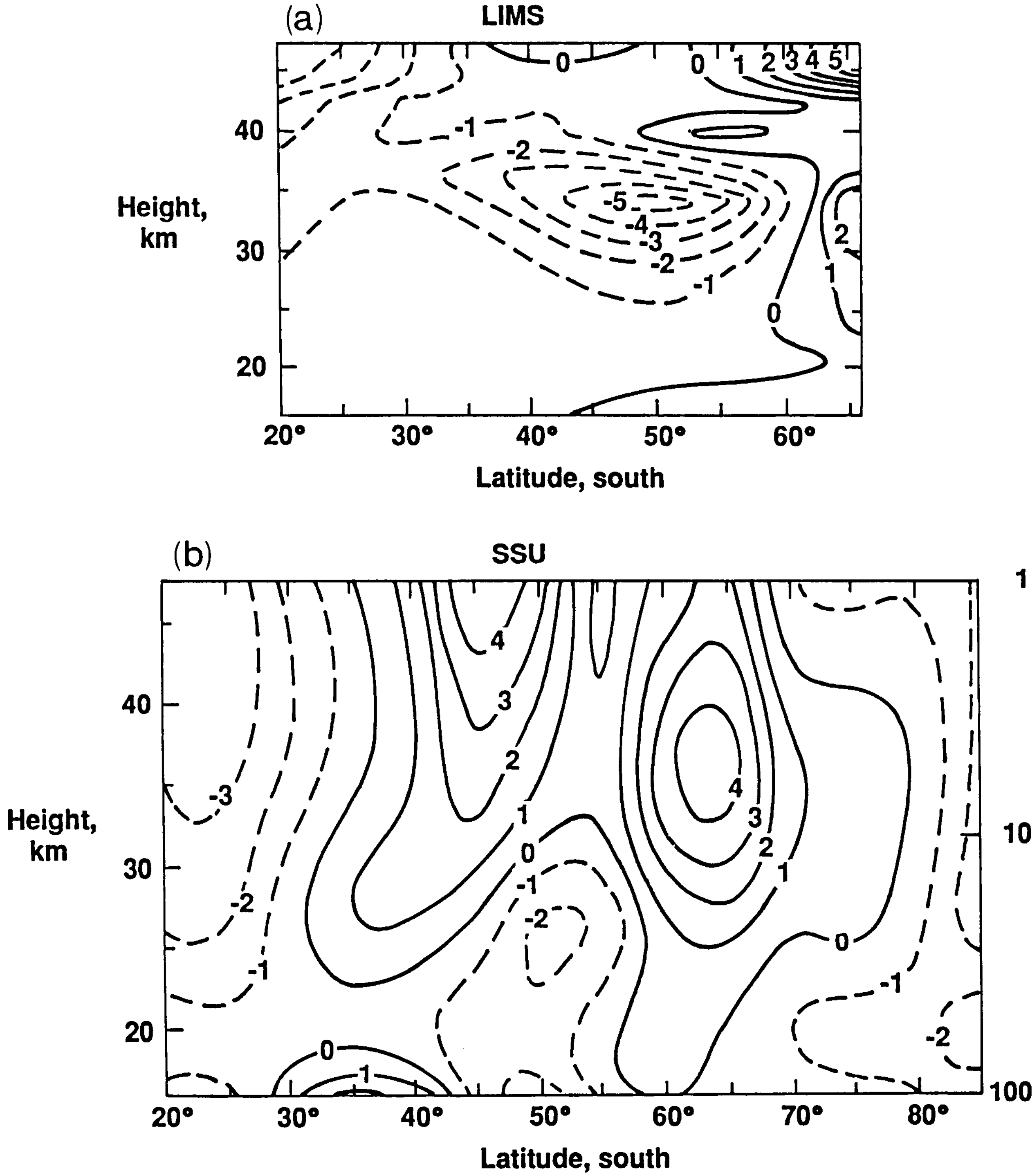

Figure 5. The divergence of the Eliassen-Palm flux from (a) LIMS, and (b) UKMO, scaled to give the zonal force per unit mass due to eddies, for the Southern Hemisphere on May 19, 1979. It is the quantity denoted as D_F by Dunkerton et al. (1981), units: 10^{-5} m s^{-2}. Pecked lines indicate negative values (convergence).

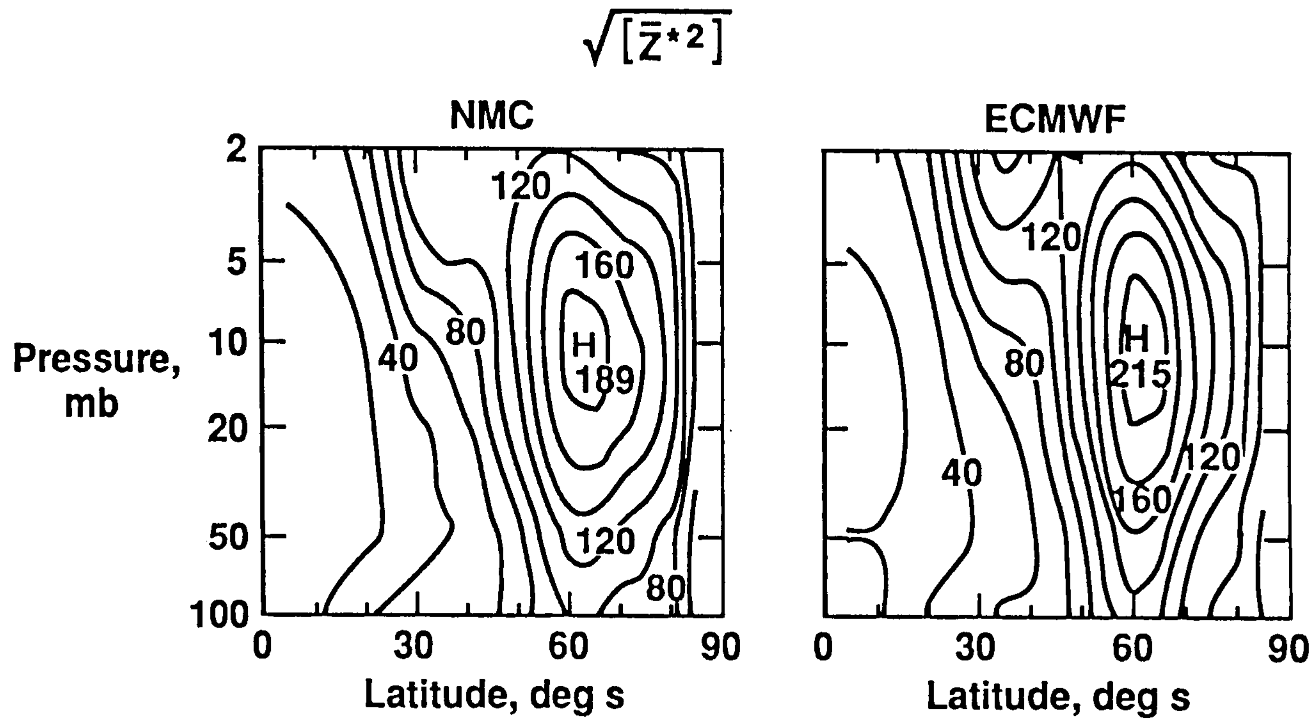

Figure 6. Stationary eddy rms zonal variations of geopotential height (m) for the Southern Hemisphere using NMC (left) and ECMWF (right) base-level analyses of geopotential height at 100 mb for June 1981.

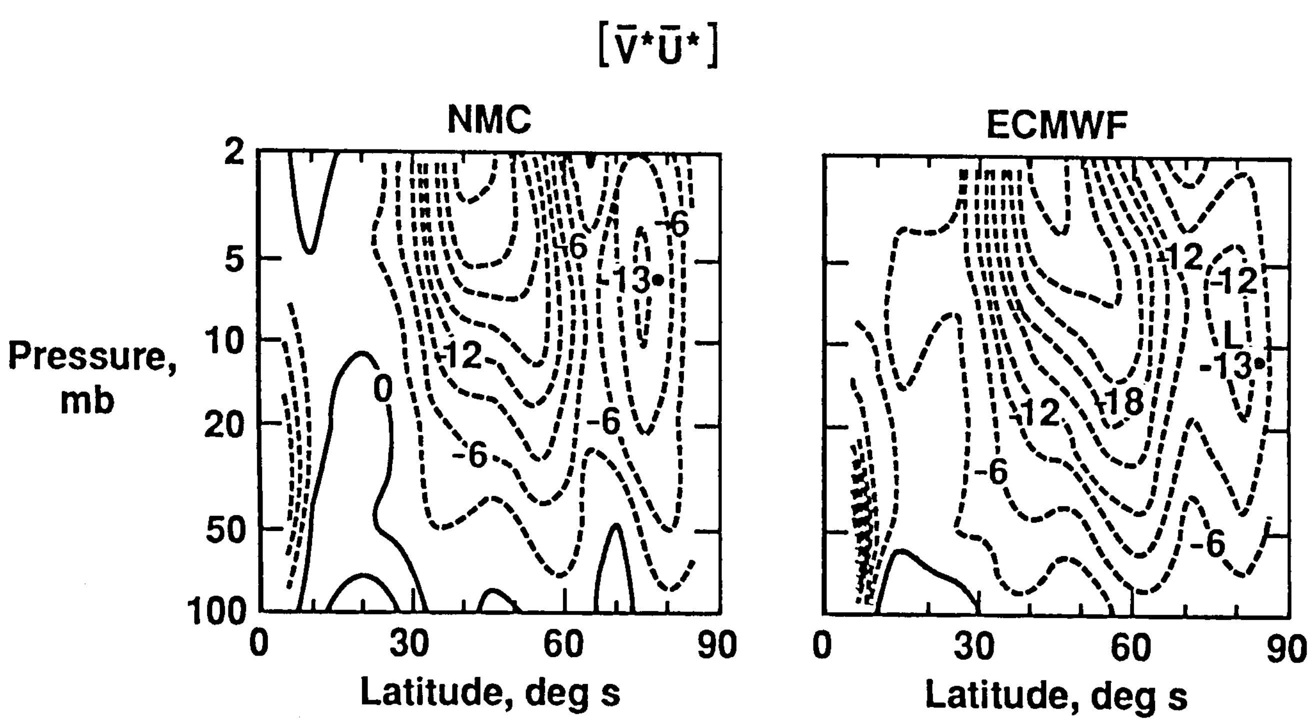

Figure 7. As in Figure 6, but for the stationary eddy momentum flux (m^2 s^{-2}).

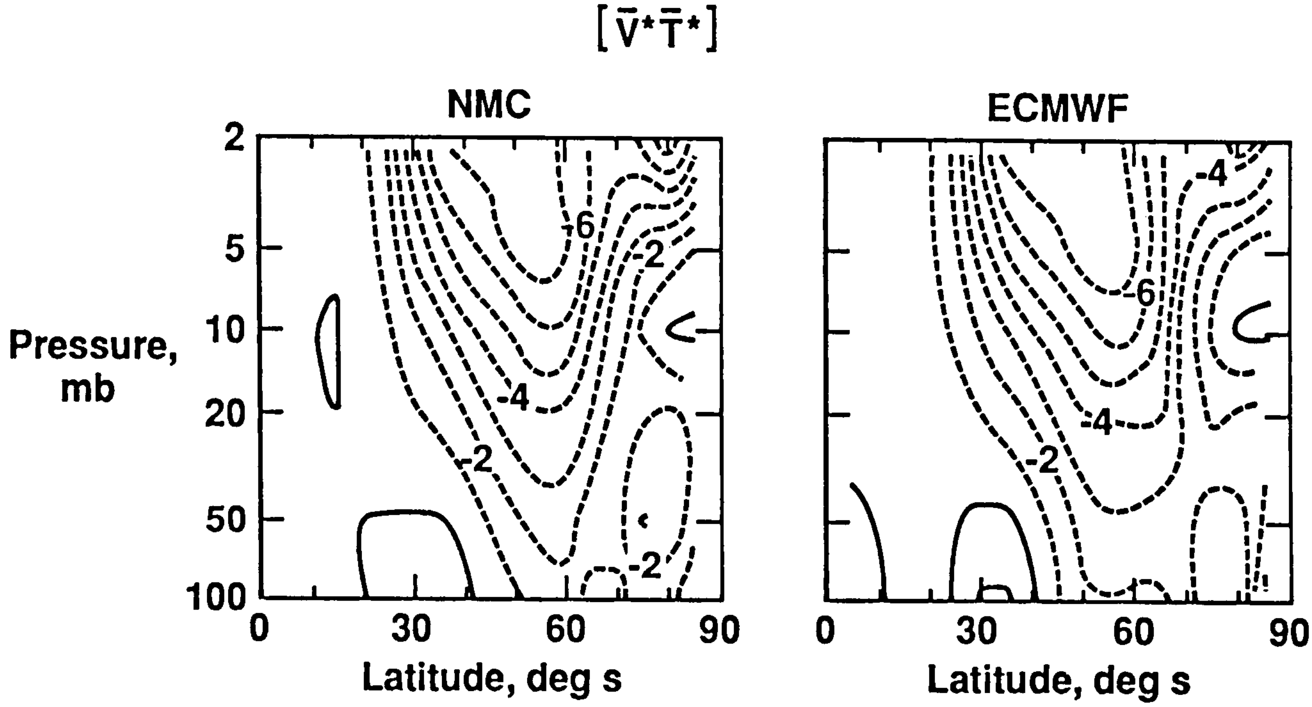

Figure 8. As in Figure 6, but for the stationary eddy heat flux (K m s^{-1}).

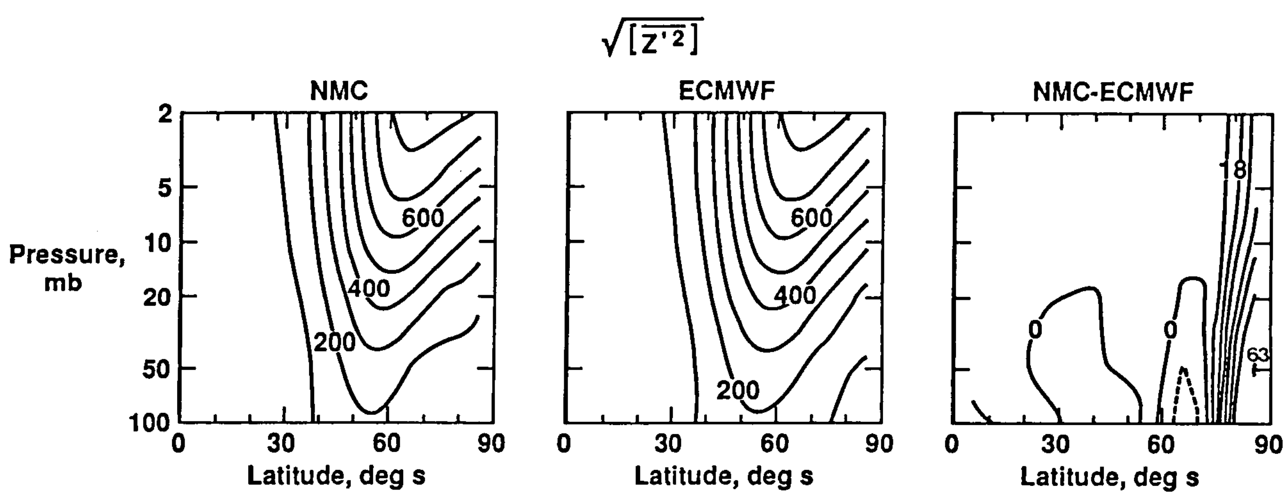

Figure 9. Transient eddy rms daily variations of geopotential height (m) for the Southern Hemisphere using NMC (left) and ECMWF (center) base-level analyses of geopotential height at 100 mb, and the difference NMC-ECMWF (right), for September 1981.

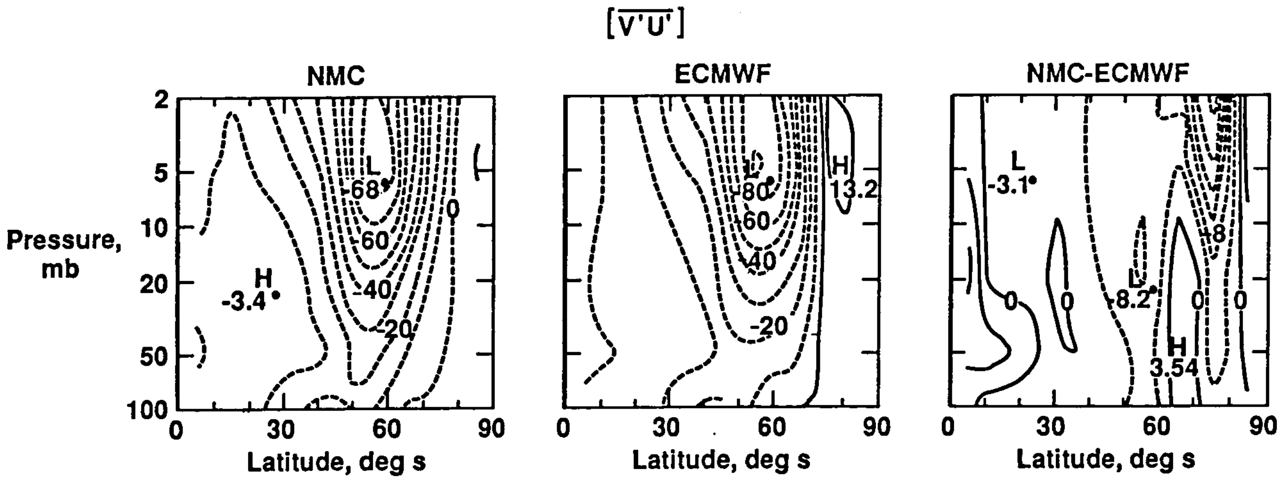

Figure 10. As in Figure 9, but for the transient eddy momentum flux ($m^2\ s^{-2}$).

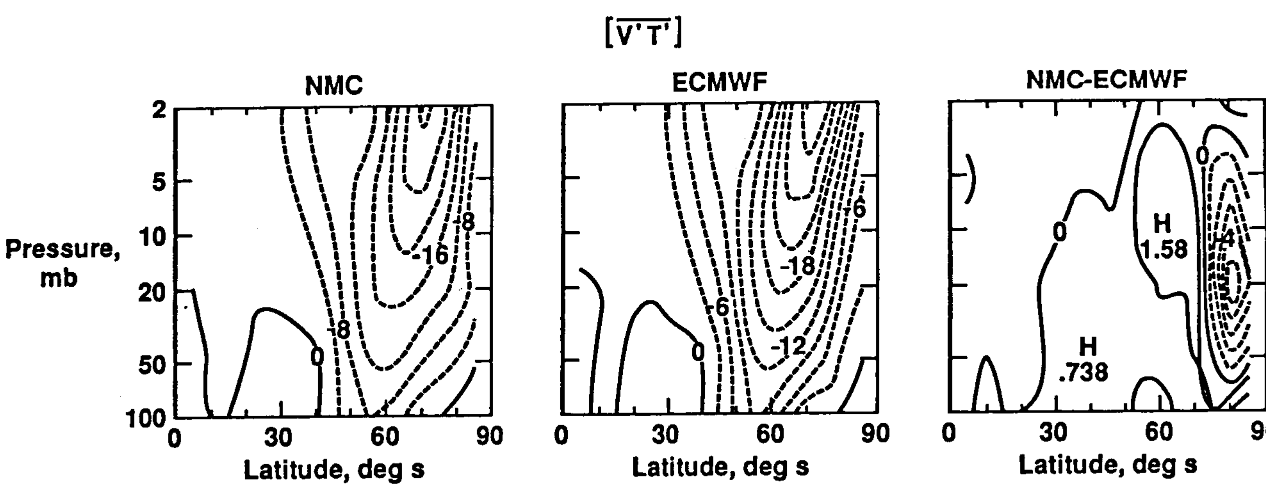

Figure 11. As in Figure 9, but for the transient eddy heat flux ($K\ m\ s^{-1}$).

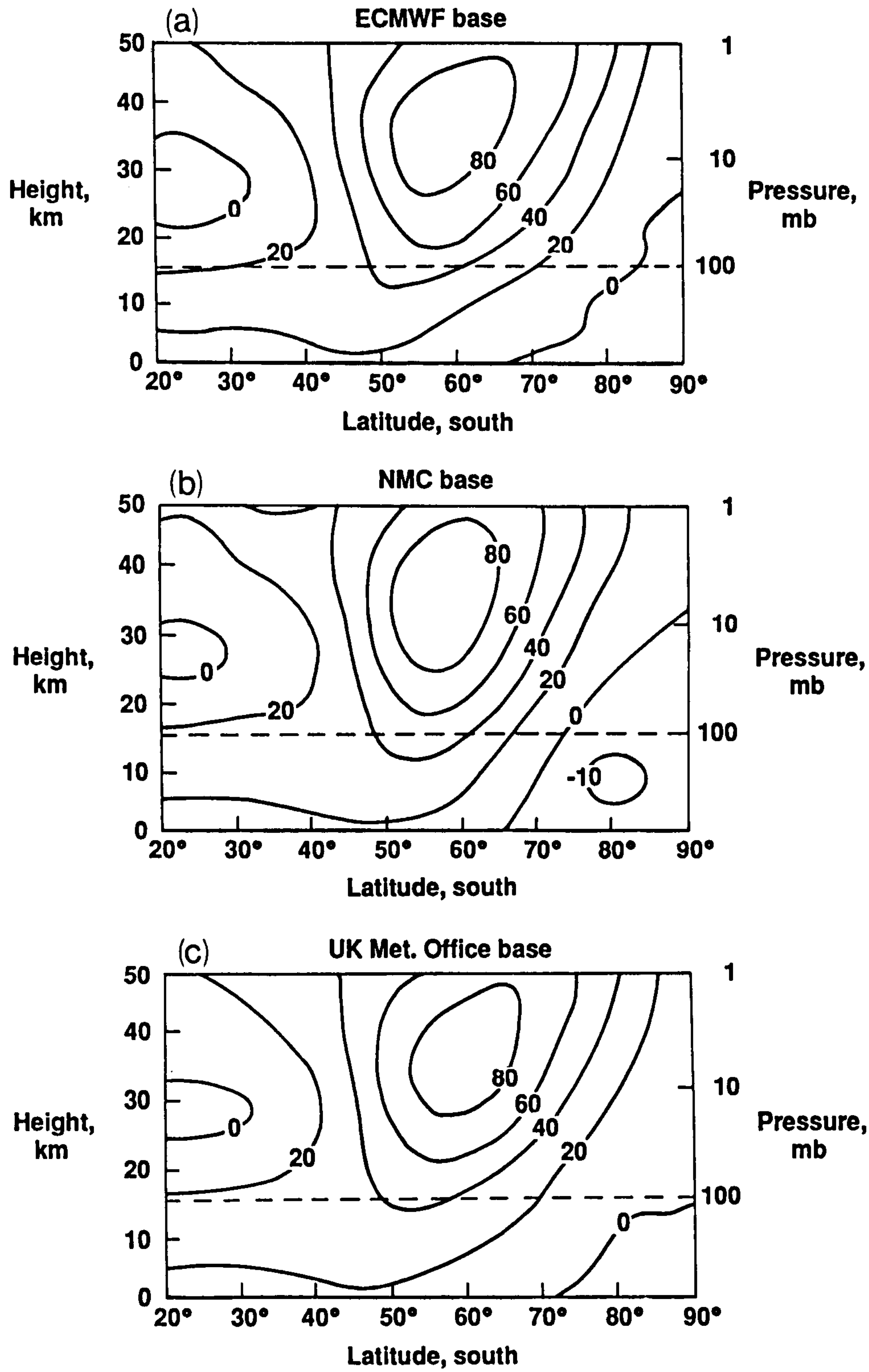

Figure 12. Zonal-mean geostrophic wind (m s^{-1}) for the Southern Hemisphere on September 8, 1985. Fields constructed using different base-level analyses of geopotential height at 100 mb from (a) ECMWF, (b) NMC, and (c) UKMO.

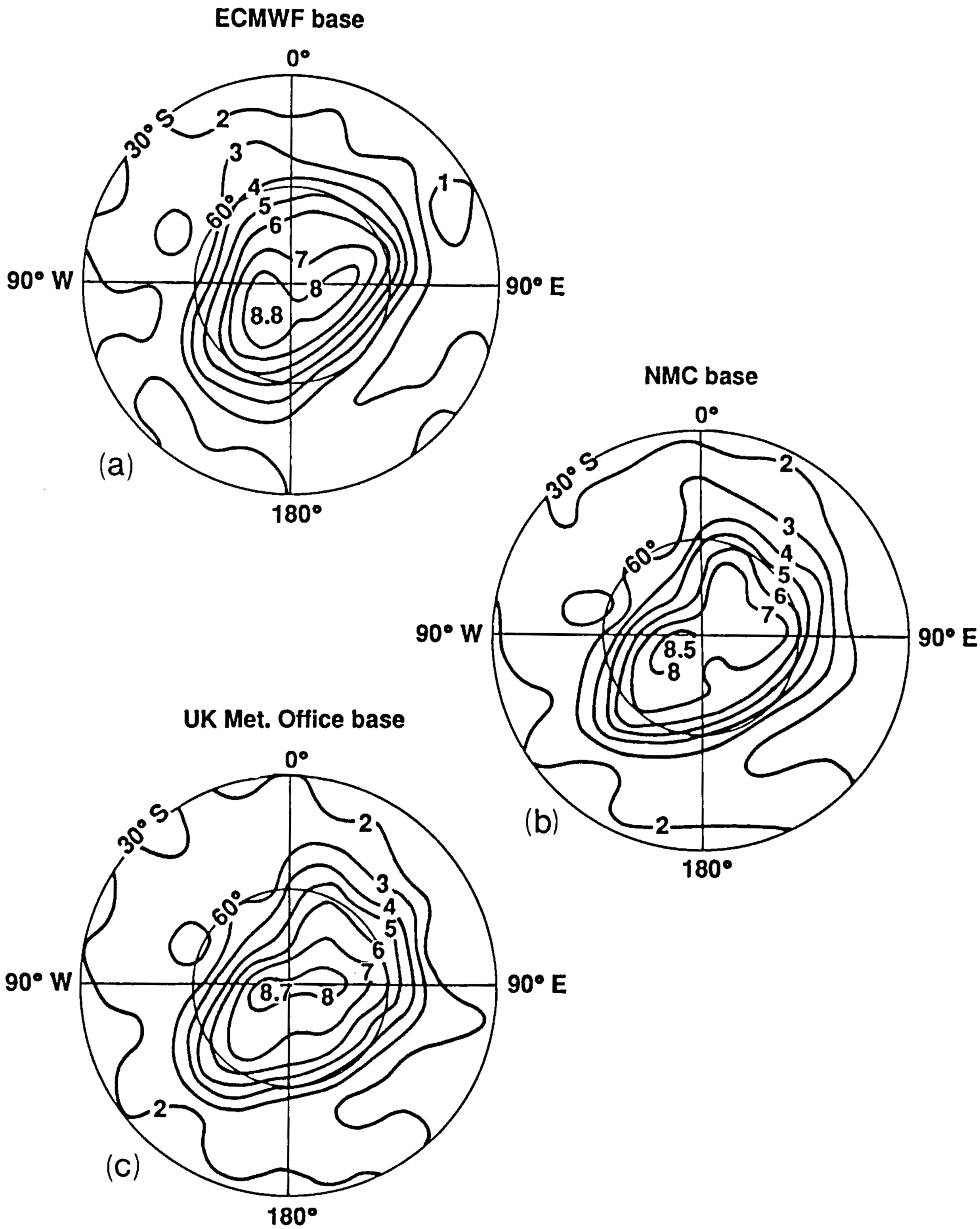

Figure 13. Synoptic maps of the modulus of Ertel's potential vorticity on the 850 K isentropic surface for the Southern Hemisphere on September 24, 1985 (units: 10^{-4} K m^2 kg^{-1} s^{-1}). Fields constructed using different base-level analyses of geopotential height at 100 mb from (a) ECMWF, (b) NMC, and (c) UKMO.

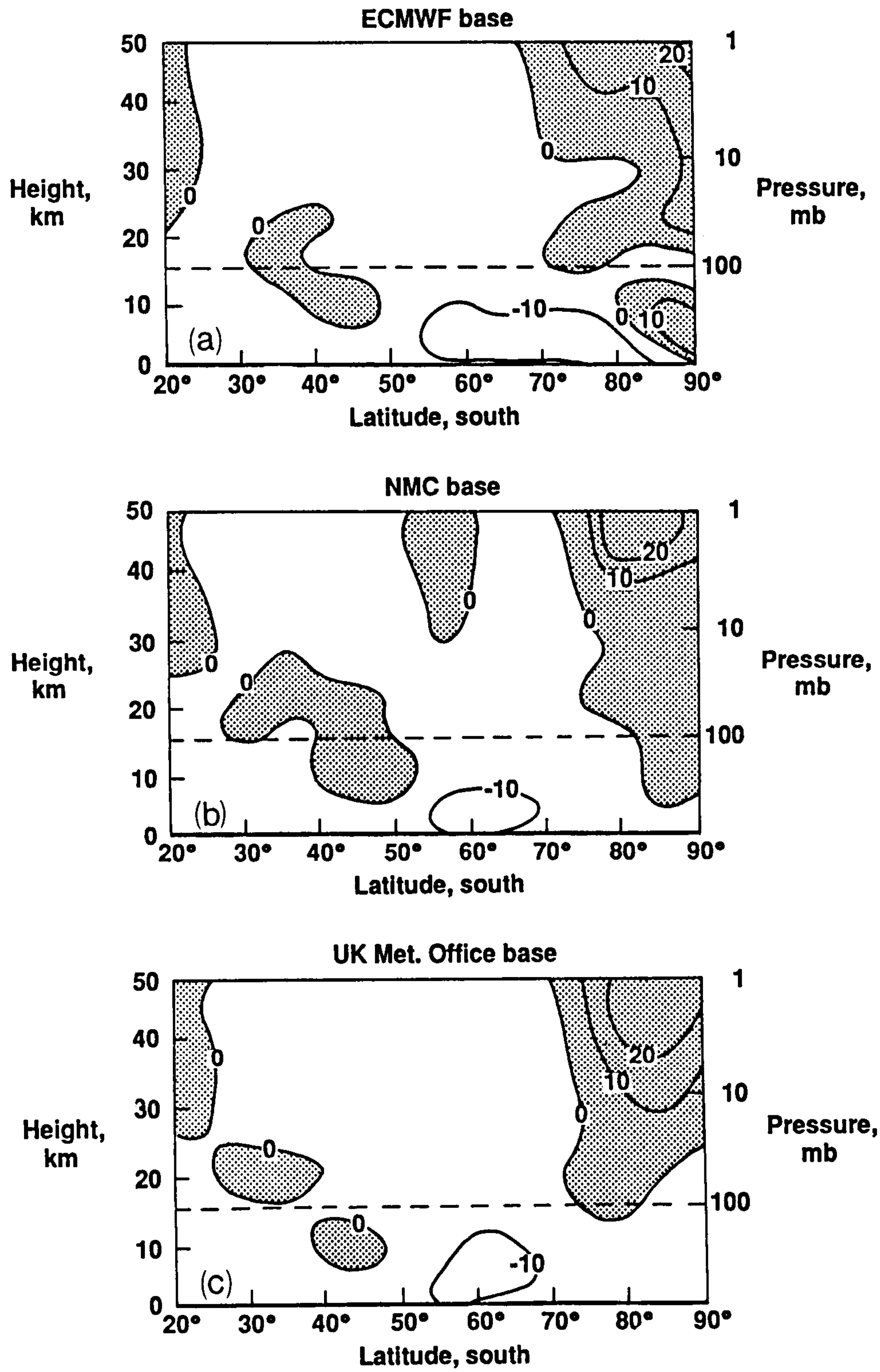

Figure 14. As in Figure 12, but for the divergence of the Eliassen-Palm flux, scaled as in Figure 5 (units: 10^{-5} m s^{-2}). Stipling denotes positive values (divergence).

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16. Abstract As part of the international Middle Atmosphere Program (MAP), a project was instituted to study the dynamics of the middle atmosphere in the Southern Hemisphere (MASH). A pre-MASH workshop was held in Williamsburg, Virginia on April 14—17, 1986. The workshop had two aims: 1) comparison of Southern Hemisphere dynamical quantities derived from various archives of satellite data, and 2) assessing the impact of different base-level height information on such derived quantities. The dynamical quantities examined included geopotential height, zonal wind, potential vorticity, eddy heat and momentum fluxes, and Eliassen-Palm fluxes. It was found that while there was usually qualitative agreement between the different sets of fields, substantial quantitative differences were evident, particularly in high latitudes. The fidelity of the base-level analysis was found to be of prime importance in calculating derived quantities - especially the Eliassen-Palm flux divergence and potential vorticity. The report recommends that improvements be made in base-level analyses. In particular, quality controls should be introduced to remove spurious localized features from analyses, and information from all Antarctic radiosondes should be utilized where possible. The report advises caution in drawing quantitative inferences from satellite data for the middle atmosphere of the Southern Hemisphere.

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