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Global empirical wind model for the upper mesosphere/lower thermosphere. I. Prevailing wind

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Abstract. An updated empirical climatic zonally averaged prevailing wind model for the upper mesosphere/lower thermosphere (70–110 km), extending from 80°N to 80°S is presented. The model is constructed from the fitting of monthly mean winds from meteor radar and MF radar measurements at more than 40 stations, well distributed over the globe. The height-latitude contour plots of monthly mean zonal and meridional winds for all months of the year, and of annual mean wind, amplitudes and phases of annual and semiannual harmonics of wind variations are analyzed to reveal the main features of the seasonal variation of the global wind structures in the Northern and Southern Hemispheres. Some results of comparison between the ground-based wind models and the space-based models are presented. It is shown that, with the exception of annual mean systematic bias between the zonal winds provided by the ground-based and space-based models, a good agreement between the models is observed. The possible origin of this bias is discussed.

Key words: Meteorology and Atmospheric dynamics (general circulation; middle atmosphere dynamics; thermospheric dynamics)

1 Introduction

Numerous attempts have been undertaken to construct a 2 D empirical wind model of the upper atmosphere that includes the upper mesosphere/lower thermosphere region. The most widely used models are the COSPAR International Reference Atmosphere 72 (CIRA-72, 1972) and the Fleming *et al.* (1988) model, which is a part of CIRA-86 model. Since it concerns areas far above the greatest heights for standard rawingsondes the CIRA-72 model was mainly based on rocket data. Only sparse meteor radar and ionospheric drift data were used to develop the CIRA-72 model. A description of the global zonal wind structure at 70–110 km is given in the Fleming *et al.* (1988) model. In that model the zonal wind below 85 km was calculated from the thermal (gradient) wind equation and the related temperature was determined from satellite radiance measurements. Above 85 km wind data were calculated from the mass spectrometer and incoherent scatter (MSIS-83) empirical model temperatures (Hedin *et al.*, 1991). This method is not a direct way of wind determination. In addition the reliability of the gradient winds is also questionable due to the low accuracy of the satellite temperature measurements in the upper mesosphere, and the absence of direct temperature data between 85 and 100 km in the MSIS model. It is useful to note that the Fleming *et al.* (1988) model does not contain information about meridional winds. We do know that, unlike in the stratosphere, the prevailing meridional winds in the upper mesosphere/lower thermosphere are only 1.5–2 times slower than the zonal winds. A well-known meridional wind model for this region (Groves, 1969) has been developed utilizing rather sporadic rocket wind data, which were obtained at only a few sites in the Northern Hemisphere (NH). As a result, this model presented a quite schematic picture of the height-latitudinal structure of a zonal mean meridional wind field at 60–110 km for separate seasons. In this case the circulation in the Southern Hemisphere (SH) was believed to be a mirror image of NH wind systems for the corresponding season, only with the opposite sign.

Nastrom *et al.* (1982) have also developed an empirical model of the meridional circulation at 95 km for NH summer. Their analysis has shown that at all measurement sites the prevailing meridional wind was predominantly southward independent of longitude. Therefore it was concluded that the prevailing wind in the lower thermosphere (LT) is mainly ageostrophic.

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This conclusion of meridional wind ageostrophicity for different seasons was made by Portnyagin (1986) who analyzed ground-based meridional wind observations for sites located in two narrow latitudinal belts and situated far apart in longitude.

A model known as "interim new CIRA" contained a set of radar derived direct wind measurements for 14 locations (Manson *et al.*, 1985). These were extensively discussed (Manson *et al.*, 1985), and much useful information about global wind structures in the upper mesosphere/lower thermosphere region was obtained. In Manson *et al.* (1991) comparisons between satellite-derived gradient winds from the Fleming *et al.* (1988) model and radar-derived winds were made. It was found that overall the agreement for the zonal winds at the particular observational sites was rather good (but not complete). The comparison of meridional winds revealed significant ageostrophy.

The first attempt to develop a global height-latitude model of meridional winds from ground-based radar measurements was undertaken by Manson *et al.* (1987). However due to insufficient data (only nine sites were used) the authors only succeeded in constructing the height-latitude cross-sections of meridional wind fields for two months and for a limited latitude range in both hemispheres.

The analytic empirical horizontal wind model (HWM93), using the height interval 70–110 km, has been recently developed by Hedin *et al.* (1996). The model is based not only on the CIRA-86 tabulations, but also on the selected historical rocket data, previous rocket data based tabulations, meteor radar and MF radar data, and lower thermosphere incoherent scatter data. However the data used for constructing of the model for the upper mesosphere/lower thermosphere region (80–100 km) were obtained at the limited number of stations (see Table 1 in Hedin *et al.*, 1996).

Recently direct wind observations from the wind-imaging interferometer (WINDII) and the high-resolution Doppler imager (HRDI) on board the Upper Atmosphere Research Satellite (UARS) have provided the principal new global wind data set for the upper mesosphere/lower thermosphere region. The corresponding empirical prevailing zonal wind models (see, e.g., Wang *et al.*, 1997) and the prevailing meridional wind model (Fauliot *et al.*, 1997) were constructed. Fleming *et al.* (1996) and Portnyagin *et al.* (1998) concluded that, in general, the space-based zonal wind models exhibited significant differences relative to the ground-based models. However, Fauliot *et al.* (1997) have stated that the WINDII-based prevailing meridional wind model are similar to the ground-based Portnyagin *et al.* (1995) model.

Here we present an updated version of our ground-based Global Empirical Wind Model (GEWM) for the upper mesosphere/lower thermosphere (70–110 km). The previous versions of the model, derived from the meteorological radar and MF radar wind measurements, have been published earlier by Portnyagin (1984, 1986, 1987), Portnyagin and Solovjova (1992), and Portnyagin *et al.* (1995). In Sect. 2 information about the data sets is presented. In Sect. 3 we describe the method of model construction. The characteristics and variations with altitude, season and latitude of the main zonal wind structures in the upper mesosphere/lower thermosphere are presented in Sect. 4. The characteristic height-latitude meridional wind patterns and their seasonal evolution is the main topic of Sect. 5. The results of validation of our model by comparison of the model values with the actual experimental data as well as with the existing empirical models are discussed in Sect. 6. Section 7 presents our conclusions and summary.

2 Data sets

To construct the GEWM we have assimilated the all now available wind measurements in the upper mesosphere/lower thermosphere, which were carried out with help of meteor radar and MF wind measurements. Table 1 gives a list of sites, their geographical positions and information about measurement periods. Since the measurement periods at the different sites do not completely coincide, it is necessary to estimate the degree of interannual variability in the wind data sets. A statistical analysis of the multi-year wind measurements at sites with sufficiently long time records allows us to estimate the mean square standard deviation σ_i of the monthly mean wind values. For mid latitudes of the NH (Obninsk, 1964–1995, 95 km height) we obtained $\sigma_i \leq 4.5$ m/s for zonal and $\sigma_i \leq 3.5$ m/s for meridional winds. For high latitudes of the SH (Molodezhnaya st., 1972–1985, 95 km height) we have $\sigma_i \leq 6$ m/s for the zonal winds and $\sigma_i \leq 4$ m/s for the meridional winds. Similar estimates for other observational sites with shorter measurement periods give similar results. Therefore on average we may adopt values of σ_i ranging from 4 to 6 m/s for the zonal wind and from 3 to 5 m/s for the meridional wind.

In developing the zonal mean model the next problem is longitudinal variations of the monthly mean values. We have calculated the mean square deviation of monthly mean values from the zonal mean σ_λ using data for the sites located in two narrow latitudinal belts: 52–57°N (Jodrell Bank/Manchester, Kuhlungsborn-Collm, Obninsk, Kazan, Badary, Saskatoon) and 45–50°N (Kiev, Kharkov, Volgograd, Durham, Khabarovsk). For both latitudinal belts we have obtained $\sigma_\lambda \leq 7$ m/s and ≤ 5 m/s for zonal and meridional wind, respectively. These values also reflect the effect of interannual variability. The results of the DYANA campaign (Singer *et al.*, 1994) also support our results. The comparison of available data for College, Poker Flat, Kiruna, Tromse and Dixon (a high-latitude belt) and for Punta Borinquen, Kauai, Kingston and Waltair (a low-latitude belt) permits us to suppose that on global scale the intensity of seasonal wind variations in the upper mesosphere/lower thermosphere is much stronger compared to longitudinal variations.

In relation to Table 1 it should be noted that some sites have height-varying measurements while others have data only at the mean height of the meteor zone

Table 1. Data base

Station	Location	Method	Observing period	References
Heiss I.	80.5°N, 58°E	MR[a]	1.1965–10.1985	Own wind measurements
Dixon	72°N, 81°E	MR[a]	10.1994–4.1995	Own wind measurements
Tromso	70°N, 19°E	MF	1987–1989	Manson *et al.* (1991)
Kiruna[b]	68°N, 20°E	MR[a]	1974–1975	Manson *et al.* (1985)
Poker Flat	65°N, 147°W	MR	7.1980–12.1984	Manson *et al.* (1987)
College	65°N, 148°W	MR[a]	1.1967–8.1968	Hook (1970)
Tomsk	57°N, 85°E	MR[a]	10.1965–12.1966	Nazarenko (1968)
Kazan	56°N, 49°E	MR	1986–1988	Fakchrutdinova (1991), Sidorov *et al.* (1988)
Obninsk	55°N, 37°E	MR[a]	1964–1995	Own wind measurements
Kuhlungsborn	54°N, 12°E	MR[a]	1977–1980	HHI Geop. Data (1977–1980)
			1–3.1990	Singer *et al.* (1994)
Juliusruh	54.6°N, 13.5°E	MF	1990–1991	Schmider *et al.* (1994)
Jodrell Bank	53°N, 2°E	MR[a]	1953–1958	Greenhow and Neufeld (1961)
Saskatoon	52°N, 107°W	MF	1979–1982	Manson *et al.* (1985)
Sheffield	53.3°N, 3.8°W	MR[a]	1–3.1990	Singer *et al.* (1994)
Badary	52°N, 102°E	LF[a]	1975–1981	Petruchin (1983)
Collm	52°N, 15°E	LF	1983–1986	Schminder and Kurschner (1988)
			1990–1991	Schminder *et al.* (1994)
Kharkov	50°N, 36°E	MR[a]	1980–1983	Kalchenko (1987)
		MR	1987	Kascheev *et al.* (1988)
Kiev	50°N, 31°E	MR[a]	9.1964–2.1966	Lysenko *et al.* (1969)
Khabarovsk	49°N, 135°E	MR[a]	1976–1985	Makarov (1988)
Volgograd	49°N, 44°E	MR[a]	1978–1985	Own wind measurements
Garchy[b]	47°N, 3°E	MR	1970–1976	Manson *et al.* (1985)
Monpazier[b]	45°N, 1°E	MR	1975–1980	Manson *et al.* (1985)
Bologna	45°N, 12°E	MR[a]	1–3.1990	Singer *et al.* (1994)
Durham	43°N, 71°W	MR	1978/79/84	Manson *et al.* (1987)
Frunze	43°N, 73°E	MR[a]	1964–1982	Karimov (1984)
Yambol	42.5°N, 26.5°E	MR[a]	2–3.1987	Lysenko *et al.* (1988)
Urbana	40°N, 88°W	MR	1991–1992	Franke *et al.* (1993)
Dushanbe	38°N, 68°E	MR[a]	1968–1969	Babadjanov *et al.* (1974)
Ashkhabad	37°N, 58°E	MR[a]	7.1988–6.1989	Ovezgeldyev *et al.* (1991)
Kyoto	35°N, 136°E	MR	5.1983–5.1984	Manson *et al.* (1985)
Atlanta	34°N, 84°W	MR	1974/75, 1976/77	Manson *et al.* (1985)
Kauai	22°N, 160°W	MF	10.1990–8.1992	Fritts and Isler (1994)
Punta Borinquen[b]	18°N, 67°W	MR	1977–1978	Manson *et al.* (1985)
Waltair	18°N, 83°E	MR[a]	7–8.1979	Devara *et al.* (1981)
Jamaica	18°N, 77°W	MR	3.1971–2.1972	Scholefield and Allyene (1975)
Ramey	18°N, 67°W	MR	2.1981–6.1981	Roper (1984)
Christmas Island	2°N, 158°W	MR	1988–1989	Avery *et al.* (1989)
		MF	1.1990–6.1991	Vincent (1993)
Mogadisho	2°N, 45°E	MR[a]	1968–1970	Babadjanov *et al.* (1974)
Jakarta	6°S, 107°E	MR	11.1992–10.1995	Tsuda (1995)
Townsville	20°S, 147°E	MF	1978–1980	Manson *et al.* (1985)
Grahamstown	33.3°S, 30°E	MR	1987–1993	Malinga and Poole (1997)
Adelaide	35°S, 138°E	MF	1978–1983	Manson *et al.* (1985)
			1984–1986	Manson *et al.* (1991)
Christchurch	44°S, 173°E	MF	6.1978–2.1980	Manson *et al.* (1985)
Mawson	68°S, 63°E	MF	1984–1986	Manson *et al.* (1991)
Molodezhnaya	68°S, 45°E	MR[a]	1967–1985	Own wind measurements
Scott Base	78°S, 167°E	MF	12.1982–11.1984	Portnyagin *et al.* (1993)

[a] Stations without height resolution; [b] Only zonal wind component

(about 95 km). It is therefore important to estimate the effect that averaging over the meteor zone has on the monthly mean winds. To do this we have used the measurement data from the Kazan meteor radar which is equipped with a height measuring system (Lysenko *et al*., 1994). These measurements were then averaged over the meteor zone and compared to the actual data at 95 km height. The result showed that the averaging effect is negligible in comparison with seasonal wind variations. Theoretical estimates (Palo *et al*., 1998) have also shown that this effect is nearly independent of latitude. We therefore conclude that measurement data from meteor radars without height resolution can be used in our analysis of the seasonal wind variations at 95 km altitude.

3 Method of the GEWM construction

The method of construction of the GEWM is as follows. As the first step all experimental monthly mean wind values (profiles), which were obtained using the equipment with height resolution, were interpolated (and some extrapolated) over height. As a result the wind values were calculated for constant height levels with a standard step over height (usually 1 km). Then for each height level the wind values were interpolated over latitude using a routine cubic spline procedure. The values obtained were additionally smoothed over latitude with help of the Legendre function's decomposition. This procedure is correct for the 2D wind models, (actually an assumption about zero winds at the poles is made).

The next step is adaptation of the obtained preliminary (first step) model to the meteor wind data without height resolution. These data are usually related to the average height of about 95 km at the different latitudes, and show very consistent and regular seasonal behaviour which is practically the same as deduced from the meteor radar wind measurements with height resolution (Lysenko *et al*., 1994). The general conclusion of this study (see also Sect. 2) is that the seasonal course of the height-averaged monthly mean meteor wind data are well matched to the corresponding monthly means at the particular height of about 95 km and that climatic features of the seasonal variations are very persistent independent of longitude and observational periods and consistent for all types of devices. This conclusion was supported by comparison of the wind measurement data with and without height resolution for the other latitudinal belts (see Table 1).

Based on these results, we tune the preliminary wind profiles at about 95 km to the data, obtained with the devices without height resolution, at the appropriate latitudes. The obtained additional wind profiles for the particular sites were also incorporated in the whole set of the wind profiles. Then, the smoothing procedures over latitude were repeated and resulting monthly mean values were calculated for the regular grid with a required height and latitude resolution (usually, 2.5° in latitude and 1 km in height). The whole model was constructed by taking into account the statistical weight (in a climatological sense) of the measurement data. Finally the height-latitude wind isoline plots were drawn with help of suitable software.

4 Global empirical zonal wind model

4.1 Monthly mean cross sections

The latitude-height cross sections of the zonally averaged mean zonal winds for all months are shown in Fig. 1. This figure clearly shows that the monthly mean zonal wind circulation is characterized by several global circulation structures with winds of a similar sign (direction). We can specify two periods with particularly stable circulation structures: November–February and May–August, and two periods when the seasonal circulation reconstruction processes are developing: March–April and September–October. During the greater part of the year (8 months) the circulation systems are rather stable. In the winter season (November–February in NH and May–August in SH) the global circulation region with dominating eastward winds extends over most of the height-latitude zone considered. Unclosed isolines in this region at 70 km and a negative vertical gradient of the zonal wind are evidence that this region is dynamically coupled with a eastward wind structure in the winter lower thermosphere (LT). Hence, it can be concluded that the considered region of eastward winds represents the upper part of a circulation structure formed in the zone of a winter circumpolar global strato-mesospheric cyclone. It is worth noticing that the height of the upper boundary of this cyclone varies non-monotonically in latitude and the latitudinal zonal wind gradient repeatedly changes its sign when passing from high to low latitudes.

During the summer season (May–August in NH and November–February in SH) in the upper mesosphere the westward circulation system is dominant. This global system is connected with a summer strato-mesospheric anticyclone as is indicated by the unclosed isotaches at 70 km and the negative vertical gradient of the westward winds.

In the LT during this season a circulation system with eastward winds is seen. Such a system seems to be connected with the axially symmetric cyclonic vortex prevailing in LT in summer. This vortex may be caused by a specific thermal regime at the mesopause/lower thermosphere heights.

As can be seen from Fig. 1 in the spring season (March–April in NH and September–October in SH) the eastward wind pattern, associated with the winter strato-mesosphere cyclone, becomes less pronounced and then disappears. This structure is gradually replaced by a structure with winds of the opposite sign (westward winds). During May this structure is transformed in two global structures, typical of summer season.

In the fall season (September–October in NH and March–April in SH) a process opposite to that in the spring season, is observed. In the upper mesosphere the eastward circulation structure, typical of the winter season, is primarily formed and then extended to the lower thermosphere.

In addition to these above considered structures, in the spring and fall seasons the intensive westward structures are well expressed at low latitudes, thus indicating the important role which the semiannual cycle plays at these latitudes.

4.2 Main parameters of the seasonal zonal wind variations

In this subsection we consider the spatial structure of annual mean zonal winds, and corresponding amplitudes and phases of annual and semiannual harmonics of seasonal zonal wind variations, which at 70–110 km make a 80–90% contribution to the integral variance of monthly mean wind values.

The height-latitude cross section of annual mean zonal wind in the upper mesosphere/lower thermosphere is presented in Fig. 3a. Some important features may be

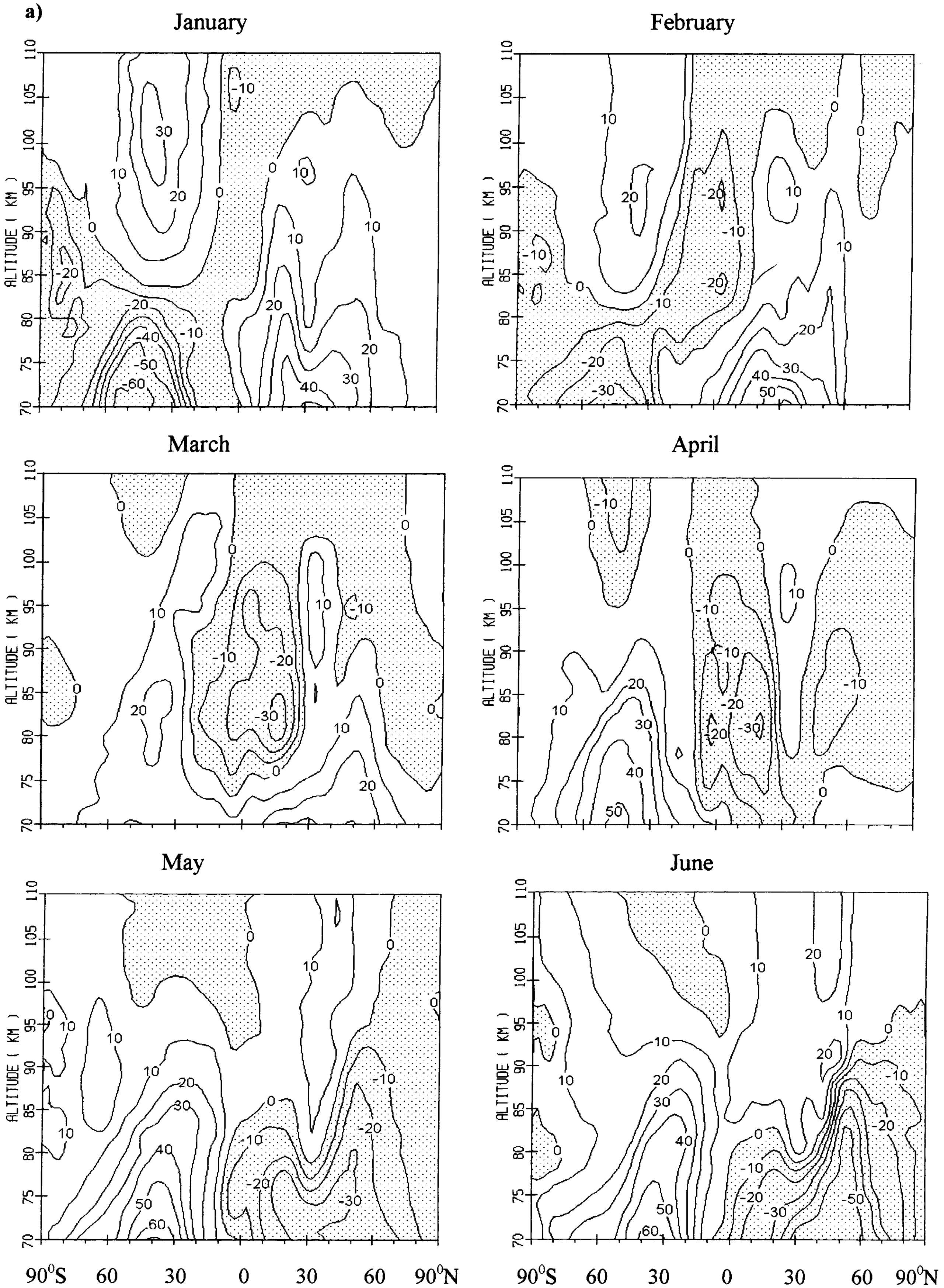

Fig. 1a, b. Height versus latitude contour plots for monthly mean zonal wind (positive eastward). Contour spacing is 10 m/s. **a** January–June; **b** July–December

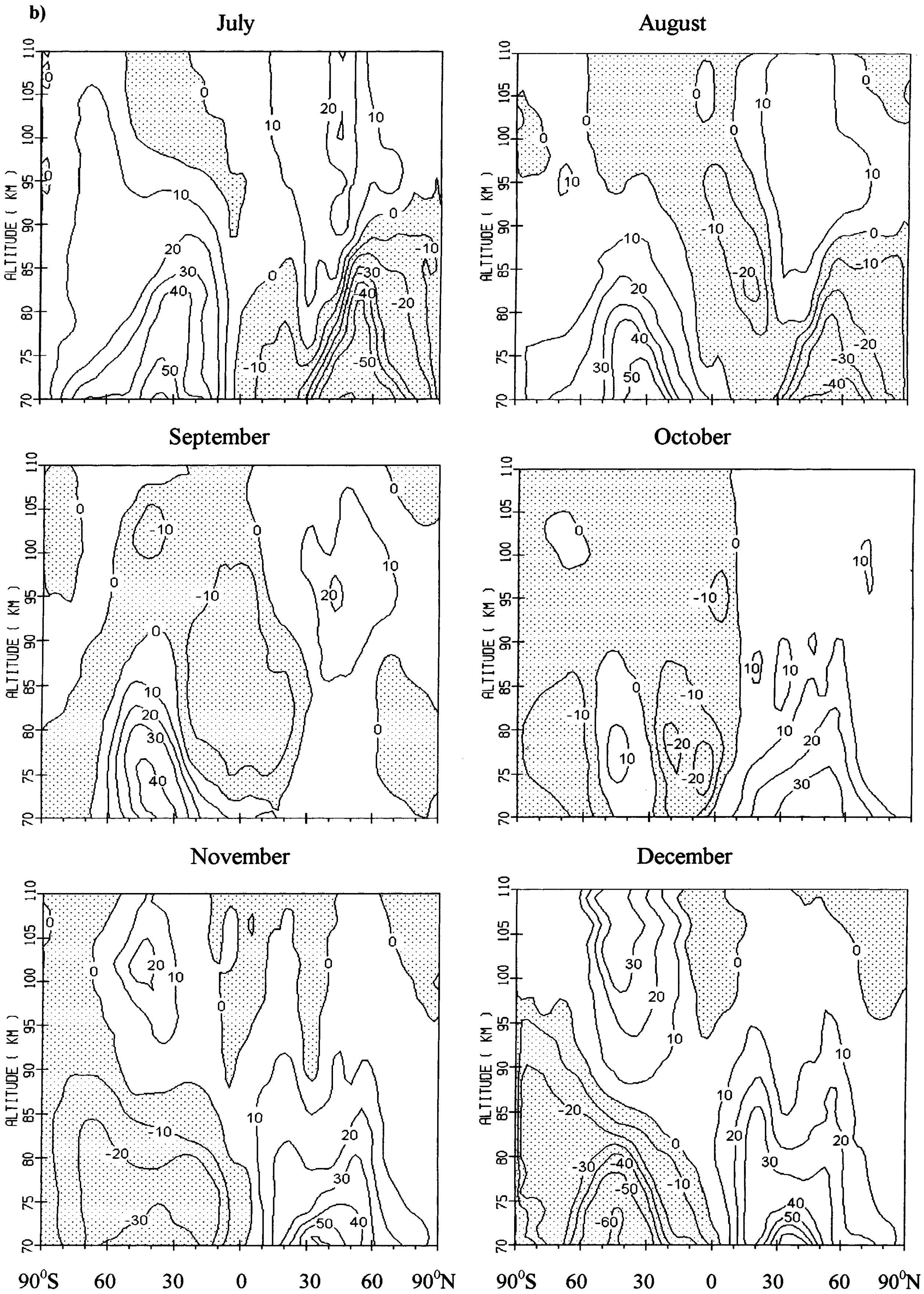

Fig. 1a, b. (Contd.)

revealed in this contour plot. We note that the annual mean zonal wind is characterized by three main large-scale structures with a certain degree of symmetry about the equator: eastward jets with maxima of order 10 m/s at moderate and subtropical latitudes and westward regions at equatorial and tropical latitudes. Below the mesopause region at high latitudes two additional westward wind structures are discernible. The annual mean eastward jets flanking a predominantly westward flow at the equatorial/tropical latitudes and a rather weak polar westward wind structures correspond closely to the well-known situation in the troposphere (Lorenz, 1976).

The contour plots of amplitudes and phases of the zonal wind annual variations are shown in Fig. 4 Clearly Fig. 4a shows that there are four regions of increased annual cycle amplitudes. Two of these regions (the most intensive) are situated at the mesospheric heights. Two less-pronounced but significant regions are revealed at the lower thermospheric heights.

The structure of the amplitude's isolines in the mesospheric regions of increased amplitudes removes all doubts that these regions are the upper parts of well-known regions of increased annual harmonic amplitudes in the stratosphere and mesosphere (Holton, 1975). Additional support for this conclusion may be found when considering annual phase behaviour (Fig. 4b). At all heights of these regions the maximum positive (eastward) winds occur in December/January in NH and in May/June in SH, which correspond to dominance of the winter season cyclonic circulation, typical also of the stratospheric and mesospheric heights. In summer an anticyclonic circulation is characteristic of strato-mesospheric layers, including the upper mesophere heights considered here.

In the lower thermosphere the zonal wind direction in the regions of increased amplitudes (Fig. 4) changes to the opposite one observed in the upper mesosphere, and the maximum of eastward winds occurs in the summer season (July–August in NH and December–January in SH). It means that the phase shift between the mesospheric and lower thermospheric annual wind oscillations in these regions is near to π for the corresponding seasons in both hemispheres. Along with the phases in NH are generally shifted at π relative to those in SH. It means that the nature of the mesospheric and lower thermospheric annual wind oscillations in NH and SH is similar. Naturally, there is no perfect symmetry between these oscillations in the two hemispheres. For example, in SH the annual cycle amplitudes in the thermospheric region exceed the corresponding values for NH by a factor of 1.5. Somewhat higher amplitude values, on average, are observed in the mesospheric region of SH, which in addition occupy a large space.

The height-latitude contour plots of amplitudes and phases of semiannual oscillation (SAO) of the zonal wind are shown in Fig. 5. The main features of this oscillation are as follows. The well-known region of increased SAO amplitudes is situated in the low-latitude zone. The isoline 10 m/s associated with this structure limits this one by the latitudes 25–30°. The centre of maximum amplitudes in this region was not observed exactly at the equator but split into two, placed near 20° in both hemispheres at 80–85 km.

Additional information about this structure may be obtained from the contour plots of the SAO zonal wind phases. According to our model (see Fig. 5b) the earliest maximum west wind (eastward wind) appears at the equator at beginning of May (and beginning of November) practically simultaneously at 85–95 km heights. The whole region of slowly changing phase, confined by the 5.5 (middle of May) isoline, is extended from about 30°N to 30°S, and is obviously related to the region of increased amplitudes of the zonal wind SAO. In the lower 80 km more rapid phase variations, which correspond to downward phase progression, are observed with average vertical gradients of about 1.5 month/10 km. Two other regions of increased amplitudes are observed at moderate and high latitudes in both hemispheres (Fig. 5a). The structure of these regions in NH and SH is not the same. The rather intensive zonal wind SAO is characteristic of the moderate latitudes of SH with maximum amplitudes of about 20 m/s in upper mesosphere at 75 km. The secondary maximum of increased amplitudes at these SH latitudes can be delineated in LT (10 m/s isoline confined this structure). It is difficult to conclude whether these two SH structures with increased SAO amplitudes are separate regions or parts of one extended region, but the phase behaviour in these regions (Fig. 5b) in the upper mesosphere is definitely different from that in LT.

The NH region of increased zonal wind SAO amplitudes is displaced toward higher latitudes in comparison with the corresponding SH region. The maximum amplitudes are limited by 15–17 m/s in the upper mesosphere and by slightly more than 5 m/s values in the lower thermosphere. The LT structure is not so definitely expressed as that in the SH. The character of phase variations in this region has certain similarities with those in the related region in SH. The position of the region with slowly varying phases (about 0.5–1.0) is observed at about 40–60°N, and the centre of increased amplitudes in LT is situated at the same latitudes. In SH the position of LT region of constant phases (isoline 6.0) also coincides with the LT region of increased amplitudes.

5 Global empirical meridional wind model

5.1 Monthly mean cross-sections

The monthly mean height-latitude contour plots of the prevailing meridional wind are shown in Fig. 2. Unlike the zonal winds the meridional wind structures in NH and SH for the same season are in general of opposite sign, in accordance with the change in sign of the Coriolis parameter, from one hemisphere to the other. Remembering this, it is more convenient to consider the meridional wind structures for separate months. In

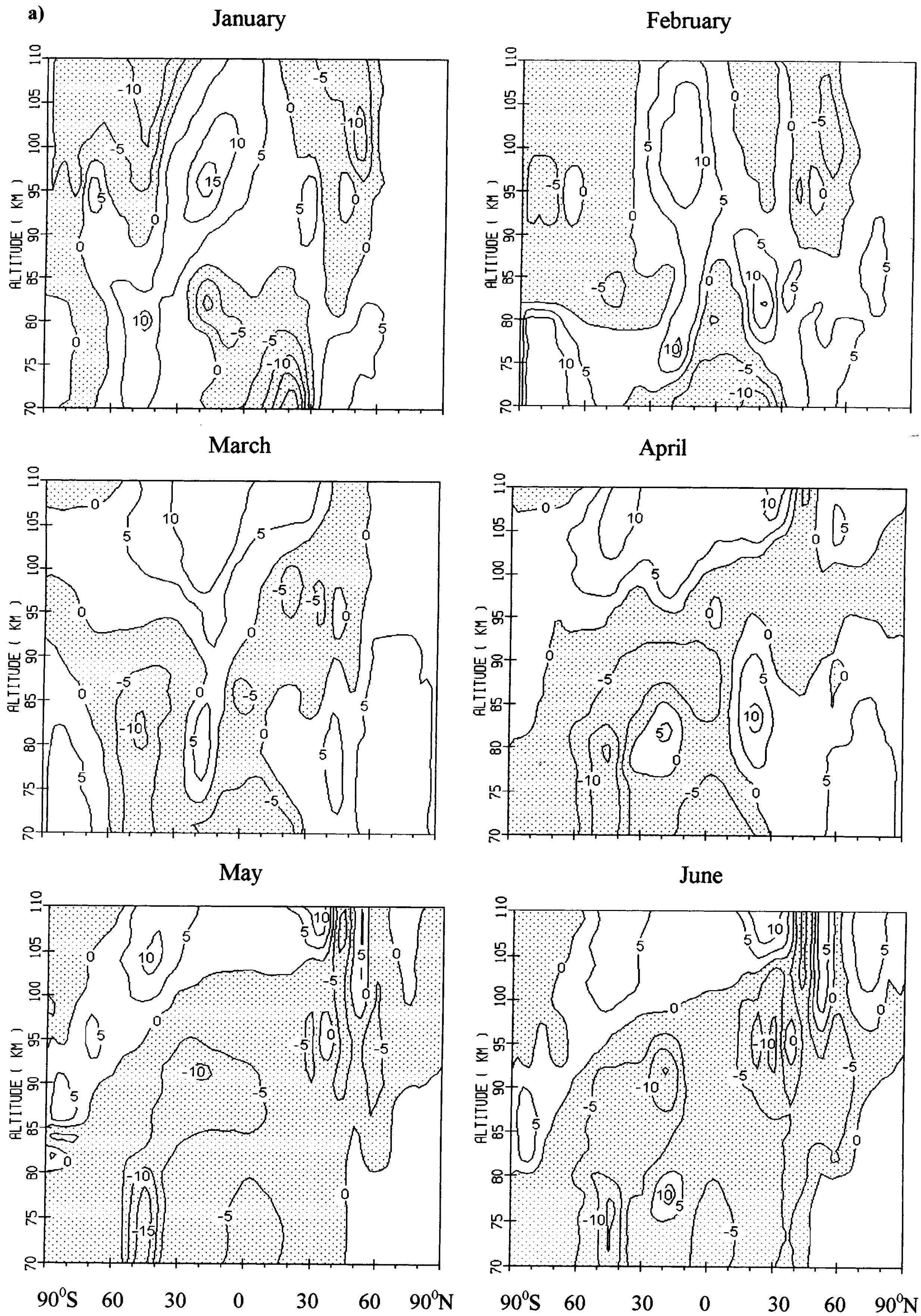

Fig. 2a, b. Same as Fig. 1, except for monthly mean meridional wind (positive northward). Contour spacing is 5 m/s

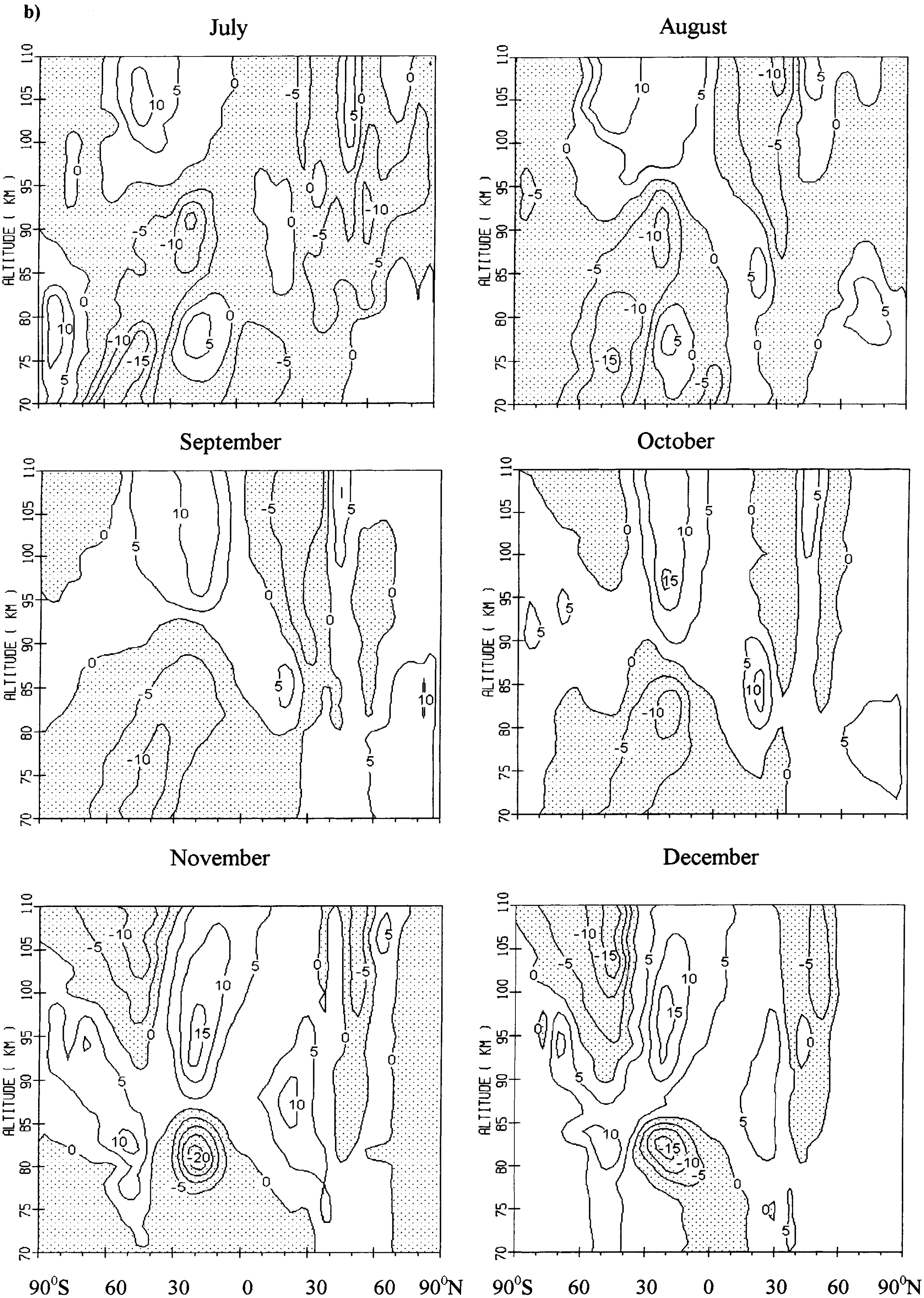

Fig. 2a, b. (Contd.)

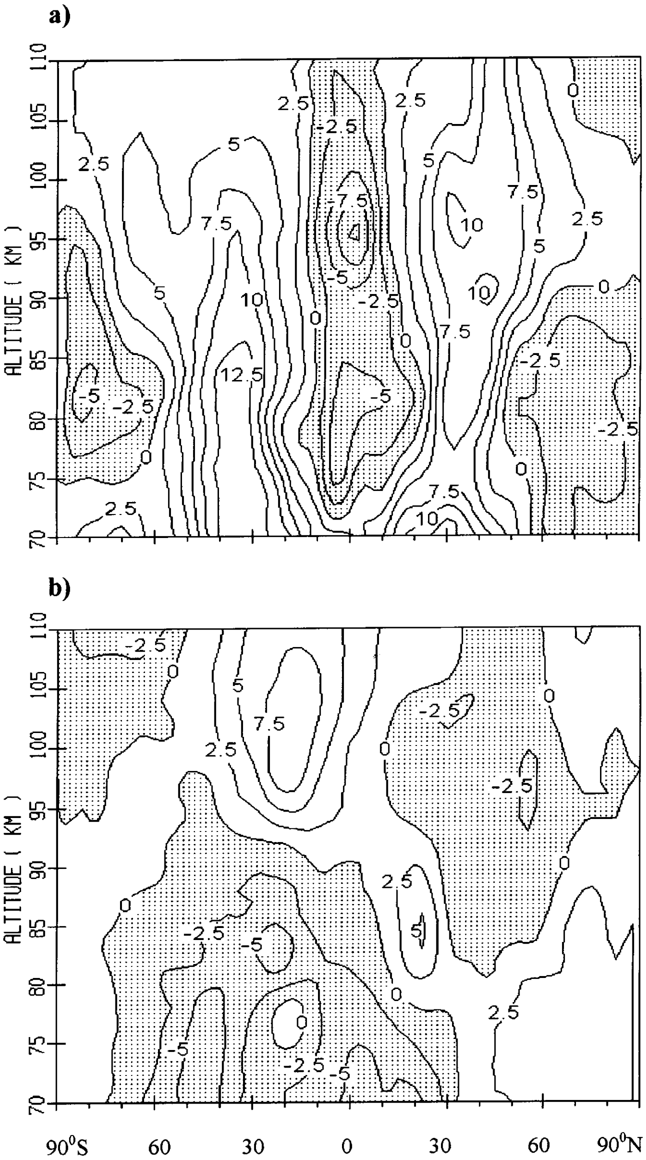

Fig. 3a, b. Height-latitude cross sections of the annual mean winds. **a** Zonal wind (contour spacing is 2.5 m/s); **b** meridional wind (contour spacing is 2.5 m/s)

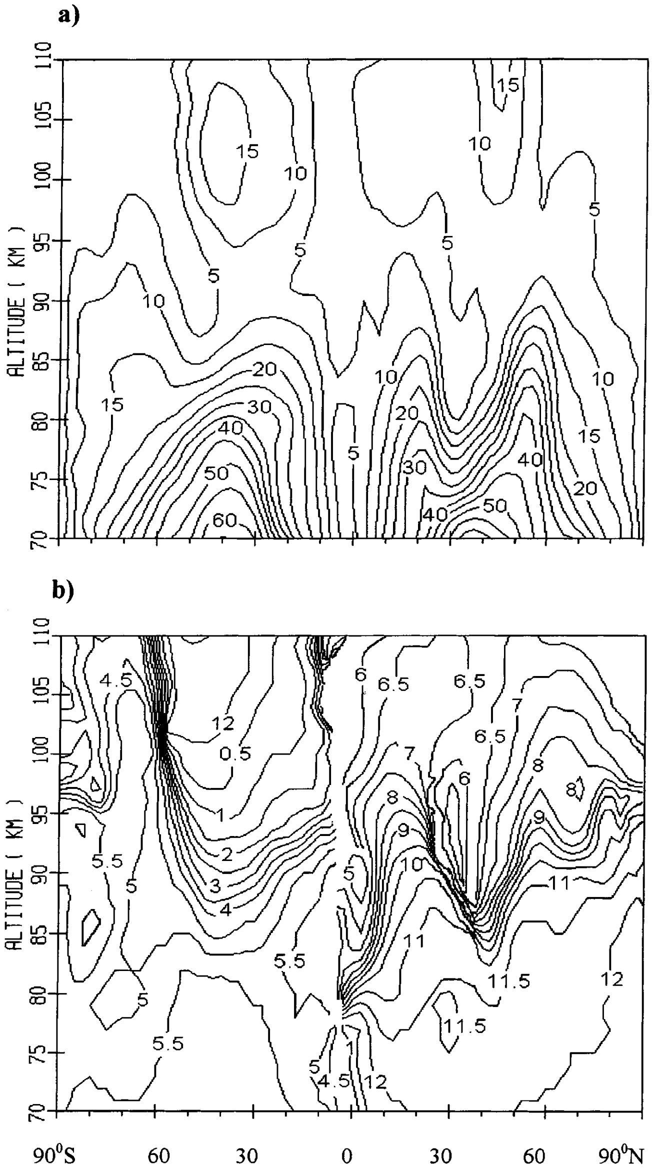

Fig. 4a, b. Height versus latitude contours of the parameters of zonal wind annual variations: **a** amplitude (contour spacing is 5 m/s); **b** phase (time of maximum of eastward winds in month and, contour spacing is 1 month)

November–January at low-latitude upper mesospheric heights there is a well pronounced and intensive meridional circulation cell with southward winds up to about 20 m/s in the centre of this cell. Two other systems of southward winds are also observed at middle and subtropical latitudes in the LT of both hemispheres. In SH the latter structure extends to high latitudes. Two systems with predominantly northward winds are found at middle-/high-latitude mesospheric heights. Above the mesopause these systems merge into one with the most intensive winds about 15 m/s occurring at SH tropical latitudes.

During February–April a gradual seasonal reconstruction of the meridional wind structures is obvious. Their winds change directions and new global circulation cells are formed. This process is practically over in May. During May–July the main meridional wind structures are rather stable and repeated from month to month. In the LT a global northward wind structure dominates at most latitudes of the globe. However the strength of the wind in this structure in SH is much larger than that in NH. The centre of this structure is situated at middle SH latitudes above 100 km. Below the mesopause the southward wind structure prevails. The wind speed in this structure changes with latitude, month and height. However, in general the southward wind in the upper mesosphere during this season is the most intensive one in SH. In August–October we can reveal the wind behaviour, is typical of seasonal wind reversal process. However, even during this period a rather limited number of the clear global structures in both hemispheres are observed. It is also interesting to note that the most prominent meridional wind struc-

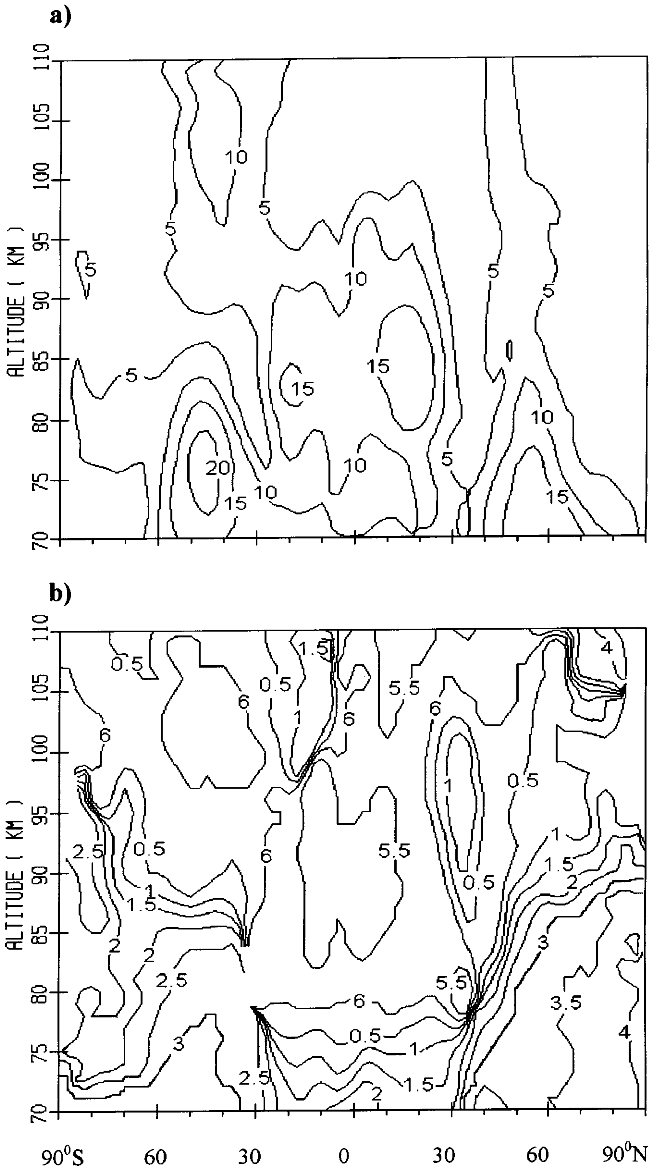

Fig. 5a, b. Same as Fig. 4, except for semi-annual variation

tures penetrate from the lower thermosphere to the upper mesosphere and vice versa, thus confirming the possibility of dynamical coupling between the different atmospheric layers.

5.2 Main parameters of meridional wind seasonal variations

The existence of a significant climatic annual mean circulation system in the MLT region is the most important output of our prevailing meridional wind model. The height-latitudinal contour plot of the annual mean meridional wind is shown in Fig. 3b. The whole picture is rather simple. If we neglect some details in this plot, which are definitely non-zonally symmetric, we may separate four global structures of ageostrophic annual mean meridional wind. Two of them observed at the upper mesosphere and mesopause heights and are characterized by northward winds in the NH and southward winds in the SH. Another two structures with opposite wind directions in relation to the underlying structures are typical of the LT region. It is clearly seen that the meridional wind in SH is more intensive than in NH, which is the indication of a certain asymmetry between the two hemispheres. It is consistent with the stronger vertical shear of zonal mean winds in SH rather than that in NH. The localization of these four structures implies that on a global scale at 70–110 km height there are a few meridional cells each with combined meridional and vertical flows. To maintain these circulation cells the annual mean momentum flux in this region must be significant (Portnyagin *et al.*, 1995).

Height-latitude cross sections of amplitudes and phases of the meridional wind annual oscillations (AO) are shown in Fig. 6. We can see from this that in

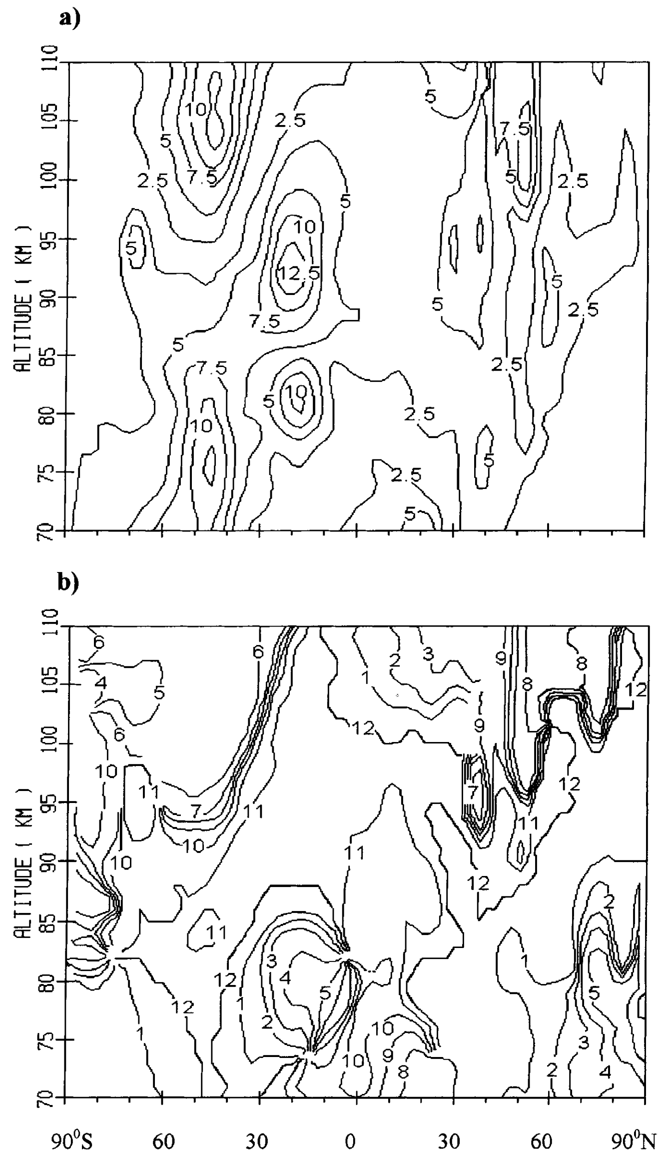

Fig. 6a, b. Same as Fig. 4, except for meridional wind. **a** Amplitude (contour spacing is 2.5 m/s); **b** phase (time of maximum of northward wind, contour spacing is 1 month) the SH these oscillations are significantly stronger in comparison with those in the NH and the height-latitude structure of amplitudes is more pronounced in the SH. We can delineate three main regions of increased amplitudes for the SH. The first of them is observed in the upper mesosphere at moderate and high latitudes. The centre of the second region, where the amplitudes approach about 13 m/s, is placed at the mesopause heights in the subtropical and tropical latitudinal interval. However, the analysis of the phase distribution (Fig. 6b) shows that in both regions discussed the time of maximum of northward wind corresponds to the summer season in the SH and the phases do not basically change with height. Hence, these regions may not be separate regions, but the merged regions of a common origin. The height behaviour of phases in the low-latitudinal part of this region shows that this region extends to LT heights. The third region is observed in LT at moderate and high latitudes. The phases of AO in this region vary between 5 and 6 months and differ by 6 months from those in the adjoining regions of increased amplitudes. The amplitudes and phases of isoline structures for this region indicate that it is the lower part of a more extensive thermospheric structure.

In the NH the structures mentioned are not so well pronounced as in SH, but some tendency for amplitude to increase in similar height-latitudinal regions, especially at low latitudes, is observed. The AO phases in NH regions do not differ from those in the corresponding SH regions. This means that the maximum positive (northward) meridional winds, stipulated by the annual cycle, in NH occur in the seasons which are opposite to those in the SH (e.g. summer versus winter). The meridional wind SAO is significantly less than those of AO and their spatial structure are not so well defined, so they are not discussed here.

6 Discussion (validation of GEWM)

In this section we consider the problem of reliability of the GEWM and to compare it with space-based models. To give an impression of correspondence of the model data to the actual experimental data at the most representative height of about 95 km, as well as to the WINDII model, in Fig. 7 the seasonal course of zonal wind for some particular latitudinal belts is presented. From this figure it may be seen that, in spite of the different averaging procedures over latitudes, longitudes, years and heights, used when constructing of the GEWM, the model's wind seasonal behaviour is on the whole well matched with experimental results. From this comparison it may be concluded that the GEWM actually describes the most significant features in the upper mesosphere/lower thermosphere global circulation structures which may be revealed by ground-based observational techniques. However, the fine structure of the height-latitudinal cross sections in the GEWM discussed results from the best fitting of the model to the available experimental data. Therefore, it is obvious that the details of the revealed global structures are not completely zonally symmetric as well as not repeated from year to year. The accuracy of model wind values is not similar everywhere and is also dependent on the amount of data for a particular latitudinal belt. On average, however, we have estimated that the actual positions of the isolines may vary within the limits of 5–7 m/s (at the confidence level of about 67%).

It is very important to verify the model by comparing it with space-based models. A comprehensive comparison of our wind model with that constructed by using the UARS (WINDII) wind data was made by Portnyagin *et al.* (1998) for zonal prevailing wind, and by Fauliot *et al.* (1997) for the meridional prevailing wind. Comparison between the zonal winds retrieved from the models has revealed a general consistency, in particular, almost the same annual and semi-annual variation components in global scale wind structures. However, systematic bias exists in the annual mean zonal wind. Table 2 illustrates this bias (see, also, Fig. 6 in Portnyagin *et al.*, 1998).

It can be concluded from Table 2, from Fig. 7 and from Fig. 6 in Portnyagin *et al.* (1998) that a good agreement between the models could be obtained, provided that the WINDII annual mean zonal wind values were reduced by a term of $A\cos 4x$, where A is about 20 m/s for all heights and x is colatitude. This significant regular offset, varying with latitude but independent of altitudes, is unlikely to be associated with model representation and/or inter-annual/longitudinal variability of the observational data sets. By comparing the global structure of this offset with Fig. 3a, we may see that the annual mean wind itself also shows a similar $A'\cos 4x$ dependence, where A' is the amplitude of the annual means and is larger than A by a factor of 2 to 2.5. The amplitude is likely to be independent of height when some fine structures are neglected. This implies that the offsets between the annual means of WINDII and GEWM can also be described by a constant factor of about 2 everywhere in the regions considered, independent of both height and latitude. For space-based wind instruments, the correction to account for the rotation of the Earth, dependent on viewing direction and latitude, would lead to such large variable wind errors, if the absolute calibration of the line shift to Doppler velocity factor was incorrect (Portnyagin *et al.*, 1998). This is most likely the possible origin of the observed differences between ground-based and space-based MLT zonal winds. The comparison between our previous version of the ground-based meridional wind model (our new updated GEWM retains all global features of this previous version) and a space-based meridional wind model, which were constructed using the WINDII MLT wind data set, was made by Fauliot *et al.* (1997). They concluded that the global structures in the annual mean meridional wind, as well as for the particular months, which may be revealed in the both models, *are very close in terms of wind velocity, cell distribution and wind magnitude*. Fauliot *et al.* (1997) wrote: "*Even if our results exhibit some differences in term of the position of wind cells when compared to the empirical models described by these*

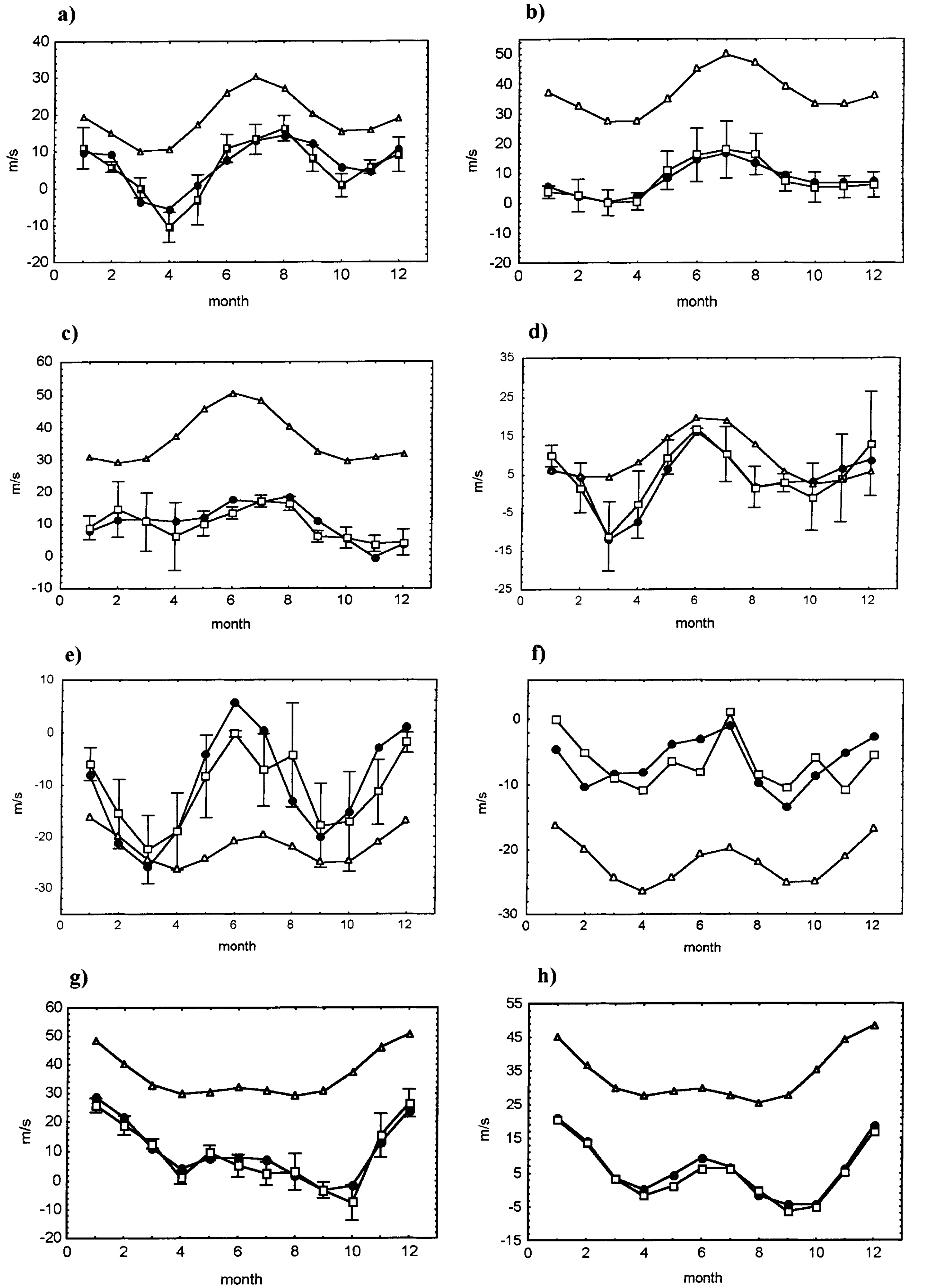
a)
b)
c)
d)
e)
f)
g)
h)
m/s
month
0
2
4
6
8
10
12

Fig. 7a–h. Seasonal variations of zonal wind at 95 km for particular latitudinal belts: **a** 52–56°N; **b** 40–45°N; **c** 34–38°N; **d** 18–22°N; **e** 2°N; **f** 6°S; **g** 33–35°S; **h** 44°S. (–●– GEWM, –△– WINDII, –□– mean experimental data, see Table 1): **a** Kazan, Obninsk, Kuhlungsborn, Jodrell Bank, Saskatoon; **b** Monpazier, Durham, Frunze, Jambol, Urbana; **c** Dushanbe, Ashkhabad, Kyoto, Altanta; **d** Kauai, Punta Borinquen, Waltair, Jamaica, Ramey; **e** Christmas Island, Mogadishu; **f** Jakarta; **g** Grahamstown, Adelaide; **h** Christchurch

Table 2. Zonal prevailing wind, seasonal course components 95 km

	A0	A1	Ph1	A2	Ph2
52°N–56°N					
GEWM 55°N	6.6	5.6	8.9	6.2	.7
Mean experiment	5.7	5.4	8.8	8.3	.6
WINDII 54°N	18.9	6.0	7.3	6.0	.4
40°N–45°N					
GEWM 42.5°N	7.7	5.8	7.2	3.7	.1
Mean experiment	7.7	7.0	6.8	4.5	.1
WINDII 42.5°N	37.0	7.2	7.3	6.5	.4
2°N					
GEWM 2.5°N	−10.2	4.1	7.4	13.3	5.5
Mean experiment	−11.2	1.7	7.9	9.4	5.8
WINDII 2.5°N	−23.8	1.0	5.7	4.1	0.2
44°S					
GEWM 44°S	6.2	7.1	1.1	8.7	0.1
Mean experiment	5.0	7.2	0.9	8.7	0.2
WINDII 45°S	33.8	9.4	11.7	5.2	5.5

A0: annual mean wind (m/s)
A1: amplitude of annual harmonic (m/s)
Ph1: phase of annual harmonic (month of maximum)
A2: amplitude of semiannual harmonic (m/s)
Ph2: phase of semiannual harmonic (month of maximum)

authors (our ground-based wind models, Y.P., T.V.S.), *these differences are weak enough to confirm their conclusions*''. It is important to emphasise that for the ground-based and spaced-based meridional wind models discussed a significant bias even between the annual mean values has not been found (contrary to that for zonal wind). This result may be considered as an additional support to our supposition that an uncertainty in the correction to account for the rotation of the Earth may cause the observed differences between ground-based and space-based zonal wind models.

7 Conclusions

We have presented here a 2-D climatic global prevailing-wind model for the upper mesosphere/lower thermosphere region, based on the analysis of multi-year ground-based wind measurement results at more than 40 stations, well distributed over the globe. This model is constructed for all months of the year, thus permitting us to investigate the main regularities of seasonal transformation of zonal and meridional wind patterns in the Northern and in the Southern Hemispheres. Analysis of height-latitude plots of monthly mean wind values for 70–110 km heights showed that for each season several global wind structures were characteristic. A definite similarity in these structures for the NH and SH are observed, but there is no complete mirror symmetry between both hemispheres. Usually in the SH the winds are more intensive than those in the NH and the spatial position and extension of the main circulation structures in NH and SH do not completely coincide. In the upper mesosphere/lower thermosphere annual and semiannual harmonics of seasonal wind velocity variations make a 80–90% contribution to the total variance of monthly mean velocity values stipulated by their seasonal course. However, the annual mean wind component, which does not reproduce in most numerical models, is also significant. Some results of comparison of the GEWM presented with space-based wind models are made. This comparison exhibits general agreement in the global prevailing wind structures, if a systematical bias term of *Acos 4x* was subtracted from the space-based zonal wind data.

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