3. Latitude-height cross sections of monthly mean quantities*

In this chapter, the latitude-height cross sections of monthly mean variables are shown. In addition to the simulated results, the corresponding observations are also shown except for total diabatic heating. Observations are taken from the U.S. NMC analyses during the period from January 1978 through February 1984. In each figure, the top left panel shows January, the top right, April, the bottom left, July and the bottom right, October. In each panel, the ordinate denotes pressure and the abscissa denotes latitude. Note that the uppermost layer that carries variables in the model is placed at about 150 mb. Therefore, the values at 100 mb are obtained by extrapolation from the values below for the simulated results. Values near the surface also need caution. Values under the ground are excluded from the calculation. A thick triangle is drawn over Antarctica in order to recall the existence of a high elevated continent there.

3.1 Zonal mean temperature

The monthly means of the zonal mean temperature simulated by the model are shown in Fig. 3.1.1 and those observed are shown in Fig. 3.1.2. The contour interval is 5℃. The values greater than 20℃ are dotted ; those less than −50℃ are shaded.

In the upper troposphere over low latitudes, the simulated temperature is slightly higher than the observed one. On the other hand, it is slightly cooler than the observed in the lower troposphere. Thus, the stratification in the low-latitude atmosphere is more stable than the observation. In other regions, the simulated temperature is generally cooler than the observation. In particular, in the lower polar layer of the winter hemisphere, the temperature difference exceeds 5° C. In the upper troposphere over high latitudes, the simulated temperature is significantly lower than the observation, which is a common problem of the GCMs. The discrepancy is most noticeable in the summer polar region. In the upper troposphere over the winter hemisphere, the relative maximum of temperature is seen around 50° N/S in the observation. On the other hand, the model failed in simulating this feature.

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3.2 Zonal mean zonal wind

Fig. 3.2.1 shows the zonal mean zonal wind simulated by the model and Fig. 3.2.2 shows the observation. The contour interval is 5 m s^{-1}. The values greater than 30 m s^{-1} are shaded; negative values (easterlies) are dotted.

In general, the wind speed of the subtropical jet is overestimated throughout the year. The discrepancy is large in the upper layer. The location of the jet is well simulated, though the simulated jet is slightly shifted poleward. The wind field in the tropics is well simulated by the model.

3.3 Zonal mean meridional wind

Fig. 3.3.1 shows the zonal mean meridional wind simulated by the model, and Fig. 3.3.2 shows the corresponding observation. The contour interval is 0.5 m s^{-1}. Negative values (northerlies) are shaded.

The simulated overall pattern and intensity are similar to the observed ones. It is noted that the strong meridional wind is confined in the near-surface layer and at 200 mb in the observation. On the other hand, the area of strong wind are broad in the model, because of the low vertical resolution.

3.4 Meridional stream function

The meridional stream functions are calculated from the zonal mean meridional winds by assuming $\chi_{,}=0$ at 100 mb both for the simulated results and the observations. Fig. 3.4.1 shows the stream functions simulated by the model and Fig. 3.4.2 those observed. The unit is 10^9 kg s^{-1}. The negative values, which correspond to clockwise flow regions, are shaded.

The simulation clearly shows a three-cell structure. In the observed analysis, the direct cells in the polar regions are not very clear. Even considering the difficulty of observing the zonal mean meridional wind, a few features are seen from the figures. The seasonal march of the intensity and meridional location and the extent of the Hadley circulation are well simulated, though the intensity itself is generally underestimated. It is intriguing to see that the upward branch of the Hadley cell is located at 10° N in October and at the equator in April. This seasonal asymmetry is simulated by the model. The centers of the cell are situated at higher levels in the model than in the observation, which is related to the low vertical resolution of the model.

3.5 Zonal mean mixing ratio of water vapor

Fig. 3.5.1 shows the zonal mean mixing ratio of water vapor simulated by the model, and Fig. 3.5.2 shows the corresponding observation. The contour interval is 1 g kg^{-1}.

The simulated seasonal change of the pattern accords with the observation, though the values are underestimated in the lower troposphere. The observed maximum values is about 18 g kg^{-1} at sea level near the equator, while the simulated maximum is about 14 g kg^{-1}. It is noted that clear double maxima are seen in October in the observation, which is also simulated by the model to some extent.

3.6 Zonal means of the standard deviations of monthly mean quantities

In this section, the zonal means of the standard deviations of monthly mean variables (z, u, v, T) are shown. Symbolically these quantities are expressed as follows :

$[\sigma(\bar{z})]$, $[\sigma(\bar{u})]$, $[\sigma(\bar{v})]$, $[\sigma(\bar{T})]$,

where σ denotes the standard deviation, the overbar $(\bar{\ })$ denotes the monthly mean and the angular bracket [ ] denotes the zonal mean. These quantities indicate the year-to-year variation of the atmospheric circulation.

Fig. 3.6.1 shows the values for geopotential height simulated by the model and Fig. 3.6.2 shows the corresponding observation. The contour interval is 10 g.p.m. The values greater than 80 g.p.m. are shaded; those less than 20 g.p.m. are dotted. The highest value appears in the antarctic upper layer of the winter hemisphere both in the simulation and the observation. In the tropics, the values are generally low. Compared with the observation, the simulated results systematically underestimate the interannual variation, especially in the upper level of the tropics mainly due to the use of the climatological value for sea surface temperature.

Fig. 3.6.3 shows the values for the zonal wind simulated by the model, and Fig. 3.6.4 shows the corresponding observation. The contour interval is 1 m s^{-1} . The values greater than 5 m s^{-1} are shaded; those less than 1 m s^{-1} are dotted. High values are seen at the middle and high latitudes of the upper troposphere both in the simulation and in the observation. Compared with the geopotential height, the fine meridional structure is dominant. Again, the simulation shows smaller interannual variation than the observation.

Fig. 3.6.5 shows the values for the meridional wind simulated by the model, and Fig. 3.6.6 shows the corresponding observation. The contour interval is 0.5 m s^{-1}. The values greater than 5 m s^{-1} are shaded; those less than 0.5 m s^{-1} are dotted. In the simulation, the maximum appears at the upper boundary, which manifests the effect of the upper lid placed at 100 mb and the low vertical resolution (see Fig. 3.3.1). Again, it is noticed that the simulation shows smaller interannual variation than the observation.

Fig. 3.6.7 shows the values for temperature simulated by the model, and Fig. 3.6.8 shows the corresponding observation. The contour interval is 0.5 K. The values greater than 5 K are shaded; those less than 0.5 K are dotted. The large interannual variation is simulated in the high-latitude lower layer of the winter Northern Hemisphere, which accords with the observation, though the large values are confined in the near-surface layer in the model. In the simulation, the interannual variation is small in the upper layer due to the artificial upper lid.

3.7 Standard deviations of monthly and zonal mean variables

In this section, the standard deviations of the monthly and zonal mean variables (the same variables as in Section 3.6) are shown. Symbolically these quantities are expressed as follows :

$\sigma\ ([\bar{z}])$, $\sigma\ ([\bar{u}])$, $\sigma\ ([\bar{v}])$, $\sigma\ ([\bar{T}])$,

where the notations are the same as in Section 3.6. Note that these quantities are not equal to the quantities shown in Section 3.6.

Fig. 3.7.1 shows the simulated values for geopotential height and Fig. 3.7.2 shows the corresponding observation. The contour interval is 5 g.p.m. The values greater than 50 g.p.m. are shaded; those less than 10 g.p.m. are dotted. This value is generally smaller than the zonal mean of the standard deviation (Figs. 3.6.1 and 3.6.2). The maximum value appears at the pole, which is related to the prominence of north-south seesawing in high latitudes. In the simulation, the local minimum appears around 50° N in April and 65° N in October, whereas the local minimum appears around 50° N – 70° N throughout the year in the observation. The largest interannual variability is found in the winter polar region of the Southern Hemisphere, which accords with the observation.

Fig. 3.7.3 shows the same value for the simulated zonal wind and Fig. 3.7.4 shows the observation. The contour interval is 0.5 m s^{-1}. The values greater than 5 m s^{-1} are shaded; those less than 0.5 m s^{-1} are dotted. It is noticed that this quantity shows a fine meridional structure. In the simulation, the maximum is found at the uppermost layer, while it is found at the 200–300 mb level in the observation. In the latitudinal direction, the maximum generally appears at the maximum latitudinal gradient of the standard deviation of the zonal mean geopotential height (Fig. 3.7.1).

Fig. 3.7.5 shows the same value for the simulated meridional wind and Fig. 3.7.6 for the observation. The contour interval is 5 cm s^{-1}. The values greater than 50 cm s^{-1} are shaded;

those less than 5 cm s^{-1} are dotted. In the simulation, the interannual variation of the zonal mean meridional wind is one or two orders smaller than the zonal mean of the standard deviation of the same variables (see Fig. 3.6.5). On the other hand, the observed values are not very small. Therefore, the observed interannual variability of the zonal mean meridional wind is much larger than that in the simulation. Especially in the upper and lower layers of the tropics, large interannual variations are observed. This suggests that the interannual variability of the Hadley cell is undersimulated by the model, probably because the climatological sea-surface temperature is used in the model.

Fig. 3.7.7 shows the same value for temperature, and Fig. 3.7.8 shows the observation. The contour interval is 0.5 K. The values greater than 5 K are shaded; those less than 0.5 K are dotted. In the model, these value are less than 0.5 K in most parts of the region. Large values are confined in the polar regions.

3.8 Total diabatic heating rate

The simulated zonal mean total diabatic heating rates are shown in Fig. 3.8. No observations are available. The contour interval is 0.5 K day^{-1}. Negative regions are shaded. In the tropics, the maximum of the heating rate is found in the middle troposphere and its meridional location coincides with that of the upper branch of the Hadley cells (Fig. 3.4.1). In the subtropical middle and upper troposphere, negative heating is found, which corresponds to the downward branches of the Hadley cells. Near the surface, positive heating is found except in the polar regions. Large negative values are simulated over Antarctica.