The resolutions which were usually used for previous studies with the GCM were $T21L20$ and $T42L20$, where $T21$ and $T42$ show the horizontal wave numbers corresponding to resolutions with 5.6 and 2.8 degree grid intervals, respectively, and $L20$ means that the number of vertical layers from the earth surface up to about 30 km was 20. The control run was performed on the resolution of $T21L74$ to precisely include the upper atmosphere into the GCM, and the following parameter studies were done at the resolution of $T21L40$. Vertical grids are distributed in the vertical direction in $L72$ as follows: the troposphere region below 15 km had the same vertical grid distribution as those in the usual $L20$. However, in the upper layer, intervals between vertical grids were changed with height from about 500 m in the lower stratosphere to about 2 km below the top. The finer resolution in the lower stratosphere is neccesary to precisely describe motions like gravity waves which have short vertical wavelengths and a long horizontal scales, since such motions are important in the physics of the lower stratosphere. Although the resolution $L40$ used for parameter studies has rather sparser resolution than that of $L72$, at least it is capable of checking the dependence of the model on parameters in the physical parameterization.

The GCM was integrated with the same physical parameters used in previous research for the lower atmosphere except that a Rayleigh friction near the top boundary layer was stronger than usual. An e-folding time of 12 hours was used *for the present case, though it was 30 days for the usual cases.*

3 Results

3.1 Control run and its climatology

Overall structures of the zonal wind show qualitative correspondence between the GCM and the corresponding observations (Fig. 1). The GCM reproduces tropospheric westerly jets, a stratospheric westerly jet in the winter hemisphere, and an easterly wind maximum in the upper stratosphere. However, there are some large discrepancies between the GCM and the observations. The most conspicuous discrepancy is in the position of the stratospheric westerly jet maximum. The latitudinal position of this jet is at about Lat. 65° N in the GCM, which is shifted poleward to the north by 30 K compared with that of the observation. In additionally, the vertical position of the feature in the GCM is a little higher than that in the observations, although the strengths of the modeled and observed jet maxima do not differ much. This poleward shift of the jet is related largely to the depression of temperature in the polar stratospheric region (Fig. 2). Although the overall structure of temperature predicted by the GCM corresponds well with that of the observations, temperature in the GCM is about 20 K cooler than that in the observations in the lower stratosphere in the polar regions. This cooling bias produces a large latitudinal gradient of temperature in the region, and this large gradient balances with a large vertical shear of zonal wind (see Fig. 1), due to the thermal wind relationship. The problem of the cooling bias in the polar stratosphere and the poleward shift of the stratospheric jet will be explored further in some parameter studies in a following subsection. Other characteristics apparent in the zonal wind are an upward invasion of westerly wind into the upper stratosphere and a strange structure in the tropospheric stratosphere. These characteristics had also been observed in previous studies mainly focused on the lower atmosphere. The causes of these observations have not yet been clarified and further studies are neccesary.

The climatology of the model during summer was also investigated (Figs. 3 and 4). Structures of wind and temperature were qualitatively reproducible. However, the discrepancy between the model and the observations in summer is larger than that in winter. Not only does the stratospheric jet shift poleward in winter, but also the maximum value of the jet is too large, nearly double that in the observations (see Fig. 3). The cooling bias appears in polar region again in the temperature field (see Fig. 4).

Next, we compared the climatology of our GCM with one of an other atmospheric GCMs to evaluate the CCSR/NIES GCM's relative performance. Figure 5 shows climatological data obtained by a SKYHI model, which is a GCM of the Geophysical Fluid Dynamics Laboratory (GFDL; NOAA, Hamilton et al., 1995). The model is one of the most sophisticated atmospheric GCMs which includes the upper atmosphere. It should be noted here that the SKYHI model is constructed without gravity wave parameterization, and therefore their results should not be exactly equivalent to our results. However, as one of the representative GCMs, the results should be roughly comparable and this model is selected. Zonal wind for winter in SKYHI (Fig. 5 (a)) shows a similar structure to that in the CCSR/NIES GCM. The maximum of the stratospheric jet is located at about Lat. 65° N, which is the same as that of our model. The problem of the poleward shift of the jet is common throughout not only our model and the SKYHI model, but also many of the other advanced GCM all over the world. For summer, the results of our model and those of the SKYHI model were similar (data not shown), both showing jet maximum a which were too strong. Worldwide atmospheric GCMs seem to be confronted by problems of the poleward shift of the jet and cooling bias in the polar stratospheric region. To solve these problems, some other physical process which is omitted from the present GCMs should be integrated into the models.

3.2 Parameter studies

The control run described in the previous subsection was computed under the same sets of physical parameters except for a parameter for the Rayleigh friction. However, the parameters which were preferred for typical integrations of the model focused on the lower atmosphere are not necessarily the optimal ones for integrations focused on the upper atmosphere. Therefore, we investigated the dependence of the climatology of the model on the parameters. Although our investigations were restricted within narrow regions of parameters by a computer resource limitation, the results are summarized here for further future development of the model including the upper atmosphere.

In the control run, rather strong Rayleigh friction was assumed near the top boundary layer, whose e-folding time is half a day. The strong friction influence much of the model behavior near the top. For example, zonal winds of the model show an unnatural large vertical gradient between the stratospheric jet maximum and the top boundary (see Figs. 1 and 3). Therefore a run with rather weak Rayleigh friction and stronger orographic gravity-wave drag was performed. Namely, the e-folding time due to the Rayleigh friction was 5 days, which is 10 times larger than that in the previous run, and the strength of the gravity-wave excited by the orography in this parameterization is about one and a half times that in the previous run. Figure 6 shows the zonal wind and temperature which were obtained under these condition. The zonal wind in the stratospheric jet, about 45 m/s, was rather weak due to the stronger gravity wave drag. The maximum region of the jet spreads toward the equator relative to that in the control run. The vertical gradient between the jet maximum and the top boundary shrank. The minimum temperature in the lower stratosphere increased by 10°. Although not all of these changes are desirable ones, they do indicate that the change in the parameters for the gravity-wave drag and the Rayleigh friction somewhat improved both in the poleward shift of the stratospheric jet and the cooling bias in the polar stratosphere.

We also made some runs with other changed parameters of the Rayleigh friction and the gravity-wave drag, however, we could not achieve results notably better than those in Fig. 6. This indicates that the treatment of the Rayleigh friction and the gravity-wave drag is important to reproduce the motion of the upper atmosphere accurately and that the problems would not be entirely solved without introducing another physical process or parameterization into the GCM to qualitatively improve the model.

We also made other parameter studies. Although these result are not presented in this monograph in detail, a simple summary is follows. Both the strength of horizontal eddy diffusivity and its order of dependence on eddy scales