

A-1.4.1 Study on physical and chemical processes of the polar vortex using a chemical-radiative-dynamical coupled model

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Total budget for FY1996-FY1998 53,088,000 Yen (FY1998; 14,235,000 Yen)

Abstract. A chemistry coupled GCM (General Circulation Model) and a nudging CTM (Chemical Transport Model) are developed in order to understand ozone depletion mechanisms within and around the polar vortices. The chemical scheme and the chemical-radiative coupling scheme of the 1D chemical-radiative coupled model that has been developed in NIES (National Institute for Environmental Studies) are modified for 3D model and introduced into the CCSR (Center for Climate System Research, University of Tokyo)/NIES AGCM (Atmosphere General Circulation Model). Gas phase reactions of Ox, HOx, NOx, and ClOx and heterogeneous reactions on NAT (nitrate trihydrate) and ice PSCs (Polar Stratospheric Clouds) have been introduced into the model successfully with model improvements on horizontal resolution and on oxygen molecule photolysis in the Schumann-Runge bands. The model results are compared to the TOMS and UARS observations. The comparison confirmed that the model results were realistic. The O₃ and HNO₃ distributions of the model around 70N in February and March 1997 are also compared to the ILAS data and SLIMCAT CTM outputs of Cambridge University. Ozone peak values of the CCSR/NIES chemistry GCM are a little higher and the peak altitudes are a little lower than those of the ILAS data and the SLIMCAT data. Peak values and peak altitudes of HNO₃ are also different among these three data. Contributions of ozone transport and the ozone destruction chemistry in and around polar vortices during Ozone Hole were investigated by numerical experiments. A nudging CTM has also been developed based on the CCSR/NIES chemistry GCM.

Key Words

Stratosphere, Ozone destruction, CCSR/NIES chemistry coupled GCM, CTM, polar vortex

1. Introduction

The Ozone Hole has been growing with its horizontal size over Antarctica. Ozone destruction was also found in Arctic regions recently, but the depletion was not as severe as the Antarctic Ozone Hole. It was also found that these ozone depletions in the both Polar Regions also affected midlatitude ozone. Thus we need to study and understand ozone destruction mechanisms in the midlatitudes as well as in the Polar Regions. Ozone destruction mechanisms are very complicated, with the transport process, the photochemical production and destruction processes, the solar and terrestrial radiation processes, and the coupling processes between them. It is obvious that a simple local model is not enough for understanding such a complicated process and the coupling processes. Recent computer developments have enabled us to calculate 3D fields and variations of chemical species by 3D chemical models¹⁾⁻⁵⁾. And global data of chemical

constituents have been accumulated by satellite observations and global ground based observation networks. These global data have made it possible to validate 3D global chemical models. The ILAS sensor on ADEOS satellite that was developed by Japanese Environmental Agency supplied useful chemical constituent distribution data in the high latitude regions. 3D modeling of the ozone depletion, and understanding of the depletion mechanisms with both model experiments and the global observation data are really necessary.

2. Research Objective

The objective of this study is to understand ozone depletion mechanisms in and around the polar vortices, and to development 3D chemical transport models to make contributions for future ozone prediction.

3. Research Method

The chemistry scheme and chemistry-radiation coupling scheme of the 1D chemical-radiative coupled model which were developed in NIES was introduced into CCSR/NIES AGCM to develop the CCSR/NIES chemistry coupled GCM. A nudging CTM was also developed to compare the model results to the observations directly, and to understand each contribution of the chemical effects and the transport effects to ozone depletion.

4. Results and Discussion

4.1. Introduction of bromine chemistry of the 1D chemical-radiative model into the CCSR/NIES AGCM

A new chemistry scheme for bromine species was formulated on the family method. The scheme was introduced into the 1D chemical-radiative model that was developed in NIES. The Ox, HOx, NOx, CHOx, and ClOx schemes introduced already were improved, and some new chemical reactions were added to them. The model totally includes about 150 photochemical reactions. Figure 1 shows vertical distributions of the volume mixing ratio of bromine species at noon at the model steady state. The Bry amount in the upper and middle stratosphere where most of bromine source gases were decomposed was about 20 pptv realistically. Figure 2 shows the distributions of bromine source gases. CHBr₃ has the absorption bands at longer wavelength regions than those of other bromine source gases, hence the photolysis is still active even in the lower stratosphere and troposphere, making the vertical gradient of the mixing ratio in the troposphere. Since bromine source gases are photolyzed in the lower altitude than chlorine source gases such as chlorofluorocarbons, the effects are large in the lower stratosphere and in the upper troposphere. O₃, OH, and ClO were decreased 5% at maximum, and NO₂ was increased 6% at maximum.

4.2. Development of the CCSR/NIES chemistry coupled GCM

4.2.1. Introduction of gas phase chemistry into the CCSR/NIES AGCM

The chemical scheme of the 1D chemical-radiative coupled model was introduced into the CCSR/NIES AGCM, which was a T10 (horizontal resolution of about 10 degrees) L30 (30 vertical atmospheric layers with the thickness of about 2 km) version of the General Circulation Model. The model atmosphere was extended from the ground/sea surfaces to 70 km high. The Ox, HOx, NOx, and ClOx chemistry schemes were modified and simplified for the GCM. Average absorption cross sections for the spectral bin of the GCM were recalculated. The temperature dependence was

parameterized by the least square method with second or third order polynomial functions of temperature difference between the atmospheric temperature and the room temperature. 60 gas phase chemical reactions have been introduced into the GCM successfully since this project study started.

4.2.2. Improvements of horizontal resolution and ultraviolet radiation of CCSR/NIES chemistry coupled GCM

The atmospheric wave activities of the T10 version of the GCM were limited. It failed to simulate fine structures of ozone and potential vorticity near the polar vortex boundaries. Thus a finer spatial resolution model, the T21 version (about 5 degree horizontal resolution) was developed. Figure 3.1 shows time-latitude cross section of zonal-mean total ozone amount calculated by the T21 version model. The amount and the seasonal variation in the tropical region, and the spring maximum in the North Polar region and in the Southern Hemisphere midlatitudes were successfully simulated. The spring Antarctic ozone decreased, but did not decrease less than 270 DU, because heterogeneous reactions on PSCs (Polar Stratospheric Clouds) were not included into the model. Note that the decrease shows lack of ozone transport from the midlatitudes into the Antarctic region during the winter and spring seasons.

The CCSR/NIES GCM does not have the ultraviolet radiation fields less than 200 nm, because such a radiation is not important for atmospheric heating. However, the ultraviolet radiation cannot be negligible for photolysis of chemical species in the atmosphere. The Shumann-Runge bands between 175 nm and 205 nm play an important role to oxygen molecule photolysis especially in the mesosphere and the upper stratosphere. An oxygen atom produced by an oxygen molecule photolysis is combined to an oxygen molecule to produce an ozone. Hence, the Shumann-Runge Bands contribute ozone production in the mesosphere and in the upper stratosphere. A calculation by the 1D coupled model showed that the Shumann-Runge bands contribute about 10% of total ozone production. The Shumann-Runge photolysis and the atmospheric heating were included into the GCM by using the Nicolet parameterization (1984). Figure 3.2 shows time-latitude cross section of the total ozone difference between the models with and without the parameterization. Generally total ozone amount was increased by 7% to 15%. Temperature was also increased by inclusion of the Shumann-Runge bands. The increase was appreciable above 50 km. But, this did not solve the cooling bias in the lower stratosphere of the GCM. The calculated distribution and seasonal variation of chemical constituents were compared to the TOMS and UARS data. The comparison confirmed that the model results were realistic.

4.3. Introduction of heterogeneous reactions on PSCs into the CCSR/NIES chemistry coupled GCM and Ozone Hole experiment

Heterogeneous reactions on Type I PSCs (nitric acid trihydrate) and Type II PSCs (ice) were introduced into the CCSR/NIES chemistry coupled GCM. Super saturation of nitric acid gas and water vapor over the PSCs was calculated, and assumed to make PSCs. The PSCs evaporated when partial pressure of nitric acid gas or water vapor was under the saturation pressure. The radius of Type I PSCs was assumed to be 1 micrometer, and that of Type II PSCs was 10 micrometers. Sedimentation process of these particles by gravity was also considered. The PSCs appeared in the model over Antarctic regions in the winter and spring, and reduced total ozone amount less than 240 DU, as shown in Figure 4. Arctic ozone decrease was also simulated over the northeast part of Greenland and over the north part of Scandinavia peninsula, as shown in Figure 5.

4.4. Comparison of the chemistry GCM results with ILAS data and SLIMCAT outputs

The longitude-height cross sections of ozone and nitric acid gas around 70N in February and March 1997 were compared with the ILAS version 3.10 data⁶⁾ and the output of a 6 year run of SLIMCAT (CTM of Cambridge University) model²⁾. Ozone maximum of the CCSR/NIES chemistry GCM was between 8 ppmv and 9 ppmv, a little higher than 6 or 7 ppmv of ILAS and SLIMCAT. The peak height was a little lower than that of ILAS and SLIMCAT. Nitric acid maximum was between 12 ppmv and 15 ppmv in SLIMCAT, between 8 ppmv and 14 ppmv in CCSR/NIES GCM, between 8 ppmv and 12 ppmv in ILAS. These are general chemical bias of the CCSR/NIES model, although comparisons of daily data of the CCSR/NIES chemistry GCM with ILAS data or SLIMCAT outputs are meaningless, because the GCM calculation did not use any data in February and March 1997.

4.5. Development of a nudging CTM

Discrepancy in temperature and winds between the GCM and the observation prevents us from understanding photochemical processes in the atmosphere by comparing the model chemical constituent distribution with the observations, because chemical processes in the atmosphere are sensitive to the temperature, and transport process is also important for chemical constituent distribution. The cooling bias of temperature of GCMs has not been solved yet. This is a reason why CTM is necessary, in which meteorological data are input and chemical processes are calculated with the input data.

The CTM that we have been developing is a nudging CTM based on the GCM, different from so-called CTMs in which meteorological input data are directly used for chemical calculation. The nudging CTM assimilates input data of winds and temperature into the model values with a time constant. That is,

$$dx/dt = -(x-X)/c,$$

where t denotes time, x is a model value, X is an observation value, and c is the time constant. The time constant of 1 day was chosen to prevent artificial oscillations due to jump of the values by the data input, and to make the model values closer to the observation data. The nudging CTM improved the temperature and zonal wind distributions. For example, as shown in Figure 6.1 and 6.2, the minimum temperature over the Antarctic in July was about 180 K, while less than 170 K in the GCM. Accordingly, the maximum zonal westerly wind was suppressed to about 100 m/s, while over 170 m/s in the GCM. Seasonal variation of the total ozone amount was also improved particularly in the tropics and in the Antarctic regions.

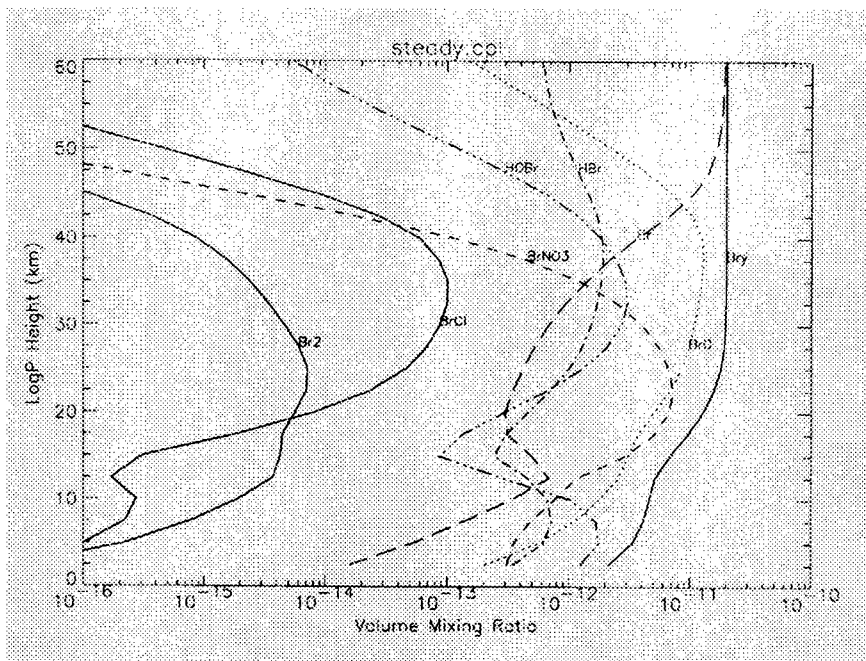


Figure 1. Vertical distribution of bromine species volume mixing ratio at noon by 1D chemical-radiative coupled model.

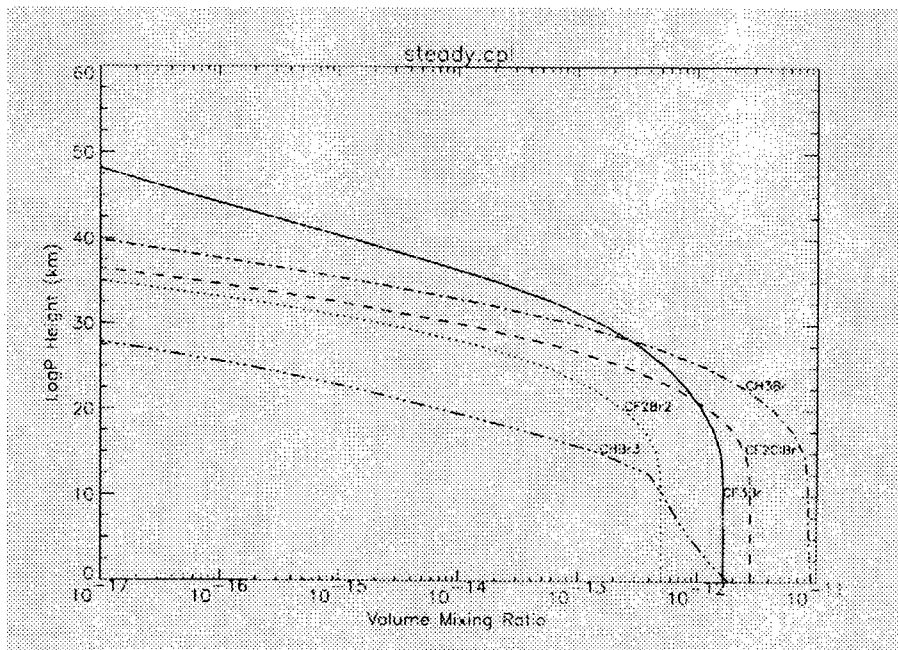


Figure 2. Vertical distribution of bromine source gas volume mixing ratio at noon by 1D chemical-radiative coupled model.

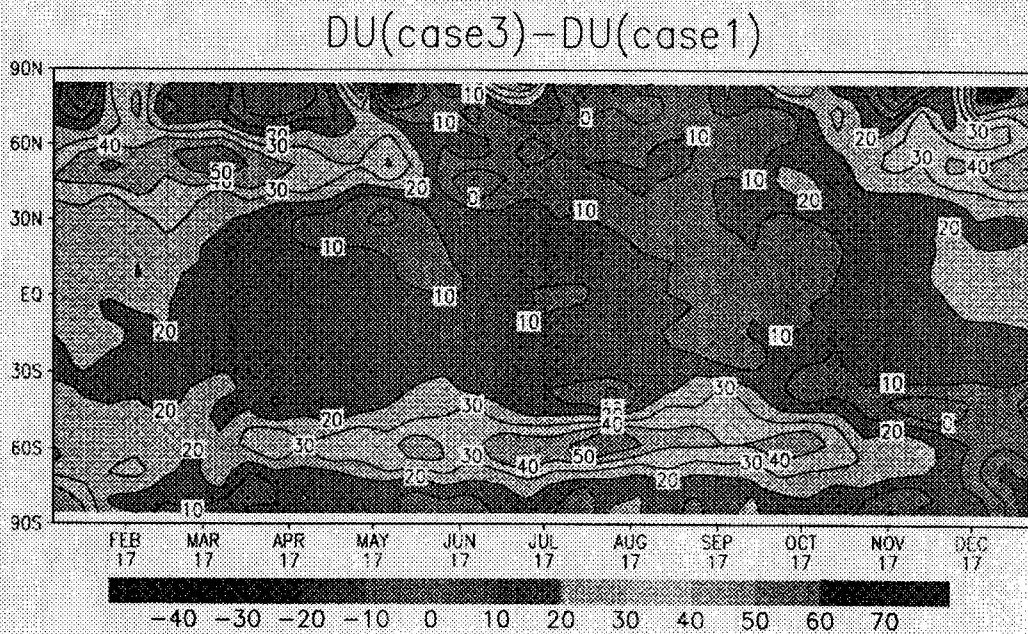
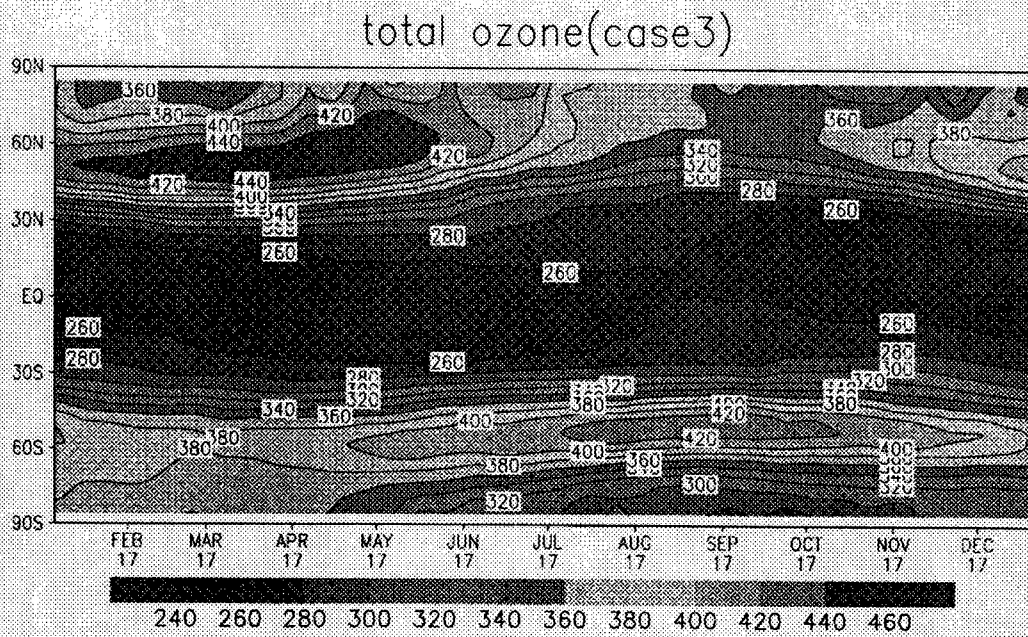


Figure 3.1 (upper): Time-latitude cross section of total ozone amount calculated by CCSR/NIES chemistry GCM with Schumann-Runge absorption.

Figure 3.2 (lower): Time-latitude cross section of total ozone difference between the chemistry GCMs with and without Schumann-Runge absorption.

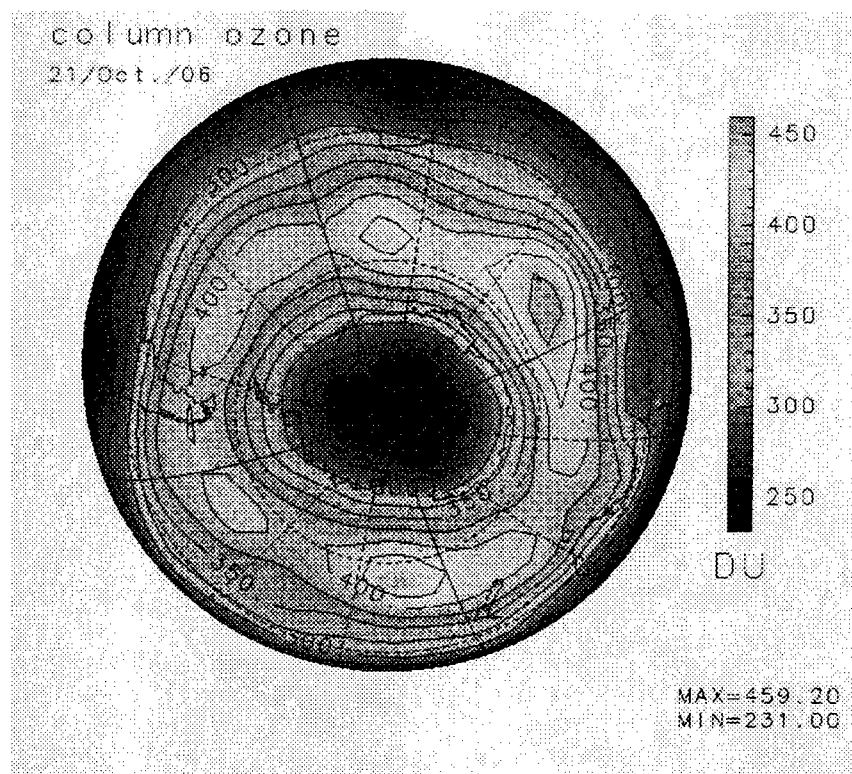


Figure 4. Total ozone distribution in the Southern Hemisphere in October calculated by the CCSR/NIES chemistry coupled GCM with heterogeneous reactions on PSCs.

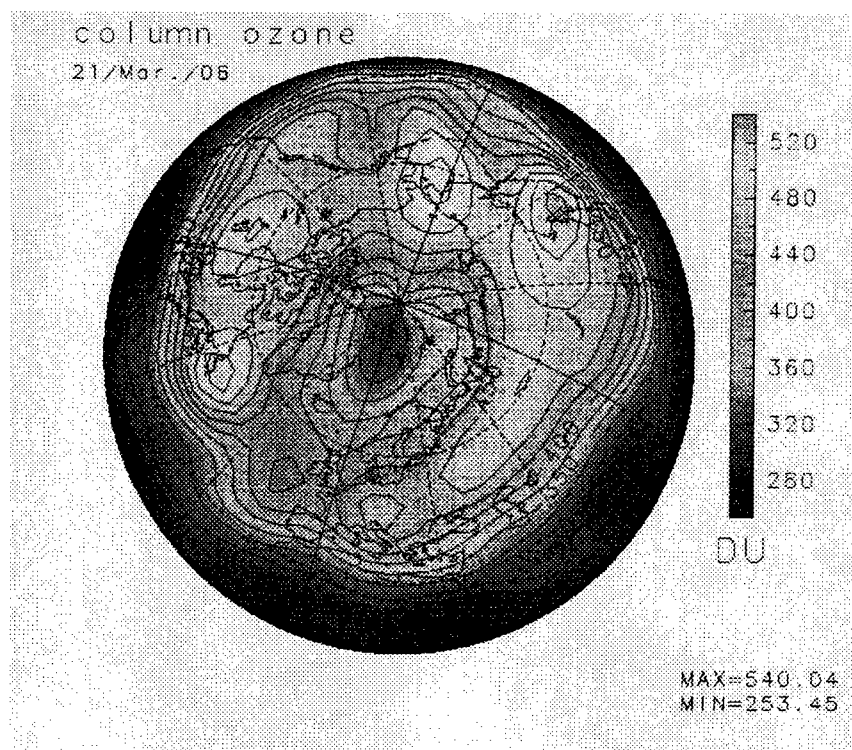


Figure 5. Total ozone distribution in the Northern Hemisphere in March calculated by the CCSR/NIES chemistry coupled GCM with heterogeneous reactions on PSCs.

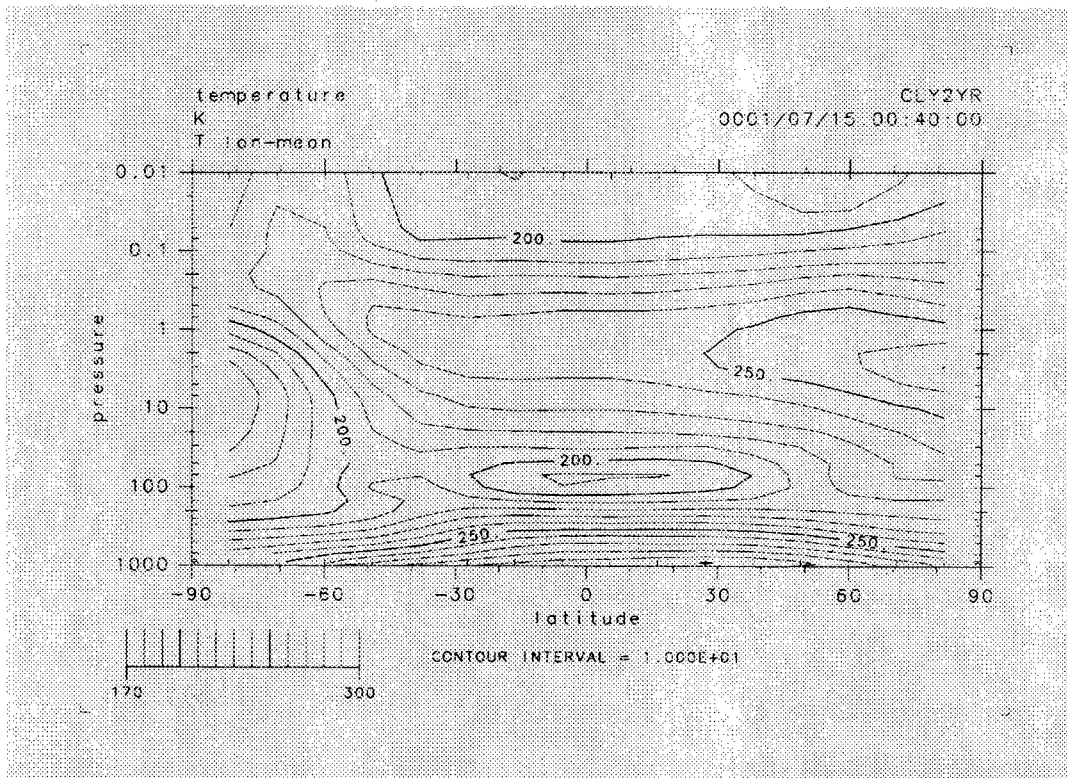


Figure 6.1: Zonal-mean temperature distribution in 15 July calculated by CCSR/NIES chemistry coupled GCM.

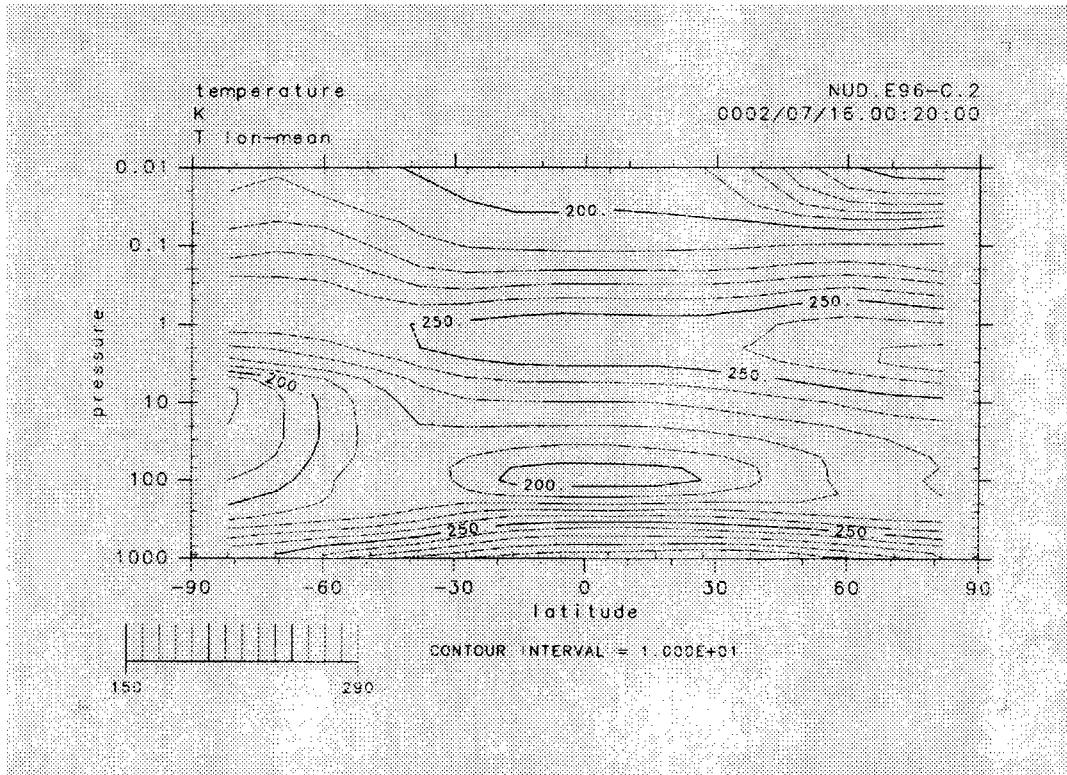


Figure 6.2: Zonal-mean temperature distribution in 15 July calculated by CCSR/NIES nudging CTM.

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