Numerical simulation of methane distribution using data of ground-based observations

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A three-dimensional global climate model [A.A. Fomenko, V.N. Krupchatnikoff, and A.G. Yantzen, Bull. Nov. Comp. Center, Num. Mod. In Atmosph., etc., No. 4, 11–19 (1996)] generalized to include a continuity equation for methane tracer is used to assimilate the available data on CH_4 concentration obtained at an extended network of ground-based stations between 1984 and 1987 [T.A. Boden, D.P. Kaiser, R.J. Sepansli, and F.W. Stoss, eds., *Trends'93: A Compendium of Data on Global Change* (Tennessee, 1994)]. The analysis of this transport model has shown that it reproduces well such observed features as north-south latitudinal gradient of concentration, interannual trend, and seasonal variations. The results of spatial simulation indicate that in midlatitudes of the Northern Hemisphere the model predicts considerable gradients of CH_4 in the regions of its continental sources in response to the observed surface distribution of methane.

Introduction

Methane (CH_4) absorbs significantly at infrared wavelengths around 7.7 μm and, thereby, influences considerably the energy budget of the Earth's atmosphere. Methane has increased from 700 ppbv in the pre-industrial era to over 1700 ppbv at present days; 15% of this increase is usually considered to be due to the anthropogenic effect. Methane plays a significant role in atmospheric chemistry, representing the main sink for the hydroxyl radical OH. Although the main sources and sinks of methane are now established, great uncertainty still exists in estimates of the strength of methane sources. Methane species mainly arises due to

(a) activity of bacteria under certain anaerobic conditions (overwetted soils, rice fields, animal activity, etc.);

(b) losses in gas, oil, coil, and the like productions and in pipe systems; and

(c) biomass burning and decay.

One of the main methods to determine the strength of methane sources is certainly to measure directly methane fluxes. Unfortunately, measured values depend on many meteorological and biological parameters and vary widely in space and time. As a result, measurements made at some ground stations can hardly be interpolated to other locations. So, large interpolation errors are expected for locations with no regular observations. The continuous record of methane measurements had been performed by the Climate Monitoring and Diagnostics Laboratory (CMDL) of the National Oceanic and Atmospheric Administration (NOAA), the U.S.A., at the global network of stations. The data record covering the period of 1983–1993 is the most comprehensive data set on methane concentration in the near-ground atmospheric layer.

Recently, a set of climate models has been used to simulate the global distribution of greenhouse gases such as carbon dioxide (CO_2) and chloro-fluoro-carbons ($CFCl_3$ and CF_2Cl_2).[3,4] Numerical experiments have been performed to simulate the global methane cycle; they reproduce the regional distribution of sources and sinks of CH_4 as well as its seasonal variations with high accuracy.[5]

In this paper, we use a global climate model[1] extended to include the tracer (methane) transport scheme in an attempt to assimilate the available information on CH_4 concentration obtained at the NOAA CMDL ground-based network of stations between 1984 and 1987. This model was used for analysis and found to reproduce well the main observed features of the large-scale CH_4 transport: north-south latitudinal gradient of concentration, interannual trend, and seasonal variations.

1. Model

Global methane distribution in the atmosphere was simulated numerically using a three-dimensional (3D) climate model of atmospheric dynamics[1] extended to include the tracer gas transport.

The continuity equation for an arbitrary tracer can be written in a general form as

$$\frac{\partial \rho c}{\partial t} + \mathrm{3DADV} = \mathrm{SOURCE},$$

where ρ is density, and c is concentration.

The total 3D advection 3DADV can be conventionally divided into three main components

$$\mathrm{3DADV} = \mathrm{HORADV} + \mathrm{VERADV} + \mathrm{VERCONV},$$

where HORADV is the horizontal advection, VERADV is the vertical advection, and VERCONV is the tracer transport by vertical convection. The vertical

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convection (subgrid-scale vertical fluxes) consists of two components

$$\text{VERCONV} = \text{CLOUDCON} + \text{VERDIFF},$$

where CLOUDCON is the tracer transport by convective clouds, and VERDIFF is the turbulent tracer transport that depends on the static stability of the atmosphere. All (but CLOUDCON) tracer transport mechanisms mentioned above are simulated by the general circulation model ECSib.[1] Of course, the absence of such an important transport mechanism as CLOUDCON is a drawback of the transport model (to be overcome by inclusion of a new convective cloud parameterization scheme of the "mass-flux" type) which, nonetheless, predicts the geographically reasonable distribution of methane in the atmosphere.

Variations of the velocity, temperature, and surface pressure fields are determined in the model from a system of equations that derive from the laws of conservation of momentum and mass and from the first law of thermodynamics. This system of equations obeys the integral laws of conservation of mass, total energy, angular momentum, potential enstrophy, and specific humidity. The equations are written in the spherical atmospheric geometry using σ-coordinates in vertical. In addition to the boundary conditions, in the model we determine the distribution of geopotential on the Earth's surface, specify the ocean surface temperature, climatically mean geographic distribution of ice cover, and latitudinal distribution of the solar declination angle, and calculate the surface temperature and soil moisture content.

The physical code of the model includes the schemes of parameterization of subgrid-scale processes: radiative heating, turbulent and convective exchange, and water vapor condensation.

The model spatial resolution is 4° latitude by 5° longitude horizontally and 15 σ-levels vertically. The spatial-difference approximation of equations is based on the Arakawa's *C*-grid that ensures fulfillment of the discrete analogs of the main integral invariant parameters of the system.[7] The numerical integration over time is made using a semi-implicit scheme.[8,9]

2. Experiment

The numerical experiment based on the climate model had the purpose to simulate the dynamics of the concentration field throughout a model year using four-year observations of methane concentration on the Earth's surface as initial and boundary conditions for the methane transport equation. This provides an opportunity to estimate the ability of the model to realistically reproduce the global methane redistribution and to check the consistency between observed and predicted concentration fields.

The data on the monthly mean methane concentration are arithmetic means of the weekly CH_4 measurements made in the period of 1984–1987 at 19 stations between 82°N and 90°S (Ref. 2). The NOAA CMDL network sites are the base stations for the many-year monitoring of the main climatically significant gases such as CO_2, CH_4, and N_2O. Located in continental coastal areas and in ocean, they are mostly far removed from continental sources of methane. Spatial and temporal CH_4 variations can be evident from analysis of the data obtained at two stations, Barrow and South Pole, of the NOAA/CMDL network.

The Barrow station (71°19′N, 156°36′E, 11 m above the sea level) is located in the Alaskan Arctic coastal zone; CH_4 has been regularly observed at this station since April 1983. According to these observations, the annually mean CH_4 concentration in the near-ground layer had increased from 1724.1 to 1806.5 ppbv for the period of 1984–1992 with an average rate of 11.1 ppbv per year. Analysis of the data for 1984–1987 has shown that the primary seasonal minimum in the CH_4 concentration occurs in summer (usually in July) at the Barrow station and M Station, i.e., at the northernmost sites of the network.

According to observations at the South Pole station (89°59′S, 24°48′W, 2810 m above the sea level), the annually mean CH_4 concentration had increased from 1576.0 to 1666.9 ppbv for the period of 1984–1992, and the average rate between February 1983 and December 1992 was 11.5 ppbv/yr (Ref. 2). Based on the measurements of 1984–1987, the CH_4 concentration and the amplitude and phase of seasonal CH_4 variations at the three southernmost sites of the NOAA/CMDL network, namely, South Pole, Palmer Station, and Cape Grim, nearly coincide (within the measurement error).

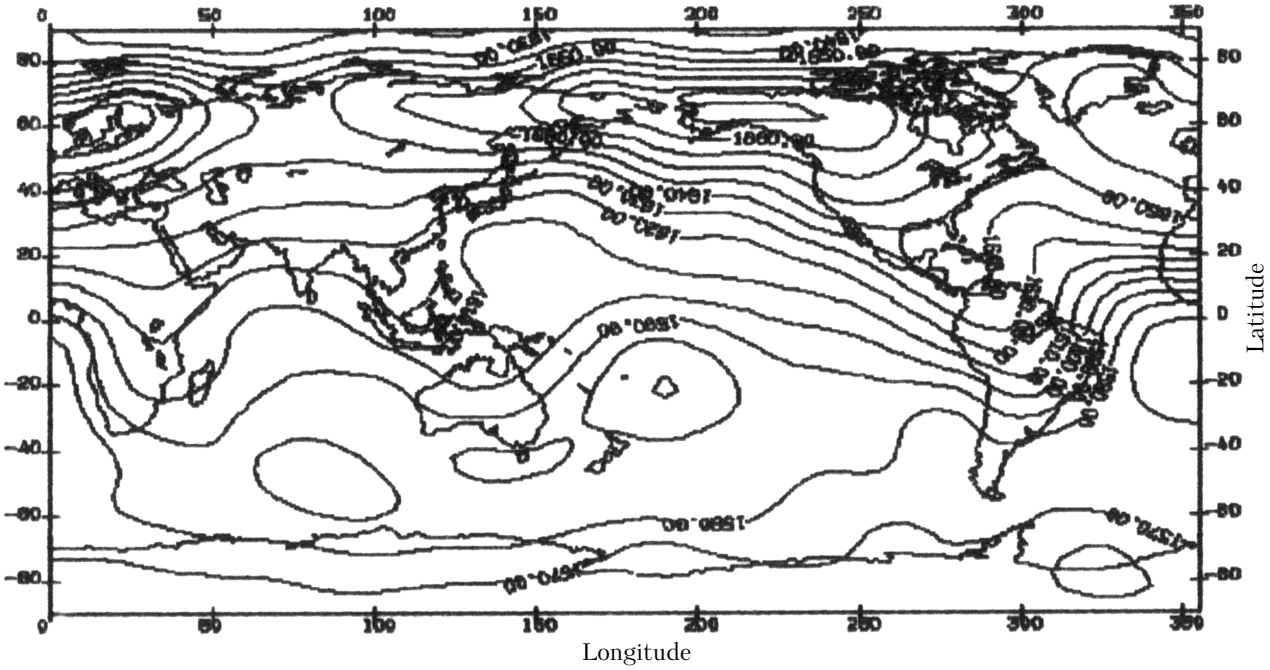
The Barrow and South Pole sites are far removed from methane sources and sinks; therefore, the data obtained at these stations can be used to identify the influence of dynamical processes on the CH_4 distribution throughout the atmospheric depth. Turning to a larger spatial scale, the main systematic feature observed at the 19 NOAA/CMDL stations is a pronounced north-south gradient in the annually mean methane concentration, whose values for the northernmost and southernmost stations differ by about 150 ppbv. At high southern latitudes, a pronounced seasonal cycle with the fall (September–October) maximum and the winter (February) minimum and the typical amplitude of ~30 ppbv is identified. At northern latitudes, seasonal variations are more complex in character, primarily because of the complex seasonal character of natural methane sources. The analysis of the obtained annually mean concentrations has revealed a positive trend, found to be, on average, 0.5–1% for the period of 1984–1987.

The initial CH_4 fields used as the input data at regular gridpoints were obtained by the method of correction[10] from the data of ground-based observations at the network stations. We have compared the obtained values for the stations with their measured counterparts and found that this method is accurate to within 2%.

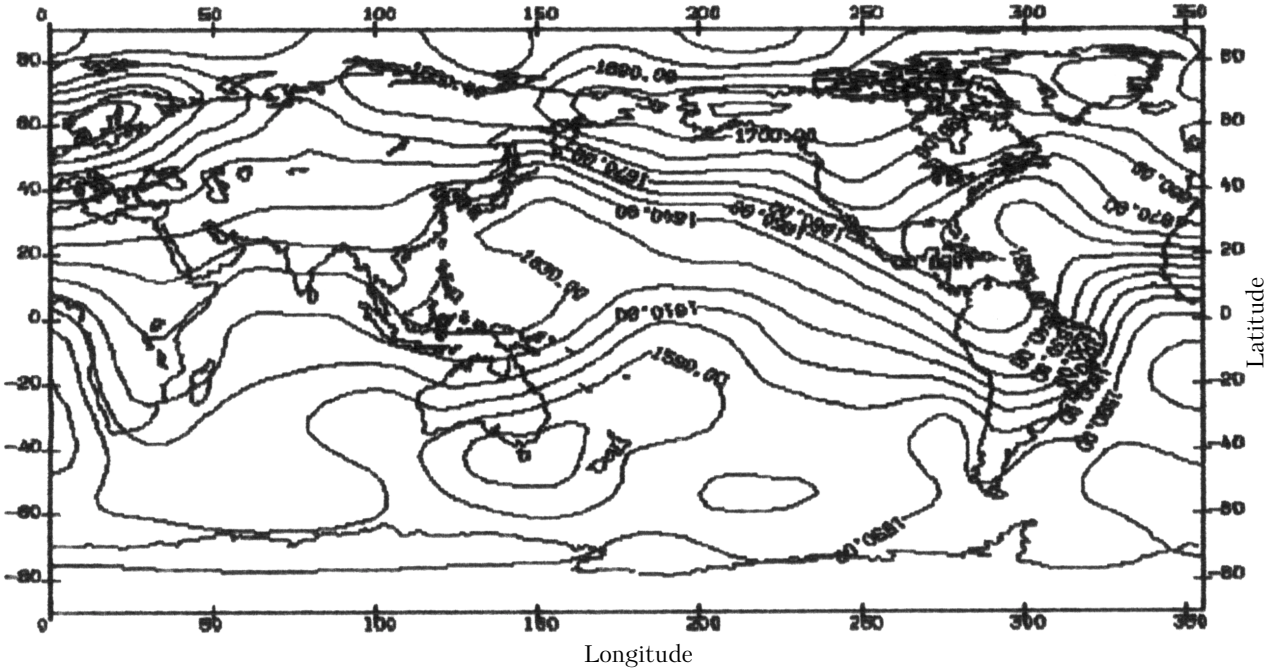
3. Results

Perhaps, one of the important findings of this study is that our model complemented with the methane transport scheme allows one to interpolate and interpret the data of ground-based observations which are few and far between. The realistic spatial and temporal patterns of variations of CH_4 concentration fields are obtained on the basis of actual measurement data.

The presented contour maps of the annually mean surface concentration of CH_4 for 1984–1987 not only indicate the increase of methane concentration in the atmosphere for this period, but also provide information on the main methane sources and sinks (Figs. 1 and 2).



a



b

Fig. 1. Annually mean (modeled) methane distribution at 1000 mb (in ppbv) for 1984 (top panel) and 1985 (bottom panel).

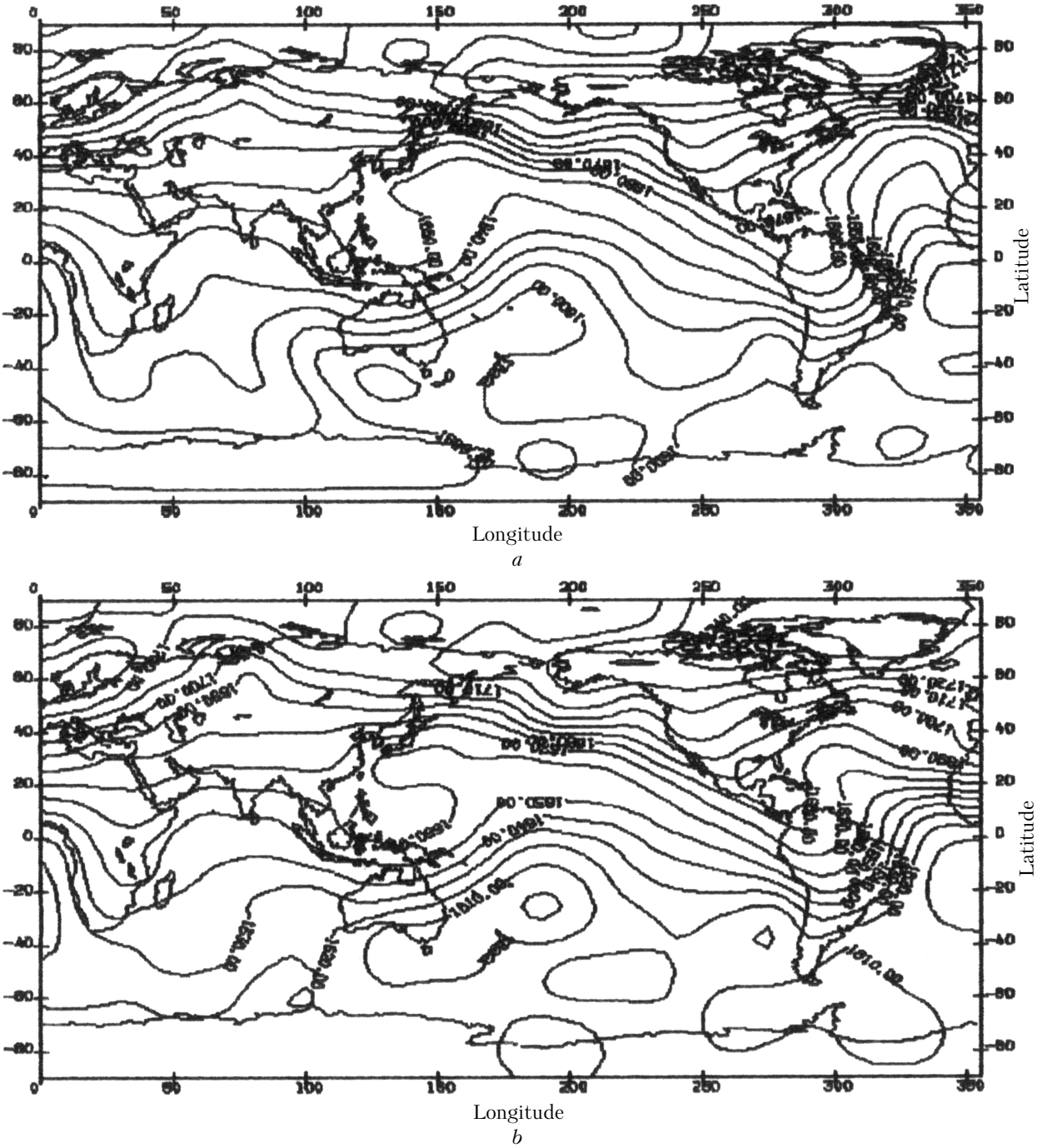


Fig. 2. Annually mean (modeled) methane distribution at 1000 mb (in ppbv) for 1986 (top panel) and 1987 (bottom panel).

Figure 3 shows the model-derived field of CH_4 concentration at ~ 960 mb averaged over 4-yr period and determined on the basis of the global-scale annually mean concentration. The methane distribution near the Earth's surface in midlatitudes of the Northern Hemisphere typically has pronounced meridional gradients caused by continental sources of methane. We note that the northern and southern tropical regions have been most difficult for simulation. So, the modeled surface concentration field is indicative of gradients in the zonal direction, suggesting that the global meridional CH_4 transport is less pronounced in this region, contrary to what the measurement data indicate.

Variations in the velocity of transport driven by convective activities in the near-ground atmospheric layer, as well as changes in the intensity of global circulation and the seasonal character of natural surface sources of methane lead to the characteristic seasonal variations of CH_4 concentration. The vertical difference between the CH_4 concentration at the surface level (~1000 mb) and in the troposphere (~500 mb) is shown in Fig. 4.

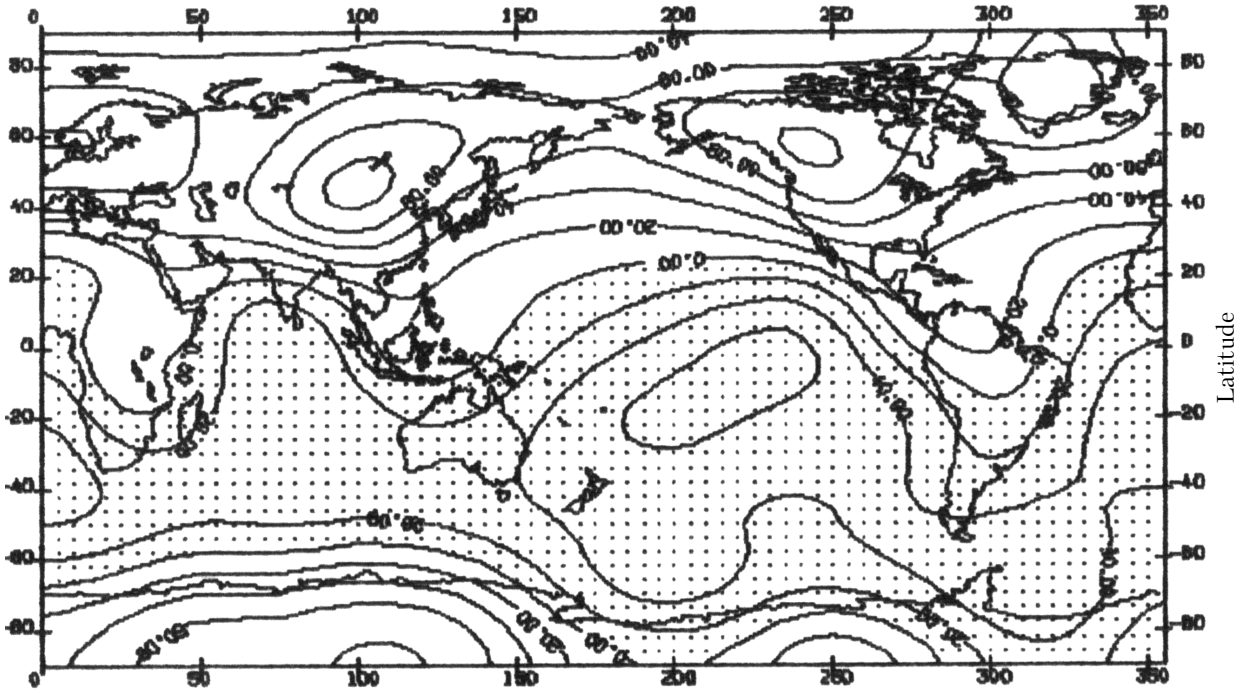


Fig. 3. Modeled annually mean distribution of CH_4 concentration (in ppbv) at 960 mb.

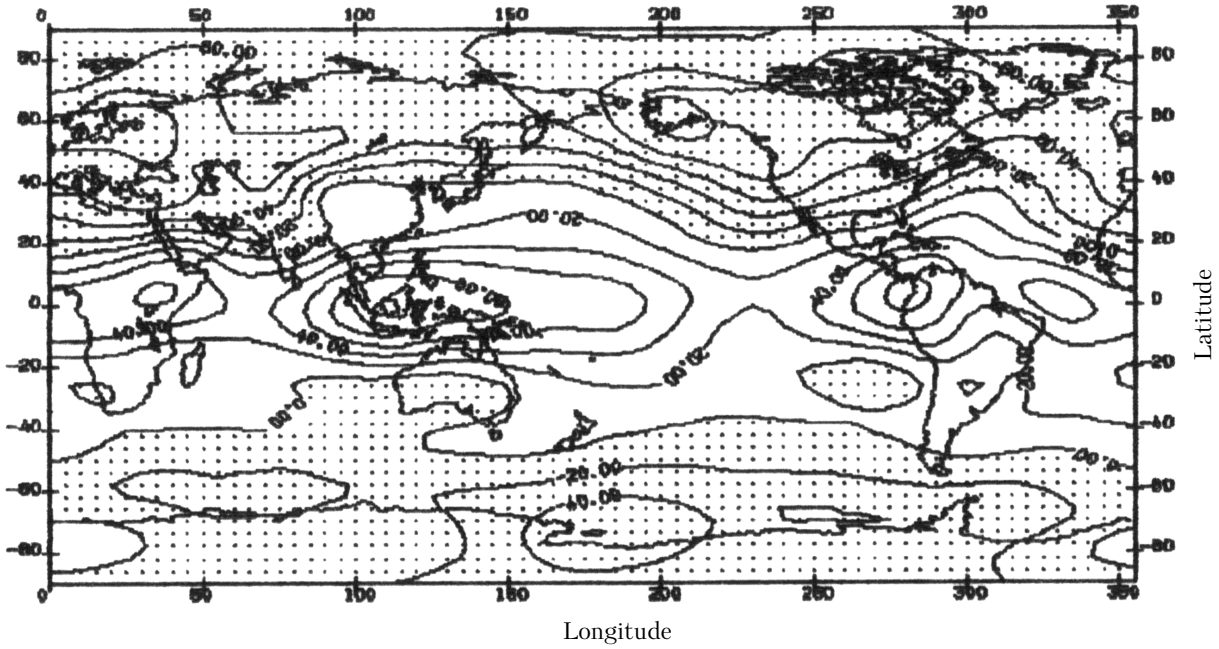


Fig. 4. Modeled distribution of the CH_4 concentration difference (in ppbv) between levels of 500 and 1000 mb.

Intense negative vertical gradients are clearly seen in the Northern Hemisphere in the regions of surface methane sources that are responsible for the global methane distribution. In the Southern Hemisphere, the only active methane source/sink seems to be chemical destruction of methane (via reaction with OH radical) which, in the absence of other physical processes, creates the vertical profile of concentration growing with altitude.

Conclusion

The climate model taking into account the large-scale methane transport is presented and used to analyze the ground-based measurements of methane concentration. The results of the spatial numerical simulation indicate that in midlatitudes of the Northern Hemisphere the model predicts considerable gradients in regions of surface methane sources in response to the

existing pattern of the observed methane distribution in the atmospheric boundary layer.

The presence of characteristic features in the near-ground fields of CH_4 concentration for the period of 1984–1987, such as seasonal cycles, positive trend, and north-south latitudinal gradient, in fact provides information on methane sources and sinks in midlatitudes.

Acknowledgments

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