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TITLE: The Impact of an Increase In Atmospheric Methane on the Temperature Field and Subsequent Climatic Effects

AUTHOR: Jeffrey Stuart Morrison, 1LT, USAF

DATE: 1988

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ABSTRACT

In this thesis, the direct radiative effects on the temperature field due to the doubling of atmospheric methane are presented, within the context of a globally representative reference atmosphere, and climatic consequences are inferred.

Based on the theory of infrared radiative transfer in a plane-parallel atmosphere, this simulation computed the vertical distribution of the change in longwave radiative heating rates that occurs as a result of doubling atmospheric methane. The interaction of methane with other atmospheric constituents which are optically active within the spectral boundaries of the 1306 cm^{-1} absorption band for CH_4 was considered in the analysis of the results.

The radiative interaction between water vapor and increased methane was shown to be the dominant reason for a positive change in heating rates in the lower troposphere when methane is doubled. Interaction with other gaseous atmospheric constituents tended to increase the heating rates of the mid-troposphere when methane is doubled. Aerosols were shown to contribute to increased heating in the lowest 1 km while the inclusion of cirrus decreased the heating rates overall when methane was doubled, with maximum effects at the layer of the cloud. All atmospheric constituents contributed to a decrease in cooling rates in the stratosphere. The change in radiative flux to the surface-troposphere system was determined to be 0.58 $W\ m^{-2}$ in response to the doubling of methane. Based on this change in flux, an increase in surface temperature due to the doubling of atmospheric methane was determined to be 0.29 K.

THE IMPACT OF AN INCREASE IN ATMOSPHERIC METHANE ON THE TEMPERATURE FIELD AND SUBSEQUENT CLIMATIC EFFECTS

Jeffrey Stuart Morrison, B.S.

A Digest Presented to the Faculty of the Graduate School
of Saint Louis University in Partial Fulfillment of
the Requirements for the Degree of
Master of Science (Research)

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DIGEST

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1. INTRODUCTION

1.1 Overview

For the Earth's climate to be in equilibrium, the incoming solar radiation absorbed by the atmosphere and surface must be balanced by outgoing thermal radiation. Water vapor and the atmospheric trace gases carbon dioxide, methane, ozone, nitrous oxide and chlorofluorocarbons partially trap this thermal radiation thereby moderating surface temperatures. Sustained changes in this trapping by even a small amount may change the Earth's radiative balance sufficiently to be of considerable importance to the climate system. Our increased reliance on synthetic chemicals, deforestation, biomass burning, and fossil fuel combustion have all contributed to observed perturbations of trace gases in the atmosphere. The likelihood of global climate change from increasing concentrations of carbon dioxide has been well studied, but the effects of increasing concentrations of the other trace gases are less known.

1.2 Statement of the Problem

This study focuses on the contribution to global climate change from increases in atmospheric methane. Although present in minute amounts, methane has a strong longwave

absorption band, centered at 7.66 μm (wavenumber 1306 cm^{-1}), which intrudes on the radiatively transparent atmospheric water vapor window region between 8 and 12 μm. Recent data suggests that atmospheric methane may be increasing by as much as 2 percent per year. At this rate, a doubling of atmospheric methane could occur within the next century. This increase may contribute to global climate change by affecting the radiative flux divergence and subsequent radiative heating rates at various altitudes. By simulating a doubling of methane within a specific model reference atmosphere with other parameters held fixed, the present research raises the questions: what will be the magnitude of the difference between heating rates of the present reference atmosphere and the future atmosphere with increased methane, and how may these differences be significant in affecting the climate system?

1.3 Thesis Objectives

Based on the questions raised in the previous section, the major topical objective of the present research is to determine the change in thermal radiative heating rates as a function of altitude when methane is doubled in a globally representative reference atmosphere and an atmosphere.

The methodological objective of this thesis is to construct a computer simulation model, based on the well-established LOWTRAN 6 computer code (Kneizys et al., 1983),

which will not only compute the net thermal radiative fluxes required to infer the heating rates as a function of altitude, but also allow for the increase in concentration of a single optically active constituent, namely methane.

An additional objective of this investigation is to infer the possible impact of the simulated radiative temperature variations on the climatic temperature fields, within the context of the model's inherent limitations.

2. REVIEW OF THE PERTINENT LITERATURE

2.1 Overview

There is mounting evidence that the concentration of global atmospheric methane is on the rise, an increase that may have begun centuries ago (Ehhalt et al., 1983). Studies of the sources and sinks of methane suggest the increase may be intimately linked to escalating world population. This is of growing concern because the direct radiative effects of methane and other minor atmospheric constituents are no longer considered negligible, and have been shown to accelerate the predicted global warming once attributed only to carbon dioxide. The argument for increased trapping of thermal energy by radiatively active atmospheric constituents, such as methane, begins with an examination of the fundamental notions of the interaction of molecules and photons. Although infrared absorption spectra are quite complex, a number of simplification procedures have been developed to model the transmission of longwave radiation through the atmosphere. Application of these procedures, such as molecular band absorption models, provide timely and reasonably accurate results to be used in studies of future climates.

2.2 Evidence of an Increase in Atmospheric Methane

Several studies have reported that levels of CH_4 in the troposphere may be increasing. Recently, Rinsland et al. (1985) reanalyzed ground-based solar infrared absorption spectra recorded in 1950 and 1951 at the Jungfraujoch Scientific Station in the Swiss Alps (46.5 N, 3578 m altitude) and discovered that in 1951 the mean tropospheric mixing ratio of methane was 1.14 ± 0.08 parts per million by volume (ppmv), about 30% less than its present mixing ratio of 1.7 ppmv. Extrapolating the 1951 data to the present day value suggests that tropospheric methane has increased at an average rate of about 1.1 ± 0.2% per year over the past 36 years. This rate of increase is comparable to the rates inferred from current measurements. Based on continuous ground-based gas chromatograph measurements at Cape Meares, Oregon (45 N), Rasmussen and Khalil (1981a) showed that the concentration of CH_4 increased at about 2 ± 0.5% per year between early 1978 and early 1981. During about the same time period, Blake et al. (1982) measured methane concentrations in remote locations between 55 N and 53 S which indicate a 1-1.5% per year increase in CH_4.

Looking for a possible trend, Ehhalt et al. (1983) examined these and other sets of CH_4 measurements including: 49 tropospheric profiles obtained from 1965 to 1967 and 1971 to 1974 by aircraft flights at the National Center for Atmospheric Research (NCAR); measurements obtained from 1968

to 1979 from ships and aircraft by the Naval Research Laboratory (NRL); and published measurements of the total atmospheric CH_4 column amount deduced from ground-based infrared spectra recorded between 1948 and 1975. Ehhalt et al. concluded that the published analyses of the ground-based infrared spectra showed little or no increase in CH_4 between 1948 and 1965. However, the NCAR and NRL measurements and data from additional studies indicate a 0.5% per year increase in CH_4 between 1965 and 1975, and there is good evidence for a global CH_4 increase of about 1-2% per year between 1978 and 1980 based on several sets of measurements including those of Rasmussen and Khalil (1981a) and Blake et al. (1982). By assuming that atmospheric methane continues to increase at a rate of 1.5% per year, a doubling of methane may occur by the year 2033.

The increase in global methane may have begun in previous centuries. From trapped air in dated ice cores, Craig and Chou (1982) have deduced that CH_4 concentrations have approximately doubled in the last 350 years, but that they were relatively constant for the previous 2,000-3,000 years. Either there were lower levels of atmospheric methane at the time the air was trapped or trapped CH_4 may have been lost by diffusion through the ice. Ehhalt et al. (1983) concluded that the relation of CH_4 levels in ice to the atmospheric CH_4 levels of the past remains unclear. However, Dickinson and Cicerone (1986) reported that H. B. Craig

maintains his results are not biased by diffusion processes. Studies of Antarctic ice cores by Pearman et al. (1986) provided further confirmation.

2.3 Sources and Sinks of Atmospheric Methane

A knowledge of both the sources and sinks of methane is required to provide insight into not only the past increase in atmospheric methane but also its future trends. Methane is produced at the Earth's surface primarily by biological fermentation due to microbial action in anaerobic environments such as wetlands and rice fields, in ruminating animals, mostly cattle, and from anthropogenic activities such as biomass burning, coal and lignite mining, automobile exhaust, and various industrial processes (Rasmussen and Khalil, 1981b). Ehhalt and Schmidt (1978) suggest that between 25 and 45% of the annual global production of CH_4 is from rice paddy fields, 10-30% is from enteric fermentation of animals, and about 2-5% due to human activities. In addition, laboratory measurements by Zimmerman et al. (1982) have shown that termites have the potential to release large quantities of methane into the atmosphere, perhaps 10-40% of the annual global production. Termites occur on about two-thirds of the earth's land surface, and human activities such as clearing of tropical forests and conversion of forests to grazing and agricultural land tend to increase the density of termites due to increased debris

accumulation. Because the major sources of methane are closely related to the production of food and energy, the concentration of methane will continue to increase with increasing population.

Due to the fact that the Earth's atmosphere is strongly oxidizing, methane cannot be produced photochemically or chemically. In fact, the dominant destruction mechanism for methane in the troposphere is the reaction of CH_4 with the hydroxyl (OH) radical in the first step of the methane oxidation chain.

$$CH_4 + OH \rightarrow CH_3 + H_2O$$

The reaction between CH_4 and OH is such a dominant loss mechanism that more than 90% of the global destruction of methane occurs in the troposphere (Levine et al., 1985). Over the past century, human activities may have depleted the concentration of the hydroxyl radicals in the troposphere thus reducing the capacity of the atmosphere for removing CH_4 (Khalil and Rasmussen, 1985).

2.4 Climate Model Results

Methane and other minor atmospheric constituents were once thought to be in such small concentrations that their direct radiative effects were negligible. However, several studies using radiative-convective models have attempted to estimate the change in global surface temperature due to an

increase in atmospheric methane. Wang et al. (1976) and Donner and Ramanathan (1980) computed an increase in surface temperature of several tenths of a degree due to a doubling of atmospheric methane. Ramanathan et al. (1985) studied a number of trace gases and identified twelve, including methane, to be of radiative importance. If increased according to recent trends, they projected methane to increase by a factor of 1.4 by the year 2030, contributing about 10% of the total global warming due to the estimated increase of all trace gases. Wang and Molnar (1985) estimate methane will increase by a factor of 1.4 as soon as the year 2010, and contribute as much as 23% of the total estimated global warming.

2.5 Radiative Properties of Atmospheric Methane

Predicting the climatic consequences due to an increase in atmospheric methane begins with the fundamental notions of the interaction of matter with electromagnetic wave energy. In a first approximation, the energy of an isolated molecule of any atmospheric constituent can be expressed as the sum of its electronic energy, vibrational energy, rotational energy, and translational energy. All but the latter are quantized and take discrete values only. These values are specified by one or more quantum numbers any combination of which defines an energy state (Goody, 1964). Radiation is absorbed or emitted when a transition takes place from

one energy state to another. Vibrational transitions never occur alone, but with many simultaneous rotational changes giving a group of lines which constitute the rotation-vibration band, usually in the intermediate infrared spectrum (Herzberg, 1971).

According to Herzberg (1945), the infrared spectrum of methane confirms the classical tetrahedral model developed by organic chemists. He points out that methane exhibits only two active bands in the infrared spectrum, centered at wavenumbers 3020 cm^{-1} and 1306 cm^{-1}, whose molecular band intensities, according to Goody (1964), are several orders of magnitude greater than the nine bands that have been identified in the solar spectrum. Although the 3020 cm^{-1} band is twice as strong as the 1306 cm^{-1} band, there is little planetary radiation at 3020 cm^{-1}. Also, less than 1.5% of the total solar irradiance is available for absorption within the 3020 cm^{-1} band. Therefore, only the 1306 cm^{-1} band is considered to significantly contribute to terrestrial climate, enhanced by its close proximity to the radiatively transparent atmospheric water vapor window region.

2.6 Modeling Thermal Radiative Transfer

Governed by the Beer-Bouguer-Lambert law, the transmittance due to a given spectral line of an atmospheric gas may be computed when the absorption coefficient is described as a function of frequency. Although the precise line shape is

a matter of uncertainty, the broadening of the absorption lines is reasonably well described by functions such as Lorentz (troposphere), Doppler (upper atmosphere), and Voigt shapes (Rodgers, 1976). The Optics Division of the Air Force Geophysics Laboratory have made available to the scientific community a data base of molecular absorption parameters from which one can calculate atmospheric absorption or radiance at high resolution (Rothman, 1986). These parameters are archived for each discrete line transition of twenty eight species, including methane. Because direct line-by-line calculations are tremendously tedious and time consuming, many efforts have been made to replace them with computationally fast and reasonably accurate band transmittance models. Rodgers (1976) provides an introduction to a variety of practical methods for estimating the transmission of atmospheric gases.

In climate models, two general classes of techniques have become accepted for the treatment of molecular absorption, the 'narrow' band method and the 'broad' or 'wide' band method. Kiehl and Ramanathan (1983) and Cess et al. (1986) have examined their effectiveness and describe their respective advantages and disadvantages. The wide band method allows one to calculate the absorption of an entire band; however, great care must be taken in choosing parameters which allow the model to accurately reflect details of the included bands and absorption of mixed gases. The nar-

row band models incorporate the detailed spectral structure over narrow spectral intervals and thus allow one to calculate spectral radiances.

McClatchey et al. (1972) employed narrow band models to develop a graphical method for the calculation of atmospheric transmission. From this method, the present Lowtran 6 computer code (Kneizys et al., 1983) evolved, which uses a numerical evaluation of the integral form of the equation of radiative transfer to predict not only atmospheric transmittance but the thermal radiation, in terms of radiance, emitted by the atmosphere and earth. Lowtran 6 uses only one band model to compute the combined transmittance of the uniformly mixed gases CO_2, CH_4, CO, N_2O, and O_2. Pierluissi and Maragoudakis (1984) addressed the need for separate molecular absorption band models for each of the uniformly mixed gases. By using a combination of laboratory measurements and the AFGL line parameter compilation (Rothman et al., 1983), Pierluissi and Maragoudakis developed and verified individual molecular absorption narrow band models for each of the uniformly mixed gases, including methane. Together with their respective atmospheric profile data (Anderson et al., 1986), these band models can be directly incorporated into the Lowtran 6 computer code.

At wavenumbers less than 2500 cm^{-1} the extinction of radiation due to scattering in the earth's atmosphere is small in comparison with the extinction due to absorption,

and Ramanathan and Coakley (1978) point out that the scattering of longwave radiation is often neglected altogether. They also suggest that at these wavenumbers the intensities of solar radiation are small in comparison with those of the radiation emitted by the atmosphere and earth's surface; consequently, the thermal emission of the earth's surface and atmosphere can be taken as the sole source of longwave radiation.

3. RESEARCH METHODOLOGY AND DATA

3.1 Overview

An indication of the climatic consequences of a global increase in atmospheric methane may come from an examination of the change in vertical heating rates of a globally representative reference atmosphere due to the prescribed increase. This involves isolating the spectral region of interest and employing an accurate yet computationally efficient means of modeling radiative transfer within the region. In addition, a sound procedure for application of the model must be determined to provide the most comprehensive analysis of the results.

For the present research, well-known radiative transfer algorithms--chosen because they have been shown to be practical, theoretically valid, and compatible with available computing facilities--are integrated into the final research model. A synergistic approach toward constructing a model atmosphere and intercomparing changes in heating rates is applied to provide insight into the results, which will be interpreted in light of the model's inherent limitations.

3.2 Specification of the Research Model

The Fortran computer code, LOWTRAN 6 (Kneizys et al., 1983), provides the backbone for the current model. In the LOWTRAN 6 model the total transmittance at a given wavenumber averaged over a 20 cm^{-1} interval is given by the product of the average transmittances due to molecular band absorption, molecular single scattering, aerosol extinction, and molecular continuum absorption. Four components make up the molecular band absorption, the separate transmittances of water vapor, ozone, nitric acid and the combined uniformly mixed gases (CO_2, N_2O, CH_4, CO, and O_2).

The current research model overcomes a serious limitation of the LOWTRAN molecular absorption models: the inseparability of the uniformly mixed gases. The existing combined model within LOWTRAN does not allow for the use of absorber concentrations that depart from the original values assumed for the gases in the model development. However, this study adopts the approach pioneered by Pierluissi et al. (1979), who previously analyzed the LOWTRAN transmission functions and concluded that they may be easily and accurately redetermined using numerical methods, thereby opening the possibility for code extensions to other absorbers, absorber concentrations, and to more recent transmittance measurements on the major absorbers.

Based on the analysis of the LOWTRAN transmission functions by Pierluissi et al., the transmission functions chosen for the present model have been derived from the early band model proposed by King (1959) and adjusted for path inhomogeneity by well-known Curtis-Godson relations. The transmission function for the uniformly mixed gases for the present research is of the form

$$T = f(X)$$

where

$$X = C' + \log_{10} W$$

and

$$W = (P/P_o)^n (T_o/T)^m U$$

C' is a spectral parameter, n and m are absorber parameters, U is the absorber amount (cm-atm) , and W is the equivalent absorber amount. Unlike LOWTRAN 6, which provides look up tables of T versus X for the transmission function for the combined uniformly mixed gases, the current research model adopts an analytical form of the transmission function (Pierluissi and Tomiyama, 1980), shown to approximate reasonably well the transmittance of a variety of gases over a wide range of meteorological conditions and spectral bands,

$$T = \exp(-10^{aX})$$

where 'a' is another absorber parameter. By employing the

parameters a, n, m, and C', which were numerically determined and validated by Pierluissi and Maragoudakis (1984) through a combination of synthetic and laboratory measured transmittance spectra, the research model is able to compute the transmittance of each of the uniformly mixed gases separately.

The data for the methane absorption band at 1306 cm^{-1} include spectral parameters from 1075 cm^{-1} to 1775 cm^{-1} given every 5 cm^{-1}. For this spectral interval, LOWTRAN's combined transmission function was replaced with the Pierluissi and Maragoudakis transmission function for each of the contributing uniformly mixed gases: CH_4, CO_2, and N_2O. Separate subroutines were added for the transmission functions and spectral parameters of each gas, and the code was revised to accept inhomogeneous atmospheric density profiles when applicable. The LOWTRAN 6 subroutine which calculates total atmospheric transmittance, TRANS, was appropriately modified to compute the separate transmittance of each of the uniformly mixed gases.

The research model solves a numerical analogue to the radiative transfer equation and is capable of calculating the spectrally integrated radiance of the 1306 cm^{-1} methane absorption band for any given methane concentration profile. Further revisions allow the model to calculate integrated infrared fluxes at specified levels. Considering a non-scattering, plane-parallel atmosphere which is in local

thermodynamic equilibrium and assuming that the thermal infrared radiation from the Earth's atmosphere is independent of the azimuth angle, the spectral upward and downward flux density can be expressed in terms of the spectrally averaged Planck radiance and the diffuse transmission function (Liou, 1980). The diffuse transmission function, which allows the transformation of radiance values to those of hemispherical flux on the basis of the isotropic nature of thermal infrared radiation, is determined for the research model from the transmission function for intensity by multiplying all absorber amounts by 1.66, the diffusivity factor. Use of the diffusivity factor provides a great simplification of the transfer calculations, but it also causes systematic error in fluxes and heating rates. However, according to Ramanathan and Coakley (1978), the errors tend to be small and are not likely to affect the response of the model to changes in atmospheric composition or external conditions. Since thermal infrared radiation is isotropic, the integrated radiance computed using the diffuse transmission functions, is multiplied by π to obtain the integrated flux for the spectral region of interest.

The present research model accepts geometric input data which dictates the calculation of the upward and downward flux at 33 user specified levels from 0 to 100 km. An additional algorithm determines the net flux at each level. The flux divergence between any two levels is then calculated

and incorporated into the Enthalpy Rate Equation to finally produce the time rate of change of thermal radiative temperature as a function of altitude for the spectral interval 1075 cm^{-1} to 1775 cm^{-1}.

3.3 Implementation of the Research Model

Prior to calculating the change in heating rates due to an increase in atmospheric methane, the model's radiative transfer scheme for the 1306 cm^{-1} methane band will be validated by comparing the model's calculation of the change in infrared flux due to a specified increase in methane to the line-by-line calculations of Cess et al. (1986).

Next begins the process of constructing a globally representative reference atmosphere, within the constraints of the model, that will allow some inference of climatic effects from the change in heating rates due to an increase in methane. To aid in the interpretation of the model output, change in heating rate calculations will be performed upon the addition of individual or sets of optically important atmospheric constituents. This diversified simulation procedure, the intercomparison of various model outputs in juxtaposition, will provide a more comprehensive basis for the analysis of results.

The present model accepts the altitude, pressure, temperature, and constituents profiles for the U.S. Standard

atmosphere and five seasonal model atmospheres provided as basic input data for LOWTRAN 6. Because this study focuses on large-scale climatic changes, the U.S. Standard atmosphere is adopted as it most closely represents a year-round average of all latitudes. The infrared emissivity of the surface of the earth is specified as 0.9 based on an examination of the tables presented in Sellers (1965). As mentioned previously, the original LOWTRAN treatment of the uniformly mixed gases assumed a constant mixing ratio at all altitudes. The present model allows concentrations to vary with altitude for CH_4, CO_2, and N_2O, by employing more recent profile data (Anderson et al., 1986).

Calculations will be performed for a doubling of methane and results of the change in heating rates will be presented in degrees K per year for each 1 km layer from the surface to an altitude of 25 km. Above 25 km the atmospheric constituent mixing ratio data becomes sparse and more subject to error. In addition, the Curtis-Godson approximation becomes less accurate as the absorption lines take on more of a Doppler shape at high altitudes. The flux calculations from 25-100 km are considered however as part of the total scheme, and included to provide an intermediate "cushion" between the lower atmosphere and space.

The first set of heating rate change calculations will include a model atmosphere which adopts the pressure and temperature profiles of the U.S. Standard atmosphere, but

which limits those constituents which remain optically active. Results will be obtained for an atmosphere in which methane is the only absorber, an atmosphere in which methane and water vapor are the only absorbers, and finally a clear atmosphere with all the standard optically active constituents.

The built-in aerosol and cirrus cloud transmittance models provide an opportunity to study their contribution to the change in heating rates due to an increase in methane as well as provide a more globally representative model atmosphere. This study adopts the rural aerosol extinction, from 0-2 km, with a meteorological range of 15 km. The model defaults to the background aerosol models for the troposphere and stratosphere which correspond to the U.S. Standard atmosphere. From the worldwide cirrus occurrence and thickness statistics of Stone (1957) and Chang and Willand (1972) , a globally representative cirrus cloud cover was determined to be 1 km thick with the cloud base at 8.25 km, and present 44.3% of the time. Change in heating rate calculations will be performed for the clear U.S. standard atmosphere plus aerosols, the clear atmosphere including aerosols and 100% coverage by cirrus clouds, and finally the globally representative model of the U.S. Standard atmosphere with aerosols and 44.3% cirrus coverage.

Although beyond the scope of the present study, a radiative-convective model, as described by Liou (1980) and

Pallmann (1976;1977), attempts to achieve a globally averaged vertical temperature profile after a series of reiterative computations of the time dependent temperature variations which eventually converge on thermal equilibrium. Although the present study is limited to inferring climatic consequences from the initial vertical distribution of time dependent temperature variations, the results of the current research model may be loosely validated by comparison with the change in surface temperature results of similar radiative-convective models. As discussed in Ramanathan and Coakley (1978), the relation between the change in the energy input to the earth-troposphere system, ΔI_T, and the change in surface temperature, ΔT_s, for a radiative-convective model with fixed relative humidity and fixed cloud altitude is given by

$$\Delta T_s \simeq 0.5\ \Delta I_T$$

The coefficient 0.5 is the climate sensitivity or feedback parameter and includes thermal infrared positive and negative feedbacks that act to displace or restore temperature from or to its equilibrium value in the absence of ΔI_T. So much uncertainty has been discussed in the literature concerning the feedback parameter (Dickinson, 1982; Hansen et al., 1982; Luther, 1982; Ramanathan, 1982) that the above relationship will be applied for cursory comparison with the

radiative-convective model outputs and the results will be presented as tentative.

3.4 Limitations of the Research Model

The major limitations of the current research model are its inability to realistically represent not only the absorption of radiative energy at the molecular level, but the many parameters that make up climate on the global scale. Although the molecular band models are derived from and verified against the more accurate line-by-line calculations, there still remains a need for more accurate and complete spectroscopic data. Even the line-by-line calculations do not fully resolve the structure of each absorption line, so inaccuracies are introduced by the line parameterizations in the line-by-line models and carried forward into the simpler band models used in the present research. The model is primitive in the sense that no attempt is made to model the regional character of climate, the various land-ocean-atmosphere interactions, lower tropospheric cloudiness, or the various non-linear feedbacks. While the results are of academic interest, the present research model calculations do provide a first order estimate of the impact on the thermal structure of the atmosphere due to an increase in atmospheric methane, without pursuing the secondary feedbacks responsive to the increase.

3.5 Expectations from the Research Model

It is expected that the change in heating rates due to an increase in atmospheric methane will be positive in the troposphere (heating) and negative in the stratosphere (cooling). The synergistic method of creating the globally representative model atmosphere and intercomparison of various model outputs will clarify the physical reasoning behind the magnitude and sign of the change in heating rates at each altitude. For example, lower tropospheric water vapor should absorb any increased emission due to the doubling of methane and cause warming. Boundary layer aerosols may have a similar effect. The addition of cirrus coverage, both partial and total, may act to enhance or diminish the change in heating rates at various altitudes. Once the shape of the profile of the change in heating rates is adequately explained, climatic consequences will be inferred. Particular attention will be focused on the change in heating rate of the layer nearest the surface, as this is where climate is most often experienced by humans. However, the change in heating rates of the other layers will not be ignored. Based on their magnitude and relative altitude, the heating rate changes of the middle and upper troposphere, as well as the lower stratosphere, will be interpreted in the context of their ability to affect the temperature of the lowest layers.

Because the real atmosphere will receive the projected increase of methane gradually and respond accordingly with a cascade of nonlinear feedback mechanisms, as opposed to the one-time doubling which is characteristic of the present simulation, the results are not intended to represent the actual difference between present heating rates and the heating rates when methane may truly be realized as doubled. Instead, the results shall be interpreted as being merely representative of the primary forcing mechanism, i.e. radiative heating, which establishes the trend by which all other secondary feedbacks must respond. Because radiative forcing is primary, climatic consequences may be inferred from results obtained by the present method.

4. DISCUSSION AND INTERPRETATION OF RESULTS

4.1 Overview

In this section the results of the validation of the narrow band model for methane which was incorporated into the current simulation are presented, followed by a discussion of the change in heating rates obtained as each component of the model reference atmosphere is added. These atmospheric constituents, which are radiatively active within the boundaries of the 1306 cm^{-1} methane absorption band, can absorb the increased emission due to the doubled methane within each layer, as well as decrease the flux of thermal radiation from neighboring layers. Without presenting a detailed analysis of the spectral dependence of each constituent at every level, their relative effects on the change in heating rates due to doubling methane can be determined from a sequential comparison of the change in heating rates as each constituent is added. Finally, the consequential heating of the layer nearest the surface is discussed, and an estimate of the increase in surface temperature due to doubling methane is presented.

4.2 Validation of the Band Model

The flux calculations obtained using the narrow band model for methane adopted for the present simulation were validated by comparison with flux calculations obtained using the line-by-line model of Cess et al. (1986). For their model, Cess et al. selected the line locations and intensities from a JPL tape (Orton and Robiette, 1980), incorporating all CH_4 lines within the wavenumber interval of 1100 to 1700 cm^{-1}. Changes in infrared flux were obtained at 25 km, 13km, and the surface due to an increase in CH_4 mixing ratio from 1.75 to 3.50 ppmv. The pressure and temperature profiles of the midlatitude summer atmosphere (McClatchey et al., 1972) were employed, but because the focus was upon the examination of radiative transfer approximations due only to methane, mixing with water vapor, clouds, and other gaseous constituents was ignored. The volumetric mixing ratio of methane was simplistically assumed to be invariant with altitude. By adjusting the current model to these specifications, changes in infrared flux due to doubling methane differed from the line-by-line results by only 2.3% at 25 km, 1.1% at 13 km, and 2.2% at the surface. This suggests very good agreement even though the narrow band model employed in the present study is derived from a different absorption line data set, and the flux calculations in the present simulation employ the diffusivity factor to transform radiance values to those of

hemispherical flux whereas the line-by-line model performed hemispherical averaging through the use of an 8-point Gaussian quadrature.

With confidence established in the current narrow band model for methane, it was used in the current research to obtain the change in heating rates as a function of altitude due to the doubling of CH_4 in a globally averaged reference atmosphere. The temperature and pressure profiles for the U.S. Standard atmosphere, chosen as the reference atmosphere, are shown in Figure 1(a) and 1(b) respectively. For the current study, the volumetric mixing ratio profile of methane was allowed to vary with altitude and is presented in Figure 1(d).

4.3 Water Vapor Effects

In order to examine the effects of water vapor on the change in heating rates due to doubling methane, two heating rate change profiles were compared. First, the change in heating rates as a function of altitude was determined for an atmosphere which retains the pressure and temperature distribution of the reference atmosphere but includes methane as the only optically active constituent. The second profile of heating rate changes includes water vapor as a second optically active constituent. Because the emphasis here is on the interaction of these two species,

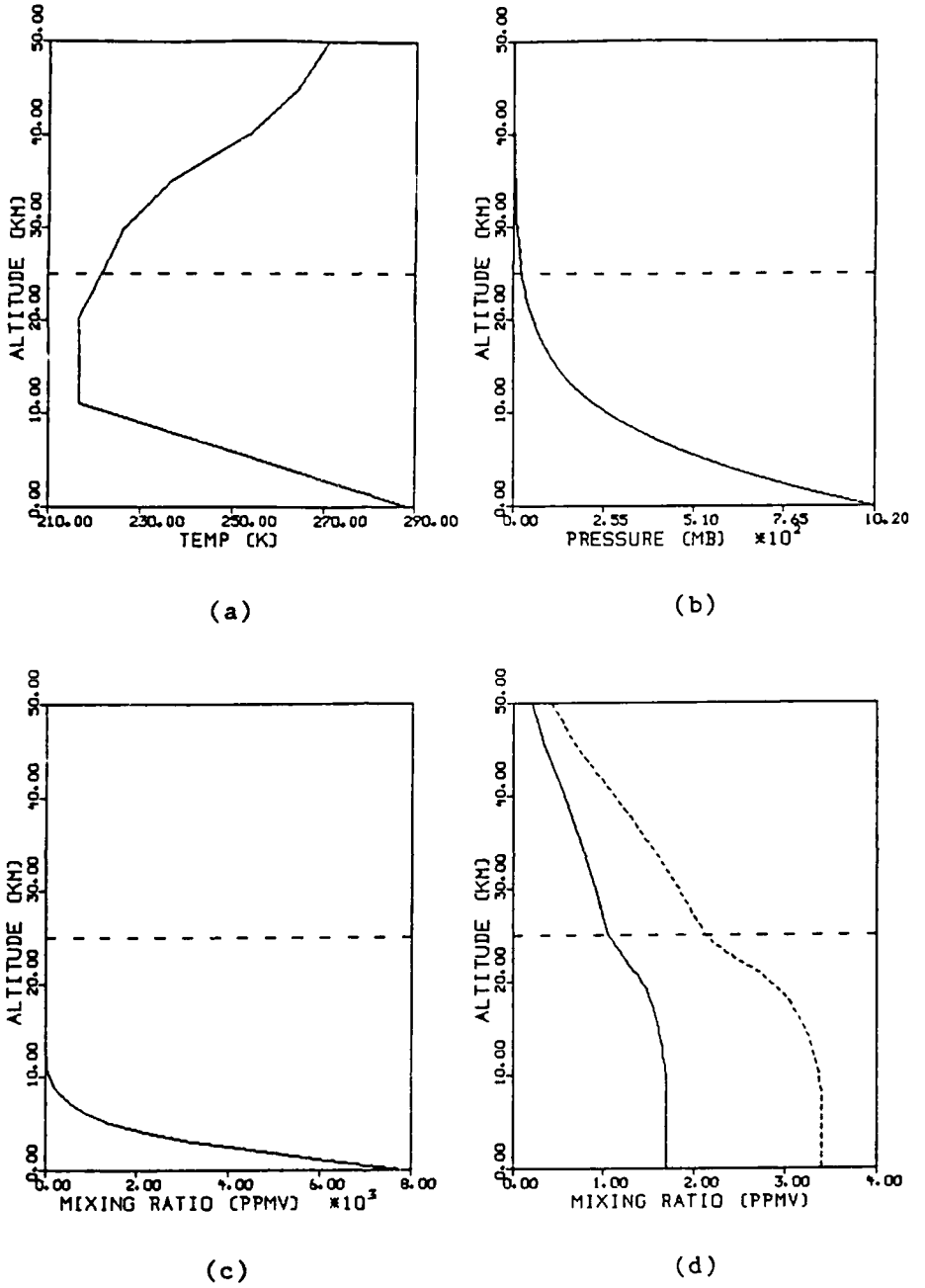

Fig. 1. The pressure (a), temperature (b), and mixing ratio profiles of water vapor (c) and methane (d) for the reference atmosphere (dashed profile indicates doubled methane, dashed horizontal line indicates upper boundary of the following change in heating rate profiles).

other gases that absorb within the interval were ignored. The comparison of these two profiles is presented in Figure 2.

The doubling of methane in the atmosphere which includes methane as the only absorber exhibits a reduction in heating rates from the surface to 5 km, with a maximum reduction of over 16 K per year in the lowest 500 m. Although doubling methane increases the opacity of each layer to upwelling thermal radiation, in these lowest layers this screening is not sufficient to counteract the increased emission of the doubled CH_4. The effect is most pronounced near the surface because the methane molecules are emitting at temperatures near the surface temperature. The ability of emission to overcome the screening effect diminishes with altitude as t' temperature of each layer decreases, until about 5 km when the attenuation of upward thermal flux and subsequent conversion to heat takes precedence over thermal emission of the layer. The maximum increase in heating rates of 3.29 K per year occurs between 10 and 11 km. In the layers above 11 km the increase diminishes because less upward flux is available for attenuation due to screening by the increased methane below. Above 18 km, so much upward thermal radiation has been screened that emission due to increased methane in each layer takes precedence and a decrease in heating rates is realized.

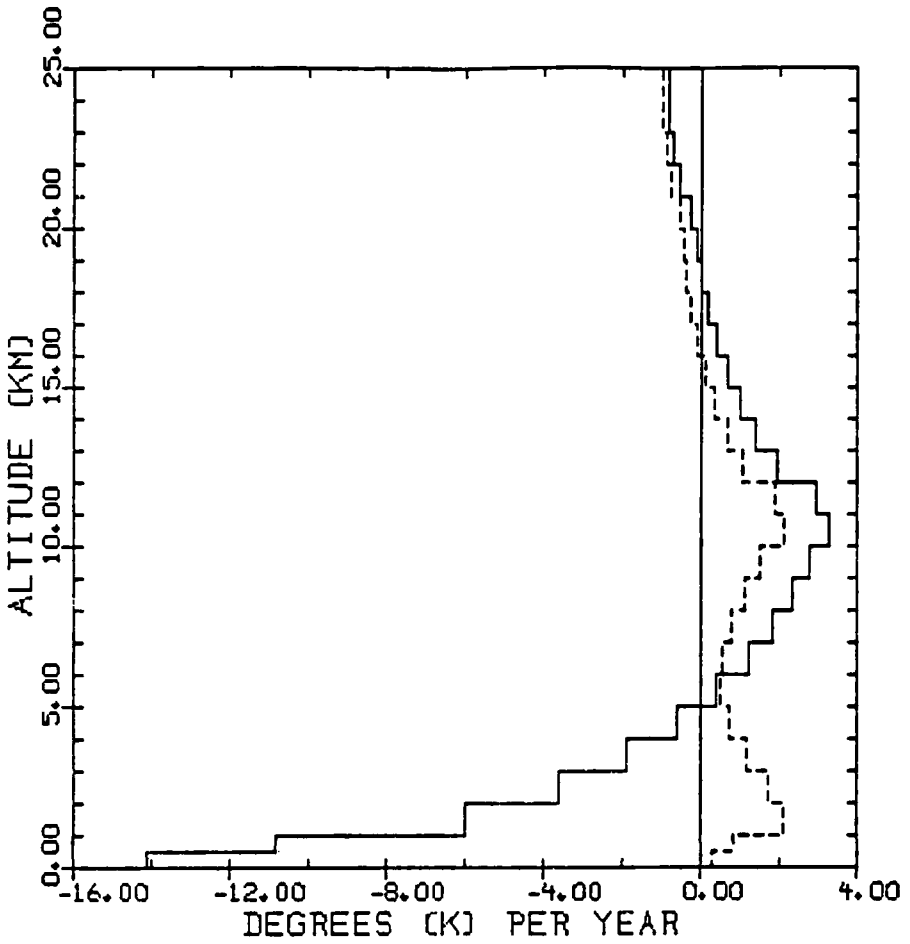

Fig. 2. The change in heating rates due to doubling methane for an atmosphere with methane as the only radiatively active constituent (solid) and an atmosphere with methane and water vapor as the only radiatively active constituents (dashed).

Because water vapor is radiatively active within the spectral boundaries of the methane absorption band, it has an important effect on the change in heating rates when methane is doubled, especially in the lower troposphere where water vapor is most abundant. The vertical distribution of water vapor is shown in Figure 1(c). The water vapor molecules are able to absorb the increased emission from the doubled methane. Also, the increased methane can absorb the counter radiation from the water vapor in neighboring layers. Therefore, doubling methane in the presence of water vapor results in an increase in heating rates from the surface to 5 km, opposed to the decrease in heating rates observed when methane was considered by itself. The effect diminishes with altitude above 6 km not only because the concentration of water vapor decreases with altitude, but emission from the doubled methane in each layer decreases with decreasing temperature. The maximum increase in heating rates now occurs between 1 and 2 km and is 2.12 K per year. The addition of water vapor also somewhat uniformly suppresses the increase in heating rates above 6 km. The increase that occurs between 10 and 11 km is about 64% of the increase observed when methane was considered alone. In addition, the cross-over from an increase to a decrease in heating rates in the stratosphere now occurs at 16 km instead of 18 km. This effect is the result of a decrease in upward thermal flux available for attenuation and conversion to heat, because it has been screened in the lower

troposphere by the water vapor. Clearly the presence of water vapor has a strong influence on the change in heating rates due to doubling methane.

4.4 Other Gaseous Constituents Effects

Addition of the complement of radiatively active molecular constituents of the reference atmosphere also affects the change in heating rates due to doubling methane. Figure 3 shows a comparison of the heating rate change profiles of the methane plus water vapor atmosphere and the clear reference atmosphere, which includes the complement of gaseous constituents. With an absorption band center at 1285 cm^{-1}, very near the band center of methane, nitrous oxide is the most optically active additional atmospheric constituent within the spectral boundaries of the methane absorption band. The volumetric mixing ratio of 0.32 ppmv for nitrous oxide is virtually invariant with altitude in the troposphere. In the layers below 2 km, the increase in heating rates is reduced because the N_2O absorbs both upward radiation from the surface and water vapor counter radiation, rendering it unavailable for absorption by the increased methane.

In the layers between 2 and 6 km the effect of absorption by N_2O of the emission from increased methane takes precedence, therefore an increase in heating rates occurs when methane is doubled. This effect is vertically short-

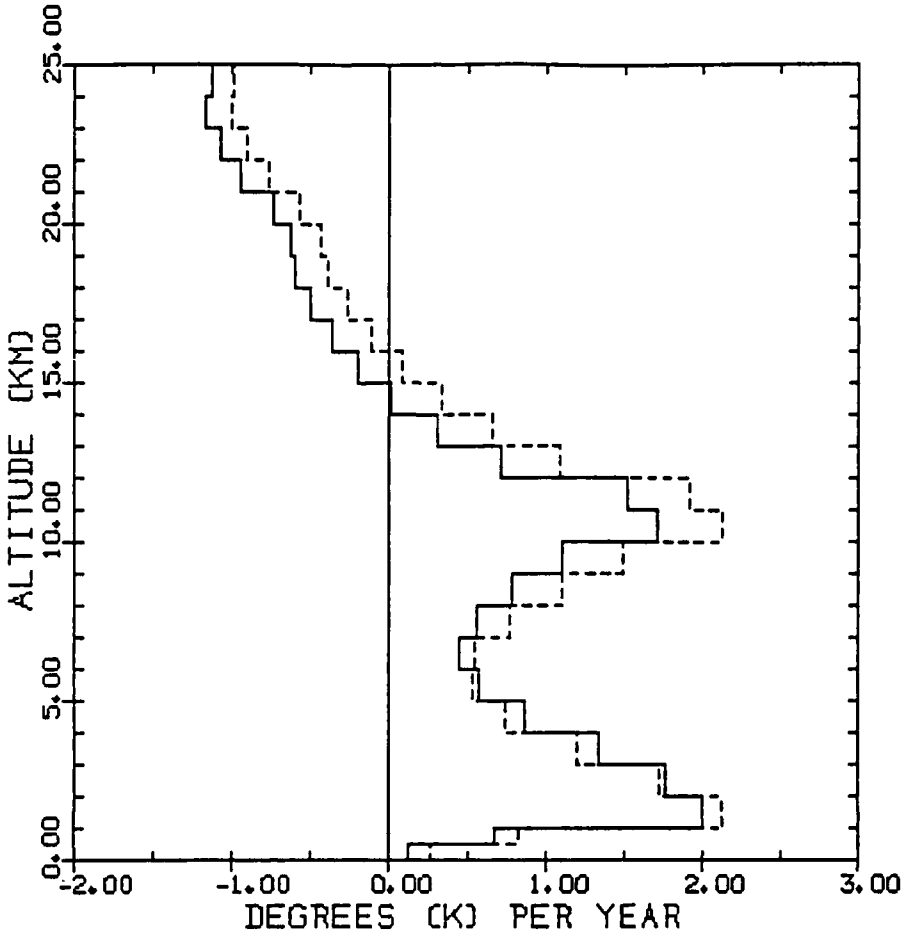

Fig. 3. The change in heating rates due to doubling methane for the clear reference atmosphere with the full complement of gaseous constituents (solid) and an atmosphere with methane and water vapor as the only radiatively active constituents (dashed).

lived as more of the upwelling thermal flux is screened until a doubling of methane results in a uniform decrease in the change in heating rates. The cross-over level from an increase to a decrease in heating rates is lowered to about 15 km when methane is doubled in the clear reference atmosphere. The maximum increase in heating rates is still between 1 and 2 km and is 2.00 K per year. The increase in the heating rate of the lowest 500 m is 0.12 K per year.

4.5 Aerosol Effects

The present simulation adopts the aerosol model built into the LOWTRTAN 6 computer code. Here, the variation of the aerosol optical properties with altitude is modeled by dividing the atmosphere into four height regions each having a different type of aerosol. These regions are the boundary or mixing layer (0 to 2 km), the upper troposphere (2 to 10 km), the lower stratosphere (10 to 30 km), and the upper atmosphere (30 to 100 km). In the boundary layer a rural model was chosen, representative of aerosols of natural origin, with a meteorological range of 15 km at the surface. Above the boundary layer a tropospheric model was chosen which describes clear and calm conditions. A background stratospheric aerosol model was specified which does not consider the direct influence of volcanic dust contamination. The aerosol extinction was taken to be independent of height up to 1 km with a pronounced decrease above that

height. The concentration of aerosols above 2 km is at least two orders of magnitude less than in the boundary layer. As a result, aerosols have very little effect on the change in heating rates when methane is doubled (Figure 4), except in the lowest kilometer. Here, the aerosols absorb the thermal emission of the increased methane and therefore augment the positive change in heating rates. The increase in the heating rate of the lowest 500 m is 0.22 K per year, an additional 83% over the clear reference atmosphere result.

4.6 Cirrus Cloud Effects

In order to examine the maximum effect an average cirrus cloud would have on the change in heating rates when methane is doubled, calculations were first made with 100% coverage. The cloud base was specified at 8.25 km with a thickness of 1 km for the current simulation. A comparison of the change in heating rates of the reference atmosphere including aerosols and the reference atmosphere including aerosols plus 100% cirrus coverage is presented in Figure 5.

Inclusion of the cirrus cloud diminishes the increase in heating rates in a nearly uniform fashion from the surface to 6 km and from 10 to 23 km. This effect occurs in the troposphere because the cloud absorbs the thermal emission of the increased methane in the stratosphere, and therefore reduces the amount of downward flux available for

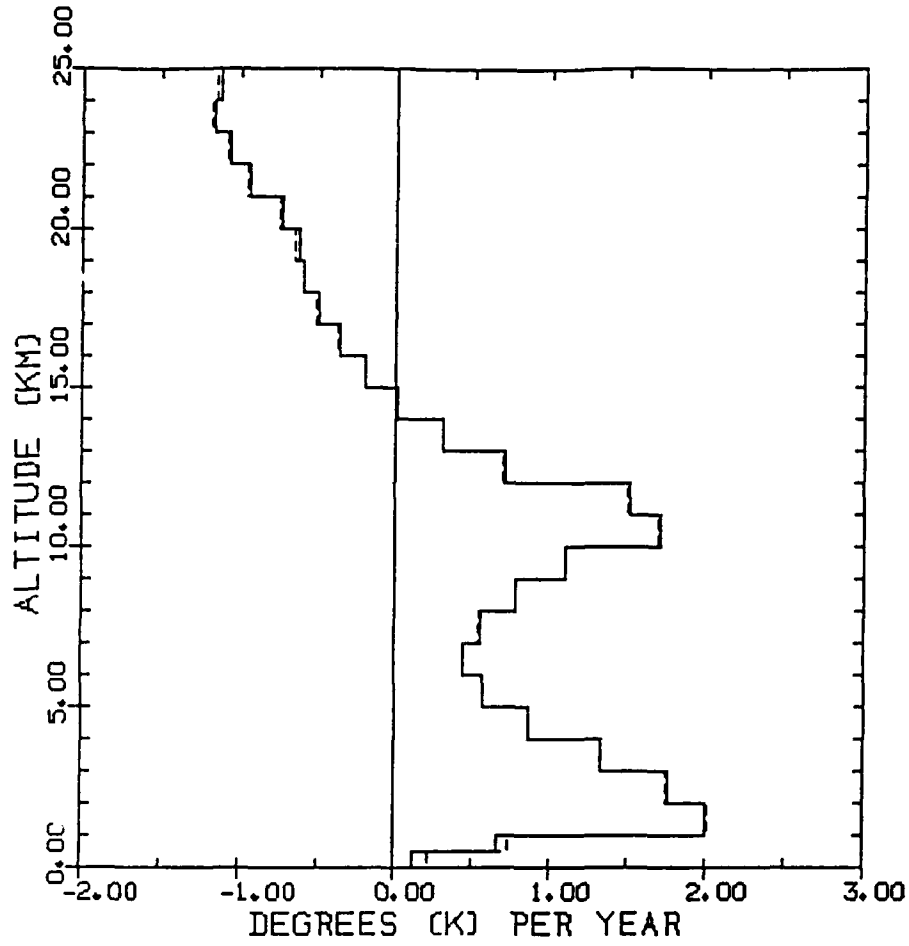

Fig. 4. The change in heating rates due to doubling methane for the clear reference atmosphere (solid) and the reference atmosphere including aerosols (dashed).

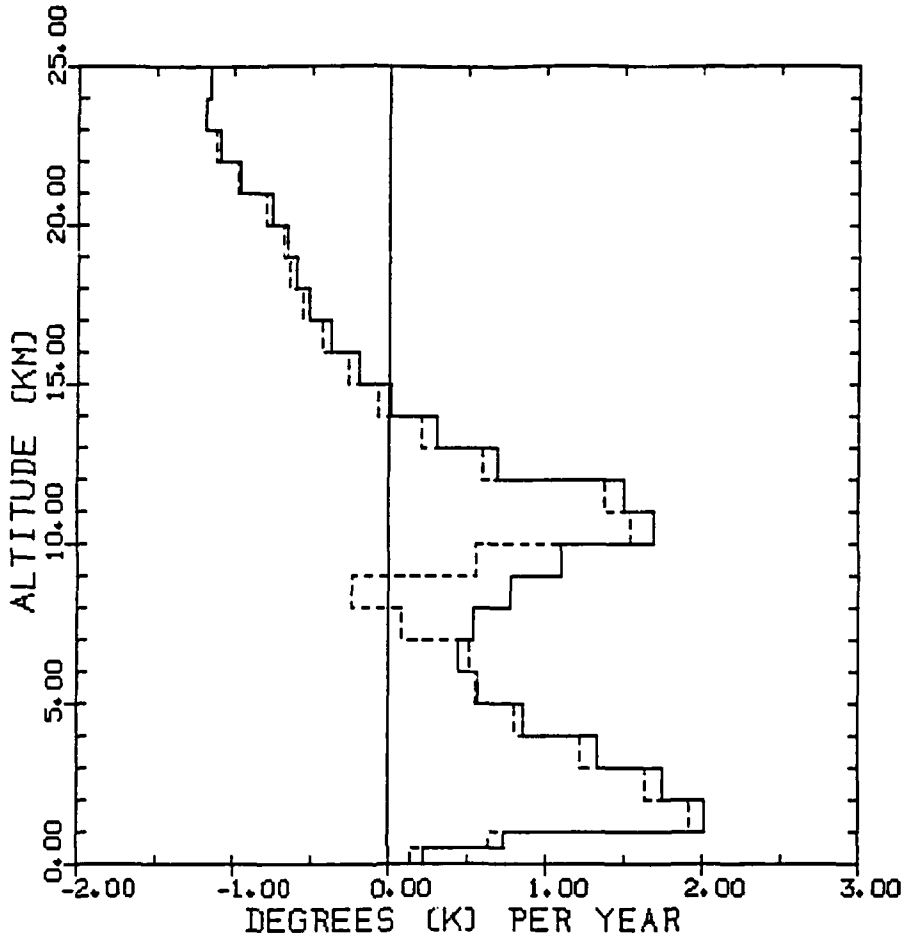

Fig. 5. The change in heating rates due to doubling methane for the reference atmosphere including aerosols (solid) and the reference atmosphere including aerosols with 100% cirrus coverage (dashed).

attenuation. Similarly, the cloud reduces the amount of upward flux from the surface and troposphere available to be converted to heat in the stratosphere. The heating rates are substantially diminished in the vicinity of the cloud. Doubling methane actually causes a decrease in the heating rate from 8 to 9 km, where 75% of the cloud exists. A reduction in heating rates at the level of cirrus occurs because the cloud absorbs some of the upward thermal radiation from the surface and lower troposphere and therefore less energy is available to be absorbed by the increased methane. However, the magnitude of the reduction in the change in heating rates in the vicinity of the cloud determined by the present simulation is in question, especially in the layer from 7 to 8 km where the cloud physically does not exist. The cirrus cloud model simplifies calculations by attributing 75% of the cirrus cloud transmittance to the 8 km level and 25% of the transmittance to the 9 km level. Therefore, the average transmittance of the layer between 7 and 8 km used in the flux calculations is anomalously affected. Similarly, the slight increase in heating rate in the layer from 6 to 7 km probably occurs due to anomalous absorption by the increased methane of the counter radiation from the inappropriately modeled portion of the cloud in the layer directly above. In short, the change in heating rates of the layers immediately surrounding the simulated cloud

should be considered tenuous while the change in heating rates of the other layers more accurately reflect the effects of the cirrus cloud.

Toward the objective of obtaining the change in heating rates due to doubling methane in a globally averaged atmosphere, where cirrus clouds were determined to be present 44.3% of the time based on the cirrus occurence statistics of Chang and Willand (1972), the effects due to cirrus were weighted accordingly and the results are presented in Figure 6 with the change in heating rates of the reference atmosphere including aerosols but without cirrus. The maximum increase in heating rates continues to occur between 1 and 2 km, here 1.95 K per year. The increase in the heating rate of the lowest 500 km is 0.18 K per year.

4.7 Climatic Consequences Near the Surface

The change in heating rates due to a doubling of methane in a globally averaged reference atmosphere including aerosols and 44.3% cirrus coverage is presented in Figure 7. Without considering diurnal or seasonal variations in the amount of increase in atmospheric methane, or the ongoing response of the climate system to such increases, the results indicate the vertical distribution of the annual injection of thermal radiative energy due to the doubling of methane. Because the change in heating rates depicts the primary forcing mechanism which initiates climatic response

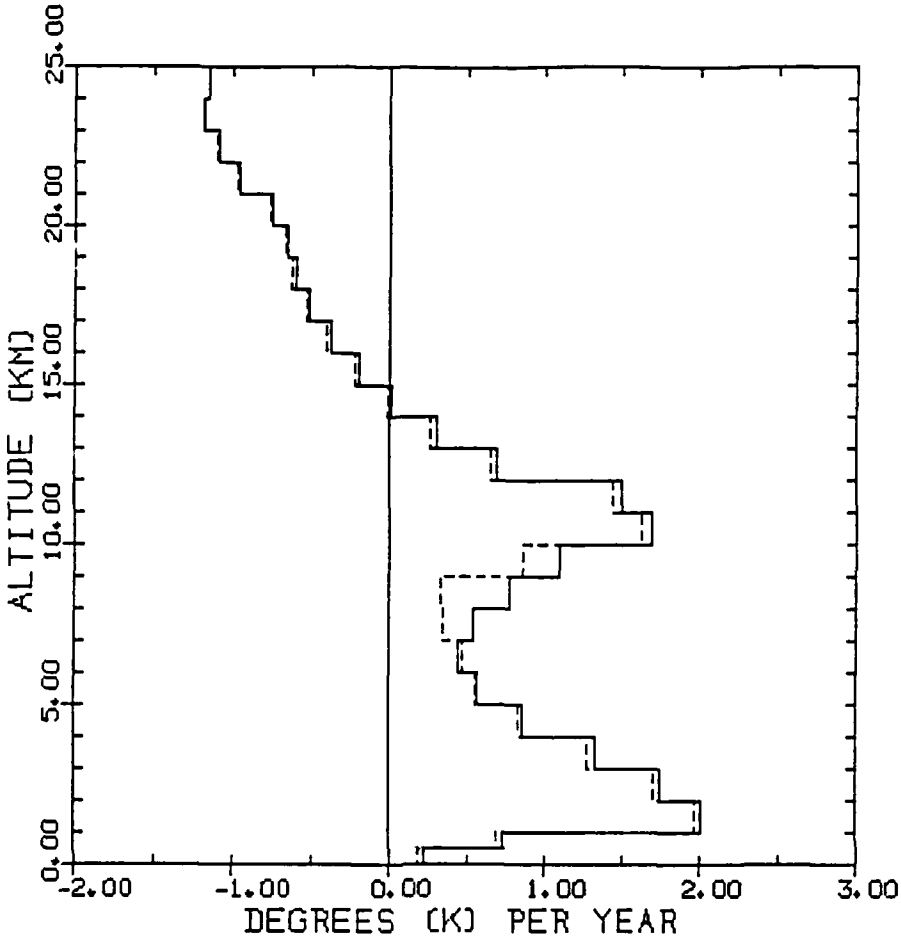

Fig. 6. The change in heating rates due to doubling methane for the reference atmosphere including aerosols (solid) and the reference atmosphere including aerosols with 44.3% cirrus coverage (dashed).

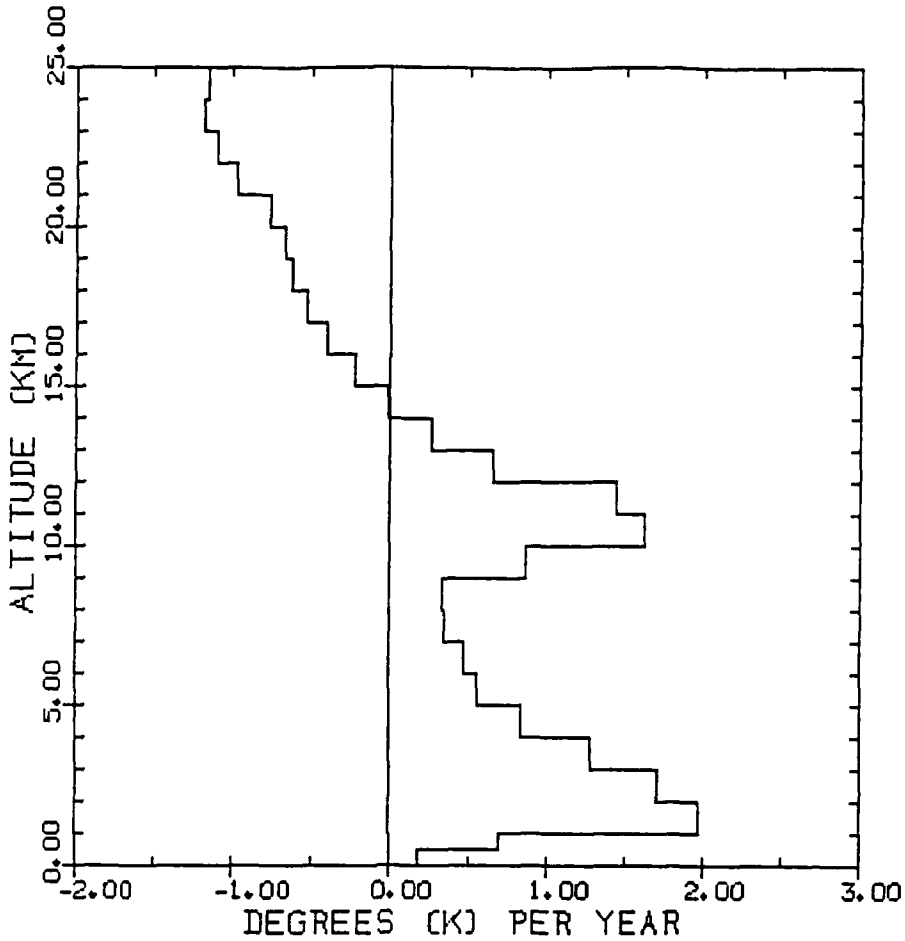

Fig. 7. The change in heating rates due to doubling methane for the globally representative reference atmosphere of the present study.

and subsequent feedbacks, interpretation of these results suggests the ability of an increase in atmospheric methane to affect the climate near the surface, where a change will be most realized by humans.

Because of the simplicity of the current simulation, it would not be realistic to quantify an actual increase in surface temperature due to the doubling of methane based soley on the increase in the heating rate by 0.18 K per year in the lowest 500 m. However, by recognizing the change in heating rates as relative indicators of radiative forcing, it is possible to infer the mechanisms by which secondary radiative responses may change the temperature near the surface. Based on this approach, the 0.18 K per year increase in the heating rate *near the surface* becomes significant in the context of the increase in heating rates of the layers just above. The reason the change is positive, if only slightly, in the lowest layer is primarily due to the ability of water vapor to absorb the thermal emission from the increased methane, and the ability of the increased methane to absorb counter radiation emitted by the water vapor from the layers above. These processes dominate the thermal emission out of the layer by the increased methane. Note that the increase in the heating rate of the layer between 1 and 2 km is an order of magnitude greater than the increase in the lowest 500 m. The increased heating of this layer and adjacent higher layers would result in the increase of

counter radiation into the lowest layer and contribute to further warming at the surface. In addition, warming of the lowest layers would increase their water vapor content. This suggests a positive feedback effect because the presence of water vapor has been shown to be the primary reason that an increase in atmospheric methane results in tropospheric warming from the surface to 5 km.

The second maximum increase in heating rates, which occurs between 10 and 11 km, although removed from the surface, may still contribute to an increase in surface temperature. Ramanathan and Coakley (1978) present the hypothesis that a change in tropopause temperature may alter the water vapor content of the stratosphere. An increase in tropopause temperature, suggested by the results of the current simulation, would allow more water vapor to be transported to the stratosphere, increase the thermal radiative opacity, and ultimately increase the surface temperature. Wang et al. (1976) estimate an increase in surface temperature of 0.65 K for a doubling of stratospheric H_2O.

Finally, it is generally accepted that the surface temperature change is governed by the radiative flux change to the surface-troposphere system. From the present study, the change in radiative flux to the surface-troposphere system was determined to be 0.58 W m^{-2} in response to the doubling of methane. In order to provide a quick estimate of the increase in surface temperature, this change was multiplied

by the climate sensitivity parameter, 0.5, presented by Ramanathan and Coakley (1978) and discussed in section 3.3 of this thesis. This result indicates a 0.29 K increase in surface temperature due to methane doubling. While there is much uncertainty concerning the climate sensitivity parameter, this result is in very good agreement with the estimate of 0.3 K computed by Donner and Ramanathan (1980) and lies within the low and high values, 0.2 and 0.4 K, computed by Wang et al. (1976).

5. CONCLUSIONS

Recent measurements suggest that atmospheric methane may be increasing at the rate of 1-2% per year. The primary sources of methane have been shown to be linked with human activities and a rising human population. This increase is of scientific concern because the 1306 cm^{-1} absorption band is near the spectral region of maximum terrestrial radiative emission and intrudes on the radiatively transparent water vapor window region. Therefore an increase in atmospheric methane serves to partially trap outgoing infrared radiation and contribute to global warming.

In this thesis, the direct radiative effects on the temperature field of a doubling of atmospheric methane were presented, within the context of a globally representative reference atmosphere. The radiative interaction between water vapor and increased methane was shown to be the dominant reason for a positive change in heating rates in the lower troposphere when methane is doubled. Other gaseous atmospheric constituents which are optically active within the spectral boundaries of methane absorption tended to increase the heating rates of the mid- troposphere when methane is doubled. Aerosols were shown to contribute to increased heating in the lowest 1 km while the inclusion of cirrus decreased the heating rates overall when methane was

doubled, with maximum effects at the layer of the cloud. All atmospheric constituents contributed to a decrease in cooling rates in the stratosphere.

The results serve as relative indicators of the primary thermal forcing mechanism by which secondary feedbacks must respond, therefore effects on the climate of the lowest layer due to the doubling of methane were inferred. The maximum increase of the heating rates in the layer from 1 to 2 km may increase the temperature of the layer near the surface due to absorption by methane and water vapor of the increased counter radiation. Warming of the tropopause, indicated by the second maximum between 10 and 11 km, may increase the water vapor content of the stratosphere, contributing to atmospheric opacity and realized as warming at the surface. The change in radiative flux to the surface-troposphere system was determined to be 0.58 W m^{-2} in response to the doubling of methane. Based on this change in flux, a methane induced increase in surface temperature was determined to be 0.29 K.

While the narrow band model for methane incorporated into this simulation proved to be compatible within a few percent with a high resolution line-by-line model, there still remains a need for more accurate and complete spectroscopic data. In addition, the simplicity of the radiative transfer scheme of this simulation limits its applicability to the real climate system. However, by computing the

vertical distribution of the change in radiative heating rates, a basic variable associated with climate, the results suggest the importance of including the direct radiative effects of atmospheric methane in studies of future climates.

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