

Upper Atmospheric Thermal Structure of Jupiter With Convective Heat Transfer

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ABSTRACT

When radiative transfer is the dominant mechanism cooling the lower thermosphere of Jupiter, CH_4 (7.7μ) is probably the dominant cooling agent; however, its low turbopause mixing ratio (10^{-4} , as compared to 10^{-3} in the lower atmosphere) contributes to a cooling rate small ($\lesssim 10^{-4}$) compared to CO_2 on Mars. This results in a Jovian mesopause density $\sim 10^2$ times the Martian density or $\sim 10^{14} \text{ cm}^{-3}$, if radiative cooling is the primary heat transfer mechanism in the lower thermosphere. An alternate method for transporting heat is convection (forced or free), which apparently emerges as the dominant transport mechanism as the effective eddy diffusion coefficient (K_v) approaches values similar to those anticipated in the earth's lower thermosphere ($10^6 \text{ cm}^2 \text{ sec}^{-1}$). Over the solar cycle, with a high heating efficiency (0.86), the temperature rise above the turbopause ranges between 19 and 53K for weak convective activity ($K_v = 10^5 \text{ cm}^2 \text{ sec}^{-1}$) and 7–19K for strong activity ($10^7 \text{ cm}^2 \text{ sec}^{-1}$), suggesting that satellite measurements of the exospheric temperature could be used to estimate the degree of convective activity present in the upper atmosphere. Reasonable variations in the H_2 -He ratio and the mesopause height ($\sim 300 \text{ km}$), temperature (140K) and cooling rate are of minor importance compared to the heating efficiency and the incident flux in establishing the thermospheric temperature profile via the heat conduction equation. The diurnal temperature variation in the Jovian exosphere over the solar cycle is small, probably less than 5–10K.

1. Introduction

Gross and Rasool (1964), using a procedure similar to that outlined by Nicolet (1959, 1960), calculated that the mean temperature difference between the Jovian mesopause and exosphere for a helium-dominated and a hydrogen-dominated atmosphere were 7 and 12K, respectively. The crucial parameter governing the thermal profile of this model was the distance separating the CH_4 cooling region from the level below which, effectively, all the solar ultraviolet radiation $< 912 \text{ \AA}$ was assumed absorbed by hydrogen. In this initial effort, Gross and Rasool obtained a hydrogen absorption layer which later appeared to be too near the mesopause. This factor, in addition to the selection of a low heating efficiency, contributed to their small temperature rise in the Jovian thermosphere.

McGovern (1968) constructed the Jovian thermospheric temperature profile by dividing the thermosphere into a large number of small layers, each of which was capable of absorbing and conducting energy toward the mesopause. The temperature profile was then generated by solving numerically for each layer the heat conduction equation in conjunction with a separate diffusion equation for each constituent. McGovern, using the photochemical analysis of the upper atmosphere of Jupiter by Cadle (1962), assumed that ethane (C_2H_6) was the dominant IR radiator in the lower thermosphere and concluded that the Jovian

temperature rise in the thermosphere could range from a few degrees Celsius to almost 100K, depending upon the heating efficiency, Jovian composition, and degree of solar activity.

Developments subsequent to this study in the areas of methane photochemistry (Strobel, 1969) and solar energy conversion in a hydrogen-dominated atmosphere (Henry and McElroy, 1969), as well as improved estimates in the hydrogen to helium ratio (Owen and Mason, 1969), motivated Hunten (1969) to suggest that the true temperature rise might be considerably greater. In particular, Strobel indicated that CH_4 , not C_2H_6 , would be the dominant hydrocarbon in the Jovian thermosphere, while Henry and McElroy have shown that a heating efficiency of 0.86 would be more appropriate than the value of 0.50 selected by Gross and Rasool and by McGovern. However, recent satellite measurements of the incident solar UV flux (Hall and Hinteregger, 1970) indicated that the flux values used in previous computations were too high, suggesting that the exospheric temperatures may be lower, not higher, than the values of McGovern (1968).

In addition, upper atmospheric planetary thermal computations in the past have generally selected a common turbopause for all constituents, either coinciding with the mesopause or fixed some distance above the mesopause. This turbopause level served as a line of demarcation between the mixed or homogeneous

distribution of constituents below and the onset of diffusion above. Neglected was the prospect that each constituent could possess an individual turbopause level which was dependent upon the vertical component of the eddy diffusion coefficient (K_v), and that the introduction of such a multilayered turbopause would permit both a more realistic estimate of the distribution of constituents with height, as well as an examination of the relative efficiency of heat transfer by eddy mixing and infrared radiation.

For these reasons, a new study into the thermal structure of the Jovian thermosphere was initiated for the specific purposes of: 1) evaluating the significances of these recent developments in methane photochemistry, solar energy conversion, and higher hydrogen concentration upon the temperature profile; 2) assessing the importance of a multi-layered turbopause and, in particular, appraising the degree of downward heat transport associated with turbulent mixing; and 3) estimating the diurnal variation of the Jovian exospheric temperature.

2. Turbopause concentrations and model outline

The major atmospheric constituents on Jupiter are molecular hydrogen and helium, with minor amounts of methane and ammonia. In the lower atmosphere, the proportions by volume of H_2 , He, CH_4 and NH_3 were selected to be 1.0:0.2:10⁻³:2×10⁻⁴; however, Hogan *et al.* (1969) have indicated that an effective ammonia "cold trap" exists in the region below the Jovian mesopause. Under these circumstances, for the above proportions, the ammonia-to-methane mixing ratio in the upper atmosphere will be further reduced by approximately 10³.

Strobel (1969), in examining the photochemistry of CH_4 in the Jovian atmosphere, concluded that ethane (C_2H_6) was the most abundant hydrocarbon resulting from the photolysis of methane, with an overall C_2H_6 to CH_4 mixing ratio of between 10⁻⁴ and 10⁻⁵. Similarly,

the atomic to molecular hydrogen mixing ratio in the vicinity of the turbopause was indicated as being slightly less than 10⁻⁵, somewhat lower than the H concentration resulting from the photoionization of H_2 at higher levels as computed by Hunten (1969). In light of this discussion, a reasonable first estimate of the relative composition by volume near the Jovian mesopause could be $H_2(1.0):He(0.2):CH_4(10^{-3}):H(10^{-5}):NH_3(10^{-7}):C_2H_6(10^{-7})$.

However, in stating that the turbopause level in the model is the level separating the mixing and diffusion region, it was implied that the scale heights and, correspondingly, the density gradients of minor constituents in these regions would undergo an abrupt change at the turbopause. Under these circumstances, the density distribution with height, for a heavy constituent, would be given by the asymptotic distribution in Fig. 1; yet, in reality, it is anticipated that the scale height and, in turn, $\partial n/\partial Z$ will vary smoothly through this region, somewhat similar to the so-called actual distribution in Fig. 1. To illustrate this, we examine the diffusion equation, including the eddy terms but neglecting the small thermal diffusion factor (Colegrove *et al.*, 1965), or

$$\phi_i = -D_i \left(\frac{\partial n_i}{\partial Z} + \frac{n_i}{H_i} + \frac{n_i}{T} \frac{\partial T}{\partial Z} \right) - K_v \left(\frac{\partial n_i}{\partial Z} + \frac{n_i}{H_m} + \frac{n_i}{T} \frac{\partial T}{\partial Z} \right), \quad (2.1)$$

where ϕ_i and H_i are, respectively, the flux and scale height of constituent i , while H_m is the mixing scale height.

Considering a static situation ($\phi_i=0$) and assuming that $D/K_v=e^{Z/H_m}$ ($Z=0$ at the turbopause) produces for a one-dimensional steady-state model

$$\frac{dn_i}{n_i} = - \left(\frac{1}{1+e^{-Z/H_m}} \right) \frac{dZ}{H_i} - \left(\frac{1}{1+e^{Z/H_m}} \right) \frac{dZ}{H_m} - \frac{dT}{T}. \quad (2.2)$$

The integration of (2.2) over a constant scale height and isothermal region yields

$$n_i(Z) = n_i(0) 2^{(H_m/H_i)-1} \times (1+e^{-Z/H_m})(1+e^{Z/H_m})^{-H_m/H_i}, \quad (2.3)$$

where $n_i(0)$ is the actual density of the minor constituent (CH_4) at the turbopause. When $Z \gg 0$, Eq. (2.3) reduces to

$$n_i(Z) = n_i(0) 2^{(H_m/H_i)-1} e^{-Z/H_i}, \quad (2.4)$$

indicating that $n_i(0) 2^{(H_m/H_i)-1}$ is equal to the turbopause density for the asymptotic solution [$n_i^*(0)$], since the asymptotic distribution above the turbopause is given by $n_i^*(0)e^{-Z/H_i}$. Conversely, for the case when $Z \ll 0$, Eq. (2.3) reduces to $n_i^*(0)e^{-Z/H_m}$.

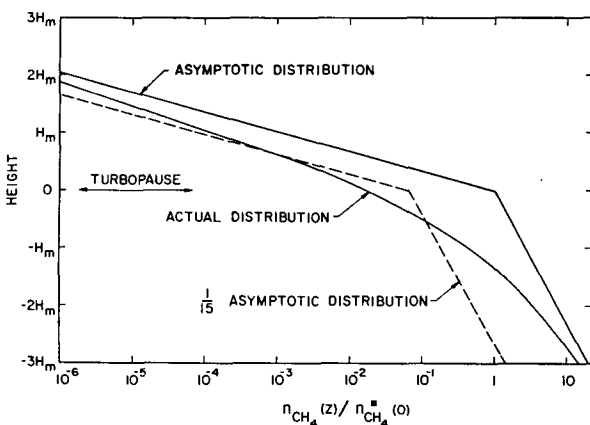


FIG. 1. Asymptotic and so-called actual distribution of CH_4 in the vicinity of the turbopause for an isothermal atmosphere.

In the Jovian atmosphere with an assumed mean molecular weight of 2.33 (H₂ to He ratio of 5), the actual concentration of CH₄ in the vicinity of the turbopause, as seen from Fig. 1, will be considerably less than that given by the asymptotic solution. In particular, at the turbopause the $n_i^*(0)$ to $n_i(0)$ ratio for CH₄ will be $2^{(H_m/H_i)-1}$ or 57.8; while, one mixing scale height on either side of the turbopause, the mean CH₄ concentration will be diminished by a factor of nearly 15, compared with the asymptotic solution.

In this simple example, the temperature profile and/or the variation of scale height with altitude were assumed to be known; however, at present these parameters are not only unknown but are, in fact, one of the primary aims of this computation. In theory, through an additional iterative process, one could obtain a stable and unique solution for $n_i(Z)$ and $T(Z)$; yet from a practical standpoint, in view of the existing uncertainties concerning the exact CH₄ concentration in the Jovian atmosphere, a simple reduction in the CH₄ turbopause concentration would produce nearly the same results and be far less time-consuming both physically and computationally. In light of this discussion, in the vicinity of the turbopause, the CH₄ mixing ratio was lowered from 10⁻³ to 10⁻⁴. Similarly, the turbopause NH₃ and C₂H₆ mixing ratios should be reduced by approximately one and two orders of magnitude, respectively.

With the onset of diffusion, H₂ and H will dominate the composition of the exosphere and upper thermosphere. Ammonia, the hydrocarbons and, to a lesser extent, helium will be concentrated near the lower thermosphere. It is in this region that the major radiative cooling by the hydrocarbons will occur, since hydrogen and helium are ineffective as radiators. Nevertheless, these latter constituents are effective in absorbing solar UV energy in the upper thermosphere and conducting this energy down to the lower thermosphere, where the energy is dissipated through radiation and convection. Under these circumstances, the average temperature profile of the upper atmosphere can be calculated by simultaneously solving numerically the heat conduction equation with a separate hydrostatic equilibrium equation for each constituent. The assumptions associated with these equations, as well as the procedure for applying these equations, are similar to those outlined by McGovern (1969), with the following exceptions: 1) introduction of a multilayered turbopause with eddy heat transport; 2) selection of a composition dependent heating efficiency (ϵ) which increased from 0.83 to 0.86 with altitude; and 3) computation of an average dayside instead of a sub-solar point temperature (this required that the absorption rate of the solar flux be reduced by $\frac{1}{2}$ and that a value of 0.636 be adopted for the cosine of the average zenith angle). Then, 4) the solar flux was limited to the wavelength interval between 30 and 950Å; 5) the additional cross sections

for H₂ and He were taken from Weissler (1956); 6) the conductivity coefficients [A] adopted for H₂ and He were 1050 and 900 ergs cm⁻¹ sec⁻¹ (°K)^{-3/2}, respectively; 7) a lower boundary or turbopause temperature of 140K and a height in the vicinity of 300 km above the opaque cloud tops were used; 8) physical parameters pertinent to Jupiter were incorporated [e.g., gravity and recent solar flux values (Hall and Hinteregger, 1970)]; and 9) the 7.7 μ band of CH₄ was selected as the principal cooling wavelength in the upper atmosphere. The justification for this selection requires that we first examine the cooling mechanism in some detail.

3. Cooling rate

Normally, in the lower atmosphere of a planet, the rate at which molecules per unit volume are collisionally excited into the first vibrational level (Q_c) can practically be considered equal to the collisional deexcitation rate (L_c); thus $Q_c = L_c$, or

$$n_0 z P_{01} = n_1 z P_{10}, \tag{3.1}$$

where n_0 and n_1 are, respectively, the number densities of the constituent in the ground level and the first vibrational level, z is the collision frequency, and P the transition probability per collision between subscripted states. In thermal equilibrium, the number densities of the states are related by the Boltzmann factor; therefore,

$$P_{01} = P_{10} e^{-h\nu/kT}, \tag{3.2}$$

$$Q_c = \frac{n_0 e^{-h\nu/kT}}{\beta}, \tag{3.3}$$

since $(zP_{10})^{-1} = \beta$ or the vibrational relaxation time (Lambert, 1962).

With increasing altitude and decreasing pressure, deactivation through radiation becomes increasingly more important, and the process of collisional excitation (Q_c) followed by radiative deexcitation (L_r) or the conversion of translational into radiative energy can be a major cooling mechanism in the upper atmosphere, if radiative excitation (Q_r) is small compared to collisional excitation and $L_r \gg L_c$. Under these circumstances, the cooling rate per unit volume (R_c) for an infrared-active constituent is given by $L_r h\nu$ or $n_E A_{10} h\nu$, where $h\nu$ is the energy of the emitted photon, A_{10} the Einstein coefficient for spontaneous emission which is equal to the reciprocal of the natural lifetime of the first excited state (ϕ), and n_E the number of molecules of constituent i per unit volume in the first vibrational level.

Below the exosphere, since the translational mode is in thermodynamic equilibrium, the collisional excitation rate, which is independent of the deexcitation mode, can

be given by Eq. (3.3). When $Q_c = L_r$, then

$$n_E = \frac{\phi}{\beta} n_0 e^{-h\nu/kT}, \quad \text{if } Q_r = L_c = 0, \quad (3.4)$$

$$R_i \approx \frac{f_i n h \nu e^{-h\nu/kT}}{\beta}, \quad \text{if } Q_r = L_c = 0, \quad (3.5)$$

where f_i is the fractional number density of constituent i , and n (the total number density) = $(n_0 + n_E)/f_i \approx n_0/f_i$.

Repeating this procedure, this time including Q_r and L_c and respectively setting them equal to xQ_c and n_E/β with the previous formulation of Q_c and L_r , yields

$$n_E \approx (1+x) \frac{\phi}{\phi+\beta} f_i n e^{-h\nu/kT}. \quad (3.6)$$

While n_E is the number density in the first vibrational level, only those molecules which transfer energy between the radiation field and the translational mode are involved in the cooling of the lower thermosphere. Collisional activation-deactivation processes and resonant scattering will not contribute to the cooling. Assuming that the fraction of molecules that participate in any of the four possible excitation-deexcitation processes is given by the product of the excitation and deexcitation rates divided by $[(Q_r + Q_c)(L_r + L_c)]$ or $[QL]$, then

$$R_i = L \left[\frac{Q_c L_r - Q_r L_c}{QL} \right] h\nu, \quad (3.7)$$

where the bracketed terms represent the net percentage of deexcitations which result in atmospheric cooling. Using the previous definitions for L_c and L_r or n_E/β and n_E/ϕ , respectively, with Eqs. (3.6) and (3.7) yields

$$R_i \approx \left[1 - \frac{x\phi}{\beta} \right] \frac{f_i n h \nu e^{-h\nu/kT}}{(\beta + \phi)}. \quad (3.8)$$

When radiative excitation is a minor process ($x \rightarrow 0$) and nonlocal thermodynamic equilibrium (NLTE) conditions exist ($\beta \gg \phi$), then Eq. (3.8) reduces to (3.5) and Eq. (3.6) to (3.4). In contrast, when $Q_r \rightarrow 0$ and $\phi \gg \beta$, then Eq. (3.8) reduces to $(n_E h\nu)/\phi$, where n_E is now the Boltzmann distribution.

The term $(x\phi)/\beta$ is equivalent to $2.0 \times 10^{14} \lambda^3 B_\nu e^{h\nu/kT}$ (cgs units), as can be seen by utilizing Eq. (3.3) in conjunction with the relationships $Q_r = 5.0 \times 10^{15} f_i n \lambda B_\nu S$ and $\phi^{-1} = 8\pi \nu^2 c^{-2} S$ (Goody, 1964, p. 41), where S is the band intensity ($\text{cm}^2 \text{sec}^{-1}$) and B_ν the incident radiation at frequency ν responsible for radiative excitation. When the blackbody temperature associated with the incident radiation (T_r) is comparable to the temperature of the cooling volume (T), then $(x\phi)/\beta$ can be considered small (< 0.1) compared to 1 for the conditions under

discussion; in fact, when $T_r = T$ and B_ν is replaced by Wein's distribution, then $(x\phi)/\beta$ is reduced to 0.08. Conversely, in the vicinity of 10μ , if $T_r > T + 30\text{K}$, where $T = 120\text{K}$, then $R_i \lesssim 0$. The term $(x\phi)/\beta$ can be deleted if the mesopause temperature is higher than T_r which presumably can be represented by some given temperature in the stratosphere. For this reason, the mesopause temperature was selected as 140K or comparable to the maximum stratospheric temperature as calculated by Hogan *et al.* (1969), thereby permitting us to neglect the term $(x\phi)/\beta$ in Eq. (3.8).

The natural lifetime ϕ , for all practical purposes, can be treated as a constant in the atmosphere (Goody, 1964, p. 41), and, based upon the band intensities from Thorndike (1947) and France and Williams (1966), ϕ was calculated to be 0.14, 2.17 and 0.05 sec, respectively, for CH_4 at 7.7μ , C_2H_6 at 12.2μ , and NH_3 at 10.5μ . In contrast, the vibrational relaxation time (β) depends upon collisional frequency (z) or pressure, temperature and composition. For the constituents under discussion, data pertaining to the variation of β as a function of these variables is very limited; for this reason, β for each constituent was formulated as

$$\beta(z, T, C) = \beta_s C_z C_T C_c, \quad (3.9)$$

where β_s is the standard relaxation time at 300K and 1 atm for the given constituent in a homogeneous environment, while C_z , C_T and C_c are correction factors due to collision frequency, temperature and composition or nonhomogeneity. In particular, the correction factors were formulated in the following manner:

$$C_z = \frac{n_L}{n} \left(\frac{300}{T} \right)^{\frac{1}{2}}, \quad (3.10)$$

$$C_T = 0.1 e^{691/T}, \quad (3.11)$$

$$C_c = \frac{\beta_s(\text{H}_2)}{\beta_s M_{\text{H}_2} + \beta_s(\text{H}_2) M}. \quad (3.12)$$

Loschmidt's number ($2.687 \times 10^{19} \text{cm}^{-3}$) is n_L , $\beta_s(\text{H}_2)$ and β_s are the standard vibrational relaxation times for hydrogen (2×10^{-9} sec) and the constituent under discussion, respectively, while M is the mole fraction. The correction factor C_z is due to the fact that β is inversely proportional to the collision frequency, and C_T was chosen so that the relative variation of β with temperature would be similar to that for CO_2 , for which temperature-dependent data are available and simultaneously correspond to the theoretical format of the variation of $\beta(T)$ as proposed by Fogg *et al.* (1953); the quenching factor or C_c is based upon Lambert's (1962) discussion of β in gas mixtures. Nevertheless, an analysis of the variation of $\beta(\text{CH}_4)$ with small amounts of H_2 (7.3% by volume), as determined in three cases by Eucken and Aybar (1940), tended to indicate that the use of Eq. (3.12) would result in severe over-quenching for CH_4 , especially at the low

temperatures found on Jupiter. For this reason, C_e for CH_4 was selected as 0.5 instead of approximately 10^{-2} , as specified by the full quenching equation (3.12).

In comparing [via Eq. (3.8)] the molecular cooling rates at 140K associated with CH_4 (7.7μ), C_2H_6 (12.2μ) and NH_3 (10.5μ), the variation of C_z and C_T with density and temperature was assumed to be the same for each of these constituents, and the term $(x\phi)/\beta$ in (3.8) was subsequently neglected. Selecting a β_s for CH_4 , C_2H_6 and NH_3 of 5×10^{-7} , 5×10^{-9} and 6×10^{-9} sec, respectively (Herzfeld and Litovitz, 1959; Strauch and Decius, 1966), with a turbopause density of 10^{14} cm^{-3} , results in R_{CH_4} exceeding $R_{\text{C}_2\text{H}_6}$ or R_{NH_3} , as long as the CH_4 to C_2H_6 and CH_4 to NH_3 mixing ratios ($W_{\text{C}_2\text{H}_6}$ and W_{NH_3}) exceed 60 and 600, respectively. Correspondingly, for a turbopause density of 10^{13} or 10^{12} cm^{-3} , $W_{\text{C}_2\text{H}_6}$ will have to exceed 500 and 5000, and W_{NH_3} will have to exceed 1600 and 2400, if CH_4 is to remain the dominant radiator.

For the previously discussed turbopause mixing ratios, it would appear that CH_4 , under these conditions, is the primary radiator throughout the entire upper atmosphere, since above the turbopause diffusive separation and higher temperatures will enhance the relative cooling by CH_4 . With slightly different boundary conditions (lower W_{NH_3} , $W_{\text{C}_2\text{H}_6}$ or turbopause temperature), NH_3 and/or C_2H_6 could be the major radiator in a well-mixed atmosphere (turbopause density $\lesssim 10^{12} \text{ cm}^{-3}$); however, as will be shown in the next section, radiational cooling under these circumstances will be of secondary importance compared to eddy mixing in dissipating the absorbed solar flux. For these reasons, in spite of its unfavorable cooling frequency, CH_4 was selected as the major radiator in the upper atmosphere of Jupiter, for when radiative transfer is the dominant mechanism cooling the lower thermosphere, it is probably the dominant cooling agent.

The rate coefficient η (where $R_i \approx f_i n^2 \eta h\nu e^{-h\nu/kT}$) for this model at 150K ($\sim 10^{-14} \text{ cm}^3 \text{ sec}^{-1}$) is approximately one and one-half orders of magnitude larger than the value selected by Chamberlain and McElroy (1966) for CO_2 cooling on Mars for their mesopause temperature of 160K. This is due mainly to the fact that $(\beta_s)_{\text{CO}_2} \approx 10(\beta_s)_{\text{CH}_4}$. Nevertheless, at a given density level, the above cooling rate is less than 10^{-4} the value used by Chamberlain and McElroy, on account of f_i and the exponential term. This decreased cooling rate, even with a smaller incident flux, will require that the Jovian mesopause density be nearly 10^2 times the Martian density, or approximately 10^{14} cm^{-3} if radiational cooling by CH_4 is the main source of heat transfer near the mesopause.

4. Eddy heat transport

Absorbed solar UV radiation is conducted downward towards the turbopause where, as just discussed, CH_4

(acting as an energy sink) radiates this energy into space or the upper mesosphere, since the intervening optical depths are far less than one. Omitted from the discussion was energy transfer through small-scale mechanical turbulence, which Johnson and Wilkins (1965) noted is of prime importance in cooling the earth's thermosphere. However, McElroy (1967) has pointed out that the eddy flux equation by Johnson and Wilkins would be valid only in the limit where the thermal identity associated with these eddies persists longer than the order of the mass mixing time.

Specifically, McElroy indicated that if the time constant associated with eddy diffusion (τ_M), which can be approximated by H^2/K_v , is considerably longer than the radiative relaxation of the thermal perturbations (τ_R), then significant heat transport will not occur through eddy motion. Quantitatively, McElroy (1967) argued that

$$\tau_R = \frac{\rho C_p}{(\partial R_i / \partial T)} \tag{4.1}$$

The application of Eq. (3.8) without the bracketed term $(x\phi)/\beta$ with (4.1), assuming a zero pressure gradient between the eddy and the gas immediate to the eddy, yields

$$\tau_R = \frac{\rho C_p}{R_i \left[\frac{h\nu}{kT^2} + \frac{\beta}{\beta + \phi} \left(\frac{691}{T^2} - \frac{1}{2T} \right) - \frac{1}{T} \right]} \tag{4.2}$$

or for CH_4 (7.7μ) at low temperatures (140–250K), τ_R can be approximated by $(\rho C_p k T^2) / (R_{\text{CH}_4} h\nu)$. Specifically, at 140K when the hydrogen rotational states are only partially populated, with a corresponding decrease in C_p and a CH_4 to H_2 mixing ratio of 10^{-4} , the associated thermal relaxation time (sec) for CH_4 is

$$\tau_R \approx 1 \times 10^7 + \frac{1 \times 10^{21}}{n} \tag{4.3}$$

Before comparing τ_R and τ_M , it should be noted that the turbopause was not treated as a single level, since the turbopause was defined for each constituent as the level where the individual diffusion coefficient (D_i) equals the given K_v ; i.e., where K_v may represent an effective eddy diffusion coefficient associated with free convection, as well as its usual usage with forced convection or mechanical turbulence. Specifically,

$$D_i = D_0 \left(\frac{T}{T_0} \right)^\alpha \frac{p_0}{p} \tag{4.4}$$

$$n_T = \frac{D_0}{K_v} \left(\frac{T}{T_0} \right)^{\alpha-1} n_0 \tag{4.5}$$

where n_T is the total turbopause density, with the

subscript 0 referring to standard conditions. The values selected for D_0 and α for various constituents in a hydrogen-dominated atmosphere are listed in Table 1. For each constituent, mixing will dominate over diffusive separation as long as $n > n_T$, with the mixing scale height (H_M) in this region being the mean H of all constituents still in a mixed state. This resulted in a multilayered turbopause of effectively 10 km in depth, with H, He, H₂ and CH₄ diffusing out in that order with altitude.

As seen from Eqs. (4.3) and (4.5), the turbopause time constants associated with radiation and eddy mixing, respectively, increase and decrease with decreasing n_T ; thus, mixing will become more important as an energy transfer mechanism as K_v increases. However, before proceeding, the approximate nature of these time constants should be emphasized, especially for τ_R , since this parameter is strongly temperature-dependent [$\tau_R(120\text{K}) \approx 40\tau_R(150\text{K}) \approx 10^3\tau_R(200\text{K})$ for CH₄]. Even then, this analysis neglects the uncertainties related with β as a function of temperature and composition, indicating that only when τ_R and τ_M differ by at least 2-3 orders of magnitude can one be reasonably sure of the dominant process.

Table 2 gives the values of τ_R and τ_M at the hydrogen-helium turbopause for various eddy diffusion coefficients (K_v), assuming a T and H_M of 140K and 20 km. As seen from Table 2, when K_v is small ($\lesssim 10^5$ cm² sec⁻¹), eddy transport appears to be less important than radiative transfer as a mechanism for dissipating the heat accumulated in the lower thermosphere; in contrast, if K_v approaches 10^7 cm² sec⁻¹, then, in all probability, eddy mixing would constitute the major energy transfer mechanism immediately below the turbopause. In this latter case, in addition to energy transfer through mixing, the increased concentration of CH₄ molecules at higher levels will enhance the effectiveness of these molecules in cooling the upper atmosphere. The net result is that, as K_v increases, the temperature difference between the mesopause and the upper thermosphere and/or exosphere should decrease.

The downward heat flux through turbulence or forced convection can be written in several alternate forms; we use the form from Sutton (1953), which is equivalent to the formula given by Colegrove *et al.* (1965), and which itself is a corrected version of the

TABLE 1. Selected values for D_0 and α in a hydrogen-helium (5 to 1) dominated environment.

Constituent	D_0 (cm ² sec ⁻¹)	α
H†	2.18	1.50
He	0.95	1.50
CH ₄ †	0.53	1.50
H ₂ *	0.95	1.50

† Based upon an analysis by McElroy and Hunten (1969).

* Assumed values similar to those for a helium-dominated environment.

TABLE 2. Turbopause radiation and mixing time constants associated with various eddy diffusion coefficients.

K_v (cm ² sec ⁻¹)	n_T (cm ⁻³)	n_{CH_4} (cm ⁻³)	τ_R (sec)	τ_M (sec)
10^5	2×10^{14}	2×10^{10}	1×10^7	4×10^7
10^6	2×10^{13}	2×10^9	6×10^7	4×10^6
10^7	2×10^{12}	2×10^8	5×10^8	4×10^5

equation by Johnson and Wilkins (1965), namely,

$$q = K_v C_p \rho \left(\frac{\partial \bar{T}}{\partial Z} + \Gamma \right), \quad (4.6)$$

where C_p is the specific heat at constant pressure, ρ the atmospheric density, and Γ the adiabatic lapse rate ($=g/C_p$). Just above the turbopause, the mean temperature gradient ($\partial \bar{T}/\partial Z$) due to conduction is small ($\lesssim 0.1-0.4\text{K km}^{-1}$) compared to Γ ($\sim 2.3\text{K km}^{-1}$), while below the turbopause, assuming a constant K_v and heat flux, $\partial \bar{T}/\partial Z$ will tend toward the adiabatic lapse rate ($\partial \bar{T}/\partial Z = -2.3\text{K km}^{-1}$) as the density increases. Thus, in the immediate vicinity of the turbopause, $\Gamma > |\partial \bar{T}/\partial Z|$, and to a first approximation

$$q \approx K_v \rho g. \quad (4.7)$$

The maximum solar flux absorbed by Jupiter above the turbopause is 0.04 erg cm⁻² sec⁻¹, signifying that the product $K_v n$ at the turbopause must equal at least 4×10^{18} cm⁻¹ sec⁻¹, in order that eddy diffusion will be capable of transporting the absorbed heat downward from the turbopause during all portions of the solar cycle. As seen from Table 2, this criterion is fulfilled at the turbopause level for all values of K_v listed.

In the Earth's mesosphere, mixing may be maintained by the breakdown of gravity or tidal waves which are probably generated in the lower atmosphere. On Jupiter, the mesospheric value of K_v is unknown, though Hunten (1969) has indicated that the Jovian value may be comparable to that of Earth (5×10^6 cm² sec⁻¹). If, indeed, K_v is moderately large ($\gtrsim 10^6$ cm² sec⁻¹), then eddy mixing may be the dominant energy transfer mechanism below the turbopause of both Jupiter and Earth. Conversely, the small thermal time constants on Mars (McElroy, 1967) and probably Venus may mean that radiative and not eddy transfer in this region is the dominant energy transport mechanism on these terrestrial planets.

Below the turbopause, when the CH₄ to H₂ and the NH₃ to H₂ mixing ratios are, respectively, 10^{-3} and 10^{-7} , τ_R for CH₄ will approach 10^6 sec, if $(x\phi)/\beta$ is small. Under these conditions, this portion of the atmosphere (either 50 to 250 km below the turbopause or above the cloud tops) will be radiatively controlled if the regional value for $K_v < 10^6$ cm² sec⁻¹. In the situation where $(x\phi)/\beta$ effectively modifies the cooling rate, then the

TABLE 3. Thermal models which include heat transfer by eddy mixing.

Trial number	K_v ($\text{cm}^2 \text{sec}^{-1}$)	Solar cycle flux	Turbopause density (cm^{-3})	Exospheric temperature ($^\circ\text{K}$)
1	10^7	Minimum	2×10^{12}	147
2	10^7	Maximum	2×10^{12}	159
3	10^6	Minimum	2×10^{13}	153
4	10^6	Maximum	2×10^{13}	175
5	10^5	Minimum	2×10^{14}	159
6	10^5	Maximum	2×10^{14}	193

threshold value of K_v necessary for a dynamically controlled atmosphere will be correspondingly reduced by the factor $(\beta - x\phi)/\beta$.

Gillett *et al.* (1969), in measuring the brightness temperature of Jupiter, noted the possible presence of a temperature inversion due to solar heating of the 3.3μ band of CH_4 . In calculating the thermal structure of Jupiter, Hogan *et al.* (1969) concluded that such an inversion layer could occur 100 km above the cloud tops if the zone of dynamic influence above the clouds did not extend to this altitude. These results would suggest that the Jovian eddy diffusion coefficient in this region is less than $10^6 \text{ cm}^2 \text{ sec}^{-1}$.

At lower altitudes, where the NH_3 to H_2 mixing ratio approaches 10^{-4} , the major radiator would be NH_3 , with an associated τ_R of $\sim 10^8$ sec implying that radiation is the primary mechanism for controlling the thermal profile above the clouds. However, radiative transfer, as indicated by Hogan *et al.*, acting alone in this region, would produce an unstable superadiabatic lapse rate and a dynamically controlled atmospheric structure. Gierasch and Goody (1969) also concluded that, in the vicinity of the cloud tops, the thermal structure of Jupiter is dynamically controlled.

5. Model results

The H_2 -He ratio, ϵ , the CH_4 mixing ratio (f_{CH_4}), and the atomic hydrogen mixing ratio were assumed to be 5, ~ 0.86 , 10^{-4} and 10^{-5} , respectively, in the subsequent models, unless otherwise specified. Below 1000 \AA , the solar flux given by Hall and Hinteregger (1970) was considered representative of mean solar conditions, and for solar minimum and maximum these values, based upon the article by Hall *et al.* (1969), were multiplied by 0.72 and 1.87.

With these boundary conditions and weak convective activity ($K_v = 10^6 \text{ cm}^2 \text{ sec}^{-1}$), the model indicates, as seen from Table 3, that the CH_4 turbopause ($n = 2 \times 10^{14} \text{ cm}^{-3}$) and the NLTE level for CH_4 ($n = 6 \times 10^{14} \text{ cm}^{-3}$, or the level where $\beta_{\text{CH}_4} = \phi_{\text{CH}_4}$) are in close proximity to one another. In this radiatively dominated model, the planetary average exospheric temperature (\bar{T}_{EX}) during the solar cycle peak (193K), as well as the range of temperatures in the upper atmosphere over

the solar cycle (34K), are relatively large due to the lack of effective convective activity.

Higher exospheric temperatures could occur on Jupiter if the turbopause were located below the mesopause [defined under these conditions as the level where the integrated solar heating and radiational cooling above are equal ($n_M \sim 6 \times 10^{14} \text{ cm}^{-3}$)], for then, through diffusive separation, the CH_4 concentration and cooling rate at the mesopause would be diminished.

For this to occur, it would be necessary that K_v in the mesosphere be less than $3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$ (as compared to the value of $5 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$ for Earth). While the depth of the Jovian atmosphere may initially lead us to expect a lower K_v on Jupiter, a value of K_v much less than $3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$ is not anticipated. Therefore, a reasonable maximum \bar{T}_{EX} for Jupiter can be calculated by permitting the turbopause to coincide with the mesopause ($K_v = 3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$, $n_T = n_M = 6 \times 10^{14} \text{ cm}^{-3}$).

The thermospheric temperature and composition profile and the integrated solar heating and radiational cooling ($\int_z^\infty R_{\text{CH}_4} dZ$) as a function of height for this model are plotted in Figs. 2-4. From Fig. 4, we note that the effective UV absorption level and the cooling level are separated by approximately 200 km. Using a simplified heat conduction equation in which cooling is neglected, or

$$\bar{K} \frac{dT}{dZ} = \int_z^\infty Q(Z) dZ, \tag{5.1}$$

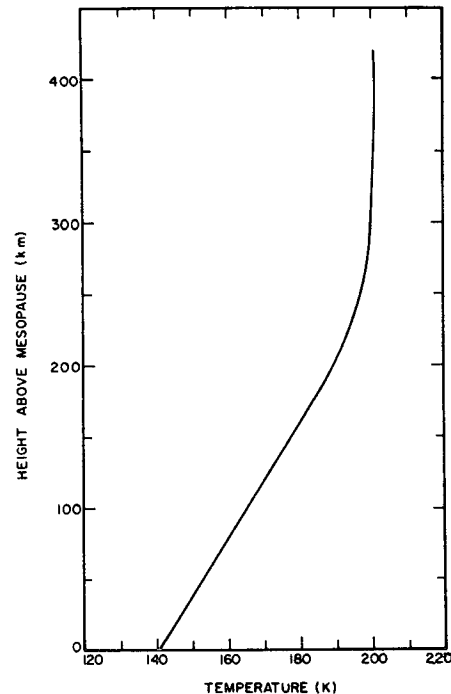


FIG. 2. Solar maximum thermospheric temperature profile when turbopause coincides with mesopause ($K_v = 3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$).

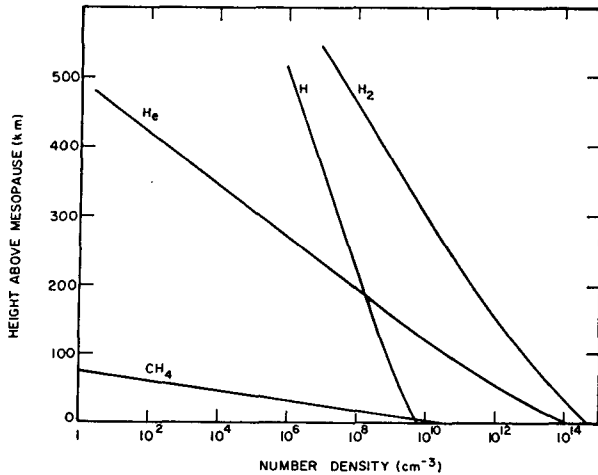


FIG. 3. Solar maximum composition distribution ($K_v = 3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$).

where $\bar{K} = AT^{\frac{1}{2}}$ {i.e., $[1020 \text{ ergs cm}^{-1} \text{ sec}^{-1} (\text{°K})^{-\frac{1}{2}}]$ $(170\text{K})^{\frac{1}{2}}$ } and an integrated heating factor ($\int_z^\infty Q dz$) of $0.037 \text{ erg cm}^{-2} \text{ sec}^{-1}$ (see Fig. 4) result in a mean temperature gradient of $2.8 \times 10^{-6} \text{ K cm}^{-1}$. In a distance of 200 km, this produces a solar maximum mesopause-exosphere temperature difference of 56K, comparable to the machine-computed difference of 62K ($\bar{T}_{\text{EX}} = 202\text{K}$). This separation of the effective absorption level from the cooling region and the quantity of solar flux that is absorbed by the atmosphere are the primary parameters governing the thermal structure of Jupiter's thermosphere.

In the opposite situation of strong convective activity ($K_v = 10^7 \text{ cm}^2 \text{ sec}^{-1}$), the distance effectively separating the absorption level from the turbopause ($n_T = 2 \times 10^{12} \text{ cm}^{-3}$) is only about 70 km; thus, a machine-computed maximum exospheric temperature and range of 159K and 12K, as indicated in Table 3, are not unexpected. In the previous models, application of the heat conduction equation, with radiative cooling, was limited to the region above the turbopause.

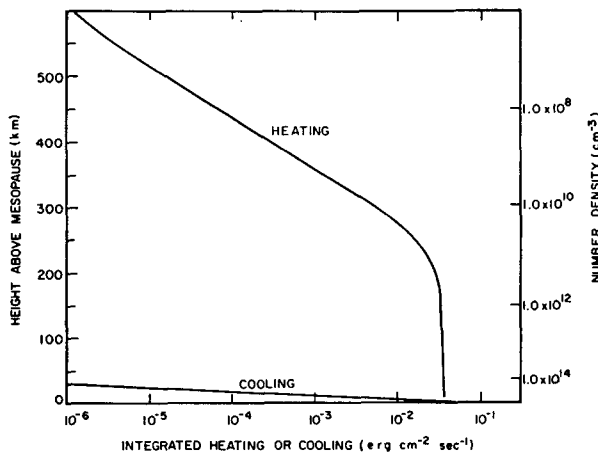


FIG. 4. Integrated absorbed solar flux (heating) and radiative cooling as a function of altitude for solar maximum conditions ($K_v = 3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$).

TABLE 4. Thermal models with heat transfer limited to conduction and radiation.

Trial number	K_v ($\text{cm}^2 \text{ sec}^{-1}$)	Solar cycle flux	Mesopause density (cm^{-3})	Exospheric temperature (°K)
1	10^7	Minimum	1×10^{14}	156
2	10^7	Maximum	2×10^{14}	187
3	10^5	Minimum	3×10^{14}	160
4	10^5	Maximum	5×10^{14}	201

In a few cases where heat transfer is limited to conduction and radiative cooling in spite of strong convective activity (Trials 1 and 2, Table 4), we observe that the effect of increasing CH_4 concentrations at higher levels through convection is of secondary importance, compared to convective heat transfer in cooling the thermosphere (Trials 1 and 2, Table 3). In addition, in the presence of significant forced convection ($K_v \geq 10^6 \text{ cm}^2 \text{ sec}^{-1}$), arbitrarily excluding radiative cooling or, conversely, increasing R_{CH_4} by three orders of magnitude produced less than 1% change in \bar{T}_{EX} . With $K_v = 10^5 \text{ cm}^2 \text{ sec}^{-1}$, a similar arbitrary increase in R_{CH_4} with no convective heat transfer produced a rather small decrease in \bar{T}_{EX} ($< 10\%$). These results are not surprising after one examines Fig. 4 ($K_v = 3 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$), for there we note that a 10^3 increase in R_{CH_4} , in effect, decreases the total conductive path length by only 10% or 20 km. In the opposite situation of heat transfer limited to conduction and forced convection ($K_v = 10^5 \text{ cm}^2 \text{ sec}^{-1}$, $n_T = 2 \times 10^{14} \text{ cm}^{-3}$), the \bar{T}_{EX} was computed to be 193K. These models, in essence, all point to the potential importance of forced convection in governing the Jovian thermal profile above the mesopause and indicate that uncertainties in the mesopause thermal emissivity are not as important as previously supposed (Hunten, 1969), especially in comparison to our lack of knowledge concerning the effectiveness of heat transfer through eddy mixing and/or free convection.

In these models, reducing the H_2 to He ratio from 5 to 3 produced a small decrease ($\lesssim 2\%$) in \bar{T}_{EX} ; however, decreasing the heating efficiency from 0.86 to 0.50 reduced the temperature difference between the mesopause or turbopause and the upper thermosphere by a comparable fraction. This is due to the relatively low absorption level for helium, while in the latter case a decrease in ϵ produces a similar decrease in the quantity of solar flux absorbed and, correspondingly, in the lapse rate. Therefore, the temperature rise between any two given levels, in the absence of significant cooling, will be directly dependent upon the heating efficiency and the incident solar flux. As an example of this relationship, in the initial computations for this model, the incorporated flux data were from Hinteregger *et al.* (1965). Hall and Hinteregger (1970) have noted that these earlier values are systematically too large, averaging 2.6 times larger than the presently used values over the pertinent wavelength intervals.

The parallel temperature rises averaged 2.4 times the values quoted in this article, emphasizing the prime importance of accurate flux values in computing the Jovian temperature rise. Finally, reasonable variations ($\pm 30\text{K}$) in the temperature of the lower boundary produced similar variations in \bar{T}_{EX} , while for all practical purposes the Jovian turbopause can be treated as a single level, since the introduction into this model of a multilayered turbopause produced no appreciable changes in the thermal structure.

6. Diurnal temperature variation

While variations in the thermal profile could be examined for various values of K_v , R_i or H_2 to He ratios, it is naturally not possible with the previous steady-state model to examine the diurnal variation of the exospheric temperature. To compute the magnitude of the diurnal variation, a complex numerical model similar to that of Harris and Priester (1962) or a combination analytical-numerical model as constructed by Cummack (1962) could be employed. As an alternative to these arduous models and more in line with our present knowledge of the Jovian thermosphere, a simplified model, similar in some respects to the Cummack model, was employed.

This model assumed that the atmosphere consisted of a single constituent which was heated by the absorption of monochromatic radiation and that the temperature profile was controlled by thermal conduction, with substantial energy losses, through radiation or turbulence, being confined to the lower thermosphere. Under these conditions, the time-dependent heat conduction equation for the upper thermosphere reduces to

$$nC_p \frac{\partial T}{\partial t} = Q(Z) + \frac{\partial}{\partial Z} K \frac{\partial T}{\partial Z}, \tag{6.1}$$

where K is the thermal conductivity and is taken equal to the product of $T^{3/2}$ and the conductivity coefficient A , while Q is the incident solar flux that is converted into thermal energy per unit volume and time. In turn

$$Q(Z) = \epsilon F(Z) \sigma n(Z), \tag{6.2}$$

$$F(Z) = F(\infty) \exp[-\tau(Z) \sec \chi], \tag{6.3}$$

where ϵ is the heating efficiency, σ the solar flux weighted mean absorption cross section, χ the zenith angle, $F(\infty)$ the incident solar flux, and $\tau(Z)$ the optical depth [equal to $n(Z) \sigma H(Z)$]. In the upper thermosphere, where the product $\tau(Z) \sec \chi$ is small (< 0.2) and the lapse rate nearly zero, Eq. (6.1), with the aid of the above equations, reduces to

$$\frac{\partial T}{\partial t} \approx \frac{\epsilon F(\infty) \sigma}{C_p}. \tag{6.4}$$

Integrating (6.4) over a quarter of a period (sunrise to local noon) with an assumed sinusoidal variation for

$F(\infty)$ yields an order-of-magnitude estimate of the diurnal temperature variation of the upper thermosphere and exosphere (ΔT_D), i.e.,

$$\Delta T_D = \frac{\epsilon F_N(\infty) \sigma P}{2\pi C_p}. \tag{6.5}$$

The period of rotation is represented by P , while the subscript N refers to local noon conditions. Since Eq. (6.5) does not include vertical or horizontal transport of heat through conduction or mass motion, the results from this equation should be viewed as upper limits, most applicable to planets with rotation periods P small compared to the advection time constant τ_A , which, by definition, is the planetary radius divided by the advection velocity. While this criterion probably excludes the application of Eq. (6.5) to Venus, results in Table 5 simulating solar cycle minimum and maximum conditions are tabulated for Jupiter, Mars and Earth. The computed diurnal variation for Earth is in excellent agreement with the published values given by Harris and Priester (1963) who obtained a ΔT_D of 336 and 605K, respectively, for a total heat source of 0.98 and 1.93 $\text{erg cm}^{-2} \text{sec}^{-1}$. Mars possesses a diurnal temperature variation in the upper thermosphere approximately one-half that of Earth, but the Jovian variation is small and is due primarily to the small quantity of solar flux converted to heat [$\sim 1/50$ that of Earth or $(1/50)\oplus$], the smaller absorption cross section, i.e., the solar flux absorbed at higher density levels ($\sim \frac{1}{4}\oplus$), and the shorter rotation period ($\sim \frac{1}{2}\oplus$).

7. Conclusions and discussions

In the vicinity of the Jovian turbopause, the mixing ratio for heavy constituents like CH_4 and NH_3 will be, on the average, an order of magnitude less than their mixing ratio in the lower atmosphere. In spite of this low turbopause mixing ratio (10^{-4}) and an unfavorable cooling frequency (7.7μ), CH_4 appears to be the major radiator in the upper atmosphere of Jupiter when radiation is the dominant energy transfer mechanism. Under these conditions, NH_3 and C_2H_6 are of secondary importance, due primarily to their low concentrations. Methane, while more effective than these products in cooling the mesopause region, still possesses a cooling

TABLE 5. Diurnal exospheric temperature variations for various planets.

Planet	Major absorbing constituent	σ (cm ²)	$\epsilon F_N(\infty)^*$ (erg cm ⁻² sec ⁻¹)	ΔT_D^* (°K)
Earth	O	7.5×10^{-18}	1.0 - 2.0	300-600
Jupiter	H ₂	2.0×10^{-18}	0.02-0.04	0.5-1
Mars	CO ₂	1.5×10^{-17}	0.5 - 1.0	175-350
Mars	O	7.5×10^{-18}	0.5 - 1.0	150-300

* Range of values is representative of those from a solar cycle minimum to a maximum.

rate that is small ($\lesssim 10^{-4}$) compared to the CO_2 rate on Mars. The net result is that, even with a smaller incident flux, the Jovian mesopause density will be approximately 10^2 times the Martian density or in the vicinity of 10^{14} cm^{-3} , if radiational cooling by CH_4 is the primary heat transfer mechanism in the lower thermosphere.

Alternate mechanisms for disposing of the absorbed solar energy are free and forced convection. These processes, whose strength depends upon the vertical component of the effective eddy diffusion coefficient (K_v), in addition to the downward transport of heat, govern the height of the turbopause and the distribution of CH_4 in the upper atmosphere. By itself, this latter increase in the CH_4 concentration, at higher levels with increasing turbulence, produces only minimal changes in the temperature structure. Of significantly more importance is the apparent emergence of convective heat transport as the dominant energy transfer mechanism in the lower thermosphere and the resulting lower thermal profile as K_v approaches and exceeds $10^6 \text{ cm}^2 \text{ sec}^{-1}$. Specifically, for minimum and maximum solar cycle conditions with weak convective activity ($K_v = 10^5 \text{ cm}^2 \text{ sec}^{-1}$), the temperature rise above the turbopause ranges between 19 and 53K, while rises of 7–19K are associated with strong convective activity ($10^7 \text{ cm}^2 \text{ sec}^{-1}$). This suggests that satellite UV photometric measurements of the Jovian exospheric temperature over the solar cycle, similar to those made for Venus (Barth *et al.*, 1968), could be used to estimate the degree of convective activity or turbulence present in the upper atmosphere of Jupiter, assuming no additional heat sources other than solar flux.

Over reasonable limits, the H_2 to He ratio, the height and temperature of the mesopause, and probably the cooling rate are of secondary importance compared to the effective eddy diffusion coefficient in establishing \bar{T}_{EX} ; thus, the lack of a definitive value for K_v is the present major uncertainty in constructing thermal models of the Jovian thermosphere. A mesospheric K_v for Jupiter similar to that on Earth [$\sim 4 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$; Colegrove *et al.* (1965)] would suggest that, as on Earth and in contrast to Mars (McElroy, 1967), eddy mixing is the dominant heat transfer mechanism in the lower thermosphere of Jupiter. Conversely, exospheric temperatures in excess of 215K would probably be indicative of a relatively low mesospheric eddy diffusion coefficient ($K_v \lesssim 10^5 \text{ cm}^2 \text{ sec}^{-1}$) associated with substantial radiative cooling by CH_4 .

The thermospheric temperature rise is nearly proportional to the quantity of solar energy absorbed and inversely proportional to the thermal conductivity. The present uncertainty in the incident solar flux is at least 20% (Hall and Hinteregger, 1970), and setting K equal to $AT^{\frac{1}{2}}$ results in an overestimation in the conductivity by 15% [for Jovian composition with temperatures between 150 and 200K (Hirschfelder *et al.*, 1964, pp. 573–574)]. Therefore, the temperature

rise for any given run possesses an associated uncertainty of 45% if the error affiliated with the heating efficiency (ϵ) would place ϵ between 0.52 and 0.90. Variations in the solar UV flux with the 27-day solar rotation period ($\pm 20\%$; Hall and Hinteregger) would further alter these models. In addition, the diurnal variation of \bar{T}_{EX} over the entire range of solar activity should be small on Jupiter ($< 5\text{--}10\text{K}$).

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