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A NEW INVERSION METHOD FOR REMOTE SOUNDING OF PLANETARY ATMOSPHERES

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ABSTRACT

A new inversion method for remote sounding of planetary atmospheres is presented which appears to have several significant advantages over the conventional methods. This method is applicable to high resolution observations where the spectral lines are fully resolved, and is based on matching the calculated slopes of the spectral line profiles with slopes of the observed lineshapes. The method is applied to inversion of ozone absorption lines in the earth's atmosphere and the results are compared with those obtained by a conventional method. The proposed method is seen to provide a significant improvement in the overall accuracy of the retrieved profiles, with higher vertical resolution and higher levels which may be probed.

1. INTRODUCTION

Following Kaplan's suggestion in 1959 that atmospheric temperature structure and composition distribution may be obtained from an analysis of spectral variation in the upwelling thermal radiation, a great deal of work has been done in developing this powerful technique. Of the available methods today, it is one of the most useful in studying the atmospheres of the earth and other planets from ground based observations, satellites and space probes. Several review articles and proceedings of special conferences covering this subject are now available (e.g. Rogers, 1971; Colin, 1972; Deepak, 1977; Twomey, 1977).

The atmospheric remote sensing technique is based on measuring the outcoming radiation at a chosen set of frequencies, and finding an inverse solution to the radiative transfer equation. This solution may be obtained for vertical temperature profiles as well as for the distribution of absorbing gases in the atmosphere. In principle, the inverse solution is unique and represents the true state of the atmosphere at the time of observations. The accuracy of this solution, the vertical resolution and the atmospheric range which may be probed, is determined by the observational technique (sensitivity, spectral range and resolution) and the inversion method employed. Several methods have been proposed and successfully used for retrieval of atmospheric profiles from planetary observations (e.g. Chahine, 1968, 1970, 1972; Smith, 1970; Conrath, et al., 1970; Conrath, 1972; Prabhakara et al., 1970).

The choice of an inversion method for a given set of observations is generally based on the following considerations:(i) the sensitivity of the solution to a-priori information about the state of the atmosphere (ii) the stability and the rate of convergence to the desired solution (iii) the effect of system noise on the stability of the solution (iv) the number of sampling frequencies used and the spectral resolution employed in the observations.

With high resolution measurements over an appropriately chosen spectral range the vertical resolution of the retrieved profiles is limited by the width of the weighting functions. When the spectral resolution is extremely high ($\Delta\nu \ll \alpha$ the half-width) individual spectral lines can be completely resolved and the lineshapes determined. Atmospheric temperature and composition profiles can then be obtained from an analysis of these individual lines. The capability of ultra-high resolution sub-doppler spectroscopy is provided by heterodyne detection. Well developed in radio astronomy, only recently it is finding applications in the infrared [e.g. Teich, 1973; Mumma et al., 1974, 1978; Abbas et al., 1976, 1978 a,b; Betz et al., 1977; Menzies and Seals, 1977]. Measurement of stratospheric ozone absorption lines with an infrared heterodyne spectrometer and the retrieval of vertical concentration profiles have been reported [Abbas et al., 1978a,b; Menzies and Seals, 1978]. The inversion methods used in the analyses of the above ozone measurements are based on an inverse solution of the radiative transfer equation.

The purpose of this paper is to present an inversion method for fully resolved spectral lines, which appears to have several advantages over the presently used methods. This method assumes that the spectral resolution is sufficiently high so that the observed line is fully resolved and the lineshape is determined. The inversion is then based on finding an inverse solution to the derivative of the radiative transfer equation with respect to frequency. This implies that the slope of the observed line is matched with the slope of the synthetic line computed for the retrieved atmospheric parameters. As will be seen, this differential technique leads to (i) narrower weighting functions providing a higher vertical resolution (ii) higher atmopsheric level which may be probed, (iii) faster and more stable convergence and (iv) more accurate retrieved profiles. Thus by taking full advantage of the powerful techniques of heterodyne and tunable-diode-laser spectroscopy the overall quality of the retrieved atmospheric profiles is significantly improved.

The formulation of the proposed differential method is given in section 2. An application of the method to an inversion of synthetic absorption line profiles of atmospheric ozone is given in section 3. A comparison of some results of this method is made with those of the presently used method.

2. Basic Equations

The emergent spectral intensity I_ν from a non-scattering atmosphere is given by the radiative transfer equation which may be written in the form

$$I_\nu(P,T) = B_\nu(T_s)\ \tau_\nu^s + \int_{y_s}^{y_t} B_\nu(T)\ K(P,T)\ dy \qquad (1)$$

where $B_\nu(T_s)$ is the Planck function at the source temperature T_s, τ_ν^s is the transmittance from the surface to the top of the atmosphere, the weighting function $K(P,T) = \frac{\partial\tau_\nu}{\partial y}$, and $y = -\ln P$. The first term in Eq. (1) is the surface contribution, whereas the second term represents the atmospheric contribution to the spectral intensity. The atmospheric transmittance τ_ν is

$$\tau_\nu = \exp\left[- \int \sum_i k_{\nu_i}\ du_i \right], \qquad (2)$$

with k_{ν_i} as the specific absorption coefficient, and du_i is the element of column density for the ith species of the absorbing gas given by

$$du_i(P) = q_i^v \left(\frac{P}{P_o}\right) \left(\frac{T_o}{T}\right) \sec\ \theta_z\ dz \qquad (3)$$

where q_i^v is the volume mixing ratio of the gas, θ_z is the solar zenith angle, and the subscript o refers to the reference quantities. Equations (1)-(3) together with the equation of state, the hydrostatic equation, and a knowledge of the absorption coefficient of the gas (the lineshape function and the line strength) provide an analytical relationship between the observable quantity I_ν and the atmospheric parameters.

The spectral intensity I_ν from a planetary atmosphere is measured for an appropriately chosen set of frequencies for which the weighting functions K(P,T) are well distributed over the atmosphere. The atmospheric profile may be obtained through an inverse solution of equation (1).

If the temperature profile and the surface pressure is known, the concentration profile of the absorbing gas may be inferred. Alternatively, if the concentration profile is known, the temperature profile and the surface pressure may be obtained. With low resolution measurement ($\Delta\nu > \alpha$) individual spectral lines cannot be resolved and average spectral intensities are measured. An inversion of such data for evaluation of atmospheric profiles is made over an absorption band, with the absorption coefficient, the transmittances and the weighting functions generally representing an average over several or many lines.

With ultra-high resolution measurements, such as in heterodyne and tunable-diode-laser spectroscopy where resolving powers as high as 10^6-10^7 may be achieved, the lineshapes of individual spectral lines are fully resolved. Assuming that the true lineshape function is known, the atmospheric profiles may be obtained through an inversion of one or two lines. Inversion of individual spectral lines offers several advantages over inversion of low resolution measurements. Since no averaging over a number of lines has to be made, the weighting functions which may be generated from fully resolved lines are narrower and reach higher into the atmosphere. In addition the accuracy of the retrieved atmospheric profiles is higher, because the errors due to uncertainties in the molecular line parameters have been reduced to those for only one or two lines.

The theory of lineshapes corresponding to various broadening mechanisms is fairly well understood (e.g., Breen, 1961, Benedict, 1962; Aller, 1963; Goody, 1964). For conditions of planetary atmospheres, when no non-thermal processes are assumed (such as maser-laser fluorescence emissions and gain narrowing) the two important broadening mechanisms in the infrared are pressure or collisional broadening and Doppler broadening. The mixed lineshape (Voight lineshape) which includes both pressure and Doppler broadening effects, is generally representative of lineshapes formed in planetary atmospheres. Various modifications to this lineshape become necessary only for special considerations, such as in contributions from the wings (Benedict's modification) for frequencies $(\nu-\nu_o) \gg \alpha$, and in high pressure regimes (when the mean free path becomes less than the wavelength) where collisional narrowing sets in.

If the lineshape is completely resolved with ultra-high resolution measurements, full advantage of the knowledge of the lineshape function may be taken the power of heterodyne method realized fully by employing an alternative method of inversion. This method is based on solving for the slope of the spectral intensity.
The slope is given by the derivative of Eq. (1) with respect to ν

$$\frac{\partial I_\nu}{\partial \nu} = B_\nu(T_s)\frac{\partial \tau_\nu^s}{\partial \nu} + \int_{y_s}^{y_t} B_\nu(T)\frac{\partial K}{\partial \nu}(p,T)\,dy \tag{4}$$

or

$$\dot{I}_\nu = B_\nu(T_s)\, \dot{\tau}_\nu^s + \int_{y_s} B_\nu(T)\, \dot{K}_\nu(P,T)\, dy \qquad (5)$$

Where the dot refers to a derivative with respect to ν, and it is assumed that the frequency interval is sufficiently small so that $\partial B_\nu/\partial\nu = 0$.

For ground-based observations of the earth's atmosphere in the solar absorption mode, the atmospheric contribution in (1) and (5) is usually negligible, and the observed intensity and its derivative are

$$I_\nu^{ob} = B_\nu(T_s)\, \tau_\nu^s \qquad (6)$$

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and

$$\dot{I}_\nu^{cb} = B_\nu(T_s)\, \dot{\tau}_\nu^s \qquad (7)$$

Since Eqs. (5) and (7) are identical in form to the radiative transfer equations (1) and (6), an inverse solution to $\dot{I}_\nu$ for the temperature or gas concentration profiles may be obtained by the usual iterative techniques. The differential quantities $\dot{I}_\nu^{ob}$ and $\dot{\tau}_\nu^s$ may be computed from observed spectral line profiles, and are directly measurable quantities in systems based on tunable diode lasers. This paper is restricted only to inversion of ground-based solar measurements of the earths atmosphere for evaluation of gas concentration profiles. Temperature sounding of atmospheres based on Eq. (5) will be considered in a subsequent paper.

It should be noted that, in principle, inversion methods based on higher order derivations of the radiative transfer equation involving $\partial^n I/\partial\nu^n$, $\partial^n \tau/\partial\nu^n$ etc. could be considered. However, in the absence of any new information and the inevitable presence of noise in the observed radiances, no significant advantage is likely to be gained.

3. Gas Concentration Profile of the Earth's Atmosphere

The concentration profiles of the earth's atmosphere may be obtained through an inverse solution of Eq. (7). We have

$$\tau_\nu = \exp[-\frac{1}{g}\int_o^P \sum_i k_{\nu_i} (P,T)\ q\ (P)\ dP], \tag{7}$$

$$\frac{\partial\tau_\nu}{\partial\nu} = \tau_\nu[-\frac{1}{g}\int_o^P \sum_i \frac{\partial k_{\nu_i}}{\partial\nu} (P,T)\ q_i(P)\ dP], \tag{8}$$

or

$$\frac{\dot{\tau}_\nu}{\tau_\nu} = -\frac{1}{g}\int_o^P \sum_i \dot{k}_{\nu_i} (P,T)\ q_i(P)\ dP \tag{9}$$

Eq. (8) is similar in form to Eq. (21) of Abbas et al. (1978)

$$\ln \tau_\nu = -\frac{1}{g}\int_o^P \sum_i k_{\nu_i} (P,T)\ q_i(P)\ dP \tag{10}$$

and may be solved with a similar iterative procedure with $\dot{k}_\nu$ as the weighting functions.

The weighting functions $\dot{k}_\nu$, in general, are expected to be narrower, peaking at higher levels than the corresponding functions k_ν. This may be seen in the pressure broadening regime where the absorption coefficient is

$$k_\nu(P,T) = \frac{1}{\pi}\ \frac{S(T)\ \alpha\ (P,T)}{(\nu-\nu_o)^2 + \alpha^2(P,T)} , \tag{11}$$

where $S(T)$ is the line strength and $\alpha(P,T)$ is the half-width given by $\alpha(P,T) = \alpha_o(P/P_o)(\frac{T_o}{T})^{1/2}$, with the subscript o referring to the reference values. For a constant temperature profile Eq. (11) shows that k_ν plotted as a function of P peaks at a pressure level where $(\nu-\nu_o) \sim \alpha(P,T)$. The weighting function $\dot{k}_\nu$ on the other hand is

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$$\dot{k}_\nu = \frac{-2\, S(T)\, \alpha(P,T)\, (\nu-\nu_o)}{\pi\, [(\nu-\nu_o)^2 + \alpha^2(P,T)]^2} \qquad (12)$$

The form of Eq. (12) indicates that the plots of $\dot{k}_\nu$ as a function of P are narrower than those for k_ν. In addition, setting the derivative $\partial\dot{k}_\nu/\partial\alpha = 0$ indicates that in a pressure broadening atmosphere, $\dot{k}_\nu$ peaks at levels where $(\nu-\nu_o) \sim \alpha(P,T)/\sqrt{3}$. The functions $\dot{k}_\nu$ for planetary atmospheres, in general, are thus narrower and peak at higher levels than the corresponding functions k_ν.

The normalized weighting functions k_ν and $\dot{k}_\nu$ suitable for inversion of the atmospheric ozone line (for solar absorption mode) with $(J', K_a', K_b'; J'', K_a'', K_b'')$ identified as (29,3,26;30,3,27) with the line center ν_o = 1011.667 cm^{-1} (lower state energy 422.96 cm^{-1}, S = 0.414 $cm^{-1}(cm\text{-}atm)^{-1}$, α = 0.07 cm^{-1}) are shown in Figs. 1-2. A comparison of the two sets shows that the plots of $\dot{k}_\nu$ are significantly narrower and peak at higher levels in the atmosphere. The weighting function k_ν for ν = 1011.670 cm^{-1} ($\Delta\nu$ = 0.002 cm^{-1}), for example, which peaks at ~ 23 km has a width (FWHM) ~ 18 km. The function $\dot{k}_\nu$, on the other hand, peaks at ~ 28 km, has a width ~ 13 km and is thus expected to provide higher vertical resolution. A comparison of the vertical resolutions of atmospheric ozone concentration profiles retrieved by the two methods is given in the following section.

The iterative solution based on Eq. (9) is similar to that employed in the literature, (Chahine 1972; Abbas et al., 1978) and is briefly outlined below. The quantity $\dot{\tau}_\nu/\tau_\nu$ is calculated from the observed spectrum for a chosen set of frequencies for which the peaks of the weighting functions ($\dot{k}_\nu$) are uniformly distributed over the atmosphere. For evaluation of concentration profiles it is assumed that the temperature profile is known. An initial guess of the mixing ratio profile $q_i^{j,m}$ is made (where j denotes the atmospheric level and m the iteration) and the quantities τ_ν and $\dot{\tau}_\nu/\tau$ are calculated. An improved estimate of the mixing ratios at levels corresponding to the peaks of the weighting functions is obtained from

$$q_i^{j,m+1} = q_i^{j,m} \frac{(\dot{\tau}_{\nu_k}/\tau_{\nu_k})^{ob}}{(\dot{\tau}_{\nu_k}/\tau_{\nu_k})^{m}} \quad \tau_{\nu_k} \tag{13}$$

The complete profile is interpolated from the corrected values and the iteration is continued until the calculated values of $(\dot{\tau}_{\nu_k}/\tau_{\nu_k})^m$ converge to the observed values $(\dot{\tau}_{\nu_k}/\tau)^{ob}$ over the chosen set of frequencies in a least square sense. The iteration process is stopped when the RMS difference in the above two quantities is on the order of the noise level of the measurements.

4. Evaluation of the Earth's Atmospheric Ozone

We shall now apply the method discussed in the previous section for inverting a synthetic absorption line of the earth's atmospheric ozone, and make comparions with the conventional method. The synthetic spectrum for a midlatitude winter model of the earth's atmosphere showing a strong ozone line at $\nu_o = 1011.6670\ cm^{-1}$ is given in Fig. 3. Following the method outlined in section 3, the mixing ratio profile obtained from an inversion of this line using 14 frequencies is shown in Fig. 4a. The initial guess profile and model profile corresponding to the synthetic absorption line is also shown. The retrieved profile has been extrapolated below ~ 7 km and above ~35 km. A comparison of the retrieved and model profiles indicates excellent agreement in the range 7-35 km. The retrieved total ozone content is 0.402 cm-atm which compares with 0.399 of the model profile, a residual error ~ 1%.

For comparison, an inversion of the above ozone line was made by using the conventional method (see Abbas et al., 1978) with the retrieved profile shown in Fig. 4b. The thirteen weighting functions used in this case extend from 0-26 km, and the profile has been extrapolated below ~7 km and above ~ 26 km. Although the total ozone content of the retrieved profile in this case also shows a residual error of < 1% (~ 0.397 cm-atm), the overall accuracy of the retrieved profile is much better in the differential method. The number of iterations required for convergence in the differential method is ~ 6-8, comparing with 15-20 iterations in the conventional method. Any reduction in computation time, however, is largely offset by the additional time required to calculate the derivatives.

For a direct comparison of the vertical resolution provided by the two methods, a synthetic absorption line generated from an assumed ozone profile (Fig. 5a) with a sharp peak (FWHM ~ 9 km) was inverted. The initial guess, the assumed model and the retrieved profile s using the two methods are shown in Figs. 5. The inverted profile in Fig.5a following the conventional method, approaches the model profile, with a somewhat broadened peak and without reproducing the dip at ~ 10-15 km. The calculated total vertical ozone content of 0.307 cm-atm compares with 0.3004 cm-atm of the assumed model profile (~2.2% error). The ozone profile obtained by the differential method (Fig. 5b), on the other hand, shows a significantly better overall retrieval with almost fully recovered peak of the assumed model profile and the dip at ~ 10-15 km. The calculated total vertical ozone content of 0.305 cm-atm shows a residual error of ~1.5 %. The proposed method thus clearly provides substantial improvement in the accuracy of the retrieved atmospheric profiles and a higher vertical resolution. Atmospheric features on the order of a scale height (~7 km for the earth) can be fully recovered. The above discussion of the vertical resolutions provided by the two methods is of an "empirical" nature. More rigorous considerations of the achievable resolution, based on the tradeoff analysis of Backus-Gilbert and Conrath (1972) will be given in a subsequent paper.

It should be remarked here that the ozone absorption line of Fig. 3 analyzed in this paper is by no means the most appropriate, and the retrieved ozone profiles of Figs. 4-5 are not the best which may be obtained by either of the two methods. The results presented here are for comparison purposes only; further improvements may be made in the quality of the profiles obtained through the two methods.

An important consideration in the inversion of spectral lines is the effect of noise on the accuracy of retrieved atmospheric profiles. In the earth's atmosphere, for species with mixing ratios $\gtrsim 10^{-8}-10^{-9}$ (such as CO_2, O_3, CH_4, NO_2, etc.), high SNR's ($\gtrsim 100$) may be achieved in the solar absorption mode so that the effect of noise is negligible. However, for less abundant species, such as ClO, H_2O_2, CFM's etc., or for weak lines, the achievable SNR's may be smaller and the presence of noise may affect the accuracy of the calculated atmospheric profiles.

For inversion of ozone absorption lines considered in this paper, the SNR's are generally quite high and the effect of noise on the retrieved profiles is insignificant. In order to evaluate the noise effect, however, we may assume a degraded SNR and use a random noise generator with Gaussian distribution to add noise to the synthetic line profile (Fig. 3). The noisy data may be smoothed by least square fitting methods to yield a uniform line profile. Figs. 6a-b show the envelopes of the retrieved profiles obtained from inversion of the synthetic line (Fig. 3) with superimposed random noise corresponding to an SNR of ~ 10. Whereas the effect of noise appears to be comparable in the two retrieval methods for the case considered here, the differential method becomes more sensitive to noisy data and poor SNR's. The usefulness of the differential method then becomes critically dependent on the sophistication of the smoothing technique employed in recovering a well structured line profile.

The smoothing process, however, results in a degradation of the achievable vertical resolution in both cases.

Conclusions

The inversion method presented here is applicable to high resolution measurements where the spectral lines are fully resolved, and appears to have several advantages over the presently used methods. The principal features of the suggested method are (i) a substantially improved vertical resolution and an overall higher accuracy with which the absorbing gas and temperature profiles may be retrieved (ii) higher vertical levels which may be probed (iii) faster and more stable convergence to the desired solution.

An application of the method for evaluation of concentration profiles of the earth's atmosphere indicates that ozone profiles to heights ~35 km may be retrieved with much better accuracy than the conventional methods, and vertical features on the order of a scale height may be fully reproduced. The method works well for data with high SNR's (> 10) but is more sensitive to noise for lower SNR's. Smoothing techniques which yield well structured spectral line profiles may be employed, but the advantage of higher vertical resolution tends to be degraded.

Although the analysis and the examples considered in this paper are restricted to evaluation of absorbing gas profiles in the earth's atmosphere, the method is generally applicable to planetary atmospheres for remote sounding of both temperature and concentration profiles. Remote sounding of atmospheric temperature profiles will be considered in a subsequent paper.

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LIST OF FIGURES

Fig. 5a. The retrieved volume mixing ratio profile of ozone obtained with the differential method, from an inversion of the synthetic line generated from the assumed sharply peaked ozone profile shown in this figure.

Fig 5b. The retrieved volume mixing ratio profile of ozone, obtained with the conventional method, from an inversion of the synthetic line generated from the assumed sharply peaked ozone profile shown in this figure.

Fig. 6a. The envelope of the retrieved volume mixing ratio profile of ozone, obtained with the differential method, from an inversion of the synthetic line of Fig. 3 with superimposed random noise of Gaussian distribution corresponding to a SNR $\sim$ 10.

Fig. 6b. The envelope of the retrieved volume mixing ratio profile of ozone, obtained with the conventional method, from an inversion of the synthetic line of Fig. 3 with superimposed random noise of Gaussian distribution corresponding to a SNR $\sim$ 10.

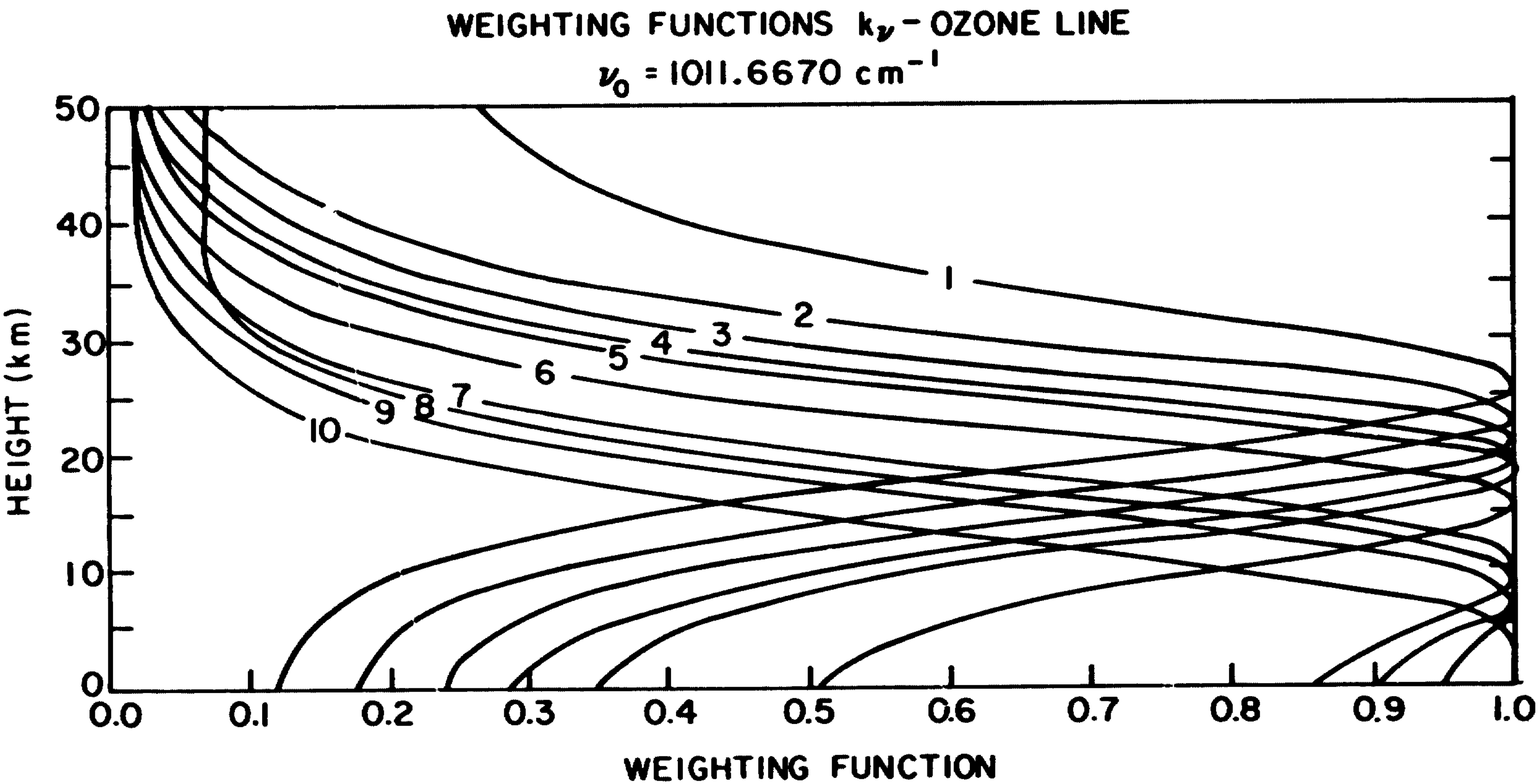

WEIGHTING FUNCTIONS kν - OZONE LINE
ν0 = 1011.6670 cm-1
HEIGHT (km)
WEIGHTING FUNCTION
1
2
3
4
5
6
7
8
9
10
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 1

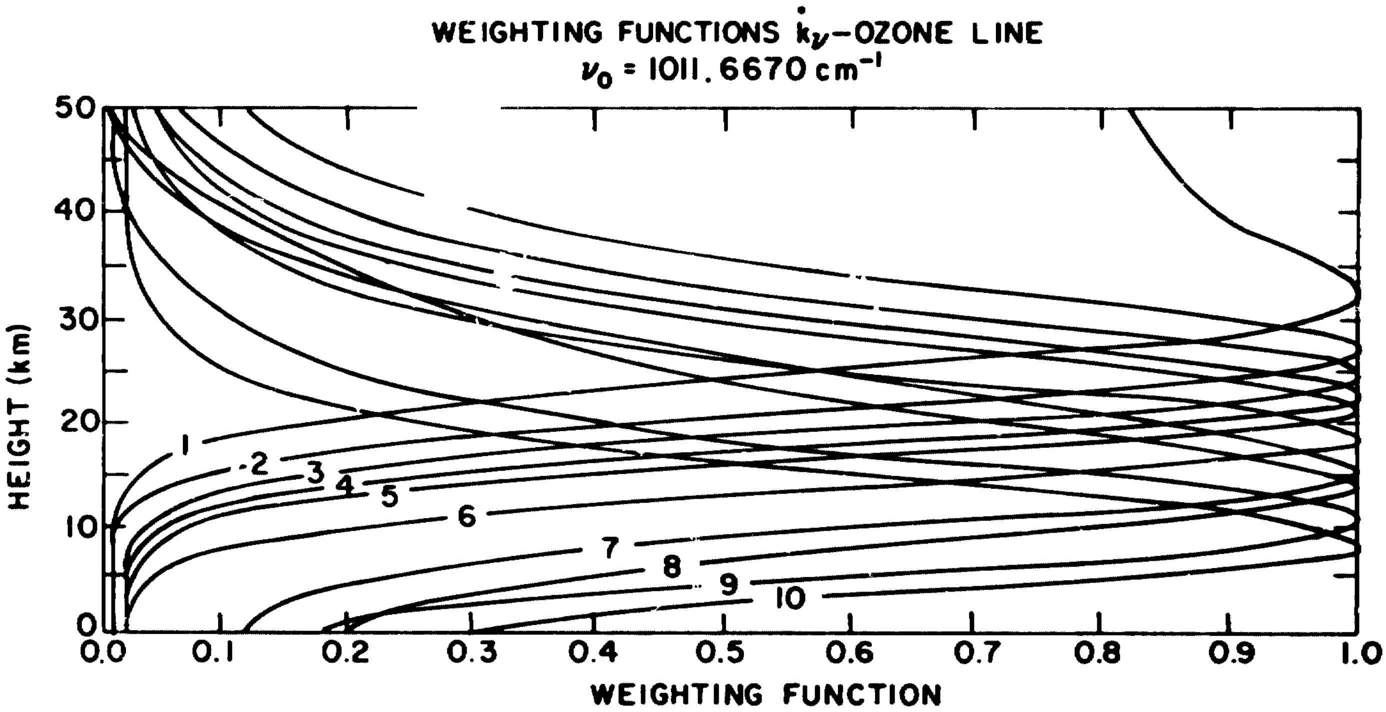
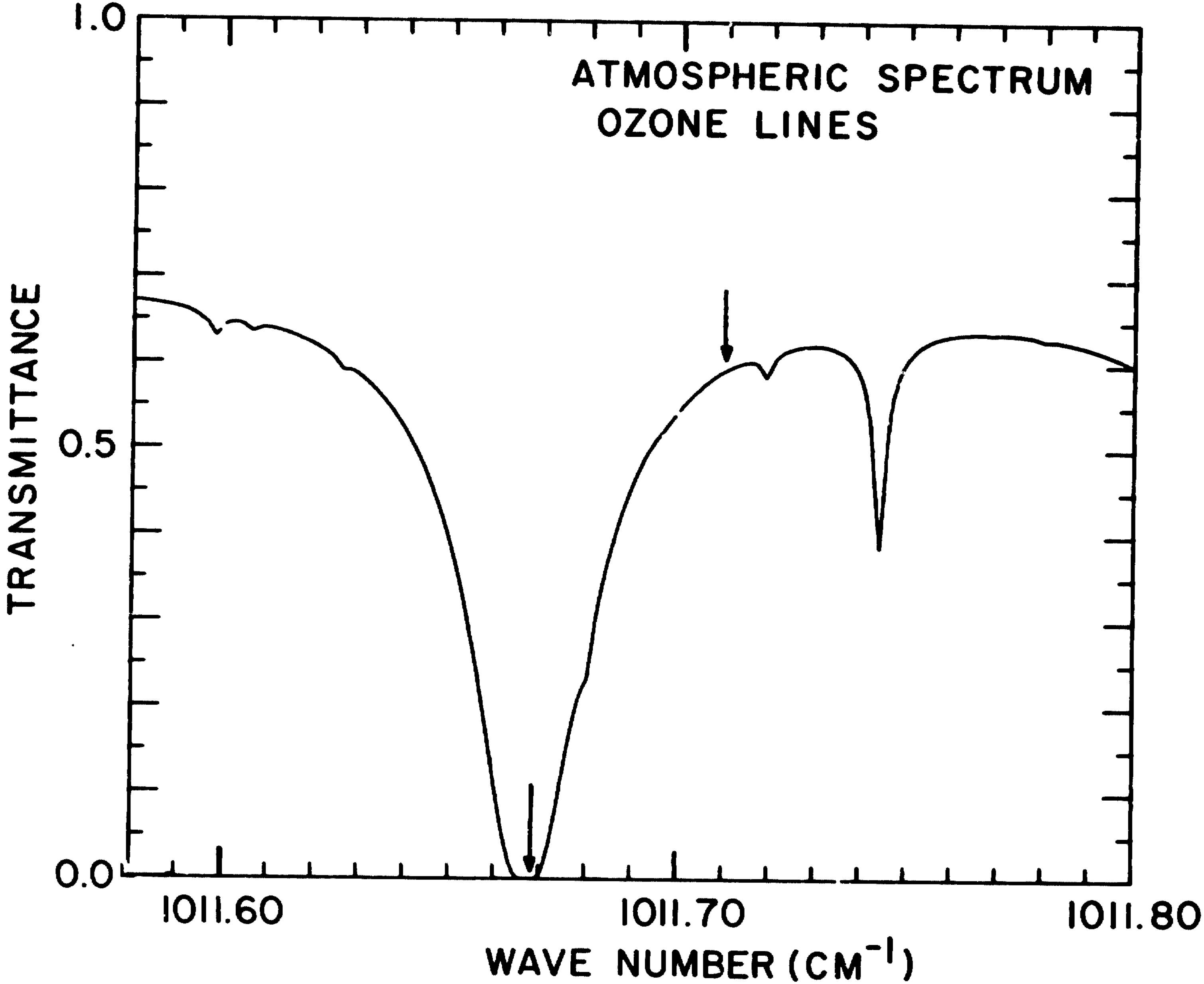

WEIGHTING FUNCTIONS $\dot{k}_\nu$–OZONE LINE
ν_0 = 1011.6670 cm^{-1}
HEIGHT (km)
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
WEIGHTING FUNCTION
1
2
3
4
5
6
7
8
9
10

Fig. 2


ATMOSPHERIC SPECTRUM
OZONE LINES
TRANSMITTANCE
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0.5
0.0
1011.60
1011.70
1011.80
WAVE NUMBER (CM⁻¹)

Fig. 3

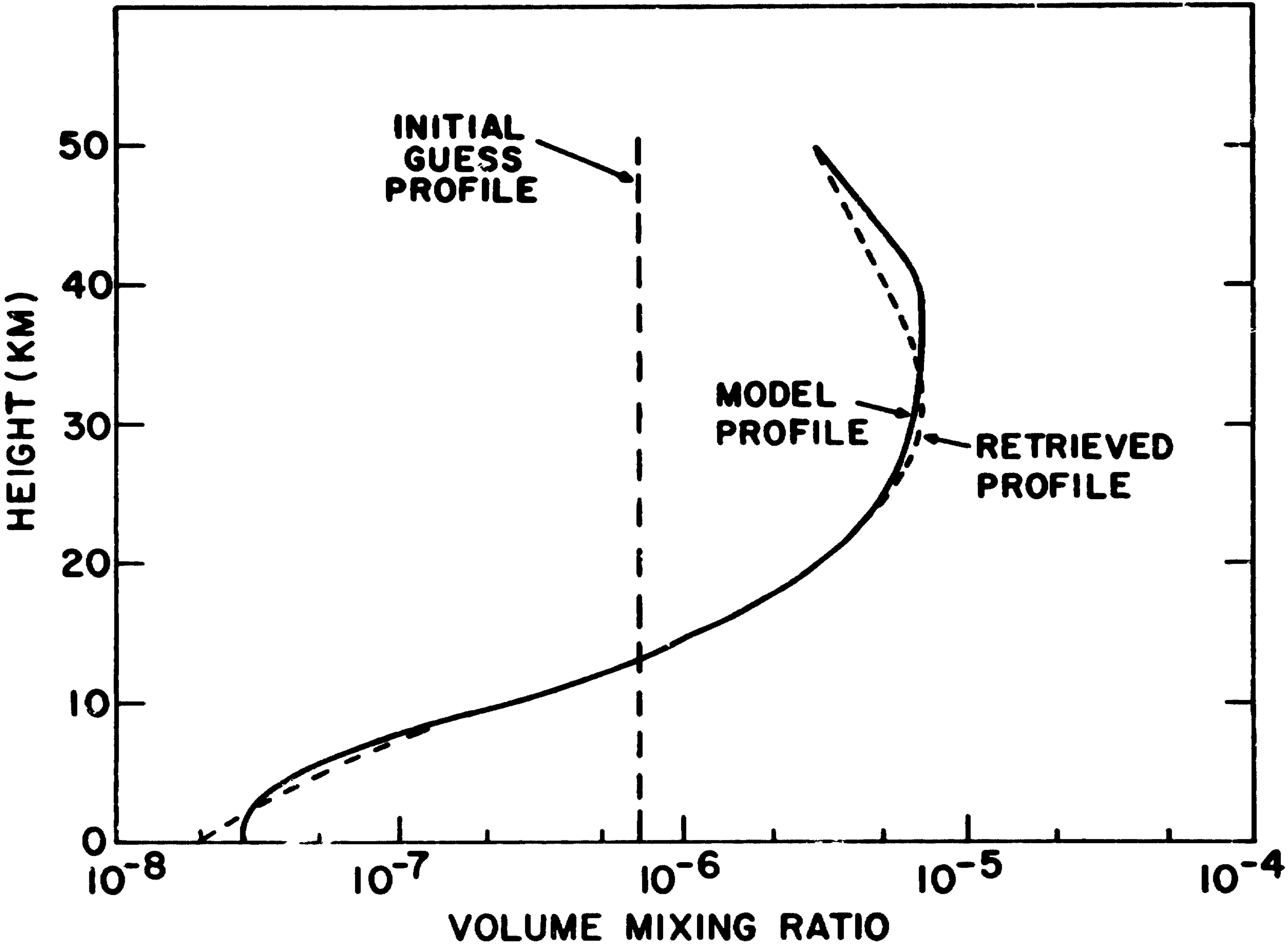

INITIAL GUESS PROFILE
MODEL PROFILE
RETRIEVED PROFILE
HEIGHT (KM)
50
40
30
20
10
0
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
VOLUME MIXING RATIO

Fig. 4a

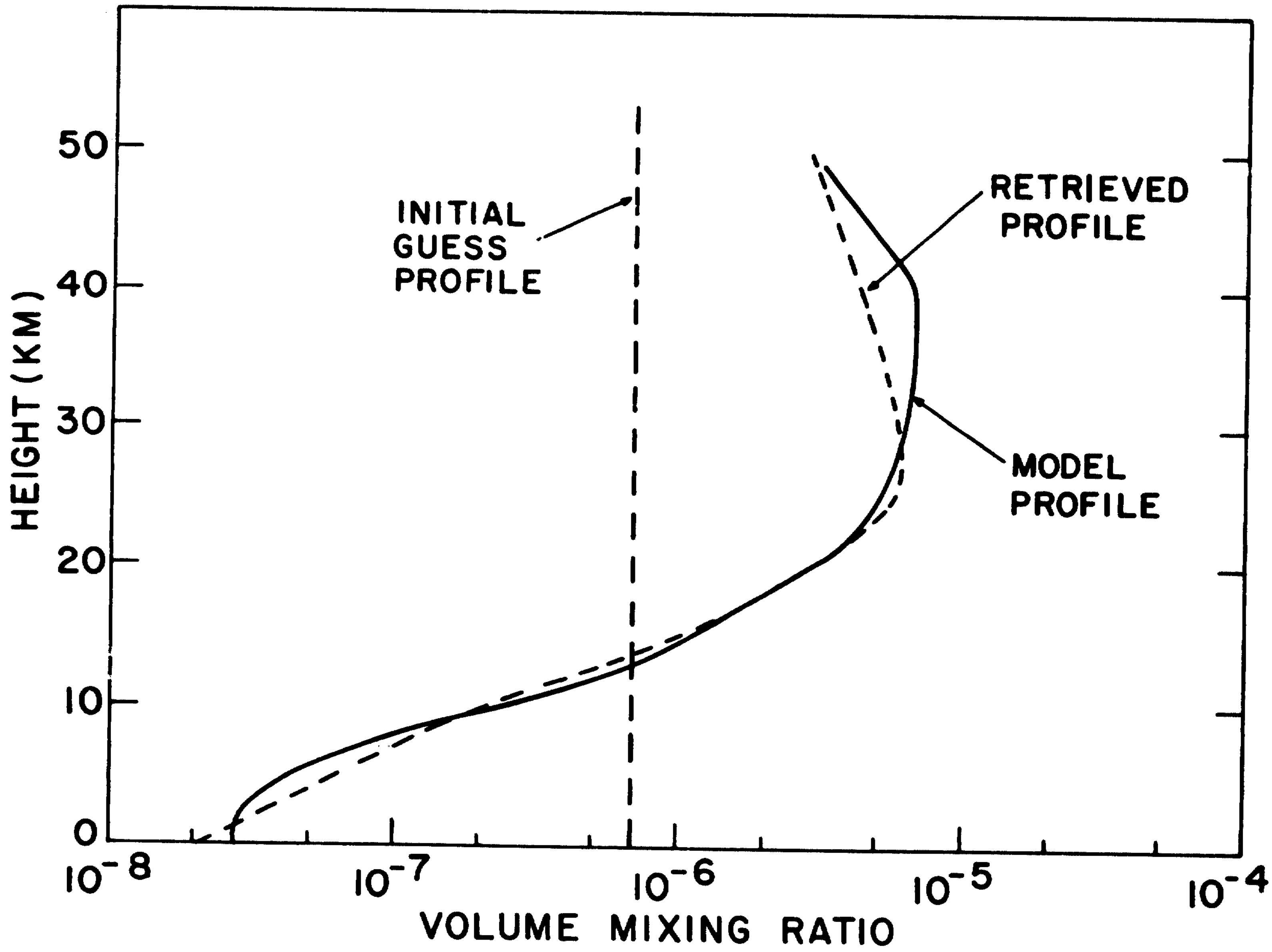
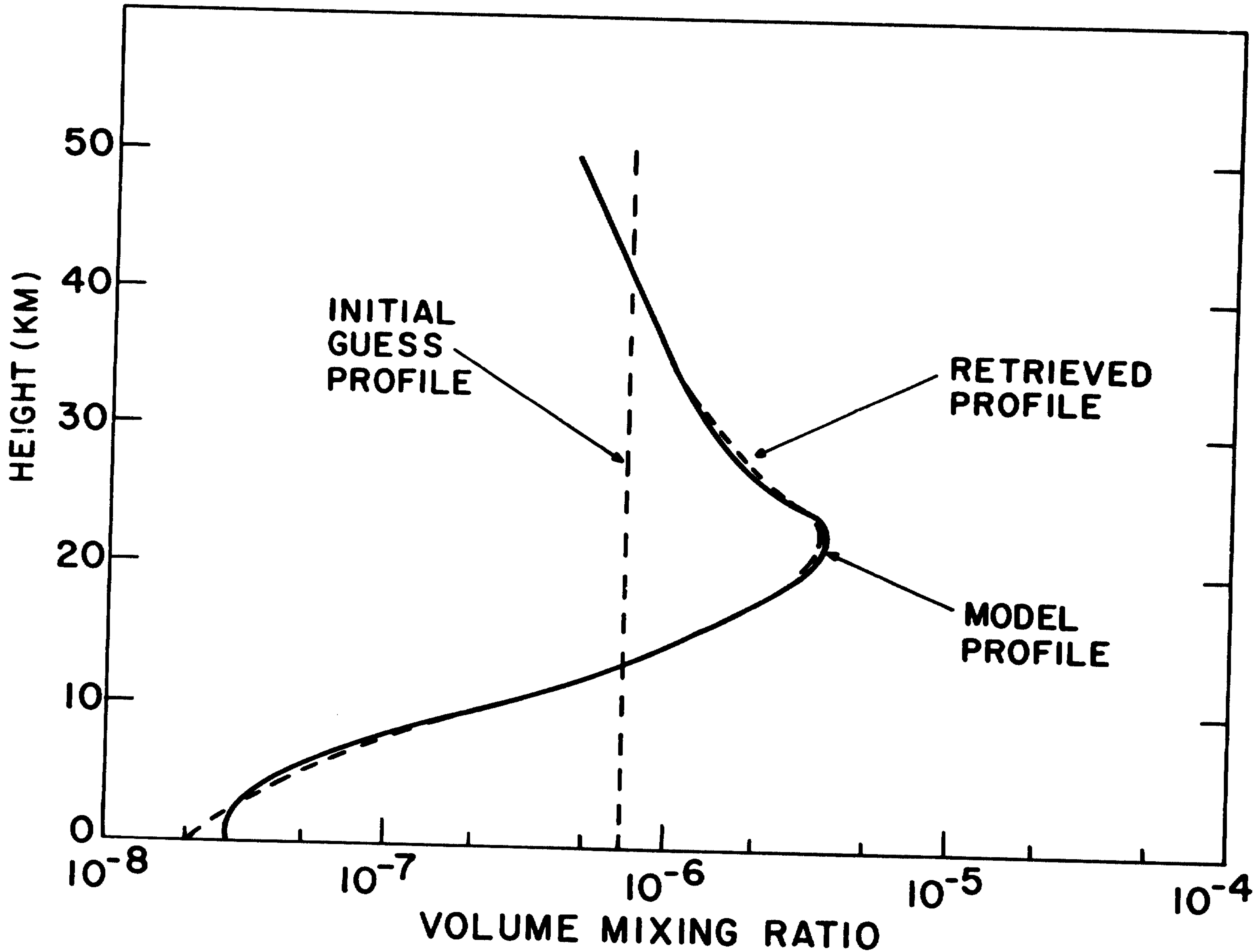

50
40
30
20
10
0
HEIGHT (KM)
INITIAL
GUESS
PROFILE
RETRIEVED
PROFILE
MODEL
PROFILE
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
VOLUME MIXING RATIO

Fig. 4b



HEIGHT (KM)
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40
30
20
10
0
INITIAL GUESS PROFILE
RETRIEVED PROFILE
MODEL PROFILE
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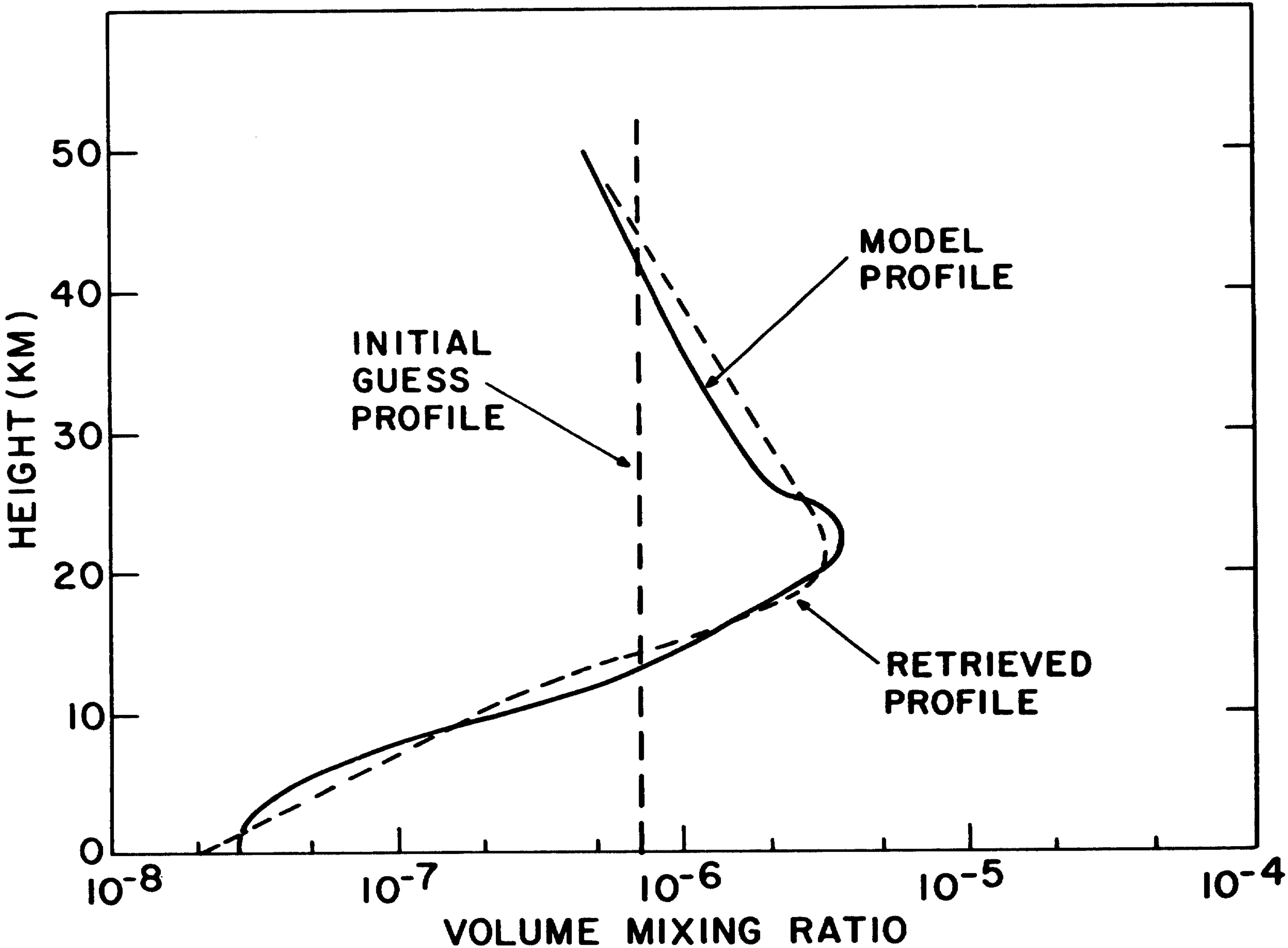
10^-7
10^-6
10^-5
10^-4
VOLUME MIXING RATIO

Fig. 5a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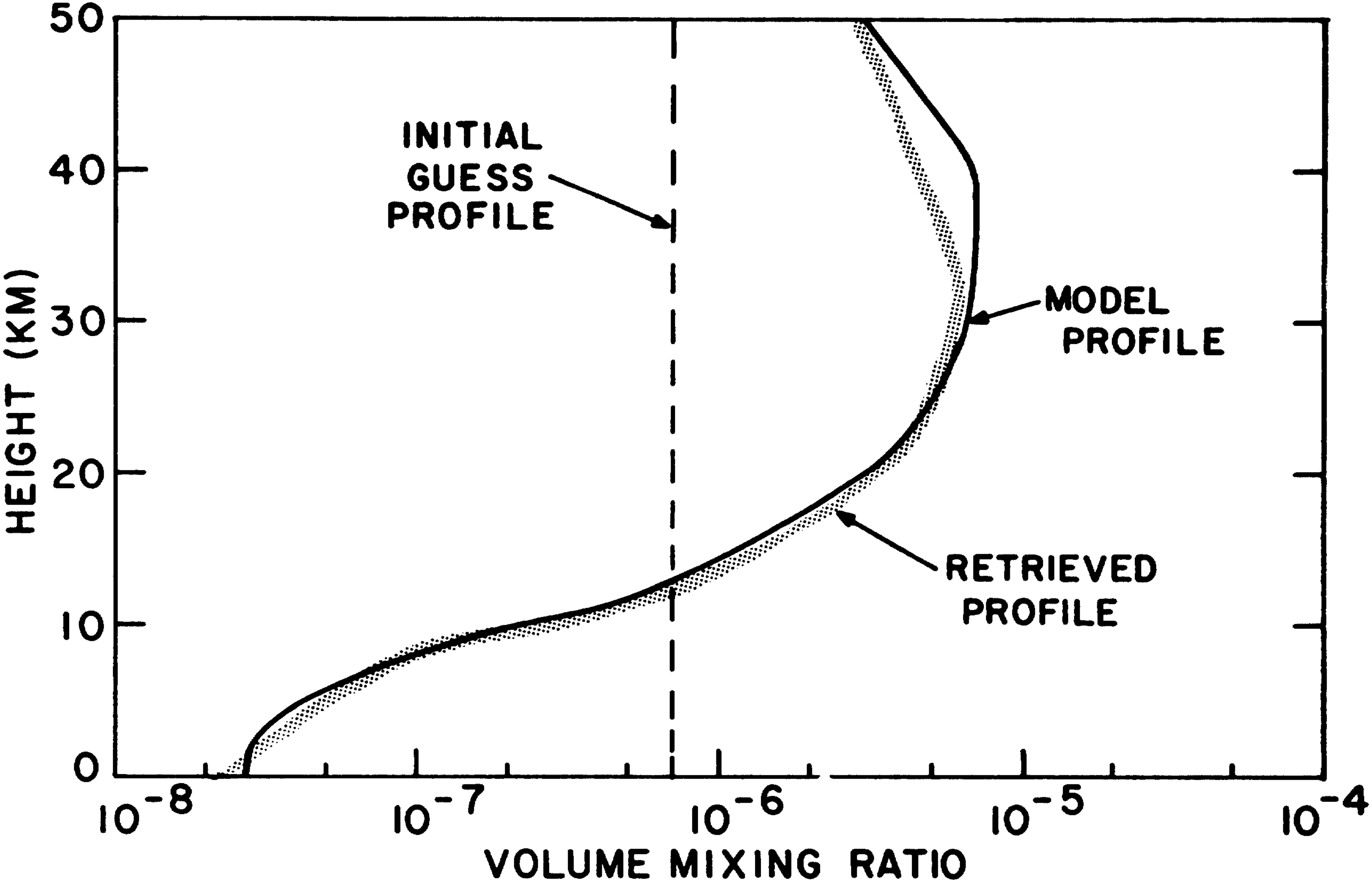
40
30
20
10
0
HEIGHT (KM)
INITIAL
GUESS
PROFILE
MODEL
PROFILE
RETRIEVED
PROFILE
10-8
10-7
10-6
10-5
10-4
VOLUME MIXING RATIO

Fig. 5b



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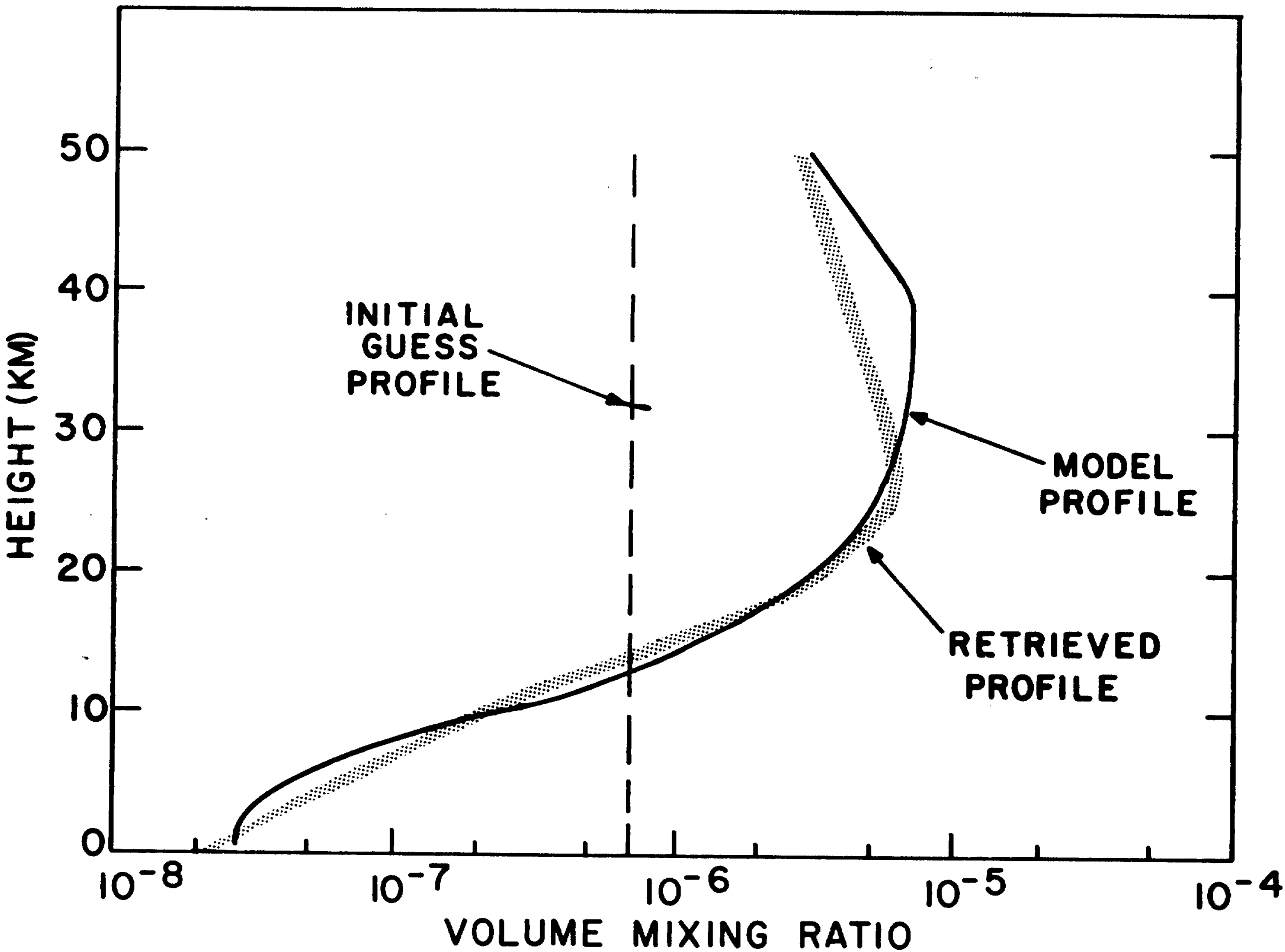
40
30
20
10
0
HEIGHT (KM)
INITIAL
GUESS
PROFILE
MODEL
PROFILE
RETRIEVED
PROFILE
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
VOLUME MIXING RATIO

Fig. 6a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MODEL PROFILE
RETRIEVED PROFILE
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20
30
40
50
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
VOLUME MIXING RATIO

Fig. 6b

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16. Abstract

A new inversion method for remote sounding of planetary atmospheres is presented which appears to have several significant advantages over the conventional methods. This method is applicable to high resolution observations where the spectral lines are fully resolved, and is based on matching the calculated slopes of the spectral line profiles with slopes of the observed lineshapes. The method is applied to inversion of ozone absorption lines in the earth's atmosphere and the results are compared with those obtained by a conventional method. The proposed method is seen to provide a significant improvement in the overall accuracy of the retrieved profiles, with higher vertical resolution and higher levels which may be probed.

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