ATMOSPHERIC RADIATION PROGRESS AND PROSPECTS

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REMOTE SOUNDING OF INFRARED SURFACE FLUXES AND COOLING RATES FROM SPACE

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A novel approach is proposed for the direct inference of infrared surface fluxes from space based on the principles of radiative transfer. The methodology proposed involves concurrent observations of broadband outgoing infrared fluxes at the top of the atmosphere and total infrared cooling within the atmosphere. To obtain the total atmospheric cooling, a combined utilization of angular and wavenumber scans is developed to retrieve infrared cooling rate profiles covering the entire infrared spectrum. We demonstrate that suitable weighting functions in the rotational and 6.3μm H_2O bands can be selected for retrieval of cooling rates, and that CO_2 and O_3 absorption can be neglected in the estimate of total atmospheric cooling.

INTRODUCTION

The determination of solar and infrared surface fluxes from available satellite radiance data has been a subject of considerable effort in recent years, as evidenced in the papers by Pinker and Corio (1984), Darnell et al. (1983), and Gautier et al. (1980). However, the methodologies employed in these papers to relate surface radiative fluxes and observed satellite radiances are empirical and statistical in nature and do not have a physical foundation for the inversion. Moreover, as cited in these papers, while there has been some progress on the inference of surface solar fluxes, the retrieval technique for infrared surface fluxes, except that reported by Darnell et al. based on an empirical and indirect method, is essentially inadequate.

A direct observation of surface radiative fluxes from satellites on a routine basis is important from several standpoints. First, a measure of the net surface radiative fluxes could be utilized to estimate sensible and latent heat fluxes, which are critical for the formation of convective, as well as large-scale clouds and the consequence of precipitation. On a more fundamental level, reliable surface radiative flux measurements are urgently needed to verify radiative transfer programs developed for weather and climate models. It is noted that large deviations of the downward infrared flux on the order of 30-60 Wm^{-2} between various detailed infrared radiative transfer programs are found.

Moreover, on the issue of infrared cooling rates, a direct measurement of infrared cooling rates from space is equally important from a number of perspectives. Measured cooling rates can be utilized to verify values computed from radiative transfer methods and optimize the tedius and time consuming computational effort in numerical models. Observed cooling rate profiles in clear columns may be used to estimate the downward velocity and employed as an independent source to supplement the water vapor concentration estimate.

In this paper, we wish to propose a novel approach to measure infrared surface fluxes directly from space on the basis of the principles of radiative transfer. This approach involves observations of outgoing infrared fluxes at the top of the atmosphere and total cooling within the atmosphere. The fundamentals and analyses are, respectively, presented in the following two sections.

FUNDAMENTALS FOR REMOTE SOUNDING OF INFRARED SURFACE FLUXES FROM SPACE

Conceptual Approach

In order to obtain surface infrared fluxes from space, based on principles of infrared radiative transfer, we begin with the fundamental connection between the flux divergence and cooling rate. Let the net infrared flux and cooling rate for a spectral interval $\Delta\nu_j$ be denoted by F_j and $\dot{\theta}_j$, respectively, then we have

$$\frac{dF_j(z)}{dz} = -C_p\rho_a(z)\,\dot{\theta}_j(z)\,, \tag{1}$$

where C_p denotes the heat capacity at constant pressure, z the height, and ρ_a the air density.

We perform an integration from the surface (z=0) to the top of the atmosphere ($z \rightarrow \infty$) to obtain

$$F_j(\infty) - F_j(0) = -\int_0^\infty C_p\,\rho_a(z)\,\dot{\theta}_j(z)\,dz. \tag{2}$$

We then carry out a summation over the spectral band $\Delta\nu_j$ and rearrange terms so that

$$F(0) = F(\infty) + \int_0^\infty C_p\rho_a(z)\sum_j a_j\dot{\theta}_j(z)\,dz\,, \tag{3}$$

where a_j represents certain weights and we have defined

$$F(0) = \sum_j a_j\,F_j(0), \qquad F(\infty) = \sum_j a_j\,F_j(\infty)\,. \tag{4}$$

Equation (3) shows that the surface flux F(0) is the sum of the outgoing flux at the top of the atmosphere $F(\infty)$ and the spectral summation of the total atmospheric cooling rate profile, which is a negative quantity. Since outgoing infrared fluxes can be derived from satellite observations, simultaneous measurements of spectral infrared cooling rates will then yield the surface infrared flux. In this manner, the determination of the surface flux depends solely on radiation measurements without requiring information on atmospheric temperature and composition. Moreover, it is noted that no empirical or statistical procedures are required. Below, we describe the manner in which atmospheric cooling rates can be inferred directly from space.

Remote Sounding of Infrared Cooling Rates

Basically, it is necessary to develop a retrieval equation that will correlate the atmospheric infrared cooling rate profile with the emergent radiance at the top of the atmosphere. Since cooling rates are associated with the flux divergence within the

atmosphere, the observed emergent radiance in units of per solid angle must therefore be used to infer the net flux and, at the same time, to achieve vertical profiling. Toward this end, we wish to develop an integral equation containing the infrared cooling rate profile, which is weighted by a kernel function. In reference to Eq. (1), we multiply, by this equation, an upwelling transmittance T_i for a subspectral interval $\Delta\nu_i$ (also referred to as a specific channel i) such that $\Delta\nu_i \ll \Delta\nu_j$. Integration from the surface to the top of the atmosphere is then carried out to obtain

$$\int_0^\infty \dot{\theta}_j(z)\, K_i(z)\, dz = -\int_0^\infty \frac{dF_j(z)}{dz} T_i(z)\, dz\,, \tag{5}$$

where we have defined the kernel function in the form

$$K_i(z) = C_p\, \rho_a(z)\; T_i(z)\,. \tag{6}$$

We wish to show that the right-hand side of Eq. (5) can be related to the emergent spectral radiance I_j and upwelling channel radiance I_i. For this purpose, we employ the k-distribution method to express the transmittance. For a spectral interval that is sufficiently small, the spectral transmittance is independent of the ordering of the absorption coefficient k_ν. Hence, the wavenumber integration may be replaced by an integration over the k-space. If the normalized probability distribution function for the absorption coefficient from k(min) to k(max), within the spectral inverval $\Delta\nu$, is given by f(k), then the spectral transmittance may be written in the form (Arking and Grossman, 1972)

$$T_{\bar{\nu}}(u) = \int_{\Delta\nu} e^{-k_\nu u} \frac{du}{\Delta\nu} = \int_0^\infty e^{-ku} f(k)\, dk\,, \tag{7}$$

where we have set k(min) $\to 0$ and k(max) $\to \infty$. Moreover, a cumulative probability function may be defined such that (Lacis et al., 1979)

$$g(k) = \int_0^k f(k)\, dk\,, \tag{8}$$

where $g(0)=0$, $g(k\to\infty)=1$, and $dg(k)=f(k)\, dk$. g(k), so defined, is a monotonically increasing and smooth function in the k-space. It follows that the spectral transmittance may be expressed in terms of the g-function in the form

$$T_{\bar{\nu}}(u) = \int_0^1 e^{-k(g)u}\, dg. \tag{9}$$

Since g(k) is a monotonic function in the k-space, the inverse will also be true so that k(g) is a monotonic function in the g-space. Consequently, the integration over the g-space, which replaces the tedius wavenumber integration, can be evaluated by summation of a finite number of exponential terms with a high accuracy.

In line with the foregoing discussion, the spectral and channel transmittances corresponding, respectively, to the emergent spectral and upwelling channel radiances may be written in the forms

$$T_j(u/\mu) = \sum_m e^{-k_m u/\mu} \Delta g_m\,, \tag{10a}$$

$$T_i(u) = \sum_n e^{-k_n u}\, \Delta g_n\,. \tag{10b}$$

Using these expressions and following mathematical procedures and analyses similar to those developed by Liou and Xue (1988), the integral equation denoted in Eq. (5) can be analytically related to the emergent radiance I_j at a specific angle $\cos^{-1}\bar{\mu}$ and channel radiance I_i in the form

$$\int_0^\infty \dot{\theta}_j(z)\, k_i(z)\, dz = I_j(\bar{\mu})\, \alpha + I_i\, \beta\,. \tag{11}$$

where the known coefficients are given by

$$\left.\begin{matrix} \alpha \\ \beta \end{matrix}\right\} = 2\pi \sum_m \sum_n \left.\begin{matrix} \alpha_{mn} \\ \beta_{mn} \end{matrix}\right\} \Delta g_m \, \Delta g_n$$

$$\alpha_{mn} = \begin{cases} \chi \; [\ln(1+1/\chi) + 1] \; , & \chi > 1 \\ \chi^2 \ln(1/\chi - 1) \, , & \chi < 1 \end{cases}$$

$$\beta_{mn} = \begin{cases} -\chi \left[\chi \ln \left[\frac{\chi - 1}{\chi + 1} \right] + 2 \right] , & \chi > 1 \\ -\chi \left[\chi \ln \left[\frac{1 - \chi}{1 + \chi} \right] + 2 \right] , & \chi < 1 \end{cases}$$

with $\chi = k_m/k_n$. In the analyses, the mean value theorem is used, in which the cosine of the emergent angle for the emergent radiance is given by

$$\bar{\mu} = \begin{cases} [1 + \chi \ln(1 - 1/\chi)] \; / \ln(1 - 1/\chi) \, , & \chi > 1 \\ \chi \, , & \chi < 1 \end{cases} \tag{12}$$

In deriving Eq. (11), it is noted that the channel transmittance, expressible in terms of a series of exponential functions, serves as the Laplace transform from which the flux divergence is transformed to physical variables relating to upwelling channel and emergent spectral radiances. The powerful Laplace transform for remote sounding applications was originally introduced by King (1963). Equation (11) represents a Fredholm equation of the first kind, which correlates cooling rates and radiances. In principle, a set of radiances measured from a satellite should provide information about the cooling rate profile. However, to ensure that a solution can be retrieved from the observed radiances, it is necessary to investigate whether appropriate transmittances in the infrared region can be selected to give adequate weights to the cooling rate profile. Furthermore, it is also pertinent to examine the relative importance of various spectral bands associated with H_2O, CO_2, and O_3 to the total cooling rate in the atmosphere.

EXAMINATION OF ATMOSPHERIC TOTAL COOLING AND POTENTIAL WEIGHTING FUNCTIONS

To estimate the components of atmospheric cooling rates in terms of the total flux divergence due to various optically active gases in the earth's atmosphere, we use the infrared radiation program developed by Liou and Ou (1981) based on a broadband emissivity approach. The infrared spectrum is divided into five spectral intervals including the H_2O rotational band, H_2O continuum, 6.3 μm H_2O vibrational-rotational band, 9.6 μm O_3 and 15μm CO_2 bands, as well as an overlap consideration for H_2O and CO_2 absorption. Shown in Fig. 1 are the cooling rate profiles for each spectral band using a tropical atmosphere. The cooling in the troposphere is largely contributed by the rotational band of H_2O, although the H_2O continuum also contributes significantly to the cooling near the surface in a moist tropical atmosphere. Contributions to cooling in the troposphere by the 6.3 μm H_2O and 15 μm CO_2 bands are relatively small. O_3 shows noticeable cooling only above about 15 km. In fact, between 15-30 km, there is a slight heating produced by the absorption and emission of O_3 due, in part, to the ozone profile, which peaks at about 20-25 km. Cooling rates due to CO_2 become predominant in the upper atmosphere. The total cooling rate profile is illustrated by the solid curve in the figure.

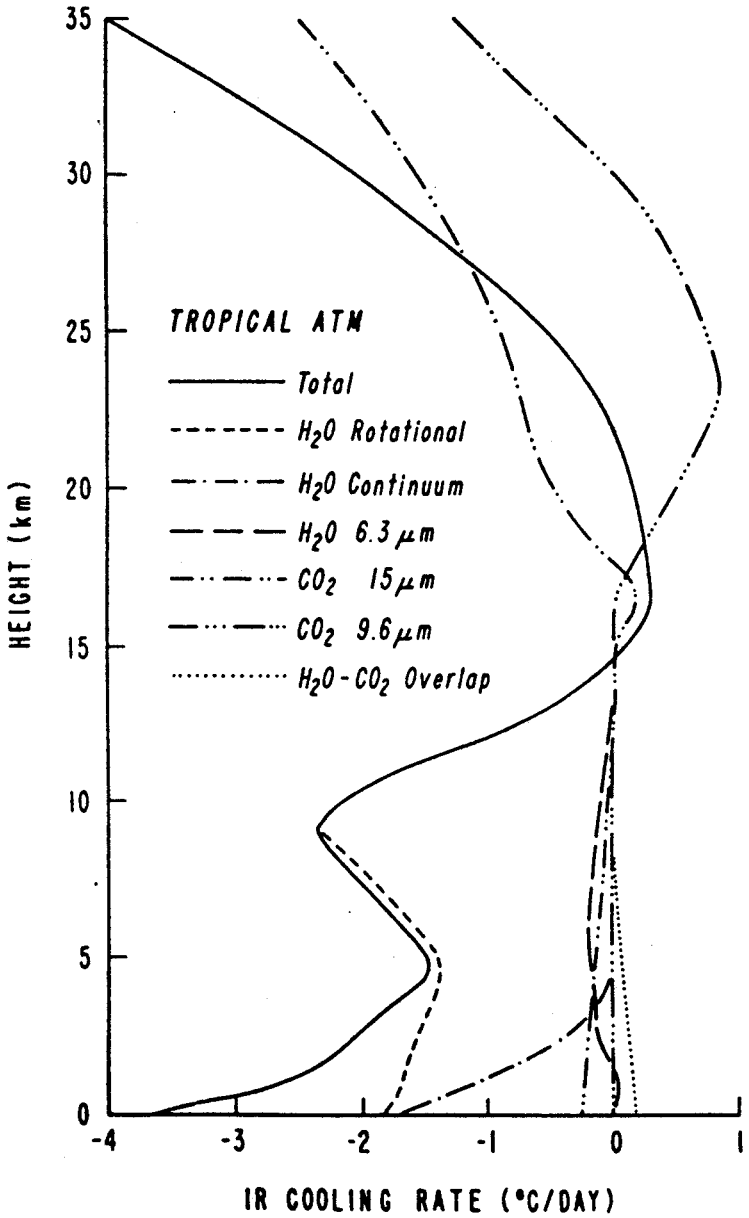

Fig. 1. Components of infrared cooling rate profiles for H_2O, CO_2, and O_3 bands and the total cooling rate profile for the tropical atmosphere.

In Table 1 are shown the components of infrared radiation budgets for each spectral band, the total cooling in terms of the atmospheric net flux divergence, and the net fluxes at the top and bottom of the atmosphere. As shown in Eq. (3), the sum of the outgoing flux and the total cooling term gives the net surface flux. With respect

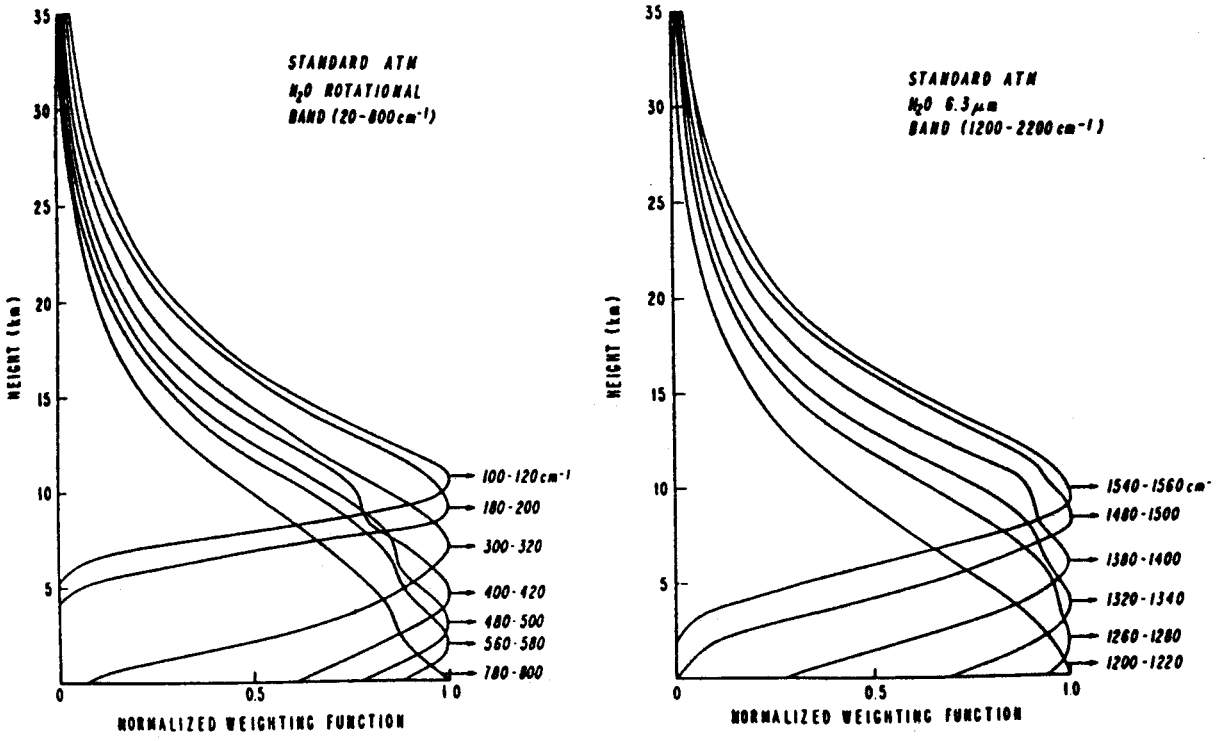

Fig. 2. Normalized weighting functions for the atmospheric cooling rate retrieval for H_2O rotational and 6.3 μm bands. The weighting functions presented here are products of the air density and channel transmittances for a 20 cm^{-1} interval. The standard atmospheric profile was used in the presentation. See the text for further discussion.

to the individual components, the largest contribution comes from the rotational band of H_2O, which accounts for about 83-88% of the total cooling. The contribution due to the H_2O continuum becomes significant for the moist tropical atmosphere. The rotational-vibrational band of H_2O contributes on the order of 10 W m^{-2}. CO_2 accounts for 13 to 21% of the total atmospheric cooling. O_3 produces the very small heating effect mentioned

Table 1. Components of Infrared Radiation Budgets (W m^{-2})

Atm.	Rot*	Cont.	Vib.–Rot.	O_3	CO_2	Overlap	Total Cooling	F(∞)	F(0)
a*	-167.6	-33.7	-9.6	4.6	-26.8	19.9	-203.1	283.7	80.6
b	-158.5	-19.1	-10.2	3.3	-29.5	26.3	-185.7	276.7	91.0
c	-108.9	-2.1	-10.8	0.8	-26.3	20.0	-127.3	227.6	100.1
d	-142.5	-9.4	-9.1	2.1	-29.2	25.1	-163.0	261.0	98.0

*a) tropical, b) midlatitude summer, c) midlatitude winter, d) subarctic summer *Rot. (40-800 cm^{-1}), Cont. (800-1200 cm^{-1}), Vib.–Rot. (1200-2200 cm^{-1}), O_3 (1000-1065 cm^{-1}), CO_2 (500-850 cm^{-1}).

previously. The overlap of H_2O and CO_2 accounts for about 15% of the total cooling. If we omit the contribution of O_3, CO_2, and the overlap correction, the estimated total cooling is within about 1-4% or 2-5 W m^{-2} of the exact value. This estimate leads us to suggest that a first approximation in obtaining the total atmospheric cooling rate would be to measure atmospheric cooling profiles due to H_2O. Owing to the variation in the planck function, it is necessary to divide the H_2O infrared spectrum

into a number of spectral intervals. In view of some success in the retrieval of cooling rates due to the rotational band of H_2O in our earlier study, we propose that the infrared spectrum be divided into the following spectral intervals: (20-500 cm^{-1}), (500-1200 cm^{-1}), and (1200-2200 cm^{-1}). Below is a discussion of the weighting function corresponding to these intervals.

Shown in Fig.2 are a set of weighting functions constructed for the H_2O rotational and 6.3 μm vibrational-rotational bands. We used the absorption coefficient data calculated by Chou and Kouvarnis (1986) for every 0.005 cm^{-1} to derive the probability distribution function f(k) and to calculate the transmittance for a 20 cm^{-1} interval covering the entire water vapor spectrum. Pressure corrections using the Curtis-Godson approximation on the path length, were performed to account for the inhomogeneous atmosphere. For the H_2O rotational band, we selected seven channels whose weighting function peaks are spaced within about 2 km in height. On the basis of our previous retrieval experience, the four uppermost channels could be utilized to retrieve cooling rates for the spectral interval from 20 to 500 cm^{-1}. For the 500-800 cm^{-1} spectral interval, we may use the three lowest channels for the cooling rate retrieval. For the 6.3 μm vibrational-rotational band, we find six channels, ranging from 1550 to 1210 cm^{-1}, that can be used. The weighting function peaks of these channels are also about 2 km apart. For practical applications, the number of channels could be reduced for this spectral band.

The presentation of these weighting functions uses the standard atmospheric profile. We have also used the moist tropical atmosphere in the analysis to investigate whether the water vapor concentration profile may affect the shape and peak of the weighting functions. It turns out that they are fairly stable, due, in part, to the utilization of air density in the construction of weighting functions.

To obtain the cooling rate close to the surface, we propose a direct inversion method. From Eq. (11), the linear sum of the emergent spectral radiance and upwelling channel radiance in the 10 μm window can be approximated by

$$\dot{\theta}_j(z \to 0)\ (1 - a_{ij}) + b_{ij} \doteq I_j(\bar{\mu})\ \alpha + I_i \beta,$$

where $\dot{\theta}_j$ denotes the cooling rate near the surface for the spectral band 800-1200 cm^{-1}, the channel radiance I_i could be any spectral sub-band within this interval, and a_{ij} and b_{ij} are small adjustment coefficients. The preceding discussion concludes our proposed methodology for deriving the total atmospheric cooling rate covering the infrared spectrum from 20 to 2200 cm^{-1}.

CONCLUSION

We have developed a novel approach for the detection of infrared surface fluxes from space based on the principles of radiative transfer. Two concurrent observations are required. One is concerned with the observation of broadband infrared fluxes at the top of the atmosphere, while the other is involved with the evaluation of total atmospheric cooling from measurements of cooling rate profiles within the atmosphere. The former has been a subject of extensive research and development in the last 25 years. However, the latter requires innovative techniques of measurement for infrared cooling rate profiles.

In order to convert the observed radiances to fluxes and, at the same time, to achieve vertical profiling, a combined utilization of angular and wavenumber scans

from spaceborne radiometers is proposed. We illustrate that an integral equation correlating the spectral cooling rate profile and spectral emergent and upwelling channel radiances can be formulated to form the basis of retrievals. For the sake of brevity, we have discussed the physical principles involved rather than the mathematical details, which require the use of the mean value theorem and Laplace transform techniques. Using a 20 cm^{-1} spectral interval and by means of the k-distribution method, we demonstrate that it is possible to select suitable weighting functions in the rotational and 6.3 μm H_2O bands for the retrieval of cooling rates covering the entire infrared spectrum. After examining the components of infrared radiative budgets produced by various spectral bands, we argue that in order to evaluate the total atmospheric cooling, contributions due to CO_2 and O_3 can be neglected in the analysis.

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