OBSERVATION MODELING IN THE INTERPRETATION OF REMOTE SENSING DATA

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Received September 28, 1988

This paper presents an algorithm for constructing an observational system for remote sensing of the atmosphere. The algorithm is based on the solution of the conjugate problem.

Systems for the interpretation of remote sensing data should be based on models of the processes under study, and on models of indirect observations. The combination of these models within the framework of a unified algorithm can be very fruitful for extracting maximum information about the optical state of the atmosphere, as well as for finding ways to improve the observational systems, taking into account certain physical features of the atmospheric processes under study.

We attempt in this paper to construct an observational model based on a system for interpreting remote sensing data which is being developed at the Institute of Atmospheric Optics, Siberian Branch, USSR Academy of Sciences, and on the use of data obtained with the high resolution multichannal radiometer[1](AVHRR). The observational model is constructed using the adjoint functions technique, which allows for an efficient description of the measurements within the framework of a given physical model for the process in question 2. The construction of the observational model will be illustrated in this paper using the first channel of the AVHRR, which operates in the visible range at $\lambda = 0.73$ μm. Radiative transfer at short wavelengths in a plane-parallel atmosphere can be described by the equation

$$\mu \frac{dI_\lambda(\mu,\tau)}{d\tau} + I_\lambda(\mu,\tau) = \sum_{k=1}^{K} F_{k_\lambda}(\mu,\tau), \tag{1}$$

where $\mu = \cos\theta$ (θ is the local zenith angle) and is defined over the range $M = \{0 < \mu \leq 1\}$; τ is the optical depth, $I_\lambda(\mu, \tau)$ is the intensity of radiation at wavelength λ, and $F_{k_\lambda}(\mu, \tau)$ is the function describing the structure and intensity of the k-th radiation source. The data-processing system is designed to work with resolution elements (pixels) that may be either cloudless or partially (including fully) cloud-covering.

In order to demonstrate the capabilities of this algorithm, we make some simplifying assumptions. Let us assume that:

a) the radiation coming from any point within the device's field of view and incident on the plane receiving area of a scanner is emitted by a horizontally homogeneous surface;

b) the underlying surface for a cloudless portion of the scanner's field of view, as well as that for a cloudy portion, is homogeneous and isotropically reflecting;

c) the single scattering approximation is valid.

These assumptions do not restrict the generality of the algorithm, while at the same time they make it possible to obtain the final results in explicit analytic form.

Taking into account the above assumptions, one can rewrite for a cloudless portion of a pixel, Eq. (1) and corresponding boundary conditions as follows

$$\mu \frac{d\bar{I}_\lambda(\mu,\tau)}{d\tau} + \bar{I}_\lambda(\mu,\tau) = \frac{S_\lambda}{4\pi} \bar{\gamma}\, e^{-\frac{1}{\mu_0}\tau} \tag{2a}$$

$$\bar{I}(\mu,\bar{\tau}_H) = (1-n)\, \mu_0 \frac{S_\lambda}{\pi} \bar{R}_\lambda\, e^{-\frac{1}{\mu_0}\bar{\tau}_H}, \quad \mu > 0, \tag{2b}$$

and

$$\mu \frac{d\tilde{I}_\lambda(\mu,\tau)}{d\tau} + \tilde{I}_\lambda(\mu,\tau) = \frac{S_\lambda}{4\pi} \tilde{\gamma}\, e^{-\frac{1}{\mu_0}\tau} \tag{3a}$$

$$\tilde{I}(\mu,\tilde{\tau}_H) = n\mu_0 \frac{S_\lambda}{\pi} \tilde{R}_\lambda\, e^{-\frac{1}{\mu_0}\tilde{\tau}_H}, \quad \mu > 0 \tag{3b}$$

for the cloudy part of a pixel, where $\bar{I}_\lambda$ and $\tilde{I}_\lambda$ are the intensities relevant to the cloudless and cloudy portions of the pixel respectively, $\bar{\tau}_H$ is the optical depth of the cloudless atmosphere along the path from the ground surface to the measuring device, $\tilde{\tau}_H$ is the optical depth of the cloudy atmosphere, n is a weighting function describing the fractional contribution of clouds to the emergent radiation at a given wavelength, $\bar{R}$ is the albedo of the underlying surface, $\tilde{R} = \bar{R} + \frac{T^2 R^c}{1 - \bar{R}R^c}$; T and R^c are the transmission and reflection coefficients of the clouds, respectively; $\tilde{\tau} = \tau_0 + \tau^n$; $\tilde{\gamma} = \gamma^0 + \gamma^h$; τ^0 and γ^0 are the optical depth and scattering phase function of the clouds; τ^n and γ^n are the optical depth and scattering phase function of the overcloud atmosphere layer; the remaining notation is standard. Bearing in mind that problems (2) and (3) are linear, the intensity function within one pixel can be cast in the form

$$I_\lambda(\mu,\tau)=\bar{I}(\mu,\tau)+\tilde{I}(\mu,\tau). \tag{4}$$

An observational model may be based on the fact that measurements can be represented by the functional

$$L_\lambda(I,\tau) = \int_M I_\lambda(\mu,\tau)\eta(\mu,\tau)dM, \tag{5}$$

where $\eta(\mu, \tau)$ is the distribution function of the instruments, characterizing their sensitivities to the variations of the measured parameters and the distribution of the devices in space. Depending on the choise of $\eta(\mu, \tau)$, the functional (5) describes either flux or intensity measurements.

The functional (5), which characterized measurements at the upper boundary of the atmosphere, can be writer in the form

$$L_\lambda(I,\tau_0)=\bar{L}_\lambda(I,\tau_0)+\tilde{L}_\lambda(I,\tau_0), \tag{6}$$

where

$$\bar{L}_\lambda(I,\tau_0)=L_\lambda(\bar{I},\bar{\tau}_H)+\int_{\bar{\tau}_H}^{\tau_0}\frac{\partial}{\partial\tau}L_\lambda(\bar{I},\tau)d\tau \tag{7}$$

$$\tilde{L}_\lambda(I,\tau_0)=L_\lambda(\tilde{I},\tilde{\tau}_H)+\int_{\tilde{\tau}_H}^{\tau_0}\frac{\partial}{\partial\tau}L_\lambda(\tilde{I},\tau)d\tau \tag{8}$$

Hereafter, we follow the discussion paper [3], where the function describing the sensitivity and spatial location of a measurement device at a height corresponding to optical depth τ is denoted .by $I^*_\lambda(\mu, \tau)$. In that case, the results may be written as

$$L_\lambda(I,\tau)=\int_M I_\lambda(\mu,\tau)I^*_\lambda(\mu,\tau)d\mu. \tag{9}$$

Assume that at. the top of the atmosphere ($\tau = \tau_0$) the function $I^*(\mu, \tau_0) = \eta(\mu, \tau)$ is known; then it follows from Eq. (9) that the functional (6) takes the value

$$L_\lambda(I,\tau_0)=\int_M I_\lambda(\mu,\tau_0)I^*_\lambda(\mu,\tau_0)d\mu, \tag{10}$$

As a consequence, expression (7) becomes

$$\bar{L}_\lambda(I,\tau_0)=\int_M \bar{I}_\lambda(\mu,\bar{\tau}_H)\,I^*_\lambda(\mu,\bar{\tau}_H)\,d\mu\,+$$
$$+\int_{\bar{\tau}_H}^{\tau_0}\int_M\left[\frac{\partial\bar{I}_\lambda(\mu,\tau)}{\partial\tau}I^*_\lambda(\mu,\tau)+\frac{\partial I^*_\lambda(\mu,\tau)}{\partial\tau}\bar{I}_\lambda(\mu,\tau)\right]d\mu d\tau. \tag{11}$$

Eliminating $\frac{\partial\bar{I}_\lambda}{\partial\tau}$ from (11) by virtue of (∂a), we obtain

$$\bar{L}_\lambda(I,\tau_0)=\int_M\bar{I}_\lambda(\mu,\bar{\tau}_H)I^*_\lambda(\mu,\bar{\tau}_H)d\mu\,+$$
$$+\int_{\bar{\tau}_H}^{\tau_0}\int_M\left\{\left[\frac{\partial I^*_\lambda(\mu,\tau)}{\partial\tau}-\frac{1}{\mu}I^*_\lambda(\mu,\tau)\right]\bar{I}_\lambda(\mu,\tau)+\frac{1}{\mu}\bar{F}_\lambda(\mu,\tau)\right\}d\mu d\tau \tag{12}$$

where $\bar{F}_\lambda(\mu,\tau)=\frac{S_\lambda}{4\pi}\bar{\gamma}e^{-\frac{1}{\mu_0}\tau}$.

Let the function $I^*_\lambda(\mu, \tau)$ satisfy the equation

$$\frac{dI^*_\lambda(\mu,\tau)}{d\tau}-\frac{1}{\mu}I^*_\lambda(\mu,\tau)=0; \tag{13}$$

then (10) can be written in the form

$$\bar{L}_\lambda(I,\tau_0)=\int_M\bar{I}_\lambda(\mu,\bar{\tau}_H)I^*_\lambda(\mu,\bar{\tau}_H)d\mu\,+$$
$$+\int_{\bar{\tau}_H}^{0}\int_M\frac{1}{\mu}\bar{F}_\lambda(\mu,\tau)I^*_\lambda(\mu,\tau)d\mu d\tau. \tag{14}$$

Equation (8) can be written similarly.

Thus, one can see that if the angular sensitivity function is taken to be instrument distribution function for an instrument looking down at the nadir and having plane receiving surface and field of view θ (see Ref. 4), one can find the functional L simply by solving the conjugate problem

$$-\mu\frac{dI^*_\lambda(\mu,\tau)}{d\tau}+I^*_\lambda(\mu,\tau)=0$$

with boundary conditions

$$I^*(\mu,\tau_0)=\delta(\mu-\mu_1)\mu, \tag{15}$$

where μ_1 is the cosine of the satellite's zenith angle.

Note that the structure of the conjugate problem is the same as for problems (2) and (3). This is only true if the measurements are made by one device at the upper boundary, and no additional radiation sources lie in the range (τ_0, τ_h).

Taking into account the solution of the conjugate problem, one can write the expression for functional (6) in the form

$$L(I_\lambda,\tau_0)=\int_M I^*_\lambda(\mu,\bar{\tau}_H)\bar{I}_\lambda(\mu,\bar{\tau}_H)d\mu\,+$$
$$+\int_M I^*_\lambda(\mu,\tilde{\tau}_H)\tilde{I}_\lambda(\mu,\tilde{\tau}_H)d\mu\,+$$
$$+\int_M\int_{\tilde{\tau}_H}^{0}\frac{1}{\mu}I^*_\lambda(\mu,\tau)\bar{F}_\lambda(\mu,\tau)d\mu d\tau\,+$$

$$+\int_{M}\int_{\bar{\tau}_H}^{\tau_0}\frac{1}{\mu}I^{*}_{\lambda}(\mu,\tau)\tilde{F}_{\lambda}(\mu,\tau)\,d\mu d\tau, \qquad (16)$$

where $I_\lambda(\mu, \tau)$ is defined by Eq. (4), and

$$\tilde{F}_{\lambda}(\mu,\tau)=\frac{S_{\lambda}}{4\pi}\,\tilde{\gamma}\,e^{-\frac{1}{\mu_0}\tau}.$$

Making use of Eq. (16) and the solution of (15) of the conjugate problem, one can write the intensity of radiation at the upper boundary as

$$I_{\lambda}(\mu_1,\tau_0) = \bar{I}_{\lambda}(\mu_1,\bar{\tau}_H)\exp(\bar{\tau}_H/\mu_1) + \tilde{I}_{\lambda}(\mu_1,\tilde{\tau}_H) \times$$

$$\times \exp(\tilde{\tau}_H/\mu_1) + \int_{\bar{\tau}}^{\tau_0}\exp(\tau/\mu_1)\,\bar{F}_{\lambda}(\mu_1,\tau)d\tau +$$

$$+\int_{\tilde{\tau}_H}^{\tau_0}\exp(\tau/\mu_1)\,\tilde{F}_1(\mu_1,\tau)d\tau. \qquad (17)$$

We now describe numerical simulations based on the foregoing algorithm. As an example, let us take the results of calculations of optical depths of clouds for the image fragment described in Ref. l, which was obtained using the observational model given in Ref. 5 and the model described here. The optical depth calculations are described in Ref. l.

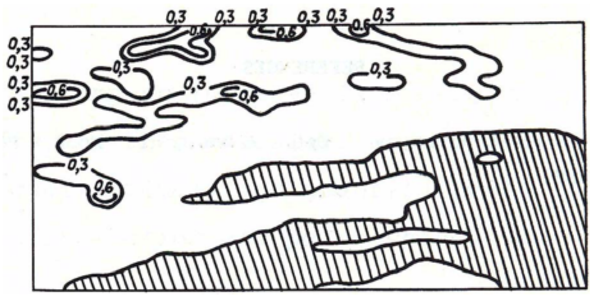

Fig. 1. Optical depth of clouds obtained with model presented in this paper.

The calculated optical depth for cirrus using our model is presented in Fig. 1, while Fig. 2 compares data obtained using the model of Ref. 5 and our model.

It is well known[6,7] that the optical depths of cirrus clouds do not exceed unity. At the same time, optical depths calculated using the model of Ref. 5 almost all exceed unity, and are often greater than 2 (see Fig. 2). For this reason, we suspect that the data from the first version of the remote-sounding data-processing system are overestimated by at least one order of magnitude, while the optical depths obtained using the model discussed in this paper are consistent with the type of clouds.

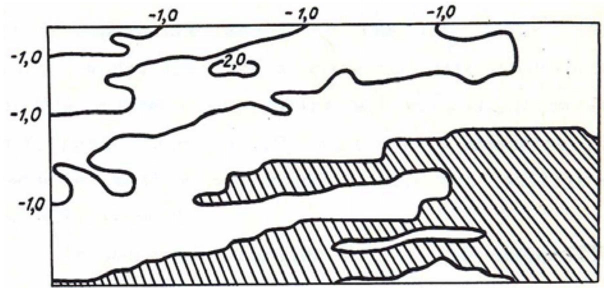

Fig. 2. Optical depth differences obtained with model discussed in this paper and Ref. 4.

We therefore suggest that the algorithm for constructing an observational model proposed in this paper describes the actual radiative transport processes more accurately than the model of Ref. 5 enabling one to improve upon the information provided by remote-sounding data-processing systems, particularly the one described in Ref. 1.

In addition the use of conjugate functions enables one to construct a more or less universal model of observations, and to optimally design the observational system itself.

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