

Toward Direct Uses of Satellite Cloudy Radiances in NWP Models. Part I:
Forward and Adjoint Models

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1. INTRODUCTION

A computationally efficient and accurate forward radiative transfer model and its adjoint are needed for assimilating satellite data into numerical weather prediction models. Currently, the radiative transfer model implemented operationally in the data assimilation system does not simulate the scattering and polarization process associated with surface and atmosphere. In absence of scattering, radiative transfer components such as optical transmittance and radiance gradient (or Jacobian) relative to a state variable can be parameterized analytically. Thus, the satellite radiances under clear atmospheres can be most successfully assimilated. In next decade when many advanced microwave and infrared sensors are deployed in space and their sensitivity to various atmospheric and surface parameters are further improved, the uses of cloudy radiances in NWP models will become a challenging issue because of a high volume of data and many complicated physical processes involved in the radiative transfer process.

In the past, the radiative transfer models computing scattering and polarization have not been optimally developed for the applications of satellite data assimilation. For example, the discrete-ordinate method (DISORT) is based on the versatile numerical packages to derive the general and specific solutions (Stamens et al., 1988). Recently, the DISORT was also expanded for Stokes vector radiative transfer process named as VDISORT (Weng, 1992; Schulz et al., 1999) that can be utilized for the simulations including scattering and polarization at all wavelengths. Other schemes such as the doubling and adding model (Evans and Stephens, 1991) and the matrix operator method (Liu and Ruprecht, 1996; Liu and Weng, 2002) were also developed with the capability similar to VDISORT. However, in these above-mentioned schemes, the efficient procedures of computing cloud optical parameters (e.g. phase matrix, scattering and absorption coefficients) and surface emission (e.g. emission vector and reflectivity matrix) have not been necessarily integrated as part of the model development. Moreover, there is no general theory developed for computing the radiance gradient. This study expands the current capability in radiative transfer modeling to include the efficient Jacobian computations under general conditions. The VDISORT model is also optimized at the formulation of its boundary conditions so that Jacobian relative to variable optical parameters can be analytically derived.

2. FORWARD AND ADJOINT MODELS

The radiative transfer equation of Stokes vector (\mathbf{I}) is solved using discrete ordinate method (VDISORT) (Weng, 1992; Schulz et al., 1999; Weng and Liu, 2002). Essentially, the azimuth-dependence of Stokes vector is expanded into a series of Fourier harmonics. The amplitude of each Fourier component is a function of the zenith angle. Furthermore, the amplitude distribution is approximated with a summation of a series of quadratures. As a result, the cosine and sine harmonics of four Stokes components can be recombined with each being solved independently (Weng, 1992).

With the VDISORT solution, the radiances at various levels are derived analytically (Weng, 1992). It is also shown that optical Jacobians (e.g. the derivative of the radiance relative to single scattering albedo or optical thickness) are also analytic in form and can be computed very efficiently (Weng and Liu, 2002). Thus, the radiance gradient relative to other physical parameters can be deduced from a combination of their optical Jacobians. For example, water vapor Jacobian is

$$\begin{aligned} \frac{\partial \mathbf{I}_l(\mu)}{\partial q_l} &= \frac{\partial \tau_l}{\partial q_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} + \frac{\partial \bar{\omega}_l}{\partial q_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \\ &= \kappa_l^{abs} \left[\frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} - \frac{\bar{\omega}_l}{\tau_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \right], \end{aligned}$$

where q_l and κ_l^{abs} are the integrated water vapor (kg/m^2) and the mass absorption coefficient (m^2/kg) of the water vapor at layer l , respectively. By the same token, cloud water Jacobian can be derived as:

$$\begin{aligned} \frac{\partial \mathbf{I}_l(\mu)}{\partial w_l} &= \frac{\partial \tau_l}{\partial w_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} + \frac{\partial \bar{\omega}_l}{\partial w_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \\ &= \frac{\tau_l - \kappa_l^{abs} q_l}{w_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} + \frac{\bar{\omega}_l \kappa_l^{abs} q_l}{w_l \tau_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \end{aligned}$$

where w_l is the integrated cloud liquid water within layer l . Furthermore, the temperature Jacobian is

$$\begin{aligned} \frac{\partial \mathbf{I}_l(\mu)}{\partial T_l} &= \frac{\partial \mathbf{I}_l(\mu)}{\partial T_l} + \frac{\partial \tau_l}{\partial T_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} + \frac{\partial \bar{\omega}_l}{\partial T_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \\ &= \frac{\partial \mathbf{I}_l(\mu)}{\partial T_l} + q_l \frac{\partial \kappa_l^{abs}}{\partial T_l} \left[\frac{\partial \mathbf{I}_l(\mu)}{\partial \tau_l} - \frac{\bar{\omega}_l}{\tau_l} \frac{\partial \mathbf{I}_l(\mu)}{\partial \bar{\omega}_l} \right] \end{aligned}$$

where the derivative of the absorption coefficient relative to temperature is generally negligible at the

visible and infrared regimes while that at the microwave range can be either analytically derived or numerically evaluated. Thus, it is obvious that these Jacobians can be readily derived from a linear combination of the Jacobians relative to the optical thickness and single scattering albedo. Resulting computation time is significantly reduced.

Jacobian corresponding to various geophysical parameters can be also calculated using a finite differential technique that computes the radiance twice with one relative to the basic state and other corresponding to the perturbed condition. In this approach, for each perturbed parameter at a layer, the new calculations of all the optical parameters are required at other layers. Thus, the technique demands a huge computational resource. Further, the perturbation of each parameter should be small but large enough to produce the meaningful radiance difference at the computations. Strictly speaking, the ratio of radiance difference to the variable increment approaches the actual gradient when the increment approaches zero. In general, there is no criterion for selecting the perturbation magnitude. Thus, there is always an uncertainty in using the finite differential method for the radiance gradient calculation.

3. RESULTS

Figure 1 displays the vertical profiles of the optical thickness and single scattering albedo used for computations of solar reflectance and Jacobian profile at 0.67 micron. The profiles are similar to the aerosol optical parameters observed over deserts. Note that the altitude is extended to 50 km so that the conditions having a small optical thickness with a large perturbation can be also taken into account. In the computation, the surface albedo is set to 0.1 for the first Stokes component and zero for the rest.

Figure 2 shows the reflectance profiles of the first three components. Note that these components initially increase with height and become constant at 10 km. Also, the fourth component is zero and therefore not shown because of the uses of Rayleigh's phase matrix in the computation. Figure 3 displays Jacobian profiles of the optical thickness. Apparently, the sensitivity of the reflectance to the optical thickness is negative in the upper atmosphere above 10 km where the lower aerosols albedo results in more absorption to the solar radiation (see Fig. 1), but the sensitivity becomes positive in the atmosphere where the higher albedo yields more reflection. The second Stokes component is the least sensitive to the aerosol optical thickness throughout the atmosphere. It is very interesting to note that Jacobian profile of the third Stokes component is similar to that of the first component (Fig. 3). Thus, the first and third Stokes component measurements may provide the unique information on the aerosol properties (e.g. size distribution and composition) and identify the aerosol scattering from the surface.

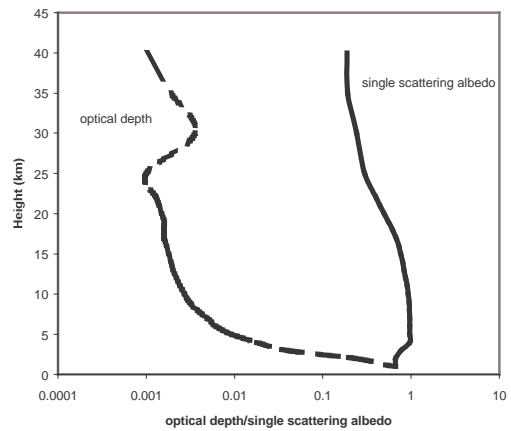


Fig. 1: Optical parameter profiles used for computing the Stokes component Jacobians

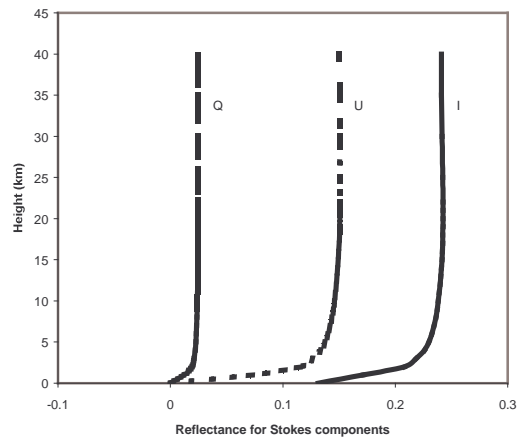


Fig. 2: Solar reflectance of Stokes components computed from VDISORT

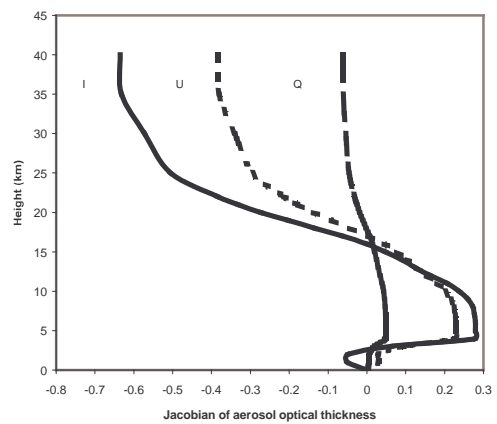


Fig. 3: Stokes component Jacobian of aerosol optical thickness computed from the analytic solution

4. SUMMARY

A new forward and adjoint radiative transfer scheme is developed from the multi-layer discrete ordinate method; and can be directly utilized for satellite data assimilation in numerical weather prediction (NWP) models. In the scheme, the effects of aerosol, cloud and precipitation emission and scattering, and the polarization from both surface and atmosphere on radiance and its Jacobian are explicitly taken into account. It is shown that the radiance from the present scheme is accurate, compared to the results from the doubling-adding technique. The Jacobians relative to various parameters are more accurate and computed faster than those from the finite differential method because they are all analytically related to the basic state parameters. In general, the current method reduces the computational time by a factor 10 to 100 when all radiative processes such as scattering and polarization are included.

References

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