1.9 ATMOSPHERIC RADIATIVE TRANSFER ADJOINT MODELS FOR THE REGIONAL ATMOSPHERIC MODELING AND DATA ASSIMILATION SYSTEM (RAMDAS)

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1. INTRODUCTION

Crucial to the development of any 4D variational (4DVAR) radiance assimilation system is evaluating the characteristics of the adjoints of the atmospheric radiative transfer (RT) models. These models are an essential part of a 4DVAR system because they provide the sensitivities of the simulated radiances to the dynamical model state variables. Both the forward and adjoint RT models comprise the so-called "observational operator".

A new 4DVAR system was recently created at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University (Vukicevic et al. 2001). Called the Regional Atmospheric Modeling and Data Assimilation System (RAMDAS), it is unique in that it will have the ability to incorporate both clear and cloudy satellite radiance data. RAMDAS uses as its forward dynamical model the Regional Atmospheric Modeling System (RAMS), a well-known mesoscale model that currently explicitly predicts clouds and precipitation species (Pielke et al. 1992; Walko et al. 1995; Meyers et al. 1997).

The main purpose of this paper is to describe the state of CIRA's RT modeling effort for RAMDAS with an emphasis on the adjoint modeling. The behavior of the adjoint models is examined under cloudy conditions. This is shown through specific examples of sensitivities of radiances to cloud microphysics as applied to the infrared channels of the Geostationary Operational Environmental Satellite (GOES) imager. Eventual plans are to use GOES imager data in future 4DVAR experiments with RAMDAS. Adjoint RT models for the shortwave channels of GOES are currently under development. It is hoped that results from these models will also be presented at the conference.

2. FORWARD RT MODELS

The forward RT models form the basis of the adjoint models that will be described in the following section. As defined here, the RT models include the RT solver (which solves the radiative transfer equation), cloud optical property models, and gas extinction model. Our strategy is to use different RT solvers depending on the problem at hand (Greenwald et al. 2001). At solar wavelengths the Spherical Harmonics Discrete Ordinate Method (SHDOM) is used (Evans 1998). This method is most often applied to 3D radiative transfer problems, but can also be used in 1D mode, which is how it is used here. SHDOM is far faster than traditional RT solvers and is very flexible, making it ideal for data assimilation systems. At infrared (IR) wavelengths we use an Eddington two-stream method (e.g., Deeter and Evans 1998). Two-stream models are faster than multi-stream models (such as SHDOM) with accuracies of generally under 1-2 K.

The cloud optical property models and gas extinction model provide the necessary linkage between the mesoscale model state variables (such as temperature, pressure, water vapor mixing ratio, and cloud water mixing ratio) and the radiance computed by the RT solver. Two cloud optical properties, namely extinction and single-scatter albedo, are derived from modified Anomalous Diffraction Theory (MADT, Mitchell 2000). The single-scatter albedo describes the probability of scatter, which ranges from 0 to 1. The third parameter, the asymmetry factor, describes the degree of forward scatter. This parameter is parameterized following the methods of Greenwald et al. (2001). Gas extinction is accounted for using the Optical Path TRANSmittance (OPTRAN) approach of McMillin et al. (1995).

RAMS uses a one-moment microphysical scheme to predict cloud liquid water mass (Walko et al. 1995). To form a continuous size distribution of droplets (which is required by the cloud optical property models) a gamma distribution is assumed. Droplet number concentration must also be specified. MADT requires temperature, pressure, and liquid mixing ratio from RAMS. OPTRAN requires temperature, pressure, and vapor mixing ratio.

The forward part of the observational operator has been completed for all GOES imager channels (see Table 1) for liquid clouds only. It is relatively straightforward to extend the system to include ice and precipitation species. This is planned for the near future. A parallel version of this system is currently working on a small cluster of PCs. For the most demanding application, which is computing radiances for channel 1, it took approximately 90 seconds (wall clock time) on 32 CPUs to compute a radiance field for a 122 x 162 grid with 50% cloud cover. The current configuration, however, has been found not to scale well with the number of CPUs. This is because the CPU load is not optimally distributed since it takes on average 10 times longer to do cloudy calculations than clear sky calculations. A load balancing approach will be implemented in the future to increase performance.

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TABLE 1. GOES Imager channel characteristics.

Channel	Wavelength Range (µm)	Effective Res. (km)	Description
1	0.52-0.74	0.57 x 1	Visible
2	3.79-4.04	2.3 x 4	Near-infrared
3	6.47-7.06	4 x 8	IR, upper tropospheric water vapor
4	10.2-11.2	2.3 x 4	IR window
5	11.6-12.5	2.3 x 4	IR window, boundary layer water vapor

3. ADJOINT RT MODELS

Adjoint models were created for each of the forward RT models described above. As mentioned previously, these models provide the gradient of the radiance with respect to the RAMS state variables. Since our focus is on the effect of microphysical properties on radiances, the gradient of the equivalent blackbody temperature (EBBT) at the top of the atmosphere with respect to cloud liquid mixing ratio (q_l) is of interest here:

$$\frac{dT_{ebb}}{dq_l} = \frac{dT_{ebb}}{d\beta_{ext}}\frac{d\beta_{ext}}{dq_l} + \frac{dT_{ebb}}{dg}\frac{dg}{dq_l} + \frac{dT_{ebb}}{d\omega_o}\frac{d\omega_o}{dq_l} \tag{1}$$

where the three terms in (1) are associated, respectively, with contributions from the three optical cloud optical properties: cloud extinction (β_{ext}), asymmetry factor (g), and single scatter albedo (ω_o). The left parts of each of these terms represent the sensitivities of the radiances to the optical properties, which are provided by the Eddington two-stream adjoint model. The right sides are the sensitivities of these optical properties to mixing ratio, where the MADT adjoint model gives the sensitivities for β_{ext} and ω_o, while the adjoint model of the Greenwald et al. (2001) parameterization provides the sensitivity for g.

4. RESULTS

The sensitivity analyses were applied to channels 3-5 of the GOES imager for three different cloud types selected from RAMS simulations conducted by Greenwald et al. (2001) for a continental stratocumulus system (see Figure 1). 50 meter vertical grid spacing was used in the boundary layer, with increasing spacing up to about 18 km. Two cases represent low-level clouds of varying mass, while the third is a mid-level cloud that also appeared in the northern part of the experiment domain.

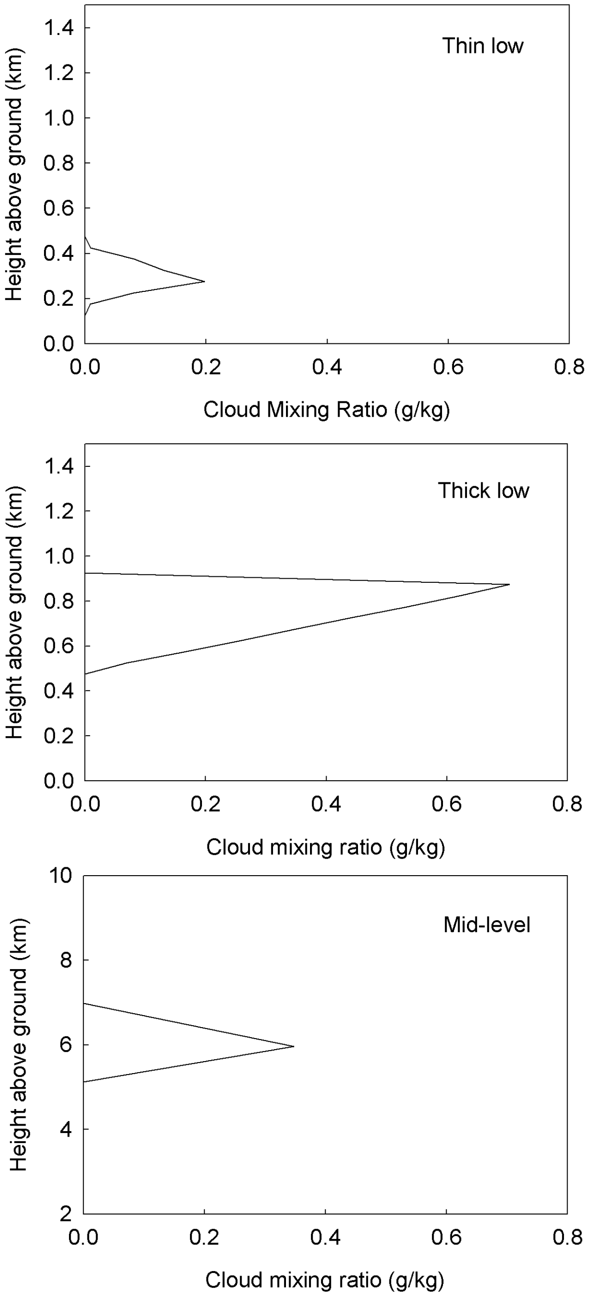


Fig. 1. Liquid mixing ratio profiles for the three cloud cases used in the adjoint model analysis.

Several assumptions were made regarding the droplet size distribution. A gamma distribution was used with a number concentration of 1.7 x 10^8 particles/kg and a distribution width parameter of 7 (Greenwald et al. 2001; Mitchell 2000), which are representative of these types of clouds. The resultant cloud optical depths for the three cloud cases are shown in Table 2 for channels 3-5. Optical depths for the mid-level cloud are larger than the thick low-level cloud, even though the mixing ratios are smaller, because the geometric thickness is greater.

TABLE 2. Cloud optical depths for each cloud type and selected GOES imager channels.

Cloud Type	Channel 3	Channel 4	Channel 5
Thin low	9.9	4.3	4.8
Thick low	38.7	24.8	24.0
Mid-level	46.6	27.6	27.3

Figure 2 shows the change in the top of the atmosphere EBBT given a 10% perturbation in q_l at each level of the thin cloud for all 3 channels. That is, (1) has been multipled by the perturbation to express the results in terms of temperature for easier interpretation. Channel 3 shows no change because this wavelength region is responsive only to atmospheric changes in the upper troposphere. Low clouds will essentially appear invisible.

Results for channel 4 reveal a complex behavior throughout the full depth of the cloud. The peak response occurs not at the level of maximum q_l but slightly above it. The asymmetry factor sensitivity is the greatest contributor to this peak (i.e., term 2 in (1)). A positive perturbation in EBBT occurs because a slight increase in the asymmetry factor means slightly more upwelling radiation from below is scattered up, hence increasing the radiance. At other levels of the cloud the extinction sensitivity (term 1 in (1)) appears to dominate but instead causes a negative response. A comparison of the adjoint results to sensitivities computed from the forward RT model (i.e., nonlinear model) shows good agreement, which suggests that the assumption of linearity is a good one in this case. Channel 5 results are similar to channel 4 except that the EBBT responses are reduced, possibly due to the effects of increased water vapor absorption at these wavelengths. We should emphasize that these results are only representative of a particular base state. As will be shown below, these results are expected to change for other base states.

In contrast to the thin cloud case, the thick cloud shows sensitivity restricted only to the cloud top (Figure 3). This occurs because for optically dense clouds, nearly all radiation upwelling from below cloud top is unable to reach the top of the atmosphere. Again, the asymmetry factor is the dominant contributor to the sensitivity but causes an even greater positive response in EBBT. The contributions from extinction and single scatter albedo tend to nearly cancel one another. Also, there are larger discrepancies with the nonlinear model indicating the linear assumption breaks down. This breakdown is attributed to the second part of term 2 in (1).

For the mid-level cloud a relatively small response is observed at channel 3 (Figure 4). The EBBT response is negative because the atmosphere is very opaque at this wavelength in the mid to upper troposphere, thus the cloud appears to emit at a greater height, hence colder temperature. In this case the adjoint model compares well with the nonlinear results. At channels 3 and 4 the behavior is very similar to the thick low cloud case, as might be expected, where the extinction and single-scatter albedo terms cancel out with the asymmetry factor term dominating. However, the magnitude of the EBBT response is somewhat greater than for the low cloud and there is a larger discrepancy with the nonlin-

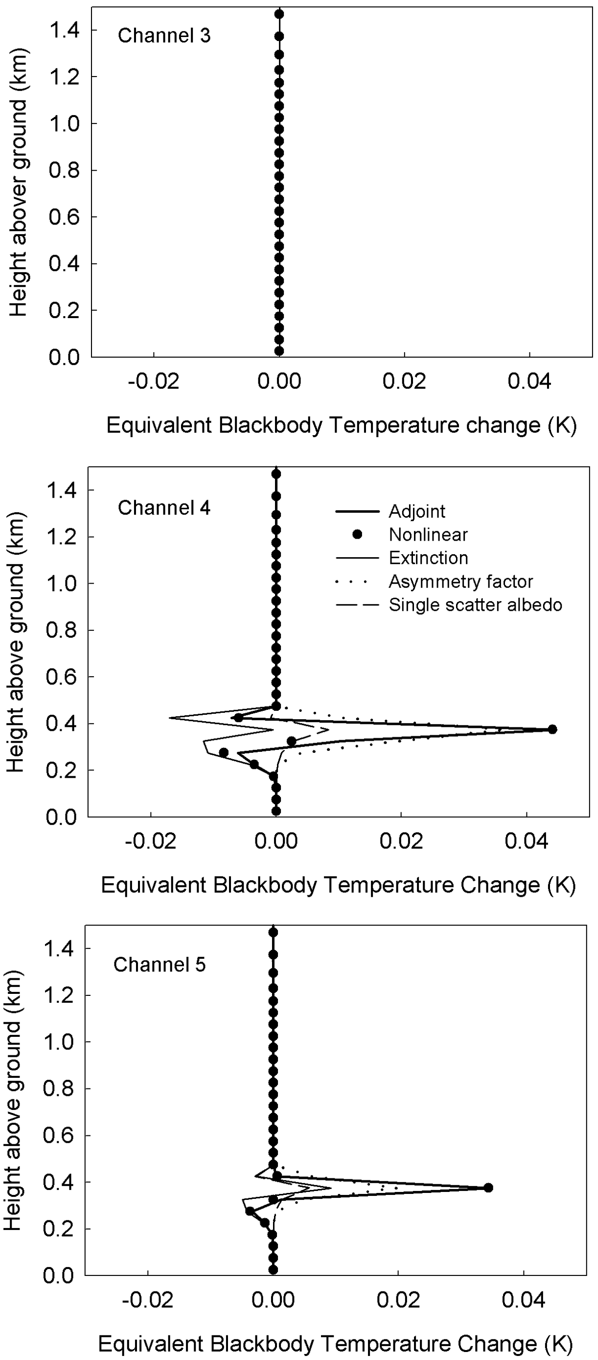
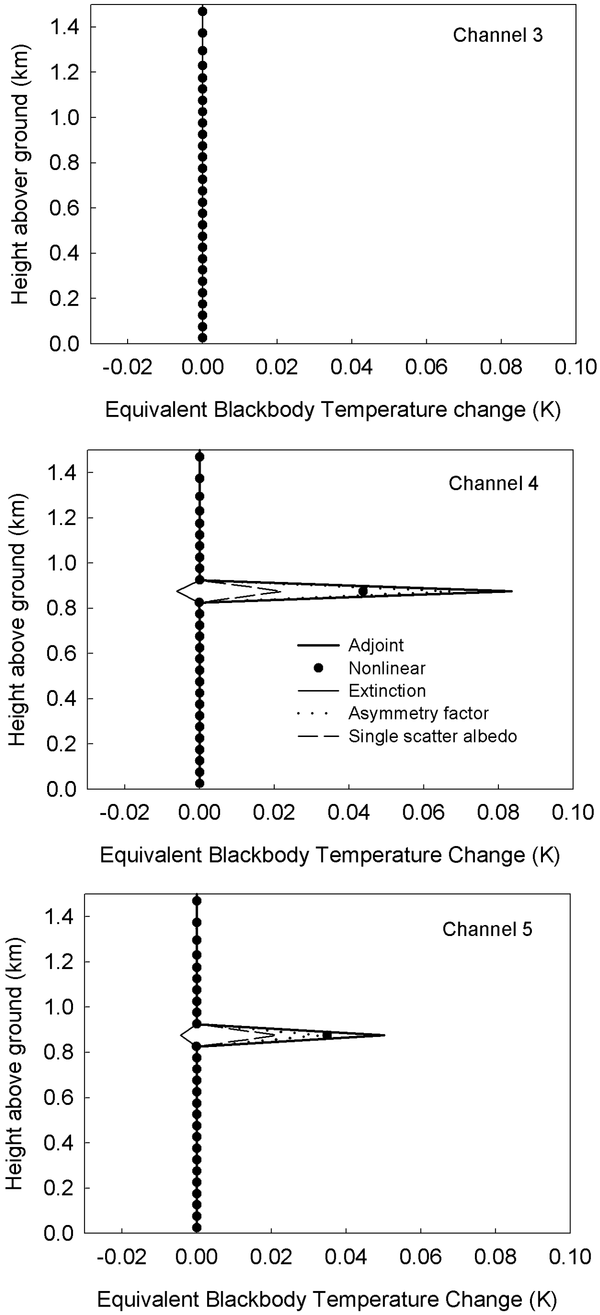


Fig. 2. Response of the top of the atmosphere equivalent blackbody temperature to a 10% change in cloud water mixing ratio at each level of the thin low cloud for three GOES imager channels. Also shown are results from the nonlinear models and the separate contributions from (1) for the adjoint models.

ear models, suggesting more nonlinearity in the physical processes.



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5. DISCUSSION

The satellite observational operator for a new 4DVAR system called RAMDAS has been described that allows, for the first time, the incorporation of cloudy satellite radiances. Currently the system is only applicable to water clouds for the GOES imager channels. However, application to satellite measurements at other visible/IR wavelengths will not involve the development of new models because the same RT solvers and cloud optical property models may be used. New coefficients, however, will be required for OPTRAN to account for gaseous absorption in the different spectral regions. Extension to cloud ice and precipitation species will be relatively straightforward because many of the same cloud optical property models, such as MADT, may also be implemented.

Examples of the sensitivities provided by the adjoint RT models were shown for the infrared GOES imager channels under different cloud conditions and tested against the nonlinear models. Of the different cloud types studied, the adjoint models best represented the sensitivities for optically thin clouds. The major finding is that the sensitivities of the radiances to the cloud mixing ratio depend greatly on the base state.

6. ACKNOWLEGMENTS

Support was provided by the Department of Defense under the Center for Geosciences/Atmospheric Research grant DAAL01-98-2-0078.

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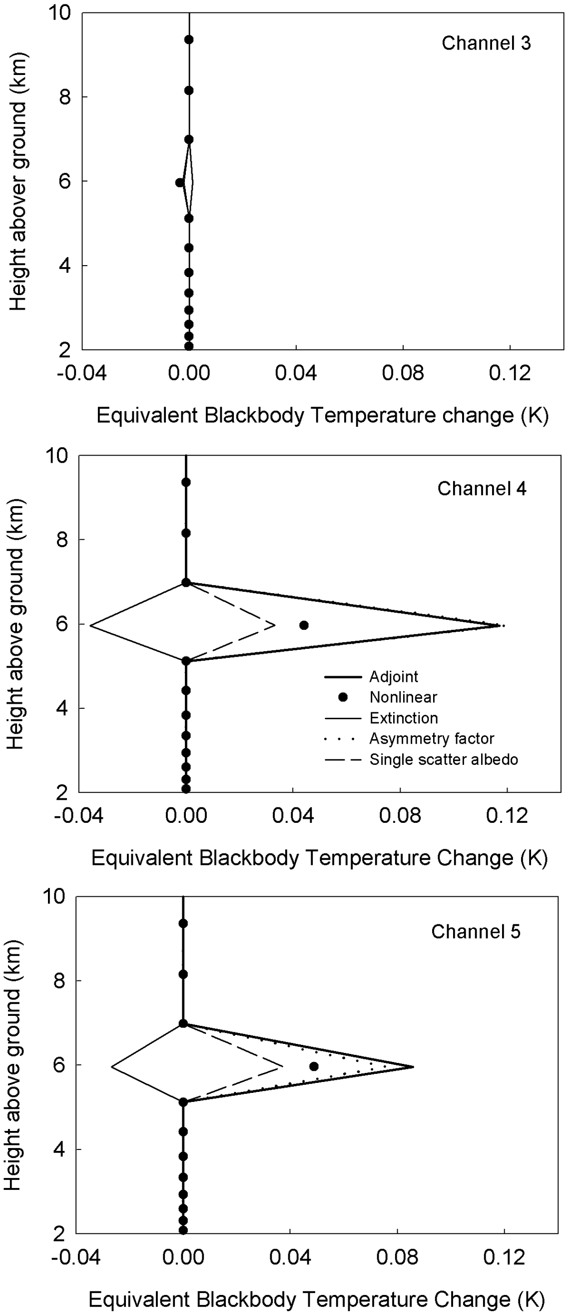

Fig. 4. Response of the top of the atmosphere equivalent blackbody temperature to a 10% change in cloud water mixing ratio at each level of the mid-level cloud at three GOES imager channels. Also shown are results from the nonlinear models and the separate contributions from (1) for the adjoint models.