Solar/IR Forward Modeling in Direct Cloud-Affected Radiance Assimilation: Status and Prospects

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Abstract

This paper summarizes the current state of forward radiative transfer modeling at solar and infrared (IR) wavelengths as it relates to operational assimilation of cloud-affected radiance data. It is suggested that certain aspects of current forward models are well established; however, outstanding issues remain. Ways to address some of these issues are offered.

1. Introduction

An essential part of any data assimilation system that directly assimilates cloud-affected radiances is the forward radiative transfer (RT) model, which provides the crucial link between the numerical weather prediction (NWP) model thermodynamics, microphysics, and surface boundary conditions with the top-of-atmosphere (TOA) radiance.

For many years, direct assimilation of radiances from satellite data has been limited to clear sky conditions. However, recent studies, both in research and operations, have begun to explore the assimilation of cloud-affected infrared radiances (e.g., Vukicevic et al., 2006; Heilliette and Garand 2007; Pavelin et al. 2008; McNally 2009; Zupanski et al. 2010; Otkin 2010). Due to the prohibitively slow calculation of RT radiances at solar wavelengths, the use of solar radiances has been explored only in research (Vukicevic et al., 2004). However, these wavelengths are where satellite measurements can potentially provide the most information to NWP models (Greenwald et al. 2004).

The purpose of this paper is to describe the current state of forward radiative transfer modeling as it relates to operational data assimilation and suggest possible directions for future work.

2. Observation operator

The observation operator, as its name implies, operates on NWP model state variables and transforms them into parameters with the same units as the observations, which in this case is radiance as seen by a space-based instrument. The operator is comprised of several different parts, although some parts are better known than others (Figure 1). For example, the development of gas absorption models and RT solvers (i.e., the solution method for the radiative transfer equation) has a long history, where several accurate and fast methods are available (e.g., Saunders et al. 2007; Heidinger et al. 2006). Others, like surface radiative properties (such as albedo and emissivity), cloud/precipitation single-scattering properties (especially ice), and cloud overlap are more uncertain and, thus, are considered the largest sources of error in the observation operator. (This paper, however, does not discuss the status of surface radiative properties.) There is also some question as to whether cloud overlap (i.e., subgrid variability of single-scattering properties and cloud cover and their effect on radiative transfer) should be part of the operator. According to the definition of the observation operator provided earlier, we will assume that it should be included.

The simplified schematic of the observation operator in Figure 1 ignores an important issue related to how radiance calculations are made across the bandpass of a given instrument channel, especially for parts of the spectrum where gas absorption varies greatly with wavelength, that can have a major impact on the accuracy of the calculations. Currently, within all operational data assimilation systems only one calculation per band is made for the simple reason is that it is too computationally expensive to do otherwise. Some mention of this issue will be made below; however, a full discussion is beyond scope of this paper.

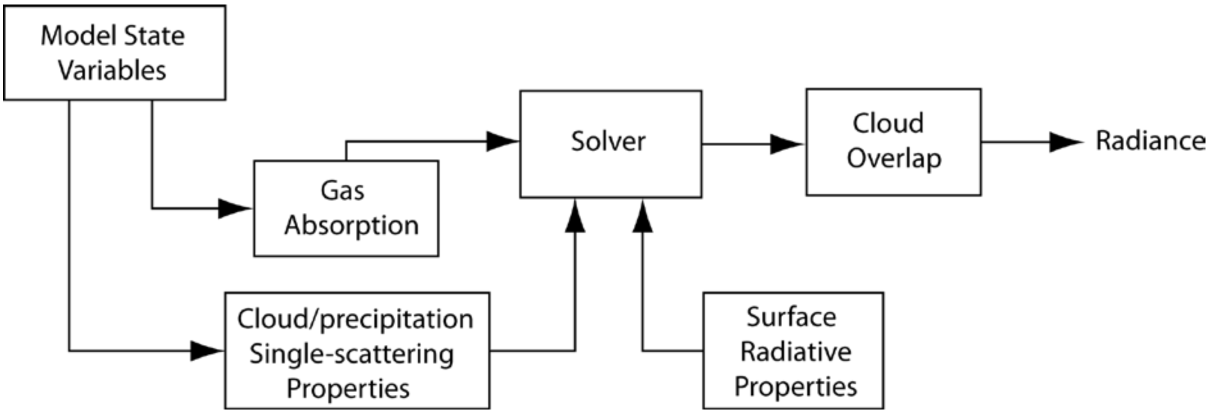

Fig. 1. Basic components of an observation operator.

3. Operational systems at IR wavelengths

Gas absorption models used in current operational systems, which provide effective band-weighted (by instrument spectral response function) gas layer optical depths, are regression methods done either on absorber amounts or fixed pressure levels. An example of the former is the Optical Path Transmittance (OPTRAN) approach, which is part of the U.S. Joint Center for Satellite Data Assimilation's Community Radiative Transfer Model (CRTM) (latest version is 2.0.2). Actually, the current CRTM uses a modified form of OPTRAN that is based on fewer predictors but has at least the same accuracy, called CompactOPTRAN. The latter, fixed pressure level method is the approach used in RTTOV (latest version is 9.1), which is used by ECMWF, Environment Canada, and other NWP centers. The main differences it has with OPTRAN are that the predictand is optical depth and NWP state variables must be interpolated to fixed pressure levels. A comparison of these methods (under clear sky conditions) has shown they agree to within 0.02 K of line-by-line calculations and within 0.2 K when compared to AIRS data (Saunders et al. 2007).

Some questions remain, however, as to whether the use of effective band-weighted gas optical depths can provide accurate band-averaged radiances in the presence of scattering. Several methods exist to provide efficient ways of accurately computing band-averaged radiances, such as optimal spectral sampling (OSS) (Moncet et al. 2008) and the *k*-distribution method (e.g., Bennartz and Fischer 2000). While these methods are impractical for present-day operational systems, they should be considered as viable options for future systems.

IR RT solvers fall into two main categories: those that approximate multiple scattering and those that explicitly calculate it. The former, which is used in RTTOV V9.1 and referred to as a “scaling approximation,” mimics the effect that multiple scattering would have on the radiances by adjusting or scaling the cloud single-scattering properties (optical depth, single-scatter albedo, and phase function). This approach has been shown to produce errors of less than 0.5-1K (except at shorter IR wavelengths), depending on cloud type. CRTM V2.0.2, on the other hand, uses a rigorous RT solver, a hybrid solver that uses the matrix-operator-method (Liu & Ruprecht 1996) to compute layer reflection/transmission properties and the adding method to compute radiances at each level of the atmosphere. There are no systematic published studies of the accuracy of this approach, however; the author’s own tests has shown the solver to be extremely fast with errors less than about 0.1 K across the IR spectrum for the 4-stream solution.

Investigators have dealt with subgrid clouds in various ways. For example, McNally (2009) avoids the problem by restricting the assimilation of cloud-affected IR observations to overcast conditions. Others have assumed various overlap schemes for subgrid clouds using either random overlap (Pavelin et al. 2008), which assumes that cloudiness in any layer is independent of cloudiness in other layers, or maximum-random overlap, which assumes that cloudiness in layers directly above and below a given layer is maximally overlapped, whereas cloud layers surrounded by clear air layers are randomly overlapped. In the context of parameterizations for broadband longwave fluxes, the maximum-random overlap scheme does not perform significantly better than either random or random-overcast schemes despite having 2.5 times the computational cost (Stephens et al. 2004).

The single-scattering properties of clouds and precipitation used in current operational systems are based on rigorous scattering calculations and presented in the form of lookup tables (LUTs). For water clouds, CRTM V2.0.2 and RTTOV V9.1 use LUTs based on Lorenz-Mie calculations. For ice clouds, RTTOV has the option of assigning either randomly oriented hexagonal columns or aggregates (Baran and Francis 2004). The CRTM, on the other hand, uses mixed-habit properties (Baum et al. 2005). Although the CRTM has the option to set the ice categories to ice, graupel, hail, and snow, these properties are technically only valid for the ice category. While these properties are deemed to be accurate, they have not been thoroughly tested for a variety of cloud systems or by satellite observations that would most likely be used in an assimilation system. However, an evaluation of CRTM V1.1 using CloudSat data and AVHRR band 4 (10.8 μm) observations showed that ice clouds had a bias of 2.2 K and standard deviation of 6 K (Chen et al. 2008).

4. Forward models at solar wavelengths

Because the assimilation of solar radiances from satellites is not done operationally, this section will review the current state of forward modeling at solar wavelengths.

CRTM V2.0.2 is believed to be the only operational code that allows for the calculation of solar radiances. As in the IR, CompactOPTRAN is used to compute effective band-averaged gas optical depths. However, an RTTOV-like approach (called ODPS) can be selected as well to compute these quantities. The RT solver for solar wavelengths is the same hybrid approach used in the IR. While the solver itself is very fast, calculations are slowed down significantly at these wavelengths due to the greater number of streams required and the calculation of additional terms to represent the azimuthal dependence of the radiation field. As in the IR, the cloud water single-scattering properties are provided in LUTs are based on Lorenz-Mie calculations. It is believed the ice properties are derived from the LUTs produced from Baum et al. (2005).

As mentioned earlier, methods that compute radiances based on band-averaged absorption quantities may be subject to errors in the presence of scattering. At solar wavelengths this is expected to be even more problematic. Again, OSS and *k*-distribution methods may be alternatives for providing more accurate calculations of radiance.

There are other options for RT solvers in the solar spectrum. The Spherical Harmonics Discrete Ordinate Method (SHDOM) has been proposed as one such solver for use in data assimilation (Greenwald et al. 2002; Evans 2007). Also, the SOI method has been extended to include the solar source term (Chris O'Dell, personal communication).

Issues related to cloud overlap have been studied in the context of broadband albedo but not for narrow-band radiances. Although all of the RT solvers proposed here are plane-parallel models, these models are more appropriate at larger spatial scales where cloud overlap dominates over 3D effects. However, at smaller spatial scales 3D effects will become dominant.

Finally, modified anomalous diffraction theory (MADT) has been proposed for both the solar and IR spectrum as a way to quickly compute cloud single-scattering properties (Greenwald et al. 2002, 2004). This approach is attractive because it is based on simple, yet physical, analytical relationships that do not have the drawbacks of LUTs, such as the need for interpolation and limits placed on the range of particle sizes. However, the accuracy of these properties is uncertain, particularly for ice particles. Other issues unique to the solar spectrum for cloud single-scattering properties are the effects of particle shape, orientation and roughness.

5. Summary and recommendations

The current state of solar/IR forward modeling in operational cloud-affected radiance data assimilation can be summarized as follows:

- Calculation of gas absorption has acceptable accuracy (at least in the IR and in non-scattering conditions)
- Several fast RT solvers exist but many operational systems use only approximate solution methods in the assimilation of cloud-affected IR radiances
- Various strategies have been used to account for cloud overlap in IR but systematic assessment of overlap assumptions are lacking
- Direct assimilation of solar measurements is not done operationally
    - ➢ Solvers are too slow (more streams needed + azimuthal terms)
    - ➢ Single-scattering properties are highly dependent on particle shape, orientation and roughness
    - ➢ Cloud overlap strategies specific to narrow-band radiances are lacking

Although it may be some time before cloud-affected solar radiances are used operationally, the following are possible ways to make use of these data but on a more limited basis:

- Relax the RT solver errors (reduce number of streams, etc.)
- Restrict to nadir measurements (azimuthal terms go away)
- Use neural networks to compute radiances
- Make use of particle absorption bands (1.6, 2.2, 3.9 μm) where scattering is less significant

A few recommendations for more effective use of forward RT models in data assimilation include:

- Infrared issues:
    - Encourage the use of rigorous solvers
    - A comparison study is needed to test the speed/accuracy of solvers
    - Explore methods like principal component analysis for hyperspectral and broader band applications to reduce computational demand (e.g., Liu et al. 2006)
- Solar and IR issues:
    - Further validation of certain observation operator components, especially cloud single-scattering properties (preferably IR & solar simultaneously; e.g., Barran and Francis 2004), and systematic testing of cloud overlap schemes is needed (e.g., Stephens et al. 2004)
    - Should quantify errors for methods that use effective band-averaged gas optical depths in scattering atmospheres and encourage the continued development of efficient, yet accurate methods for computing band-averaged radiances
    - Should make better use of existing solvers (e.g., finding ways of setting optimal number of streams automatically and selecting optimum solver for a given situation)

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6. References

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