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Numerical Weather Prediction Utilization of Cloud Affected Radiances – Progress So Far

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Abstract: Current and future operational high spectral resolution infrared sounding measurements are observing unprecedented information content about earth atmosphere and surface. The recent NWP centers have demonstrated the use of only fractional of clear radiances can improve 3 to 5 days of forecast by 6 hours (Le Marshall, et al., 2005) [1]. The cloudy radiances observed from the weather active areas, no doubt, can provide even richer information to further improve the forecast skill. This paper will review the progress that has been made so far for either indirect or direct assimilation of cloudy radiances in to NWP models.

Key-Words: Numerical Weather Prediction, Cloudy radiances, Data Assimilation, Forward Model

1 Introduction

Satellite infrared radiances, multispectral or hyperspectral, are greatly attenuated by clouds, aerosol, and dust within the line of sight of their observations. Recent studies reported by Smith et al., 2005 [2], and Huang and Smith, 2005 [3] indicate that the probability of finite field of view (fov) infrared sensors making clear sky measurements from space is inversely proportional to their fov size; there is a low probability cloud free observation when the fov size is large (Fig. 1). The planned operational hyperspectral sounders CrIS and IASI have fovs at nadir of 14 and 12 km, respectively. The probability of cloud free fovs within a 48 by 48 km area (the nadir field of view size of the accompanying microwave radiance measurement) are less than 30% for a single field of view (based on the MODIS cloud mask). The probability for the 48 by 48 km area to be cloud free is less than 5%. The probability for an AIRS fov 13.5 by 30 km to be fully clear is estimated at less than 10%. Therefore it is necessary to seek optimal approaches to correct for the influence of clouds in hyperspectral sounding radiances.

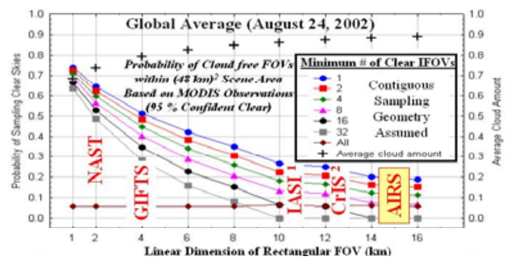

Fig. 1: Probability of sampling clear air as a function of fov size. IASI is circular with a diameter of 12 km, CrIS is circular with a diameter of 14 km, GIFTS is square with 4 km along a side, AIRS is elliptical with 13.5 by 30 km, and NAST-I is circular with diameter of 2 km.

Huang and Smith [3] noted that cloud clearing is an indirect approach to enable use of measurements corrected for cloud contamination; the cloud cleared observations represent clear sky atmospheric conditions either within or alongside partly cloudy areas. There is a potential of biasing the NWP model towards clear sky conditions if cloud-cleared radiances are used. They compared a single day of ECMWF analysis and AIRS science team sounding retrieval profiles to demonstrate this point; Figures 2 and 3 show one day of ECMWF global analysis data (129960 profiles, half of the total available profiles) and all available AIRS science team retrieval profiles taken during the same day (2 September 2003) respectively.

Global temperature structures are distinctly different under regions covered by clouds. Unlike the ECMWF analysis, the AIRS cloud cleared radiance temperature retrieval structure shows no distinction between clear and cloud cleared regions. This is precisely what cloud clearing is designed to achieve, that is, to produce retrievals of temperature profiles for the clear portion of the partly cloudy sky. However there is a consequence of representing the whole globe without clouds; this will bias the model fields when NWP models are provided only clear sky atmospheric profiles, through the assimilation of cloud-cleared radiances or their respected retrievals.

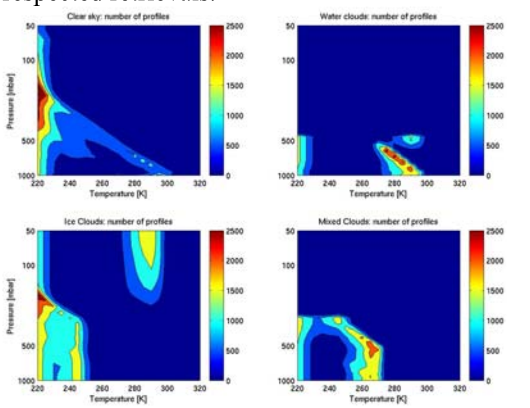

Fig. 2: Color contour histograms of ECMWF global temperature classified into (a) clear (upper left), (b) water cloud (upper right), (c) ice cloud (lower left) and (d) mixed phase (lower right) cloud according cloud information flag recorded in the analysis data file.

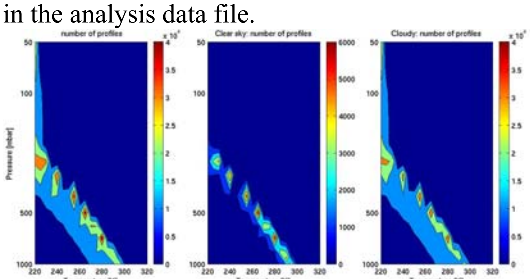

Fig. 3: Color contour histogram of AIRS science team standard temperature retrieval classified into (a) all (clear and cloud cleared combined, left panel), (b) clear (middle panel), and (c) cloud cleared (right panel) in the retrieval data file.

The same conclusion has been drawn when Huang and Smith compared the clear and cloudy water vapor profiles from the ECMWF analysis with the AIRS science team cloud-cleared retrievals (not shown). The clear water vapor profiles are vastly different from those associated with water, ice and mixed phase cloud conditions. NWP model assimilation of cloud cleared water vapor radiances tends to produce a clear sky bias.

As alternatives to the cloud-clearing approach, Smith, et al., 2005 [2] offered two other ways to extract profile information from cloud contaminated radiances: (1) retrieval based upon the assumption of opaque cloud conditions, and (2) retrieval or radiance assimilation using a physically correct cloud radiative transfer model which accounts for the absorption and scattering of the radiance observed. Using NAST-I (NPOESS Airborne Sounder Testbed - Infrared) data they demonstrated under opaque cloud conditions retrieval of the correct atmospheric profile above the cloud top level and retrieval of a fictitious isothermal, and saturated, profile below the cloud top level. The abrupt change in vertical temperature lapse rate enables one to determine the cloud level. If the clouds are high and there is significant spectral structure in the absorption of the clouds (i.e., a common characteristic of cirrus clouds), errors in the profiles above the clouds might occur. Thus for high cloud cases, a more realistic cloud model is required to get accurate profiles down to the cloud top level. If the cloud is semi-transparent or broken, the profile below the cloud level should be retrievable using a physically based cloud radiative transfer model.

2 Modeling of Cloud Microphysical Properties

Yang et al [4] calculated single scattering properties of clouds using rigorous composite models, such as the finite-difference time-domain (FDTD) technique, the T-matrix method and an improved geometric optics method (IGOM) for non-spherical ice crystals, and the Lorenz-Mie solution for “equivalent” ice spheres. The principles of geometric optics can be applied to obtain the scattering properties of a particle whose size is much larger than the incident wavelength. The total scattered field can be assumed to consist of the diffracted waves and the reflected and refracted rays. But, this approach has a number of inherent shortcomings. First, the extinction efficiency of a particle is assumed to be 2 regardless of size parameter. Second, the vector properties of the electromagnetic field are not completely accounted for because the Frauenhofer diffraction formulation in the context of geometric ray tracing is in a scalar form. Third, calculation of the far field by using the ray-tracing procedures will produce a discontinuous distribution of the scattered energy, such as the delta transmission produced by the 0° refraction associated with two parallel prismatic faces in ice particles such as plates. Because of these shortcomings, the conventional ray-tracing method breaks down at size parameters (the size of the particles 2Πr in comparison to the wavelength of the incident radiation λ) of 50 or 100, depending on whether the cross section or phase function is computed. To overcome the disadvantages of the conventional ray tracing, they use the improved geometric optics method (IGOM) developed by Yang and Liou [5]. In this method, the ray-tracing technique is applied to solve for the near-field at the surface of the scattering particle, which is mapped subsequently to the far-field on the basis of a rigorous electromagnetic relationship between the near-field and the far-field.

Based on the preceding computational methods, the single-scattering properties were computed for aggregates, hexagonal solid and hollow columns, hexagonal plates, bullet-rosettes, and droxtals at 49 wavelengths within the wavelength spectrum ranging from 3.08 μm to 100 μm by Yang et al. (2004). At each wavelength, computations were made for 38 particle-size bins ranging from 2 μm to 3100 μm specified in terms of the maximum dimension. The results can be interpolated to a high spectral resolution. In Figure 4 Yang et al. show the variation of the single-scattering properties for these various habits as a function of the particle maximum dimension at a wavelength of 8.5 μm. The locations and amplitudes of extinction and absorption maxima are sensitive to ice crystal habit. The single scattering properties of these ice particles converge to the asymptotic limits given by the geometric optics solution when the maximum dimension is greater than 1000 μm. For example, the extinction efficiencies converge to 2 when the scattering particle is large.

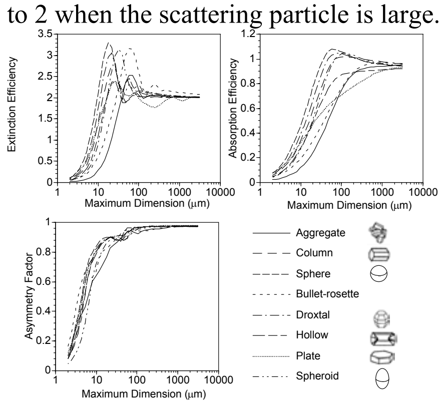

Fig. 4: Single-scattering properties of different ice crystals vs. maximum dimension at wavelength of 8.5 μm (after Yang et al.).

Figure 5 demonstrates the variation of the ice habit single-scattering properties as a function of wavenumber for a particle maximum dimension of 10 μm. The extinction and absorption efficiencies are related to the refractive index (real part and imaginary part) of ice. The asymmetry factor increases with wavenumber because the size parameter also increases with wavenumber.

The differences of the single-scattering properties between the different habits are relatively small if the values in Figures 4 and 5 are plotted as a function of effective particle size instead of maximum dimension of the ice crystal. Here the effective particle size of a crystal is defined as 1.5 times of the ratio of the ice crystal's volume to its projected area. The scattering properties of the individual habits are still different over a wide range of particle sizes no matter how the effective size is defined.

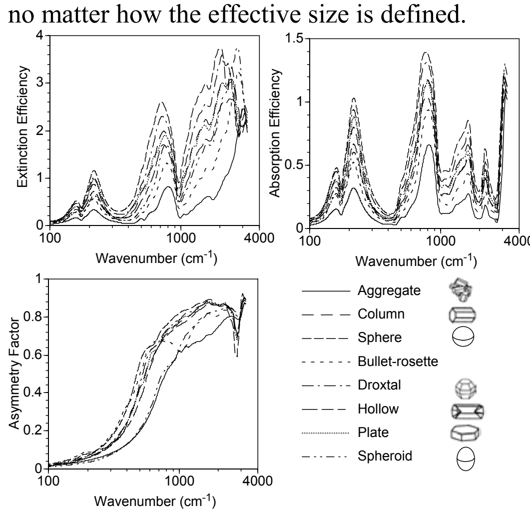

Fig. 5: The single-scattering properties of different ice crystals vs. wavenumber (Maximum Dimension of 10 μm) (after Yang et al.).

Yang has also developed a forward computational program to generate the bulk optical properties of water clouds. This forward computational program is used to generate the optical thickness, single-scattering albedo, and asymmetry factor of the phase function for spectral regions 685-1130 and 1650-2250 cm^{-1} for given droplet effective size, liquid water content (LWC), and cloud physical thickness.

Ongoing cloud microphysical property modeling efforts continue to improve the methodology for computing the single-scattering properties of ice crystals and aerosol particles; particularly, by enhancing a library of the single-scattering properties of ice clouds. The enhanced data library will include the high spectral resolution single-scattering properties (extinction efficiency, absorption efficiency, asymmetry factor, and phase function) of ice crystals with a wide size range (from 1µm to 3000 µm in maximum dimension) covering the wavelength range of traditional IR band (685-2250 cm^{-1}) with the ice crystal habits of bullet rosette, solid and hollow hexagonal column, plate, aggregate and droxtal. The bulk single-scattering properties are derived on the basis of the realistic size distributions for ice clouds. The bulk single-scattering properties of cloud and aerosol particles will be parameterized in a manner suitable for current and future hyperspectral sounder applications.

Combining the line-by-line atmospheric absorption model, the DIScrete Ordinates Radiative Transfer (DISORT) model and the parameterized single-scattering properties, CIMSS/UW-Madison and Texas A&M are continuing to study the sensitivity of the hyperspectral sounder IR spectral radiances to cloud properties. They are also investigating the influence of aerosols on the forward radiance simulation and improving fast cloud radiance model by including more realistic cloud optical properties.

More recently Bryan Baum of NASA LaRC has developed a comprehensive bulk scattering models available for multiple instruments including MODIS, AVHRR, AATSR, MISR, VIRS, MAS, ABI, POLDER, and SEVIRI. The bulk properties (mean and standard deviation) evenly spaced in effective diameter from 10 to 180 microns for asymmetry factor, phase function, single-scattering albedo, extinction efficiency and cross sections, ice water content and mean diameter. These models are available at http://www.ssec.wisc.edu/~baum.

3 Modeling of Fast Clear and Cloudy Radiative Transfer Process

Integrating gases, clouds, and aerosol/dust absorption, scattering and extinction effects in a fast and accurate radiative transfer model is the fundamental step towards the direct assimilation of cloudy radiances in NWP model. To account for the cloud signal, a rapid and accurate cloudy radiative transfer model has been developed to simulate the radiances and brightness temperatures over a broad spectral band (~3-100µm). The principal purpose of this effort is to generate cloudy radiances over large spatial domains for realistic surface and atmospheric cloud states to assist in retrieval algorithm development for next-generation hyperspectral IR sensors.

The representation of clouds is achieved by:

- A single cloud layer (either ice or liquid) is inserted at a pressure level specified in the input profile.
- Spectral transmittance and reflectance for ice and liquid clouds interpolated from a multi-dimensional lookup table.
- Spectral wavenumber range (500 – 2500 1/cm)
- Observation zenith angle range (0 – 80 deg)
- Effective particle diameter range (ICE: 10 – 157 um, LIQUID: 2 – 100 um)
- Visible optical depth range (ICE: 0.04 - 100, LIQUID 0.06 – 150)

The radiative transfer approximation of a single cloud layer model is briefly described in Figure 6. The cloud radiative signature is parameterized by transmission and reflectance terms that account for the absorption and multiple scattering effects.

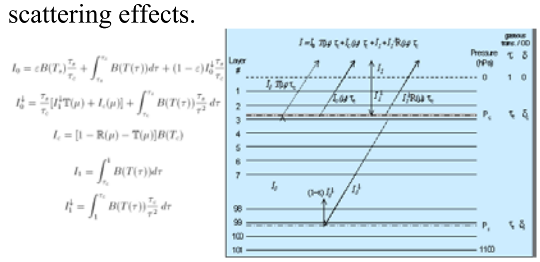

Fig. 6: Radiative transfer approximation of single cloud layer model.

The single layer cloud model is further extended to include ice over water cloud conditions and is under rigorous evaluation and refinement.

Using the fast cloudy forward model, a simulation was developed producing spectra of clear, ice and water clouds. The simulation configurations conducted are:

- Clear sky conditions assuming different surface emissivities
- Liquid cloud of optical depth 5 with effective diameter of 10 µm located at 500 hPa
- Ice cloud of optical depth 5 with effective diameter of 30 µm located at 200 hPa.

These spectra are shown in Figure 7; distinct spectral signatures are evident.

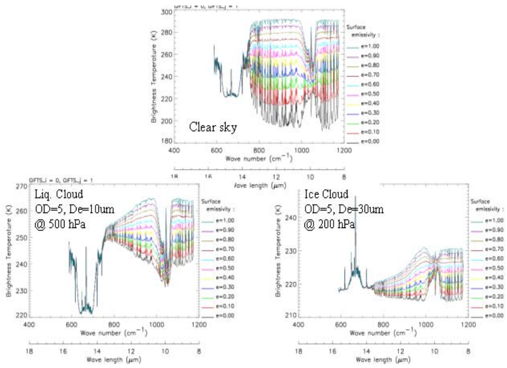

Figure 7: Example spectra of clear sky (upper middle), liquid cloud (lower left), and ice cloud (lower right) generated from the fast cloudy forward model.

Beyond cloud parameterization and fast forward model development, an aerosol/dust database required to model microphysical properties is also under development.

A fast two-layer cloudy forward model is also being developed by the scientists of CIMSS/SSEC at UW-Madison. A manuscript that documents their approach and performance is under preparation.

4 Progress So Far and Summary

In summary, accounting for clouds adequately so that cloud affected radiances can be assimilated in numerical weather prediction models still requires some work. Current infrared sounders with fov size greater than 14 km are likely to make cloud free measurements less than 5 to 10 % of the time. To improve the use of hyperspectral sounding data in numerical weather prediction model and generation of environmental and atmospheric products one must find ways to efficiently account for the effect of clouds. Unfortunately clouds greatly complicate the processing of hyperspectral infrared sounding data and, at present, a complete physical treatment of clouds is prohibitive. Progress is being made in modeling cloud microphysical properties, generating fast and accurate cloudy radiative transfer model, and assimilating cloudy radiances directly and indirectly. Direct and indirect assimilation of cloudy radiances are still pending.

Using AIRS cloudy data Huang et al. [3] have shown that spectral signatures of clouds are compounded by, not only the atmospheric variations (vertical inversion, horizontal temperature and water vapor gradient, solar reflection, etc), but also cloud in-homogeneity (multiple cloud layers and mixed phase sub-pixel elements), surface effects (spectral variation of surface emissivity and reflectivity) and local thermodynamic non-equilibrium.

Cloud clearing extrapolates clear sky spectral radiances from cloudy spectra with differing cloud contamination. The AIRS/AMSU cloud clearing performance was compared with a synergistic AIRS and MODIS approach by Huang et al. [6], Li et al. [7], Guan et al. [8], and Smith et al. [9]. Over ocean, the AIRS/AMSU cloud clearing performs in a reasonable manner; the bias and root mean square error of cloud cleared radiances compare favorably with nearby "cloud free" AIRS radiances used as the "clear truth" (i.e., within a factor of two). However, AIRS/AMSU cloud clearing retrieval over land suffers from the surface effects (infrared emissivity and solar reflection). Case studies over land (especially over desert) demonstrate the advantages and disadvantages of both AIRS/AMSU and AIRS/MODIS synergistic approaches. A preliminary analysis showed large biases and root mean square errors over land areas using the AIRS/AMSU approach. The AIRS/MODIS approach seems to be able to produce cloud cleared radiances much more reliably with smaller bias and random error.

While major efforts and advances have been made in the AIRS/AMSU and, more recently, the AIRS/MODIS cloud clearing retrieval [7], cloud clearing by definition accounts for the cloud effects with a clear sky replacement strategy. Cloud cleared radiances and their associated sounding profiles, in practice, cannot represent cloudy sky sounding nor should be directly assimilated into a numerical weather model without the necessary ancillary cloud information. The example single day of ECMWF analysis and AIRS/AMSU cloud cleared retrieval profiles, shown by Huang and Smith [3], have demonstrated the argument that AIRS/AMSU cloud cleared sounding profile, both temperature and water vapor, are distinctly different from the cloudy profiles exhibited by the ECMWF analysis. Replacing the whole globe of cloudy profiles with cloud cleared profiles, without the benefit of ancillary cloud property data, is essentially providing the NWP model with initial states not consistent with the truth.

The need for improving the AIRS data usage in numerical weather prediction models and the coverage in global sounding retrievals is urgent. Novel approaches to the assimilation of cloudy infrared radiances need to be developed. At present University of Wisconsin-Madison is partnering with Texas A&M University to develop a physically based fast parameterized cloudy infrared hyperspectral forward model that is both fast and sufficiently accurate to allow future direct assimilation and retrieval of cloudy data without other preprocessing such as cloud clearing. Preliminary cloud microphysical parameterization approach (Yang et al., 2001 [11] and 2004 [4]) are summarized by Huang and Smith as:

Cloud single scattering properties are computed by rigorous composite models, such as the finite-difference time-domain (FDTD) technique, the T-matrix method and an improved geometric optics method (IGOM) for nonspherical ice crystals, and the Lorenz-Mie solution for "equivalent" ice spheres. Seven ice crystal habits (aggregate, hexagonal column, hexagonal plate, bullet rosette, hexagonal hollow column, spheroid, and droxtal) are considered.

A database of the single-scattering properties of ice crystals at the infrared spectrum, from 3 to 100 µm, and a particle size spectrum from 2 µm to 10000 µm in terms of the particle maximum dimension are generated. Parameterized cloud transmissivity and reflectivity are derived to account for the multiple scattering effects due to clouds. Fast infrared gaseous absorption forward model is modified to include cloud transmissivity and reflectivity to form fast parameterized cloudy model.

"True" cloudy forward model calculations are performed by LBLRTM follow by the DISORT multiple scattering to accurately account for both gases and clouds effects in deriving the top of atmosphere radiances to characterize the accuracy of the fast parameterized cloudy forward model.

Fast cloudy forward model performance is estimated by the comparison of the differences between the cloud radiances of this fast model and the "true" model.

Improved cloud parameterization will be necessary if testing against the "true" model shows difference above NWP threshold requirements.

Initial application of these cloud radiative transfer models to AIRS retrievals has already been conducted by Smith et al 2004 [2] and rigorous study is underway to demonstrate the practical utility of such an approach.

Huang and Smith, 2004 [3] have summarized that direct and indirect assimilation of cloudy radiances is possible. For the indirect method, cloud cleared radiances potentially create a clear sky bias that negatively impacts NWP analyses and forecasts. In the direct method, a parameterized cloudy forward model that is both fast and accurate is needed. A significant research and development effort is still needed in order to implement a method for the direct assimilation of cloud contaminated radiance observations. Although so far both one-layer and two-layer fast cloudy forward model are under development, the limitation of the accuracy of the fast cloudy sky radiative transfer model and its practical application into the radiance assimilation process still require considerable study and attention. The validation of these cloudy fast models remains a major challenge.

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