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1. Introduction

The presence of clouds and precipitation indicates that some dynamically important weather is occurring. The correspondence of cloud and precipitation occurrence with regions of high forecast sensitivity suggests that improving initial conditions in cloudy and precipitating regions is particularly important for advancing the skill of numerical weather prediction systems. Remote sensing now provides critical observations for analyzing the atmosphere. The propagation of infrared or microwave radiation is strongly affected by detailed properties of clouds or precipitation including shape and size distribution of hydrometeors. Thus retrieving temperature and moisture fields from radiance observations in the presence of clouds and precipitation is sensitive to the characterization of these details. Since such details currently are neither analyzed nor modeled well, about half of all current radiance observations suspected of being affected by cloud have been discarded (Errico et al. 2007).

Recently, several operational institutes have been making efforts to use cloud and precipitation affected radiances in data assimilation systems. Most of them are based on variational schemes. The objective of this report is to compare approaches to the assimilation of cloud-affected microwave radiances in state-of-the art data assimilation systems in National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP), Met Office, the European Center for Medium range Weather Forecasting (ECMWF), and Japan Meteorological Agency (JMA). Particular focus will be given to differences in the radiative transfer model (Section 2), cloud and rain screening procedures (Section 3), increments and preliminary impact study results are summarized (Section 4).

2. Radiative Transfer Models

The radiative transfer model employed for radiance data assimilation system in NOAA NCEP Global Data Assimilation System (GDAS) is the Community Radiative Transfer Model (CRTM) while ECMWF and Met Office employ Radiative Transfer for TOVS (RTTOV).

2.1 CRTM

The Joint Center for Satellite Data Assimilation (JCSDA) has developed the CRTM which calculates radiances and jacobians in GDAS (Han et al. 2005). Figure 1 shows the schematic diagram of the CRTM major components.

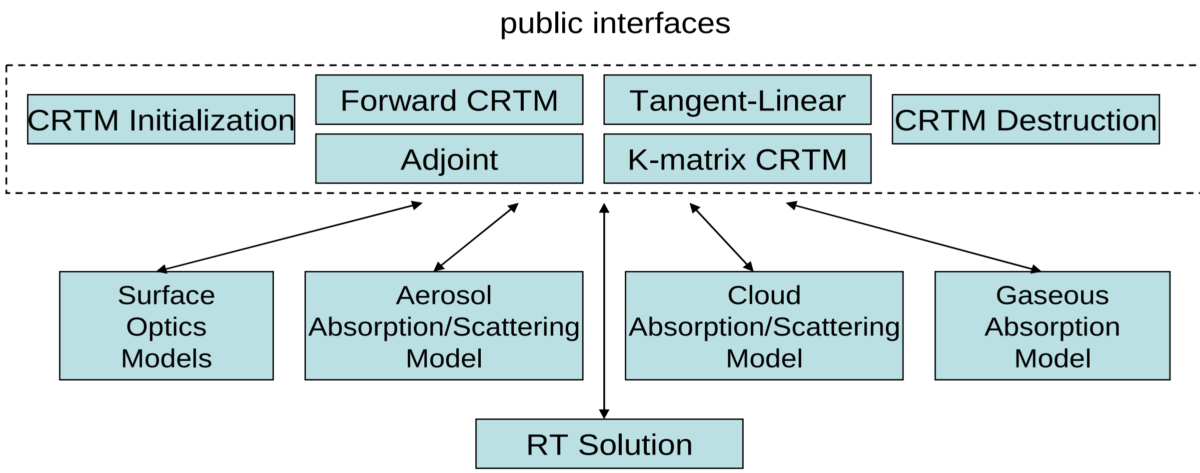

Figure 1. Schematic diagram of CRTM major components

The CRTM public interface consists primarily of a set of user callable routines (Fortran95 functions and subroutines). For example, the CRTM initialization routine is called to load a set of CRTM data files, which define the set of sensors and channels to be covered in the subsequent calls to the CRTM Forward and K_Matrix (Jacobians) models, and when the model calculations are completed the CRTM destruction routine is called to release the memory occupied by CRTM.

Gaseous absorption model component computes gaseous optical depth profile. Currently it is implemented with the compact version of OPTRAN (Optical Path TRANsmittance), due to high efficiency in using computer memory and improved Jacobians. OPTRAN currently treats water vapor and ozone as the only variable gases and other absorbing gases as "fixed" gases.

A collection of surface emissivity/reflectivity models are implemented in this version of CRTM. The following is a list of the surface emissivity/reflectivity models.

Microwave:

- Land – LandEM (Weng et al., 2001)
- Snow and sea ice – (Yan et al. 2004, 2008). For some sensors it offers improved calculations if brightness temperature observations at specified channels are provided.
- Ocean, FASTEM – (English and Hewison, 1998)
- Ocean emissivity at low frequency – (Kazumori et al., 2008)
- Ocean polarimetric model – (Liu and Weng, 2003)

Infrared:

- Ocean – IRSSE (Wu-Smith, 1997)
- Land – measurement database for 24 surface types (NPOESS, Net Heat Flux ATBD, 2001)

In addition, the user may pass his/her own emissivity values to CRTM through the optional arguments of the user interface.

The RT solution module solves radiative transfer equation. It is currently implemented with the Advanced Double-Adding (ADA) method. (Liu and Weng, 2006).

Spherical scatterers are used for liquid and ice clouds in the infrared and microwave ranges. A look-up table contains the extinction coefficients, single scattering albedos, asymmetry factors, delta truncation factors for removing forward peaks, and expansion coefficients from Mie calculations. The look-up table contains also the extinction coefficients, single scattering albedos, asymmetry factors for non-spherical particles of cirrus clouds in the infrared range. This model first reads these coefficients and scattering properties from a lookup table. The lookup table includes the Mie computation results for 31 frequencies (1.4 GHz and 190.31 GHz), 6 radii (10 um – 1 mm) for MW and 701 frequencies (102-2902 cm^{-1}), 6 radius (5 um – 100um) for IR at 3 density (0.1, 0.4, and 0.9 g/cm^3) and 5 temperature ranges (263.16, 273.16, 282, 290, and 300K).

All MW and IR liquid phase and solid phase with the density < 0.9 g/cm^3 are generated using a MIE code (Simmer, 1994). IR solid phase with the density = 0.9 g/cm^3 is adopted from non-spherical particle of Ping Yang (Liou and Yang, 1995). The asymmetry factor for non-spherical particles is used for the phase function.

2.2 RTTOV

The Radiative Transfer for TIROS Operational Vertical Sounder (RTTOV) radiative transfer model is a fast regression model designed for use in data assimilation and retrieval system dealing with passive infrared and microwave sounders. RTTOV computes brightness temperatures from atmospheric state variables input on 43 fixed pressure levels between 0.1 and 1013 hPa (Pavelin et al. 2008).

Currently RTTOV-9, which includes emission and IR scattering from cloud in radiative transfer process, is released to public. RTTOV-Scat, which use lookup table for scattering parameters to include microwave scattering effect from cloud, has been publicly available and will be merged in RTTOV-10.

3. Cloud and rain screening procedures

3.1 NCEP

The current operational system doesn't assimilate microwave radiances affected by thick cloud and/or precipitation. The cloud and precipitation screening procedure for microwave radiance observations in the current GDAS is summarized here.

AMSU-A:

The degree of non-precipitating cloud effect is determined by channel 4 related parameter, factch4 from an empirical relationship:

$$\text{factch4} = \text{clw} **2 + [(\text{tb}_o^{ch4} - \text{tb}_c^{ch4}) * 3]**2$$

Similarly, the degree of precipitating cloud effect is determined by channel 6 related parameter factch6 from another empirical relationship:

$$\text{factch6} = \text{dsval}**2 + [(tb_o^{ch6} - tb_c^{ch6})*0.1]**2$$

where tb_o is observed brightness temperature after bias correction and tb_c is computed brightness temperature with first guess profiles for cloud cleared sky. The gradient of scattering index, dsval is determined depending on the surface type.

$$\text{dsval} = \{[2.41 - 0.0098*(tb_o^{ch1} - cbias_{nadir}^{ch1})]*(tb_o^{ch1} - tb_c^{ch1}) + 0.454*(tb_o^{ch2} - tb_c^{ch2}) - (tb_o^{ch15} - tb_c^{ch15})\}*0.1$$

for sea surface and dsval = 0.8 for land

If factch6 ≥1, the observation is considered affected by precipitation and screened out. If factch4 > 0.5, the observation is considered affected by thick cloud and screened out.

SSM/I and AMSR-E:

Observation data are being employed only over the ocean. If retrieved cloud water amount is greater than criteria depending on instrument and channels, the observations are considered cloud contaminated and screened out. The followings are the cut off criterion [kg/m^2]:

0.35(ch1), 0.35(ch1), 0.27(ch3), 0.10(ch4), 0.10(ch5), 0.024(ch6), 0.024(ch7) for SSM/I
0.35(ch1), 0.35(ch2), 0.35(ch3), 0.35(ch4), 0.3(ch5), 0.3(ch6), 0.25(ch7), 0.25(ch8), 0.1(ch9), 0.1(ch10), 0.02(ch11), 0.02(ch12) for AMSR-E

3.2 Met Office

In the Met Office operational NWP system, satellite radiances are subjected to an initial 1D-Var processing stage before being passed to the 4D-Var data assimilation system.

The Met Office is currently preparing to put the cloudy radiance data observed by AMSU-A channel 1 and channel 2 over ocean (except between 20°S and 20°N) in the operation in near future. Data are subjected to an initial 1D-Var processing stage before being passed to the 4D-Var system. At first, AMSU-A radiance observations go through 1D-Var quality control process. The soundings that do not converge within the cloudy 1D-Var framework are screened out before they passed to 4D-Var. The moisture control variable of the cloudy radiance assimilation system is qtotal (= q + clw+ciw) and does not include precipitation. If the 1D-Var quality control process determines the cloud is precipitating cloud by scattering signal, the observations are screened out.

3.3 ECMWF

1D+ 4D-Var assimilation of SSM/I cloudy and rainy radiances has been running in operational mode at ECMWF since June 2005. In the prescreening process, liquid water path (LWP) is estimated by SSM/I 22GHz (v) and 37 GHz (v) Tb observations and rain amount is estimated by Tb differences between 37GHz (V) and 37 GHz (H). If LWP and/or rain water amount exists, observations go through 1D variational retrieval process, otherwise, observations are passed to 4D-Var process.

3.4 JMA

JMA assimilates clear radiances of ATOVS and microwave imagers such as SSM/I, TMI and AMSR-E in the global assimilation system. Cloudy or rainy data are screened out using retrieved clw: If clw > 0.1 (0.3) kg/m2, the radiance data are considered affected by cloud (rain). In addition, for AMSU-A, the difference between tb_o^{ch15} and tb_c^{ch15} simulated from tb_o^{ch1}, tb_o^{ch2} and tb_o^{ch3} exceeds criteria, the data is determined to be rain-affected. For AMSU-B and MHS, the difference between tb_o^{ch1} and tb_o^{ch2} is used to identify rain affected data.

In contrast, JMA assimilates retrieval products in the regional assimilation system: temperature profiles from ATOVS in clear region, and total precipitable water in clear region and surface rain rate from the microwave imagers. ATOVS temperature retrievals are generated by NESDIS and the Meteorological Satellite Center (MSC) of JMA, and cloud affected data are identified with cloud amount information contained in the data. For microwave imager retrievals, cloud/rain classification is based on a threshold technique using several parameters from observations (Takeuchi 2002).

4. Increments and impact studies

4.1 NCEP

The Gridpoint Statistical Interpolation (GSI) system (Wu et al. 2002), Global Forecast System (GFS) model, and CRTM are three main components of the NCEP GDAS (Global Data Assimilation System). The GSI system was developed for use as the next generation systems for both the global and regional systems . The GSI is based on the Spectral-Statistical Interpolation (SSI) analysis system (Parrish and Derber 1992) and replaced the spectral definition for background errors with grid point version based on recursive filters. It became operational in June 2006(regional analysis) and in May 2007 (global analysis). First guess fields are derived from 06hr GFS forecast for global anaysis and 03hr NMM forecast for regional. Background errors are calculated from NMC method for global analysis and from ensemble method for regional analysis, respectively. Currently assimilated observations include: conventional data, GPS, SSMI-rain, TMI-rain, sbuv, goes-snd, AMSU-A and B, HIRS2,3, and 4, MHS, MSU, and AIRS data. New instruments like SSMIS, OMI, and IASI are being tested.

Currently the control variables in GSI analysis are stream function, velocity potential, temperature, q/qs(guess), ozone, and cloud liquid water profiles and surface pressure and surface skin temperature. Cloud liquid water is only being modified slightly by TMI and SSMI-surface rain rate assimilation. The cloudy radiance assimilation component is under development. AMSU-A will be tested first before including other microwave radiance observations and challenging IR cloudy radiances. Currently, tangent linear model and adjoint models for cloud water profiles are being derived consistently with microphysics scheme in GFS model. Once these TL and AD models are included, details of channel selection and bias correction method will be determined afterward. Impact studies will be implemented once we have done these.

4.2 Met Office

Met Office variational assimilation system uses an incremental 4D-Var formulation. Its linearization states and background fields come from a Unified Model (UM) forecast. The variational minimization uses a perturbation forecast (PF) model. A single moisture variable defined as specific total water q_w (the sum of specific humidity q, specific cloud liquid water q_{cl}, and specific frozen cloud water q_{cf}) provides an interface between the PF model and both the transformation to control variable space, in which the minimization problem is better conditioned and easier to work with. This variable is also used to output analysis increments to be applied in the forecast model. The partitioning of q_w into q and $q_c(=q_{cl} + q_{cf})$ at the beginning of the PF model integration is done using a modified form of the PF latent heating scheme, designed to retain the initial temperature increment, T.
The preliminary impact study results showed that there was a strong positive impact on southern hemisphere and tropical large-scale fields. Most fields (geopotential height, temperature, humidity, and wind) and forecast ranges showed an improvement in the southern hemisphere. The impact was more mixed in the northern hemisphere. (Sharpe et al. 2008)

4.3 ECMWF

ECMWF variational assimilation system uses 4D-Var formation. Tangent linear and adjoint model components except for cloud and precipitation microphysics component are derived from ECMWF Integrated Forecasting System (IFS) model. The tangent linear and adjoint of cloud and precipitation microphysics are not derived from the operational prognostic schemes but from simple diagnostic schemes after significant comparison and validation studies (Tompkins and Janiskova 2004, Lopez and Moreau 2005). The 1D+ 4D-Var assimilation of SSM/I cloudy a
nd rainy radiances is currently part of current operational analysis system. The 1D-Var retrievals include T, q, ciw, clw, snow, rain, near surface u and v. The moisture variable

passed from 1D-Var to 4D-Var is total column water vapor (TCWV) which is used as pseudo-observations in 4D-Var.

The main impact of adding rainy radiance assimilation to the baseline came in the tropics. Rainy radiance assimilation was found to be beneficial in almost all regions and levels and improved forecasts. The beneficial impact was found not just in the directly observed moisture fields but also in the dynamical fields (e.g. vector wind). However, ECMWF found a number of areas where the 1D+4D-Var system needs to be improved (Geer et al. 2007).

- Because of the choice to assimilate only the TCWV retrieval into 4D-Var, much information was lost.
- Excessive rain in the simplified moist physics operators was found. ECMWF has completed with tuning the simplified moist physics operators and the improved operators have been used operationally since June 2008.
- First guess departure threshold needs to be changed.
- Roughly 20% of 1D-Var retrievals failed to minimize.
- The bias correction scheme does not fully eliminate the bias caused by excessive rain in the simplified moist physics.

This 1D+4D-var will be replaced with 4D-Var direct assimilation of cloudy radiances in near future. Their recommendation for direct 4D-Var of SSM/I radiances is that the distinction between 'clear' and 'rainy' observation streams should be removed. The observation operator must take into account rain and cloud whenever it appears in the model. In the all-sky 4D-Var direct assimilation system, the moisture control variable will be "normalised relative humidity". Note that neither precipitation nor cloud is a control variable but they will test the possibility of including these hydrometeor variables in due course.

4.4 JMA

JMA global assimilation system uses an incremental 4D-Var formulation. Tangent linear and adjoint models of physical processes related to cloud and precipitation are derived from simplified models of operational prognostic schemes of cloud, large-scale precipitation and Arakawa-Schubert cumulus convection processes.(JMA 2007). Control variables are relative vorticity, unbalanced divergence, unbalanced temperature and surface pressure, and logarithm of specific humidity. In other words, although the tangent linear and adjoint models are able to handle cloud/rain perturbation, no increment of cloud nor rain is generated. To assimilate cloudy/rainy radiance, we are considering the possibility of including control variables such as total water amount and/or developing diagnostic schemes connecting current control variables (e.g. temperature and humidity) to cloud/rain. Currently some diagnostic schemes, such as Tompkins and Janiskova (2004) are tested in 1D-Var. Preliminary studies where first guess of clw profile is modified to match retrieved clw from AMSU-A showed promising results and made us recognize the importance of first-guess in the assimilation context. Bias correction and estimation of background error covariance of clw, if necessary, are future issues.

JMA regional assimilation system also uses an incremental 4D-Var formulation but is different from the global system. Control variables are unbalanced wind, virtual temperature, surface pressure and specific humidity. Tangent linear and adjoint models are based on the previous hydrostatic regional prognostic model and include simplified schemes of large scale condensation, evaporation and moist convective adjustment processes. Rain-rate retrieved from microwave imagers are averaged in 20 km grid corresponding to the inner model resolution. It is assimilated over the ocean as 1-hour accumulated rain amount data. This approach follows a successful assimilation of radar rain-gauge composite data (Koizumi et al. 2005). The assimilation of the satellite-derived rain data improved analysis of humidity field over the ocean around Japan and consequently precipitation forecast over Japan. The radiance assimilation will replace the retrieval assimilation in future in tandem with advancement of assimilation system.

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