Satellite Data Assimilation in Numerical Weather Prediction Models. Part II: Uses of Rain-Affected Radiances from Microwave Observations for Hurricane Vortex Analysis

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ABSTRACT

A hybrid variational scheme (HVAR) is developed to produce the vortex analysis associated with tropical storms. This scheme allows for direct assimilation of rain-affected radiances from satellite microwave instruments. In the HVAR, the atmospheric temperature and surface parameters in the storms are derived from a one-dimension variational data assimilation (1DVAR) scheme, which minimizes the cost function of both background information and satellite measurements. In the minimization process, a radiative transfer model including scattering and emission is used for radiance simulation (see Part I of this study). Through the use of 4DVAR, atmospheric temperatures from the Advanced Microwave Sounding Unit (AMSU) and surface parameters from the Advanced Microwave Scanning Radiometer (AMSR-E) are assimilated into global forecast model outputs to produce an improved analysis. This new scheme is generally applicable for variable stages of storms. In the 2005 hurricane season, the HVAR was applied for two hurricane cases, resulting in improved analyses of three-dimensional structures of temperature and wind fields as compared with operational model analysis fields. It is found that HVAR reproduces detailed structures for the hurricane warm core at the upper troposphere. Both lower-level wind speed and upper-level divergence are enhanced with reasonable asymmetric structure.

1. Introduction

While the skill for tracking tropical cyclones has been significantly improved during the past decades, an accurate prediction of their intensity, formation, and dissipation processes remains challenging. This forecast difficulty is due partially to a lack of knowledge on storm structures, especially when their circulations are weak and diffuse over open oceans and few upper-air observations are available from ships and commercial and reconnaissance aircraft. By using satellite observations, many attempts were made to improve hurricane analyses for forecasts. Krishnamurti et al. (1991) developed a method to physically initialize the Florida State University global cumulus parameterization spectral model, which mainly depends upon the surface rain rates derived from the Special Sensor Microwave Imager (SSM/I). A comparison study was conducted by Tibbetts and Krishnamurti (2000) to evaluate the performance of four different rain-rate algorithms in hurricane track forecast using a physical initialization method, and found that SSM/I rain-rate products developed by the National Oceanic and Atmospheric Administration (NOAA) produced the best prediction results. Zou and Xiao (2000) assimilated the Geostationary Operational Environmental Satellite (GOES)-8/9 upper-tropospheric water vapor-tracking wind vectors into the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Meso-scale Model (MM5) through the four-dimensional
variational data assimilation (4DVAR) scheme. Hou et al. (2000) assimilated the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI)–derived surface rainfall and total precipitable water into the Goddard Earth Observing System (GEOS) global analysis with one-dimensional variational data assimilation (1DVAR) minimization procedure. Pu et al. (2002) found significant impacts of TMI rain rate on simulations of Supertyphoon Paka.

One of the key components in these studies is the bogus scheme that constructs a hurricane initial vortex from the global forecast model outputs at coarse spatial resolutions. In the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, surface wind field is first defined using a formula relating some observable parameters (Kurihara et al. 1993) such as the storm location, the radius of maximum wind, and the minimum central pressure. The tropospheric winds are obtained by multiplying the surface winds with empirical factors. The asymmetric wind components are derived from environmental observations. Wang (1995) also used the similar method to generate hurricane initial vortex by specifying wind field first and then invert mass field from the balance equation. Zou and Xiao (2000) developed a bogus data assimilation scheme, in which the sea level pressure of a hurricane vortex is specified according to the observed central pressure and the radius of maximum wind. This sea level pressure field is treated as observation to be included into a 4DVAR cost function for minimization. Pu and Braun (2001) evaluated the above bogus vortex scheme with 4DVAR data assimilation.

The National Centers for Environmental Prediction (NCEP) operational hurricane model uses a vortex replacement scheme to initialize hurricanes (Kurihara et al. 1993; Liu et al. 2004). The scheme performs well for initializing strong hurricanes but has difficulties for weak systems, because the derived hurricane vortex is too shallow for the model to maintain the storm after a few hours into integration. NCEP hurricane modeling group recently requested to generate a scheme for weak and diffuse systems that can give hurricane structures in both lower and upper levels. In this study, we develop a new hybrid variational scheme, which directly assimilates microwave radiances in rain-affected areas to produce a best analysis for hurricane circulation. The satellite microwave radiances are obtained from the Advanced Microwave Sounding Unit (AMSU) on board NOAA-15, NOAA-16, and NOAA-18 satellites and the Advanced Microwave Scanning Radiometer for Earth Observing System (EOS; AMSR-E) on board the National Aeronautics and Space Administration (NASA) EOS Aqua satellite. To extend radiance assimilation to all-sky conditions, we have upgraded the assimilation system with fast radiative transfer models that include scattering and emission from clouds and precipitation.

2. Satellite microwave observations under cloudy conditions

The passive microwave radiation can penetrate through clouds and precipitation and provide rich information on hurricane structures (e.g., temperature, moisture, rain rate, and surface winds) from the signals received by the sensor. In this study, we are applying the measurements from two microwave sensors for hurricane model initialization. Currently, NCEP's Global Data Assimilation System (GDAS) uses a 3DVAR approach to assimilate microwave radiances and products, such as AMSU radiances, SSM/I surface wind speed, and precipitation products, in clear sky only (McNally et al. 2000). For weather systems like tropical cyclones, almost all the satellite microwave measurements are not assimilated because of cloudy and rainy conditions. This study demonstrates the impacts of AMSU and AMSR-E data on hurricane model initialization by using the newly developed hybrid variational scheme.

a. Advanced Microwave Scanning Radiometer for Earth Observing System

The EOS satellite Aqua was launched on 4 May 2002. On board Aqua, AMSR-E is one of the important satellite sensors and provides microwave observations at frequencies ranging from 6.9 to 89 GHz. The AMSR-E is a conically scanning passive microwave radiometer with dual polarization at all frequencies. The spatial resolution of the individual measurements varies from 5.4 km at 89.0 GHz to 56 km at 6.9 GHz. Compared to current space-based microwave sensors, such as SSM/I and AMSU, AMSR-E provides new measurements at 6.925 and 10.65 GHz with a higher spatial resolution and allows for retrievals of sea surface temperature (SST) and wind speed (SSW) in the presence of clouds and precipitation.

Figure 1 shows the brightness temperature measurements at 6.925 and 10.65 GHz at 0600 UTC 28 August 2005, when Hurricane Katrina reached intensity of category 4, with minimum central pressure of 935 hPa. In general, the brightness temperatures measured at vertical polarization (Figs. 1c,d) are higher than that from horizontal polarization (Figs. 1a,b) due primarily to the difference of sea surface emissivity. An increase in brightness temperature at 10.65 GHz at the northeast side results from the increased emission from cloud and precipitation within the eyewall and strong rainfall.
bands, as well as the ocean surface emission when the surface becomes very rough (Figs. 1b,d). At 0600 UTC August 25, Katrina was at its incipient stage with a minimum central pressure of 997 hPa when strong convection developed near its center and the northeast side of the storm (Fig. 2).

b. Advanced Microwave Sounding Unit

The first AMSU instrument on board NOAA-15 was launched in 1998. Since then we have seen many studies utilizing this dataset to monitor and simulate tropical cyclones. Currently, there are four satellites (NOAA-15, NOAA-16, NOAA-18 and Aqua) carrying AMSU instruments that provide eight observations each day on a large portion of the earth. The AMSU instrument contains two modules: A and B. The A module (AMSU-A) has 15 microwave channels ranging from 23.8 to 89.0 GHz and is mainly designed to provide information on the atmospheric temperature profiles, while the B module (AMSU-B) allows for profiling the moisture field. The AMSU-A has an instantaneous field of view of 3.3° and a nominal spatial resolution of 48 km at its nadir. The AMSU-A-derived temperature was used to estimate the hurricane’s maximum wind (Kidder et al. 2000) and central pressure (Kidder et al. 1978; Velden and Smith 1983; Kidder et al. 2000). In addition, the temperature gradient could be utilized to derive the tangential winds when a hurricane reaches its mature stage with a well-defined circular structure (Grody et al. 1979; Kidder et al. 2000). A statistical algorithm was first developed to retrieve three-
dimensional atmospheric temperature, and a dynamically constrained model was developed to obtain the geopotential height, wind, and moisture fields for a hurricane system from AMSU-derived temperature data (Zhu et al. 2002). Positive impacts have been shown in the simulation of Hurricane Bonnie (1998). This study will explore a direct assimilation of rain-affected microwave radiances to further improve hurricane analysis using a new hybrid variational scheme.

3. Hybrid variational scheme (HVS) for hurricane vortex analysis

Satellite radiances are not components of atmospheric state vectors predicted by numerical weather prediction (NWP) models. For radiances to be assimilated by NWP models through a variety of variational schemes, a relationship between the model state vectors and the observed radiances is required. In addition, the Jacobian vector (or the derivative of radiance relative to the state vector) is also needed for satellite radiance assimilation. In past several years, the United States Joint Center for Satellite Data Assimilation (JCSDA) has taken a great stride toward a community radiative transfer model (CRTM), which is now being implemented into several NWP models in NOAA, NASA, and the Department of Defense, as well as in universities.

a. Community radiative transfer model (CRTM)

For a plane-parallel atmosphere, the radiance vector can be derived from

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Fig. 2. Brightness temperatures for horizontal polarization at (a) 6.925 and (b) 10.65 GHz and for vertical polarization at (c) 6.925 and (d) 10.65 GHz for Hurricane Katrina at 0701 UTC 25 Aug 2005.
\[
\frac{dI(\tau, \mu, \phi)}{d\tau} = -I(\tau, \mu, \phi) + \frac{\sigma T_{0}}{4\pi} \int_{0}^{1} \int_{-1}^{1} M(\tau, \mu, \phi; \mu', \phi') I(\tau, \mu', \phi') d\mu' d\phi' + S(\tau, \mu, \phi; \mu_{0}, \phi_{0}),
\]

and

\[
S = (1 - \sigma T_{0}) B[T(\tau)] \left[ \begin{array}{c}
1 \\
0 \\
0 \\
0
\end{array} \right] + \frac{\sigma T_{0}}{4\pi} \exp(-\tau/\mu_{0}) \left[ \begin{array}{c}
M_{1}(\mu_{0}, \phi; \mu_{0}, \phi_{0})) \\
M_{13}(\mu_{0}, \phi; \mu_{0}, \phi_{0})) \\
M_{14}(\mu_{0}, \phi; \mu_{0}, \phi_{0})) \\
M_{14}(\mu_{0}, \phi; \mu_{0}, \phi_{0}))
\end{array} \right],
\]

where \( M \) is the phase matrix; \( I = [I, Q, U, V]^{T}; B(T) \) is the Planck function at a temperature \( T \); \( F_{0} \) is the solar spectral constant; \( \mu_{0} \) and \( \phi_{0} \) are the cosine of zenith angle and the azimuthal angle of sun; \( \mu \) and \( \phi \) are the cosine of zenith angle and the azimuthal angle at scattering direction; \( \sigma \) is the single-scattering albedo; and \( \tau \) is the optical thickness. The \( I, Q, U, V \) in \( M \) are the Stokes parameters. Intensity (denoted by \( I \)) is the sum of the vertical and horizontal linearly polarized components. Polarization difference \( (Q) \) refers to the intensity difference between the vertical and horizontal linearly polarized components. Plane of polarization \( (U) \) measures the difference in intensities between linearly polarized components oriented at \(+45^\circ\) and \(-45^\circ\). Ellipticity \( (V) \) is defined as the difference in intensities between right and left circularly polarized components. Several schemes are proposed to discretize differential and integral radiative transfer equations and provide the solution for the radiative transfer (RT) in the vertically stratified plane-parallel atmosphere. This part in the CRTM is referred as RT solution module. Several RT solution modules are being tested, including

- vector discrete ordinate radiative transfer model (VDISORT) originally developed by Weng (1992), and several improved versions (Schulz et al. 1999; Weng and Liu 2003, hereafter Part I);
- successive order of interaction (SOI; Greenwald et al. 2005);
- delta–four stream vector radiative transfer (DS4; Liou et al. 2005);
- fast multistream scattering-based Jacobian for microwave radiance assimilation (Voronovich and Gasiewski 2004);
- advanced doubling and adding (ADA; Liu and Weng 2006); and
- spherical harmonics (SHDOMPPDA; Evans 2007).

The ADA method has been recently developed at the JCSDA and implemented into CRTM as a placeholder scattering model. With a much more simplified algorithm than the traditional doubling and adding method, the ADA runs 60 times faster at a Linux workstation. The radiance (i.e., forward) computational codes of ADA are compiled and translated into tangent-linear and adjoint codes for the radiance gradient calculations.

The RT solution module selected for the CRTM implementation is largely dependent on several performance factors (e.g., speed, accuracy, storage for coefficients, Jacobian, potential developments for future instruments).

Under clear atmospheric conditions, a radiative transfer model uses atmospheric absorption coefficients as key inputs. The absorption varies with the atmospheric conditions in a complicated way and is often computed through line-by-line (LBL) models. Although LBL models are accurate, they take considerable time to calculate transmittances for just a few atmospheres. To provide accurate transmittances in a timely fashion, the JCSDA has generated and used a fast approximation, commonly known as optical path transmittance (OPTDRA), for specific instrument channels. For atmospheric transmittance calculations, the gas absorption coefficients are predicted from the atmospheric parameters at fixed levels of the integrated absorber amount (Kleespies et al. 2004). This approach significantly reduces the coefficients that reside in computer memory and preserves the accuracy. Recently, a fast and optimal spectral sampling (OSS) absorption model developed by AER, Inc. (Moncet et al. 2004) is also being tested and integrated as part of CRTM. The OSS is a new approach for radiative transfer modeling that addresses the need for algorithm speed, accuracy, and flexibility. The OSS technique allows for a rapid calculation of radiance for any class of multispectral, hyperspectral, or ultraspectral sensors at any spectral resolution operating in any region from microwave to ultraviolet wavelengths by selecting and appropriately weighting the monochromatic radiances contributed from gaseous absorption and particle scattering over the sensor bandwidth.

Note that both radiance and Jacobian computations require accurate knowledge of surface emissivity and
reflectivity. Without an emissivity model, the measurements from those channels of current and future advanced sounders that are sensitive to the lowest atmospheric layers may not be assimilated into NWP models. As a critical part of the radiative transfer model, the surface emissivity model is developed to properly include the variability of both emissivity and reflectivity. Presently, the CRTM is built on the existing surface emissivity modeling. With the launch of the first AMSU in 1998, an ocean microwave emissivity model developed by the National Environmental Satellite, Data, and Information Service (NESDIS) was successfully implemented into the NCEP global data assimilation system. In collaboration with NCEP, NESDIS also tested and compared two ocean emissivity models. It was found that the model developed by the Met Office, United Kingdom (English and Takashima 1998) produced better results in assimilating the AMSU data, especially at high latitudes. A microwave emissivity model was developed for land surfaces (Weng et al. 2001) and has resulted in major impacts in improving uses of microwave data over land and in polar regions. Critical issues remain in simulating the emissivity spectra over extreme surface conditions and at infrared wavelengths. Evidence of these model deficiencies comes from comparisons of the simulated global emissivity distribution with satellite retrievals from AMSU and SSM/I (Weng et al. 2001).

b. Analysis for atmospheric temperature

The direct radiance assimilation has become a routine practice in NWP centers and results in major success in the use of clear-sky radiances in global forecast systems. However, cloud- and rain-affected satellite radiances have not been assimilated into operational forecasting models although the measurements contain considerable information pertinent to the atmospheric hydrological cycle. Recently, operational NWP centers have a growing interest in assimilating satellite observations in cloudy and rainy regions (Treadon et al. 2002; Marécal and Mahfouf 2000, 2002). Satellite measurements in cloudy regions contain valuable information on temperature, humidity, and wind that is fundamentally different from clear-sky areas. Regions where forecast error is most sensitive to initial-condition error are often cloudy (McNally 2002). In the European Centre for Medium-Range Weather Forecasts (ECMWF) 4DVAR system, two approaches were tested for assimilating water vapor information from satellite microwave imager data. In the first approach, 1DVAR technique was used to generate increments of total column water vapor, which is then assimilated through 4DVAR, which is referred to as “1DVAR + 4DVAR” (Bauer et al. 2006a,b). The second approach is direct assimilation of surface rain-rate observations from satellite retrievals by a 4DVAR system. The conclusion is that the 1DVAR + 4DVAR method generates better surface rain-rate assimilation and reduces humidity biases in both clear and cloudy conditions. Also, the 1DVAR partly avoids the convergence problem by treating the strong nonlinearities in the observation operators for rain rates outside of 4DVAR (Andersson et al. 2005).

In our current analysis, we also applied 1DVAR and 4DVAR schemes, referred as a hybrid variational scheme (HVAR) for analyzing storm conditions. In 1DVAR, satellite radiances from AMSU are assimilated to obtain atmospheric temperature profiles. In the presence of clouds and precipitation, the assimilation requires an advanced forward radiative transfer model with the state vectors as inputs (Part I). In addition, the Jacobian vectors (or the derivative of radiance relative to the state vectors) are also needed for satellite data assimilation systems. The assimilation of rain-affected microwave radiances requires the development of a fast RT model that accounts for scattering effects due to raindrops and ice particles (Part I; Chevallier and Bauer 2003; Bauer et al. 2006a,b). In Part I, we discussed the 1DVAR approach in deriving atmospheric and surface parameters via the satellite data assimilation method. Note that 1DVAR retrievals that are assimilated in the ECMWF 4DVAR system succeeded in producing reasonable and coherent temperature and specific humidity increments, which correct the simulated radiances toward the satellite observations, as discussed above (also see Moreau et al. 2004). As discussed in other studies (Liu and Weng 2003), 1DVAR is designed with the climatology profiles of temperature and water vapor as a background and the error statistics for background and forward radiative transfer models are documented in the study. 1DVAR outputs not only temperature profiles but also the mean error associated with the profiles. This error profile is used to derive the error covariance matrix that is used in 4DVAR. In this study, the radiance and its Jacobians used in 1DVAR are derived analytically from the JCSDA community radiative transfer model (Weng et al. 2005) as discussed above.

In 1DVAR, the atmospheric temperature profile is retrieved from AMSU-A brightness temperatures. In the analysis cycle, the physical scheme linking the clouds and precipitation to the temperature profile is largely reflected through uses of advanced radiative transfer scheme that include scattering and emission from cloud and rainwater, cloud ice and graupel, and snow. The effectiveness of using raindrop and ice par-
Particle scattering to modify temperature profiles is evaluated with Hurricane Isabel (2003) case. Figure 3 shows the atmospheric temperature anomalies retrieved from AMSU with and without scattering effects. The temperature anomaly is defined as a deviation from the unperturbed environmental temperature at each level. It can be seen that the temperature retrieved without raindrop scattering model have a very cold (<−12°C) anomalies within the eyewall, which is physically unreasonable (Figs. 3a,b). Once the scattering model is used, the retrieved temperature is improved (Figs. 3c,d). The upper-level warm core is about 12°C, which is reasonable for a category 5 hurricane with 922-hPa minimum central pressure. Zhu et al. (2004) found an 8°C warm core in Hurricane Bonnie when it was at category 3 intensity. The lower-level cool anomalies within the hurricane eyewall are reduced for about 6°C. Thus, it is important to include the scattering scheme in the re-

Fig. 3. Vertical cross section of temperature anomalies retrieved without scattering model (a) west–east cross section along 22°N and (b) south–north cross section along 56°W and with scattering model (c) west–east cross section along 22°N and (d) south–north cross section along 56°W for Hurricane Isabel at 0600 UTC 12 Sep 2003.
retrieval when scattering effect becomes a prevailing process.

We compared the retrieved temperature with the NOAA aircraft dropsonde measurements. Figure 4a shows the NOAA/Hurricane Research Division (HRD) aircraft dropsonde measurements over 700 hPa during 1200 to 2000 UTC 12 September 2003. One of the dropsonde temperatures near hurricane center is 18.6°C. All other dropsondes are located in the hurricane eyewall, and the temperatures range from 13.0°C to 16.0°C. Therefore, the warm core at this level is about 2–4 K, in good agreement with the retrieved (Fig. 3). At surface level (Fig. 4b), three temperatures near the center are about 25.5°C, another three temperatures in the east side of the environmental region are around 27.5°C, and the remains are around 24.5°C in the eyewall. The cool anomalies in hurricane eyewall are about 3 K, and they are about half of the cool anomalies retrieved by 1DVAR scheme.

c. Analysis of sea surface temperature and wind

To derive surface temperature and wind speed from microwave instruments, we developed analytic retrievals through linearization of the radiative transfer model. At lower microwave frequencies, brightness temperatures at the top of the atmosphere can be simplified from Eq. (3.1) as

$$TB_P = e_P \zeta S + T_u + (1 - e_P)\zeta T_d,$$

where $e_p$ is surface emissivity; $S$ sea surface temperature; the subscript $p = V/H$, which denotes vertical and horizontal polarizations, hereafter; $T_u$ and $T_d$ are the brightness temperatures in upwelling and downwelling directions, respectively; and $\zeta$ is the atmospheric transmittance. These parameters are related to atmospheric temperature and constituent profiles through

$$\zeta = e^{-\tau_{v2}},$$

$$T_d = \int_0^\tau T(\tau')e^{-\tau'/\mu} d\tau'/\mu,$$

$$T_u = \int_0^\tau T(\tau')e^{-\tau'/\mu} d\tau'/\mu.$$  (3.6)

At microwave frequencies, the atmospheric optical thickness $\tau$ can be accurately parameterized as a function of oxygen optical depth $\tau_{O_2}$, water vapor mass absorption, and liquid water mass absorption coefficients ($k_v$ and $k_l$; Weng et al. 2003):

$$\tau = \tau_{O_2} + k_v V + k_l L,$$

where $V$ and $L$ are the vertically integrated water vapor and liquid water, respectively (Weng et al. 2003). The parameters in Eq. (3.3) can be individually assessed for their contributions to the brightness temperatures at the top of the atmosphere. It is found that upwelling and downwelling brightness temperatures $T_u$ and $T_d$ at microwave window channels are nearly identical (Liu and Weng 2003). Thus, in our following discussions, $T_u$ and $T_d$ are assumed to the name and expressed as $T_a$.
From Eq. (3.3) and with some algebraic manipulations, the tangent-linear surface temperature, wind speed, and atmospheric transmittance can be related to the measurements at four AMSR-E channels as

\[
\begin{bmatrix}
\Delta T_6 \\
\Delta w \\
\Delta T_{a6} \\
\Delta T_{a10}
\end{bmatrix} = (A^T A + E)^{-1} A^T \begin{bmatrix}
\Delta TB_{V6} \\
\Delta TB_{H6} \\
\Delta TB_{V10} \\
\Delta TB_{H10}
\end{bmatrix},
\]

(3.8)

where \(A\) is a 4 \times 4 matrix and the elements are related to atmospheric transmittance, its derivative to effective air temperatures at 6 and 10 GHz; and to sea surface emissivity and its derivative relative to surface temperature, wind speed, and salinity; \(A^T\) is the matrix transposed from \(A\); and \(E\) is an error matrix related to instrument noise and RT model if the direct measurements are used. In our studies, \(E\) represents the errors related to the standard deviation with which satellite measurements are adjusted to the RT model brightness temperatures. Note that in Eq. (3.8), the wind speed and salinity are related to the brightness temperatures through the ocean emissivity (English and Takashima 1998). For example, a strong wind speed or a low salinity usually results in a large ocean emissivity when other properties of sea waters are the same. With the large ocean emissivity, the high brightness temperature is usually seen.

In a physical retrieval, a bias correction procedure is developed to adjust satellite brightness temperatures to those predicted by the emission-based radiative transfer models. In doing so, satellite measurements are collocated with buoy SST and SSW, and temperature and water vapor profiles from the numerical prediction model. The brightness temperatures at each collocated site are calculated at all AMSR-E frequencies and polarizations. The AMSR-E simulations and observations are used to derive regressional relationships that allow for predicting the RT model brightness temperatures from observations. Once the measurements are adjusted to the RT model brightness temperatures, the surface parameters can be mathematically elegantly obtained through iteratively solving Eq. (3.8), which calculates the increments of surface and atmospheric parameters relative to those from the previous iteration. The iteration stops when the differences from two consecutive iterations are less than a set of thresholds.

Figure 5 displays the NOAA/HRD surface wind analysis and the retrieved SSW for Hurricane Katrina at 0600 UTC 25 August 2005. The detail patterns of the two figures do not match. This difference is partly due to the observation noise from AMSR-E data and partly due to the fact that the HRD analysis field is too smooth. However, the two figures have the similar dynamic range and similar asymmetric structures. The retrieved SSW shows strong winds in the north side of the...
storm, which is similar to the pattern in HRD surface wind analysis field. The AMSR-E-retrieved maximum wind speed is 37 kt (19 m s\(^{-1}\), where 1 kt = 0.514 m s\(^{-1}\)), which is close to the best analysis value of 41 kt.

d. Four-dimensional variational scheme

MM5 and its adjoint system (Zou et al. 1998) are used to generate hurricane initial vortex by assimilating AMSR-E SSW and AMSU 3D temperature data from a 1DVAR scheme. Applications of the MM5 adjoint model to a variety of mesoscale weather systems have been demonstrated in papers by Kuo et al. (1996) and Zou and Xiao (2000). The limited-memory quasi-Newton method of Liu and Nocedal (1989) is used to minimize the objective function in this study. The cost function to be minimized can be written as

\[
J(X) = J_b(X) + \sum_{k=1}^{2} J_o(X),
\]

where \(J_b\) is the cost function for background term, and the background fields are obtained from NCEP Global Forecast System (GFS) Data Assimilation System (GDAS) analysis. Here \(J_o\) is the cost function for two kinds of satellite observations, and can be expressed as

\[
J_o(X) = \sum_{t_x} \sum_{i,j \in R} [H(T) - T_{obs}]^T W_T (H(T) - T_{obs})
+ \sum_{t_y} \sum_{i,j \in R} [H(V) - V_{obs}]^T W_V (H(V) - V_{obs}),
\]

where \(T_{obs}\) and \(V_{obs}\) are the AMSU temperature and AMSR-E SSW, \(T\) and \(V\) are the model analysis fields, and \(H\) is the operator used to transform the model gridded analysis fields to observation points. The \(t_x\) and \(t_y\) are the satellite observation times within the 4DVAR assimilation window, and \((i, j) \in R\) represents the cloud-affected microwave radiances region where the satellite data is assimilated. Here \(R\) is defined as the region where satellite-retrieved cloud water path (CLW) > 0.3 mm. The strategy for defining \(R\) means that only satellite observations near the hurricane core region are assimilated. The background fields (GDAS data) in the hurricane environmental region will not be changed because AMSU and AMSR-E data are already assimilated under clear-sky conditions. The \(W_T\) and \(W_V\) are the empirically determined diagonal weighting matrices for AMSU temperature and AMSR-E SSW data.

Assimilation of the AMSU-derived temperatures into NWP analysis fields are generalized by using an AMSU-derived temperature anomaly field, rather than the temperature itself. This will make our scheme applicable for any NWP model outputs. The areas with the assimilated AMSU temperatures can be smoothly connected to the background regions with GDAS analysis. A digital filter is also applied (as a weak constraint) to smooth out high-frequency time oscillations. The digital-filter initialization was proposed by Lynch and Huang (1994), and was demonstrated to be effective in reducing dynamic imbalance and improving the qualities of analysis by Wee and Kuo (2004).

The physical processes that were employed in the minimization procedure are the medium-range forecast (MRF, a previous version of GFS) planetary boundary layer parameterization (Hong and Pan 1996); Kuo-type cumulus parameterization; and large-scale precipitation process, surface friction, surface fluxes, and dry convective adjustment. The variational analysis is carried out on a 27-km horizontal resolution domain with 76 \times 73 grid points. Before the 4DVAR assimilation, the high-resolution (27 km \times 27 km) background fields are created from low resolution (1° \times 1°) GDAS fields through interpolation. The assimilation window is 6 h, and the integration time interval is 90 s.

4. Case studies

The HVAR scheme is applied in creating the vortex analysis for Hurricanes Katrina and Ophelia. Hurricane Katrina was the second category-5 hurricane of the 2005 Atlantic hurricane season, and the sixth-strongest storm ever recorded in the Atlantic basin. It caused more than 1300 deaths, and over 1.2 million people were evacuated. The damage is estimated to be about $75 billion by the National Hurricane Center (NHC), which makes Hurricane Katrina the most expensive natural disaster in U.S. history. Formed at the same location as Hurricane Katrina, Hurricane Ophelia had a very different evolution cycle and track. Ophelia traveled along the U.S. eastern coastline from Florida and North Carolina to New England, and eventually to Atlantic Canada. It caused significant damage and beach erosion along its path.

a. Hurricane Katrina

Katrina became the eleventh tropical storm of the 2005 Atlantic hurricane season at 1200 UTC 24 August when it was located over the central Bahamas. The strengthening ridge over the northern Gulf of Mexico and southern United States produced a northeasterly upper-level flow that forced Katrina to turn southwestward as it was slowly approaching southern Florida. Katrina made its first landfall on the southern Florida peninsula at 2230 UTC 25 August as a category-1 hur-
Katrina emerged into the Gulf of Mexico. Once back into the ocean, Katrina quickly intensified for about a 2-day period, and became a category-5 hurricane with a peak intensity of 902 hPa at 1800 UTC 28 August. As Katrina continued its northwestward movement and made its second landfall near the mouth of the Pearl River at the Louisiana and Mississippi border 1100 UTC 29 August, it weakened to a category-3 hurricane. The NHC official track forecasts issued within two and half days before the second landfall were very accurate. However, the track forecasts issued between 24 and 26 August had relatively large errors. The errors were associated with the southwestward motion during Katrina’s first landfall, which is mainly attributed to the difficulty in predicting upper-level northeasterly flow. The official intensity forecasts errors were considerably larger than the Atlantic 10-yr average errors, especially during the rapid intensification period from 26 to 28 August. Therefore, we select 0600 UTC 25 August as the analysis time to examine the improvement in hurricane initial vortex by HVAR scheme as compared with the GDAS analysis fields. At 0600 UTC 25 August, Katrina was at tropical-storm intensity with a minimum central pressure of 997 hPa. Figures 6a,b compare the GDAS analysis temperature field near 250 hPa with the HVAR analysis field. It is demonstrated that the hurricane warm core temperature is increased for about 1.5 K in the new vortex. In associated with the enhanced warm core, the upper-level divergent winds
and northeasterly flow near the storm center are also increased. Near the surface level (Figs. 6c,d), the HVAR-analyzed temperature field shows asymmetric distributions, with a 2-K cooling in a rainband located at northeastern side of the storm, which is consistent with the deep convections shown on the NOAA-17 Advanced Very High Resolution Radiometer (AVHRR) channel 4 image (not shown).

There is some NOAA/HRD aircraft dropsonde data available around 1200 UTC 25 August for verifying the HVAR analysis results. However, the HVAR analysis at 1200 UTC is not suitable for comparison, because at this time the storm is too close to the land and there is not enough AMSR-E–retrieved SSW and AMSU-retrieved temperature data available. Thus, the HVAR analysis result at 1200 UTC is similar to the background field (GDAS). We think the HVAR analysis at 0600 UTC (Fig. 6) can be used to do the verification, because the storm minimum central pressure only decreased 1 hPa during this 6 h and the eyewall and rainband relative positions were quasi stationary, which can be seen from NOAA-17 AVHRR images at 0359 and 1615 UTC (not shown).

Figure 7 compares the HVAR-analyzed temperatures with dropsonde observations. To make an easy comparison, the positions of dropsondes plotted in Figs. 7 and 8 at 1200 UTC are shifted to eastward for about 100 km, according to the moving distance of the hurri-
cane center during the 6 h. At 850 hPa, the HVAR-analyzed temperature field shows a 1-K warm tongue at storm center (Fig. 7b). This improvement is confirmed by the dropsonde observations. At surface level, two dropsonde measurements of 26.6°C can be found in the northeast side of the storm, which indicates that the HVAR-retrieved 2-K cool anomalies in the strong convection region are reasonable. Both HVAR and GDAS analysis show that temperatures at south side are about 1 K warmer than observed.

Figure 8 compares the HVAR-retrieved wind field with HRD dropsonde observations. Over the 850-hPa level at the northeast side, the HVAR winds are increased for about 2.5 m s⁻¹ as compared with GDAS winds. The HVAR wind speeds are closer to the dropsonde measurements. The improvement of the analyzed wind field is similar at the surface level. The increment of HVAR wind speed is mostly contributed by AMSR-E SSW data, and is also dynamically consistent with the increment of the temperature gradient at lower levels. By comparing Figs. 4b, 8c, and 8d, we can see the interaction of GDAS data with the AMSU- and AMSR-E-retrieved fields. The effect of GDAS winds is to smooth the original AMSR-E-retrieved wind field.

Fig. 8. Comparison of the HRD dropsonde-observed winds (in red) at 850 hPa to (a) the GDAS winds and (b) HVAR-retrieved winds and at sea surface to (c) the GDAS winds and (d) HVAR-retrieved winds (in blue). The contours are isotaches at intervals of 5 m s⁻¹. A full barb is 5 m s⁻¹. The storm centers at 0600 and 1200 UTC are denoted by red star and triangle symbols, respectively.
Meanwhile, the environmental wind speed is increased because of the influence of AMSR-E data and inner-core dynamics.

b. Hurricane Ophelia

Ophelia formed over the northern Bahamas on 6 September as a tropical depression, and became a tropical storm on 7 September. Under very weak middle- and upper-environmental flow, it was nearly stationary for two days off the coast of Florida. From 9 to 12 September, Ophelia moved very slowly and erratically in a northeasterly direction, and completed a clockwise loop till 12 September. During these five days, Ophelia’s intensity oscillated between tropical storm and category-1 hurricane many times. At our analysis time, 0600 UTC 7 September, Ophelia was a tropical storm with minimum central pressure of 1003 hPa. The new variational scheme produces a relative broad upper-level warm core, which is about 1 K warmer than that of GDAS analysis (Figs. 9a,b). At sea surface level, a relative uniform temperature distribution near the storm core region is given by GDAS analysis (Fig. 9c). The new analysis result shows a cold area at the northeast side of the storm (Fig. 9d), which is associated with precipitation evaporation cooling in a rainband in a NOAA-17 AVHRR image (not shown). The low-level wind speed in the hurricane eyewall is also increased after reanalysis, which is mainly attributed to the assimilation of AMSR-E winds.

In summary, the new variational scheme can improve
hurricane vortex temperature and wind fields at both upper and lower levels. It can also generate asymmetric structures in good agreement with observations.

5. Summary and conclusions

A new hybrid variational scheme (HVAR) is developed to directly assimilate microwave radiances in rain-affected areas into the GDAS analysis fields for a best analysis of hurricane circulation. The atmospheric temperature and sea surface parameters in the storm are derived from AMSU and AMSR-E measurements. The retrieved temperature and sea surface wind fields are then assimilated into GDAS analysis to generate hurricane vortex by a 4DVAR system. To assimilate satellite microwave radiances under cloudy and rainy conditions, an advanced radiative transfer model that accounts for scattering effects due to raindrops and ice particles is used. The AMSU-derived temperature anomaly filed is assimilated in the 4DVAR scheme to avoid any possible bias between 1DVAR-retrieved temperature and background (GDAS) temperature. The analysis displays significant impacts on the hurricane initial vortex structures associated with Hurricanes Katrina and Ophelia in 2005 in the following aspects:

- HVAR effectively assimilates the AMSU cloudy radiances and produces large positive impacts on hurricane upper-warm-core structures and therefore upper-level divergence;
- HVAR effectively assimilates the AMSR-E cloudy radiances and improves lower-level wind circulation and temperature field, which are in reasonable agreement with HRD dropsonde observations; and
- HVAR also allows reasonably developments of asymmetric structures in hurricane mass and wind fields.

It should be pointed out that for weak and diffuse circulation system, HVAR produces weaker hurricane intensity than observation as indicated by minimum central pressures. This may be due to several factors such as coarse model resolution, the lack of an explicit cloud microphysics scheme in HVAR, or the lack of atmospheric wind and humidity information, to name a few.

More information related to atmospheric winds and water vapor is needed to improve the analysis of hurricane vortex. GOES cloud and water vapor track winds and Quick Scatterometer (QuikSCAT) surface winds will be tested for further improvements. Also, the atmospheric 3D winds from NOAA G4 reconnaissance Doppler radar will be considered as vital although the data are limited for certain cases.

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