DEVELOPMENT OF 1-D CLOUD MICROPHYSICS DATA ASSIMILATION SYSTEM (CMDAS) BY USING AMSR-E DATA

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In this paper, an 1-D Cloud Microphysics Data Assimilation System (CMDAS) is developed for retrieving reasonable cloud distribution. The general framework of CMDAS includes the Kessler warm-rain cloud microphysics scheme, a microwave radiative transfer model in the atmosphere and a global minimization method of Shuffled Complex Evolution (SCE). The paper investigates potentials of the CMDAS to modify the cloud properties by considering integrated cloud liquid water content as a assimilation parameter and to introduce the heterogeneity into the initial state of the atmosphere, by applying the CMDAS to the satellite microwave radiometer data set obtained by the international cooperative observation experiment, "Wakasa Bay Experiment 2003", in Japan. The simulated microwave brightness temperature by CMDAS is in good qualitative and quantitative agreement with the observed one.

Key Words: Data assimilation, Cloud Liquid Water Content, Cloud Microphysics, Shuffled Evolution Method, Kessler Warm Rain Macrophysics, Radiative Transfer Model, Microwave Remote Sensing

1. INTRODUCTION

For reliable numerical weather prediction, complete and accurate description of the initial state of the atmosphere is required. But the current operational in-situ observation systems, which are used in numerical weather prediction (NWP) to intermittently update and improve our knowledge of the current atmospheric state, can not observe the cloud liquid water content (CLWC). Therefore, the unavailability of CLWC in the observation data may result into poor initialization of atmospheric model, giving unreliable prediction of precipitation.

In order to address this problem, remotely sensed data from space can be used for getting critically important information for better understanding of the cloud microphysics processes and for improving predictability on its effects on weather. Various studies have shown that the use of satellite derived products in diabatic or physical initialization can reduce the model spinup and improve the short-range forecast which in turn can improve the first

guess for the analysis[1],[2],[3],[4]. By viewing the significance and sophistication of cloud microphysics processes and its effects on the NWP model initialization, this research is directed towards satellite data assimilation.

Over the last few years, the variational form of statistical estimation has been implemented at many operational centres. Lorenc showed that the statistical estimation problem could be cast in a variational form (3D-Var) which is just a different way of solving the problem that the so-called optimal interpolation attempts to solve directly[5]. Eyre showed, in a 1D-Var context, that a variational formulation leads to a more natural framework for the direct assimilation of radiances instead of retrieved temperature and humidity profiles. This is also true for any indirect measurement of the state of the atmosphere[6]. Talagrand and Courtier showed that the use of the adjoint of a numerical model makes it possible to determine the initial conditions leading to a forecast that would best fit data available over a finite time interval[7]. These two formulations can be combined to yield what is now
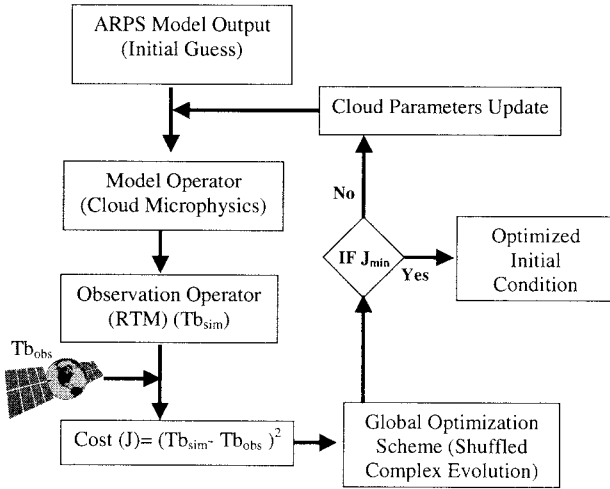
Fig.1 General framework of CMDAS

estimation problem or 4D-Var. Therefore, it has been realized that the assimilation of satellite derived rainfall and related data types can offer a way to compensate for model deficiencies and tightness estimates of atmospheric parameters given by different assimilation systems.

The present study explores the variational framework of an 1-D Cloud Microphysics Data Assimilation System (CMDAS) for retrieving reasonable cloud distribution. This paper investigates potentials of the CMDAS to modify the cloud properties by considering integrated cloud liquid water content as a assimilation parameter and to introduce the heterogeneity into the initial state of the atmosphere, by applying the CMDAS to the satellite microwave radiometer data set.

2. DEVELOPMENT OF CMDAS

Fig. 1 shows the general framework of the 1-D CMDAS in this study. It includes the Kessler warm-rain cloud microphysics scheme as a model operator, a microwave radiative transfer model (RTM) for the atmosphere as an observation operator and a global optimization method of SCE.

In order to provide the first guess to run CMDAS, a non-hydrostatic model named Advanced Regional Prediction System (ARPS) developed by the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma is used by coupling with the global analysis data set. ARPS includes four packages: an atmospheric model, a land surface scheme, a radiation package and parameterization of cloud microphysics. Therefore from simulation of ARPS, control variables of relative humidity, mixing ratios of cloud water and rainwater, accumulated grid scale rainfall, rain rate profile, pressure and base state air density are obtained in

order to run the model operator.

Considering that the satellite microwave radiometer can provide an integrated value of CLWC (ICLWC) but not a vertical profile, we chose the ICLWC as an assimilation target parameter. In addition, we introduce a parabolic CLWC distribution with zero values at cloud top and bottom, for combining the ARPS outputs and the assimilation target, as it looks feasible regarding to the cloud system development.

The Kessler warm-rain cloud microphysics scheme is run by using the available first guess of the control variables provided from ARPS and modifies the variables of water vapor specific humidity, pressure, air temperature, perturbation potential temperature. All these variables along with other supplementary parameters, salinity, satellite frequency, drop size distribution, are input to the observation operator i.e., radiative transfer model (RTM) to estimate the microwave brightness temperature observed by satellites.

During the assimilation process, the ICLWC is updated, until the simulated microwave brightness temperature (TB_{sim}) is in good agreement with the observed one (TB_{obs}). Then SCE minimization method tries to find the best assimilated parameter to minimized the discrepancy between TB_{sim} and TB_{obs}.. In this way, we found better initial condition of the targeted parameter.

Each component of the algorithm is described in detail as follows.

(1) Cost Function

The assimilation scheme is used to minimize the cost function J by adjusting state vector x[9]. In general J can be separated into two different costs i.e., the background error J_B and the observation error J_0:

$$J = J_B + J_0 \qquad (1)$$

For this application the background error J_B is neglected. Therefore J reduces to the observation error J_0, which is expressed as:

$$J_0 = J(x_0) \qquad (2)$$

$$J_0 = \frac{1}{2}\sum_{i=1}^{N}\left(H[x_i] - y_i^0\right)^T R^{-1}\left(H[x_i] - y_i^0\right) \qquad (3)$$

y_i^0 is a vector representing the satellite observation at 89 GHz (vertical and horizontal polarization), which will be assimilated. H is the radiative transfer model (observation operator) and R is the error covariance matrix of the observation. x_i represents the state vector at time t_i calculated by the cloud microphysics model M (model operator) using the

state vector x_0 at time t_0 as initial conditions.

R is assumed as unit matrix because of no information to estimate it while environmental forcing data are neglected at the moment. The state vector x_i comprises of

$$x_i = M(x_0, t_i) \qquad (4)$$

where x_0, x_i represents the intial state and state at time t_i of the ICLWC respectively. Combining Eq.(3) and Eq.(4) yields the cost function for the assimilation scheme:

$$J(x_0) = \frac{1}{2}\sum_{i=1}^{N}\left(H[M(x_0,t_i)] - y_i^0\right)^T \cdot$$
$$\left(H[M(x_0,t_i)] - y_i^0\right) \qquad (5)$$

The above equation shows that the TB_{obs} is directly included into the minimization process of the cost function J as y_i^0.

(2) Model Operator

To address the condition of Japan Sea in winter, the effect of the ice particles physics have to be considered but however, the ice schemes consume long computational time and physically more complex. In order to understand the effectiveness of CMDAS framework along with computationally less cost, we select the Kessler warm rain microphysics scheme as a model operator in this study.

As at this stage of the paper, we focus only on the assimilation of cloud rather than assimilation of precipitation. Due to that reason, the snowfall particles have not been introduced into this data assimilation system. Therefore to remove complicated processes including the evolution of cloud condensate from very small water or ice particles up to precipitation-size particles, we chose simple microphysical parameterizations, employing as few field variables as possible to represent cloud condensate[9] seems more reasonable at a first step of system development rather than using complex ice microphysics.

Fig. 2 explains the processes involved in Kessler scheme[10),11)], which includes three categories of water i.e., water vapor, cloud liquid water and rain water. Each of the liquid water forms is implicitly characterized by a droplet distribution. Small cloud droplets are first formed when the air becomes saturated and nucleation occurs. If the cloud water-mixing ratio exceeds a threshold value, raindrops are formed by auto-conversion from the cloud droplets.

The raindrops then collect smaller cloud droplets by accretion as they fall at their terminal speed. The evaporation rate is used only when the air is unsaturated. The saturation adjustment scheme
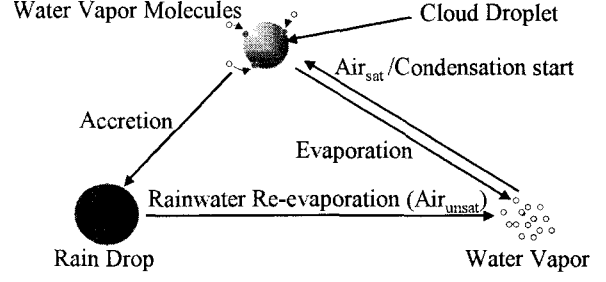

Fig.2 Processes involved in Kessler scheme

computes the amount of water vapor converted to cloud water if super-saturation exists, or the amount of cloud water evaporated if sub-saturation exists. The adjusted values for temperature, water vapor specific humidity, cloud water mixing ratio and rainwater mixing ratio are obtained at each integration time step and are finally passed to the observation operator.

(3) Observation Operator

RTM as the observation operator is used to calculate the microwave brightness temperature corresponding to the outputs from the model operator. Considering the scattering effect of snow particle as well, the 4-stream fast model developed by Liu[12] is used as an observation operator.

The radiative transfer in a plane-parallel and azimuthally symmetric atmosphere with spherical particles can be expressed by Tsang and Kong[13].

$$\mu \frac{d}{d\tau}\begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix} = \begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix}$$
$$-\frac{\omega_0}{2}\int_{-1}^{1}\begin{bmatrix} P_{VV} & P_{VH} \\ P_{HV} & P_{HH} \end{bmatrix}\begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix}d\mu'$$
$$-(1-\omega_0)B(\tau)\begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad (6)$$

where $I_P(\tau,\mu)$ is the radiance at optical depth τ in direction μ for vertical or horizontal polarization, ω_0 is the single-scattering albedo, $B(\tau)$ is the Plank function and P_{ij} (i, j = H or V) is the scattering phase functions. The 4stream model solves Eq.(6) by using the Discrete Ordinate Method (DOM) and introducing the approximations that no cross-polarization exist. The scattering phase function is expressed by the Henyey-Greenstein formulation[14]. These considerations and the limitation of the number of streams to four make it possible to solve Eq. (6) efficiently from the computational point of

view. In order to solve Eq. (6) boundary conditions for the top and the bottom of the atmosphere need to be applied. The upper boundary layer is assumed to be a constant stellar background with a brightness temperature of 3° K. The bottom of the atmosphere is bounded by the ocean surface.

As we are not using ice microphysics as a model operator, therefore scattering effect of snow particles are not taken into consideration.

(4) Shuffled Complex Evolution (SCE) Method

In order to reduce the cost function, the algorithm uses heuristic global optimization method of SCE[15], which has become one of the most popular among water resources engineers. It involves the evaluation of the function usually at a random sample of points in the feasible parameter space, followed by subsequent manipulations of the sample using a combination of deterministic and probabilistic rules. It guarantees asymptotic convergence to the global optimum. The basis of its algorithm is based on an iterative method, where the difference between modeled and observed brightness temperature is minimized by adjusting the assimilated parameter. Mathematically, this can be expressed as

$$\min\left(\sum_{i=1}^{L} T_{B,i} - M(P)\right) \qquad (6)$$

where $T_{B,i}$ is the brightness temperature observation at a specific frequency and polarization i and M is the radiative model using the atmospheric parameters of interest P which in our case is the ICLWC.

3. CASE STUDY

A case study is conducted over the Sea of Japan on 25th Jan 2003 under the strong winter monsoon. The domain area includes the filed of the Wakasa Bay Experiment 2003, which is close to the city of Fukui. Its size is 240 km x 240 km x 11 km with vertical and horizontal resolutions of 0.375 km and 4 km respectively. The GANAL data 136° E longitude and 36.2° N latitude is used as the initial condition of the simulation.

Rough estimate of cloud top (**Fig. 3**) of 3500 m is derived from available data from Moderate-resolution Imaging Spectroradiometer (MODIS) onboard of Aqua. This ensures that the time of the cloud top and the microwave brightness temperature observations should be matched, while no observation data of the cloud bottom is available; therefore it is assumed to be 2500 m below the cloud top.

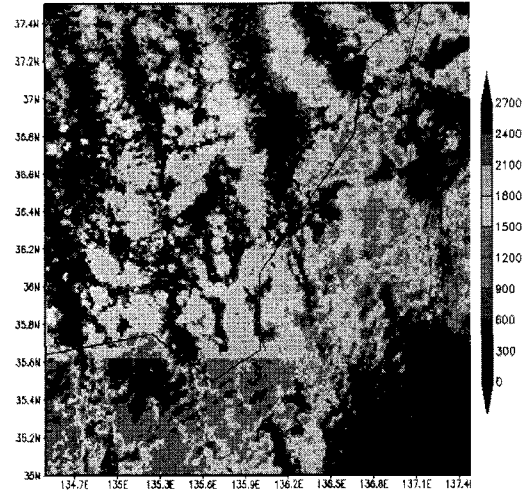To have initial condition (x_o) of CMDAS, firstly

Fig.3 Estimated Cloud Top from MODIS for 25th Jan 2003 at 03:55z.

ARPS model simulation is setup to run at 25th Jan 2003 from 00:00z to 03:55z by initializing it with the use of external global re-analysis (GANAL) data set.

The simulated output of ARPS at 03:30z is then used as a initial condition (i.e first guess) in order to run the assimilation system of CMDAS. The CMDAS is run for assimilation window of 25 minutes in order to compare the results of TB_{sim} and TB_{obs} at the observation time of 03:55z.

(1) Data Sets
a) AMSR-E Brightness Temperature Data

The AMSR-E brightness temperature data is provided by Japan Aerospace Exploration Agency (JAXA) for the area of 131° E to 141° E and 31° N to 41° N. The data is grided at a resolution of 0.05°. It should be noted that the actual average footprint size for the 89.0 GHz frequency channel is 5.4 km[16] which represents around 0.04° at this latitude.

b) GANAL Atmospheric Data

The GANAL data set provided from the Japanese Meteorological Agency (JMA) contains sea level pressure, geo-potential height, air temperature and dew point temperature with a 1.25° for horizontal resolutions, and 13 vertical levels from surface to 100 hPa, which correspond to a height of 16 km and is sufficient for the radiative transfer in the microwave region. It provides temperature, pressure and relative humidity every 12 hours (00z and 12z).

(2) Results and Discussions

In this paper a basic study is presented to develop an algorithm in order to get a reliable cloud distribution by applying the CMDAS to the AMSR-E data and the GANAL outputs.

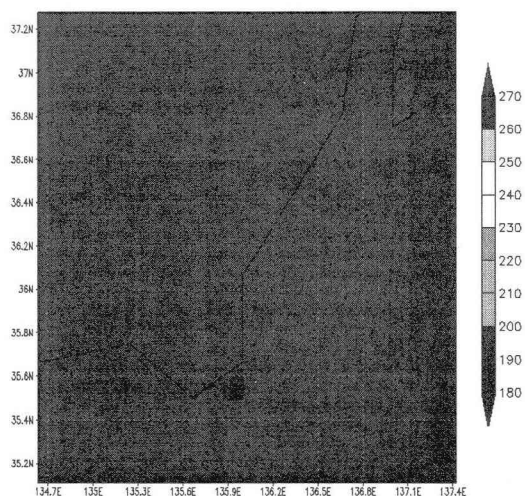The CMDAS during the assimilation of ICLWC

Fig.4 TB_{sim} at 89.0H GHz without CMDAS retrieved for 25th Jan 2003 at 03:55z.

Fig. 5 TB_{sim} at 89.0H GHz with CMDAS for 25th Jan 2003 at 03:55z.

Fig.6 Difference between TB_{sim} (**Fig. 5**) and TB_{obs} by AMSR-E at 89.0H GHz for 25th Jan 2003 at 03:55z.

Fig.7 Initial ICLWC [g/m^2] retrieved for 25th Jan 2003 at 03:30z.

modify the water vapor field, temperature field, pressure field, mixing ratio of cloud water and rainwater.

In order to identify effects of the CMDAS on the cloud distribution mapping, the results of the simulation in two cases, i.e. without the CMDAS (Case 1) and with (Case 2) the CMDAS, are compared.

For Case 1, the simulated microwave brightness temperature at 89.0H produces a completely homogeneous structure of brightness temperature as shown in **Fig.4**. It can't be successful to generate cloud formation effectively mainly due to homogeneity of the external GANAL data set i.e. the poor initial conditions. It is also suspected that water vapor is not sufficient for reliable prediction of cloud distribution and precipitation. Therefore, there is need to incorporate the information of CLWC in the initialization of model for improved forecast of precipitation.

In Case 2, the short assimilation time period is selected due to neglecting impacts of environmental forcing, which cause changes very dramatically, for checking the impacts of the CMDAS at the cloud distribution mapping.

Fig. 5 shows that the assimilation system improves the performance of cloud microphysics scheme significantly. That's mainly due to intrusion of heterogeneity into the external GANAL data, which resultantly improved atmospheric initial conditions by considering the ICLWC as the assimilation parameter.

Fig. 6 shows the difference between observed and simulated brightness temperature after the iteration stopped in Case 2. Almost all parts of the simulation result show very good agreement with the observed one with around $\pm 2K$ discrepancy. **Fig. 7** and
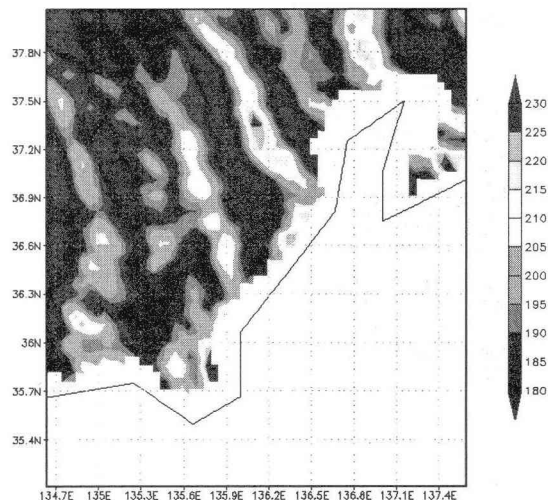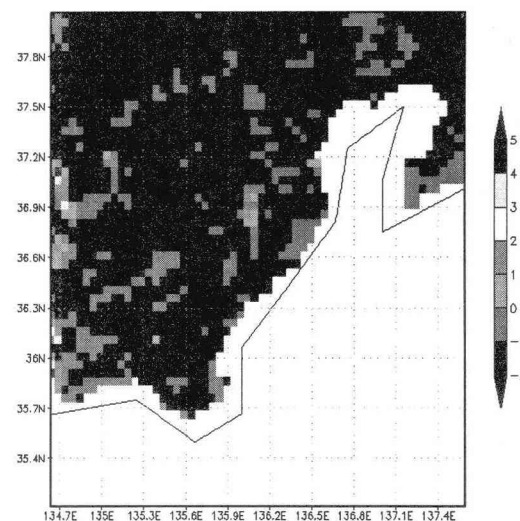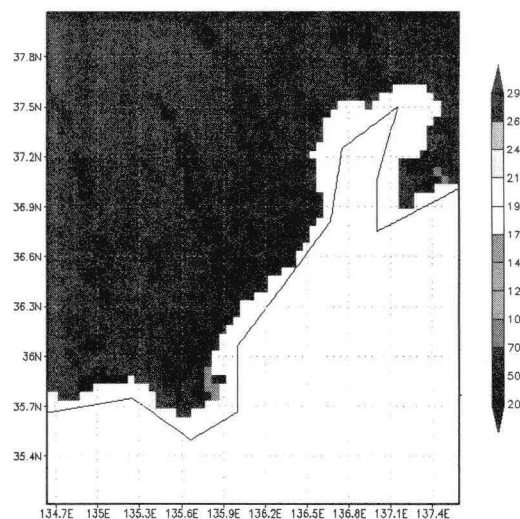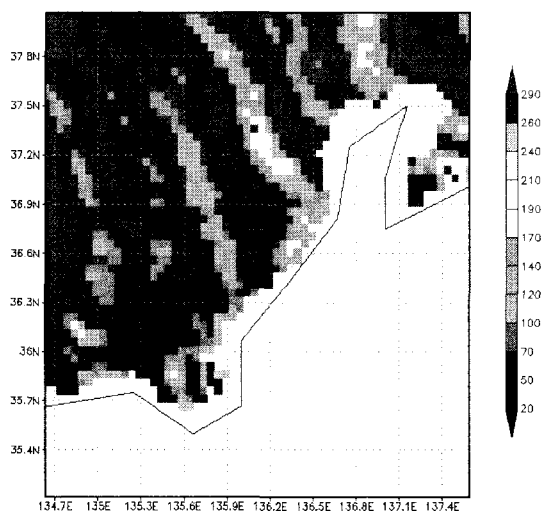
Fig.8 Final ICLWC [g/m^2] retrieved for 25th Jan 2003 at 03:55z.

Fig. 8 reveal that the CMDAS has significantly improved the amount of assimilated ICLWC. Final ICLWC (**Fig. 8**) result shows the comparable structure of cloud system with MODIS image for cloud top (**Fig. 3**). ICLWC horizontal spatial distribution output seems better than simulation results without the CMDAS (Case 1).

4. CONCLUDING REMARKS

The CMDAS shows the ability to introduce the spatial heterogeneity of ICLWC into the downscaling for the global model to the regional one.

Regarding the future step, there is need to consider the environmental forcing data for the assimilation system in order to dynamically modify the atmospheric fields.

Furthermore, there is need to validate the products of CMDAS i.e., whether the new initial conditions provided by CMDAS can improve weather prediction of forecast or not. Therefore by using CMDAS output as new initial conditions of the mesoscale model especially for remote areas where no gauge network can be found, we can make initial conditions for finer grid scale model in combination with observed satellite brightness temperature data. By this downscaling method, we may get more reliable forecast of precipitation, which will ultimately contribute to ungauged basins.

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