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RETRIEVING CLOUD PARAMETERS OVER OCEANS FROM AMSR-E DATA BY DEVELOPING AN 1-D CLOUD MICROPHYSICS DATA ASSIMILATION SYSTEM (CMDAS)

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SYNOPSIS

In order to retrieve reasonable cloud distributions, the development of an 1-D Cloud Microphysics Data Assimilation System (CMDAS) has been adopted. The general framework of CMDAS includes the Kessler warm-rain cloud microphysics scheme, a 4-stream fast microwave radiative transfer model (RTM) in the atmosphere, and a global minimization method known as Shuffled Complex Evolution (SCE). The CMDAS assimilates the satellite microwave radiometer data set of Advanced Microwave Scanning Radiometer (AMSR-E) and retrieves integrated cloud liquid water content (ICLWC). The retrieved ICLWC values are then used to construct the cloud profile according to the cloud base level and top level. This new method successfully introduces the heterogeneity into the initial state of the atmosphere, and the modeled microwave brightness temperatures agree well with observations of Wakasa Bay Experiment 2003 in Japan.

INTRODUCTION

Clouds as a key component in regulating the energy cycle and water cycle of the climate system have been a focus of the cloud physics community over the last few decades (Cotton et al. (8), Liu et al. (35), Meijgaard et al. (41)). Clouds exert various influences on the earth-atmosphere system such as modification of the radiative fluxes in the atmosphere, the transport of heat, moisture, and momentum which have their origin in cloud microphysical processes (Jakob, (23), Rotstayn, (50)). Changes in cloud microphysical processes can modify the spatial extent, spatial distribution, lifetimes of clouds, the water vapor distribution outside of clouds and the fluxes of water and radiation through the atmosphere.

Given the importance of the various influences clouds have in the evolution of both the atmosphere and the surface, the accurate parameterization of cloud microphysical processes is of fundamental importance in numerical simulations of tropical climate and their effects need to be included in the numerical weather prediction (NWP) models (Gates et al. (17), Li et al. (32), Randall (47), Young (59), Schultz (51),). For reliable NWP, an accurate description of the initial state of the atmosphere is required. However, current operational in-situ observation systems, which are used in NWPs to improve atmospheric state, can not observe the cloud liquid water content (CLWC). Therefore, the unavailability of CLWC in the conventional observation data may result into a poor initialization and an unreliable precipitation prediction of the atmospheric model.

In recent years, retrieval of atmospheric hydrological variables such as CLWC, precipitation rate etc. over the oceans from Defense Meteorological Satellite Program (DMSP), and Special Sensor Microwave Imager (SSM/I) brightness temperatures have been used in the context of mesoscale analysis (Alliss et al. (1), Chang et al. (7)), NWP (Illari (21), Isaacs et al. (22), Nehrkon et al. (44)), and in the production of global climatoligies (Bauer and Schulessel (4), Liu et al. (34), Tjemkes and stephens (54)). However, most of these studies were based on the retrievals of atmospheric variables from SSM/I brightness temperature directly by using either statistical or non-linear regression approaches.

Various approaches to the assimilation of precipitation data in NWP models have been developed such as 3-D and 4-D variational methods (Barker, et al. (3), Cucurull (9), Guo et al. (19), Lorenc et al. (36), Zupanski et al. (60, 61)), "physical" initialization (Krishnamurti et al. (29, 30, 31), Treadon, (56)) and "dynamical nudging" (Davidson and Puri (10)) to make reliable short-range forecasts by improving the initial conditions for the analysis (Donner (12), Manobianco et al. (37), Mathur et al. (39, 40)).

Since 1998, there has been an ongoing studies to assimilate retrieved rain rates from the TMI and SSM/I instruments into the ECMWF model to correct the model initialization by assimilating brightness temperatures directly through the use of a radiative transfer operator (Bauer (5), Marécal and Mahfouf (38), Moreau et al. (43)) in a 1D variational (1D-Var) context. Lorenc (36) showed that the statistical estimation problem could be cast in a variational form which is just a different way of solving the problem that the optimal interpolation attempts to solve directly. Eyre (14) 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. The advantage of using brightness temperatures is that they control some of the assumptions required to convert the model state variables into microwave brightness temperatures through the use of a radiative transfer model (RTM). The direct use of brightness temperatures also ensures greater flexibility in selecting useful channels and allows an easier definition of observational errors (Benedetti et al. (6)).

Keeping in mind the positive impact of variational satellite data assimilation in the NWP model analysis (Fillion and Errico (15), Fillion and Mahfouf (16), Moreau et al. (42), Treadon (55)), 1D-VAR assimilation method is adopted in the current research for the development of an Cloud Microphysics Data Assimilation System (CMDAS). The main purpose of development of CMDAS is to retrieve the reasonable cloud distribution and to investigate its potential regarding the cloud properties by considering integrated cloud liquid water content (ICLWC) as an assimilation parameter.

DEVELOPMENT OF CMDAS

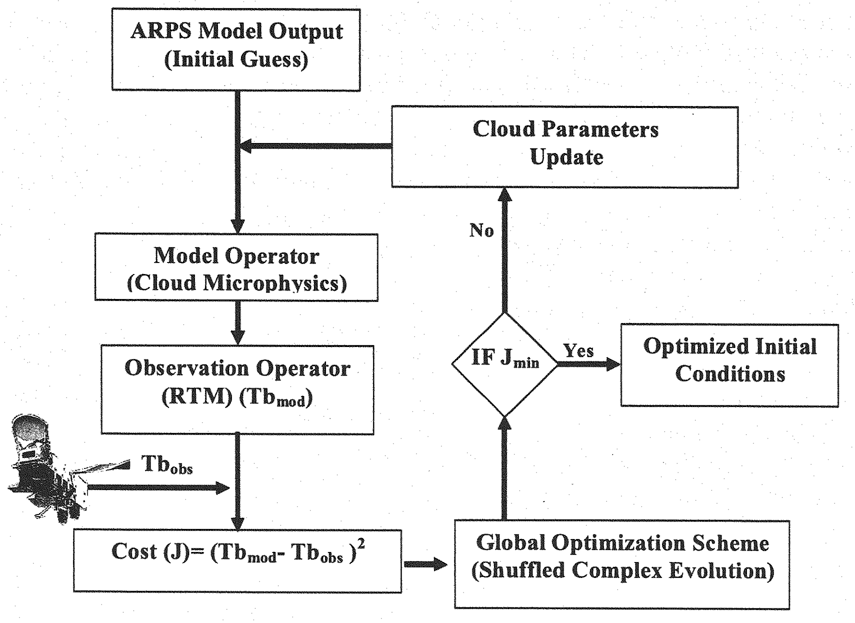

Fig. 1 General framework of the CMDAS

Fig. 1 shows the general framework of the 1-D CMDAS. It includes the Kessler warm-rain cloud microphysics scheme as a model operator, a 4-stream fast microwave radiative transfer model (RTM) for the atmosphere as an observation operator and a global optimization method of Shuffled Complex Evolution (SCE). In the following, we will at first introduce the general framework, and then describe details of each components.

In this study, the first guess for the CMDAS simulation was produced by a non-hydrostatic model named Advanced Regional Prediction System (ARPS), by using global reanalysis (GANAL) data set to supply boundary and initial conditions. The ARPS was developed by the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma. It includes four packages: an atmospheric model, a land surface scheme, a radiation package, and a parameterization scheme of cloud microphysics (Xue et al. (58)). From simulation of ARPS model, control variables of relative humidity, mixing ratios of cloud water and rainwater, accumulated grid scale rainfall, rain rate profile, pressure, temperature and base state air density are obtained, which is used as an initial guess to run the Kessler warm rain microphysics scheme as model operator of CMDAS.

Considering that the satellite microwave radiometer represents integrated information of the whole atmospheric layer and lower boundary condition, it is impossible to retrieve a vertical profile directly, so we used the ICLWC as an assimilation target parameter. To obtain the cloud profile, we assume a parabolic distribution (Anthes (2), Karyampudi et al. (26), Raymond and David (48)) of CLWC distribution with zero values at cloud top and bottom.

The Kessler warm-rain cloud microphysics scheme as model operator 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 and potential temperature. All these variables as well as other supplementary parameters such as salinity to calculate the emission from the ocean surface, satellite frequency and drop size distribution, which are important for accurate description of the ocean state (Ricci et al. (49)), are input to the observation operator i.e. the 4-stream fast RTM to estimate the modeled microwave brightness temperature.

The assimilation itself is an iterative process during which the SCE updates the initial ICLWC to minimize the cost function "J". The cost function "J" expresses the discrepancy between the observed brightness Temperature (TB_{obs}) and the brightness temperature modeled by the radiative transfer model (TB_{mod}). In this way, we can find better initial conditions for the targeted parameters.

Each component of the algorithm is described in detail in the following sections:

Model Operator

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 (Grabowski et al. (18)). It seems more reasonable to do this at the first stage of system development rather than using computationally expensive and physically more complex scheme of ice cloud microphysics.

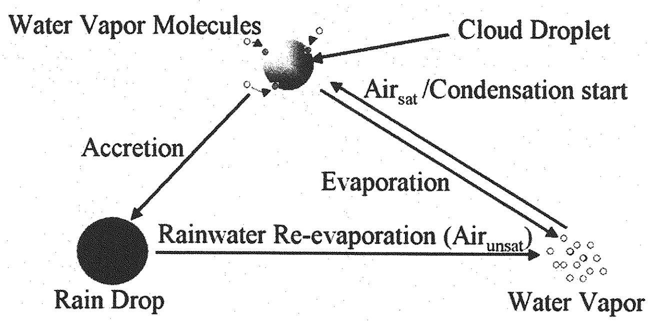

Fig. 2 Cloud microphysics Processes involved in the Kessler scheme

Fig. 2 illustrates the processes involved in Kessler scheme (Klemp et al. (27), Soong et al. (52)), which includes three water categories of water vapor, cloud liquid water and rain water. Each of the liquid water forms is implicitly characterized by a droplet distribution.

Auto conversion rate of cloud water to rain water

Small cloud droplets first form when the air becomes saturated and condensation occurs. If the cloud water-mixing ratio exceeds a threshold value, raindrops are formed by auto-conversion from the cloud droplets. The simple relation approximates the rate of auto conversion of cloud to rain water

$$A_r = C_{ar}\left(q_c - q_{c_{crit}}\right) \tag{1}$$

where A_r = auto conversion rate of cloud water to rain water in kg kg^{-1}s^{-1}; q_c = cloud water mixing ratio in kg kg^{-1}; $q_{c_{crit}}$ = 1 x 10^{-3} kg kg^{-1} is the cloud water mixing ratio threshold; and C_{ar} = 1 x 10^{-3} s^{-1} represents the auto conversion rate.

Accretion (collection) of cloud water by rain water

The raindrops then collect smaller cloud droplets by accretion as they fall at their terminal speed. The rate of accretion of cloud water by rainwater is approximated by

$$C_r = C_{cr} q_c q_r^{0.875} \tag{2}$$

where C_r = accretion rate of cloud water by rainwater in kg kg^{-1}s^{-1}; q_r = rainwater mixing ratio in kg kg^{-1}; and C_{cr} = 2.2 s^{-1} is the auto conversion rate.

Terminal velocity of rainwater

The terminal fall velocity for the averaged-sized raindrops is

$$V_{tr} = 36.34\left(0.001\bar{\rho} q_r\right)^{0.1364}\left(\rho_o / \bar{\rho}\right)^{0.5} \tag{3}$$

where V_{tr} = terminal velocity of air in m s^{-1}; $\bar{\rho}$ = base state density in kg m^{-3}; and ρ_o = 1.225 kg m^{-3} is the reference density.

Rainwater evaporation

The evaporation rate of raindrops is defined as

$$E_r = \frac{1}{\bar{\rho}} \frac{C\left[1 - q_v / q_{vs}\right]\left(\bar{\rho} q_r\right)^{0.525}}{2.030 \times 10^4 + 9.584 \times 10^6 / \left[q_{vs}\bar{p}\right]} \tag{4}$$

where E_r = evaporation rate in kg kg^{-1}s^{-1}; q_v= water vapor mixing ratio in kg kg^{-1}; and p = pressure in Pa. The ventilation coefficient is given by

$$C = 1.669 + 30.3922\left(\bar{\rho} q_r\right)^{0.2046} \tag{5}$$

The evaporation rate is used only when the air is unsaturated.

Saturation Adjustment

The saturation adjustment scheme computes the amount of water vapor converted to cloud water if super-saturation exists $\left(q_v > q_{vs}\right)$, or the amount of cloud water evaporated if sub-saturation exists $\left(q_v < q_{vs}\right)$. Here q_{vs} is the saturation mixing ratio calculated from Teten's formula. The amount of adjustment to q_v is given by

$$\delta q_{vs} = \frac{-\left[q_v^* - q_{vs}^*\right]}{1 + \dfrac{a_w(273.15 - b_w)q_{vs}^* L_v / C_p}{\left[T^* - b_w\right]^2}} \tag{6}$$

with δq_{vs} subjected to the following test:

$$\delta q_{vs} = \min\left[\delta q_{vs}, q_c\right] \tag{7}$$

Here the asterisked variables have been updated for the purpose of advection, diffusion filtering, and other forcing processes; and δq_{vs} = the amount of cloud mixing ratio in kg kg^{-1} created by condensation (if negative) or evaporation (if positive). The adjustment to the potential temperature corresponding to the change in q_v is

$$\delta\theta' = -\overline{\Gamma}\delta q_{vs} \tag{8}$$

where $\overline{\Gamma}$ is defined as

$$\overline{\Gamma} = L_v / \left(\overline{\Pi} C_p\right) \tag{9}$$

where L_v = latent heat of evaporation defined by

$$L_v = 2500780.0\left(273.15\overline{T}^{-1}\right)^{\left(0.167+3.67\times10^{-4}\overline{T}\right)} \tag{10}$$

The temperature has units of K, and L_v has units of J kg^{-1}. $\overline{\Pi}$ is the Exner function (or the non-dimensional pressure) given by

$$\overline{\Pi} = \left(\overline{p}/p_o\right)^{R_d/C_p} \tag{11}$$

where R_d =286.04 J /(kg K) is the gas constant for dry air; C_p = 1004. J / (kg K) is the specific heat for dry air; and P_o = 1000 mb is a constant reference pressure.

Observation Operator

The 4-stream fast RTM developed by Liu (33), as the observation operator, is used to calculate the microwave brightness temperature from the outputs of the model operator. It has the capability of considering the scattering effect of snow particles and also has high computational efficiency.

The radiative transfer in a plane-parallel and azimuthally symmetric atmosphere with spherical particles can be expressed by Tsang and Kong (57).

$$\mu\frac{d}{d\tau}\begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix} = \begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix} - \frac{\omega_0}{2}\int_{-1}^{1}\begin{bmatrix} P_{VV} & P_{VH} \\ P_{HV} & P_{HH} \end{bmatrix}\begin{bmatrix} I_V(\tau,\mu) \\ I_H(\tau,\mu) \end{bmatrix} d\mu' - (1-\omega_0)B(\tau)\begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{12}$$

where $I_P(\tau,\mu)$ = radiance at optical depth τ in direction μ for vertical or horizontal polarization; ω_o = single-scattering albedo; $B(\tau)$ = Plank function; and P_{ij} (i, j = H or V) = scattering phase functions.

The 4-stream model solves Eq. 12 by using the Discrete Ordinate Method (DOM) and introduces the approximation of non-existence of cross-polarization. The scattering phase function is expressed by the Henyey-Greenstein (20) formulation. These considerations and the limitation of the number of streams to just four make it possible to solve Eq. 12 efficiently from a computational point of view. In order to solve Eq. 12, the upper and lower boundary conditions of the atmosphere must be applied. The upper boundary layer is assumed to be a constant stellar background with a brightness temperature of 3 K. The bottom layer of the atmosphere is bounded by the ocean surface.

As we do not use ice microphysics as a model operator, therefore the scattering effect of snow particles are not taken into consideration for the time being.

Cost Function

The assimilation scheme is used to minimize the cost function '*J*' by adjusting state vector *x* (Philippe (45)). A cost function usually comprises of both the background error and the observation error. For this application, it is assumed that the background error 'J_B' is zero (Kapitza (25)), therefore the cost function is expressed as follows:

$$J_0 = \frac{1}{2}\sum_{i=1}^{N}\left(H[x_i] - y_i^0\right)^T R^{-1}\left(H[x_i] - y_i^0\right) \tag{13}$$

where y_i^0 = vector representing the satellite observation at 89.0 GHz (vertical and horizontal polarization), which will be assimilated; H = radiative transfer model (observation operator); R = error covariance matrix of the observation; and x_i = state vector at time t_i calculated by the cloud microphysics model M (the model operator) using the state vector x_0 at time t_0 as initial conditions.

R is assumed as unit matrix because there is no data to estimate it while environmental forcing of water vapor and air mass convergence and divergence are neglected. The state vector x_i evolves with time, that is

$$x_i = M(x_0, t_i) \tag{14}$$

where x_o, x_i = initial state and state at time t_i of the ICLWC respectively. Combining Eqs. 13 and 14 yields the cost function for the assimilation scheme:

$$J(x_0) = \frac{1}{2}\sum_{i=1}^{N}\left(H[M(x_0,t_i)] - y_i^0\right)^T \cdot \left(H[M(x_0,t_i)] - y_i^0\right) \tag{15}$$

The above equation shows that the Tb_{obs} (i.e. y_i^0) is directly included into the minimization process of the cost function '*J*'.

Global minimization scheme: the Shuffled Complex Evolution (SCE) Method

In order to minimize the cost function, ICLWC uses the heuristic global optimization method of SCE (Duan et al. (13)), which has become one of the most popular methods among water resource 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. Its algorithm is based on an iterative method, where the difference between the modeled and observed variable is minimized by adjusting the state vector.

CASE STUDY

Study Area

The domain area includes the field of the Wakasa Bay Experiment 2003, which is 240 km x 240 km x 11 km with vertical and horizontal resolutions of 0.375 km and 4 km respectively.

The Wakasa Bay is located close to the city of Fukui (Japan), which is located at around 136± eastern longitude and 36±northern latitude (fig. 3). Wakasa Bay, on the eastern end of the Sea of Japan, has fairly predictable cold air outbreaks in which cold air from the Eurasian continent blows over the relatively warm Sea of Japan.

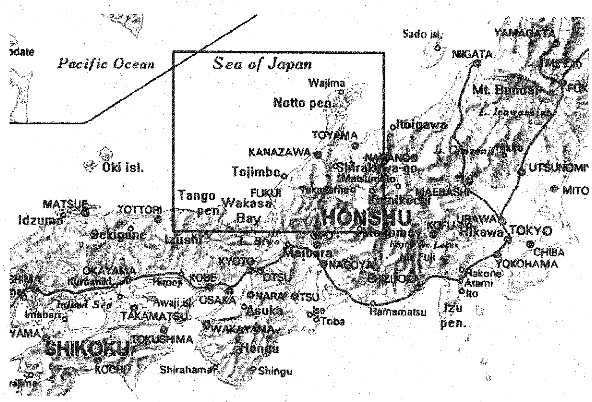

Fig. 3 Location of Study Area

Data Sets

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 gridded 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 (JAXA (24)) which represents around 0.04° at this latitude.

The GANAL data set provided from the Japanese Meteorological Agency (JMA) includes 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.

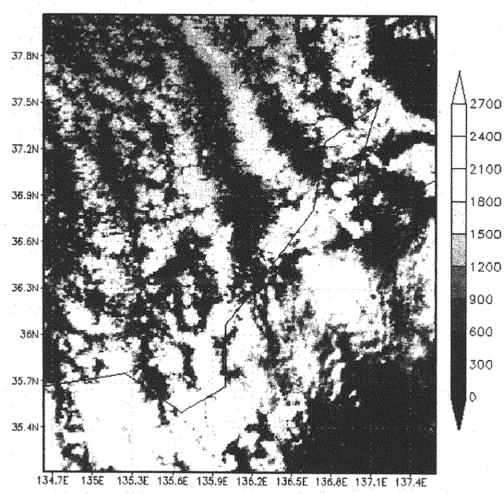

Fig. 4 Estimated cloud top from MODIS thermal IR image for 25th Jan 2003 at 03:55z

Model Setup

In order to create initial condition (x_o) of CMDAS, firstly an ARPS model simulation is setup to run for 1 day from 12:00z of 24th Jan 2003 to 12:00z of 25th Jan 2003 by initializing it with the use of external GANAL data set. The simulated output of ARPS at 03:30z is then considered as an initial condition (x_o) (i.e. initial guess) to run CMDAS. This means that the initial guess obtained at 3:30z at 25th Jan. 2003 from ARPS to run CMDAS should also not be affected by the "spin up" problem.

Before running the assimilation system, rough estimate of cloud top (Fig. 4) of 2500 m is derived from available data from Moderate-resolution Imaging Spectroradiometer (MODIS)

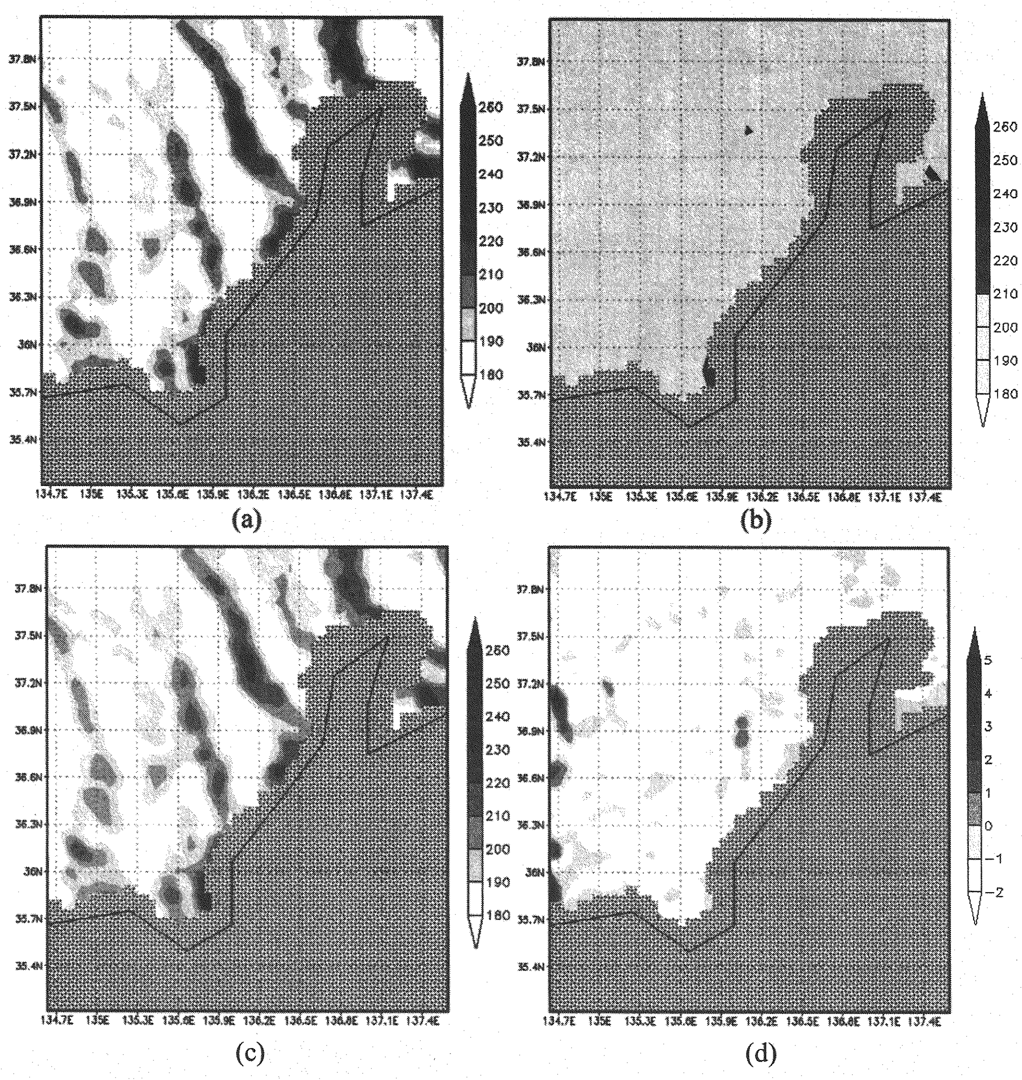

Fig.5 (a) Tb_{obs} by AMSR-E; (b) Tb_{mod} at 89.0H GHz without CMDAS and (c) with CMDAS; (d) quantitative analysis (Tb_{mod} - Tb_{obs}) retrieved for 25th Jan 2003 at 3:55z.

onboard of Aqua. This ensures that the timing of the cloud top and the microwave brightness temperature observations can be matched. The cloud bottom is arbitrarily assumed to be 1500 m below the cloud top, because no observation data is available. We use the MODIS image to compare the cloud distribution qualitatively not for the absolute or quantitative distribution.

The CMDAS is then run for the assimilation window of 25 minutes ranging from 03:30z to 03:55z. The values of Tb_{mod} and Tb_{obs} at the observation time of 03:55z are compared to analyze the effectiveness of CMDAS.

Results and Discussions

In order to identify the 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 CMDAS (Case 2) are compared.

For Case 1, the modeled microwave brightness temperature at 89.0H GHz produces a completely homogeneous structure of brightness temperature as shown in Fig. 5(b). It did not successfully generate cloud formations due to homogeneity of the external GANAL data set, which results into a poor initialization. As ICLWC from MODIS image in the study area is giving us the information that the cloud is composed of cloud liquid water content at the 3:55z of 25th Jan 2003 but the initial conditions of GANAL reanalysis data doesn't include the CLWC information. Therefore, there is a need to incorporate the information of CLWC in the initialization of model for improved forecast of precipitation.

Furthermore, as we assimilate over the ocean only, due to the big footprints of satellite, the footprints are overlapped over the land near to the shoreline (costal line). Therefore, the observed brightness temperature is discarded in those grids.

In Case 2, as the impacts of environmental forcing, which dramatic changes, are neglected, the short assimilation time period is selected in order to check the impacts of the CMDAS at the cloud distribution mapping.

Fig. 5(c) shows that the assimilation system improves the performance of cloud microphysics scheme significantly. This is mainly due to intrusion of heterogeneity into the external GANAL data, which resulted in improved atmospheric initial conditions by considering the ICLWC as the retrieved parameter.

Fig. (d) shows the difference between observed brightness temperature (Tb_{obs}) (fig. 5(a)) and modeled brightness temperature (Tb_{mod}) (fig. 5(c)) after the iteration stopped in Case 2. Almost all parts of the simulation results were in line with the observed ones with around $\pm 2K$ discrepancy.

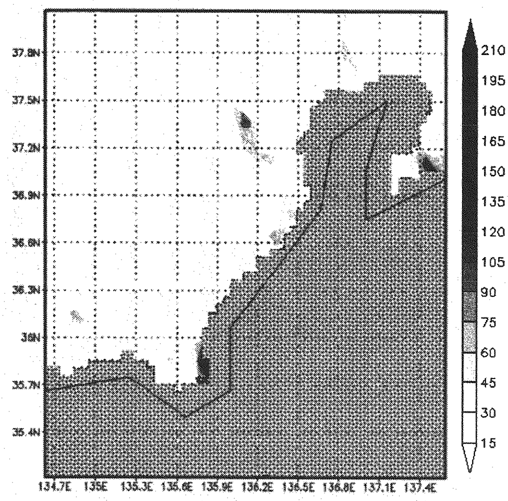

Fig. 6 ICLWC [g/m^2] retrieved for 25th Jan 2003 at Observation time of 03:30z.

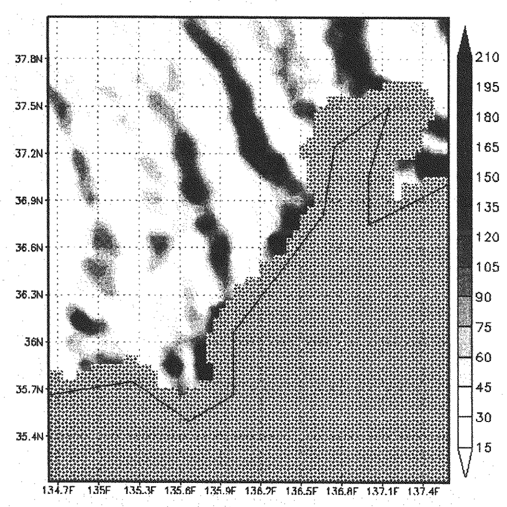

Fig. 7 ICLWC [g/m^2] retrieved for 25th Jan 2003 at Observation time of 03:55z.

Fig. 6 and Fig.7 reveal that the CMDAS has significantly improved the amount of assimilated CLWC. ICLWC result retrieved for 25th Jan 2003 at observation time of 03:55z (Fig. 7) shows the comparable structure of cloud system with MODIS thermal infrared image for cloud top (Fig. 4). ICLWC horizontal spatial distribution output seems better than simulation results without the CMDAS (Case 1).

For validation of ICLWC, a scatter plot (fig. 8) is drawn to examine the correlation of the retrieved ICLWC by AMSR-E satellite observation with the assimilated ICLWC taken from CMDAS simulation at 03:55z of 25th Jan 2003. The ICLWC from AMSR-E is obtained by taking the average of four grid cells collocated with the CMDAS grid points. The scatter plot reveals a close association between the observed and simulated ICLWC with a correlation coefficient of 0.79 although data points are scattered around the y = x line, where the root mean square error (RMSE) in the assimilated ICLWC is estimated to be 18.5 gm /m^2. While mean bias error (MBE) of 10.1 gm /m^2 signals a little overestimation in the assimilated ICLWC.

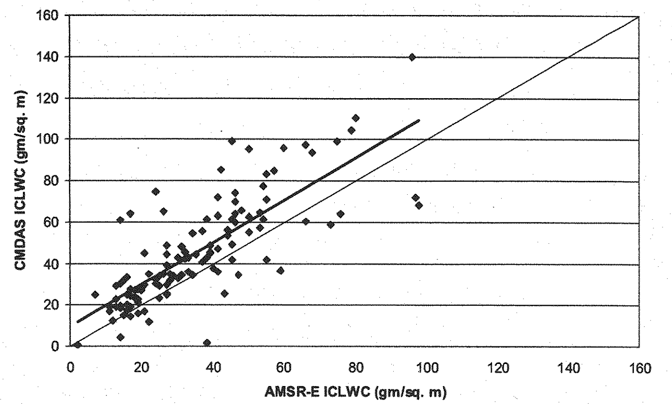

Fig. 8 Scatter plot of CMDAS vs AMSR-E ICLWC retrieved for 25th Jan 2003 at 03:55z.

CONCLUDING REMARKS

The present research work has highlighted in detail the methodology, application and validation of satellite data assimilation systems of CMDAS over the ocean by considering the assimilated parameter of ICLWC by using AMSR-E passive microwave remote sensing observations.

The simulation results of CMDAS with the observed AMSR-E Tb 89.0H GHz values identify clearly their effects on the cloud distribution mapping and show a comparable spatial distribution of a cloud system with MODIS thermal infrared (TIR) image for cloud top. CMDAS has shown the potential to assimilate passive microwave remote sensing observations into the cloud microphysics scheme. It shows the ability to introduce the spatial heterogeneity of ICLWC into the downscaling for the global model to the regional one and whose output can be used to improve initial conditions of the atmospheric model. However, to have better initial conditions, there is still a need to consider the environmental forcing data for the assimilation system in order to dynamically modify the atmospheric fields. This research provides clear evidence that ICLWC retrieved by CMDAS together with observations can be used to generate the reliable initial conditions in future.

Furthermore, there is a need to validate the products of CMDAS regarding the reliable weather prediction of forecast i.e., whether the new initial conditions provided by CMDAS have been improved or not. By the downscaling manner, initial conditions for local grid scale model can be obtained for having reliable precipitation forecast over the ungauged basins, especially for remote areas where gauge network cannot be established.

As CMDAS framework includes the Kessler warm rain microphysics as model operator which doesn't include the information of solid precipitation like snow, ice, hail and graupel. In order to apply our algorithm in severe winter, the processes involved in the ice cloud microphysics need to be considered. It may provide us with more detailed and improved initial conditions for NWP models analysis in the future.

It is also important to emphasize that the variational methods applied to operational, real-data numerical forecasting normally do not evolve the background error covariance in space and time during the assimilation period as is possible when using a Kalman filter approach (Derber and Bouttier (11), Klinker et al. (28), Rabier et al. (46)). Specification of time-varying, flow-dependent background error covariances is a challenge for all current operational data assimilation systems (Tanya et al. (53)).

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APPENDIX – NOTATION

The following symbols are used in this paper:

AMSR-E	= advanced microwave scanning radiometer on EOS (Earth Observing System);
A_r	= auto conversion rate of cloud water to rain water (kg $kg^{-1}s^{-1}$);
ARPS	= advanced regional prediction system;
$B(\tau)$	= Plank function;
C_{ar}	= auto conversion rate (1 x 10^{-3} s^{-1});
C_{cr}	= auto conversion rate (2.2 s^{-1});
C_p	= specific heat for dry air (1004. J / kg K);
C_r	= accretion rate of cloud water by rainwater (kg $kg^{-1}s^{-1}$);
CAPS	= center for analysis and prediction of storms;
CLWC	= cloud liquid water content;
CMDAS	= cloud microphysics data assimilation system;
DMSP	= Defense Meteorological Satellite Program;
DOM	= discrete ordinate method;
GANAL	= global reanalysis;
H	= radiative transfer model (observation operator);
ICLWC	= integrated cloud liquid water content;
$I_P(\tau,\mu)$	= radiance at optical depth τ in direction μ for vertical or horizontal polarization;
J	= cost function;
JAXA	= Japan aerospace exploration agency;
J_0	= observation error;

J_B = background error;
JMA = Japan meteorological agency;
L_v = latent heat of evaporation (J kg^{-1});
M = radiative model using the atmospheric parameters of interest *P* which in our case is the ICLWC;
MODIS = modern imaging spectro-radiometer;
NWP = numerical weather prediction;
P = pressure (Pa);
P_o =constant reference pressure (1000 mb);
P_{ij} = scattering phase functions at polarizations of (i,j = H, V);
q_c = cloud water mixing ratio (kg kg^{-1});
$q_{c_{crit}}$ = cloud water mixing ratio threshold (1 x 10^{-3} kg kg^{-1});
q_r = rainwater mixing ratio (kg kg^{-1});
q_v = water vapor mixing ratio (kg kg^{-1});
q_{vs} = saturation mixing ratio (kg kg^{-1});
R = error covariance matrix of the observation;
R_d = gas constant for dry air (286.04 J /kg K);
RTM = radiative transfer model;
SCE = shuffled complex evolution;
SSM/I = Special Sensor Microwave Imager;

Tb_i = brightness temperature observation at a specific frequency and polarization i;
Tb_{mod} = modeled brightness temperature (K);
Tb_{obs} = observed brightness temperature (K);
V_{tr} = terminal velocity of air (m s^{-1});
x = state vector;
x_o, x_i = initial state and state at time t_i of the ICLWC respectively;
y_i^0 = vector representing the satellite observation at 89.0 GHz (vertical and horizontal polarization), which will be assimilated;
$\bar{\rho}$ = base state density (kg m^{-3});
ρ_o =reference density (1.225 kg m^{-3});
δq_{vs} = amount of cloud mixing ratio (kg kg^{-1}); and
ω_o = single-scattering albedo.

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