DEVELOPMENT OF A SATELLITE BASED SEQUENTIAL LAND DATA ASSIMILATION SYSTEM COUPLED WITH A REGIONAL-SCALE ATMOSPHERIC MODEL

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In order to physically address the mechanism of land-atmosphere interaction based on land surface heterogeneity for better reproduction of local phenomena such as local circulation, convective cloud processes and associated rainfall events, a sequential land data assimilation system (LDAS) was developed to assimilate soil moisture by using satellite microwave data. LDAS consists of ensemble Kalman filter as an assimilation scheme, a radiative transfer model (RTM) as an observation operator and a land surface scheme (SiB2) as a model operator. RTM represents microwave radiative transfer in soil surface by considering surface roughness effects, volume scattering and emission effects in the soil volume. In addition, it also considers the attenuation and emission of microwave signal in vegetations layer. The LDAS has been coupled with a stand-alone regional atmospheric model. In order to assess the performance of new system (coupled land-atmosphere data assimilation system – LADAS), there-dimensional numerical experiments were carried out in a meso-scale area of the Western Tibetan Plateau. The assimilated soil moisture, surface temperature and heat fluxes are well agreed with observed data. While LADAS addresses land surface heterogeneities through improving soil moisture and heat fluxes, it also improves the atmospheric components in an indirect way. The Assimilation shows improvement in profiles of potential temperature and humidity when it compared with radio-sonde data.

Key Words: *Downscaling, data assimilation, radiative transfer model, microwave remote sensing*

1. INTRODUCTION

While general circulation models (GCMs) demonstrate significant skill at larger continental scale including substantial portion of those intricacies of global system, they are still unable to represent local sub-grid scale features and dynamics such as local circulation, convective cloud processes and precipitation[1)2)]. To reproduce meso-scale and local atmospheric phenomena accurately, several downscaling methods have been developed. Dynamical downscaling or nesting which is the most common practice used in numerical weather prediction (NWP), where regional scale models have been forced with initial and boundary conditions from GCMs. However this method is still unable to reproduce local phenomena and extreme events[3)] since the accurate land and atmospheric heterogeneities were not taken into account.

Soil moisture is not only directly affected by atmospheric conditions such as precipitation; it can in turn also influence these atmospheric conditions through its control on the surface energy balance. Recent modeling studies indeed have successfully isolated the effect of soil moisture on droughts, heat waves, floods and precipitation[4)5)6)]. Therefore soil moisture as an initial and boundary conditions to an atmospheric model should be accurate enough in spatial and temporal scale to capture realistic atmospheric structures through land-atmosphere feedback mechanism.

Global or regional soil moisture monitoring, however, is complicated due to its higher spatial and temporal variability. Space-borne passive microwave remote sensing (such as Advanced Microwave Scanning Radiometer on NASA's Earth Observing System - AMSR-E) is among the most promising technique due to its global and frequent coverage. The microwave region is the only part of the electromagnetic spectrum that permits quantitative estimation of soil moisture through the larger contrast in the dielectric constant of dry soil (~4) and water (~80) and the resulting dialectic properties of soil-water mixture. To get land surface information, longer wavelengths have been used since atmospheric contamination could be neglected due to their higher penetration properties.

Moreover soil moisture retrievals using microwave remote sensing are limited to few centimeters of soil depth while atmospheric models require moisture information in all model layers. This setback could be overcome by integrating retrieved soil moisture from satellite observation within a land surface scheme (data assimilation) to provide realistic and physically consistent soil moistures profile for atmospheric models.

Therefore developing a system which is to assimilate soil moisture state, coupled with an atmospheric model could overcome the limitation in standard nesting approaches. In this paper, we discuss about land data assimilation system development, its coupling with a meso-scale atmospheric model, validation with surface observation and finally the effect of improved soil on atmospheric structures using radio-sonde observations.

2. SYSTEM DEVELOPMENT

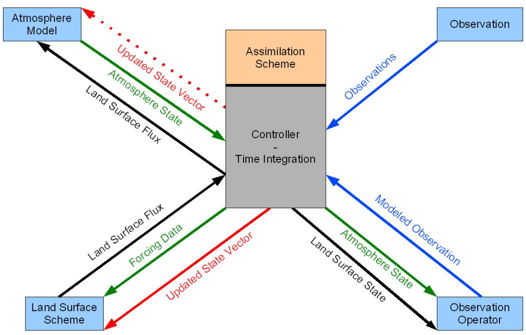

Fig.1 Schematic diagram of land data assimilation system coupled with an atmospheric model (LADAS)

The system (Fig.1) which was named as the coupled land-atmosphere data assimilation system (LADAS) consists of models and schemes. Following sub-sections are here to describe the significant components of the system.

(1) Atmosphere model

In this study, a regional to storm scale prediction system (the advanced regional prediction system - ARPS) has been chosen as an atmospheric model. It is three-dimensional, non-hydrostatic and fully compressible model. It includes advanced parameterizations for radiation, turbulence and cloud microphysics processes. Further detail could be fond in Xue et al.[7].

(2) Land surface model (LSM)

ARPS includes very simplified two layers, snow free, non-frozen land surface model. Considering physically based formulation and accuracy of estimating soil moisture, surface temperature and heat fluxes, simple biosphere model version 2 (SiB2) was chosen as an alternative to ARPS LSM.

SiB2 has incorporated a number of significant changes from its original version such as incorporating satellite observation for describing surface conditions, improved hydrological formulation for soil moisture interlayer exchanges and base flow and replacement of empirical stomatal models with photosynthesis-conductance model[8]. SiB2 model includes three soil layers: a surface soil layer (0-5cm), which act as a significant source of direct evaporation when moist. A root zone (5-20cm), which is the supplier of soil moisture to the roots and accounts for transpiration; and a deep soil layer, which acts as a source for hydrological base flow and upward recharge of the root zone.

On the other hand SiB2 does not consider freezing and thawing processes overtime during the freeze/thaw cycles. This water phase transition results significant changes in soil moisture content and then impacts on evaporation, canopy transpiration and thermal and hydraulic properties of soil. A modified Stefan solution was proposed by Li and Koike[9] to be incorporated in SiB2 to calculate the frost/thaw depth. This method also incorporated with currently available SiB2 to better estimate soil moisture, heat and moisture fluxes during the freeze/thaw cycles.

(3) Observation operator

Since the satellite does not directly measure soil moisture instead, it measures brightness temperature, observation operator provides the linkage between model and observations. It converts model surface moisture, temperature and roughness information into brightness temperature using a forward model called as radiative transfer model (RTM).

A sophisticated physically based RTM was developed in our laboratory which represents microwave radiative transfer in detail within the soil volume, on the soil surface and subsequently through vegetation layers.

At lower frequency, by neglecting atmosphere and rainfall effects, brightness temperature at satellite level can be simplified as,

$$T_b = T_{bs} e^{-\tau_c} + (1 - \varpi_c)(1 - e^{-\tau_c}) T_c \quad (1)$$

Where, T_b is the brightness temperature at satellite level, T_{bs} is the brightness temperature at surface, ϖ_c is the single scattering albedo of canopy, τ_c is the vegetation optical thickness and T_c is the canopy temperature.

Shibata et al.[10] has pointed out that soil moisture retrieved over very dry or desert area highly overestimated by available RTMs. This effect is due to deeper penetration of microwave in the very dry region, where profile and volume scattering effects within soil layer are become more dominant. Lu et al.[11] has proposed a method based on both field and numerical study to overcome this particular issue.

Further the electromagnetic signal which is emitted from surface depends on soil moisture and roughness of that particular surface. Therefore, roughness is also equally important and should be addressed correctly; if roughness is neglected, soil moisture will be underestimated. Many RTMs employ an empirical model[12] to account for surface scattering due to roughness effect. Kuria et al.[13] has showed that the advanced integral equation model (AIEM) with incorporation of shadowing effect is well agreed with observed data and it is best suited among the available physically based models. These two major achievements were incorporated in our RTM.

Once the signal leaves soil/air interface, it also experiences volume scattering and emission effects by vegetation layer. Vegetation optical thickness (τ_c) strongly depends on vegetation columnar water content W_c, the relationship can be expressed as [14].

$$\tau_c = \frac{bW_c}{\cos\theta} \quad (2)$$

Where, b is a coefficient that depends on frequency and canopy structure, θ is incident angle.

(4) Observation

AMSR-E is multi-frequency and dual polarized passive microwave radiometer that detects microwave emission form Earth's surface as well as atmosphere. It measures brightness temperature at 6.925, 10.65, 18.7, 23.8 and 89.0 GHz. It maintains a constant Earth incident angle of 55°, covering a swath of 1445 km on Earth surface and having spatial resolution of individual measurement varies from 5.4 km at 89.0 GHz to 56 km at 6.9 GHz. This study employs the vertical polarization of 6.925 and 10.65 GHz to retrieve the soil moistures.

(5) Assimilation scheme

The Kalman filter is the statistically optimal sequential estimation procedure for linear dynamical systems which updates the system whenever observations are available. The ensemble Kalman filter (EnKF) is introduced by Evensen[15] as an alternative to the traditional Kalman filter. EnKF represents the distribution of the system state using a collection of state vectors, called an ensemble, and replaces the covariance matrix by the sample covariance computed from the ensemble. The ensemble is operated with as if it is a random sample, but the ensemble members are really not independent and EnKF ties them together. It makes the assumption that all probability distributions involved are Gaussian and therefore it is computationally inexpensive than the particle filter.

EnKF was originally developed for atmospheric data assimilation and has been proved to handle non linear dynamic system and large state spaces efficiently. In the field of hydrology, Reichle et. Al[16] applied the EnKF to soil moisture estimation and found it performed well against the variational assimilation method. In our model development, we have adopted EnKF as an assimilation scheme.

(6) Controller

With the consideration of making a standard system which could have options to plug-in and test the combination of different models and data sources in the future, the controller was designed based on object oriented programming (OOP). It is modular, extensible and enabled on parallel computing technology to satisfy increasing high performance computing requirements. It has two integrations loops. First one is time integration where atmospheric model is integrated forward in time. When the model reaches the grid integration (second integration loop) which is nested inside the time integration, each grid calls its own combination of LSM, RTM and assimilation technique on run time. In this way the controller effectively handles the accessing and data transferring from one model to another.

3. Numerical Experiments

The Tibetan Plateau is climatologically very unique due to its high elevation and vastness.

Numerous studies have been conducted in the plateau such as thermal and orographic effects on atmospheric circulation patterns[17)], dry convection and heat transporting mechanism to upper layer[18)], synoptic scale rainfall and relationship with the plateau[19)], diurnal atmospheric boundary layer development, convergence of convective system and contribution of heat flexes on forming and developing boundary layers[20)].

These studies suggested that thermal effect of the giant plateau, large amount of solar radiation absorption and dramatic seasonal changes of surface heat and water fluxes greatly influence on atmospheric dynamics and circulations over Asia. The lack of quantitative understanding of land-atmosphere interactions makes difficult to understand and model the complete energy and water cycles over the Plateau and their effects on regional and global climate changes. In recent years, number of atmosphere-land interaction studies over the Plateau has increased but all these studies are limited to a particular period or in few locations using point observation or limited by observational variables or uses reanalysis data [21)22)23)].

In order to overcome these limitations and to get better understanding of land-atmosphere interaction over the plateau, it is very important to accurately reconstruct the land surface heterogeneity such as soil moisture, heat and moisture fluxes. Therefore LADAS will help greatly and could be a perfect tool to achieve the target.

(1) Study area and model set-up

The meso-scale area which is located in the western part of the plateau bounded within 82.65E-85.25E, 30.6N-33.2N, centered at Gaize station has been selected as a study area. Primary reason to select this region was the availability of surface as well as atmospheric sounding measurements for the system validation. Radio-sonde measurements were launched four times a day during 13th May to 13th June, 2008 (JICA-IOP).

Fig.2 shows the topography maps of regional and meso-scale models with spatial resolution of 20km and 5km respectively. The meso-scale model was nested inside the regional model. Initial and boundary condition were derived from NCEP FNL (1°X1°), six hourly data set.

In ARPS model, the following configurations such as 1.5 TKE turbulent mixing as sub grid-scale turbulent mixing, Coriolis parameters as latitude dependent, ice microphysics (Lin Ice) as microphysical process, Kain and Fritsch cumulus parameterization as convective cumulus parameterizations were set-up.

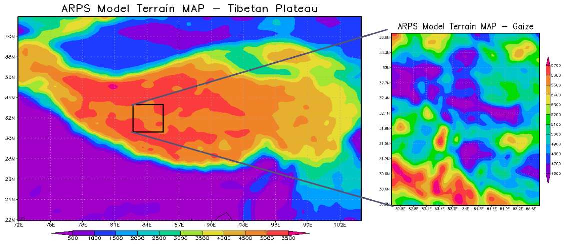

Fig 2: Topographical maps of regional and meso-scale models

In order to get spatially distributed soil moisture information from satellite data, the radiative transfer model requires spatially distributed parameters such as soil texture, porosity, roughness height, correlation length and vegetation parameters[13)24)]. These parameters were derived form a method (LDAS-UT) introduced by Yang et al.[24)]. Spatially distributed forcing data were prepared using ARPS model for two months and the accuracy was verified with observed forcing data in Gaize station (not shown here). Fig.3 illustrates the parameters which were derived from LDAS-UT method and used in RTM.

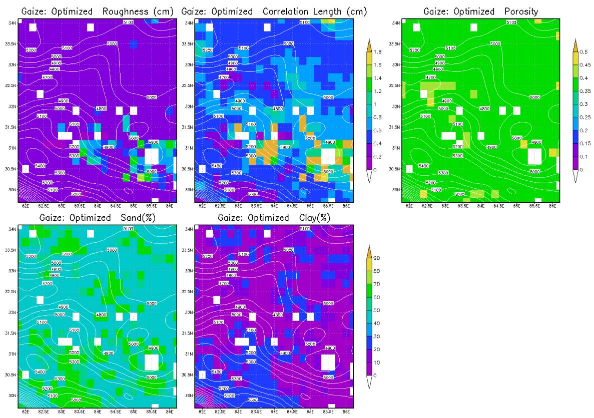

Fig 3: Spatially distributed parameters derived from LDAS-UT

4. Results and discussion

Two numerical simulations were carried out to test the system during pre-monsoon season. First simulation covers the period starting from April 21st to May 20th 2008 while second one covers from May 20th to June 20th 2008. No-assimilation is considered as ARPS run with its own LSM while assimilation is considered with LADAS run with models explained in section 2 with ensemble 50 members of soil moisture.

Fig.3 shows the observed and simulated surface soil moisture at Gaize station. From observation it is clear that soil surface was frozen and dry from April 21st to May 9th 2008. The assimilation which considered SiB2 with inclusion of frozen processes and volume scattering effect has better simulated soil moisture than no-assimilation during this period. During other periods, assimilation is more consistent with observation. During June, three consecutive rainy periods has been observed from observed soil moisture (Fig.4). While the system well assimilated later two surface soil moistures change due to rainfall events, it failed to capture the first event of soil moisture increment accurately.

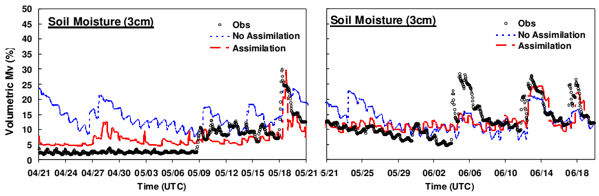

Fig 4: Time series plot of observed and model surface soil moisture at Gaize station

To verify this problem, AMSR-E data which is closer to Gaize station has been investigated. It could be clearly noticed from Fig.5 that there are sudden drops of brightness temperature at three instances at 5th, 12th and 18th June respectively and these drops are corresponding to the increase in soil moisture. The difference of brightness temperature at 5th is smaller (~10K) than other two drops (~20K), however, soil moisture increment in all instances show similar soil moisture increment. This could be resulted from spatial representativeness of AMSR-E (~50km) where the rainfall could have occurred at smaller scale.

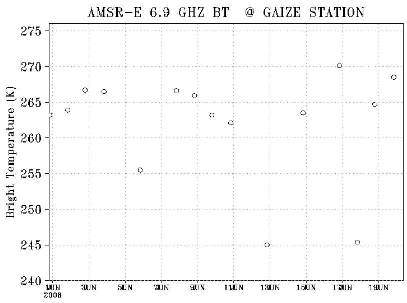

Fig 5: AMSR-E 6.9GHZ brightness temperature

Simulated surface temperature in assimilation case is much better than no-assimilation case (Fig.6). During daytime, no-assimilation case shows much lower surface temperature which is caused by high surface soil moisture (Fig4). During nighttime, again no-assimilation shows much lower values than observed values. This problem could be resulted from the absence of frozen processes in LSM which ignores the energy release due to freezing. The absence of energy reduces temperature much lower. These two problems have been overcome in the assimilation by estimating surface soil moisture and its phase changes accurately through improved LSM and data assimilation process.

Turbulent flux data were not available in Gaize and therefore Bowen ratio method has been used to estimate the fluxes from PBL tower observations.

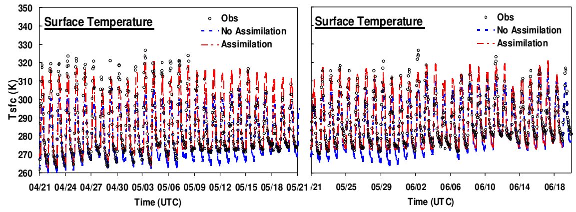

Fig 6: Time series plot for surface temperature at Gaize station

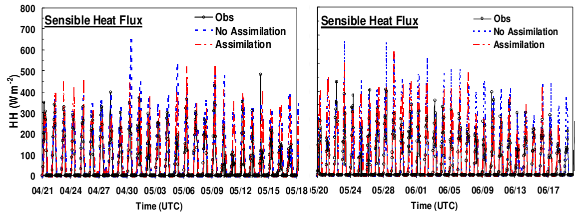

Fig 7: Time series plot sensible heat fluxes at Gaize station

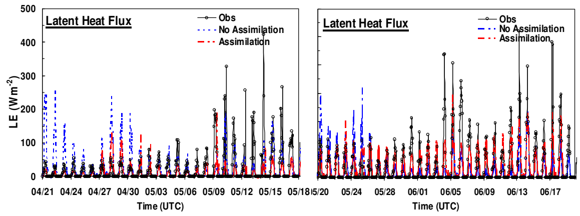

Fig 8: Time series plot latent heat fluxes at Gaize station

The assimilation (Fig.7 and Fig.8) has well estimated the fluxes; particularly during dry period no-assimilation has overestimated latent heat fluxes which are resulted from overestimation of surface soil moisture (Fig.3). In Fig.8, few days shows abnormal high of latent heat fluxes. These days are corresponding to rainfall events where Bowen ratio method can not be applied. In addition, these errors were also caused by the inaccuracy of model precipitation prediction (time and intensity).

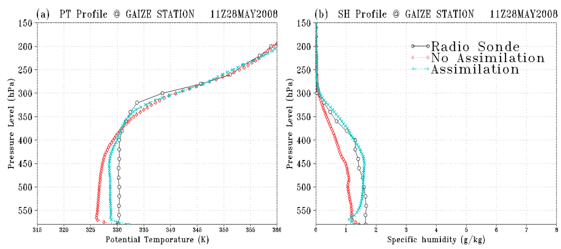

Fig 9: Comparison of soundings of (a) potential temperature (b) specific humidity at Gaize station

In order to quantitatively assess the effect of improved soil moisture on atmosphere, sounding data which were observed during JICA/IOP have been used. Fig.9 shows the comparison between no-assimilation and assimilation cases with observation on 28th May 2008 at 11UTC (other cases not shown). The results shows that improving the surface soil moisture and turbulent heat fluxes (Fig.8 and Fig.9) will eventually improve the profiles of potential temperature and specific humidity from surface to about 350~400hPa.

4. Conclusion

A sequential land data assimilation system coupled with regional scale model is developed to assimilate soil moisture using microwave satellite data. In this study, the system has been validated using point observation at Gaize station. The assimilated results show more consistent with observation than no-assimilation case. By improving the lower boundary conditions such as soil moisture, surface temperature and turbulent heat fluxes of an atmospheric model, eventually improves the land-atmospheric interaction and atmospheric processes. Further investigations are underway to assess the influences of spatial distribution of land surface heterogeneity on the mechanism of atmospheric processes such as local circulation, convective precipitation.

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