論文の内容の要旨

論文題目　Development of Satellite based Data Assimilation Systems
for Improving the Predictability of Numerical Weather Prediction
(数値気象予測モデルの改良へ向けた衛星データを利用した
データ同化システムの開発)

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The skill of operational weather forecasts has increased substantially over the last five decades. The improvement has taken place gradually and relatively steadily, driven by advances in scientific understanding of physical processes and rapidly increasing computational resource developments. Numerical Weather Prediction (NWP) is an initial-boundary value problem: given an estimate of the present state of the atmosphere and land surface, the model simulates (forecasts) the evolutions of land and atmosphere. Due to the chaotic and nonlinear nature of the atmospheric processes, numerical weather forecasts are more sensitive to the conditions that represent the present reality of land and atmosphere in the model. More and better observations that represent the complete nature of the current atmosphere and land surface will greatly improve our understanding and will enhance the forecasting capabilities of NWP models. Therefore, the first step in numerical weather forecasting is to collect the adequate information about land surface and atmosphere in real or near-real time.

The potential of remote sensing to monitor the Earth weather and climate system has been demonstrated over the years. The last decade has seen remarkable progress in exploring satellite observations, especially microwave measurements and the launching of new platforms (e.g., Terra, Aqua, and Advanced Land Observing Satellite (ALOS)). In microwave frequencies, many earth materials and atmospheric constituents exhibit a distinctive character for their electrical property called dielectric constant, which is more sensitive to the amount of water (e.g., at lower frequencies, dielectric constant for dry sand and for free water). This dielectric property allows for the quantitative estimation of moisture quantities such as soil moisture, vegetation water and snow water contents as well as atmospheric water vapor and cloud

condensate. Low-frequency passive microwave sensors are uniquely suited for soil moisture measurements owing to their penetration capability through atmosphere, whereas higher frequencies contain both land and atmospheric information.

Land surface processes play an essential role in understanding and predicting both global water and energy budgets. Soil moisture has been the central focus for accurate land surface and atmospheric modeling because it controls surface water and energy fluxes and it consequently influences land-atmosphere interactions. In addition, it possesses a long and persistent memory in forcing atmosphere over land surface. Numerous sensitivity studies on NWP models have shown that the consideration of accurate soil moisture content can influence short- and medium-range forecasts, has strong coupling with precipitation in mid-continental region, and can improve the cloud convection processes.

However, the use of in-situ soil moisture information in NWP models is not practical owing to limitations in such datasets. Current practices to incorporate actual soil moisture conditions are based on proxy observations (2 m air temperature and humidity), but this method has several limitations and does not directly linked to the actual moisture conditions. Use of space--borne microwave observations is most promising owing to their frequent overpasses and wider coverage. In addition, the spatial resolutions of microwave sensors are compatible with NWP models requirements. On the other hand, the current satellites microwave measurements cannot provide complete space-time coverage and their observations are limited to a few centimeters of soil depth. To overcome these limitations, data assimilation methods are developed to merge the satellite surface information with Land Surface Model (LSM) outputs to produce spatially and temporally complete information of superior products such as profile information of soil moisture and temperature.

Although global or regional satellite-derived surface soil moisture datasets are readily available from this approach, knowledge about assimilating these datasets into NWP models is very limited and to date only very few studies have been reported. In addition, the proposed methods have several limitations and cannot be applied in operational near-real-time practices. Therefore, at present, land surface analysis is not considered in operational forecasting. With increasing satellite observations, there is an urgent need to enhance research activities on exploring new methods and techniques that can be feasibly adopted in real or near-real time applications. As a result, this research initially focused on introducing the satellite observed land surface heterogeneities in a NWP model using physically based model and data assimilation methods and to investigate the soil moisture influences on simulated land-atmosphere interactions and atmospheric structures.

Consequently, a system (LDAS-A) that couples a satellite based land data assimilation with an atmospheric model was developed to physically introduce land surface heterogeneities into a land-atmosphere coupled model. LDAS-A consists of a mesoscale atmospheric model (Advanced Regional Prediction System-ARPS) as an atmospheric driver, a land surface model (SiB2) that acts as a land surface driver for the atmospheric model and the model operator for land data assimilation system, a physically based and well described land surface microwave radiative transfer model as an observation operator and an ensemble Kalman Filter (EnKF) as a sequential assimilation algorithm. LDAS-A has adopted the concepts of sequential and on-line data assimilation, which directly integrates the satellite raw (level 1B) data and reinitializes the model with observed land surface conditions whenever the observations are available. Sequential and on-line assimilation strategy removes many restrictions reported in the previous studies. LDAS-A was implemented on a standardized interface (Coupler) that consists of a superstructure to effectively handle the coupling and exchanges of data between individual components of the system (i.e., atmospheric model, model operators and assimilation algorithms). To meet the computational requirements, the Coupler was designed to run on a parallel computing platform. All these features make the system feasible for operational near-real-time NWP applications.

LDAS-A was validated on a mesoscale domain in the western Tibetan Plateau using surface measurements, atmospheric sounding and satellite observations. LDAS-A effectively improved the land surface variables (i.e., soil moisture and temperature) and has the potential to correct the uncertainties resulting from model-specific parameters and model atmospheric forcing (i.e., precipitation and radiation). The improved land surface conditions resulted to an improvement in the land-atmosphere feedback mechanism and the assimilated results showed better prediction of atmospheric profiles (i.e., potential temperature and specific humidity) when compared with radiosonde soundings. In addition, cloud-top temperatures predicted by LDAS-A showed significantly better spatial distributions and diurnal trends of cloud activity over the model domain, as confirmed by satellite observations of the infrared brightness temperature (MTSAT/1R1).

However, during or immediately after the assimilation, the reinitialized land surface conditions often suffered from substantial errors and drifts owing to predicted atmospheric forcing especially precipitation that destroyed the improved land surface conditions at very short time and in wider scales, misguides the land-atmosphere interactions thus severely affecting the model forecasts. Due to very strong influences of model predicted rainfalls on the assimilated land surface conditions, land surface assimilation processes dropped their merits and become unproductive during model forecasts. This problem is very severe and cannot be corrected in operational weather forecasting owing to the unavailability of future observations during the model execution. Therefore, the operational pitfall that arises between model atmospheric conditions and nature is one of the most challenging and unresolved problems encountered by both LSM and NWP communities.

To overcome the issues related with model inaccurate atmospheric forcing, atmospheric model physics should be in conjunction with land data assimilation. As an initial step to improve the model atmospheric conditions, LDAS-A modeling framework was extended by coupling the available Cloud Microphysics Data Assimilation System (CMDAS). CMDAS was basically developed over ocean (due to weak and homogeneous ocean surface emission) to improve the atmospheric moisture variables by assimilating AMSR-E higher frequency observations. It has been widely recognized that the use of AMSR-E higher frequency observations over land is not practical owing to the strong and variable land surface emission. However, LDAS-A has shown its merits in improving the land surface emission by assimilating lower frequency of AMSR-E observations and therefore has the potential to facilitate the microwave higher frequency (atmospheric) observations over land surface.

Consequently, a new, extended system that is referred to as Coupled Atmosphere and Land Data Assimilation System (CALDAS) was developed. CALDAS merges the land surface information obtained from lower frequencies (6.9 and 10.6 GHz) of AMSR-E channels with that of higher frequencies (23.8 and 89 GHz) to obtain the atmospheric moisture information over land surface, whereas the model operators maintain the consistency between model variables and assimilated variables. In this way CALDAS performs a synchronized improvement of land and atmospheric initialization in a physically consistent manner in a land--atmosphere coupled model.

Though it has been cited that higher frequency data have been contaminated by land surface emission, CALDAS has better exploited the multi frequency observation of AMSR-E and thus the assimilated cloud activities showed high correlation and compared well with MTSAT satellite observations. Particularly, CALDAS removed the model inaccurate rainfall events that contaminated the reinitialization of land surface conditions, and maintained the assimilated surface conditions during model forecasts. The elimination of model predicted rainfall events and cloud coverage improved the atmospheric forcing (e.g., solar radiation and rainfall) to the

LSM. The improved atmospheric forcing combined with the assimilated soil moisture content guided the LSM to accurately represent the surface processes and land--atmosphere interaction in the land-atmosphere coupled model as confirmed by surface and radiosonde observations.

CALDAS also introduced cloud distribution that was not simulated by model but observed by AMSR-E channels. However, the significant reduction in the assimilated cloud condensate was observed after few hours from model reinitialization. This could be related to the model dynamics that were not adjusted in accordance with the assimilated atmospheric parameters. Improving the model dynamics in a physically consistent manner has been proposed as one of the future directions of this research.