A SATELLITE LAND DATA ASSIMILATION SYTEM COUPLED WITH A MESOSCALE MODEL: TOWARDS IMPROVING NUMERICAL WEATHER PREDICTION

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ABSTRACT**:** Soil moisture is the central focus of accurate land surface and atmospheric modeling because it controls surface water and energy fluxes and consequently influences the lower atmospheric phenomena. However, knowledge relating to the assimilation of satellite-derived soil moisture observations into NWP models is still limited and at present, the surface soil moisture analysis is not part of NWP models. As a result, this study focused on the development of a system (LDAS-A), which couples satellite land data assimilation with a mesoscale model. LDAS-A was designed to be a sequential land data assimilation system, and to directly assimilate lower frequency passive microwave (level 1B) brightness temperature observations for soil moisture. LDAS-A was validated for the Tibetan Plateau using in-situ, radiosonde and satellite observations. The model results showed that LDAS-A effectively improved the land surface variables (i.e., surface and deep soil moisture contents and skin temperature) as well as spatial distribution of surface soil moisture content compared with the no-assimilation case. The improved land surface conditions in LDAS-A improved the land–atmosphere feedback mechanism and the assimilated results provided better prediction of atmospheric profiles (i.e., potential temperature and specific humidity) when compared with radiosonde soundings.

KEYWORDS: microwave remote sensing, soil moistures, numerical weather prediction,

1. INTRODUCTION

Understanding and predicting weather and climate have been a human quest for millennia because of its influences in the aspect of daily life, resource allocations, food productions, water and food security, natural disaster preventions and early warnings (e.g., floods and droughts) and policy marking. Modern weather forecasting relies on observations and computer simulations of the atmosphere, land, and ocean. General Circulation Models (GCMs) are the only tools available to simulate global weather and climate. On the other hand, a GCM could only be run at crude scales owing to the trade off between physical processes and computational requirements; it fails to represent sub-grid scale phenomena such as cloud convection and precipitation processes (Wilby and Wigley, 1997). To overcome these limitations, dynamical downscaling approach, which nests the GCM outputs within a high-resolution mesoscale model, is the common approach adopted in Numerical Weather Prediction (NWP).

Moreover, Numerical Weather Prediction (NWP) is an initial-boundary value problem: given an estimate of the present state of the atmosphere, land, and ocean, the model simulates (forecasts) the evolutions of land and atmosphere. As the initial and boundary conditions derived from GCMs by nesting approach simply represents the larger scale phenomena, observations from various sources (e.g., conventional and remote sensing techniques) have to be integrated within mesoscale models to enhance the forecasting capabilities of NWP models.

Land surface heterogeneities, which control land surface processes and therefore land-atmosphere interactions, have an essential role in determining both water and energy budgets. Soil moisture is a crucial element in accurate land surface modeling owing to its control on the partitioning of water and energy fluxes, which in turn regulates land-atmosphere interactions. Several studies revealed that soil moisture content strongly affects both large- and small-scale circulations, convection and precipitation processes, and also modulates meteorological droughts and floods (Nicholson, 2000: Pal and Eltahir, 2002: Koster et al. (2004); Boussetta et al. (2008); Conil et al. (2009)). Therefore, proper consideration of the soil moisture content in NWP models will enhance weather forecast and climate prediction.

The potential of remote sensing to monitor the Earth weather and climate system has been demonstrated over the years. Low-frequency passive microwave space-born sensors (such as that carried out by the Advanced Microwave Scanning Radiometer on NASA's Earth Observing System (AMSR-E)) are uniquely suited for soil moisture measurements owing to their penetration capability through atmosphere even if the presence of clouds and moderate rainfalls. In addition, these remote observations are available in near-real time, at global scale bi-daily that is useful for the initialization of NWP models. However, knowledge relating to the assimilation of Satellite derived soil moisture observations into NWP models is still limited and at present, the surface soil moisture analysis is not part of any NWP models. A significant hurdle to assimilate the near-surface soil moisture in NWP models has been the computational expenses of the additional model integrations required by advanced assimilation methods. To reduce the computational expenses, the assimilation processes were carried out into an off-line version of the land surface model and then use the assimilated product with NWP models (Draper et al. (2009)). However, this approach has several limitations and therefore development of more advanced assimilation schemes has been emphasized for more effective use of satellite observations in NWP applications (Scipal el al. (2008)).

1.1 Objectives

Accordingly, to account the actual land surface heterogeneity in regional simulations, we developed physically based approach (a Land Data Assimilation System coupled with a mesoscale Atmospheric model (LDAS-A)) that can overcome the limitations stated in previous studies by directly assimilating lower-frequency microwave brightness temperatures (level 1B) within the NWP model rather than using soil moisture products. The LDAS-A was implemented on a standardized and robust interface called as *coupler*, which consists of a superstructure that effectively handles the coupling and exchange of data between individual components of the system (atmospheric model, LSM and land data assimilation algorithm) and it was also designed to run in parallel computing platforms to meet the computational requirements. LDAS-A was applied to a mesoscale domain in

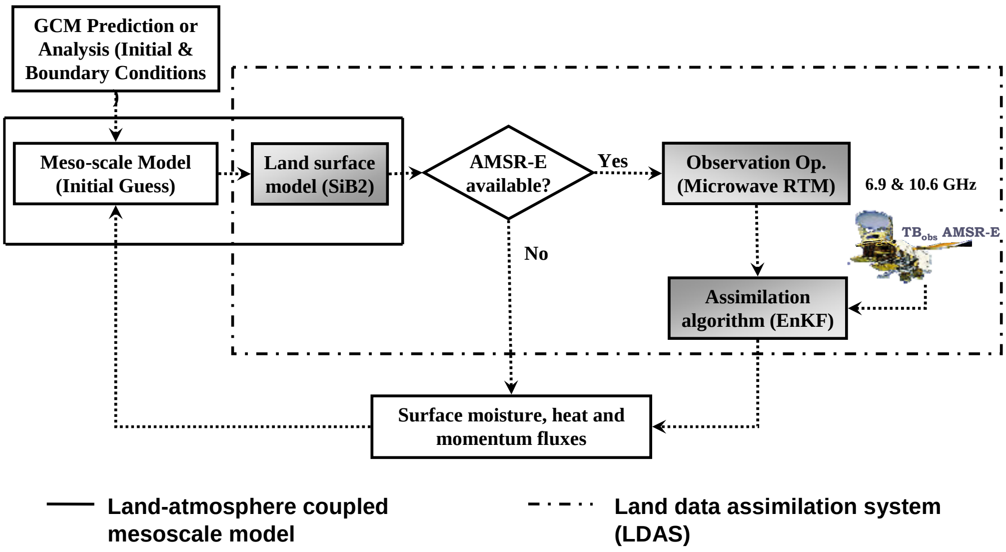


Fig. 1. Framework of the land data assimilation system coupled with an atmospheric model (LDAS-A)

Tibetan Plateau to investigate the land-atmosphere feed-back mechanism. For model validation, in addition to ground observations, intensive radiosonde and satellite observations were used.

2. METHODOLOGY

LDAS-A uses a mesoscale model (ARPS) as atmospheric driver, a physically based microwave Radiative Transfer Model (RTM) as an observation operator, a land surface model (SiB2) as a model operator, and a sequential assimilation technique (Ensemble Kalman Filter (EnKF)) as an assimilation algorithm. The EnKF is capable of resolving the nonlinearity and discontinuity within the model operator and the observation operator and it updates the land surface states whenever observations are available. The flow of LDAS-A model simulation is described below.

- As shown in Fig. 1, ARPS was set up using initial and boundary conditions from NCEP FNL operational global analysis data and runs for a predefined period (10 min) and passes the forcing data to the land surface model SiB2.

- At the beginning of SiB2 integration time, the ensemble (50 members) of soil moisture profiles is generated and SiB2 is simulated for every ensemble member of the soil moisture profile, model parameter and atmospheric forcing independently.

- At the end of the SiB2 calculation, the mean values of the soil moisture profile, soil temperature profile, and surface heat and momentum fluxes are computed from the ensemble of the forecast and fed back to the ARPS.

- At times when AMSR-E observations are available, the brightness temperatures at frequencies of 6.9 and 10.65 GHz are perturbed to produce an ensemble of observations. The SiB2-driven soil ensemble of moisture profiles are used to obtain the simulated brightness temperatures (at 6.9 and 10.7 GHz) using the forward radiation transfer model. The EnKF calculates the updated soil moisture profile with the ensemble of forecast soil moisture profiles, the ensemble of brightness temperatures simulated by the RTM and the ensemble of observed brightness temperatures. The resulting updated land surface conditions are then used to reinitialize the land-atmosphere coupled model.

- With the reinitialized land surface conditions, the ARPS model is integrated forward in time for atmospheric prediction.

3. EXPERIMENTAL DESCRIPTIONS

In this study, a mesoscale area located in the western part of the Plateau, bounded by the area (82.7E - 85.2E, 30.7N - 33.2N), and including the Gaize station was considered.

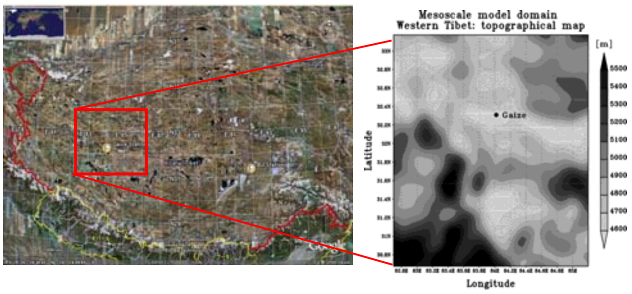


Fig. 2. Model domain: topographical map (m) including the Gaize station.

This region is especially characterized by a wider flat valley and mountainous topography with a heterogeneous soil moisture distribution that is favorable for investigating land-atmosphere interactions. The land-use type is bare land or sparse vegetation without intense human activity, which ensures the applicability of microwave radiative transfer model to AMSR-E observations without great complication.

The performance of the new system was investigated by considering two cases: (1) the one-way nesting procedure employing the land–atmosphere model (ARPS) (without AMSR-E data) and (2) the land–atmosphere model coupled with a sequential land data assimilation system (LDAS-A). To capture small-scale atmospheric features related to the land surface effect, the model domain horizontal resolution was set to 0.05° X 0.05°. Total domain area was 350 X 350 km^2. For the vertical grid, the atmospheric model used a hyperbolic tangent function to stretch the grid interval from 40 m at the first level and 53 atmospheric layers in total (~18 km above the ground surface).

The simulation periods were selected based on Index of Cumulus Occurrence (Ico) derived from model domain averaged MTSAT/1R1 brightness temperature observations. Ico was defined as (Taniguchi and Koike (2008))

$$Ico = 250 - \min[T_B(06UTC), T_B(12UTC)] \qquad (1)$$

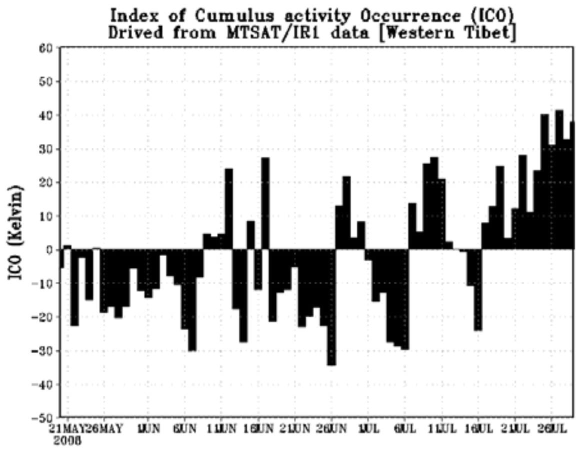


Fig. 3. The Index of Cumulus activity Occurrence [ICO] derived from MTSAT 1R1 data spatially averaged over model domain from May –July 2008.

As shown in Fig. 3, the cumulus activities are less frequent from late may to mid June. Numerical experiments that were carried out during this period have also shown little rainfall. This will be a favorable condition to test the LDAS-A against no assimilation because the reinitialized soil moisture by the assimilation procedures will not be contaminated by model rainfall and will be kept remembered during forecast period. As a result, the effect of surface soil moisture on land-atmosphere interaction can be seen clearly. Therefore, the period starting from 20th May 2008 to 19th June 2008 was selected for the investigation.

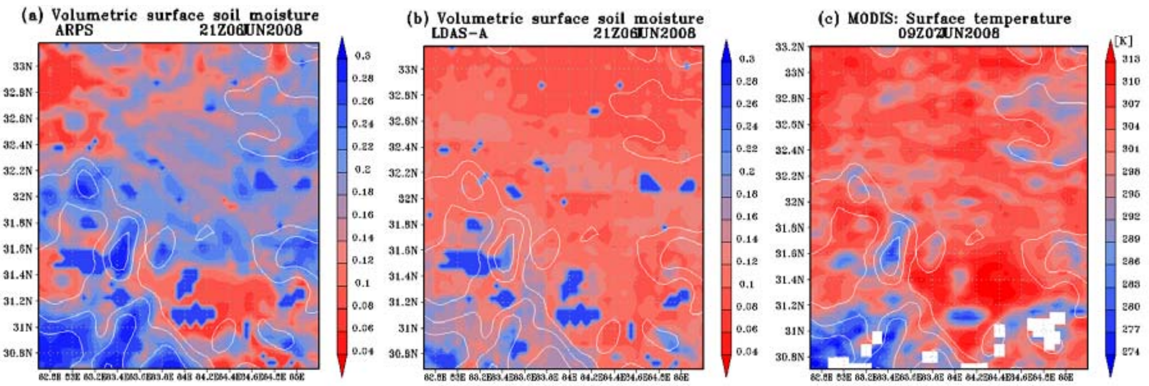


Fig. 4. Spatial distribution of simulated surface soil moisture contents (m^3/m^3) at 0730 UTC on 6th June 2008; (a) ARPS (no-assimilation case), (b) LDAS-A, and (c) MODIS land surface temperature (K) at 0900UTC on 7th June 2008, contour lines depict topography.

4. RESULTS AND DISCUSSIONS

To assess the soil moisture assimilation capabilities of LDAS-A at regional scales, the spatial distribution of model simulated surface soil moisture contents were investigated with daytime Terra MODIS Land Surface Temperature (LST) products. Since vegetation effects are negligible in the simulated domain, the diurnal range of the MODIS LST can indirectly indicate the amount of surface soil moisture conditions (i.e., a larger diurnal range of the land surface temperature is associated with lower surface soil moisture content, and vice versa). As shown in Fig. 4(a) and (b), the soil moisture content simulated by ARPS was much higher than that simulated by LDAS-A in most of the model cells, particularly in the central to northern regions. When the model results are compared against MODIS LST (Fig. 4(c), the LDAS-A soil moisture was reasonably comparable to the distribution of the MODIS LST, and especially, regions with lower moisture content corresponded well to regions with higher MODIS land surface temperatures. On the other hand, ARPS did not agree with the MODIS LST, and showed wet and dry surface conditions for higher LST.

Fig. 5(a) and Fig. 5(b) compares soil moisture contents simulated by ARPS and LDAS-A with the soil moisture recorded at the Gaize station at 3 cm and 20 cm respectively. As shown in the figures, the initial sate of soil moisture contents derived from the NCEP/FNL dataset in both models were higher than the soil moisture content recorded at the Gaize station. However, procedures of the assimilation in LDAS-A reduced biases (consecutive sudden drops in the figure) and realigned the model simulation with observation. On the other hand, biases in the soil moisture contents of the ARPS model were much higher than biases in LDAS-A's simulation at the Gaize station.

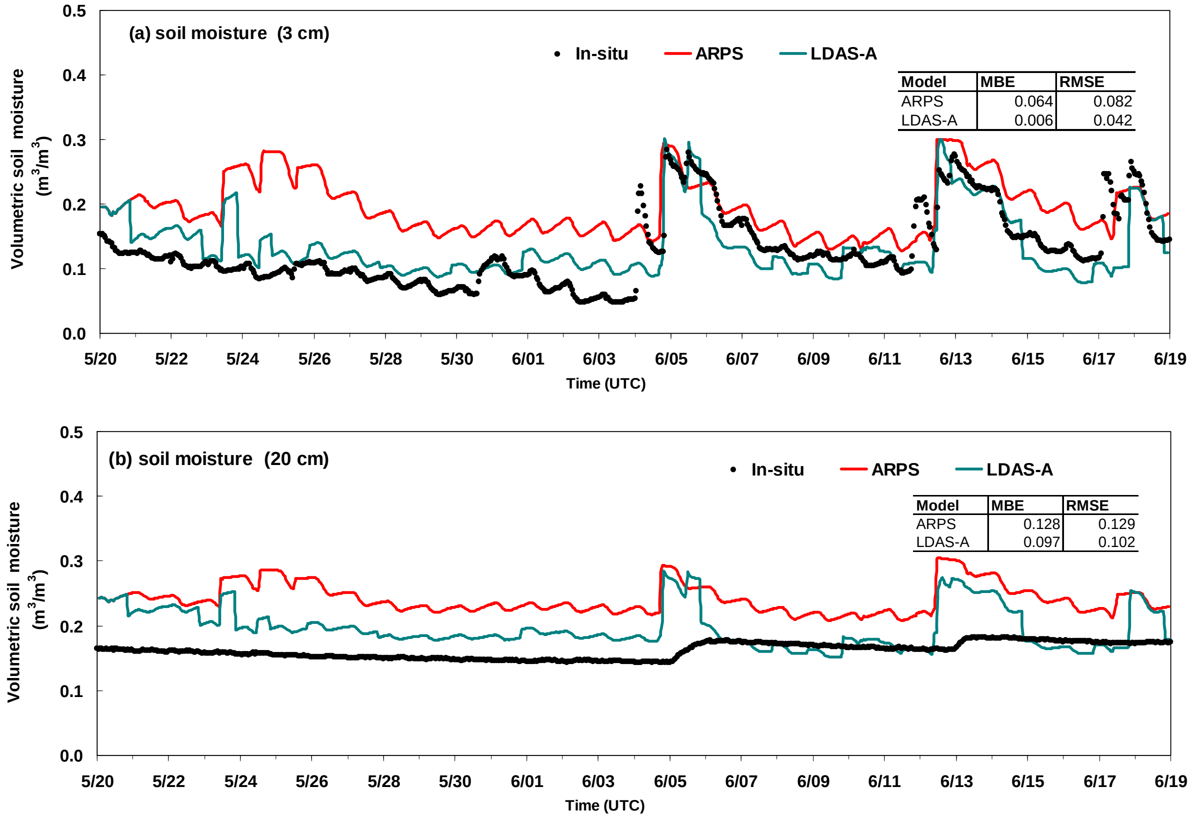


Fig. 5. Comparison of observed and simulated soil moisture content at the Gaize station from 20th May 2008 to 19th June 2008; (a) at 3 cm, (b) at 20 cm.

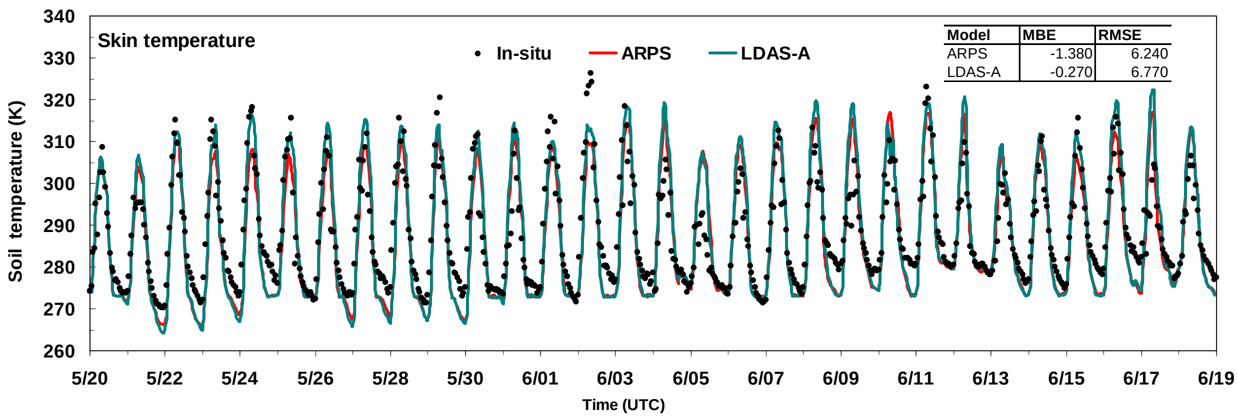


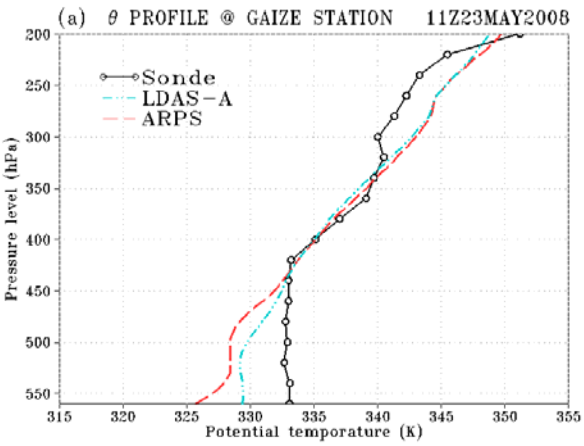
Fig. 6. Comparison of observed and simulated surface temperature at the Gaize station.

It could be noted from Fig. 5(b) that models soil moisture at 20 cm showed higher response to rainfall events, whereas observation showed much smaller response. However, these high responses are greatly improved in LDA-A through the assimilations. A portion of this bias could be due to the treatment of water flow (only in vertical direction) in land surface models. Soil moisture in deep layers also equally important as it supplies water to roots and surface zones and account for evaporation and transpiration.

It also plays an important role in modulating long term climate. For better results, future generation of land surface models should account for lateral and/or slope driven water movements. Furthermore, the mean bias error (MBE) and root-mean-square error (RMSE) presented in the figures supported the performance of LDAS-A.

As shown in Fig. 6, the diurnal variations in the surface temperature, especially daytime highs simulated by LDAS-A, agreed well with observed diurnal variations, whereas the variations during the dry period are underestimated by ARPS. The ARPS underestimates daytime highs because of the overestimation of the soil moisture content (Fig. 5(a)), which inaccurately partitions the available surface energy to give a higher estimate of evaporation and lower estimate of the daytime surface temperature. Since assimilation significantly improved the soil moisture variations such that they are comparable to observations especially during dry or no-rain periods, the simulation results of LDAS-A capture the daytime highs well.

Soil moisture and surface temperature control the heat and moisture transfer within the lower part of the troposphere (planetary boundary layer) and influence the dynamic and thermodynamic properties of the overlying atmosphere. To investigate the effect of improved land surface conditions on the overlying atmosphere, radiosonde soundings were examined with model soundings. It has been found that the improvements in atmospheric model sounding were seen especially from noon to evening, when the surface is heated by strong solar radiation and the land surface memory is translated to the overlaying atmosphere (not shown). As a result, Fig. 7 (a) and Fig. 7(b) compare the observed soundings of the potential temperature and specific humidity with the soundings simulated by ARPS and LDAS-A at 1100 UTC (17 local time) on 23rd May 2008, respectively. On this day lower soil moisture in LDAS-A enhanced land surface heating, which resulted in an increment in potential temperature profiles with improvements over the ARPS model. In addition, lower soil moisture conditions in LDAS-A limited moisture fluxes to the atmosphere within the boundary layer, and therefore, specific humidity profiles simulated by LDAS-A were better than those simulated by ARPS.



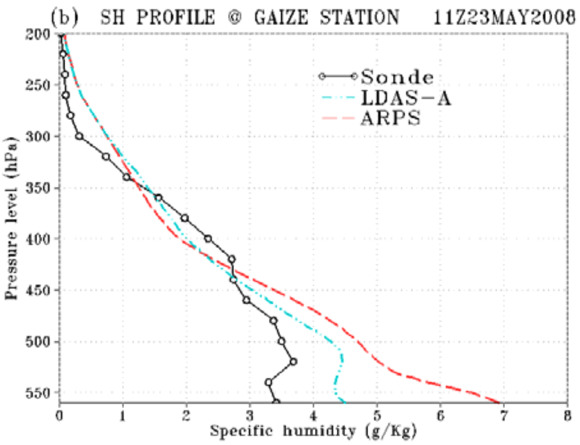


Fig. 7. Comparison of observed soundings with ARPS and LDAS-A model soundings at 1100 UTC on 23rd May 2008; (a) potential temperature (K) and (b) specific humidity (g/kg).

Improving the surface soil moisture and thus heat and moisture fluxes eventually improved the atmospheric profiles of the potential temperature and specific humidity from land surfaces to a maximum pressure height of about ~450 hPa. Although the profiles of potential temperature and specific humidity simulated by the models were not exactly the same as the observed profiles, the simulation results of LDAS-A are better than those of the ARPS model. The model atmospheric structures are not only controlled by land surface conditions but also affected by simulated atmospheric conditions (e.g., moisture fields and cloud conditions), forcing of the LSM (e.g., downward shortwave and longwave radiation and rainfall), environmental forcing (dynamics), and the lateral boundary conditions used to derive mesoscale models. However, simulated results suggested that the consideration of land surface heterogeneities has the potential to improve the land–atmosphere interactions and atmospheric structures in NWP models.

5. CONCLUSION

Soil water content is the single most important land surface variable in land–atmosphere coupled models and it controls moisture and heat fluxes, and thus land-atmosphere interactions. To physically introduce accurate and existing land surface conditions into numerical prediction, a land data assimilation system is coupled with a mesoscale atmospheric model. The results show that the simulation of surface and deep soil moisture content was much better than that in the case without assimilation. Improvements in the soil moisture content improved the simulated land surface temperature, especially the trend of the daytime highs simulated by LDAS-A, agreed well with the trend observed at the Gaize station. Improved land surface conditions produced better model soundings of potential temperature and specific humidity and the improvement in the LDAS-A model could be clearly seen from the surface to ~450 hPa.

These results are very promising in terms of reliably predicting land surface water and energy budgets and therefore improved land–atmosphere interactions in remote regions where no observation networks are available. Although results proved that the investigated system is capable of improving land surface variables and the land–atmosphere interactions in NWP models, further improvements are necessary for full-fledged applications. (a) In this study, we did not address improvement of the atmospheric initialization, which is more critical in a numerical weather forecast. (b) At present, the system only assimilates soil moisture; however, the assimilation of remotely sensed surface temperature and cloud information into the system has the potential to improve soil moisture and solar radiation estimations, the land surface fluxes and land–atmosphere interactions effectively.

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