JP4.16 TESTING OF SEVERAL RECENT MODIFICATIONS TO ARPS LAND SURFACE MODEL

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1. INTRODUCTION

Deardorff (1978, D78 henceforth) showed that a two-layered force-restore scheme is superior to bulk scheme in describing the surface soil moisture content because it contains the mechanism by which a deeper soil layer can influence the thin surface layer. This gives the flexibility and advantages in superficial soil moisture prediction especially when there are precipitation and very active evaporation from the ground surface. Further, an accurate estimation of surface latent heat flux resulting from the use of surface layer moisture content rather than that of the thick, slow responding bulk layer is very important for the prediction of surface air temperature and humidity.

Another significant contribution of Deardorff (1977, D77 hereafter) and D78 is the inclusion of a vegetation layer in the description of the land surface processes. Without proper consideration of the shielding effects and the transpiration of the root zone soil moisture, force-restore temperature and moisture schemes can only be applied to bare ground for reasonably good results. With his approach, the vegetated surface is conceptually divided into bare ground and the portion covered by vegetation. Energy balance for vegetation was derived that includes the diagnosis of canopy temperature, the parameterization of a representative leave for its potential evapotranspiration rate, and the fractional exponent description of dew formation and evaporation. He used the concept of canopy surface resistance originated by Monteith (1965) and implemented the daylight, soil moisture and seasonal dependence of the stomatal resistance. The representative leaf-to-canopy scaling is connected by the leaf area index through a linear proportionality. Land surface models inspired by Deardorff's philosophy of explicitly describing the land surface processes include Biosphere Atmosphere Transfer Scheme (BATS, Dickinson 1984) and the Simple Biosphere Model (SiB, Sellers et al. 1986), among others, for different specific purposes. Contrary to the approach that makes the parameterization and the description of the physical processes more detailed and complex, the Interactions Soil Biosphere Atmosphere (ISBA) by Noilhan and Planton (1989, NP89 henceforth) is a relatively simple scheme that includes only the most important components of the land surface processes.

Because its relative efficiency and suitability for mesoscale modeling applications, ISBA has been actively tested and improved by many researchers, among them are the improvement in heat capacity description by Pleim and Xiu (1995), the continuous formulation for the secondary soil parameters by Noilhan and Mahfouf (1996, NM96 henceforth), re-calibration of the force-coefficient for surface soil moisture by Giordani et al. (1996, G96 henceforth), and several reconsiderations of the parameterization philosophies ranging from the surface soil moisture availability, the stomatal resistance, and leaf-to-canopy scaling as proposed by Xiu and Pleim (2001, XP01 henceforth). Recently, Brotzge and Weber (2002), using the Oklahoma Atmospheric Surface-layer Instrumentation System (OASIS, Brotzge et al. 1999) measurements, identified some further problems with the ISBA-type land surface scheme used in the Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001). Our study here is to further test and evaluate some of the aforementioned modifications, using a comprehensive OASIS data set.

2. Recent changes to the ARPS land surface scheme

Compared to the original implementation based on primarily NP89, the ISBA-type scheme in the ARPS has been modified based on several recent studies.

a) Ren and Xue (2003) modifications to soil temperature equations

XP01 apparently realized the problem in the expression for deep soil temperature by the ISBA as described in NP89. Their remedy of enlarging the restore time constant τ may reduce the error for the deep soil temperature prediction; the underlying physics for doing so is unclear, however. A careful reexamination of the force-restore model used for soil temperature forecast in ISBA soil is performed by Ren and Xue (2003, RX03 hereafter). An important and widely present misuse resulted from the original assumption of equal mean temperature for different soil depths was corrected by incorporating the mean lapse rate of soil temperature. The modifications are found to significantly improve the forecast of force-restore model, in particular that of the deep soil temperature. The formulations of the soil moisture equations are essentially unchanged from ISBA of NP89.

b) Xiu and Pleim (1995 and 2001) modifications

The first modification Pleim and Xiu (1995, PX95 hereafter) made to NP89 is to the inverse of the bulk heat capacity C_T. NP89 made a linear interpolation between the bare ground and the closed vegetation conditions according to vegetation coverage (*veg*). Because their vegetation heat capacity C_V^{-1} was two orders of magnitude smaller than that of the ground, implying that there is essentially no heat transfer between the canopy and the ground underneath hence little heat storage at the surface. Pleim and Xiu (1995) found this assumption to be against the observational evidence for the FIFE (Sellers et al. 1988) site which is in an area completely covered by tall grass. They thus proposed using soil heat capacity rather than the weighted average of soil and vegetation heat capacities. In a later work by Noilhan and Mahfouf (1996, NM96 hereafter), C_V^{-1} was amplified by more than two orders of magnitude, i.e., to be of the same order as the heat capacity of the thermally active (for daily cycles) soil layer, apparently in response to the suggestions by P X95.

Believing that ground temperature, especially for clear sky conditions during warm seasons, is governed by intense daytime heating and slower nighttime cooling processes, we stick to the NP89 parameterization during peak hours of daytime heating (from 10am to 14pm local time) and switch to NM96 scheme (equivalent to the suggestion of PX95) during the remaining period of a day when the heat transfer between canopy and ground underneath is relatively important among the forcings.

Xiu and Pleim (2001, Eqs. (1)-(3)) also modified the NM96 (Eqs. (8)-(10) and (13)-(15)) parameterization for ground evaporation (LE_g). The former uses a β-approach rather than an α-approach to account for soil moisture availability (i.e., the h_u factor) that multiplies only on the saturated specific humidity at the ground surface temperature q_{sat} (T_s) (while not on the air specific humidity q_a) in the latent heat flux formulations. The surface moisture dependence of the β factor used in XP01 follows a formulation of Lee and Pielke (1992) rather than that suggested in NP89. A stated reason for doing so is to avoid the frequent sign changes of LE_g merely due to the slight changes in the surface soil moisture content, as frequently happens during very dry conditions and daytime heating period.

At daylight, soil moisture and seasonal dependence of the stomatal resistance as initially proposed by D77 was expanded to include four environmental stress functions in ISBA as of NP89. Recent modifications to these factors by XP01 will be carefully examined and selectively applied in this study.

c) Braud et al. (1993) and Giordani et al. (1996) modifications to C_1

Formulation of surface evaporation in force-restore model is an important issue. As pointed out by NM96, accurate prediction of surface evaporation requires the use of sophisticated multi-layer soil models with very high spatial and temporal resolutions. High spatial resolution is especially required near surface layer under very dry conditions, because surface crusting usually happens then. Braud *et al.* (1993) and Giordani *et al.* (1996) suggested expressions for soil moisture restore coefficient C_1 that supposedly considered vapor (not only liquid phase) phase diffusion. The related expressions can be found at Appendix A.4 of NM96.

3. Test Data

In contrast to the soil moisture and flux measurements during short, intensive observing periods for several well-known field experiments (e.g., FIFE, Sellers et al., 1988; HAPEX-MOBILHY, Andre et al., 1986), OASIS within the Oklahoma Mesonet provides year round continuous direct measurements of soil moisture and temperature at four different depths, and all four components of the surface energy fluxes, providing an opportunity for rigorously testing and improving the dynamic framework of the land surface models.

The OASIS data set at Norman, Oklahoma site used here was provided by Jerry Brotzge, and has been used for model calibration purposes (e.g., Brotzge and Weber 2002). At the Norman site, soil type is classified as silty clay and vegetation type as shrub. The Norman site is flat and its immediate surroundings can be considered as uniform within a range of several thousands meters at an elevation of 360 m.

The routinely available measurements of meteorological variables include surface temperature, water vapor mixing ratio, wind speed, surface pressure, and precipitation rate. At the OASIS site, an infrared sensor records surface skin temperature and data are collected at 5 min intervals. The soil moisture and soil temperature are measured using the Campbell Scientific 229-L sensors, every half an hour at 5, 25, 60 and 75 cm depths. Vegetation parameters such as vegetation type, leaf area index (LAI), vegetation coverage, and NDVI index are estimated biweekly. Data from two 2-day periods in July and August of year 2000 are selected to test the land surface model and its modifications. These periods are described below.

Two major rain events (on 28 June and 2 July) occurred within one week period from 00UTC, 28 June to

00UTC, 4 July, 2000. The total precipitation amount of 103.72 mm wetted the soil up to 60 cm deep. July 6th -7th, 2000 signifies a synoptically quiescent period following this wet period, with clear sky and wind speed generally less than 5 m s^{-1}. Under periodical (daily) radiative flux forcing, air pressure, air temperature, mixing ratio and soil temperatures within 25 cm all shows apparent daily cycles. These two days show a drying down process of the surface soil moisture. The volumetric soil water content at 5cm dropped from 38% steadily to about 35% during these 48 hours from 00UTC, July 6th to 00UTC July 8th. The soil moisture measurements at the remaining three depths show little change. This 2-day period thus belongs to the *'Stage I'* of drying as defined by Idso et al. (1974). The vegetation was very active during this period and a vegetation cover of 85% was estimated base on the study of Brotzge and Weber (2002) for 20 May, 2000.

High pressure also dominated during the second selected period, i.e., from 12 to 13 August, 2000, which represents a soil dry-down period with much lower soil wetness but higher air temperatures (maximum temperature of 42° C) and stressed vegetation (NDVI = 0.5 rather than the 0.55 for the July 6-7 period) because the soil moisture contents at the top three measurement depths all fall below the wilting point value of 24% for silty clay soil.

4. Numerical experiments

a) Model initialization

ARPS is applied in a 1D vertical column mode throughout this study. A stretched vertical grid was used such that the lowest atmospheric layer matches the atmospheric observations, i.e., at 2 m for temperature. Different from earlier work, all experiments presented in this study are performed with the land surface model coupled with the atmospheric component.

The initialization of soil temperature using layered soil temperature measurements to the revised force-restore model is thoroughly discussed in RX03. Because our proposed scheme requires at least a week-long period to diagnose the vertical lapse rate of the mean soil temperature, clear sky condition over one week are preferred from the temperature simulation view point. The two depths for the superficial layer and a deep reservoir layer for soil moisture are set as 0.1 and 1.0 m in this study. The OASIS soil moisture measurements at 5 cm are directly used to initialize superficial soil moisture w_g. The soil moisture of the bulk layer of 1 m depth (w_2) is obtained from a weighted average of soil measurements at four depths (see Section 3). Because the soil moisture contents below 60 cm vary little on a weekly basis, heavier weights are given to the top two layers (0.3, 0.4, 0.2 and 0.1 respectively). Vegetation characteristics such as *LAI* and *veg* and soil basic properties such as soil type are stipulated using the values representing those found at the Norman OASIS site.

b) Numerical experiments design

Different proposals for modification will be compared and their effectiveness evaluated in this study. For the conclusions to be more generally applicable, two periods during the warm season, as described in the previous section, were selected, representing a wet period and a dry period. For each selected period, sensitivity experiments with respect to soil moisture force-restore coefficients (C_1 and C_2), *veg* and minimum stomatal resistance R_{smin} were conducted first to identify the importance of uncertainties in these parameters. If the model responses are significant in the simulation of latent (*LE*) and sensible (*SH*) heat fluxes, or in the surface and bulk layer soil moisture contents, modifications proposed by PX95, XP01, Giordani et al (1996), and our results from parameter retrieval (Ren et al 2002) are applied separately to identify their respective functionality and collectively to hopefully improve the general simulation of the land surface processes.

5. Results

For the selected wet period (6-7 July, 2000), measured by the relative error as defined in D78, the simulations for surface energy fluxes and volumetric soil water contents are not sensitive to variations of R_{smin} from 40 to 500 sm^{-1} (<5%), C_1 from 0.375 to 0.04, or C_2 from 0.3 to 2.0.

The sensitivity experiments of surface and deep soil volumetric water contents to *veg* are conducted using *veg*=0.5, 0.6, 0.7, 0.85, and 0.9. The response to *veg* variation is nonlinear because equal increments to *veg* result in different increments in soil moisture contents and the sensitivity varies with time. However, in the sense that a larger *veg* signifies a slower drying up process, the sensitivity to *veg* is a monotonic process. Bulk soil moisture content is less sensitive to *veg* than does the superficial soil moisture. Further analyses indicate that *veg* signifies a partition among the three water reservoirs of ISBA. A larger *veg* means a larger portion of evaporation is from the vegetated surface. Since the magnitude of dew formation which occurred during the late night hours on 6-7 July, 2000 is one order of magnitude smaller than transpiration from vegetation (*LEv*) and *LEg*, the *veg* factor mainly affects the partition among the latter two components of latent heat flux. The total amount of latent heat flux is less sensitive except for the peak hours. Since ground surface evaporation is the only mechanism that extracts moisture from the superficial surface layer, the surface soil moisture content must be rather sensitive to *veg* parameter. Sensible heat flux also shows a significant sensitivity to *veg*. This suggests that *veg* factor does a re-partitioning between *SH* and ground heat flux *G*. The denser the vegetation, the smaller the *G* is. This result agrees with the finding by Jacquemin and Noilhan (1990), where they find the most sensitive parameter for simulation of surface energy fluxes is *veg*. Generally speaking, ISBA after our soil temperature equation revisions did a rather satisfactory job in simulating the surface energy fluxes and the soil moisture evolutions. Although there lacks direct measurements of dew amount, the magnitude and timing of dew formation and dissipation (figures not shown) seem reasonable for such a soil moisture condition and the synoptic background (clear sky condition after heavy rainfalls, combined with relatively weak winds).

When w_2 falls below the wilting point, the surface resistance for transpiration goes to infinity. Transpiration part of the latent heat flux becomes zero (Eq. (15) of NM96). The evaporation from the vegetated surface will also be zero if there is no dew or intercepted water on leaves (Eqs. (10) and (13) of NM96). Thus the minimum stomatal resistance plays no role during the second selected study period (12-13 August, 2000), simply because the low root zone soil moisture contents (which started at 0.267 on 12 August, 2000) but fell near wilting point for silty clay soil.

Numerical simulations for this dry period reveal two apparent problems with the ISBA simulated w_g and surface fluxes. Specifically, the ISBA simulated w_g shows excessive amplitude of diurnal cycle that is about ten times larger than the observed daily variation (the phase problem is beyond the simulation ability of ISBA because it contains no mechanism for vertical soil moisture exchange due to vegetation activity, personal communication with J. Brotzge). When the simulation time period is increased to one week, we noticed that the model surface moisture was depleted much more quickly than observations. Correspondingly, the simulated *LE* and *SH* are problematic (Figs. 1a and 1b). In Fig. 1a, besides the peak value differences, one apparent problem for night time simulation during 13-15 August is the downward latent heat flux (dew formation) of excessive magnitude (usually >30 W m^{-2}), which is not supported by the corresponding observations. The corresponding *SH* (Fig. 1b) shows positive waggles of comparable magnitude. Compared against the observations, these waggles are unrealistic. This attests to the assertions made by XP01 that, for α scheme, the surface soil moisture had a tendency to oscillate during the daytime in the more arid regions and this is caused by frequent sign change of the difference ($\alpha q_{\text{sat}} - q_a$). This phenomenon is not sensitive to the choice of C_2. However, varying the reference C_{1sat} (i.e., value of C_1 at saturation) from 0.0375 (which is one tenth of the original categorical values assigned by NP89) to 0.75 indicates that, for this extremely dry period, the surface soil water content simulation is very sensitive to the choice of C_{1sat}. Within this value range, the smaller the C_{1sat}, the smaller is the amplitude of daily cycle in superficial soil moisture forecast (Fig. 2a). Similar is true for w_2 (Fig. 2b), although the sensitivity is not as apparent. The soil water variation in the superficial layer is dominated by atmospheric evaporation demand over ground surface. The vertical diffusion from the bulk/deep layer plays a secondary role for the surface soil water content in this dry period. Ground surface evaporation is the only water consuming mechanism that depletes deep/bulk layer soil moisture. Hence, an accurate simulation of the ground surface evaporation contributes to the accurate simulation of soil water contents in the superficial layer as well as in the bulk/deeper layer. Fortunately, there are several recent literatures addressing this fast drying phenomenon. For example, Braud et al. (1993) and G96 reformulated the C_1 coefficient using a Gaussian distribution function in order to include the vapor phase transfer within very dry soil. Sticking to the original formulation of C_1 against its saturation value C_{1sat}, NM96 proposed a continuous formulation for C_{1sat}. Alternatively, a parameter retrieval procedure described in Ren et al. (2002) can be used to optimize the value of C_{1sat}.

At Norman site, we tried using the sand and clay fraction measured at 5 cm level to parameterize C_{1sat}. This yields a value of about 2.24. This value does not work well for our testing period, however. Actually, this value is much larger than any of the listed value in Table 2 of NP89, posing doubts on the proposal of NM96 about continuous formulation of the soil secondary parameters. Using the four time periods (all during the warm season, though), i.e., 12 April, 20 May, 25 June, and 15 August, of quite different synoptic conditions and vegetation growth stages, Ren et al (2002) conducted variational parameter retrieval for C_{1sat}. A mean value of about 0.03 over these four periods was obtained and the root mean squared error of surface soil moisture forecast decreased to 1 percent of the value from using the original categorical value as given in NP89. Although this C1sat value of ~0.03 (the curve labeled as 'original' in Fig. 3) works to decrease the error in simulation of w_g for August 14 and 15, it is inefficient to overcome yet another shortcoming as indicated in Fig. 1. There still exist waggles of quite significant magnitude (over 40 W m^{-2}) during 9-14Z, 16 August, in the sensible and latent heat flux predictions. The timing coincidence with that of dew formation leads us to doubt the parameterization of *LE* during the dry period.

A similar problem was also reported by XP01 and their proposed solution was to change the parameterization of soil moisture availability factor and switch to the β parameterization scheme for LE_g. After carefully evaluating those methods, they chose to use a formulation proposed by Lee and Pielke (1992) rather than sticking to that of NP89. Although both approaches assume that evaporation can occur at potential rate once surface moisture content exceeds field capacity, shapes of their curves diverge for the lower end of soil moisture contents.

Numerical experiment performed for our selected dry period confirmed the assertions made by XP01 (see Fig. 3). For both *LE* (Fig. 3a) and *SH* (Fig. 3b), XP01 modification essentially eliminated the late night waggles. The shapes of the latent and sensible heat flux curves are now similar to the observed ones. This is achieved by an improved simulation of the soil moisture contents for both layers. The XP01 modification underestimates the *LE* during the daytime intense heating period of 16 August while overestimating the counterpart of *SH*. This flaw, although argued by XP01 as not being a severe problem for most purposes, reveals in the simulated surface soil moisture content as a constant underestimation. This hence fosters a smaller gradient between the equilibrium and surface moisture content to satisfy the daytime overevaporation. We believe that this shortcoming is not inherent to XP01 modifications and should be correctable if a proper mechanism is introduced to prevent the over exhaustion of the surface moisture. We do so by adding the modification of G96 to XP01 modification. As expected, this problem was satisfactorily solved (Figs. 4a, b, c and d).

To understand why the parameterization of G96 works well for the very dry condition, the time evolution of C_1 was analyzed and compared with the original proposal by NP89 and with the one resulting from variationally retrieved C_{1sat}. We found that (figures not shown) the curve according to NM96 parameterization becomes flat after 13Z, 12 August, resulting from a numerical bound to prevent avoid C_1 from going into infinity in the event of very small w_g (Eq. 20 in NM96). The general shapes of 'optimized' (using the optimized C_{1sat}) and the 'Giordani' curves agree with each other. However, the latter is always smaller than the former by a factor of about 4 for most of the time. G96 formulation has a clever design because they introduced a surface temperature in addition to surface moisture control to the C_1 factor. Since daytime intense evaporation correlates with the high surface temperature, their approach increases C_1 as surface temperature increases. This feedback mechanism is believed to be the physical reason that works during extremely dry period. Interestingly enough, if we take the model-data misfit in both surface soil moisture content and latent heat flux as the constraint, and give them the same weight in the cost function of the parameter retrieval, we obtain a similar curve (not shown) as that proposed by G96. Thus, without knowing the results that be given by a parameter retrieval procedure, G96 found a proper way to describe both the surface water content and the surface latent heat flux for the case when soil moisture content falls below wilting point.

6. Conclusions

After removing a conceptual error from the temperature equations, with the proper initialization of the model and implementations of several recent modifications, a force-restore type land surface scheme (ISBA) can produce rather satisfactory predictions of both soil hydrology and surface energy fluxes.

During wet periods, as long as the vegetation coverage is suitable specified, ISBA can produce pretty accurate simulations of the surface energy fluxes and the soil water contents.

For extended dry periods, model is not sensitive to minimal stomatal resistance since transpiration process ceases. However, except for the apparent importance of the vegetation coverage, model simulated surface latent and sensible heat fluxes and the superficial soil moisture content are all sensitive to the force-restore coefficient C_1 for surface moisture content. Unfortunately, adjustment of this factor alone generally cannot simultaneously satisfy the dual requirements for accurate simulations of surface fluxes and soil moisture.

Three possible remedies, i.e., optimization of C_1 based on the root mean squared error of the superficial soil water content, implementing the modification of XP01, implementing the modification of G96 in addition to that of XP01, are compared. The combined change of XP01 and G96 is found to work best for the dry period tested. Parameterizations based on the understanding of the underlying physics seem promising in improving simple land surface scheme such as ISBA.

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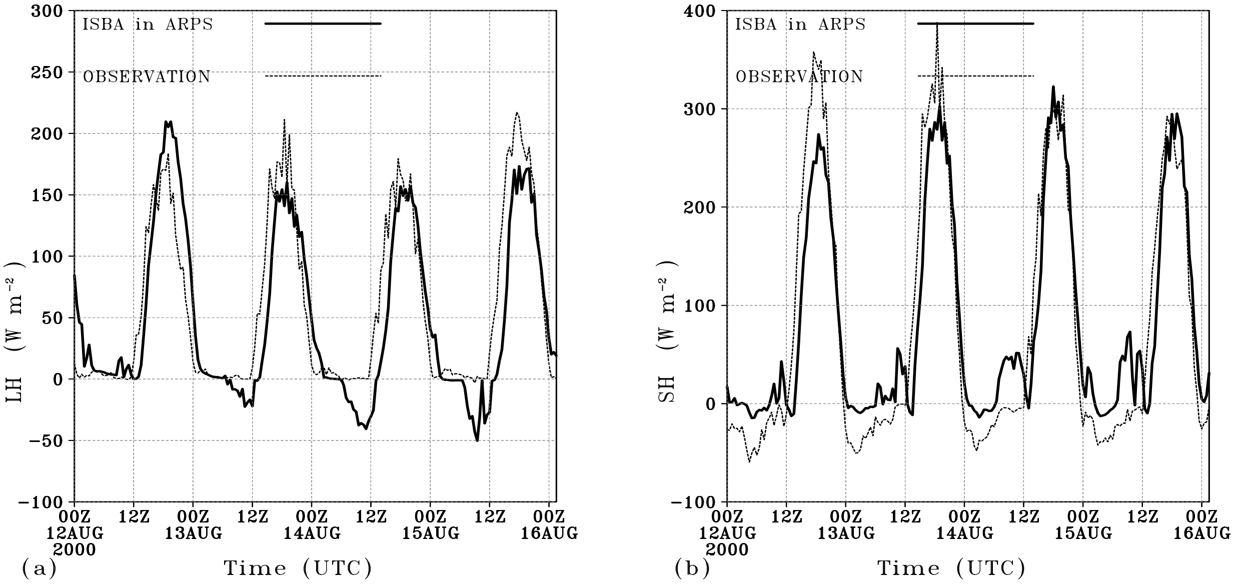

Fig. 1. Predicted latent heat flux (a) and sensible heat flux (b) for a 4-day period during August 2000, using the original setting as in NP89.

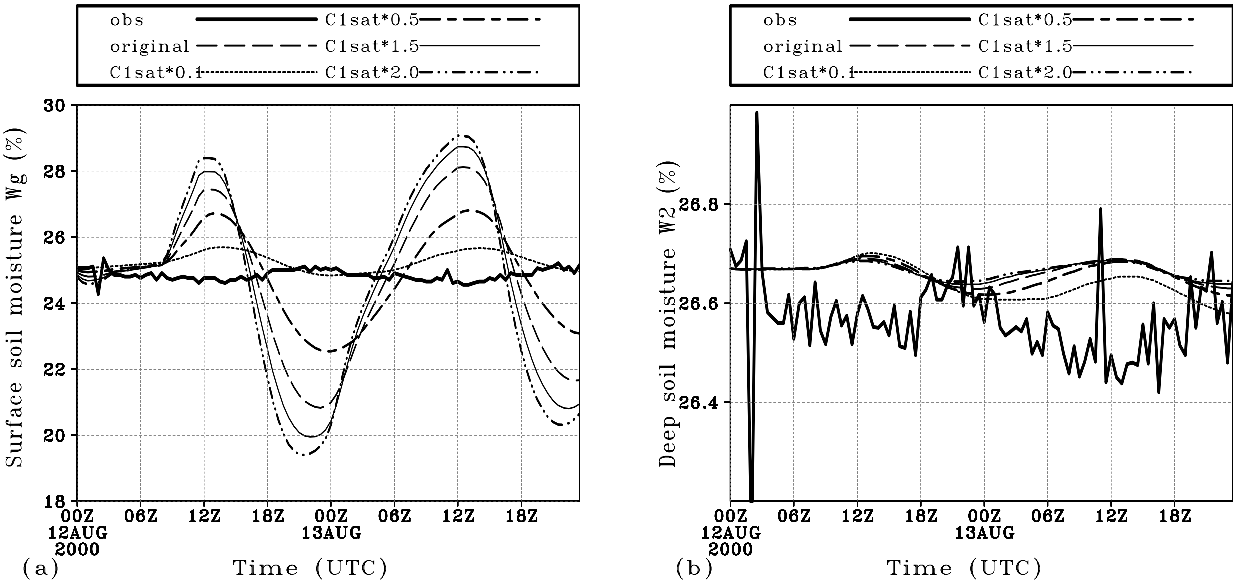

Fig. 2. Predicted surface soil moisture (a) and bulk soil moisture (b) for the 2-day period for six values of the C_{1sat} factor, where C_{1sat}=0.375, using the original NP89 formulation.

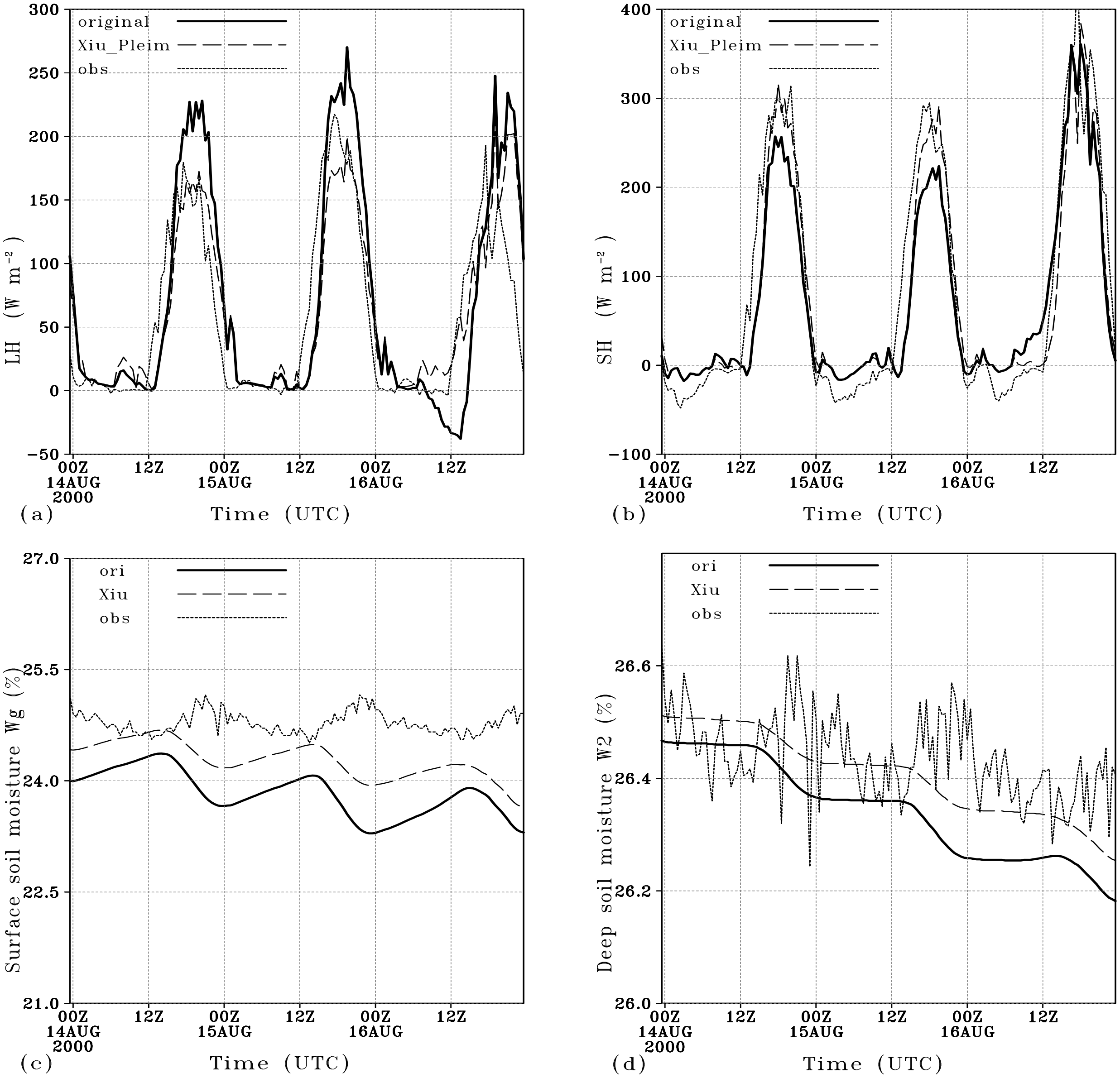

Fig. 3. Model predicted latent heat flux (a), sensible heat flux (b), surface soil moisture content (c) and bulk soil moisture content (d) by the original NP89 formulation (solid lines), the formulation including XP01 modification (dashed lines) as compared to the observations (dotted lines).

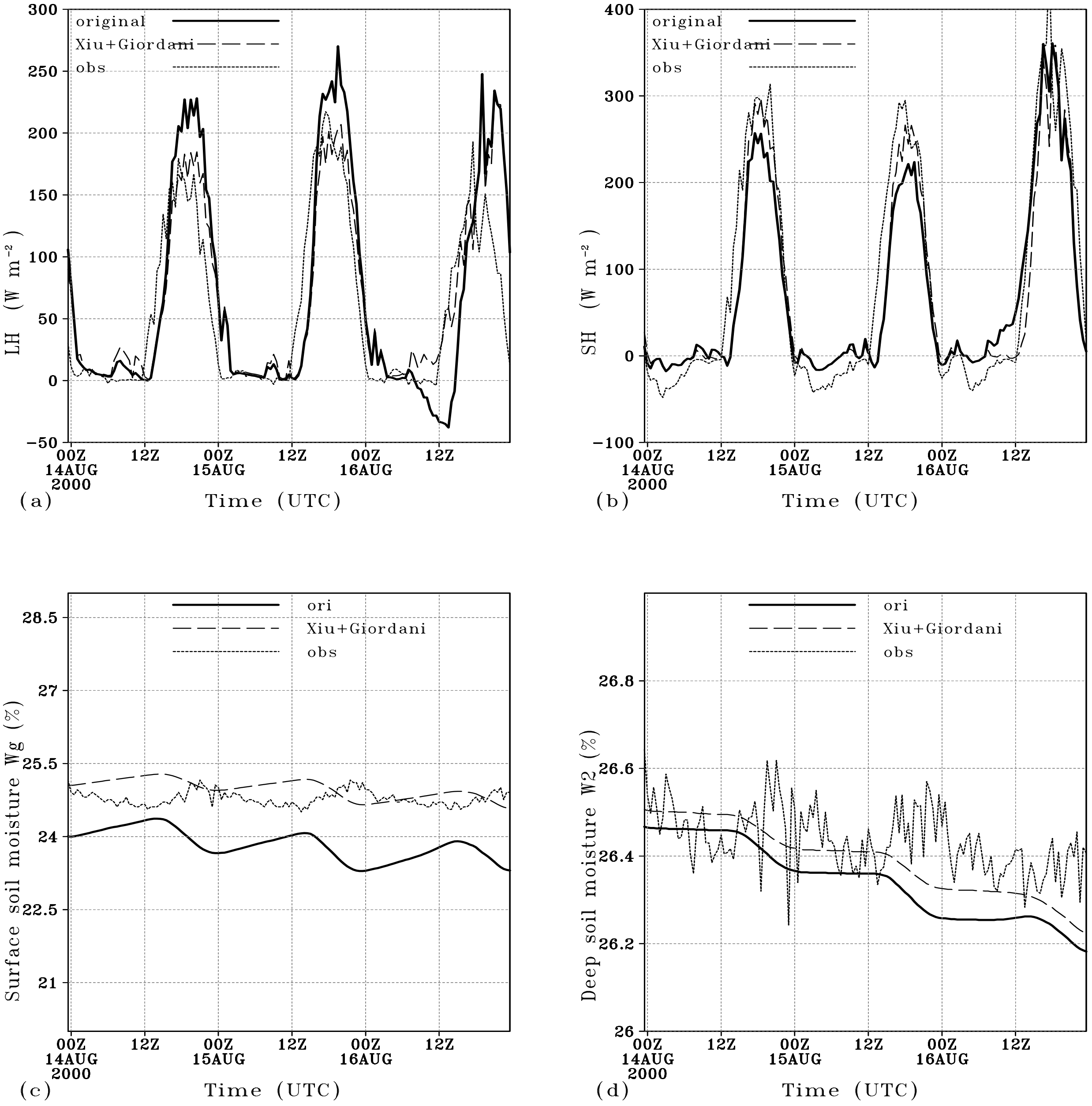

Fig. 4. Model predicted latent heat flux (a), sensible heat flux (b), surface soil moisture content (c) and bulk soil moisture content (d) using the original NP89 formulation (solid lines), and XP01 plus Giordani et al. (1996) modifications (dash lines), as compared to the observations (dotted lines).