J1.1 REDUCING NEAR-SURFACE COOL/MOIST BIASES OVER SNOWPACK AND EARLY SPRING WET SOILS IN NCEP ETA MODEL FORECASTS VIA LAND SURFACE MODEL UPGRADES

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1. INTRODUCTION

Since 1996, a series of NOAA GAPP/GCIP-sponsored land-surface related advances have been implemented in the NCEP mesoscale Eta model and its Eta-based data assimilation system (EDAS). This began with the introduction in January 1996 of a multi-layer soil-vegetation-snow land-surface model originally developed at Oregon State University (Mahrt and Pan, 1984), and modified for use in the Eta model (Chen et al 1996). At that time, the Eta model used initial soil moisture and temperature from the NCEP global model data assimilation system (GDAS), which employs soil moisture nudging to a fixed, annual-cycle soil moisture climatology.

Over the following 2-3 years, subsequent advances to the Eta model land-surface treatment included the use of the NESDIS, high-resolution, NDVI-based vegetation greenness fraction database, adjustments to the initial global model soil moisture, an increase from two to four soil layers, and the use of the NESDIS operational daily 23-km North American snow cover and sea ice analysis. This late 90's period of Eta land-surface improvements culminated in June 1998 with the introduction of continuous self-cycling of Eta soil moisture and soil temperature in the Eta 4-D Data Assimilation System (EDAS). The latter employs no soil moisture nudging. Since then and up to the present (over three years), the Eta model's initial soil moisture and soil temperature have been sole products of the continuous cycling of these two land states in the coupled land-atmosphere EDAS.

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Between June 1998 and July 2001, no further significant changes were implemented to the operational Eta/EDAS land-surface package. Section 2 presents examples of the validation of Eta model performance during that period. Simultaneously during that period, off-line development focused on our next generation of land-surface improvements, to include frozen soil processes, plus substantial advances to the snowpack physics and ground heat flux physics. This phase of significant upgrades, in collaboration with our GAPP/GCIP and other partners, led us to coin the name "NOAH" to designate our new LSM. Section 3 describes these LSM upgrades and Section 4 presents some results from the successful testing of these upgrades in the coupled Eta/EDAS, which culminated in their operational implementation on 24 July 2001.

2. OPERATIONAL ETA MODEL VERIFICATION

Since the self-cycling of Eta land states began in June 1998, our verification efforts have been seeking evidence of any undue drift in EDAS soil moisture, or corresponding drift in Eta forecast 2-m air temperatures and relative humidity, which would arise from any severe bias in EDAS precipitation or surface radiation. For this purpose, we use a number of tools to assess the performance of the NOAH LSM coupled to the operational mesoscale Eta model.

The NCEP Forecast Verification System (FVS) provides near-surface verification statistics of 2-meter air temperature and relative humidity for the Eta model. These statistics are generated for about 20 different FVS regions covering the Eta model domain, and include monthly diurnal time-series composites of the 0-48 hour forecast compared with surface observations. Monthly compositing allows averaging of transient weather systems so that systematic tendencies emerge, which aid in evaluation of the diurnal nature of model forecasts related to the LSM. Annual time series of the mesoscale Eta model 48-hour forecast bias for the different FVS regions help in understanding the long-term (i.e. seasonal) trends (and potential drift) in model forecasts. (See: http://www.emc.ncep.noaa.gov/mmb/research/nearsfc/nearsfc.verf.html)

Monthly precipitation and water budget plots also aid in following trends in the Eta model versus observed precipitation and the resulting patterns in soil moisture fields for different soil model layers in the LSM. (See: http://www.emc.ncep.noaa.gov/mmb/gcp/h2o/index.html)

Monthly scatter plots of GOES satellite-based skin temperatures are compared with Eta/EDAS land-surface skin temperatures for cloud-free conditions; these comparisons provide another assessment of LSM performance, and are generally consistent with monthly FVS verification plots of 2-m air temperature and relative humidity described above. (See: http://orbit-net.nesdis.noaa.gov/goes/gcip/html/scatter.html)

2.1 *North American Monsoon*

As an example of this assessment, we examine the performance of the Eta model for the North American monsoon in the interior Southwest US (AZ, NM, CO, UT) during July 1999 and July 2000, which are relatively wet and dry months, respectively (Figure 1, top). The Eta/EDAS captures this interannual variability in this region's July precipitation (not shown), which is in turn reflected in interannual EDAS soil moisture variability. For example, the EDAS layer-2 (10-40 cm) volumetric soil moisture (Figure 1, middle) is relatively *moist* (dry) at end of *July 1999* (July 2000). Verification of the Eta model multi-station, monthly-mean 2-m air temperature for the interior Southwest (Figure 1, bottom) shows the model's excellent ability to capture the observed interannual variability of 2-m air temperature between July 1999 (cooler) and July 2000 (warmer). In summary then, in this region and season, the operational coupled land-atmosphere Eta model captures the observed interannual variability of maximum daytime surface temperature, in response to the different surface Bowen ratio that reflects the modeled interannual variability of soil moisture.

2.2 *North-central US cold versus warm season*

In another example we examine the cold versus warm season Eta model performance for the north-central US. The 2-m air temperature during March 2000 (low green vegetation cover) shows a slight daytime cool bias and a nighttime warm bias (Fig. 2, lower left), due to excess ground heat flux in moist bare soils typical of early spring, which yields a damped diurnal temperature cycle. In the drier soil conditions of August 2000 (also higher green vegetation cover), there is a several-degree daytime warm bias (Fig. 2, lower right). The latter is due (not shown) to a model high bias in both a) surface solar insolation and b) vegetation canopy resistance. This daytime warm bias persists over the nighttime. This contrast in cool spring bias versus warm summer bias over the north-central US is reflected also in the monthly verification of GOES-satellite versus Eta skin temperature (Fig. 2, top).

3. RECENT NOAH LSM ADVANCES

The LSM upgrades presented in this section were introduced in order to address various biases in near-surface air temperature and relative humidity that vary by region and season in Eta model forecasts (e.g. Section. 2.2). These biases were due in part to land surface-flux biases arising from certain limitations in the LSM physics. Extensive stand-alone uncoupled testing of the LSM at surface flux stations (not shown here) yielded several parameterization improvements that significantly reduced these biases. These improvements are related to 1) soil heat flux, 2) bare soil evaporation, 3) cold season processes, 4) canopy and aerodynamic resistance and 5) surface characteristics.

Soil heat flux changes include a soil thermal conductivity (Peters-Lidard et al 1998) that is less nonlinear than the previous formulation, so wet (*dry*) soils have lower (*higher*) conductivity. For example, over wet soils with sparse green vegetation common during early spring, the new formulation reduces the thermal conductivity and thus reduces the excess soil heat flux that had previously resulted in a dampened diurnal surface temperature cycle. For dry soils, the opposite is true, with the new formulation increasing the soil heat flux and reducing a previously exaggerated diurnal temperature cycle (e.g. Marshall 1998; Marshall et al 2001). Also, reduction of soil heat flux under vegetation canopy is included (Peters-Lidard et al 1997), as is a new snowpack thermal conductivity treatment (Lunardini, 1981, pg 148).

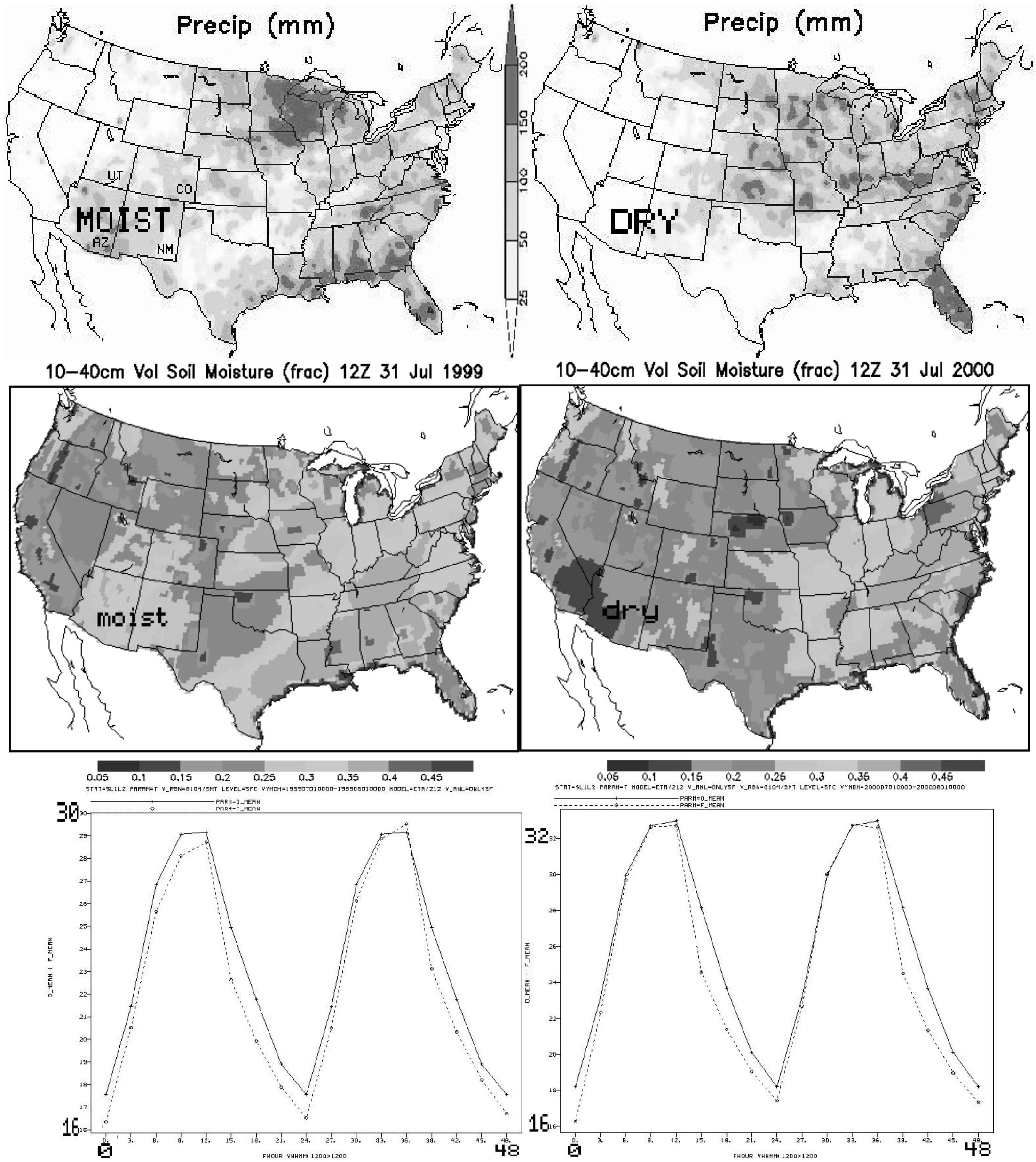

Fig. 1. *Left* (Right) column: *July 1999* (July 2000). **Top**: monthly accumulation of *observed* precipitation from 0.25-degree lat/lon gridded analysis of daily gauge-only data (Higgins et al 2000); **Center**: Eta model end-of-month layer-2 volumetric soil moisture; **Bottom**: monthly mean, over interior Southwest US, of 0-48 hour Eta forecast time (x-axis, hours) versus 2-m air temperature, C (y-axis) for Eta model (dashed) and station observations (solid). Mean *July 1999* (July 2000) daytime maximum temperature is about *29 C* (33 C).

Bare soil evaporation from the model's first soil layer was previously formulated as a linear function of the fraction of saturation of the soil moisture in the first soil layer. This is now modified so that as the near-surface soil dries, bare soil evaporation falls off more rapidly in a non-linear manner. This more properly reflects the real process whereby as bare soil dries, the top few millimeters of the soil become significantly drier than the several centimeters below and thus act as a capping evaporative "crust" barrier at the upper boundary of the near surface soil layer.

Many of cold season improvements were taken from the collaborative work of Koren et al (1999). Frozen soil was added as a new state variable, along with the attendant freeze/thaw

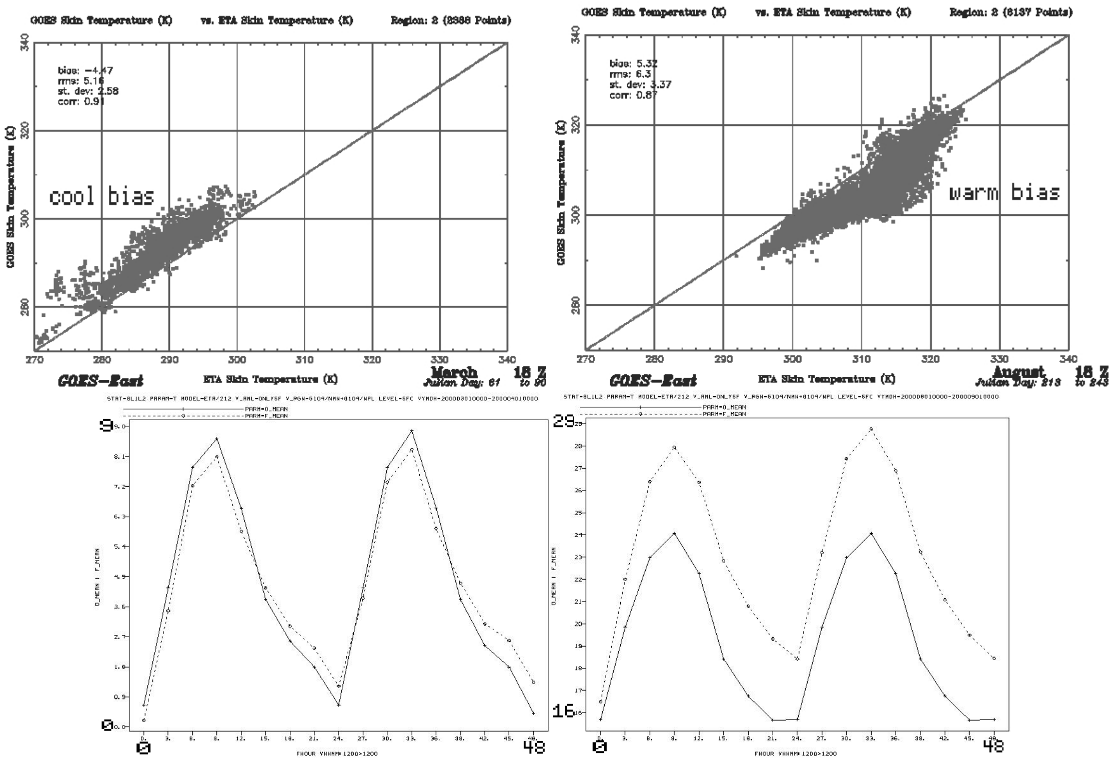

Fig. 2. For north-central US. *Left* (<u>Right</u>) column for *Mar* (<u>Aug</u>) 2000. **Top**: monthly scatter plot of 18 Z skin temp, K (~local noon) for GOES (y-axis) versus Eta 18-h forecast (x-axis); **Bottom**: monthly mean over 0-48 hr Eta forecast time (x-axis, hours) versus 2-m air temp, (y-axis, C), for Eta model (dashed) and obs (solid).

physics. The physical processes of 1) temporally varying snow density and 2) nighttime refreezing of daytime snowmelt were added to the snowpack physics, along with a parameterization of patchy snow cover that allows fractional snow cover over the range of 0-100 percent as a function of snow depth and vegetation type. Previously, the snow cover fraction had been assumed to be 100 percent regardless of the snow depth and vegetation type.

Including frozen soils during winter ameliorates an underestimation (when frozen soil processes are ignored) of soil temperature (and thus surface skin and air temperatures) during soil freezing periods, and temperature overestimation during thawing periods. Subgrid patchiness of a shallow snowpack (with attendant patches of exposed ground) allows for greater surface temperatures over a melting/retreating snowpack, more upward sensible heat flux, and air temperatures above freezing (Koren et al 1999)

The maximum surface albedo attained over a deep snowpack depends on vegetation type and coverage, e.g., substantially lower albedo for a conifer forest (dark trees sticking through the snowpack), compared to high albedo for a deep snowpack covering short grassland. To capture this effect, we now specify the maximum allowable albedo over deep snow using a spatially varying 1.0-degree global database (Fig. 3), derived from the deep-snow albedo database of Robinson and Kukla (1985). The spatial patterns in this database clearly manifest the major vegetation ecosystems.

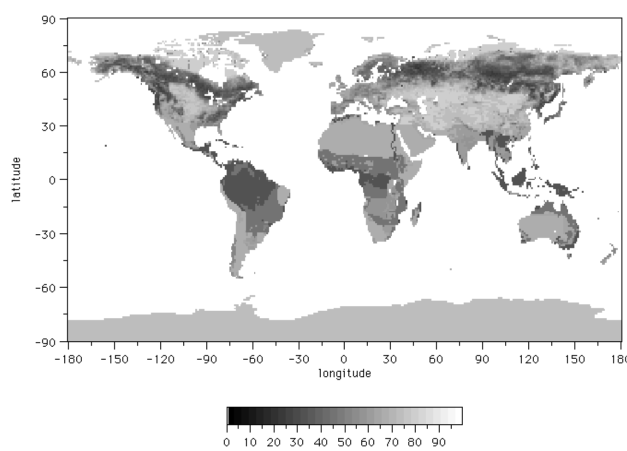

Fig. 3 Deep-snow maximum albedo field used in Eta model.

Finally, we 1) refined a coefficient in the Chen et al (1997) formulation for the thermal roughness length, 2) uniformly increased the leaf area index, and 3) increased the rooting depths for forests.

4. COUPLED ETA MODEL TESTING

Pre-implementation testing of the upgraded NOAH LSM in the coupled Eta model spanned 1) a summer month (12 Aug - 12 Sep 2000), 2) a winter month (01 Feb - 01 Mar 2001), and a spring month (24 Apr - 24 May 2001). Over these three periods we continuously executed the cycled EDAS and launched twice-daily 60-h Eta forecasts (one each from the 00Z and 12Z initial times) for both A) the control configuration (then operational suite) and B) the test configuration with the NOAH LSM encompassing the land-surface changes summarized in the previous section. The next two sub-sections present two examples of model bias reduction in the test case.

4.1 *Spring case*

The Eta model control case (i.e. as operational prior to the 24 Jul 2001) exhibits a near-surface cool (moist) bias in forecasts of air temperature (dewpoint) throughout the U.S. north central plains in spring, when the near-surface soil is typically moist from spring rains and the recent snowmelt season, and before substantial green vegetation has emerged. Inspection of Fig. 4 of the 60-h Eta forecast, valid at 00Z on 30 Apr 2001, of the dew point temperature in the lower boundary layer reveals that the test (right frame) is substantially less moist than the control (left frame).

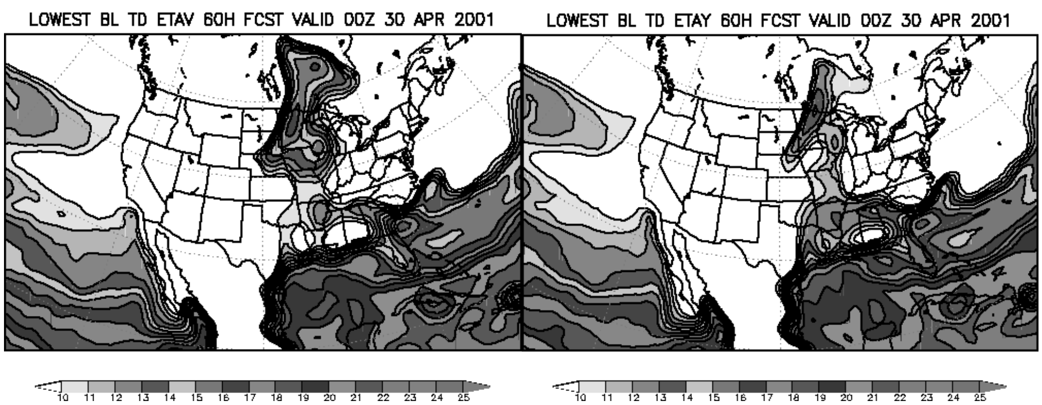

Fig. 4. Eta model 60-hour forecast of lower boundary layer (~100-150 m) dew point temperature, C, valid at 00Z on 30 April 2001, for control case (left) and test case (right).

The improved formulations of bare soil evaporation (less evaporation from moist soils) and soil thermal conductivity (less ground heat in moist soils) in the new NOAH LSM in turn allow more of the net surface radiation to be realized as surface sensible heat flux, yielding a deeper and drier daytime boundary layer and drier near-surface humidity. Fig. 5 shows that for the north central plains, the test case for the spring period nearly eliminates the notable positive bias of 2-m relative humidity seen in the control case.

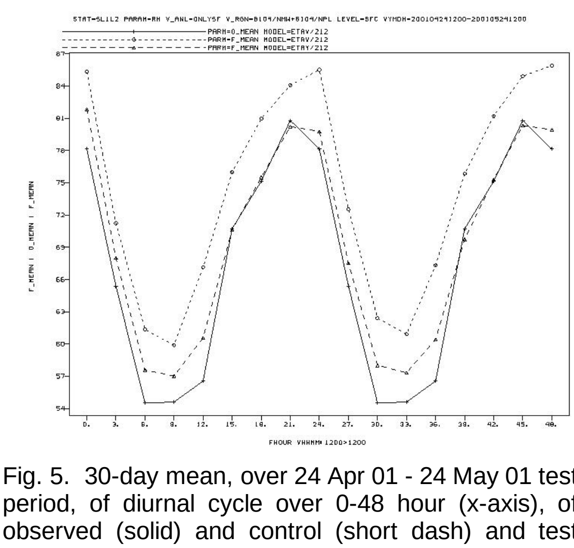

Fig. 5. 30-day mean, over 24 Apr 01 - 24 May 01 test period, of diurnal cycle over 0-48 hour (x-axis), of observed (solid) and control (short dash) and test (long dash) Eta forecast of 2-m RH (y-axis, range 53-87 RH), at all surface stations of U.S. northern plains.

4.2 *Winter snow-melt case*

In the winter test period, we examine the case of southerly warm advection over daytime melting snowpack for 02 Feb 2001 in the central US. In the physics of the control case, until all the snowpack in a model grid box completely vanishes, all available incoming energy at the surface is used to melt and sublimate snow. The surface skin temperature is concurrently bounded at 0ºC, and the resulting 2-m air temperature holds near freezing (Fig. 6, top). The physics of the test case allows for patchy snow cover if below a snow depth threshold (that varies by vegetation type), and hence allows exposed ground, lower albedo, aggregate surface skin temperature above 0ºC, and 2-m air temperature (Fig. 6, bottom) that rises further above freezing (i.e. during daytime). Thus in the *control* (test) case, *more* (less) energy available at the surface goes towards melting snow and *less* (more) toward surface sensible heating. Hence the physics of the test case substantially reduces the daytime cold bias (Fig. 6) in 2-m air temperature that is typical in the control case over relatively shallow melting snowpack.

4.3 *Summer case*

The warm bias in Eta forecasts of 2-m air temperature typical in the control case in the summer season east of the Rockies (see lower right frame of Fig. 2) was only slightly reduced (not shown) by the LSM changes of the test case. The two likely chief causes of this warm bias are 1) the known positive bias in Eta model surface insolation, and 2) a suspected high bias in NOAH LSM canopy resistance. These two areas will be the focus of our near-future effort.

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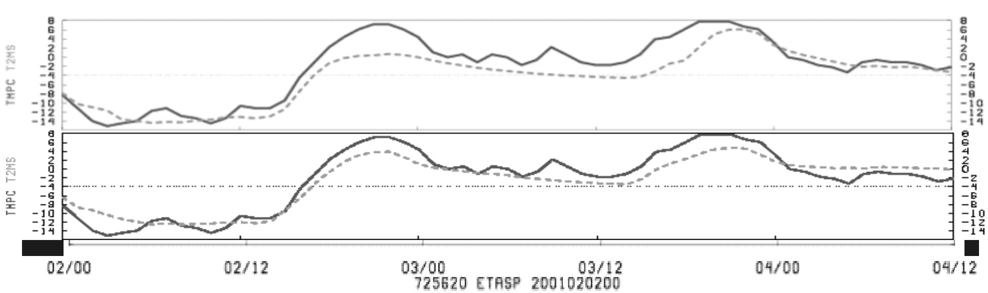

Fig. 6. Hourly time series over 60-hour Eta model forecast (long dash) of 2-m air temperature (C), starting from 00Z, 02 Feb 01, versus observations (solid) for North Platt, NE over relatively shallow snow, in control case (top), and test case (bottom). Y-axis range is -16 to +8 C, with middle horizontal reference line at -4 C.