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New soil physical properties implemented in the Unified Model at PS18

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Abstract

This note describes the improvements to the Unified Model (UM) soil hydraulic and thermal properties implemented in Parallel Suite 18 (PS18) that became operational in April 2008. Also described are trials of a two-stream multi-layer canopy radiation scheme that has been implemented in PS20 and became operational in November 2008.

The soil hydraulic properties affect the soils ability to hold water and the rate at which water moves through the soil. The soil moisture together with the soil hydraulic properties control transpiration from plants and direct evaporation from bare soil. The UM soil hydraulic properties are derived using the Cosby et al (1984) equations from information about soil texture; fractions of sand, silt and clay particles. Also, the soil thermal conductivity and heat capacity both depend on soil moisture and soil texture, so that these properties in turn influence the land surface temperature. Thus, soil moisture and the soil physical properties control the partitioning of net surface radiation into sensible, latent and ground heat fluxes.

Improvements to the calculation of the soil thermal conductivity result in a reduction of the models northern hemisphere (NH) summer warm bias by about 0·2 K and a reduction in the models NH winter cold bias by over 0·5 K. Average errors in screen temperature for the NH winter are reduced by about 10%. During the summer, the new soil thermal conductivity gives a greater flow of heat from the surface into the ground which results in atmospheric cooling. While in winter, there is a greater flow of heat from the ground towards the surface resulting in a warming of the atmosphere. The direction of the ground heat flux depends on the vertical temperature gradient. Improvements to the model soil hydraulic parameters are found to significantly increase the model soil moisture, by reducing surface evaporation. The new soil hydraulic properties also significantly reduce errors in screen temperature and humidity. However, by reducing surface evaporation, the new soil hydraulic parameters cause the model to become warmer during the summer. The new two-stream multi-layer canopy radiation scheme is found to cool the model by about 0·25 K during the summer. In our trials, the effect of the full changes is to eliminate the UM NH summer warm bias.

1. Introduction

Knowledge of soil is essential for meteorological, climatological, agronomic and hydrological applications. The properties of soil can have a significant impact on near surface temperature and humidity, low clouds and precipitation by influencing the exchange of heat and water between the land surface and the atmosphere. Soil moisture is thought to be one of the most important variables influencing the weather over land regions, far from the sea, during the summer. Fischer et al (2007) suggest that the continental European summer climate depends on winter and spring soil moisture accumulation, years with low spring-time soil moisture corresponding to warmer and drier summers.

Soil moisture can vary significantly over short distances and so measurements made at one location are not so informative about conditions at neighbouring locations. The variability in soil moisture is partly due to the spatial distribution of rainfall but also due to the spatial variation of the soil physical properties, vegetation and topography. This is part of the reason that, currently, no extensive global soil moisture observation network exists. Some regional near real-time soil moisture observing networks do exist, such as the USDA: SCAN (United States department of agriculture: Soil climate analysis network).

Until 2005, the soil moisture in the Met Office operational global Unified Model (UM) was specified at the start of the forecast using a scaled[1] version of the Willmott et al (1985) soil moisture climatology. Willmott et al (1985) assumed a total soil moisture storage capacity of 150 mm and derived their soil moisture climatology using observed average monthly precipitation and near surface air temperatures with a water-balance procedure. More recently, soil moisture climatologies have been derived using off-line versions of the Met Office land surface model (Essery et al, 2001), driven with data provided by the Global soil wetness project 2 (GSWP2, Dirmeyer et al 2005). The GSWP2 driving data consists of observation and reanalysis based precipitation, surface downward short-wave and long-wave radiation, near surface air temperature, humidity, wind speed and surface pressure. GSWP2 based soil moisture climatologies suggest that the scaled Willmott et al (1985) soil moisture climatology is too moist for the northern hemisphere (NH) during spring and early summer. Trials were performed (Walters 2007, unpublished) using the PS11 version of the UM with the soil moisture reset every week to the Willmott et al (1985) scaled climatology, for the June to August 2006 period. These trials show that use of the scaled Willmott et al (2006) soil moisture climatology causes forecasts of NH screen temperature to be too cold by about 0·5 K for June 2006 and too cold by about 0·3 K for July 2006. Conversely, for August 2006, the trials using the Willmott et al (1985) soil moisture climatology causes forecasts of NH screen temperature to be too warm by between 0·3 K (at T+24) to 0·6 K (at T+144).

1 Details of the scaling of the soil moisture climatology are given by Jones (2004). The rescaling significantly increases the soil moisture.

In August 2005 a more accurate method of specifying the UM initial soil moisture was introduced that uses observations of screen temperature and humidity. Because errors in the UM initial soil moisture field cause errors in forecasts of screen temperature and humidity, knowledge of errors in forecasts of screen temperature and humidity can be used to slowly correct (nudge) the UM initial soil moisture (Best and Maisey 2002, Best et al 2007). Errors in forecasts of screen temperature and humidity are due to many factors, with only a small proportion of the error due to the model soil moisture. The soil moisture nudging scheme seeks to identify and correct for this contribution. Drusch and Viterbo (2007) have examined the performance of the ECMWF soil moisture nudging scheme (they call it an Optimal interpolation scheme) and concluded that soil moisture nudging significantly improves weather forecasts on large geographical domains. Temperature forecasts for the northern hemisphere were significantly improved for up to nine days and to a level of 700 hPa. However, by comparison with in-situ soil moisture observations from the Oklahoma mesonet they also conclude that soil moisture nudging fails to improve the analysis and forecasts of soil moisture itself.

In the summer of 2006, operational global UM forecasts were too warm, by as much as 1 K, and initially attention was focussed on the soil moisture nudging scheme as the cause of the warm bias. However, careful investigation showed that the soil moisture nudging scheme has a positive impact on UM forecasts, reducing root mean square (RMS) errors in screen temperature and humidity and increasing the NWP Index. It was realised that long-standing biases in the UM had been hidden by use of the scaled Willmott et al (1985) soil moisture climatology. Improvements were made to reduce biases in model clouds, introduction of a climatology for naturally produced biogenic aerosols, new surface albedos based on satellite measurements and better treatment of snow-melt over frozen soils that gives moister soils. All these improvements significantly reduced the UM summer warm bias. This package of improvements was originally developed to reduce the summer warm bias in the Met Office climate model, HadGAM1 (Rowell, 2006).

More recently, in early 2007, a long-standing error was found in the way that the UM ANCIL programs use the Cosby et al (1984) equations to calculate the soil hydraulic parameters. At the time, it was thought that this error might significantly contribute to the UM summer warm bias[2]. In addition, Anne Verhoef and Pier Luigi Vidale at Reading University suggested that the UM soil thermal conductivity was too low and that parametrisations based on Johansen (1975) are more accurate.

2 However, work using the off-line UM land surface model shows that the error in the interpretation of the Cosby equations, actually causes surface evaporation/latent heat flux to be over-estimated (Compton 2008).

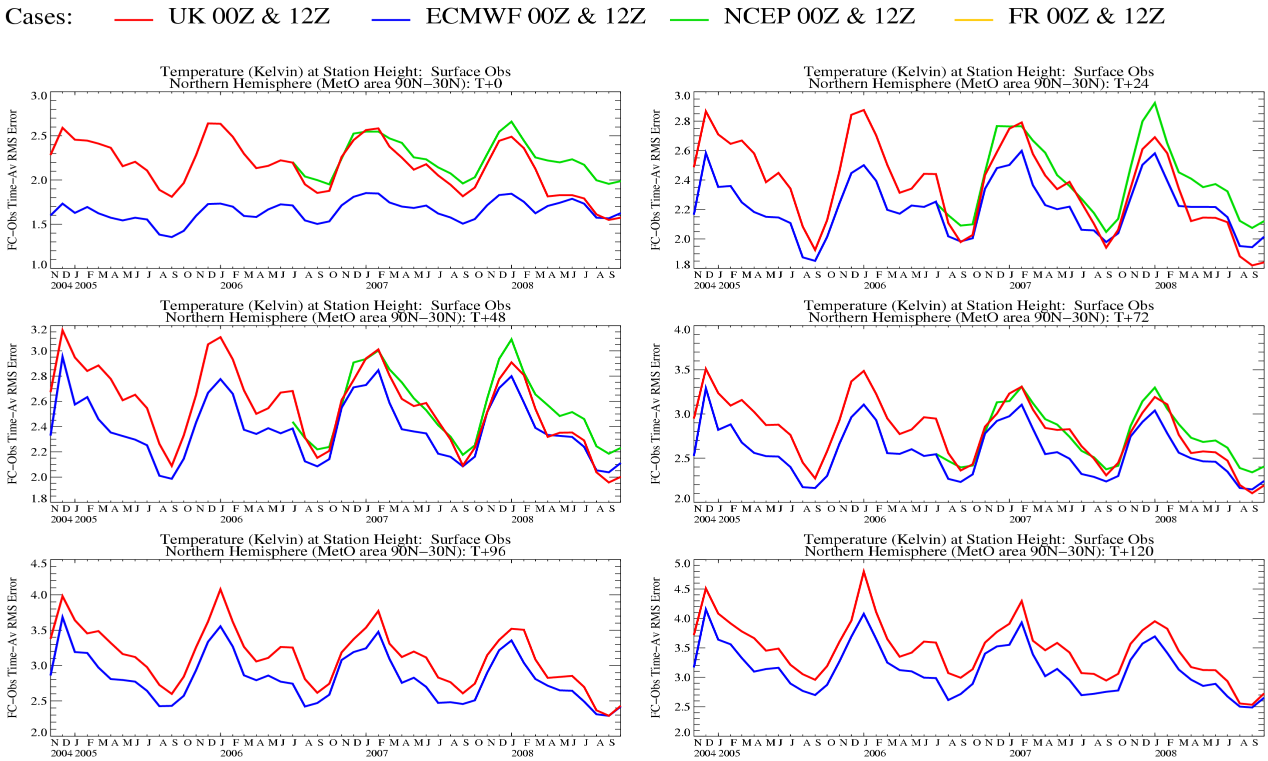

Figure 1: Operational verification of model northern hemisphere screen temperature RMS errors. Results are shown for the global UM (red curve, label UK), ECMWF (blue curve) and NCEP models (green curve).

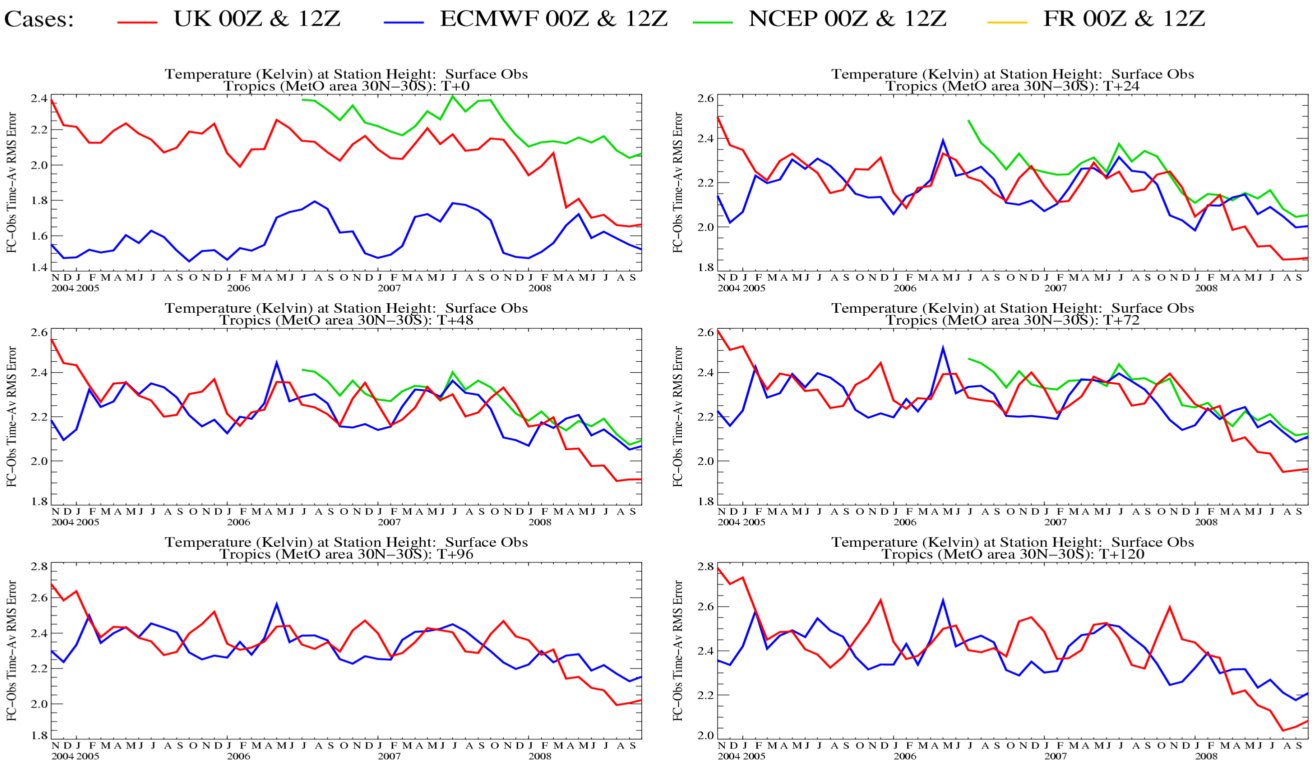

Figure 2: Operational verification of model tropics screen temperature RMS errors. Results are shown for the global UM (red curve, label UK), ECMWF (blue curve) and NCEP (green curve) models.

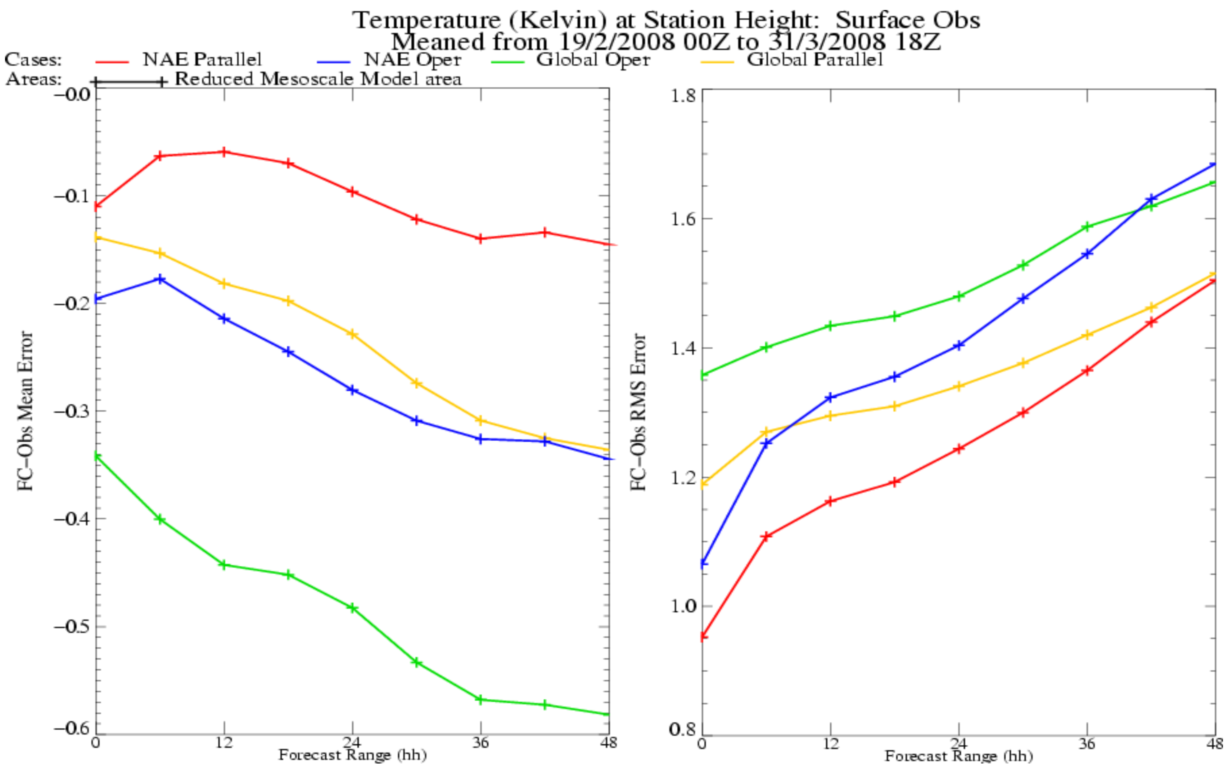

Figure 3: Bias and RMS errors in screen temperature from PS18 for the reduced mesoscale model area (~UK area). Results are shown for both the NAE and global UM models. The *Parallel* models (red and yellow lines) implement the new soil physical properties. The *Oper*ational models (blue and green lines) use the old soil physical properties.

Pre-operational trials with the global UM were performed to assess the impact of new soil hydraulic and thermal properties on forecast performance. These trials show significant improvements to UM forecasts of screen temperature and humidity. The improved UM soil physical properties were implemented in the global UM, the North Atlantic European (NAE) and United Kingdom 4km (UK4) models at Parallel Suite 18 (PS18) that started mid-February 2008 and became operational at the start of April 2008. Operational verification shows that there has been a clear improvement in operational UM forecasts of screen temperature and relative humidity[3] since April 2008 and that the operational UM performance for screen temperature forecasts is now as good as, or better than ECMWF (European Centre for Medium Range Weather Forecasts). The magnitude of the improvement seen in the operational verification is similar to the magnitude of the improvement shown by the pre-operational trials. Figure 1 shows operational verification of NH screen temperature RMS errors. Results are shown for the global UM, ECMWF and the National Centre for Environmental Prediction (NCEP). Figure 2 shows operational verification for the tropics.

PS18 shows that the NAE and UK4 regional models also benefit significantly from the new UM soil physical properties (Figure 3 shows results for the NAE and global UM). Operational global UM soil moisture also increases significantly after the PS18 improvements to UM soil physical properties. The increase in soil moisture is largest for the lower soil levels and is quite small

3 Unfortunately, operational verification doesn't compare the performance of relative humidity forecasts against ECMWF.

for the top-most soil level (Figures 4 and 5).

Note that PS18 implemented other changes in addition to the improvements to the UM soil physical properties and these will also have contributed to the observed operational improvements. At PS18 the global UM also implemented soil temperature nudging and assimilation of SYNOP screen temperature, relative humidity (RH) and wind observations. The NAE and UK4 regional models already used soil temperature nudging and assimilation of SYNOP screen T/RH/wind observations, before PS18.

Apportioning benefit between the different PS18 changes is not an exact science. Pre-operational trials with the global UM indicate that for forecasts of screen T/RH, the assimilation of SYNOP screen T/RH/wind observations has the largest benefit in the tropics and for shorter forecast ranges. In the tropics improvement is seen for forecast times up to about T+72 while for the extra-tropics most of the improvement is at T+24. The PS18 UM soils changes shows improvements at all forecast times from T+24 to T+144, for the tropics and extra-tropics regions. The biggest improvement is at the longer forecast times and for the extra-tropics winter hemisphere.

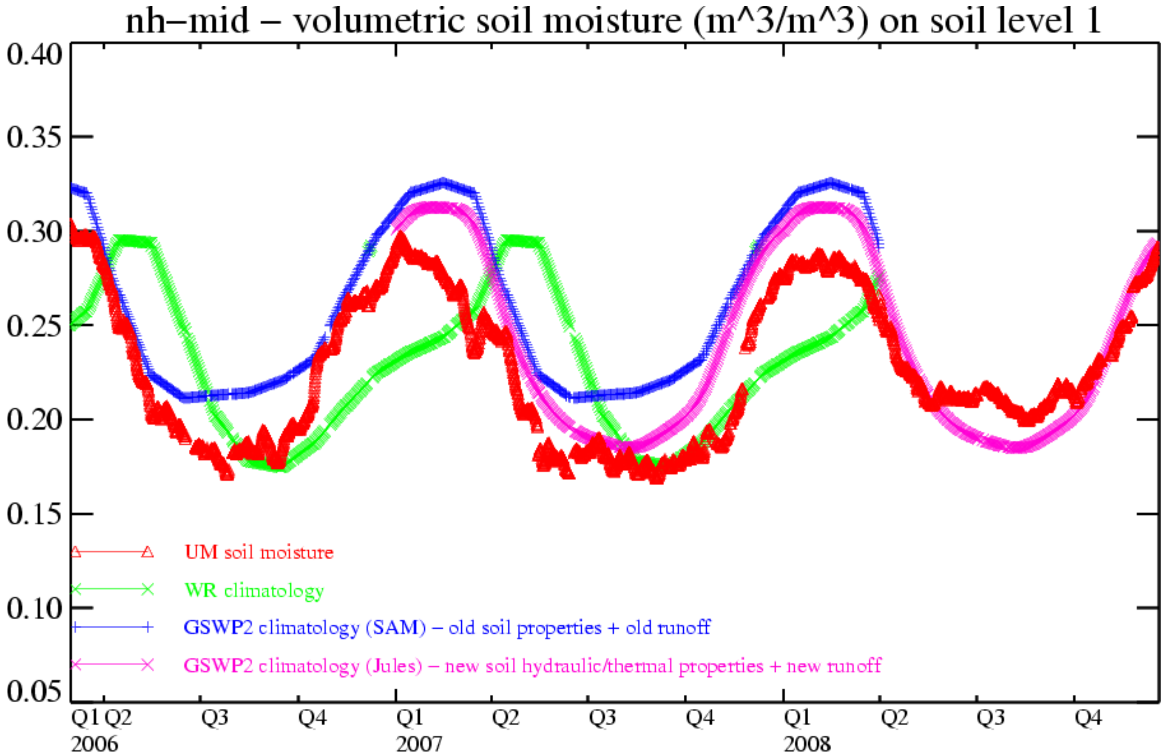

Figure 4: Time series of area averaged volumetric soil moisture on soil level 1 for the NH mid-latitude region (30N to 60N). The red curve shows the operational global UM soil moisture. The green curve shows the scaled Willmott et al (1985) soil moisture climatology. The blue (old soil properties) and purple (new soil properties) curves show climatologies created using GSWP2 driving data.

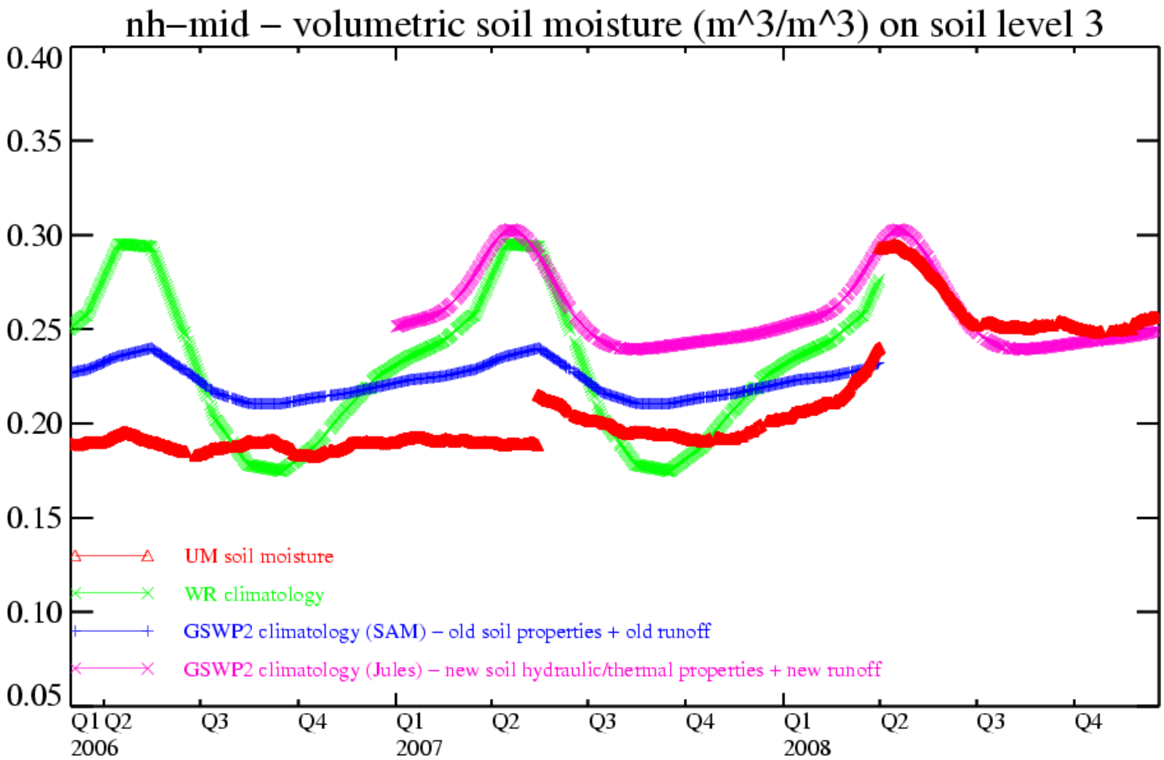

Figure 5: Time series of area averaged volumetric soil moisture on soil level 3 for the NH mid-latitude region (30N to 60N). Note the jump in operational global UM soil moisture (red curve) at the beginning of Q2 2008 when PS18 became operational. The jump in May 2007 is due to improved treatment of snow-melt over frozen ground.

2. New Soil Physical Properties

Soil Hydraulic properties

The Unified Model (UM) has three soil textural types; coarse, medium and fine. The soil hydraulic properties are calculated using the Cosby et al (1984) regression relationships from the soil sand/silt/clay fractions. The sand/silt/clay fractions are derived from the $1^o x 1^o$ soil classes data of Wilson and Henderson-Sellers (WHS). The Clapp and Hornberger (CH) equations are used to describe the soil water retention curve and the relationship between soil moisture and soil hydraulic conductivity (see Appendix A).

A long-standing error has been found in the way that the UM ANCIL programs use the Cosby relationships. Correcting this error causes a large change to the UM soil hydraulic properties, as shown in the tables below. Note the order of magnitude increase in SATHH and the large increase to $\theta_c - \theta_w$ of the medium soil type. The new values of SATHH are now in much better agreement with observations (for example see Table 2 of Clapp and Hornberger, 1978). Note that the UM sand/silt/clay fractions have not been changed.

	Critical point θ_c	Wilting point θ_w	Critical minus Wilting $\theta_c - \theta_w$	$-\psi_s$ SATHH (m)	K_s (mm/s)
Fine	0.310	0.221	0.090	0.045	0.0036
Medium	0.242	0.136	0.106	0.049	0.0047
Coarse	0.096	0.033	0.062	0.022	0.0110

Table 1: Old UM soil properties, for the three UM soil textural types. SATHH is the soil suction at saturation, K_s is the hydraulic conductivity at saturation, the critical point θ_c is the volumetric soil moisture for a soil suction of 3.364 m, the wilting point θ_w is the volumetric soil moisture for a soil suction of 152.9 m.

	Critical point θ_c	Wilting point θ_w	Critical minus Wilting $\theta_c - \theta_w$	$-\psi_s$ SATHH (m)	K_s (mm/s)
Fine	0.370	0.263	0.107	0.324	0.0015
Medium	0.332	0.187	0.145	0.397	0.0028
Coarse	0.128	0.045	0.083	0.062	0.0195

Table 2: New, PS18, soil properties calculated using the correct Cosby equations, for the three UM soil textural types.

Soil thermal conductivity

The old UM parametrisation of soil thermal conductivity is described by Appendix B of Cox et al (1999) and page 16 of UM documentation paper 70 (Jones 2004). The effective thermal conductivity is given by

$$\lambda_s=(\lambda_{sat}-\lambda_{dry})\frac{\theta}{\theta_s}+\lambda_{dry} \quad (1)$$

where λ_{dry} is the dry thermal conductivity. The thermal conductivity when the soil is saturated is given by

$$\lambda_{sat} = \lambda_{water}^{\theta_u^s}\times\lambda_{ice}^{\theta_f^s}\times\lambda_{dry}/\lambda_{air}^{\theta_s} . \quad (2)$$

θ_s is the volumetric soil moisture at saturation. λ_{air} , λ_{water} and λ_{ice} are the thermal conductivities of air, water and ice. $\theta_f^s=\theta_s[S_f/(S_u+S_f)]$, $\theta_u^s=\theta_s-\theta_f^s$ and S_u and S_f are the fractional saturation of unfrozen and frozen water

Anne Verhoef and Pier Luigi Vidale at Reading University have suggested that the Cox et al (1999) parametrisation predicts too low values of soil thermal conductivity and that parametrisations based on Johansen (1975) are more accurate. The Johansen parametrisation is described by Peters-Lidard et al (1998**.** Implementing the Johansen parametrisation in the UM would require a substantial amount of recoding. Therefore, Imtiaz Dharssi has proposed a simpler parametrisation based on Johansen (1975).

$$\lambda_s=(\lambda_{sat}-\lambda_{dry})K_e+\lambda_{dry} \quad (3)$$

where the Kersten number

$$K_e=\begin{cases}\log\frac{\theta}{\theta_s}+1.0 & \frac{\theta}{\theta_s}\geq 0.1\\ 0 & \text{otherwise}\end{cases} . \quad (4)$$

$$\lambda_{sat}^u=1.58+12.4\times(\lambda_{dry}-0.25) \text{ with the constraint } 1.58\leq\lambda_{sat}^u\leq 2.2 . \quad (5)$$

$$\lambda_{sat}=\frac{\lambda_{water}^{\theta_u^s}\times\lambda_{ice}^{\theta_f^s}}{\lambda_{water}^{\theta_s}}\times\lambda_{sat}^u . \quad (6)$$

Values of λ_{dry} are calculated off-line based on UM soil texture (Jones 2004); $\lambda_{dry}=\lambda_{air}^{\theta_s}\times\lambda_m^{(1-\theta_s)}$, $\lambda_m=\lambda_{clay}^{F_c}\times\lambda_{silt}^{F_{st}}\times\lambda_{sand}^{F_s}$ where $\lambda_{air}=0.025$ $W\ m^{-1}\ K^{-1}$, $\lambda_{clay}=1.16025$ $W\ m^{-1}\ K^{-1}$ and $\lambda_{silt}=\lambda_{sand}=1.57025$ $W\ m^{-1}\ K^{-1}$. F_c , F_{st} and F_s are the soil clay, silt and sand fractions.

When using van Genuchten soil hydraulics, the UM only stores the free soil water $\theta - \theta_r$ (see Appendix A) and uses the approximation $\theta / \theta_s \simeq (\theta - \theta_r)/(\theta_s - \theta_r)$ when calculating the soil thermal conductivity. For non-zero values of θ_r, this approximation will cause the calculated soil thermal conductivity to be underestimated. Section 2 of Vanapalli et al (1998) offers an interesting review of the meaning and relevance of the residual water θ_r.

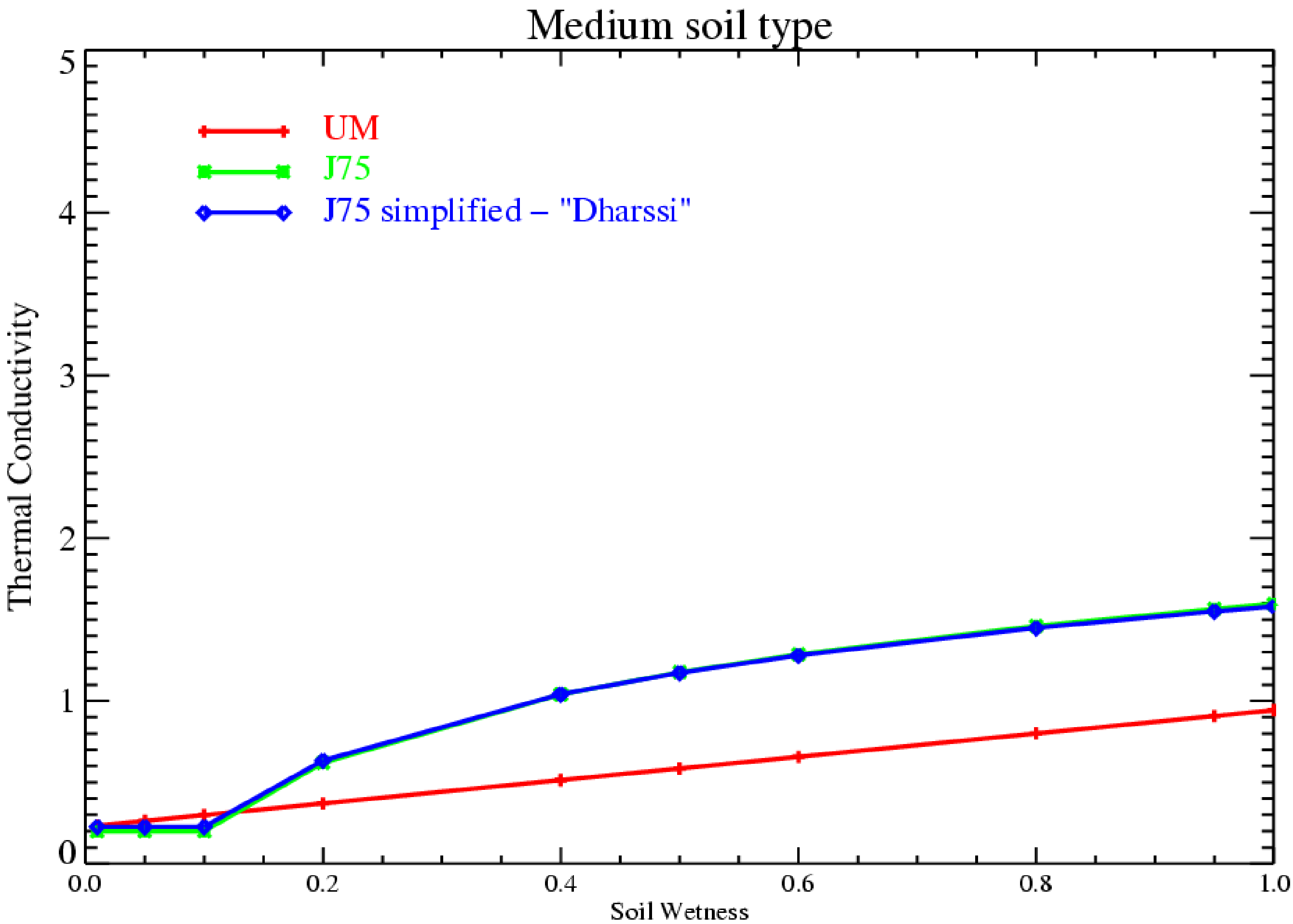

Figure 6a: Inter-comparison of the parametrisations of soil thermal conductivity for the UM medium soil type. The red curve shows results for the Cox et al (1999) parametrisation which was used by the UM before PS18. The green curve shows results for the Johansen (1975) parametrisation. The blue curve shows the results for the simplified Johansen parametrisation which is used by the UM since PS18.

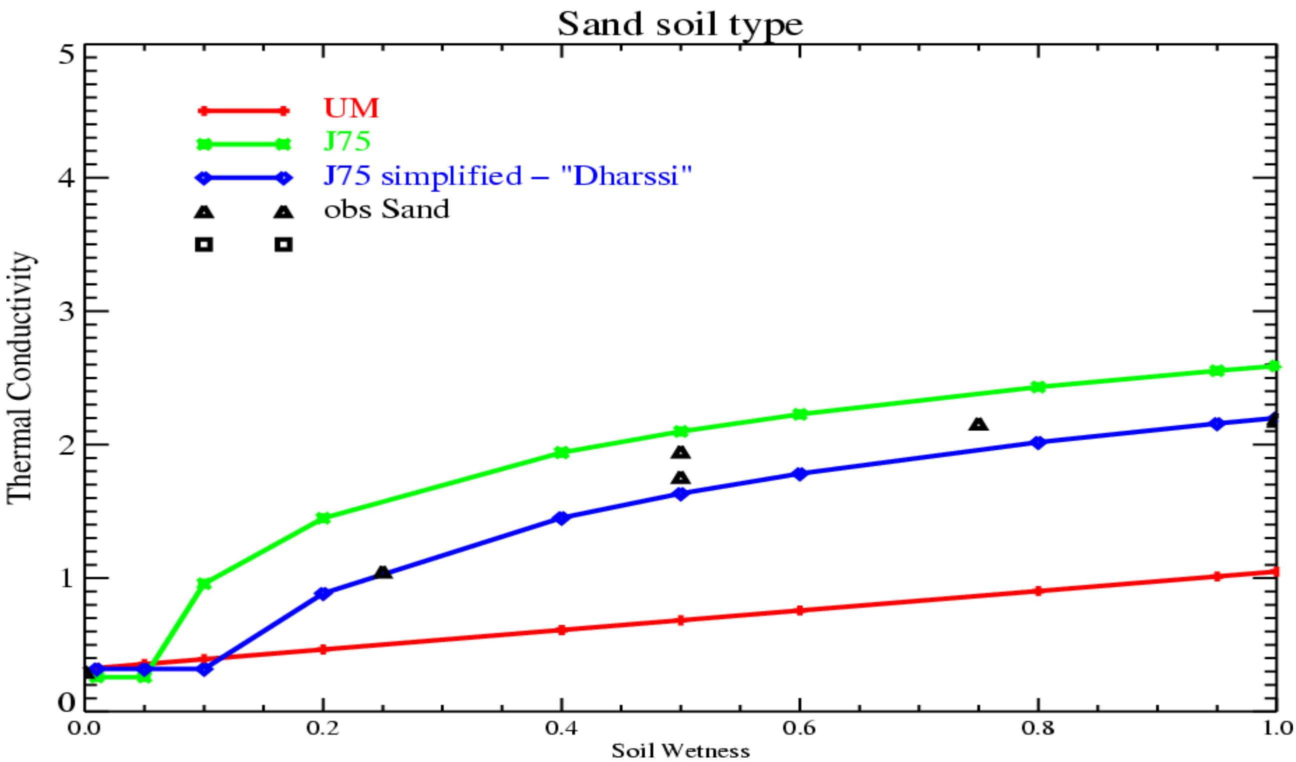

Figure 6b: Inter-comparison of the parametrisations of soil thermal conductivity for the UM coarse soil type. The red, green and blue curves have the same meaning as in Figure 6a. The black triangular symbols show the observed values of soil thermal conductivity and are the reference values given in table 3 of Peters-Lidard et al (1998) for sandy soil.

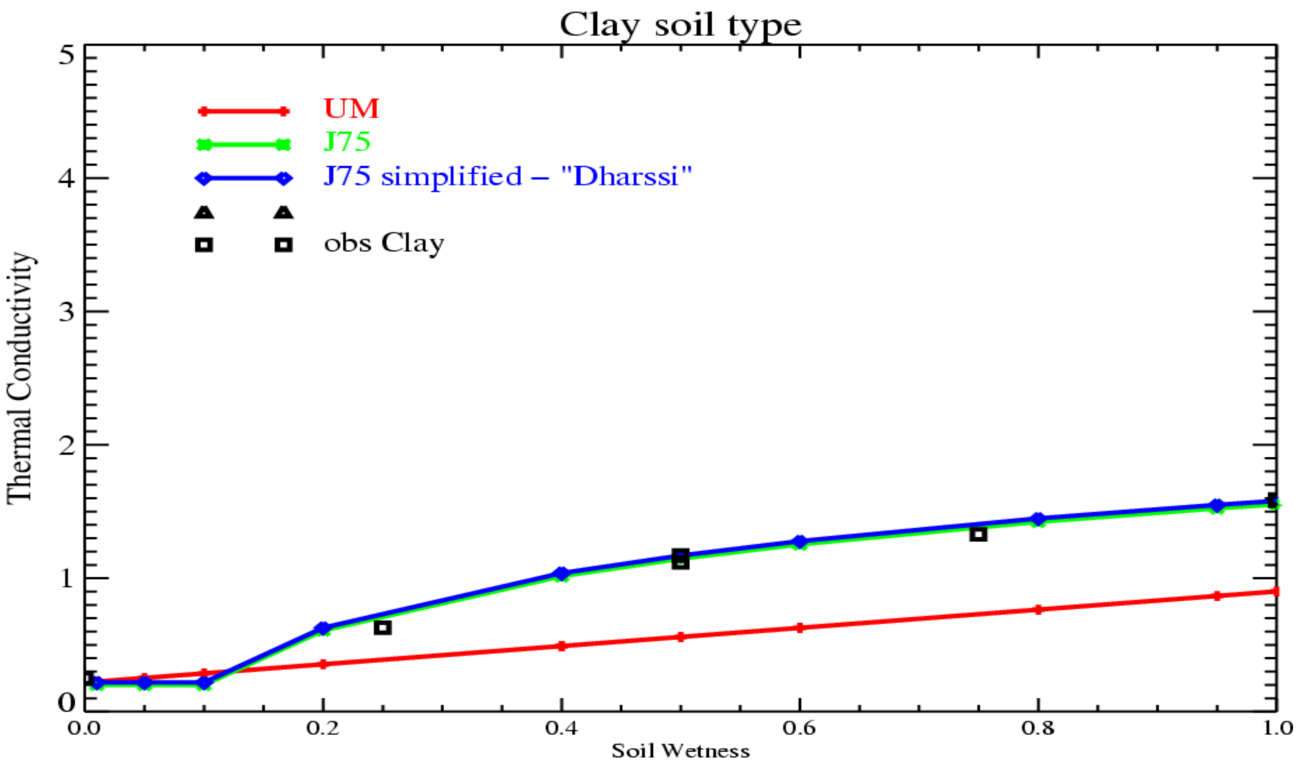

Figure 6c: Inter-comparison of the parametrisations of soil thermal conductivity for the UM fine soil type. The red, green and blue curves have the same meaning as in Figure 6a. The black square symbols show the observed values of soil thermal conductivity and are the reference values given in table 3 of Peters-Lidard et al (1998) for clay soil.

3. Canopy radiation model

The old UM canopy radiation model uses the “big-leaf” approximation which treats the canopy as a single leaf. Comparison of model simulations against observations from flux towers shows that this “big-leaf” approximation leads to a very poor simulation of the diurnal cycle and underestimates the importance of light-limitation on photosynthesis (Jogireddy et al, 2006 and Mercado et al, 2007). That is, there is too much photosynthesis in low light conditions (e.g. morning/evening) and too little photosynthesis in bright light conditions (e.g. mid-day). Light saturation occurs when the incident short wave radiation exceeds about $100\, Wm^{-2}$ (a very low value). This is important for NWP, since transpiration by plants is directly connected to photosynthesis. During photosynthesis plants open their stomata (tiny pores on their leaves) to breath in carbon-dioxide and while doing so they lose water. A new two-stream multilayer canopy radiation model has been developed for the UM that implements both decreasing leaf nitrogen with height and light inhibition of leaf respiration. Jogireddy et al (2006) find that the new canopy radiation model (with N=10 layers) gives much better agreement with flux measurements. Since November 2008 the operational global UM uses the new two-stream multilayer canopy radiation model.

4. Impact of new soil physical properties on UM forecasts

Pre-operational trials

A number of June 2006 (NH summer) and December 2006 (NH winter) trials have been run using a N216L50 version of the UM using 3DVAR atmospheric data assimilation and PS15 model parametrisations. All these trials use soil moisture nudging. None of these trials use soil temperature nudging or assimilation of SYNOP screen temperature, relative humidity (RH) and wind observations (except trials sekco and sekcl). See Tables 3a and 3b for a summary of the pre-operational trials. In the trials where the soil hydraulic properties are changed to those calculated using the correct Cosby equations, the initial soil moisture is rescaled such that the soil suction remains unchanged. This is equivalent to preserving the soil moisture availability.

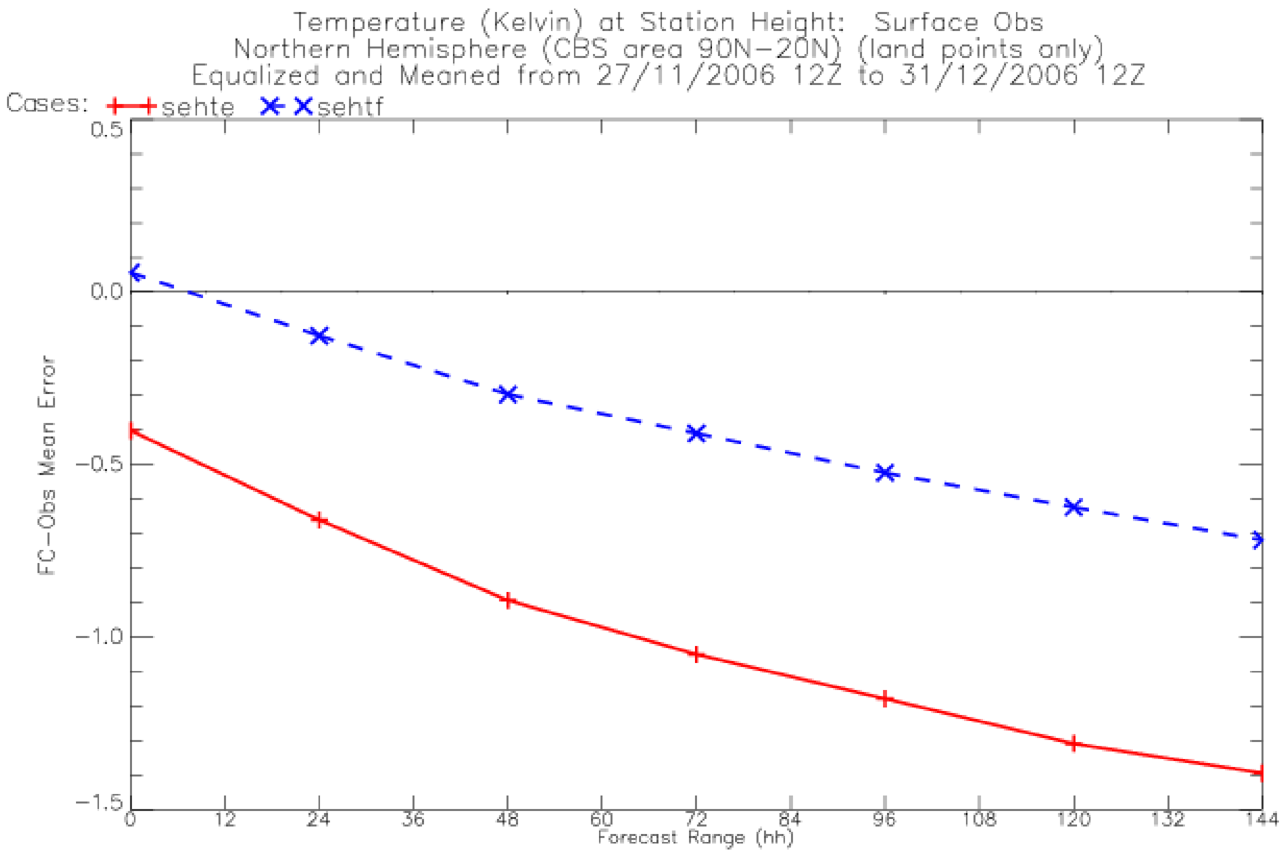

Figure 7: Bias in UM forecasts of screen temperature from the pre-operational winter trials. Both trials are run at a resolution of N216L50, use 3D-VAR atmospheric data assimilation and PS15 model parametrisations. The control (red curve - sehte) uses the old soil physical properties. The test (blue curve - sehtf) uses the new soil hydraulic and thermal properties. The new soil physical properties reduce the UM winter cold bias by about 0·6 K.

Trial	Soil Hydraulic Properties	Soil Thermal Conductivity	Soil Hydrology	Canopy Radiation Model	Soil Moisture Nudging	Soil Temperature Nudging	Extra SYNOP assimilation
sehte	WHS sand/silt/clay with **old Cosby** equations (Table 1).	UM – Cox et al (1999)	CH	Big Leaf	Yes	No	No
sehtf	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	J75 Simplified - Dharssi	CH	Big Leaf	Yes	No	No
sekcl	WHS sand/silt/clay with **old Cosby** equations (Table 1).	UM – Cox et al (1999)	CH	Big Leaf	Yes	Yes	Yes
sekco	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	J75 Simplified - Dharssi	CH	Big Leaf	Yes	Yes	Yes

Table 3a: Summary of December 2006 trials run.

December 2006 trials

The new soil physical properties have a large beneficial impact in the NH winter; reducing the model NH cold bias by over 0·5 K and reducing the RMS errors in screen temperature by about 10%, see Figures 7 and 8. The December 2006 trials also show an improvement to southern hemisphere (SH) screen temperatures. For the tropics, the screen temperature results are mixed, showing an improvement at 00Z but a slight deterioration at 12Z. Trials show an improvement to screen RH in the NH, tropics and SH regions.

For December 2006, the new soil physical properties have a neutral impact on the NWP index (sehtf vs sehte: -0·05 vs observations , +0·02 vs analysis). When the assimilation of SYNOP screen T/RH/wind observations is included in both the control and test, the new soil physical properties have a much greater positive impact on the NWP index (sekco vs sekcl[4]: +0.43 vs observations, +0.56 vs analysis). This indicates a strong synergy between the PS18 soils changes and the assimilation of SYNOP screen T/RH/wind observations. It seems likely that the combined improvement of all the PS18 changes is greater than the sum of of the individual improvements.

4 Results for trials sekco and sekcl are courtesy of Bruce Ingleby.

Trial	**Soil Hydraulic Properties**	**Soil Thermal Conductivity**	**Soil Hydrology**	**Canopy Radiation Model**	**Soil Moisture Nudging**	**Soil Temperature Nudging**	**Extra SYNOP assimilation**
secwb	WHS sand/silt/clay with **old Cosby** equations (Table 1).	UM – Cox et al (1999)	CH	Big Leaf	Yes	No	No
sedsl	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	UM – Cox et al (1999)	CH	Big Leaf	Yes	No	No
sedso	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	J75 Simplified - Dharssi	CH	Big Leaf	Yes	No	No
sehlb	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	J75 Simplified - Dharssi	CH	Two-stream 10 layers	Yes	No	No
sedsv	WHS sand/silt/clay with **correct Cosby** equations (Table 2).	J75 Simplified - Dharssi	VG	Big Leaf	Yes	No	No
sedsr	IGBP	UM – Cox et al (1999)	VG	Big Leaf	Yes	No	No
sedst	IGBP	J75 Simplified - Dharssi	VG	Big Leaf	Yes	No	No

Table 3b: Summary of June 2006 trials run.

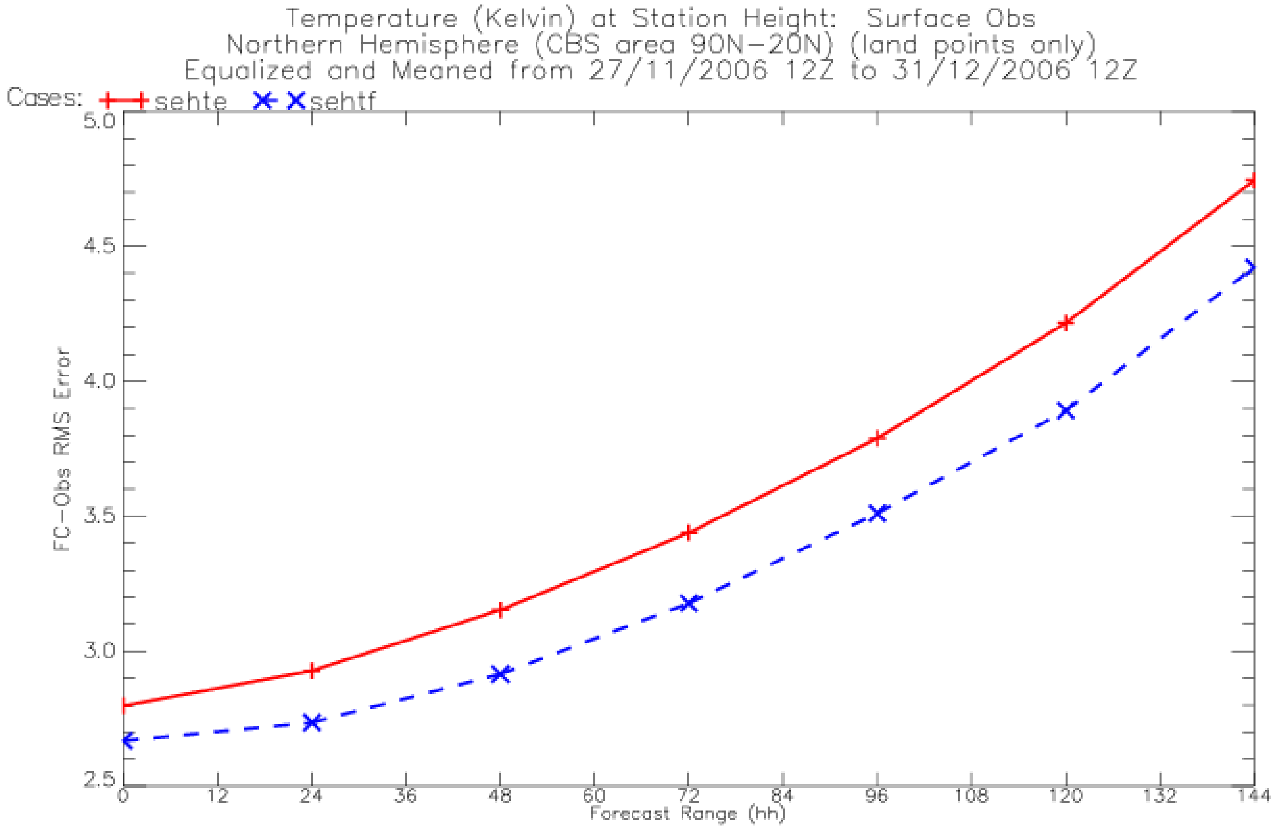

Figure 8: RMS errors in UM forecasts of screen temperature from the pre-operational winter trials. The control (red curve - sehte) uses the old soil physical properties, the test (blue curve - sehtf) uses the new soil hydraulic and thermal properties. The new soil physical properties reduce RMS errors by about 10%.

June 2006 trials

The higher wilting and critical points and lower saturated hydraulic conductivity of the new soil hydraulic properties significantly increases the model soil moisture. The higher wilting and critical points reduce evaporation from the soil while the lower saturated hydraulic conductivity reduces the runoff.

Simulations using the off-line UM land surface model with observation based driving data and validation against observed fluxes shows that use of the old soil hydraulic properties produces too much surface evaporation/latent heat flux (Wainwright 2006) while use of the new soil hydraulics properties gives much better estimates of surface evaporation/latent heat flux (Compton 2008).

The reduced evaporation means that the new soil hydraulic properties actually increase the NH summer warm bias. The new soil thermal conductivity parametrisation reduces the NH summer warm bias. The new multilayer two-stream canopy radiation model also significantly reduces the NH summer warm bias, shown in Figure 10. Similar results are found for the NH summer mslp bias (see Figure 9).

The new soil hydraulic properties do provide benefits; root mean square (RMS) errors in screen temperature are reduced in the tropics and southern hemisphere (SH). RMS errors in screen RH are reduced in the NH, tropics and SH regions.

Figure 14 is interesting as it shows that the UM SH winter cold bias is also significantly reduced by the new soil physical properties. Most of the improvement is due to the new soil thermal conductivity parametrisation.

Paradoxically, the change to the soil hydraulic properties has a significantly positive impact on the NWP Index while the change to the soil thermal conductivity has a neutral impact. The new canopy radiation model seems to very slightly increase the NWP Index (see Figures 16, 17 and 18).

The new multilayer two-stream canopy radiation model significantly reduces the NH summer biases but otherwise provides little additional benefit. Figure 19 shows the impact of the new canopy radiation model on evaporation from the surface. The impact is greatest in regions with trees. During mid-day evaporation is increased while in the early morning and evening the evaporation may decrease.

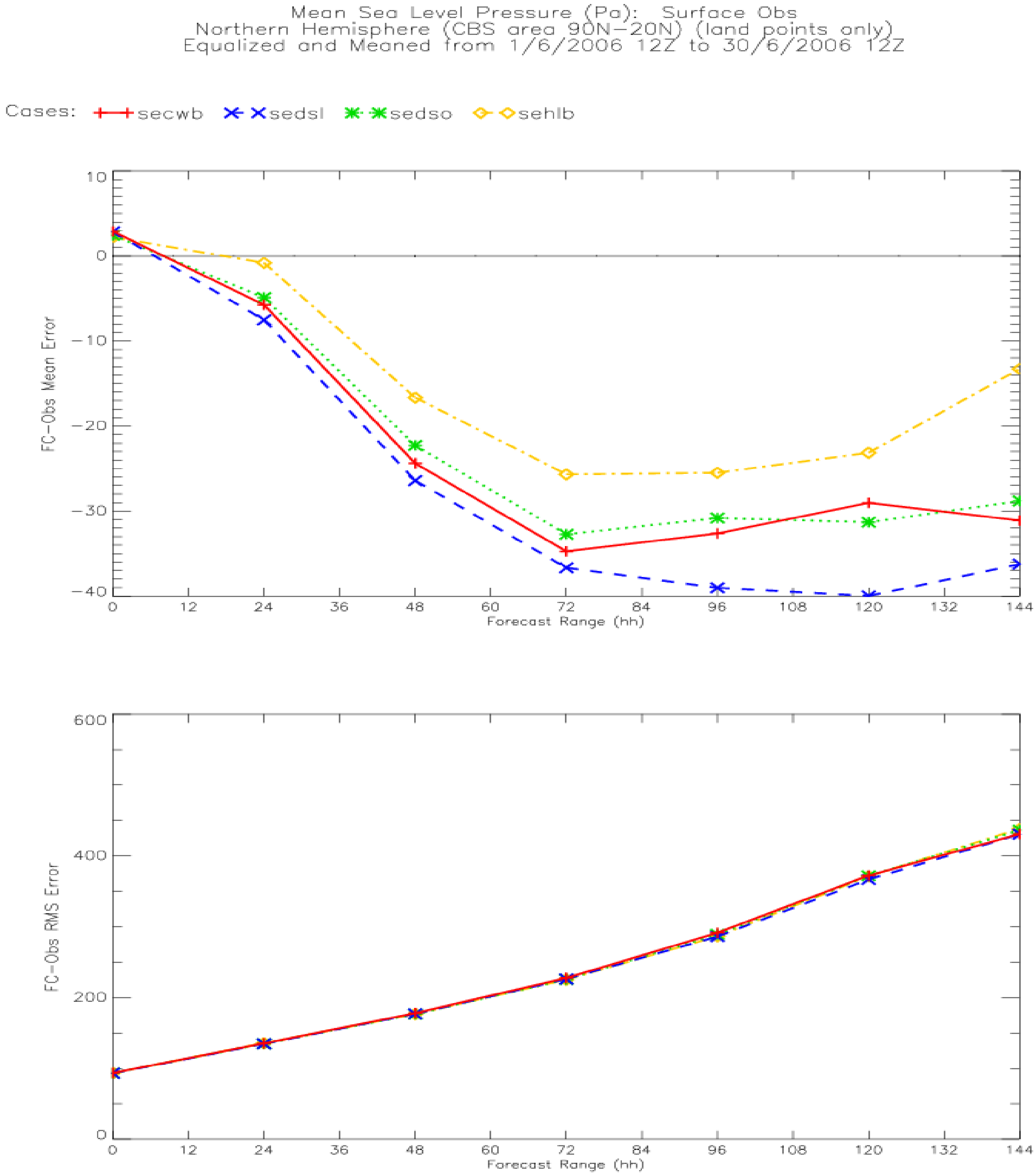

Figure 9: Biases and RMS errors in model forecasts of mean sea level pressure (mslp) for NH land during June 2006. The new soil hydraulic properties worsen the mslp bias while the new soil thermal conductivity reduces the bias. The new two-stream multilayer canopy radiation model significantly reduces the bias. The red curve (secwb) shows results for a model that uses the old soil properties. The blue curve (sedsl) shows results for a model that uses the new soil hydraulic properties calculated using the correct Cosby equations. The green curve (sedso) shows results for a model that uses both the new soil hydraulic properties and the new J75 simplified parametrisation of soil thermal conductivity. The yellow curve (sehlb) shows results for a model that uses a new two-stream multilayer canopy radiation model as well as new soil physical properties.

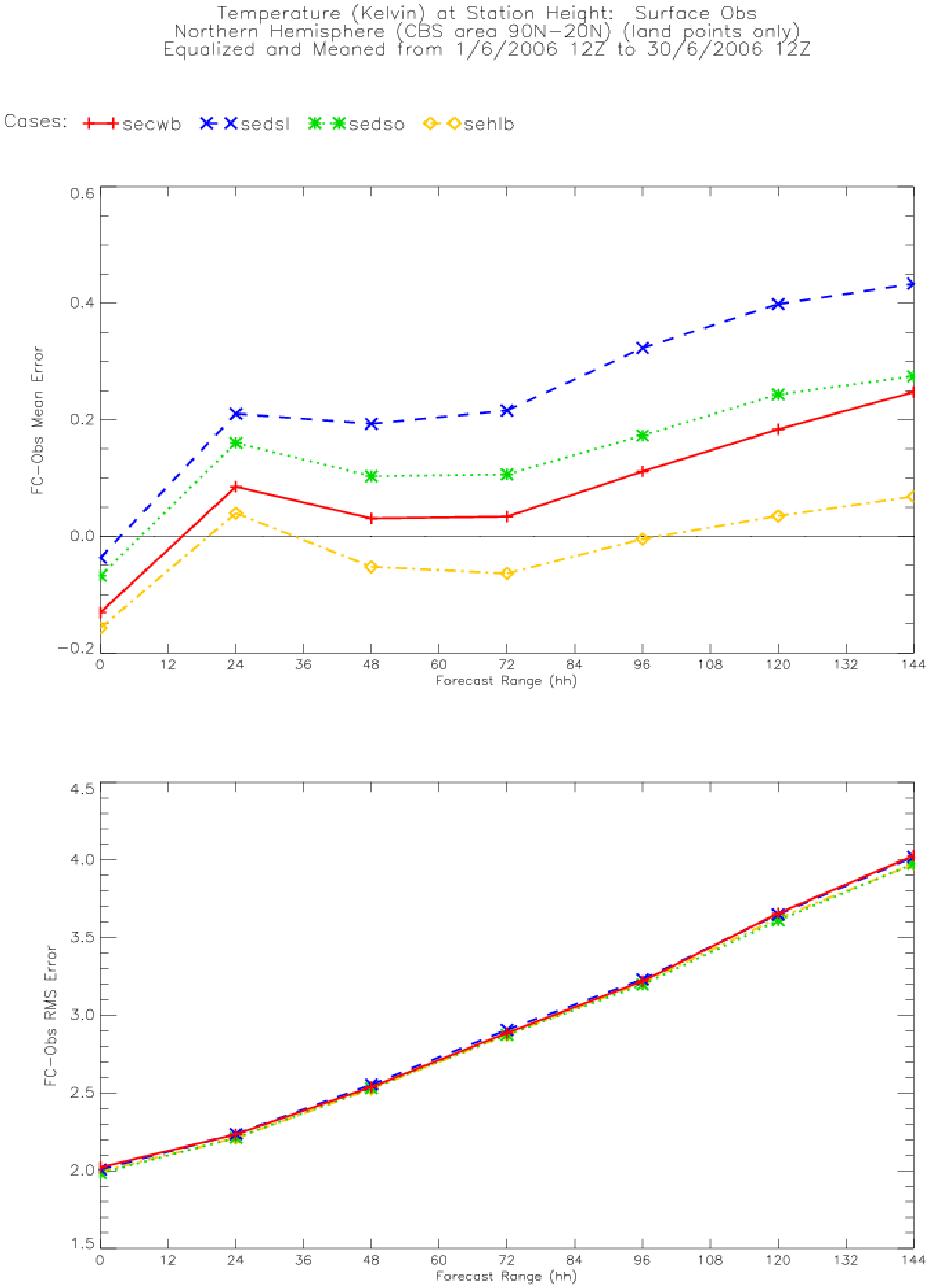

Figure 10: Bias and RMS errors in model forecasts of screen temperature for NH land during June 2006. The curves labels have the same meaning as in Figure 9.

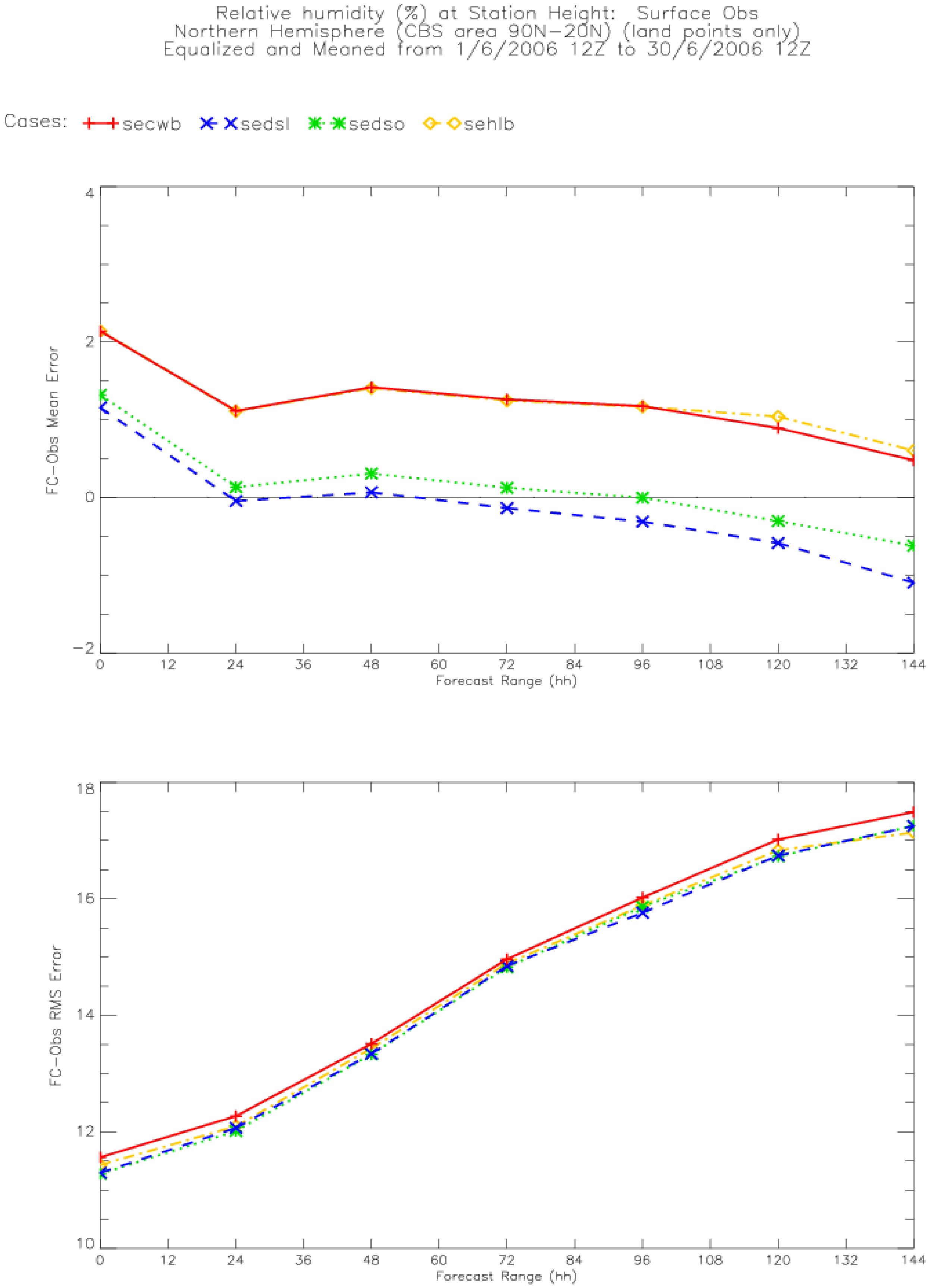

Figure 11: Bias and RMS errors in model forecasts of screen RH for NH land during June 2006. The new soil physical properties reduce the RMS errors. The curves labels have the same meaning as in Figure 9.

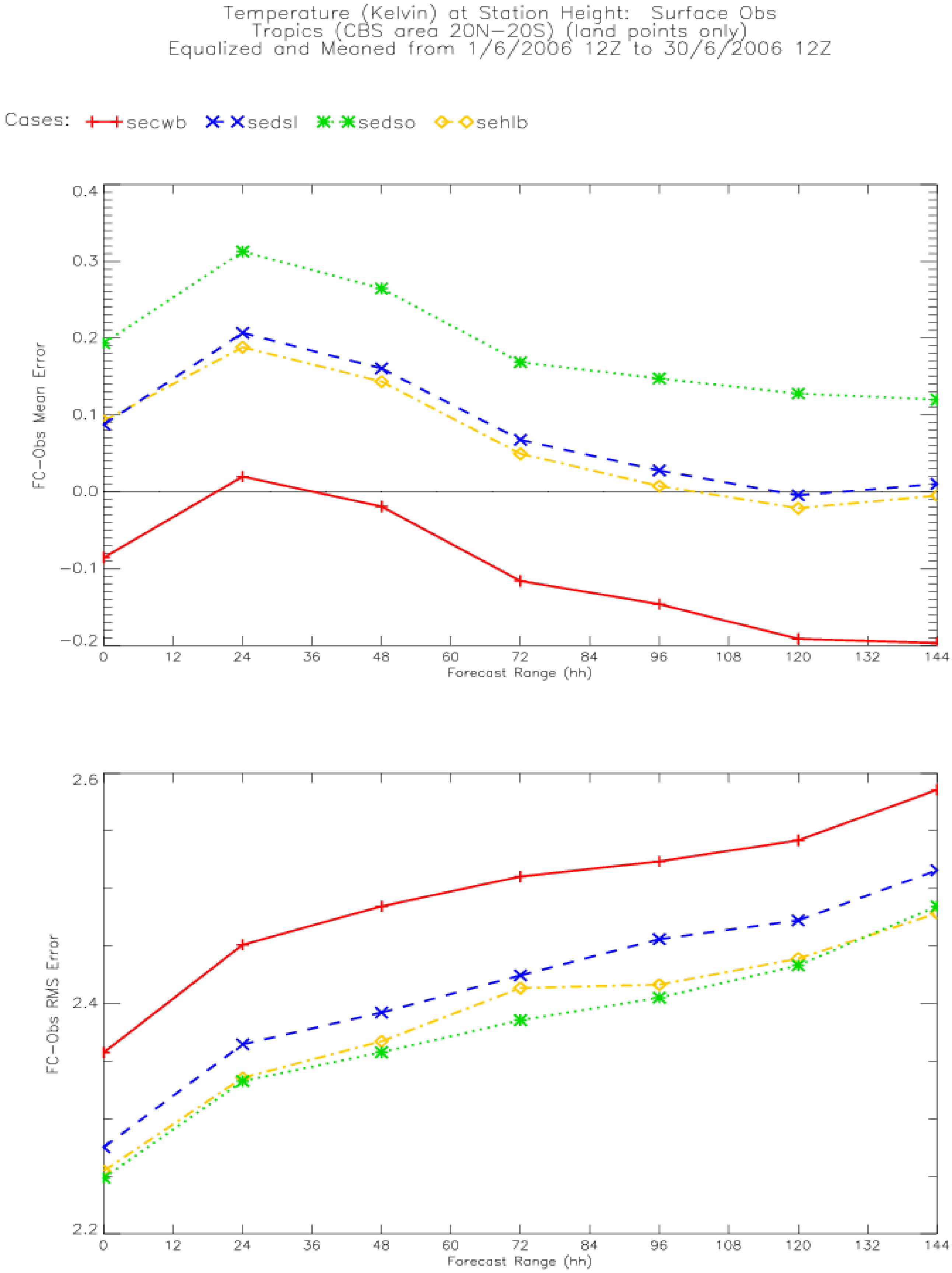

Figure 12: Bias and RMS errors in model forecasts of screen temperature for tropics land during June 2006. The new soil physical properties reduce the RMS errors. The curves labels have the same meaning as in Figure 9.

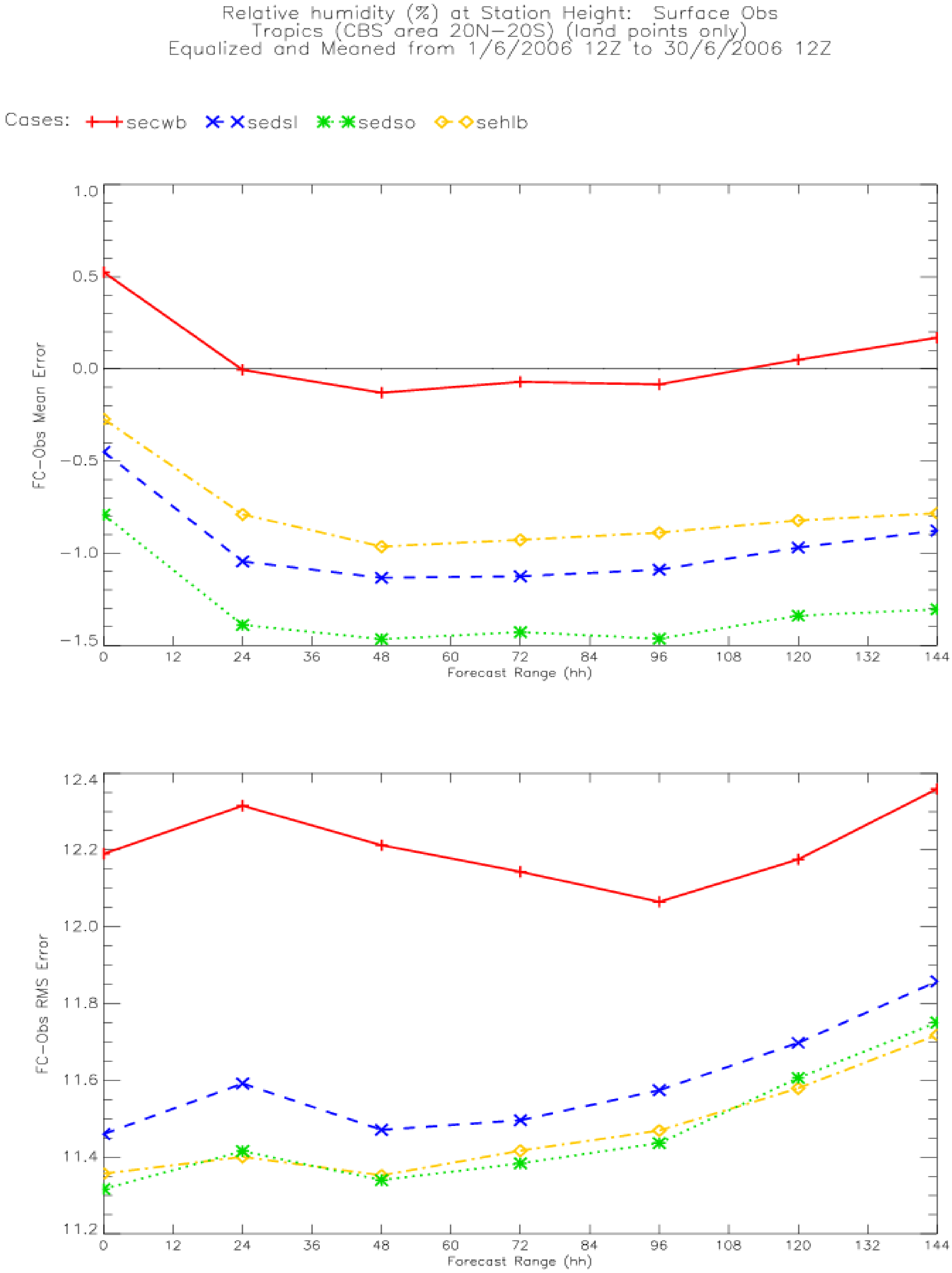

Figure 13: Bias and RMS errors in model forecasts of screen RH for tropics land during June 2006. The new soil physical properties reduce the RMS errors. The curve labels have the same meaning as in Figure 9.

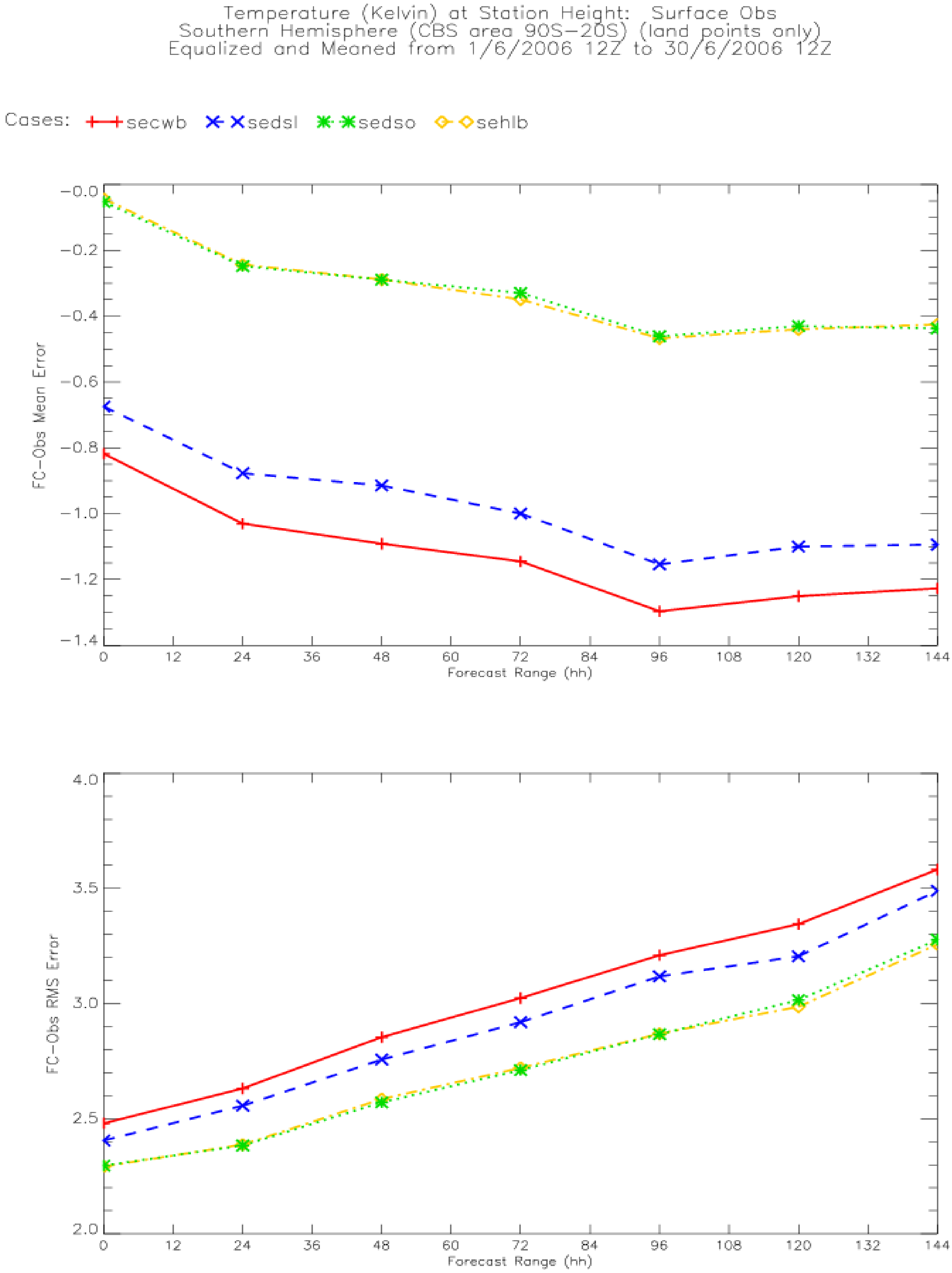

Figure 14: Bias and RMS errors in model forecasts of screen temperature for SH land during June 2006. The new soil physical properties reduce the RMS errors and the model cold bias. The curves labels have the same meaning as in Figure 9.

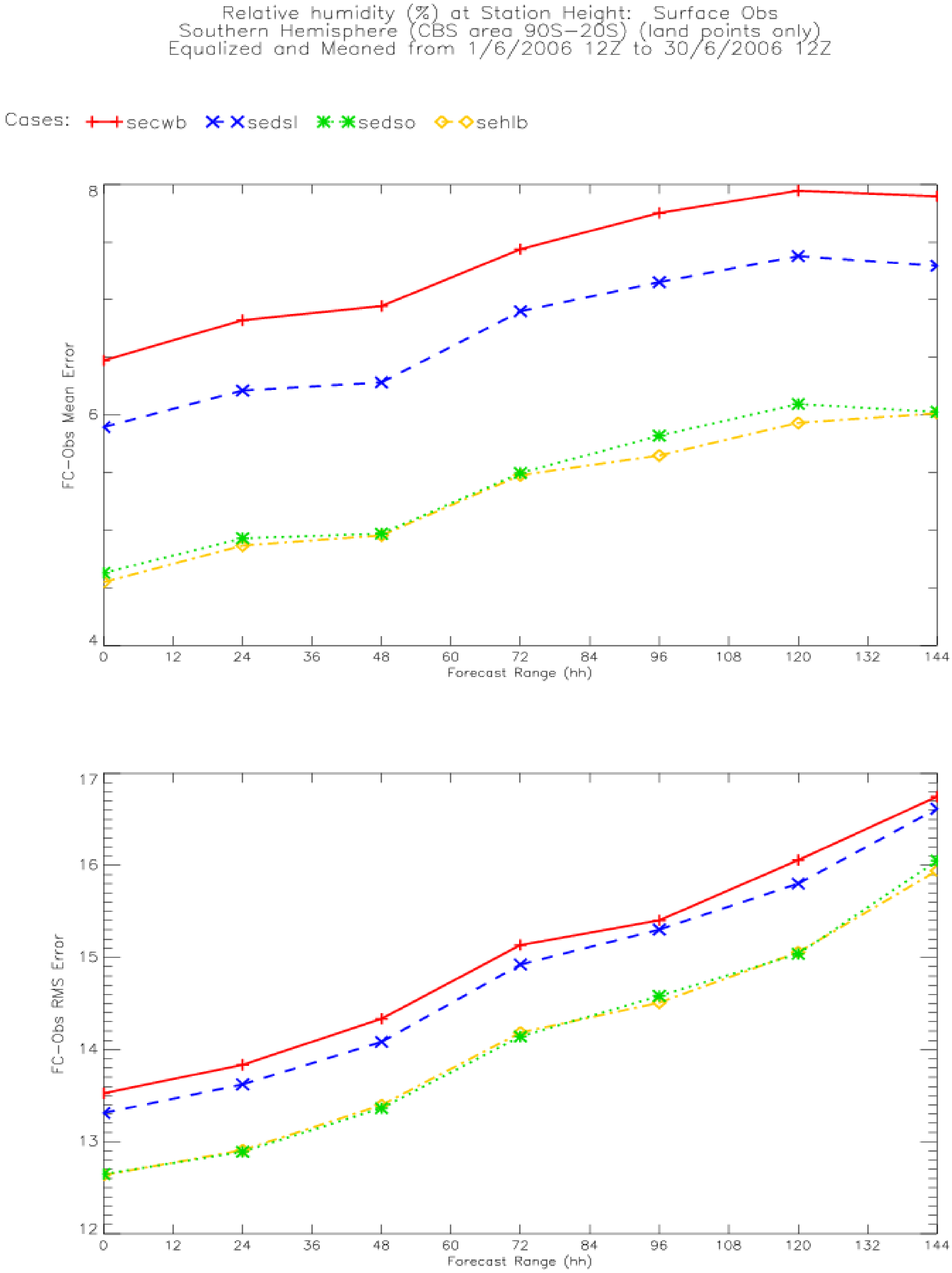

Figure 15: Bias and RMS errors in model forecasts of screen RH for SH land during June 2006. The new soil physical properties reduce the RMS errors and bias. The curves labels have the same meaning as in Figure 9.

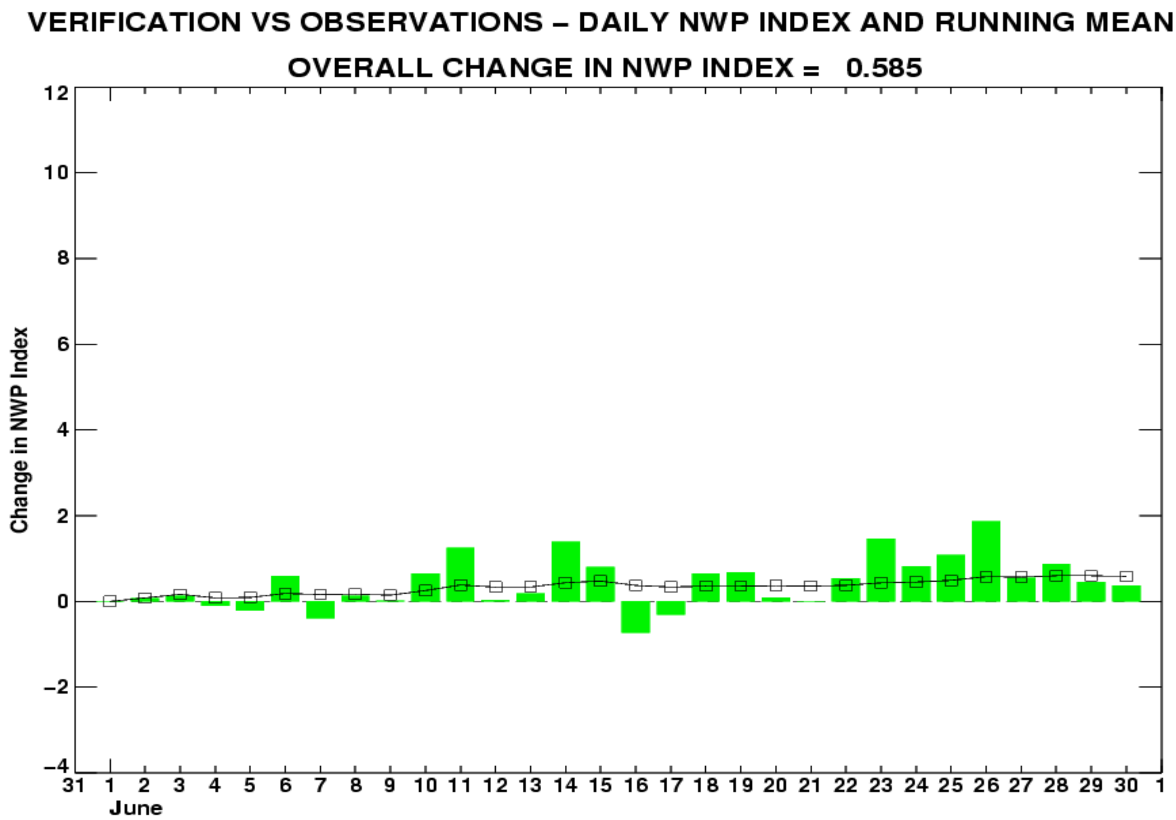

Figure 16: June 2006 impact on the NWP Index of changes to the soil hydraulic properties (sedsl vs secwb).

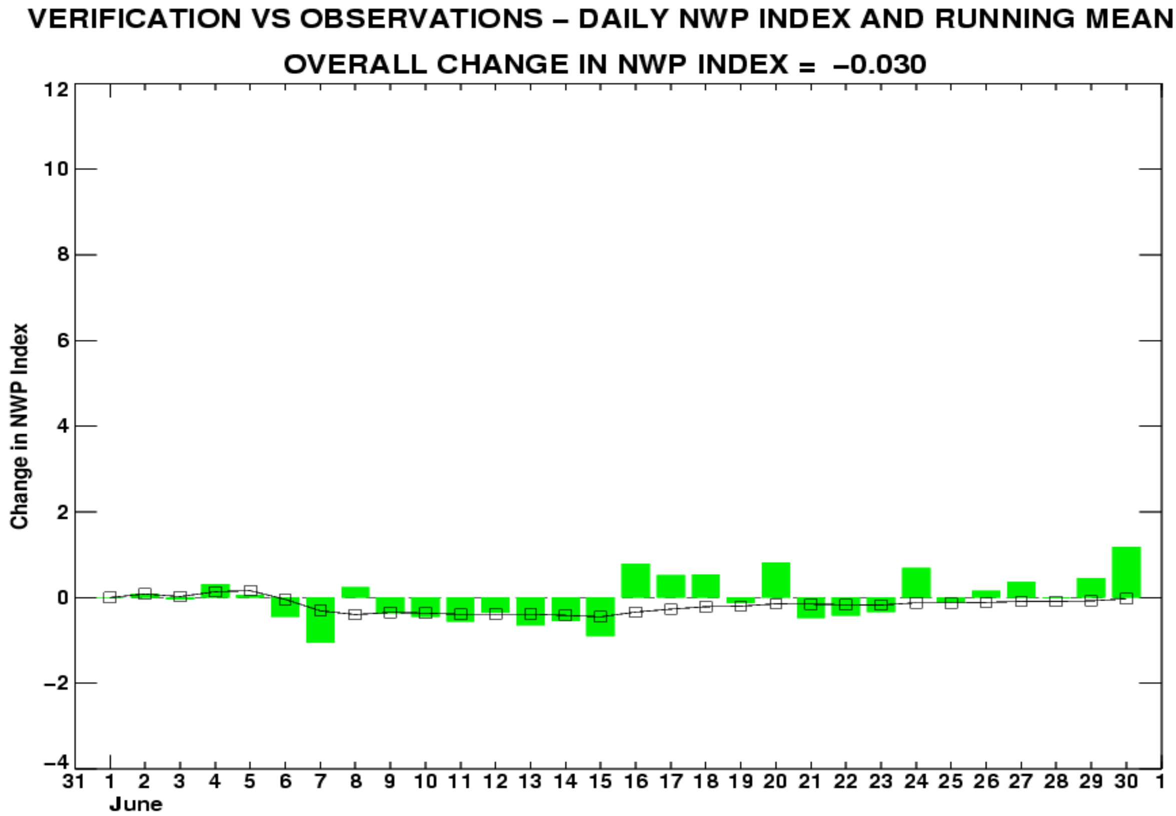

Figure 17: June 2006 impact on the NWP Index of changes to the soil thermal conductivity (sedso vs sedsl).

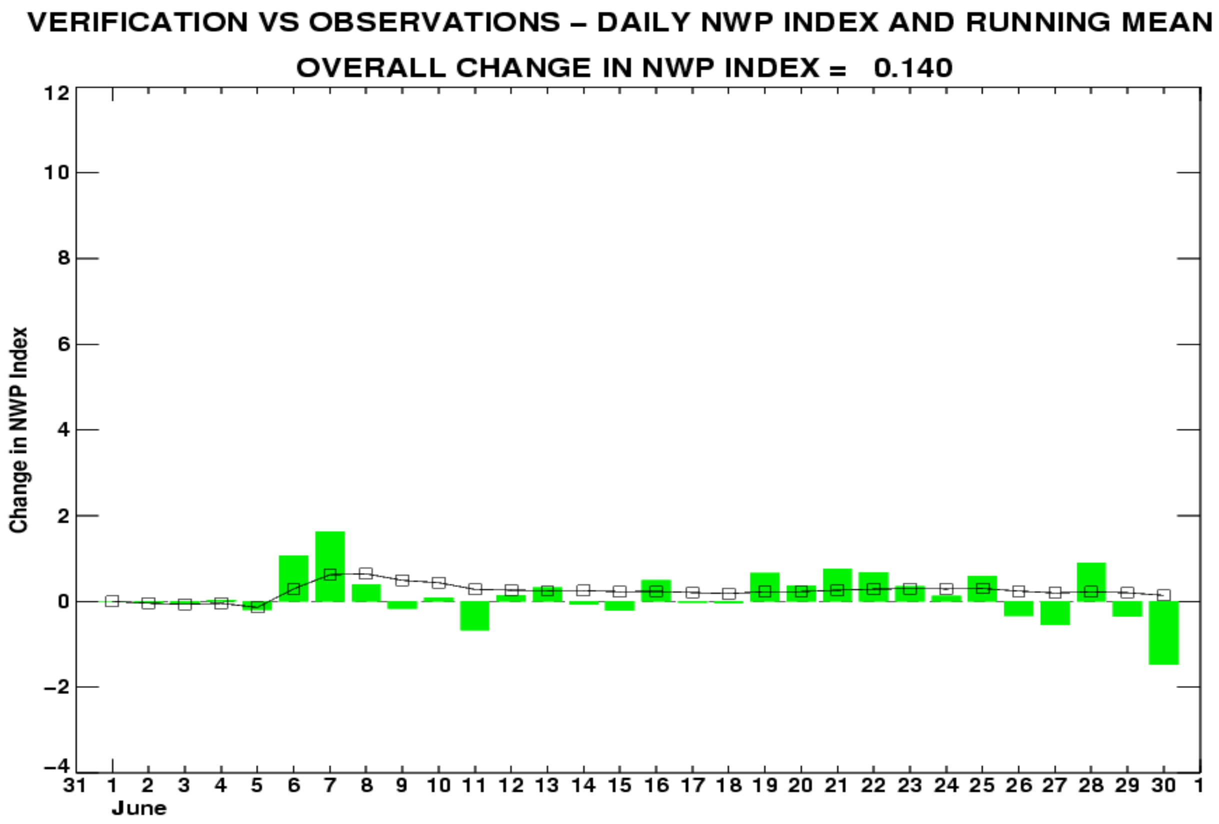

Figure 18: June 2006 impact on the NWP Index of changes to the canopy radiation model (sehlb vs sedso).

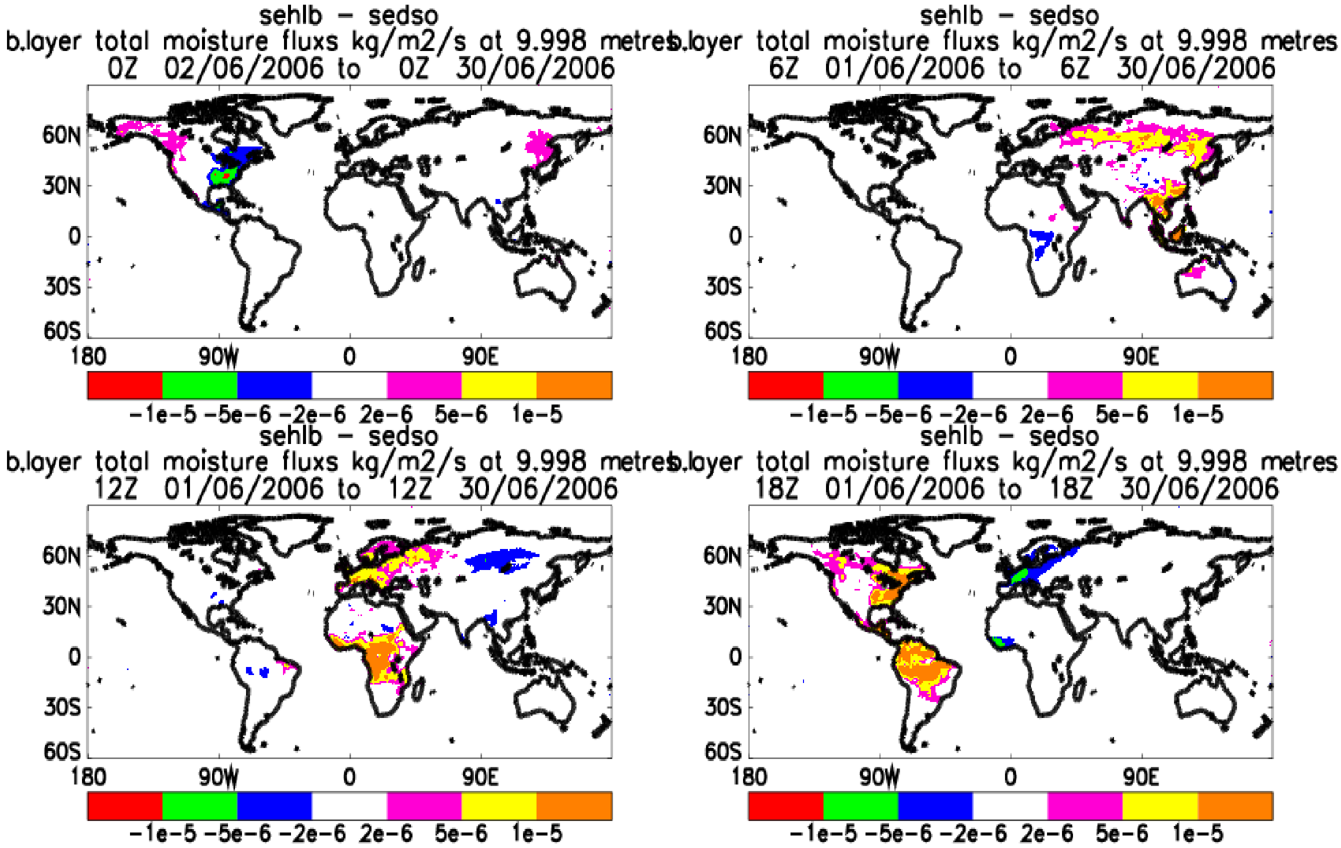

Figure 19: Impact of the two-stream multi-layer canopy radiation scheme on surface evaporation.

5. IGBP soil properties and van Genuchten hydraulics

The International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) contains global data on soil hydraulic properties and global maps of soil distributions at a resolution of 5x5 arc-minutes. The IGBP data is attractive because of the high spatial resolution.

The IGBP data assumes the van-Genuchten (VG) relationship between soil moisture and soil suction (rather than the CH relationship currently assumed by the UM). Therefore the UM would need to be modified to use the VG relationship. See Appendix A for a comparison of CH and VG hydraulics.

A trial has been run to look at the impact of using IGBP soil hydraulic properties and van Genuchten hydraulics. For this trial, the initial soil moisture has been rescaled to preserve the soil moisture availability. Results are generally disappointing as the IGBP soil hydraulic properties make the NH warm bias and pmsl bias worse. RMS errors are also generally worse.

We believe that the reason for the poor performance of the IGBP soils is because the IGBP soils have much lower values for the wilting and critical points. This causes the model soil moisture to be lower and affects the model soil thermal conductivity and soil heat capacity[5]. VG soil hydraulics are not the cause of the problem. Trials (not shown) that use IGBP soil hydraulic parameters converted to CH parameters (as described in Appendix A) and CH soil hydraulics give even worse performance.

Comparison of IGBP soils with observations and the regional State soil geographic database (STATSGO, Miller and White 1998) suggests that IGBP soils have too much sand and too little silt and clay. Too much sand would cause the wilting and critical points to be underestimated. IGBP used an early version of the Rosetta program (Schaap et al, 2001) to derive the VG soil parameters from the IGBP soil sand/silt/clay fractions and bulk density. Schaap et al (2004) show that the early version of Rosetta gives biased estimates of the VG soil parameters which also causes the wilting and critical points to be underestimated (see Figure 3a of Schaap et al 2004).

We have started to derive global maps of sand/silt/clay fractions and % organic carbon using the Harmonized world soil database (FAO 2008), regional soil datasets such as STATSGO and observations of soil sand/silt/clay fractions. We have considered a number of methods to derive the VG soil parameters. The conservative option is to convert the CH soil parameters in Table 2 using the formulae; $K_s^{VG}=K_s^{CH}$, $\theta_r=0$, $\theta_s^{VG}=\theta_s^{CH}$, $\alpha=1/\mathrm{SATHH}$ and $n=1+1/b$. Alternatively, the VG soil parameters given in Table 4 of Wosten et al (1999), for six soil textural classes, can be used. ECMWF use this option, but they find that the critical points are too low and have therefore re-defined the critical point to be at a soil suction of 1m (pages 7 and 8 of Balsamo et al, 2008). Another option would be to use the continuous pedotransfer functions (PTFs) of Wosten et al (1999).

5 The relationship between model soil heat capacity and model soil moisture is given by equation 37 of Cox et al (1999).

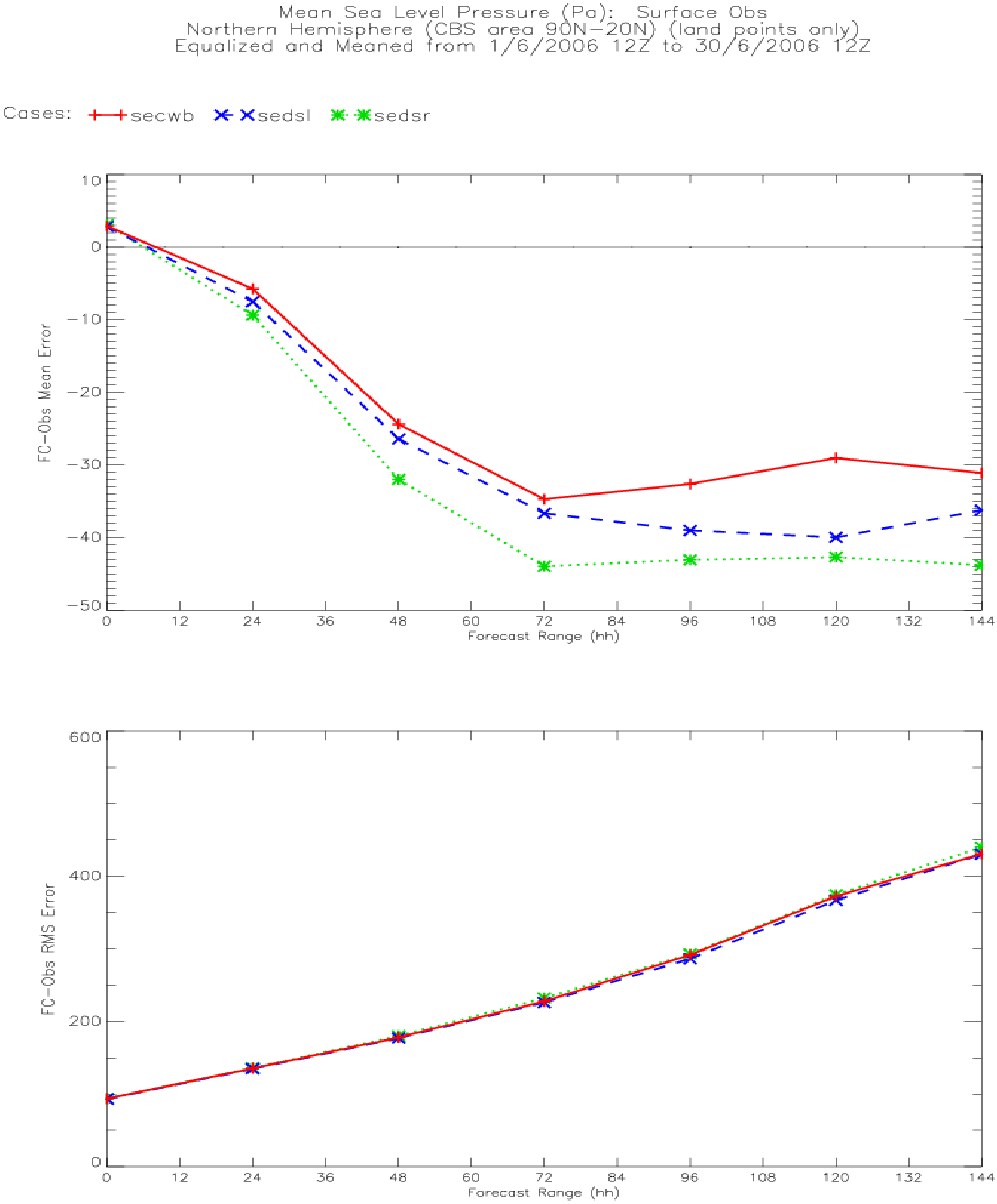

Figure 20: Bias and RMS errors in model forecasts of mslp for NH land during 1 June to 30 June 2006. The red curve (secwb) shows results for a model that uses the old soil properties. The blue curve (sedsl) shows results for a model that uses the new soil hydraulic properties calculated using the correct Cosby equations. The green curve (sedsr) shows results for a model that uses IGBP soil properties and van Genuchten soil hydraulics.

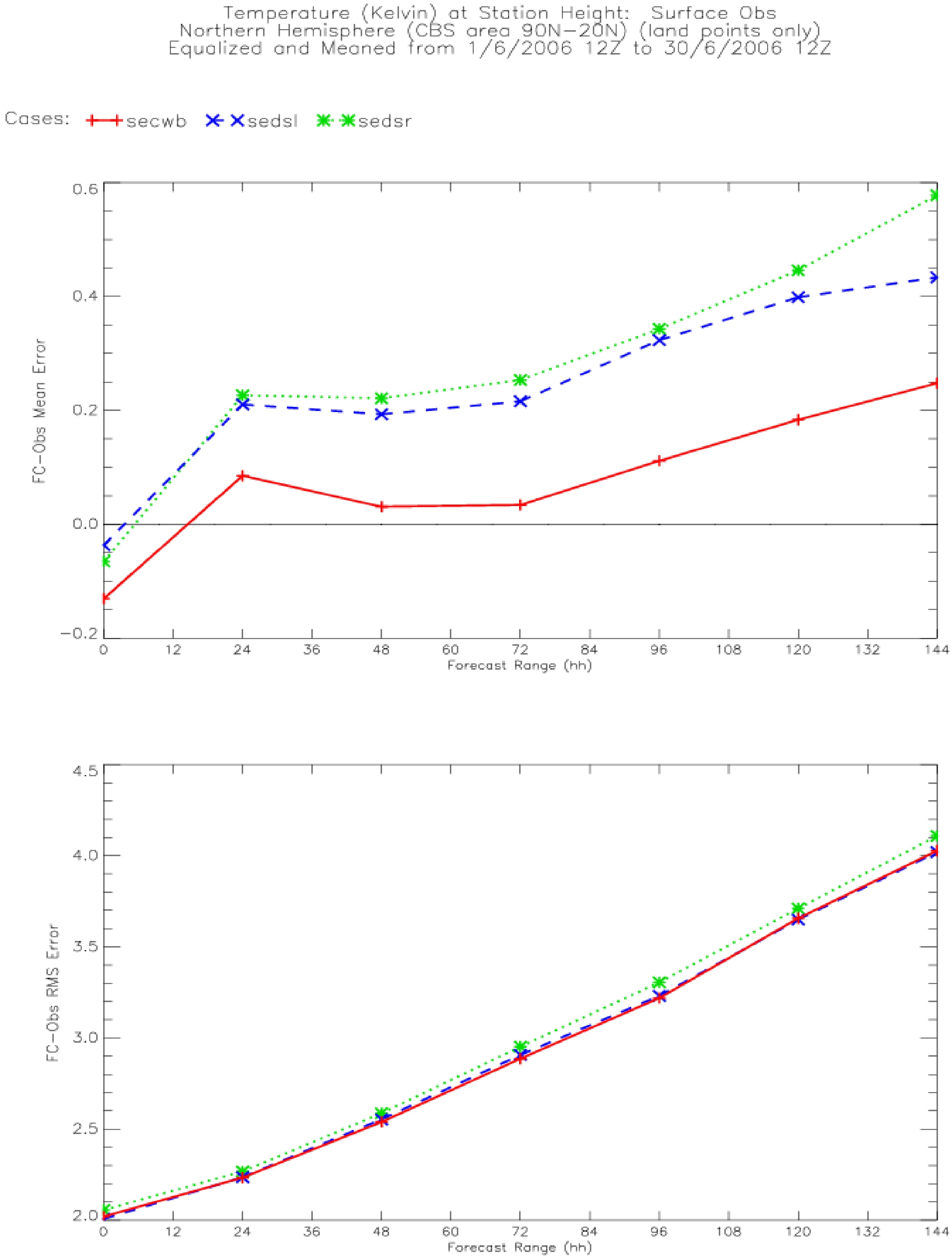

Figure 21: Bias and RMS errors in model forecasts of screen temperature for NH land during 1 June to 30 June 2006. The curves labelled secwb, sedsl, sedsr have the same meaning as in Figure 20.

Acknowledgements

Thanks go to David Walters for creating the original JJA2006 SCS suite and enabling land-only verification. Thanks also to Malcolm Brooks for upgrading the SCS suite to PS15. Thanks to Chris Jones for advice and discussions on the multi-layer canopy radiation scheme. Thanks to Bruce Ingleby for information on the impact of assimilation of SYNOP screen temperature, relative humidity and wind observations.

Appendix A: Clapp and Hornberger vs van Genuchten hydraulics

The Clapp and Hornberger (CH) and van Genuchten (VG) parametrisations both describe the soil water retention curve which is the relationship between volumetric water content θ and the soil suction h [6]. Both CH and VG parametrisations also describe the relationship between volumetric water content θ and the soil hydraulic conductivity K.

Clapp and Hornberger:

$$\frac{\theta^{CH}}{\theta_s^{CH}} = \left(\frac{h}{h_s}\right)^{-1/b} \quad . \tag{7}$$

The above equation has three adjustable parameters; θ_s^{CH}, h_s and b. These parameters depend on the soil texture (sand/silt/clay fractions and organic content). The soil hydraulic conductivity K^{CH} is given by

$$K^{CH} = K_s \left(\frac{\theta^{CH}}{\theta_s^{CH}}\right)^{(2b+3)} \quad . \tag{8}$$

The saturated hydraulic conductivity K_s is an adjustable parameter whose value depends on the soil texture.

van Genuchten:

$$\frac{\theta - \theta_r}{\theta_s^{VG} - \theta_r} = \frac{1}{\left(1 + (\alpha h)^n\right)^{1-1/n}} \quad . \tag{9}$$

The above equation has four adjustable parameters; θ_s^{VG}, α, n and θ_r. Again, these parameters depend on the soil texture.

From the above equations, it is possible to show that the Clapp and Horberger equation is an approximation to the van Genuchten equation. When $(\alpha h)^n$ is

6 The soil suction is just the negative of the soil matric potential.

much greater than 1 (usually true, except when the soil is close to saturation)

$$\frac{\theta-\theta_r}{\theta_s^{VG}-\theta_r} \approx \frac{1}{\left((\alpha h)^n\right)^{1-1/n}} = (\alpha h)^{(1-n)} \quad . \tag{10}$$

Equations (7) and (9) are approximately equivalent when we define; $\theta^{CH}=\theta-\theta_r$, $\theta_s^{CH}=\theta_s^{VG}-\theta_r$, $h_s=1/\alpha$ and $b=1/(n-1)$. It is also worth pointing out that MOSES/JULES stores $\theta-\theta_r$ as it's soil moisture variable and doesn't explicitly deal with θ_r when using VG hydraulics. The soil hydraulic conductivity K^{VG} is given by

$$K^{VG}=K_s S_e^L\left[1-(1-S_e^{1/m})^m\right]^2 \quad , \tag{11}$$

where $m=1-1/n$ and $S_e=(\theta-\theta_r)/(\theta_s^{VG}-\theta_r)$. Note that in the UM code, $L=0.5$ is hard-wired. Although there is evidence that L should be an adjustable parameter whose value depends on soil texture (Schaap and van Genuchten, 2005).

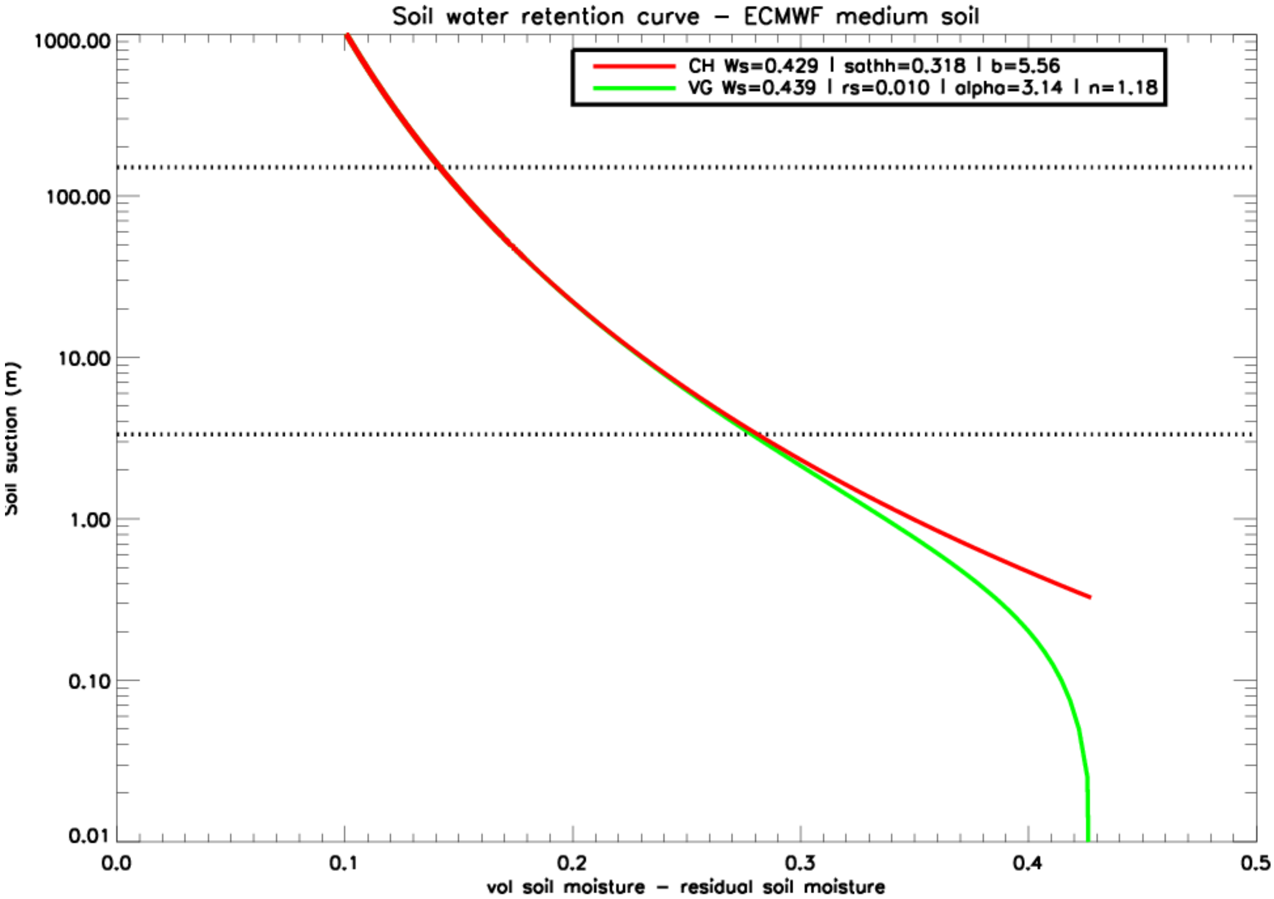

Figure 22: Example comparing the relationship between $\theta-\theta_r$ and soil suction for the VG (green curve) and CH (red curve) parametrisations. The VG parameter values used are for the ECMWF medium soil type; $\theta_s^{VG}=0.439$, $\alpha=3.14$, $n=1.18$ and $\theta_r=0.01$. The CH parameter values are given by; $\theta_s^{CH}=\theta_s^{VG}-\theta_r$, $h_s=1/\alpha$ and $b=1/(n-1)$. The lower horizontal dotted line marks the critical point and the upper horizontal dotted line marks the wilting point.

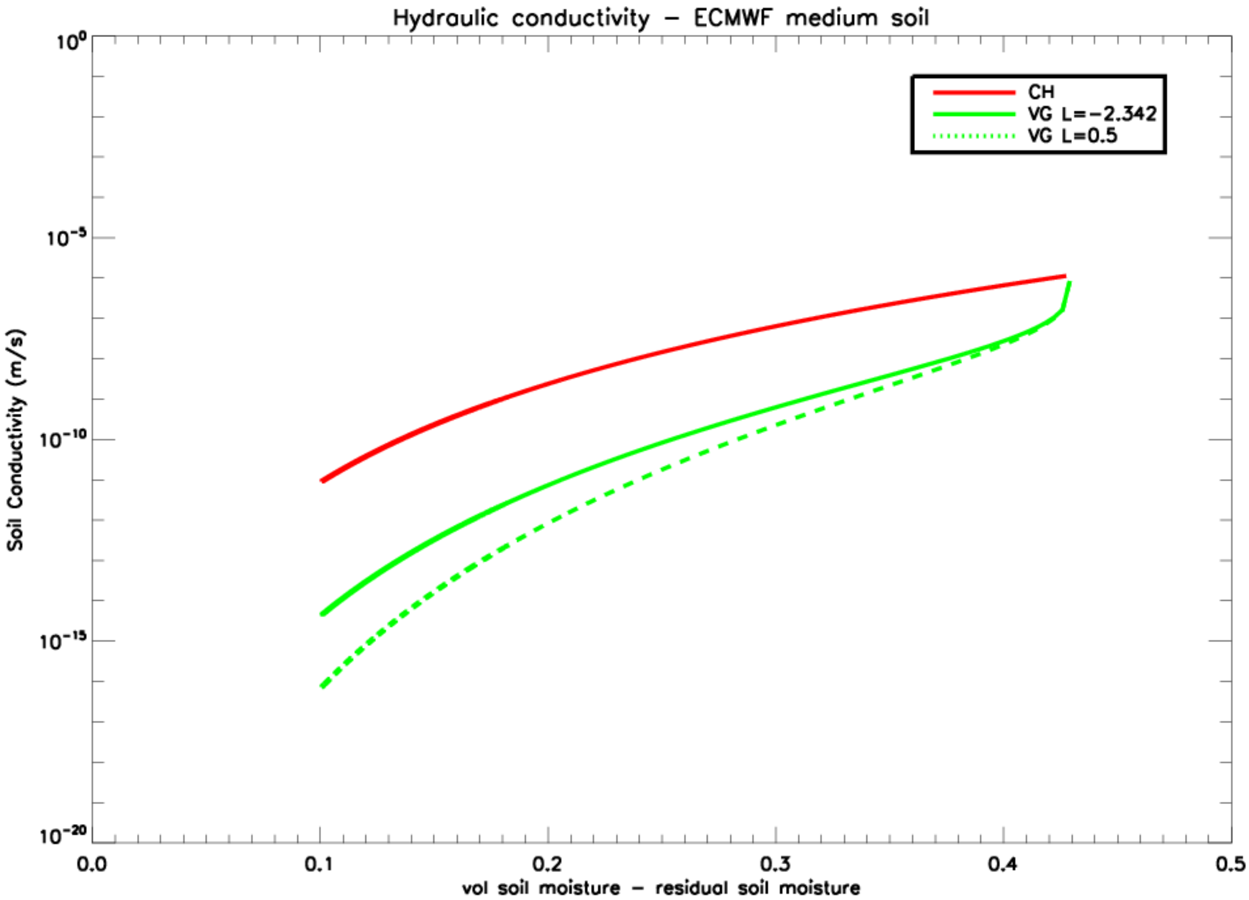

Figure 23: Example comparing the relationship between $\theta-\theta_r$ and soil hydraulic conductivity for the VG (green curves) and CH (red curve) parametrisations. The soil parameter values used are the same as in Figure 22. The solid green curve uses the ECMWF value that $L=-2.342$ and the dashed green curve assumes that $L=0.5$. The saturated hydraulic conductivity $K_s=1.16\times10^{-6}$ m/s.

Figure 22 shows that when we choose $\theta^{CH}=\theta-\theta_r$, $\theta_s^{CH}=\theta_s^{VG}-\theta_r$, $h_s=1/\alpha$ and $b=1/(n-1)$, both the VG and CH parametrisations give nearly identical soil water retention curves. However for this choice, VG gives much lower values of the soil hydraulic conductivity (Figure 23). Recent work (not shown) shows that the VG parametrisation (without IGBP soils) is preferable for NWP and climate simulations.

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