A Physically Based Soil Moisture Nudging Scheme

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Abstract

A physically based soil moisture nudging scheme is presented. Unlike previous nudging schemes which are based upon empirical relationships between soil moisture errors and screen level errors, this new approach uses the physical equations for the turbulent fluxes of heat and moisture to link the soil moisture with these screen level errors. The nudging scheme is tested within a single column of the Met Office Unified Model and compared against observations taken at a grass field site in Cardington, U.K.. The results show that the nudging scheme improves the model simulations, and despite the fact that screen level errors are often caused by other model problems, the nudging scheme can achieve an improvement without causing unrealistic soil moisture.

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1 Introduction

A perfect Global Circulation Model would have free-wheeling soil moisture which was accurately represented. However, in reality model errors can give incorrect soil moistures which can lead to positive feedbacks between the soil moisture, cloud cover and surface temperature: less soil moisture gives reduced evaporative fluxes and reduced cloud cover. The resultant increase in net radiation at the surface encourages further soil moisture depletion. An initial error in cloud cover can therefore be amplified by the positive feedback loop. In numerical weather prediction models it is common to control the soil moisture so that it does not drift to unrealistic states.

In the Met Office Mesoscale model, the soil moisture is set to values derived from the Met Office Rainfall and Evaporation Calculation System (MORECS (Thompson *et. al.* 1981)), an off-line surface model which is driven by observed atmospheric data, such as radiation and precipitation. Since the Met Office Surface Exchange Scheme (MOSES (Cox *et. al.* 1999)) and MORECS have different sets of soil parameters, it is difficult to convert the MORECS data into a form that can be substituted into MOSES.

It is not practical to run an off-line model to derive the soil moisture on a global scale, due to the density of observations required. Therefore in the Met Office Global model, the soil moisture is reset to climatological values on a regular basis. Whilst this ensures that the positive feedback between the soil moisture and surface temperature is avoided, it means that extreme events cannot be accurately forecast.

An alternative to an off-line soil model driven by soil moisture anomalies is to use soil moisture nudging techniques based upon screen temperature and humidity errors. Such schemes are already used in other weather forecast models, but all of these use empirical relationships between screen level variables and soil moisture (e.g. Mahfouf 1991 and Douville *et. al.* 2000). This is not a desirable property as, in theory, the scheme would have to be re-tuned for every model physics upgrade which affected the screen level variables. Therefore we have attempted to design a soil moisture scheme which is based upon the physical connection between the screen level variables and the soil moisture.

The two approaches described above as alternatives to resetting the soil moisture to climatology are very different in nature. The off-line model is designed to provide an accurate estimate of the soil moisture, whilst the nudging scheme is designed to minimise screen level temperature and humidity forecast errors. By reducing screen levels errors, soil moisture nudging could give incorrect soil moisture which compensates for other model errors, such as radiation errors.

2 Theory

The approach suggested is based upon the definition of the surface layer, i.e. that the fluxes of heat and moisture are constant through the layer.

$$H = \frac{\rho C_p (T_* - T_1)}{r_a} = \frac{\rho C_p (T_* - T_{scr})}{\bar{r}_a} \tag{1}$$

$$E = \frac{\rho (q_{sat}(T_*) - q_1)}{r_a + r_s} = \frac{\rho (q_{scr} - q_1)}{r_a - \bar{r}_a} \tag{2}$$

where H is the turbulent flux of heat, E is the turbulent flux of moisture, ρ is the density of air, C_p is the specific heat capacity of the air, T_*, T_1 and T_{scr} are the surface, first atmospheric level and screen level temperatures respectively, q_1 and q_{scr} are the first atmospheric level and screen level specific humidities respectively, $q_{sat}(T)$ is the saturated specific humidity at temperature T, r_a is the aerodynamic resistance between the surface and the first atmospheric level, $\bar{r}_a$ is the aerodynamic resistance between the surface and screen level and r_s is the surface resistance.

In MOSES, as in many other land surface schemes, r_s varies with soil moisture:

$$r_s = r_s^{max}/\beta \tag{3}$$

where β is a moisture limitation factor and r_s^{max} is the value r_s takes in the absence of moisture stress.

By rearranging equation (1) we can obtain an equation for the screen temperature in terms of the surface and first atmospheric level temperatures,

$$T_{scr} = T_* + \frac{\bar{r}_a}{r_a} (T_1 - T_*) \tag{4}$$

If we write the model values of a variable A as $A = A^o + \Delta A$, where A^o is the observed value of the variable and ΔA is the model error of the variable, then equation (3) becomes:-

$$\Delta T_{scr} = \left(1 - \frac{\bar{r}_a}{r_a}\right) \Delta T_* + \frac{\bar{r}_a}{r_a} \Delta T_1 \quad (5)$$

by assuming that r_a and $\bar{r}_a$ are well represented by the model so that

$$T^o_{scr} = T^o_* + \frac{\bar{r}_a}{r_a} \left(T^o_1 - T^o_*\right) \quad (6)$$

To obtain a relationship between ΔT_* and ΔT_{scr}, we need a closure relationship between ΔT_* and ΔT_1. We shall assume that

$$\Delta T_1 = (1 - \delta) \Delta T_* \quad (7)$$

where δ is a parameter to be determined.

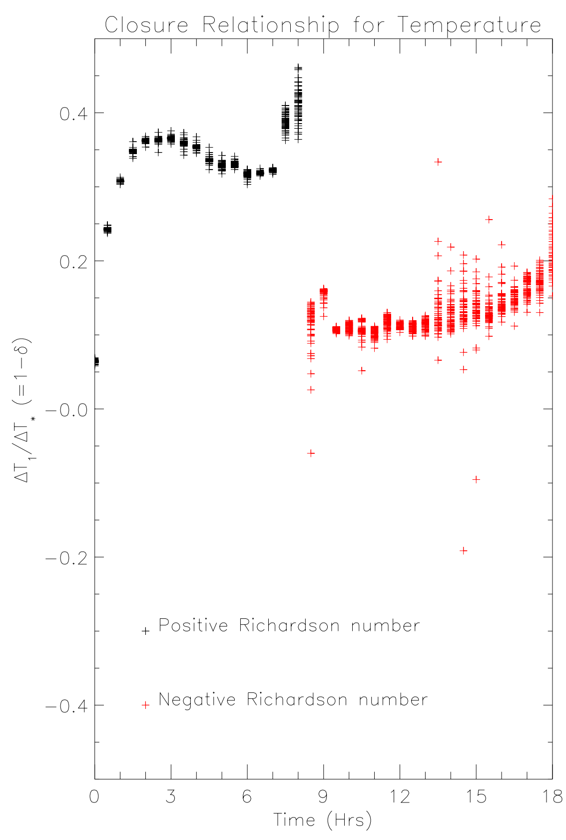

Figure 1: Relationship between surface temperature and first model level temperature for a summer day at Cardington.

To find an appropriate value for δ, a single column atmospheric model based upon the Met Office Unified Model (Cullen 1993) was used for two summer days in England, with initial soil moisture limitation factor (β) set to values of 0.0, 0.1, 0.2, ..., 1.0. The ratio of the difference in the first atmospheric level temperature to the difference in the surface temperature was calculated for all possible combinations of these 11 runs. The combined results for both days are shown in figure (1), with the points on the plot divided into ones with negative and positive Richardson numbers. In stable conditions (positive Richardson numbers) it is not possible to select one value of delta which could represent model results. For unstable conditions, (i.e. negative Richardson numbers) there is less variation in the value of delta. Therefore we choose to apply the soil moisture nudging scheme only in unstable conditions and assume $\delta = 0.9$.

Equations (5) and (7) now give:

$$\Delta T_* = \frac{\Delta T_{scr}}{1 - \delta \bar{r}_a / r_a} \tag{8}$$

Figure (2) shows a plot of surface temperatures from single column model runs. Shown in the plot are the temperatures from a run with an initial soil moisture limitation factor of $\beta = 0.4$ (considered in this plot to be the 'observed' surface temperatures) along with the temperatures from a run with an initial soil moisture limitation factor of $\beta = 0.6$

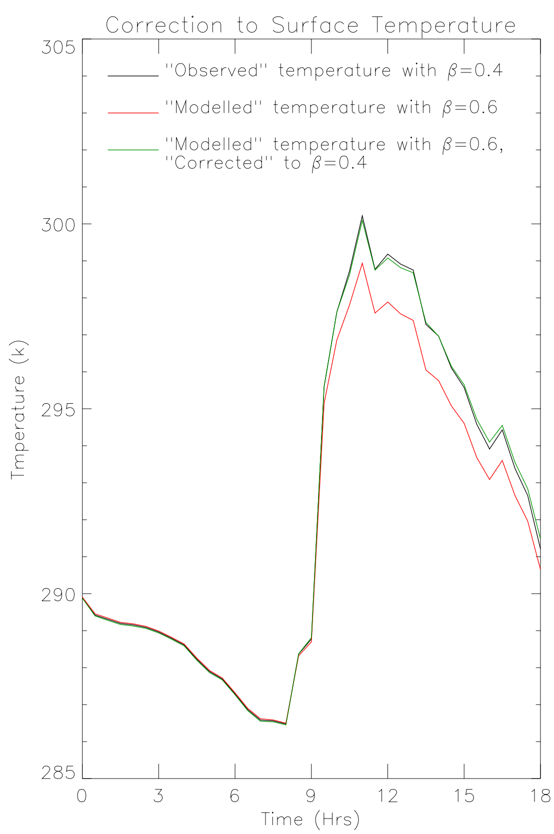

Figure 2: Impact of surface temperature correction calculated from the scheme.

(considered in this plot to be the 'modelled' surface temperatures). Also plotted are the values of the surface temperature obtained by adding the increment from equation (8) to the 'modelled' value. The corrected surface temperature is very close to the 'observed' value, showing that equation (8) is a good approximation.

From equation (2) we obtain

$$q^o_{scr} - q^o_1 = \Delta q_1 - \Delta q_{scr} + r_a \left(1 - \frac{\bar{r}_a}{r_a}\right) \frac{E}{\rho} \tag{9}$$

Also using equation (2) we get:

$$\begin{aligned} q^o_{scr} - q^o_1 &= \left(1 - \frac{\bar{r}_a}{r_a}\right) \left(\frac{r_a}{r_a + r^o_s}\right) \left(q_{sat}\left(T^o_*\right) - q^o_1\right) \\ &= \left(1 - \frac{\bar{r}_a}{r_a}\right) \left[\frac{r_a}{1 - \Delta r_s / \left(r_a + r_s\right)}\right] \left[\frac{E}{\rho} - \frac{\alpha \Delta T_* - \Delta q_1}{r_a + r_s}\right] \end{aligned} \tag{10}$$

where Δr_s is the error in surface resistance caused by the incorrect available soil moisture, $\alpha = dq_{sat}/dT_*$ and assuming $q_{sat}\left(T^o_*\right) = q_{sat}\left(T_*\right) - \alpha \Delta T_*$.

Now equating equations (9) and (10) gives the following expression for Δr_s :-

$$\begin{aligned} \Delta r_s &= \left[\Delta q_1 - \Delta q_{scr} + \left(1 - \frac{\bar{r}_a}{r_a}\right) \left(\frac{r_a}{r_a + r_s}\right) \left(\alpha \Delta T_* - \Delta q_1\right)\right] \\ &/ \left[\left(\frac{1}{r_a + r_s}\right) \left(\Delta q_1 - \Delta q_{scr} + r_a \left(1 - \frac{\bar{r}_a}{r_a}\right) \frac{E}{\rho}\right)\right] \end{aligned} \tag{11}$$

From equations (7) and (8) we obtain

$$\Delta T_1 = \frac{(1 - \delta) \Delta T_{scr}}{(1 - \delta \bar{r}_a / r_a)} \tag{12}$$

If we make the assumption that this relationship also holds for Δq_1 and Δ_{scr} then combining equations (8) and (11) gives a relationship for Δr_s which is a function of the screen level errors in temperature and humidity and model values only:-

$$\Delta r_s = \frac{\alpha \Delta T_{scr} - (1 + \delta r_s / r_a) \Delta q_{scr}}{(1 - \delta \bar{r}_a / r_a) E / \rho - (\delta / r_a) \Delta q_{scr}} \tag{13}$$

Therefore we have the information required to solve for Δr_s and hence the change in the soil moisture limitation factor ($\Delta \beta$) through equation (3), as a function of the errors in screen temperature (ΔT_{scr}) and humidity (Δq_{scr}).

3 Idealised Experiments

To test this soil moisture nudging theory in an idealised situation, single column model simulations were carried out with a given soil moisture limitation factor to provide a set of 'observations' which can be used with the soil moisture nudging scheme. The single column model was then used again with a different initial soil moisture limitation factor, and the average increment to the soil moisture over the forecast was calculated retrospectively. This increment was applied to the initial soil moisture limitation factor and the single column model was run again. This procedure was repeated 5 times (results in figure (3)). It can be seen that the soil moisture limitation factor converges to the 'observed' value within 5 iterations.

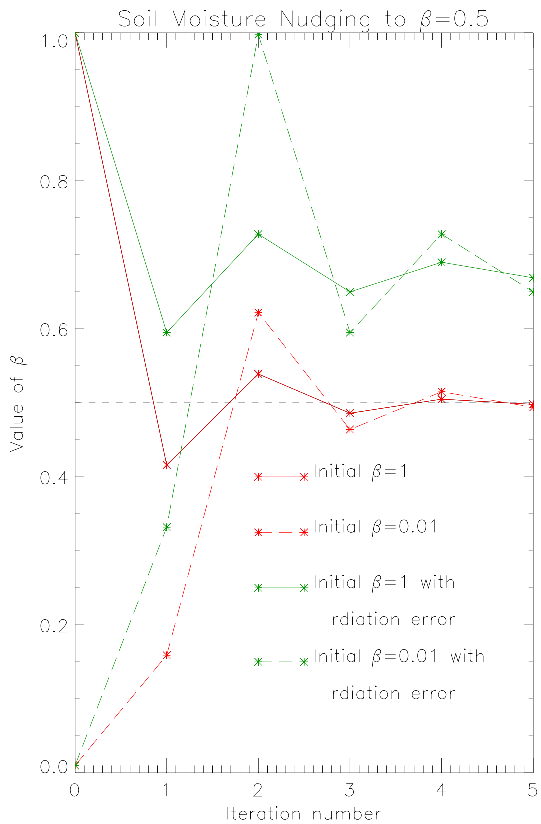

Figure 3: Convergence of soil moisture limitation factor with the nudging scheme for idealised case studies.

Problems could occur with the soil moisture increments if there were radiation errors in the surface energy balance. To investigate this, the iteration process described above was repeated with a single column model which had 100 Wm^{-2} added to the net radiation at the surface. The results of these runs are also shown in figure (3). Under these circumstances the soil moisture limitation factor converges to an incorrectly high value in an attempt to counteract the effect of the radiation error on the screen variables. Without the soil moisture nudging, the soil would eventually dry out, resulting in unrealistically high screen level temperatures and low screen level humidities.

Figure 4 shows the screen level temperature and humidity compared between model runs with and without the radiation error. A model simulation without the radiation error was carried out with an initial soil moisture limitation factor of $\beta = 0.5$. Model simulations with the radiation error and initial soil moisture limitation factor values of $\beta = 0.5$ and $\beta = 0.65$ (the value to which the nudging scheme converged) were carried out for comparison. When using the incorrect soil moisture limitation factor with the model radiation error there is a trade-off between the temperature error and the humidity error. The R.M.S. screen temperature error was improved by 6.5% using the nudging scheme, whilst the R.M.S. humidity error was increased by 2.5%.

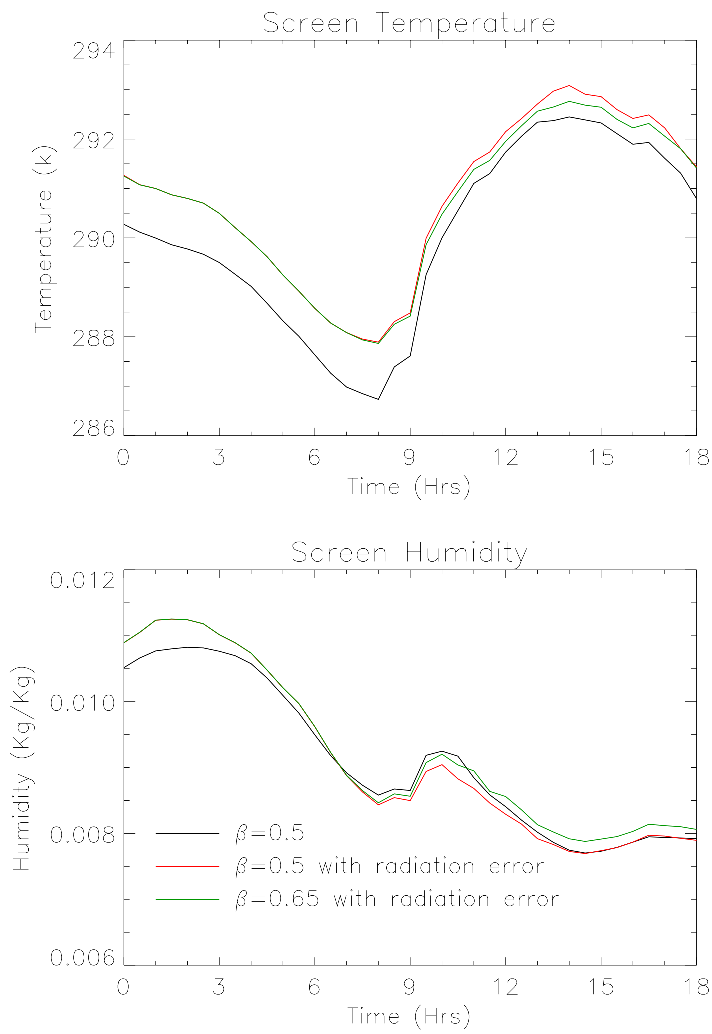

Figure 4: Impact of soil moisture nudging scheme on screen level variables with a model radiation error.

To be able to use the nudging scheme within an NWP model, we require increments to the soil moisture in each of the soil layers. Therefore we need to convert from soil moisture stress increments to increments in the layer soil moisture. Details of how this is done for MOSES are given in Appendix A.

4 Simple Case Study Experiments

Some initial tests were carried out in the single column model using screen levels temperature and humidity data from the Met Office field site at Cardington. Simulations of 18 hours were completed with an arbitrary initial soil moisture limitation factor of $\beta = 0.45$. The soil moisture nudging scheme was used only during the first six hours of the model run, so that the impact of the scheme could be assessed during a period when the observations were not being assimilated. In these simple experiments, the soil moisture increments were calculated and applied every hour during the assimilation period. Figure (5) shows the results from one of the case studies. It is clear from this case study that the soil moisture nudging has a positive effect on both the temperature and humidity. The R.M.S. temperature error over the whole run is improved by 8.8%, whilst the R.M.S. humidity error is improved by 37.5%.

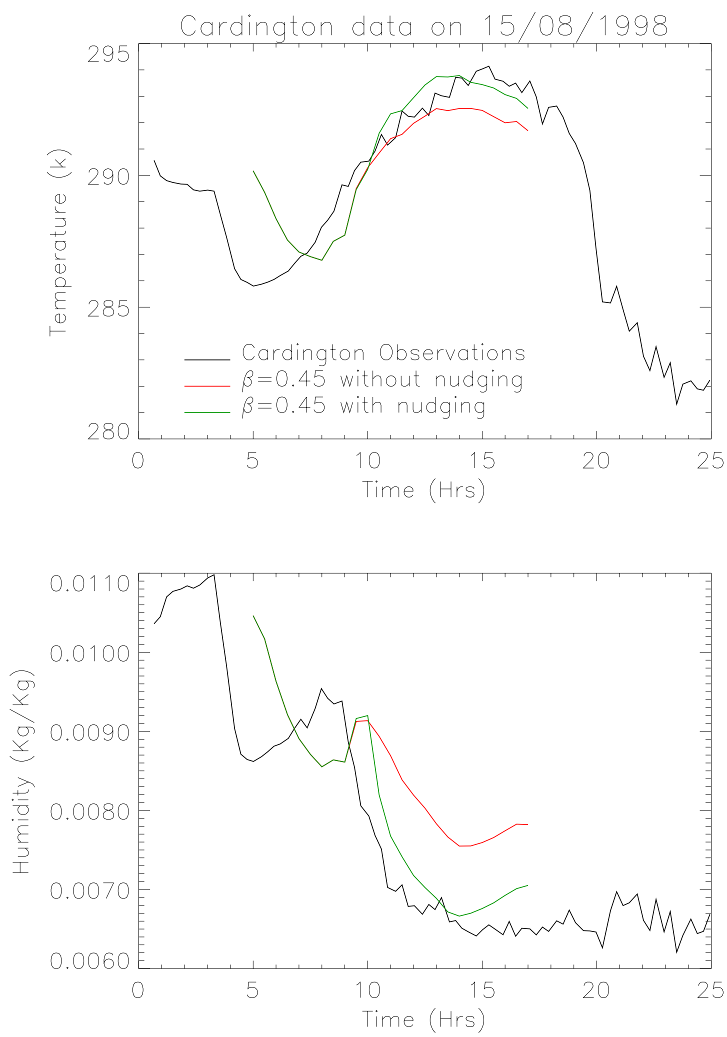

Figure 5: Impact of the soil moisture nudging scheme compared to observations at Cardington for 15th August 1998.

A second case study is shown in figure (6). It is not obvious that the impact of the soil moisture nudging scheme is positive in this case. The R.M.S. temperature error over the whole run is improved by 11.8%, but the R.M.S. humidity error is made worse by 37.5%. It is evident from figure (6) that the model has other sources of error since the initial state of the model is essentially too cold and too dry. This is a case in which changing the soil moisture alone will not be sufficient to decrease both screen level errors. Also, the whole of the increment has been added at each hour during these runs, so that these other model errors can have a large effect on the soil moisture. In practice however, the soil moisture would be relaxed back to the new state using a chosen timescale, so that only a fraction of the calculated increment would actually be applied. Therefore temporary model errors caused by, for example, incorrect cloud cover would only have a small impact on the soil moisture.

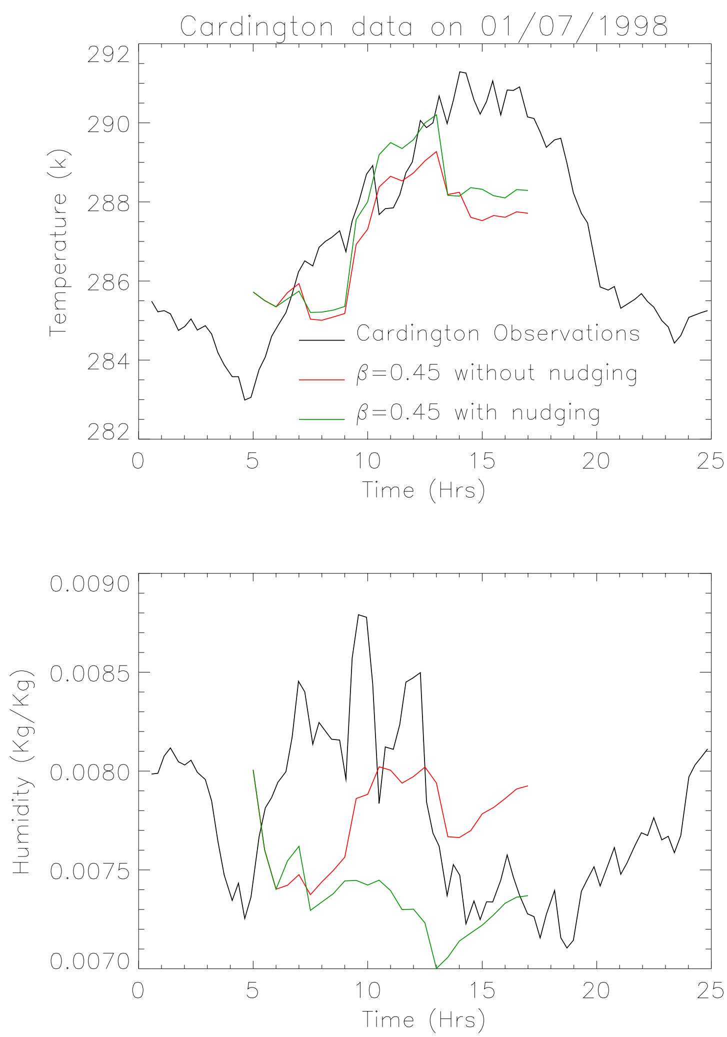

Figure 6: Impact of the soil moisture nudging scheme compared to observations at Cardington for 1st July 1998.

To assess the impact of the soil moisture nudging scheme with a relaxation timescale, simulations are required over a longer timescale than these individual case studies. Therefore the nudging scheme was implemented and tested in the Site Specific Forecast Model.

5 Site Specific Forecast Model (SSFM)

To assess the impact of the soil moisture nudging scheme, it was implemented within the Site Specific Forecast Model (SSFM). The SSFM is a 1-dimensional numerical model which has been developed by the Met Office (Clark et al., 1996, 1997). It derives most of its physical schemes, such as those for calculating precipitation, cloud and convection, from the Unified Model to maintain compatibility and reduce maintenance overheads. Through the use of increased vertical resolution and detailed data on the local environment, the SSFM is designed to give improved local forecasting for specific sites by better representation of the evolution of the boundary layer, especially fog formation and near surface temperature forecasting.

One of the basic assumptions inherent within a 1D modelling approach is that the atmosphere is stationary, i.e. advection can be neglected. However, for practical forecasting this is not a good assumption. Therefore an approximation to advection is included in the SSFM by extracting appropriate vertical profiles from the Mesoscale or Global NWP output and calculating gradient terms required to relax the 1D profiles back towards those of the 3D model. The relaxation terms are set up so that the 1D profile is the same as the 3D profile above the boundary layer, but the relaxation has less impact towards the surface where the 1D model is allowed to come into a local equilibrium (Dunlop and Clark, 1997).

The similarity of the physics schemes and the approximation to the advection terms mean that the SSFM can give almost an identical evolution to a specific Mesoscale model grid box, given the same model setup. Since the computational cost of running the SSFM is significantly less than the full 3D model, it forms an ideal test bed to assess the initial impact of new physical schemes and parametrizations.

The Met Office field site at Cardington, Bedfordshire (52.10 N, 0.42 W) was chosen as the location for testing the soil moisture nudging scheme as the permanent surface measurement site provided not only the data required for the scheme, but additional data (such as turbulent flux measurements) which were used to assess its performance. A trial of the nudging scheme was carried out for a 3-week period during August 1998. This was a particularly dry period which provided a good test of its impact on spurious drying.

The SSFM was integrated for a period of 18 hours, forced by Mesoscale model data throughout the run, with a set of initialisation variables output after the first six hours of the integration, which provided the initial conditions for the next SSFM run. During these first six hours of the run, observed values of the screen level temperature and humidity were input into the model so that the nudging scheme could calculate increments to the soil moisture. This ensured that there was essentially continuous data assimilation in a six hour cycle throughout the whole three week period for the soil moisture. The impact of the soil moisture nudging scheme was then assessed by taking the output from T+6 onwards in the forecast, i.e. after the six hour assimilation cycle for the soil moisture.

In order to provide a basis for the assessment of the soil moisture nudging scheme, the SSFM was used for the 3-week period without the nudging scheme. This enables a comparison of the nudging scheme against continuous running with no soil moisture correction. In addition, the SSFM was used with the two methods currently used in the operational Global and Mesoscale models for correcting soil moisture; namely resetting to climatology and resetting to the values derived from MORECS respectively.

MORECS uses observations of temperature, sunshine, wind and humidity to calculate values of soil moisture and evaporation at a horizontal resolution of 40km, taking into account local soil type and vegetation cover (Hough et al., 1997). The data for the trial was extracted for the grid box containing the Met Office site at Cardington, then converted so that it was consistent with MOSES, and used to reset the soil moisture once a week at the 06Z run each Wednesday. This is the same as the current procedure in the operational Mesoscale model. For the climatological run, the soil moisture was also reset once a week at the 06Z run on the Wednesday.

Since MORECS is forced by observed values of temperature, sunshine, wind and humidity, it is believed that the resultant soil moisture should be constrained from drifting far from reality. Therefore values converted from the MORECS data were used to initialise the SSFM runs at the start of the 3 week period. So each SSFM configuration started with the same initial soil moisture profile, except the climatological run, which was initialised to the climatological soil moisture profile.

6 Results

The SSFM was run throughout the period with a root depth of 2, 3 and 4 soil layers, to assess the impact of different amounts of available water within the root zone. The standard for short vegetation, such as the grass at Cardington, is a root zone with 3 soil layers. This equates to 1 m. in depth. Setting the root depth to 4 soil layers allows access to soil water over a depth of 3 m., whereas setting the root depth to 2 soil layers restricts the available water to the first 0.35 m. Therefore as the number of layers is increased, there is more water available within the root zone, and less potential for soil water limitation.

Figure 7 shows the soil moisture limitation factor throughout the period for root depths of 2, 3 and 4 soil layers, for both continuous running (Fig. 7a) and with the soil moisture nudging scheme (Fig. 7b). Figure 7a clearly shows the large difference in soil moisture limitation factor due to the variation in available water within the root zone for 2, 3 and 4 layers. For the nudging scheme however, the values of the soil moisture limitation factor are all similar, despite the differences in the depths over which soil water can be extracted. The implication is that the nudging scheme can compensate for errors and uncertainties in the rooting depth.

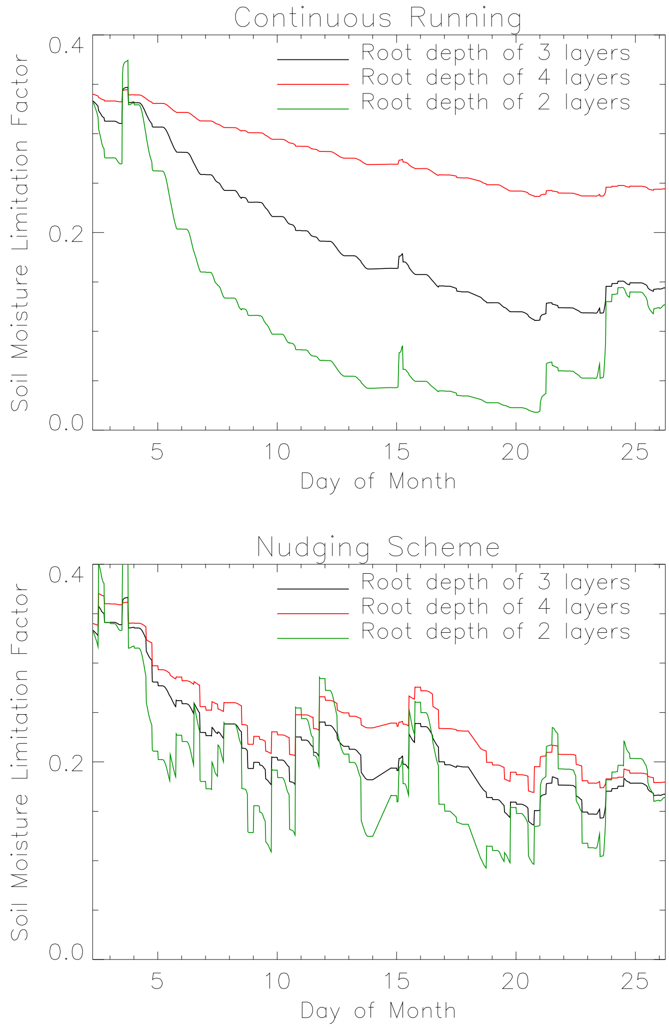

Figure 7: Soil moisture limitation factor for varying root depths.

6.1 Evaporative Fraction

The evaporative fraction for each of the rooting depths is shown in Fig. 8. The evaporative fraction is calculated by dividing the latent heat flux by the sum of the latent and sensible heat fluxes, i.e. it is a measure of how much of the available energy at the surface is translated into the moisture flux. Only data during the daytime and when the net radiation is positive are plotted. The data has been selected with the following criteria:- the observed net radiation at the site is greater than 50 Wm^{-2}, the observed and modelled sensible heat fluxes are positive and the observed latent heat flux is positive. Also, since this type of plot is inherently noisy, the data have been smoothed using a continuous average of 11 data points. This algorithm ensures that the evaporative fraction is a meaningful diagnostic of water availability.

The evaporative fraction of the continuous running has a significantly large variation depending upon the number of soil layers which are within the root depth. There is up to 5 times more evaporation from the 4 layer run compared to the 2 layer run. With the

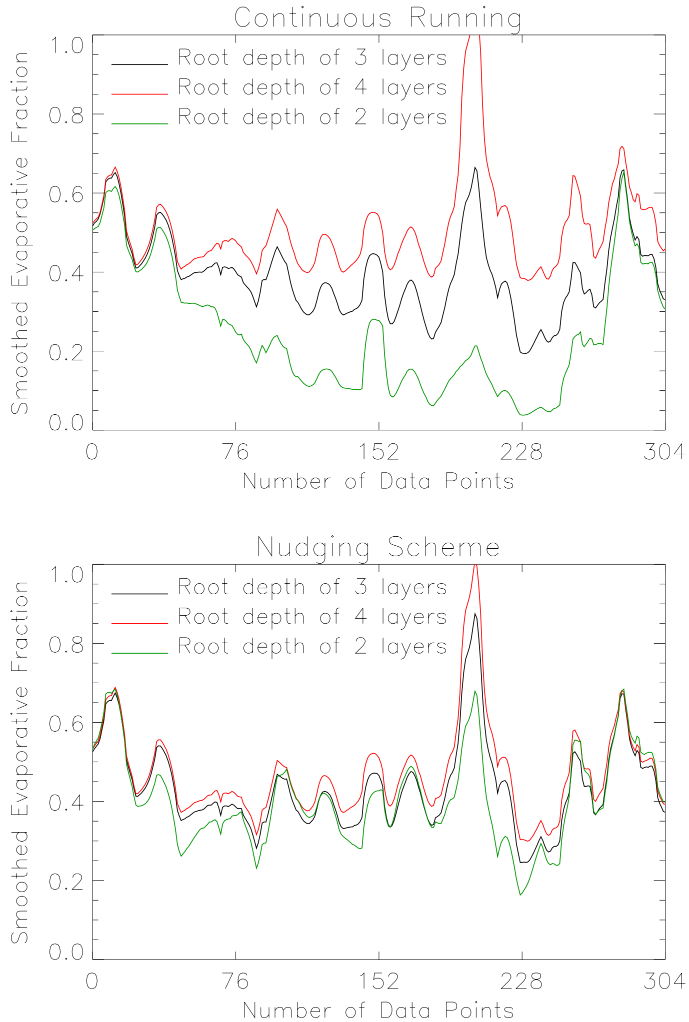

Figure 8: Evaporative fraction, continuously smoothed over 11 data points, for varying root depths.

nudging scheme the evaporative fractions are much closer, with the differences between the 2 layer and 4 layer runs being around 50%; 10 times smaller than with the continuous run.

Simulations using the soil moisture nudging scheme were compared to three other possibilities for controlling soil water over the forecast period, namely continuous running of the soil moisture, resetting the soil moisture back to climatological values and resetting the soil moisture back to the values calculated by the off-line program MORECS. The evaporative fraction from each of these methods is shown in Fig. 9, along with the evaporative fraction calculated from the observed turbulent fluxes of heat and moisture. It is clear from this figure that resetting soil moisture to climatological values does not give a good simulation of the evaporative fraction, because the period of the trial is warmer and drier than the climatological mean.

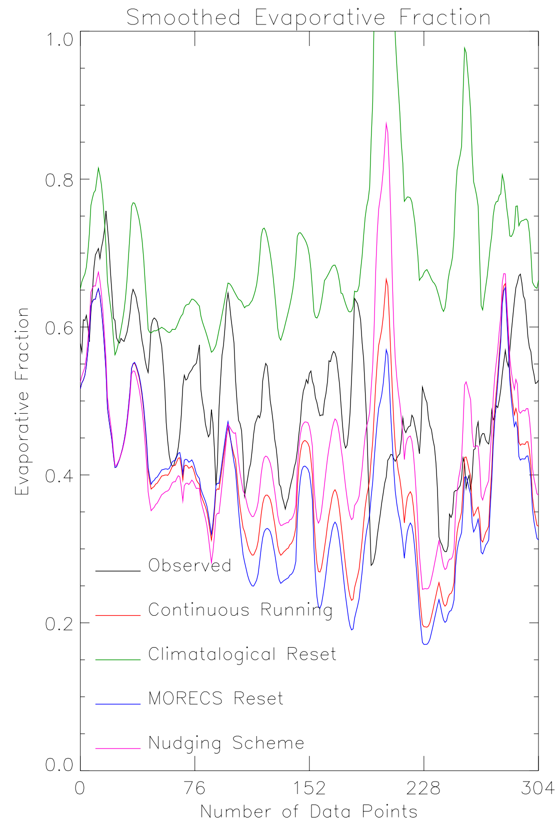

Figure 9: Evaporative fraction, continuously smoothed over 11 data points, for each method of determining soil moisture.

The continuous running gives a low evaporative fraction compared to the observations, implying that there is not enough available water in the root zone with continuous running. Resetting to soil moisture values calculated by MORECS gives values of the evaporative fraction which are even lower than the continuous running during the middle of the period. So even though the MORECS soil moisture is calculated using observed forcing data, the soil moisture determined for MOSES is less accurate than using the MOSES scheme running continuously with the imperfect forcing data from the SSFM.

The soil moisture nudging scheme also gives values of the evaporative fraction which are low compared to the observations, but the error is smaller than any of the other methods for most of the period. The only exception to this is near the beginning of the period where the nudging scheme removes too much of the available water within the root zone (Fig. 10)

6.2 Available Soil Moisture

The measurements of soil water within the top 1 m. of soil at Cardington were affected by lateral flows due to the proximity of a drainage ditch. Therefore "Observed" available soil moisture has been determined by taking the initial MORECS soil moisture and changing

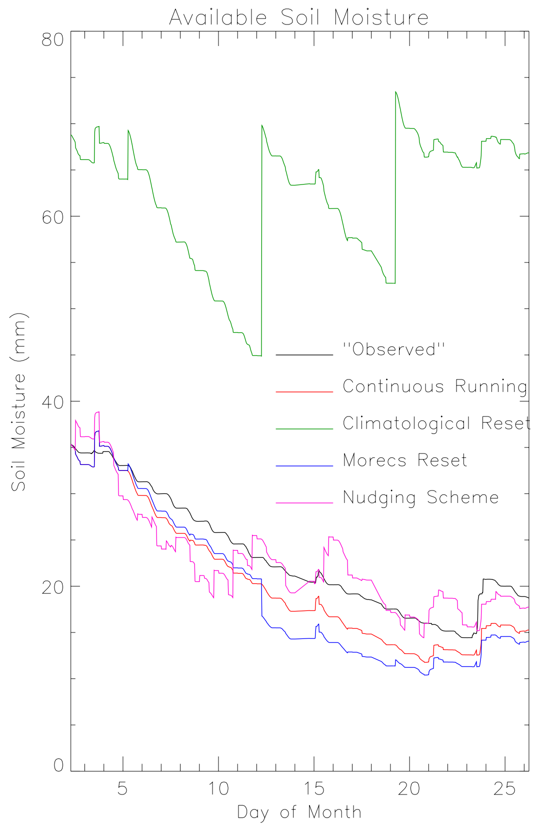

Figure 10: Available soil moisture for each correction method.

it through the observed precipitation and evaporation only, i.e. we are assuming that the initial MORECS soil moisture is correct, and that the only change in soil water can come from either precipitation or evaporation. The second of these assumptions is a reasonable one to make, since under such conditions of low soil moisture, runoff is typically negligible.

Figure 10 shows how the high climatological values of available soil moisture are quickly reduced by high evaporation rates, but are then returned to the high values at the weekly soil moisture reset. This produces an inaccurately high evaporation rate throughout the whole of the period.

On the 5th of August, the MORECS reset compensates for the slight over drying in MOSES and gives a more accurate available soil moisture. However, the MORECS reset of the 12th of August significantly reduces the available soil moisture giving less accurate values and causing the lower evaporative fractions, compared to the continuous run, as seen in Fig. 9.

Overall the nudging scheme gives the best simulation of the available soil moisture, especially towards the end of the simulation period. However, during the period from the 4th of August to the 11th of August, the nudging scheme incorrectly reduces the available soil moisture.

6.3 Improved Nudging Criteria

The soil moisture nudging scheme used to date is based upon the assumption that the errors in screen levels temperature and humidity are caused solely by an error in the soil moisture. If this is the case, then there should be a negative correlation between the temperature and humidity errors, i.e. a warm dry bias, or a cold wet bias. However, there can be other sources of error, such as radiation or cloud errors, which can lead to incorrect screen level temperature and humidity errors. These errors may not have a negative correlation in temperature and humidity (although sometimes they will). Therefore, an alternative nudging scheme was tested whereby the increments to the soil moisture were only added if there was a negative correlation between the screen level temperature and humidity errors.

The results of the alternative nudging scheme are shown in Fig. 11. Although there is still a negative bias in the evaporative fraction (Fig. 11a), the error is again slightly

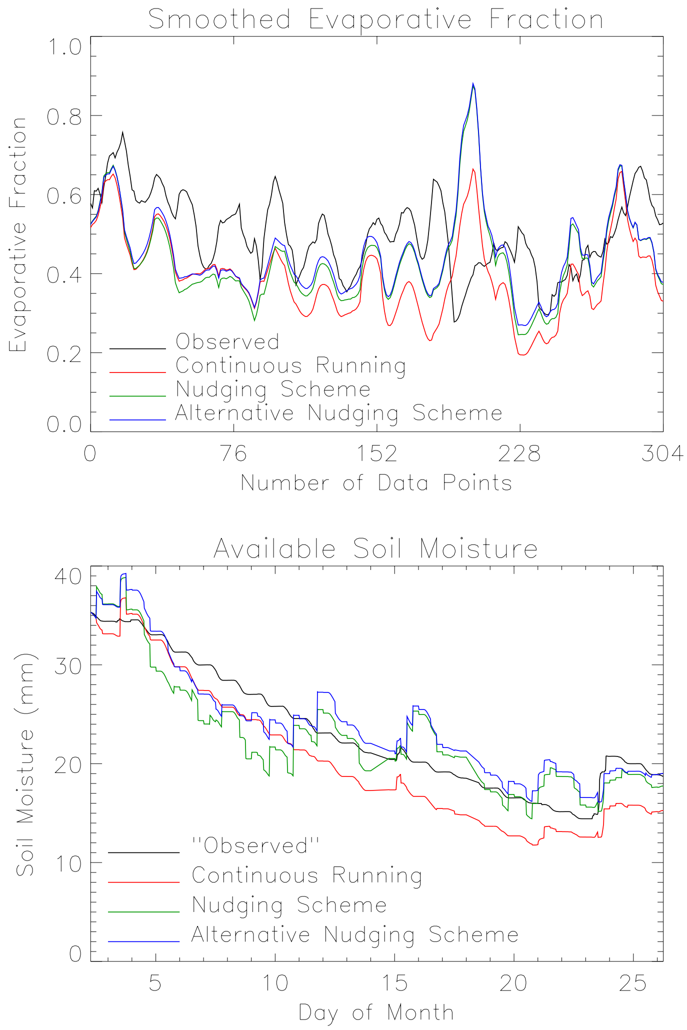

Figure 11: Comparison of nudging criteria. a) Evaporative fraction, continuously smoothed over 11 data points. b) Available soil moisture.

reduced by the alternative nudging scheme compared to both the continuous running and the original nudging scheme. From the 12th August the available soil moisture (Fig. 11b) from both the original nudging scheme and the alternative nudging scheme are roughly the same, although the alternative nudging scheme has slightly more soil moisture. The alternative nudging scheme has the benefits of additional soil moisture at the end of the period, whilst not having the disadvantage of drying the soil in the first part of the period. Hence the alternative nudging scheme outperforms the original nudging scheme.

The results described so far all have a relaxation timescale of 3 days. To investigate the sensitivity of this relaxation timescale, runs were carried out with the alternative nudging scheme for relaxation timescales of 7 and 30 days. The results of these runs are shown in Fig. 12. There is little difference in the first part of the period, since the nudging increments are rarely applied, for the reasons described above. For the second part of the period it is clear the 3 day relaxation timescale produces large fluctuation increments, whereas the 7 day relaxation timescale gives a remarkably good fit to the "observed" values. Although the 30 day relaxation timescale diverts only slowly from the continuous running, it still gives a better simulation and slows down the rate at which the soil is dried.

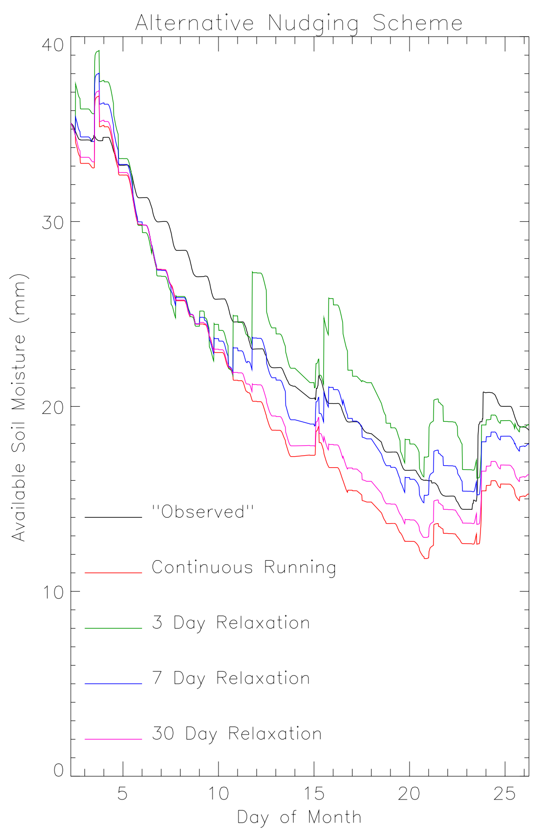

Figure 12: Available soil moisture for various relaxation timescales

6.4 Sensitivity to δ

The main physical assumption to the soil moisture nudging scheme is the closure assumption for temperature and moisture. This closure assumes a fixed relationship between the error in the screen level temperature/humidity and the error in the temperature/humidity at the first model level. The closure relationship includes the unknown parameter δ, which in the tests presented so far, takes the value $\delta = 0.9$. To investigate the sensitivity of this parameter, the alternative nudging scheme was used with a relaxation timescale of 3 days for $\delta = 0.8$, $\delta = 0.7$ and $\delta = 0.5$. The results are shown in Fig. 13.

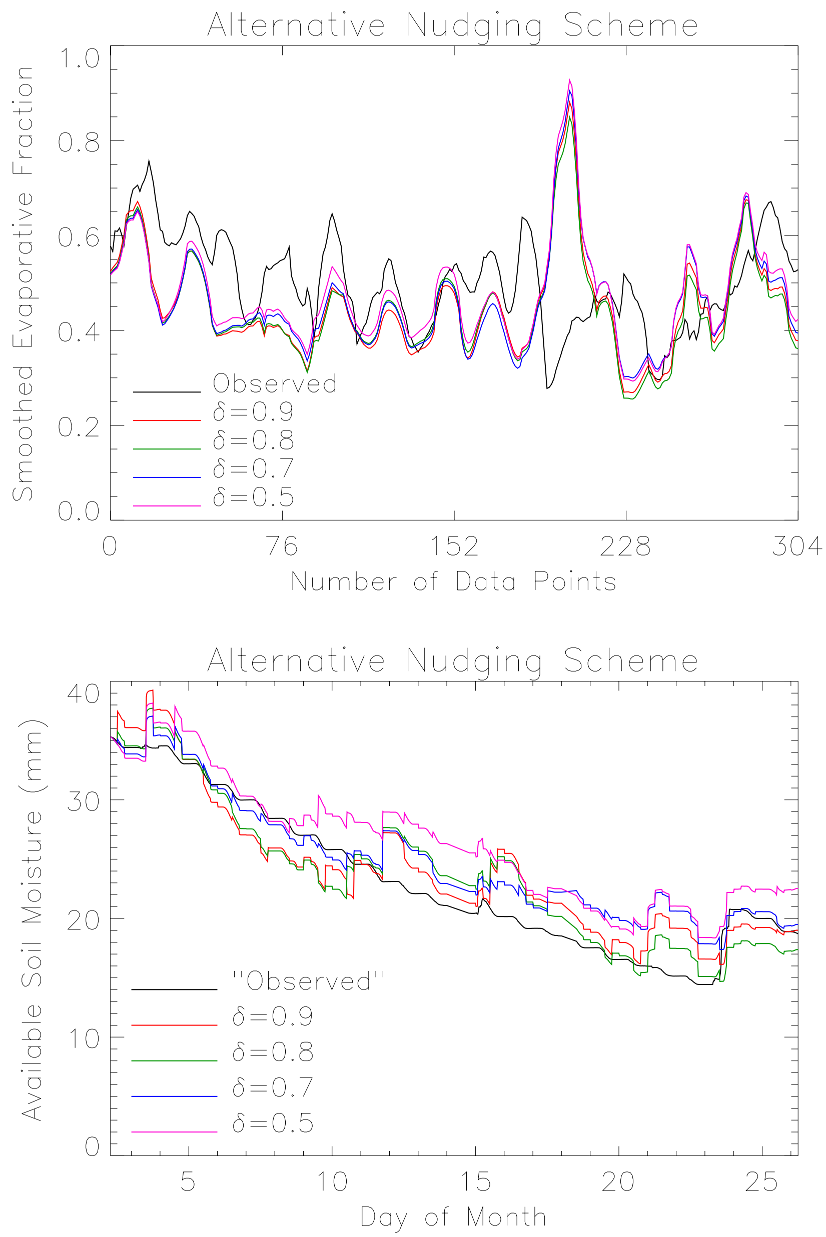

Figure 13: Varying values of the unknown closure parameter δ. a) Evaporative fraction, continuously smoothed over 11 data points. b) Available soil moisture.

The spread in the evaporative fraction (Fig. 13a) is small for this range of δ, implying that the evaporative fraction is relatively insensitive to the choice of this parameter. The general impact of reducing the parameter δ is to increase the amount of available soil moisture (Fig. 13b). The error in the available soil moisture with $\delta = 0.5$ is around the same magnitude as the error in continuous running (Fig. 10), although the errors have different signs. The results suggest that any value between $\delta = 0.9$ and $\delta = 0.7$ would provide a good simulation and give improvements compared to continuous running or resetting to either climatology or MORECS values.

7 Discussion

A physically based soil moisture nudging scheme has been developed. The scheme has been compared to continuous running and resetting the soil moisture back to both climatological values and values determined from the off-line calculations of MORECS. The Site Specific Forecast Model has been used over a period of 3 weeks to ascertain the medium term impact of the nudging scheme. August 1998 was chosen, because it was a particularly dry period, to see if the available soil moisture would dry out. By choosing this period, however, it means that the soil moisture did not have a significant impact of the screen levels errors in temperature and humidity, which were dominated by other model errors. However, the simulations were able to show how well the different schemes could simulate the available soil moisture and the evaporative fraction.

Resetting to climatology is inappropriate during this period, since it was warmer and drier than the climatological mean. However, it is exactly this type of extreme situation that we would hope to be able to model, so resetting to climatology is not an appropriate thing to do.

There are no long term tests of free wheeling the soil moisture in MOSES within the context of an operational model which is constrained by data assimilation. Therefore it is not possible to be certain that the soil moisture will not drift due to errors in the model, which may be due to the surface scheme, or other schemes in the model such as radiation or cloud. The tests within the SSFM have shown that the continuous running throughout this dry period does tend to have a slight bias towards drying the soil still further. Although this drift is small, these tests can not give sufficient confidence to suggest that the soil moisture should be free wheeled within the operational model.

The method currently used in the operational Mesoscale model is to reset the soil moisture values to that determined by MORECS. MORECS is scientifically a less accurate model than MOSES, but is constrained by the fact that it is driven by observational data, rather than data calculated by the operational Mesoscale model. Despite the fact that the MORECS data has to be interpolated before it can be used within MOSES, this use of data should ensure that it is more accurate than the continuous running of MOSES. However, the simulations presented here show that this is not the case. The continuous running of MOSES does better than the MORECS resets through most of the period. This can only be due to the better representation of the surface processes in MOSES compared to MORECS.

The introduction of the nudging scheme gives a better simulation of both the available soil moisture and the evaporative fraction than any of the other methods, although it does incorrectly dry the soil in the early part of the period. This incorrect drying is due to the fact that other model errors are contributing to the screen level temperature and humidity errors, and hence the assumption that the screen level errors are solely a result of an error in the soil moisture is incorrect. By ensuring that the soil moisture increments are only applied if there is a negative correlation between the screen level temperature and humidity errors, the incorrect drying at the beginning is significantly reduced, while the overall benefits of the nudging scheme during the period are retained.

Since the continuous running of MOSES only gives a slight drift in soil moisture, there is a good argument for ensuring that the relaxation timescale for the nudging scheme should be long. The results show that a relaxation timescale of 30 days gives an improvement over the continuous running and dries at a slower rate. However, the simulation with a weekly relaxation timescale is better and in remarkably good agreement with the "observed" available soil moisture. It also does not give such large and undesirable increments as are occasionally seen with the 3 day relaxation timescale.

Simulations varying the number of model soil layers within the root zone show that whilst there is a large variation in the soil moisture limitation factor and the resultant evaporative fraction with the continuous running, the nudging scheme has a small spread in both parameters. This means that the nudging scheme is able to correct for errors in the initial soil moisture. Correcting these errors on such a timescale would not be possible with continuous running of MOSES.

To formulate the physical equations for the nudging scheme, a closure assumption has to be made about the relationship between the temperature and humidity errors at screen level and the first model level. This closure assumption introduces the parameter δ which can be considered to take an unknown value. A simple experiment (described in the physical basis of the scheme) suggests that $\delta \approx 0.9$. Simulations with values of $\delta = 0.9$, $\delta = 0.8$, $\delta = 0.7$ and $\delta = 0.5$ show that there is little sensitivity in the evaporative fraction within this range. There is also little spread in the available soil moisture although the small values of δ tend to have more available soil moisture. These simulations suggest that a value of $0.8 < \delta < 0.9$ should be chosen, which is in general agreement with the original simple experiment.

8 Conclusions

A physically based soil moisture nudging scheme has been developed and has a positive impact on the simulation of available soil moisture and evaporative fraction over a dry period of 3 weeks in August 1998. These non-idealised tests show that although the screen level errors in temperature and humidity may not be caused by soil moisture errors, by ensuring that the increments are only applied when there is a negative correlation in the screen level temperature and humidity errors, the nudging scheme can improve results without causing unrealistic available soil moisture. This is a known problem in other empirical soil moisture nudging schemes.

Appendix

A Converting from soil moisture limitation factor increments to actual moisture increments

In MOSES, the soil moisture limitation factor is related to the layer soil moisture by the following equation:-

$$\beta = \frac{\left(\sum_{i=1}^{n} \rho_r(i)\ S_{thu}(i)\ V_{sat} \Delta z(i)/z_{root}\right) - V_w}{V_{cr} - V_w} \tag{14}$$

where n is the number of model soil levels, $\rho_r(i)$ is the plants' normalised root density in the i'th soil layer, $S_{thu}(i)$ is the fraction of saturation for unfrozen soil moisture in the i'th soil layer, V_{sat} is the saturated soil moisture, $\Delta z(i)$ is the thickness of the i'th soil layer, z_{root} is the depth of the root zone, V_w is the soil moisture wilting point and V_{cr} is the soil moisture critical point.

Hence,

$$\Delta\beta = \frac{\sum_{i=1}^{n} \rho_r(i)\ \Delta S_{thu}(i)\ V_{sat} \Delta z(i)/z_{root}}{V_{cr} - V_w} \tag{15}$$

If $\rho_r(i) = 0$, then ΔS_{thu} is undefined and is therefore set to zero.

In order to distribute the total increment of soil moisture into each of the model layers, assume that

$$\rho_w \rho_r(i)\ \Delta S_{thu}(i)\ V_{sat} \Delta z(i) = \Delta M_{AV}\ \frac{\Delta z(i)}{z_{root}} \tag{16}$$

where ΔM_{AV} is the total increment to soil moisture and ρ_w is the density of water.

Substituting equation (15) into equation (14) gives

$$\begin{aligned} \Delta\beta &= \left(\frac{\Delta M_{AV}}{\rho_w z_{root}^2} \sum_{i=1}^{k} \Delta z(i)\right) / \left(V_{cr} - V_w\right) \\ &= \frac{\Delta M_{AV}}{\rho_w z_{root} \left(V_{cr} - V_w\right)} \end{aligned} \tag{17}$$

since $\sum_{i=1}^{k} \Delta z(i) = z_{root}$ by definition. Re-arranging equation (16) to obtain an expression for ΔM_{AV} and substituting back into equation (17) gives the following expression for the increment to the fraction of saturation in each layer:-

$$\Delta S_{thu}(i) = \frac{(V_{cr} - V_w)}{\rho_r(i)\ V_{sat}}\ \Delta\beta \qquad \text{for } \rho_r\ (i) \neq 0 \tag{18}$$

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