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Sequential soil moisture analysis in the presence of internal and prescribed errors using the ECMWF single column model

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Abstract

Initialisation of land-surface prognostic variables is a crucial issue for short and medium range forecasting as well as at seasonal time scales. In this study, two sequential soil moisture analyses are tested, both based on the comparison between observed and predicted 2m parameters : the nudging technique used operationally at ECMWF and the optimum interpolation technique proposed by Mahfouf (1991) and used operationally at Météo-France. Both techniques compute the soil moisture corrections as a linear function of the errors in the 2m parameters (specific humidity at ECMWF, temperature and relative humidity at Météo-France). Following the preliminary study by Hu et al. (1998), the optimum interpolation technique has been adapted to the 4 soil-level ECMWF land-surface scheme. Both methods are tested in the ECMWF single column model, which has been run for 4 months in 1987 at a grid point close to the location of the FIFE field experiment. The upper-air variables are updated every 6 hours using the ECMWF reanalysis. The surface downward radiation and precipitation fluxes are prescribed at each time step according to in situ observations. The soil moisture analysis is performed every 6 hours, using either the nudging or the optimum interpolation. The nudging is shown to be very sensitive to model biases and sometimes produces unrealistic results. The optimum interpolation technique is more robust and reliable, due to the use of two screen-level parameters and a careful selection of the meteorological situations for which the atmosphere is expected to be informative about soil moisture. It leads to improved evaporation and soil moisture and is able to compensate for biases in both the land-surface scheme and the precipitation forcing. Prospects for further improvements of the optimal interpolation are discussed.

1 Introduction

Since the early developments of General Circulation Models (GCMs) at the end of the 1960s, the major role played by the land-surface boundary conditions has been widely recognized. The influence of soil moisture has been particularly emphasized. Various climate sensitivity studies have suggested that soil moisture anomalies can persist long enough to modify the atmospheric circulation over seasonal to interannual time-scales (Shukla and Mintz 1982; Yeh et al. 1984; Delworth and Manabe 1988, Serafini 1990). As a consequence, climate simulations commonly start with an extended "spin-up" period, in order to avoid any drift of the model due to the poorly specified initial soil moisture.

Soil moisture also has a strong impact on short-and-medium range forecasts in Numerical Weather Prediction (NWP) models. Miyakoda et al. (1979) demonstrated that the use of realistic initial soil moisture conditions could lead to improved forecasts of precipitation and evaporation over a two-week summer period. Rowntree and Bolton (1983) showed that the atmospheric anomalies induced by an inaccurate specification of soil moisture could persist for several days, due to the relatively slow evolution of deep soil wetness. More recently, Yang et al. (1994) performed 10-day integrations with the COLA GCM in order to investigate the importance of initial soil wetness (ISW) for medium-range weather forecasts. They found that the impact of an accurate initialization was strongly positive at the surface, but mainly confined to the low atmospheric levels, and showed the potential interest of a continuous update of ISW for medium-range forecasting. Beljaars et al. (1996) also emphasised the relevance of soil moisture initialization in the ECMWF (European Centre for Medium-Range Weather Forecasts) NWP. Two ensembles of 30-day integrations with contrasted initial soil moistures were performed for July 1993, during the extreme rainfall events that occured in the United States. The integrations with initally moist soil produced a much more realistic pattern than the dry ones. The results also suggested that there is some predictive skill, not only in the short but also in the monthly range, related to the status and the size of the soil moisture reservoir.

The "spin-up" strategy adopted for climate simulations is clearly unsuitable for avoiding a drift in NWP models. Various strategies have been proposed in order to initialize soil moisture in these models, as reviewed by Mahfouf and Viterbo (1998). A precipitation and meteorological analysis can be used to drive an off-line simulation of the land-surface scheme, thereby providing a more realistic field of ISW than the on-line simulation (Mitchell 1994, Smith et al. 1994, Jones and MacPherson 1995, MacPherson 1996). Remote sensing can also provide some information about the surface soil moisture (Jin et al. 1997, van den Hurk et al. 1997, Calvet et al. 1998). However, there are still large uncertainties in the surface emissivities on the global scale, and substantial scientific and technical issues must be resolved before implementing such a strategy in operational NWP systems.

An alternative approach has been proposed by Mahfouf (1991), in which the soil moisture adjustments are derived from the discrepancies between predicted and analysed 2m temperature and humidity. Variational or sequential methods can be used. The variational technique was tested in a 5-day experiment by Rhodin et al. (1997) at the German Weather Service. The quality of the forecasts was improved but the analysed soil moisture was consistently very low and likely to be unrealistic for the selected springtime period. This was partly due to the crude land-surface parametrization scheme used (Blondin 1991). Soil moisture was merely considered as a parameter to be tuned to compensate for various model biases thereby providing better lower boundary conditions for the atmosphere. Due to its low cost and its relative simplicity, the sequential assimilation technique was implemented in the ECMWF and Météo-France NWP models. At ECMWF, the soil moisture corrections are computed from the specific humidity increments at the lowest model level (Viterbo 1996). At Météo-France, the routine is closer to the initial proposal of Mahfouf (1991), since the corrections are computed following an optimal interpolation (OI) technique from the 2m increments of temperature and relative humidity (Giard and Bazile 1996, 1998).

Recently, Hu et al. (1998) have tested both techniques in the ECMWF single column model (SCM). They have confirmed that these methods can provide good estimates of near-surface weather variables and surface fluxes even when the NWP model gives poor simulation of precipitation (and thereby poor soil moisture). However, questions have been raised concerning the use of correlated information (temperature and relative humidity) in the OI technique, and the behavior of both techniques in the presence of errors in the radiative forcing. The present study is a continuation of this previous work. The operational ECMWF analysis and the OI analysis are tested against in situ observations collected during the First ISLSCP Field Experiment (FIFE) (Sellers et al. 1988, Sellers et al. 1992, Betts and Ball 1995, 1998). This field campaign provides radiative and precipitation data for the atmospheric forcing, 2m temperature and relative humidity for the sequential assimilation, as well as turbulent fluxes and soil moisture measurements for the validation. The SCM is integrated for 130 days from the 1st of June 1987. The atmospheric profile is updated 4 times a day from the ECMWF reanalysis (ERA), but is free to interact with the land-surface for 6-hour periods.

In the following section, the ECMWF land-surface scheme and soil moisture analysis are presented, as well as the OI technique. In section 3, the FIFE data set and the experiment design are described. Section 4 shows the results of the simulations using observed initial values for soil moisture and observed precipitation and radiative forcings. Section 5 compares the performances of the two sequential analyses when a perturbation is introduced either in the initial soil conditions, in the vegetation parameters or in the atmospheric forcing. Possible improvements of the OI technique are investigated in section 6, while conclusions are drawn in section 7.

2 Land-surface scheme and soil moisture analysis

2.1 The ECMWF land-surface scheme

The ECMWF land-surface scheme has been developed by Viterbo and Beljaars (1995). It has four prognostic layers in the soil for moisture and temperature, with a free drainage and a zero heat flux condition at the bottom of the deepest layer. It also includes a thin interception layer for the water budget, as well as a thermal "layer" with no heat capacity at the top, in order to compute the skin temperature. From the surface to the bottom of the soil, the layer thicknesses are respectively 0.07, 0.21, 0.72 and 1.89 m. The three top layers correspond to the root zone whose total depth is 1 meter. The root density decreases exponentially with depth. The surface evaporation is assessed separately for bare soil and vegetated areas. The role of the vegetation is represented explicitly, through a transpiration term and an interception loss corresponding to the evaporation of dew and intercepted rain at the potential rate. The transpiration is controlled by the leaf area index (LAI) and the stomatal conductance, which is regulated by the water availability and the photosynthetically active solar radiation.

The current scheme uses a crude description of the soil and vegetation parameters. Most vegetation properties are constant in both space and time. The leaf area index ($LAI = 4$) has no seasonal cycle and does not depend on the vegetation type. The minimum stomatal resistance, R_{smin}, is set to 240 s/m, so that the canopy resistance (R_{smin}/LAI) has a uniform and constant value of 60 s/m, which seems reasonable for the dominant vegetation type (grassland) observed on the FIFE site chosen for this study. The vegetation fraction, C_v, is prescribed according to the Wilson and Henderson-Sellers (1985) vegetation map. A fraction of 87% is used in the present study, corresponding to the model value at the closest grid point. The soil properties are uniform and representative of a loamy soil. The volumetric soil water content is 0.171, 0.323 and 0.472 m^3/m^3, at wilting point, field capacity and saturation respectively. The model field capacity is underestimated compared to the field measurements. It has been increased by 0.03 m^3/m^3 in the current SCM simulations. The wilting point has been increased by the same amount, in order to keep the 15.2 cm of maximum available water in the 1 meter root zone of the model.

This land-surface parameterization was shown to perform much better than the former one in stand-alone simulations using an observed meteorological forcing (Viterbo and Beljaars 1995). The results were less convincing in a multi-year integration of the ECMWF GCM, where the forcing provided by the atmospheric component of the model might include significant systematic biases. Such biases can induce a drift in the surface conditions, thereby masking the benefit of a more physical land-surface scheme. This problem was actually encountered after the scheme was implemented in the ECMWF NWP model in 1993 and was the result of no longer relaxing the deep soil variables to climatologies. Every 6 hours, the ISW was kept at the first guess value. A serious drift in the model surface parameters appeared in spring 1994, showing the need for a soil moisture analysis. The drift was particularly obvious in the mid-latitude continents showing a dry bias at the surface as well as in the low troposphere. It was therefore decided to develop a technique for initializing soil moisture in the ECMWF forecast system.

2.2 The ECMWF soil moisture analysis

A simple analysis was proposed by Viterbo (1996), based on the comparison between the analysed and predicted specific humidity at the lowest model level. This so-called "nudging" is not really an additional contribution in the prognostic equations but a correction in the top three soil layers which is added every 6 hours in the following way :

$$\theta^a = \theta^f + C_v D \Delta t \times (q^a - q^f) \tag{1}$$

where θ^a and θ^f are the analysed and first guess values of the volumetric soil water contents, q^a and q^f are the analysed and first guess values of the lowest model level specific humidity, C_v is the fraction of vegetation cover, $\Delta t = 6$ hours and D (units $m^3 m^{-3}/(kgkg^{-1} 6hr)$) is an empirically determined constant which is applied globally. In the operational model $D = 2.77$ while in ERA $D = 1.04$. The operational value of D is used in this study. This method was shown to be efficient in a pre-operational test of one month (June 1994). The 10-day forecasts were better than the operational results at practically all ranges. The area where the impact was the largest of all was North America, where the 200hPa geopotential was significantly improved up to day 6 of the forecasts. This soil moisture analysis was therefore put into operations in December 1994 and no critical drift in the surface conditions was noticed since that date.

Recent comparisons of the ECMWF reanalysis (ERA, Gibson et al. 1997) with observations from the FIFE field experiment (Betts et al. 1998a) and the Arkansas Red-river basin (Betts et al. 1998b) suggest that the ECMWF surface analysis is affected by some model deficiencies, both at the land surface and in the atmospheric forcing. Though the simulated diurnal and seasonal cycles are both reasonable, they show systematic biases which are compensated by the nudging. The low level specific humidity shows too strong a midmorning peak and too low a late afternoon minimum, leading successively to negative and positive soil moisture increments in the analysis cycle. Over the Arkansas Red-river basin, the nudging exhibits a strong seasonal cycle with negative values in winter and positive values in summer. Betts et al. (1998b) suggested that the absence of an annual cycle in the ECMWF model vegetation might be partly responsible for the seasonality of the soil moisture analysis.

Looking more generally at the global geographical distribution of the ECMWF operational increments for various months in 1996 and 1997, a recent study by Douville et al. (1998) led to similar conclusions. The diurnal and seasonal behaviors of the soil moisture analysis identified by Betts et al. (1998a,b) are found not only over the United States but also over most continental areas, and are probably due to systematic biases in the model surface climatology. The monthly mean increments can be of the same order of magnitude as the monthly mean precipitation and are likely to jeopardize the realism of the analysed annual cycle of soil moisture at least in the mid-and-high latitudes. The nudging contributes to some significant improvements in the predicted precipitation between the first guess and the forecast, but the analysis could be more efficient if it did not have to compensate for the model biases. All data assimilation algorithms are primarily designed for bias-free models and observations, and they do not give optimal results in the presence of model biases.

It is clear that there is a need for an improved soil moisture analysis in the ECMWF model, even if the current routine has shown some ability to avoid degradation of the forecasts due to a drift in the land-surface conditions. As suggested by previous studies (Mahfouf 1991, Bouttier et al. 1993a, b, Giard and Bazile 1998), the corrections should be applied only when the low level atmosphere is really informative about soil moisture. The use of two predictors (temperature and relative humidity) instead of one (specific humidity), and at the screen level (2 meters) instead at the lowest model level (around 30 meters) could also have a positive impact. Finally, the analysis could also benefit from the use of model and location dependent coefficients instead of an empirical constant to relate the soil moisture corrections to the atmospheric increments.

2.3 The OI soil moisture analysis

The sequential soil moisture analysis defined by Mahfouf (1991) is based on the prediction errors of 2m temperature and relative humidity. Every 6 hours, corrections applied in each soil layer are linear combinations of atmospheric increments of 2m temperature and relative humidity. Like for the nudging, only the three top soil layers are considered by the analysis since the deep soil layer does not contain any roots and does not influence directly the surface evapotranspiration. The analysed increment in soil moisture at layer i is defined by

$$\Delta\theta_i = \theta_i^a - \theta_i^f = \alpha_i(T^a - T^f) + \beta_i(RH^a - RH^f)$$

Superscript a stands for analysed values and superscript f for forecasted values, and subscript i identifies the soil layer. The coefficients α_i and β_i minimize the variance of analysis error and are weighted by two empirical functions F_1 and F_2 :

$$\alpha_i = \frac{\sigma^f_{\theta_i}}{\Phi\sigma^f_T}\left\{\left[1+\left(\frac{\sigma^a_{RH}}{\sigma^f_{RH}}\right)^2\right]\rho_{T,\theta_i} - \rho_{T,RH}\rho_{RH,\theta_i}\right\}F_1F_2$$

$$\beta_i = \frac{\sigma^f_{\theta_i}}{\Phi\sigma^f_{RH}}\left\{\left[1+\left(\frac{\sigma^a_{T}}{\sigma^f_{T}}\right)^2\right]\rho_{RH,\theta_i} - \rho_{T,RH}\rho_{T,\theta_i}\right\}F_1F_2$$

with :

$$\Phi = \left[1+\left(\frac{\sigma^a_T}{\sigma^f_T}\right)^2\right]\left[1+\left(\frac{\sigma^a_{RH}}{\sigma^f_{RH}}\right)^2\right] - \rho^2_{T,RH}$$

where $\rho_{x,y}$ represents the correlation of forecast errors between parameters x and y, σ^f and σ^a are respectively the standard deviations of forecast and analysis errors. The funtions F_1 and F_2, to be defined later, reduce the optimum coefficients when the coupling between the soil and the lower boundary layer is weaker.

In the framework of the SCM simulations using observed data, the specified analysis errors, σ^a, are only measurement (observation) errors. However, when applied in the ECMWF forecast system, the analysis errors will be the sum of representativeness and measurement errors. For the SCM simulations presented here, the standard deviations of the observation errors have been set to $\sigma_T^o = 2$ K and $\sigma_{RH}^o = 10\%$, which appeared as reasonable values given our knowledge of the analysis errors in the operational ECMWF model.

The statistics of prediction errors have been obtained through a Monte Carlo method, following Mahfouf (1991). An ensemble of one hundred SCM simulations performed with different ISW is used to estimate the statistics. Several ensembles have been obtained with different values of the vegetation cover in order to assess the sensitivity of the statistics to that parameter. A clear sky situation with maximum insolation (summer solstice along the Tropic of Cancer) has been selected in order to get the largest atmospheric forecast errors produced by errors in ISW. Volumetric soil moisture contents have been perturbed randomly between 0 and θ_{sat} (saturation) around a mean value of $\theta_{sat}/2$.

The size of these random perturbations is obviously unrealistic in the framework of an operational NWP model. It allows the full phase space of the system to be explored but the resulting standard deviations of forecast errors in soil moisture, $\sigma_{\theta_i}^f$, must be rescaled to a more realistic magnitude. This study uses a uniform value $\sigma_{\theta_i}^f = 0.01 m^3/m^3$ for the three soil layers in the root zone. This volumetric content corresponds to 10 mm of water since the root zone is 1 m deep. Such a value is not too far from the P-E-R (precipitation minus evaporation minus runoff) errors that can be seen in summer over Kansas in the ECMWF NWP model from the difference between day 1 and day 2 forecasts (see, for instance, Rabier et al. 1998). However, maps of these estimated forecast errors show large variability in both space and time. In arid areas, the errors are close to zero while they exceeds 10 mm in rainy regions. The definition of the standard deviations of the forecast errors on the global scale will therefore require more work in the future.

The statistics thus derived from the Monte Carlo method are appropriate for "ideal" conditions with strong insolation. They need to be weighted by two empirical functions, F_1 and F_2, in order to reduce the optimum coefficients when the coupling between the soil and the lower boundary layer is weaker. A first dependency is introduced with the diurnal cycle and the seasonal cycle, since the statistics have been recorded on 21st June at the time of the day when the forecast errors on 2m parameters show the maximum standard deviation (early afternoon). In order to obtain negligible soil moisture corrections during the night and in winter, F_1 is a function of the cosine of the mean solar zenith angle, μ_M, averaged over the 6 hours prior the analysis time :

$$F_1 = \frac{1}{2}\left[1 + \tanh\left(\lambda(\mu_M - 0.5)\right)\right] \quad ; \quad \lambda = 7$$

The OI coefficients are also reduced when the radiative forcing is weak in cloudy situations. For this purpose, the atmospheric transmittance, T_r, is computed from the mean surface downward solar radiation forecasted during the previous 6 hours, $\overline{R_g}$, as :

$$T_r = \left(\frac{\overline{R_g}}{S_0 \mu_M}\right)^{\mu_M}$$

S_0 is the solar constant, and the empirical function F_2 is expressed as :

$$F_2 = \left(\frac{T_r - T_{rmin}}{T_{rmax} - T_{rmin}}\right)$$

with T_{rmin}=0.2 and T_{rmax}=0.9.

Additional thresholds have been implemented which are also used in the operational analysis of Météo-France. No soil moisture correction is done if the last 6-hour precipitation exceeds 0.6 mm, the instantaneous wind exceeds 10 m/s, for subfreezing surface air temperatures, or if there is snow on the ground.

Finally, the dependency with vegetation cover is quadratic between minimum ($C_v = 1\%$) and maximum ($C_v = 99\%$) values :

$$\begin{aligned}
\rho_{RH,\theta_i} &= (\rho_{RH,\theta_i})_{min} + C_v^2\left[(\rho_{RH,\theta_i})_{max} - (\rho_{RH,\theta_i})_{min}\right] \\
\rho_{T,\theta_i} &= (\rho_{T,\theta_i})_{min} + C_v^2\left[(\rho_{T,\theta_i})_{max} - (\rho_{T,\theta_i})_{min}\right] \\
\sigma_{RH}^f &= (\sigma_{RH})_{min} + C_v^2\left[(\sigma_{RH})_{max} - (\sigma_{RH})_{min}\right] \\
\sigma_T^f &= (\sigma_T)_{min} + C_v^2\left[(\sigma_T)_{max} - (\sigma_T)_{min}\right]
\end{aligned}$$

The numerical values used in the previous equations are summarized in Table 1.

Apart from the differences in the land-surface schemes (Viterbo and Beljaars (1995) at ECMWF, Noilhan and Planton (1989) at Météo-France), the OI soil moisture analysis presented in this section is similar to the one which has been recently implemented at Météo-France by Giard and Bazile (1998). The OI coefficients are not the same due to the use of different statistics and different empirical functions. In particular, we set the standard deviation of observation errors to $\sigma_T^o = 2$ K and $\sigma_{RH}^o = 10\%$, so that the two-metre temperature data has more influence on the soil moisture corrections than the relative humidity data. Moreover, the OI coefficients do not depend upon soil or vegetation properties at ECMWF since these quantities are global constants. However, a temporal filtering of the temperature increments has been implemented at Météo-France in order to smooth diurnal oscillations of soil moisture. Note that this is substantially different from the filtering discussed in Section 6.2.

$\sigma^f_{\theta_i}$	0.01
σ^o_T	2
σ^o_{RH}	0.1
$(\sigma_T)_{min}$	1.25
$(\sigma_T)_{max}$	0.87
$(\sigma_{RH})_{min}$	0.095
$(\sigma_{RH})_{max}$	0.090
$\rho_{T,RH}$	-0.99
$(\rho_{T,\theta_i})_{min}, i = 1,2,3$	(-0.90,-0.91,-0.86)
$(\rho_{T,\theta_i})_{max}, i = 1,2,3$	(-0.82,-0.92,-0.90)
$(\rho_{RH,\theta_i})_{min}, i = 1,2,3$	(0.93,0.90,0.83)
$(\rho_{RH,\theta_i})_{max}, i = 1,2,3$	(0.83,0.93,0.91)

Table 1: Statistics used in the simulations presented in this paper. Units correspond to the use of $m^3 m^{-3}$ for θ_i, K for T, and $(0-1)$ for RH.

3 Data and experiment design

3.1 The FIFE data set

The FIFE field campaign took place in 1987 in the Konza prairie, Kansas. The observations were made on a 15km × 15km site. Betts et al. (1993) averaged the surface meteorological and flux data to give a single time series representative of the FIFE site for the period May-October. During that period, the conditions over the FIFE grassland site are considered relatively homogeneous, so that simple averaging of the data gave a representative mean.

The present study focus on a 130-day period between 1st June and 9 October 1987. Figure 1a shows the 6-hourly evolution of the observed precipitation, which will be used to force the ECMWF land-surface scheme in the SCM experiments. June was a rainy month, while the second half of July showed a prolonged dry spell. Some strong precipitation events were also observed in August and at the beginning of September. The end of the period was fairly dry.

Figure 1b shows the downward shortwave and longwave radiation forcing during the 130-day period. The maximum solar flux is around 700 W/m^2 in June and slowly decreases at the end of the summer season. Consistent with the rainy spells, there are periods of low solar radiation due to the presence of clouds. The longwave downward radiation varies generally around 400 W/m^2 but is slightly reduced at the end of the period, due to the cooling associated with the decreased insolation.

As for precipitation, the observed downward radiative fluxes have been used to force the land-surface in the ECMWF SCM. The model radiative scheme is activated but the simulated fluxes

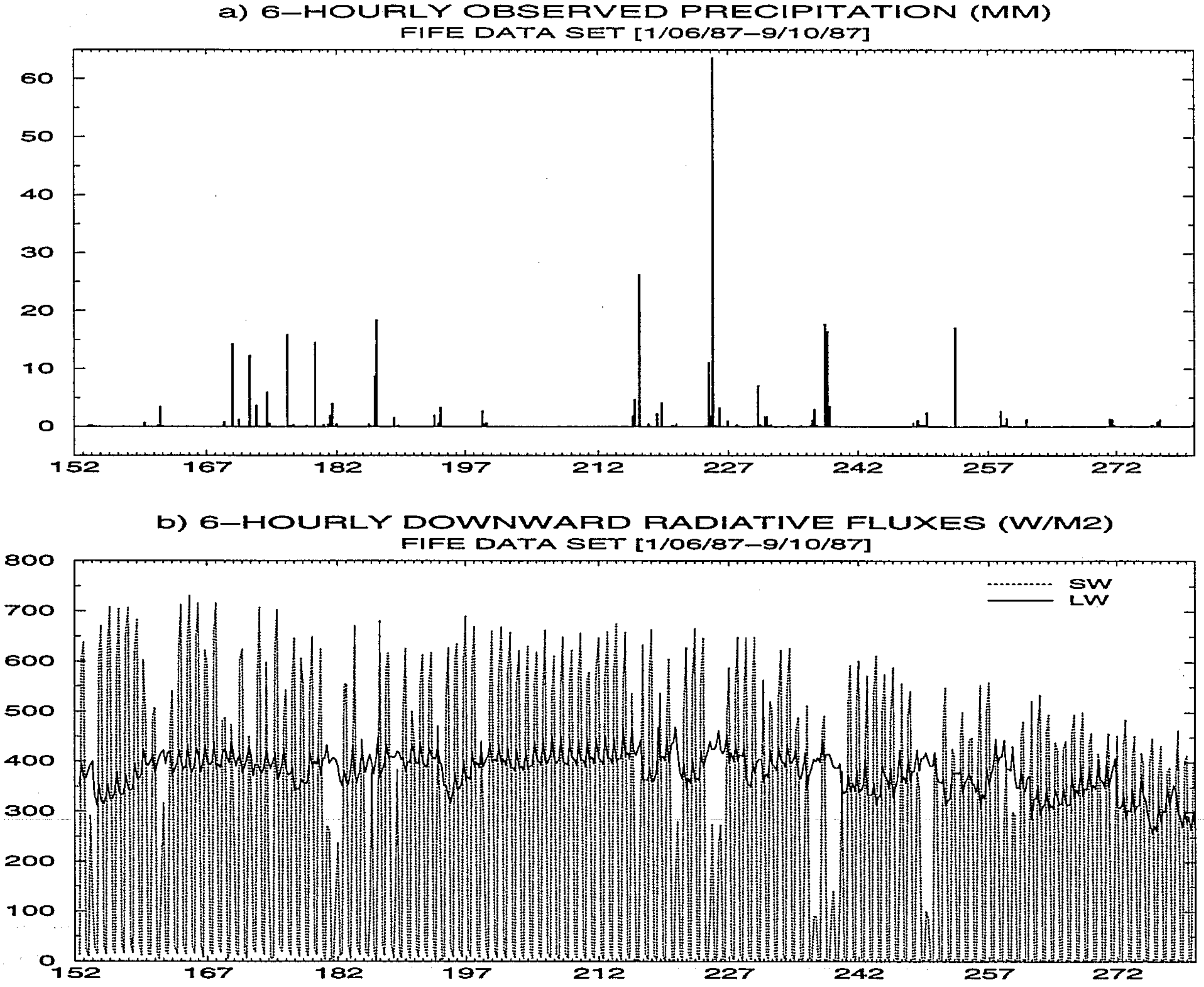


Figure 1: Area-mean precipitation and radiative fluxes observed during the FIFE field experiment from 1 June to 9 October 1987 : a) 6-hour precipitation in mm, b) 6-hour downward solar and infrared radiation in W/m^2

are replaced by the observed values at the surface. This is done after the calculations of the radiative scheme so that the divergence of the fluxes is not modified as far as the atmospheric column is concerned. Note that the model albedo is set to 16.5%, slightly lower than the 18% which was observed.

Besides the radiative and meteorological observations, the FIFE data set also includes measurements of soil moisture and temperature. The temperature has been measured at 10 and 50 cm below the surface. Gravimetric and neutron probe techniques have been used to estimate soil moisture profiles down to 200 cm. The mean soil moisture for each layer of the ECMWF land-surface scheme has been calculated from the site-averaged data. However, the comparison between simulated and observed values will be imperfect due to the irregular time sampling during the FIFE field campaign, so that the observed evolution will look smoother than the simulation.

3.2 Experiment strategy

All experiments start at local midnight (6 UTC) on 1st June 1987. The SCM is integrated following a 6-hour cycling for a 130-day period up to 9 October 1987. The initial atmospheric conditions are provided from the ERA analysis and the initial soil conditions are either derived from in situ observations (for most experiments) or set up with wrong values in order to test the analysis routines. The SCM runs with the full physics package (including the radiative scheme described in Morcrette 1990, 1991, the convection scheme of Tiedtke 1989, and a prognostic cloud scheme described in Tiedtke 1993 and Jakob 1995) and geostrophic wind forcing. The large scale advection and the vertical velocity are also included according to estimates from the ERA analysis. The fluxes simulated at the land-surface (shortwave and longwave downward radiation, as well as precipitation) are replaced every time step by the linearly interpolated observations, which can themselves be modified in order to mimic a systematic bias in the model.

i) Unperturbed control run

This control experiment does not perform any soil moisture corrections. The initial conditions of soil moisture at 1 June 1987 are set to observations, and during the model integrations the observed radiative and precipitation forcing replaces the corresponding model values at the surface. The SCM atmospheric initial conditions are taken every 6 hours from the ERA, but the soil moisture is driven solely by the model atmosphere. The experiment emulates atmospheric data assimilation with no initialization of soil moisture. This configuration serves to establish that the results obtained are reasonable, when compared to the observed values. It also provides a reference to assess the performance of the analysis experiments.

ii) Unperturbed analysis experiments

Every 6 hours, the atmospheric profile is still initialized according to the ERA and the soil and skin temperatures are still taken from the SCM, but the soil wetness in the three top layers is analysed. The method is either the OI technique or the operational ECMWF technique ("nudging"). In this framework, data assimilation and soil moisture initialization are performed with observed (i.e. "perfect") downward radiation and precipitation forcing and with realistic initial values for soil moisture and temperature . The surface analysis compensates only for deficiencies in the ECMWF land-surface scheme, in the ERA boundary layer structure and in the SCM experiment design (prescribed advection for 6 hours).

iii) Perturbed control runs

As in i), the model runs without any soil moisture correction but with a perturbation in either the ISW, the vegetation parameters or the atmospheric forcing. These experiments are still referred to as "control" since they represent a reference for assessing the quality of the assimilation techniques. Several types of perturbations are tested :

- Initial soil wetness too dry : the 4 soil layers are initialized at the wilting point whereas the observations are close to the field capacity.
- Vegetation cover too low : the vegetation cover, C_v, of the ECMWF model (87%) is divided by 10 and is therefore strongly underestimated for a prairie.
- Biased precipitation : the precipitation rate is zero during the first half of the experiment and triple the observations during the second half.
- Biased solar radiation : the downward solar radiation is increased/decreased by 25% during the first/second half of the experiment.

For the two last cases, the soil moistures and temperatures are reinitialized according to in situ observations in the middle of the integration (1 August 1987) in order to avoid any compensation between the biases prescribed in the first and second half of the experiments.

iv) Perturbed analysis experiments

The perturbations described in iii) can be also prescribed in analysis experiments. Now the surface analysis must also compensate for errors in either the ISW, the vegetation parameters or the atmospheric forcing.

4 Simulations with observed ISW and forcing

In this section, three simulations, forced with the observed precipitation and radiative forcing and initialized with the observed soil moisture at the 4 soil levels, are compared. The control experiment, CTL, is a reference simulation without any soil moisture analysis. Two analysis experiments have also been performed, using respectively the nudging and the OI technique.

4.1 Behavior of the nudging and OI techniques

In order to understand the behavior of both the nudging and the OI soil moisture analyses, it is useful to look at the diurnal cycle of the 2m parameters. For this purpose, a 10-day period has been selected at the end of June (day 172 to day 182). It is the first month of the integrations so that the soil moisture and the errors in the 2m parameters are not very different between the 3 experiments. However, it will be shown that the nudging and the OI techniques lead to contrasted soil moisture corrections.

Figure 2 compares the evolution of the 2m parameters for the 3 simulations against the observed values. In all experiments, the model two-metre temperature is too warm, especially during the night. This systematic bias was not found by Betts et al. (1998a) in the ECMWF reanalysis and is probably due to the increase of the turbulent transfer coefficients in stable conditions that has been recently introduced in the ECMWF model (Viterbo et al. 1998). The specific humidity does not show strong biases though it tends to be overestimated during the night and sometimes underestimated during the day time. In agreement with the previous results, the relative humidity is generally underestimated during the day time but is reasonably predicted during the night due to the balance between the temperature and specific humidity errors.

Figure 3 shows the 6-hourly increments obtained for that 10-day period, as well as the corresponding 6-hour precipitation values. The nudging is performed every 6 hours, whatever the meteorological conditions (and particularly the precipitation) are. The same soil moisture correction is applied onto the three soil layers. Due to fluctuations (mainly the diurnal cycle) of the specific humidity errors, the corrections show a succession of positive and negative increments. During the precipitation events, the increments are mainly negative, which means that the model is systematically too wet in rainy conditions. This is probably due to the warm atmospheric bias which allows the atmosphere to sustain an overestimated amount of water when the relative humidity is close to 100%.

The OI has a smoother behavior and exhibits increments of lower magnitude. The analysis is switched off if the low atmosphere is considered to be weakly influenced by the underlying soil conditions, especially during the night and during the precipitation events. The OI increments are mainly positive, due to the warm and dry biases noticed in the 2m temperature and relative humidity. They are almost the same for the three soil layers due to the choice of uniform standard deviations for the forecasts errors in soil moisture. Note also that summer relative humidity errors are obviously correlated with the temperature errors, i.e. a model positive evaporation bias will lead to a near-surface atmosphere that is too dry and too warm. Hu et al. (1998) demonstrated that this could raise a problem of instability in the idealized framework of perfect observations. With non zero observation errors, the OI technique takes account of this correlation and remains stable.

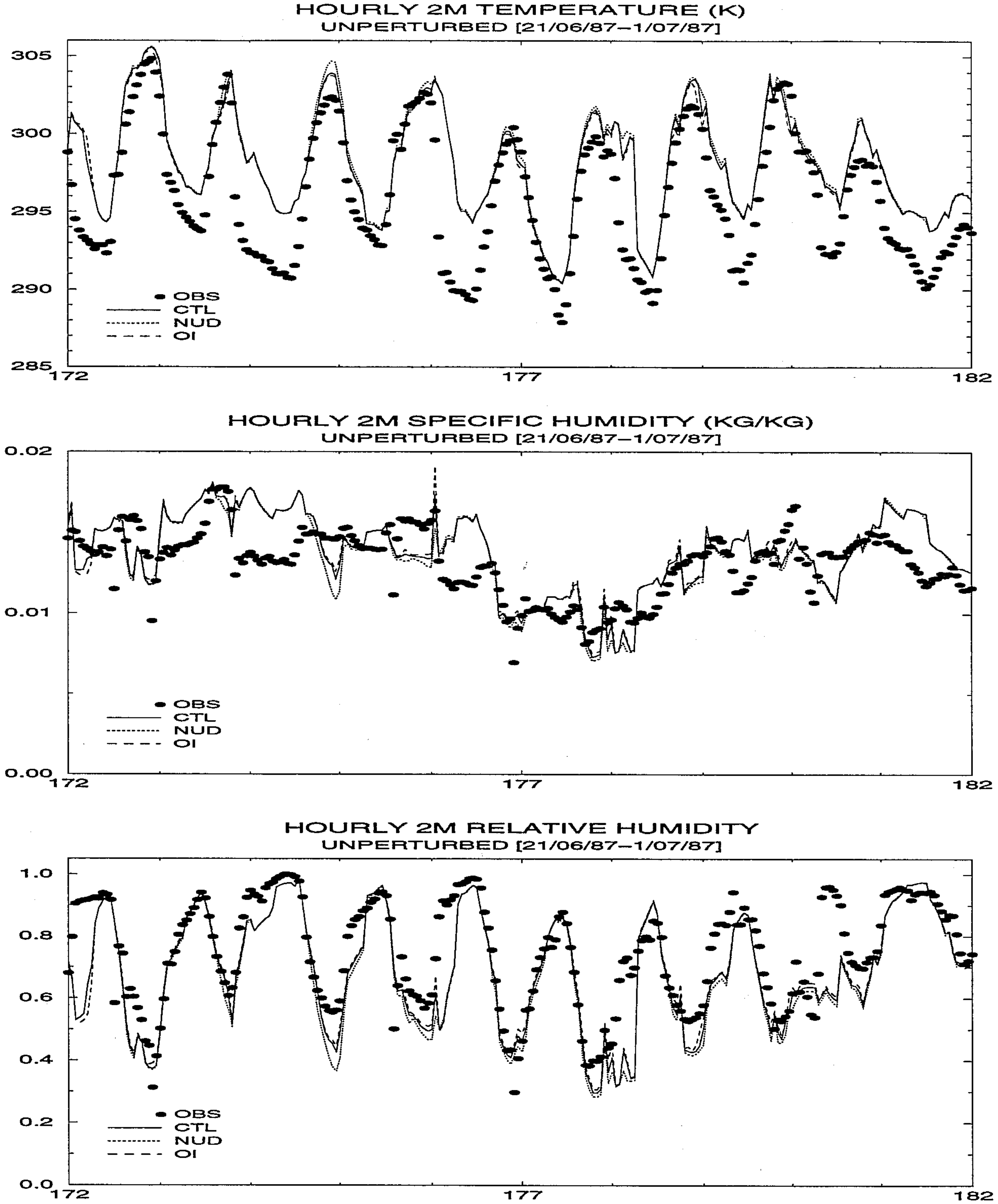


Figure 2: Hourly evolution of the 2m parameters for the 3 unperturbed experiments (control, nudging and OI) between day 172 and day 182 : temperature in K (top), specific humidity in kg/kg (middle), relative humidity (bottom).

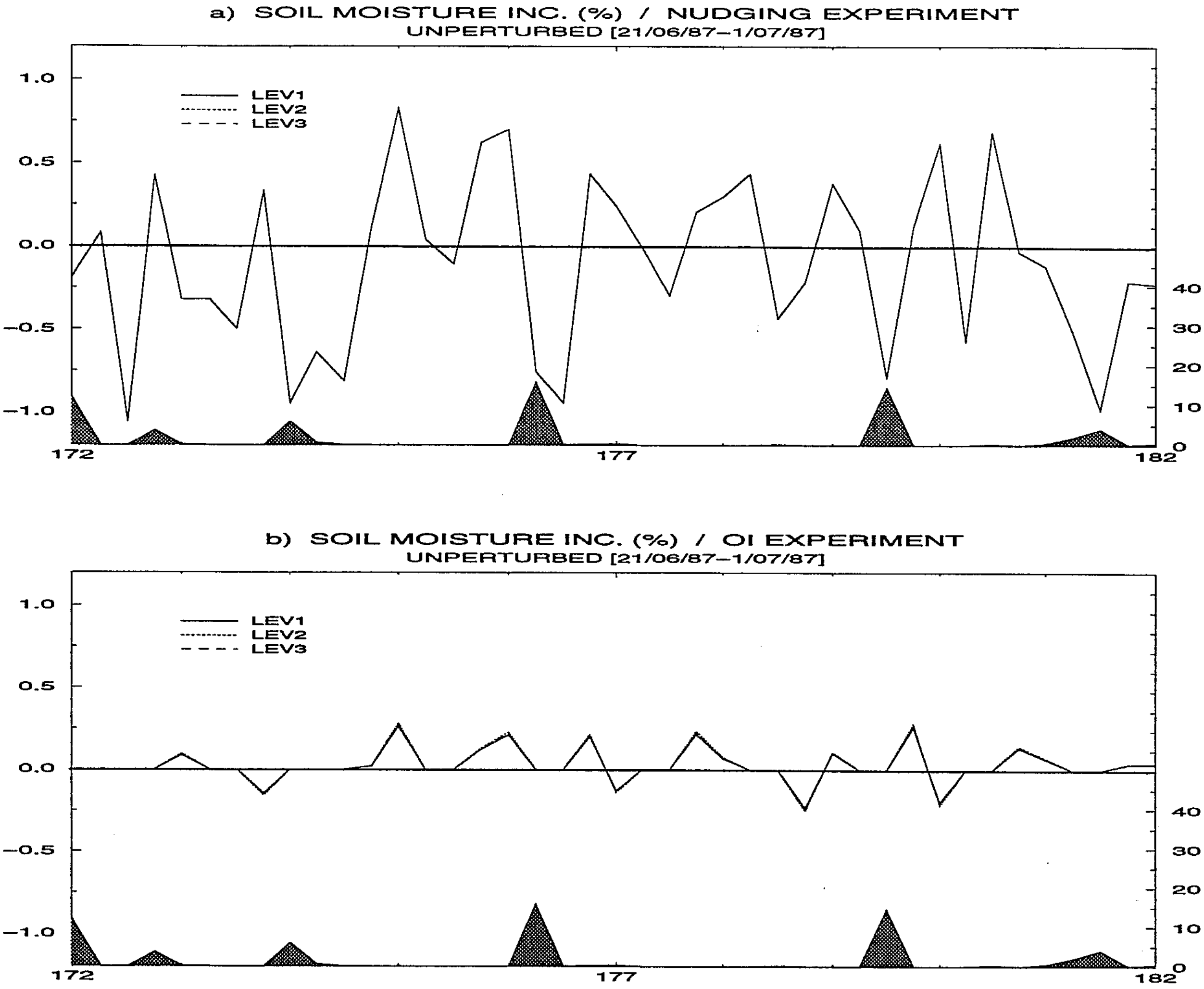


Figure 3: 6-hour volumetric soil moisture increments (%) produced by the unperturbed analysis experiments between day 172 and day 182 : a) nudging, b) OI. Also shown are the simultaneous 6-hour precipitation (mm).

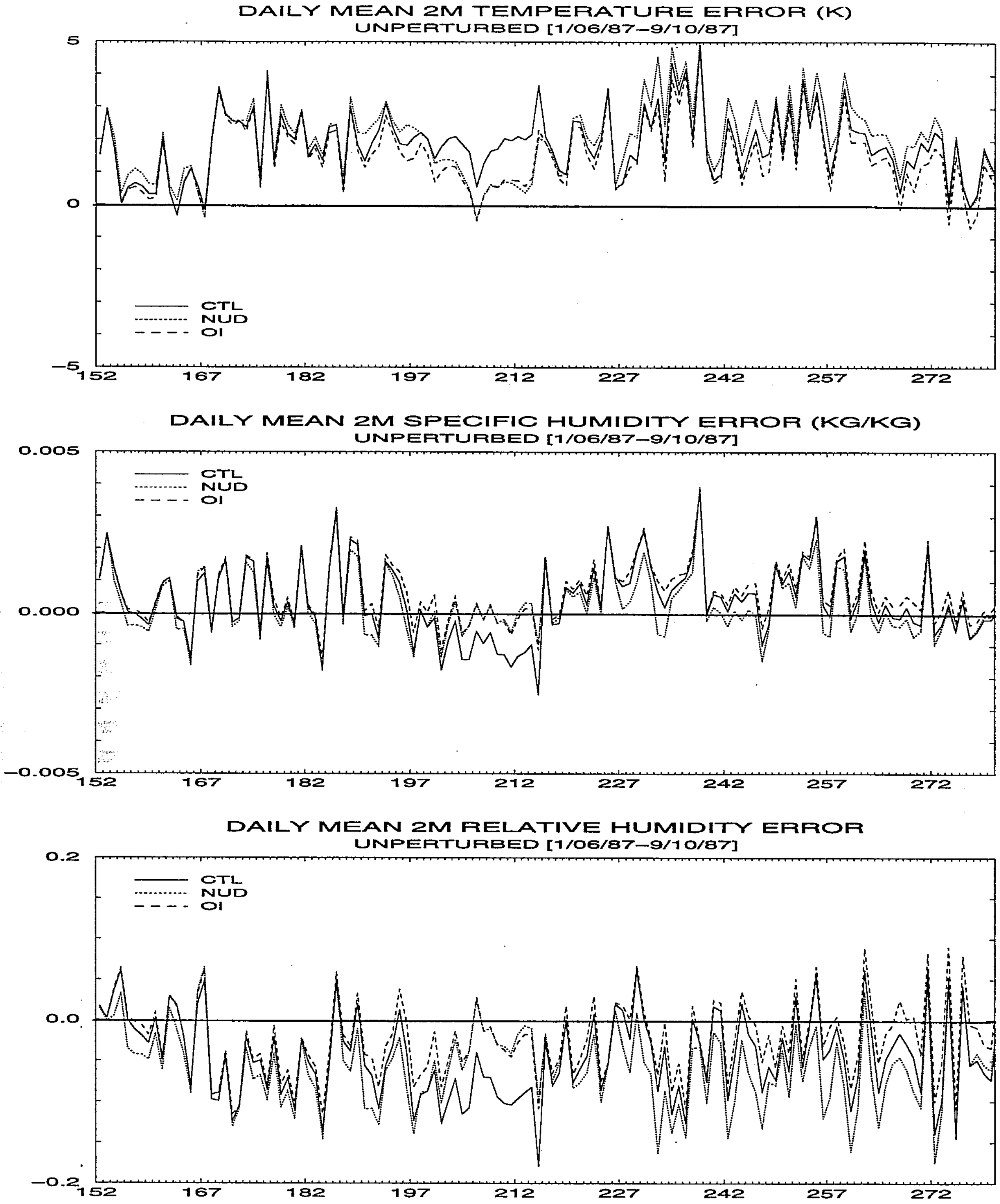
4.2 Daily mean results

Figure 4 shows the evolution of the daily mean 2m temperature, specific humidity and relative humidity errors. In keeping with the previous results, all simulations show a clear warm bias, with an average value of about 2 K and a maximum peak of 5 K. This is mainly a night time error although the day time biases are also generally positive. During the dry spell in July (days 200-210), the warm bias is significantly reduced in both analysis experiments. During the second half of the integration, the warm bias is still obvious, but the OI is slightly cooler than the control experiment while the nudging is warmer. The specific humidity is generally overestimated, which is mainly due to the night time biases discussed in section 4.1. The control experiment becomes too dry in July, whereas the specific humidity is close to the observations in the analysis experiments. From day 215 to day 281, the wet bias is slightly reduced by the nudging but slightly increased by the OI run. Opposite results are found for relative humidity, which is much better predicted by the OI run, showing the relevance of the choice of the parameters that drive the soil moisture analysis. Note that the errors in the 2m parameters are consistent with the results of the ECMWF reanalysis shown by Betts et al. (1998a), which was expected since the reanalysis provides the daily update of the atmosphere in the SCM model. However, the SCM is warmer, especially during the night, due a modification of the turbulence parametrization in stable conditions.

Figure 5 shows the evolution of the daily mean latent heat flux, as well as the soil moisture variations in the 1 meter root zone and in the deep soil (level 4 of the ECMWF land-surface scheme). The control experiment underestimates surface evaporation during most of the 4-month period, and particularly during the dry spell in July. During these two weeks, both analyses techniques have a strong impact and the latent heat flux is even overestimated at the end of July. The analysis impact is rather weak in June and the evaporation remains apparently underestimated, but the observations of turbulent fluxes might be biased during that period (A. Betts, personnal communication). Most of the time, the OI performs better than the nudging, which is actually worse than the control experiment in the second half of the integration. The nudging run is influenced by the nightime wet bias and tends therefore to dry the soil, thereby reducing the evaporation. This is confirmed by the soil moisture evolution in the root zone. The nudging experiment is generally drier than the control experiment which is itself too dry, whereas the OI is much closer to the observations. However, the nudging adds water into the soil during the dry spell in July, when the specific humidity becomes too low in the control. During that period, both thr OI and nudging analyses are wetter than the observations, which is consistent with the fact that the evaporation is overestimated. This could mean that the dry and warm biases found in the control run during that period are not due only to soil moisture errors, as discussed in section 6. The deep soil moisture is not directly modified by the analysis, which is applied only in the root zone, but it is influenced through the water exchange between the layers. A drift towards dry conditions appears in the control experiment, and the nudging run is even drier while the OI run is the only simulation which is able to sustain a reasonable amount of water in the deepest soil layer.

4.3 Hydrological budget

The dry drift found in the control experiment could have several explanations, which can be understood through a comprehensive hydrological budget of the total soil depth (2.89 m in the ECMWF model). Figure 6a shows the evolution of the various components of this budget, with all quantites accumulated from the beginning of the integration. The precipitation is prescribed from the measurements. Observations of evaporation and soil moisture variations are also available to validate the model. As noted previously, the control experiment drifts



DAILY MEAN 2M TEMPERATURE ERROR (K)
UNPERTURBED [1/06/87–9/10/87]

DAILY MEAN 2M SPECIFIC HUMIDITY ERROR (KG/KG)
UNPERTURBED [1/06/87–9/10/87]

DAILY MEAN 2M RELATIVE HUMIDITY ERROR
UNPERTURBED [1/06/87–9/10/87]

Figure 4: Evolution of the daily mean errors in the 2m parameters in the 3 unperturbed experiments (control, nudging and OI) from 1 June to 9 October 1987 : temperature in K (top), specific humidity in kg/kg (middle), relative humidity (bottom).

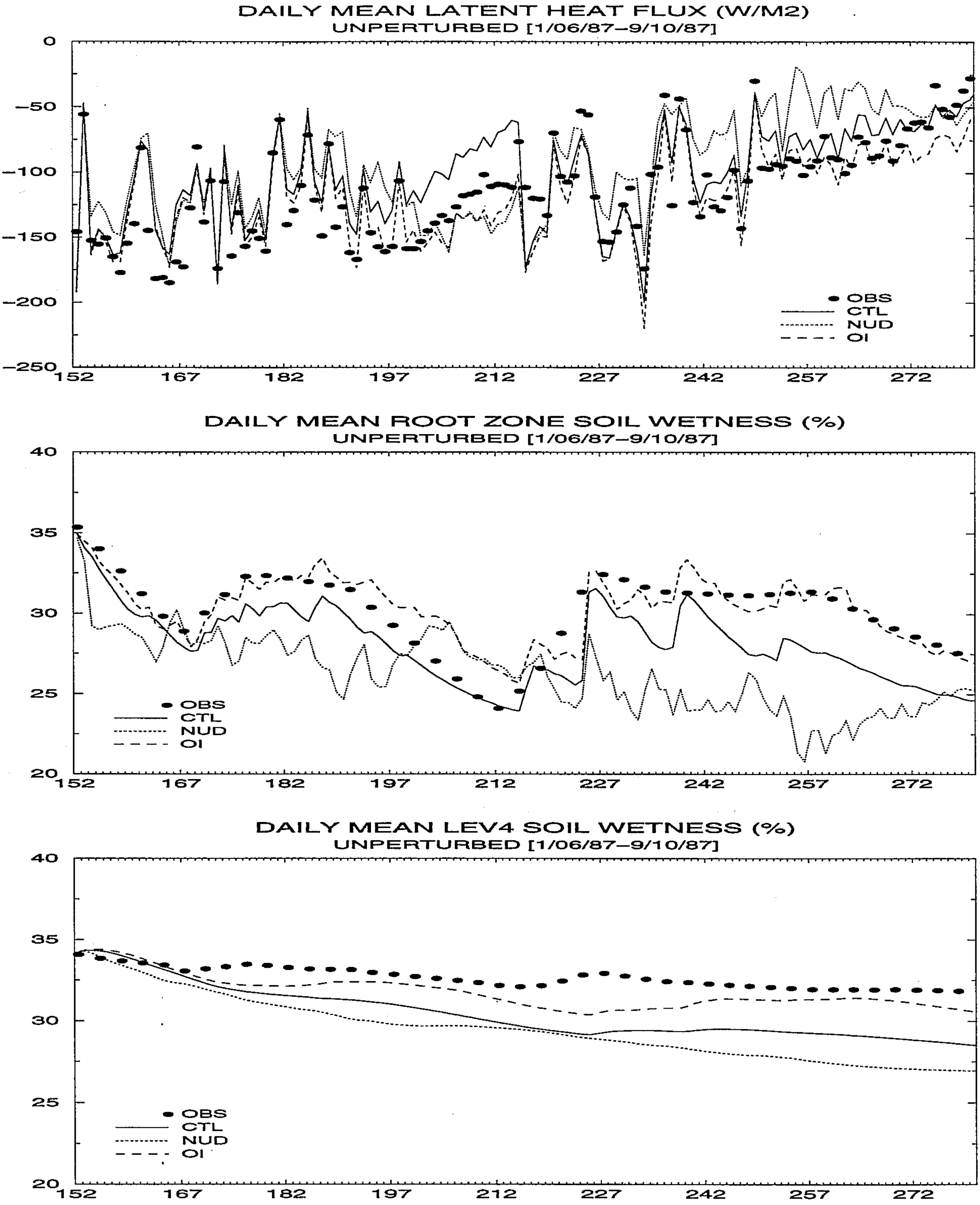


Figure 5: Evolution of the daily mean latent heat flux (W/m^2), root zone volumetric soil moisture (%) and deep soil (level 4) volumetric soil moisture (%) in the 3 unperturbed experiments (control, nudging and OI) from 1 June to 9 October 1987.

towards too dry conditions and underestimates the surface evaporation. Due to the balance between soil moisture fluctuations and P-E-R (precipitation minus evaporation minus runoff), the observations can be used to assess the real runoff. The resulting cumulated runoff during the 130-day period is −39 mm, which means that the model 2.89 m soil depth would have to be supplied with an upward flux from the deep water table or an horizontal flux from the surrounding areas. An alternative and possibly more plausible hypothesis is that the measured precipitation has been underestimated, which is common especially in windy conditions. The dry drift in the control simulation might also be partly explained by an overestimation of the runoff (+108 mm), but the underestimation of P seems to be confirmed by the fact that the drift appears mainly during the rainy events while the runoff (essentially deep drainage) is a low frequency component.

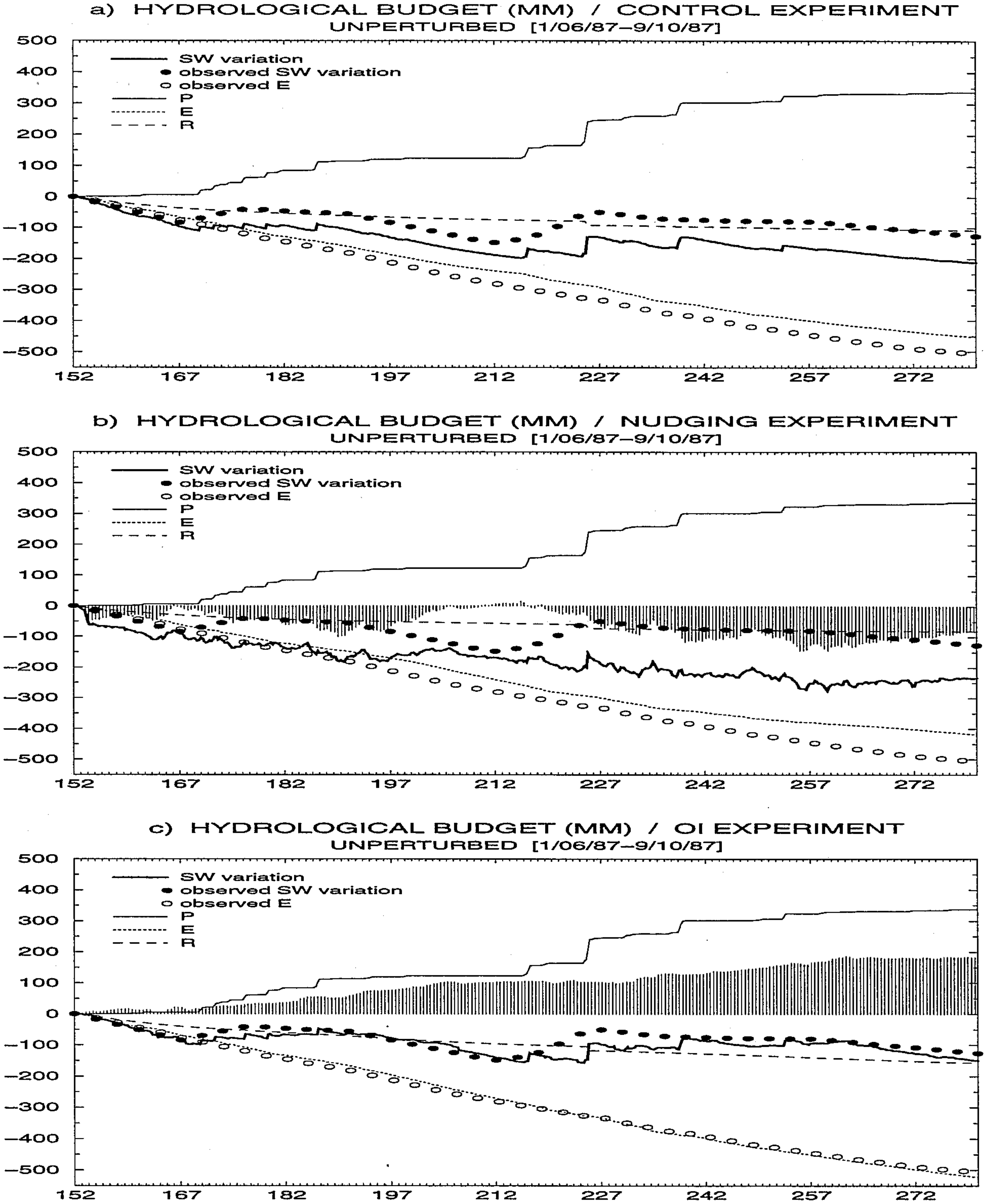
Figures 6b and 6c show the hydrological budgets of the analysis experiments. The time-integrated soil moisture increments (represented by vertical hatching) are an additional component of the water balance, so that the observed soil moisture variations must be now compared to P-E-R+I where I stands for the increments. The accumulated total (levels 1, 2 and 3) increment produced by the nudging is mainly negative (except during the dry spell in july) so that both soil moisture and evaporation are worse than in the control at the end of the 4 months. On the contrary, the OI exhibits a smoother behavior and adds water into the soil most of the time. The largest positive increments appear after the rainy periods, which seems to confirm the hypothesis of an underestimated precipitation forcing. The OI is able to produce a reasonable evolution for both soil moisture and evaporation. On the other hand, the runoff (+159 mm in 130 days which means more than 1 mm/day) is probably overestimated. This is likely to confirm that the dry drift in the control is also partly due to too strong drainage. In order to compensate for the dry bias, the OI adds water into the soil (+184 mm in 130 days) and thereby further increases the runoff until the evaporation (as well as the 2m parameters) is corrected.

5 Simulations with prescribed errors

5.1 Dry initial conditions

In this section, the three previous experiments are repeated but they are initialized with low soil moistures (wilting point value at all levels) instead of the observed values. While this initial dry bias persists for a long time in the control, it should vanish progressively in the analysis experiments.

Figure 7 shows the evolution of the daily mean latent heat flux and of soil moisture in the 1 meter root zone as well as in level 4 of the land-surface scheme. As expected, the control remains much too dry during the whole integration so that the latent heat flux is strongly



a) HYDROLOGICAL BUDGET (MM) / CONTROL EXPERIMENT
UNPERTURBED [1/06/87–9/10/87]

b) HYDROLOGICAL BUDGET (MM) / NUDGING EXPERIMENT
UNPERTURBED [1/06/87–9/10/87]

c) HYDROLOGICAL BUDGET (MM) / OI EXPERIMENT
UNPERTURBED [1/06/87–9/10/87]

Figure 6: Time-integrated hydrological budget simulated by the 3 unperturbed experiments from 1 June to 9 October 1987 : a) control, b) nudging, c) OI. P, E, R and I stand for precipitation, evaporation, runoff and soil moisture increments respectively. The accumulated increments are represented by vertical bars. The observed soil moisture variation and evaporation are represented by black disks and circles respectively.

underestimated. On the contrary, the nudging and the OI runs add large amounts of water into the soil at the beginning of the integration and the root zone soil moisture converges towards the same solution as in the unperturbed experiments (Figure 5). After about two weeks, the OI is able to restore the correct soil moisture in the root zone, thereby producing realistic latent heat fluxes. In the deep soil, the moisture deficit remains very large in the nudging runs. The OI run is much more efficient, but due to the time scale of the water transfer between levels 3 and 4, it takes more than 4 months to compensate for the strong moisture deficit prescribed in the deep soil layer (which has a depth of 1.89 m).

5.2 Mispecification of the vegetation parameters

An important source of uncertainty at the Earth's surface in NWP and climate models is the definition of the vegetation parameters, whose distribution is sometimes poorly known on the global scale. Such uncertainties can have a double impact in NWP models since they can influence both the forecast and the soil moisture analysis. At Météo-France, the OI coefficients depend on the vegetation cover as well as on the ratio between LAI and R_{smin}. In the present study, the vegetation cover is the only parameter that is considered by both the nudging and the OI. Therefore, the effect of an extreme underestimation ($C_v = 8.7\%$ instead of 87%) of this fraction will be investigated. The experiments are the same than in section 4, with observed initial soil moistures but with a mispecified vegetation cover.

Figure 8 compares the daily mean latent heat flux and the soil moisture simulated by the 3 experiments to the field measurements. In the control, the low evaporation bias is even stronger than in the unperturbed experiment (Figure 5) since the evaporative fraction is smaller over bare ground than over relatively dense vegetation. The soil moisture is reasonably simulated since the deficit noticed in the unperturbed experiment is here partly compensated by the lower evaporation.

The nudging is rather close to the control simulation because the increments are directly proportional to the vegetation cover in the ECMWF operational analysis (equation 1) in order to avoid strong corrections in arid areas where soil moisture errors should be generally weak. The nudging is active and has a positive effect only during the dry spell in July when the increments become large despite the low value of C_v.

The OI run is the only experiment that is able to simulate a reasonable latent heat flux during most of the four months, though the evaporation is too low at the beginning and slightly overestimated around day 212. On the other hand, this is obtained with an overestimated soil moisture since the OI has to add a lot of water into the soil in order to compensate for the low evaporative fraction induced by the low vegetation cover. This result demonstrates that the OI cannot improve both turbulent fluxes and soil moisture if the vegetation parameters are poorly specified.

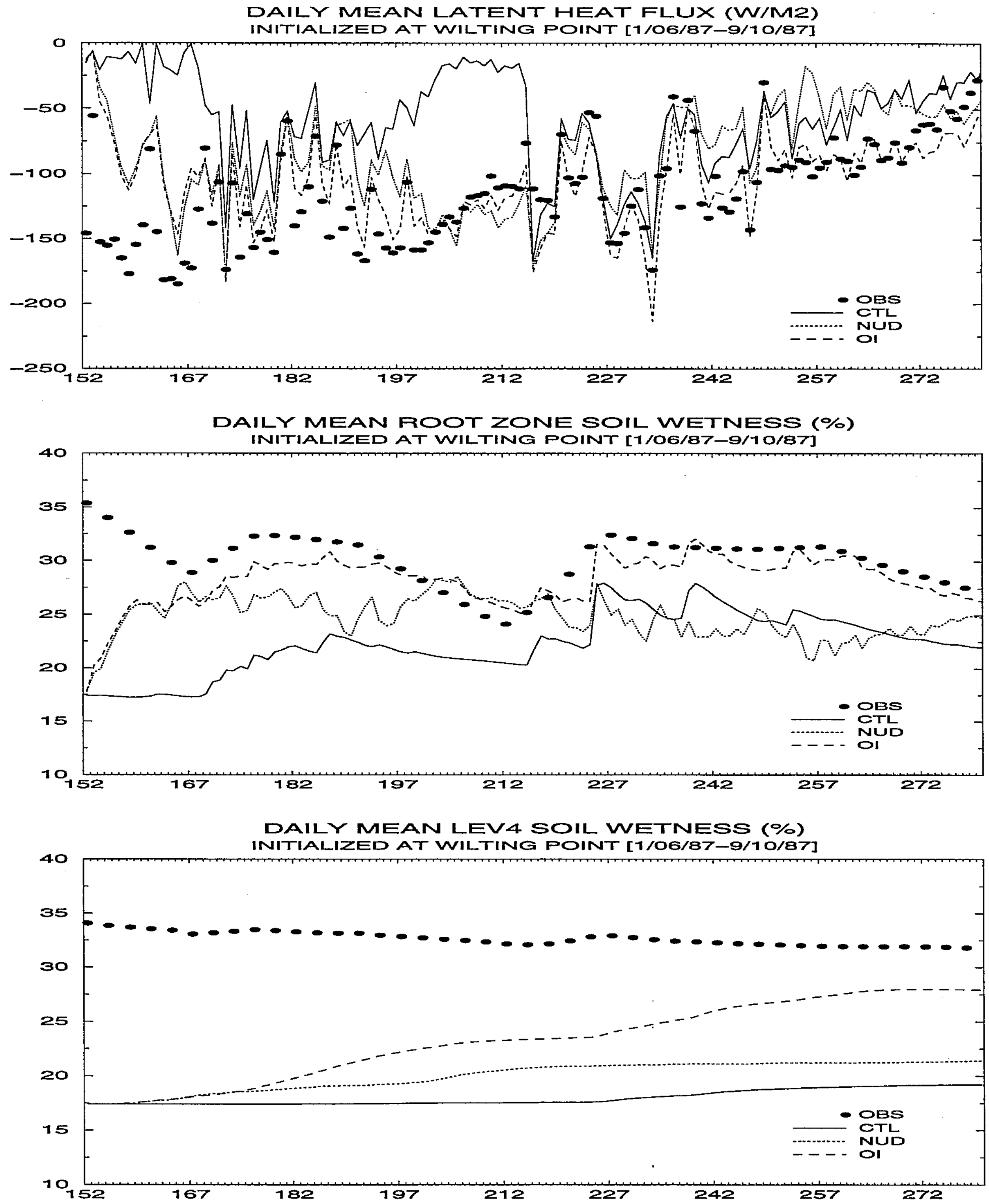
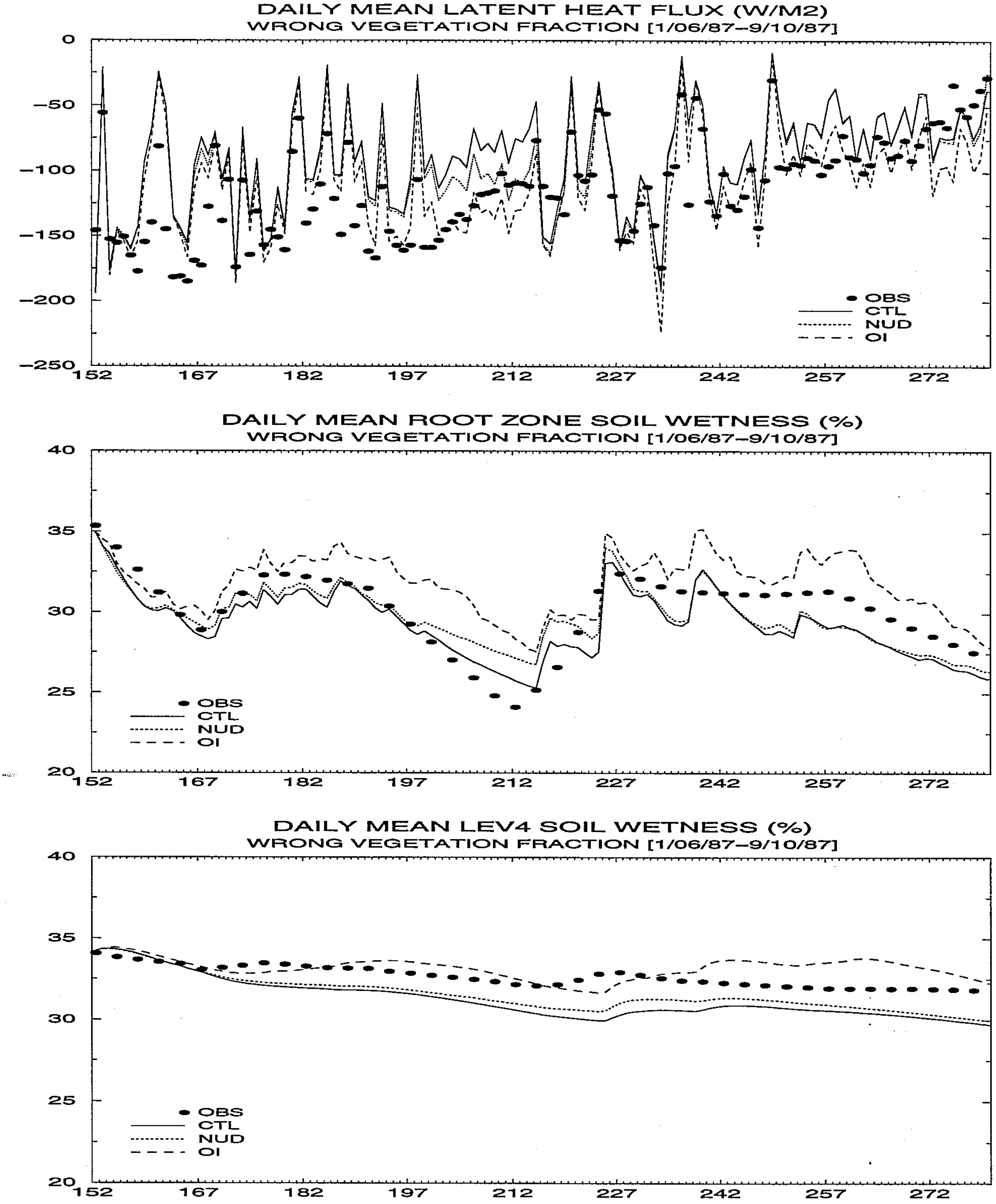


Figure 7: As in figure 5, but all the experiments are initialized at the wilting point (much drier than the observed soil moisture).


DAILY MEAN LATENT HEAT FLUX (W/M2)
WRONG VEGETATION FRACTION [1/06/87–9/10/87]

DAILY MEAN ROOT ZONE SOIL WETNESS (%)
WRONG VEGETATION FRACTION [1/06/87–9/10/87]

DAILY MEAN LEV4 SOIL WETNESS (%)
WRONG VEGETATION FRACTION [1/06/87–9/10/87]

Figure 8: As in figure 5, but all the experiments are performed with a mispecified vegetation cover (8.7% instead of 87%).

5.3 Biased precipitation forcing

The previous perturbed experiments were simple cases in which the "perturbation" was due either to the initial conditions or to the vegetation parameters. The atmospheric forcing is another, if not the most important, source of errors in 2m parameters predicted by NWP models. The consequences of errors in the precipitation forcing are examined first. In this experiment, as explained in section 3.2, the precipitation has been simply set to zero during the first half of the integration and multiplied by a factor of 3 in the second half (from day 213 to day 281). This crude experiment design is used to get a feel for the response of the analysis methods to model biases.

Figure 9 compares the errors in the 2m parameters. In the first half of the simulations, the warm bias found in the unperturbed experiments (Figure 4) is reinforced by the absence of precipitation. A dry bias also appears in specific humidity, which is even worse for relative humidity due to the overestimated temperature. These biases are weaker in the analysis experiments than in the control, and are particularly low at the end of July.

From day 213 onwards, the precipitation is overestimated by a factor of three. The specific humidity becomes too high. This wet bias is weaker for relative humidity which is also influenced by the warm bias. During this unrealistically large rainy period, the OI is close to the control experiment due to the counteracting effects of errors in temperature and relative humidity. Moreover, throughout the period the model is close to the field capacity and no corrections are performed beyond this value since soil moisture has no more impact on surface evaporation which takes place at an usntressed rate. The same rule applies for the nudging, but the nudging experiment has a lower soil moisture so that the analysis is still active. It decreases the errors in specific humidity to the detriment of the errors in temperature and relative humidity.

Figure 10 shows the hydrological budget of the three experiments. Note that the simulated soil moisture is reinitialized according to the observations on 1 August (day 213) in order to avoid a compensation between the biases prescribed before and after this date. As expected, the control experiment is much too dry during the first half of the simulation. Both analysis experiments tend to reduce this strong bias, but the results confirm that the OI performs better than the nudging for both evaporation and soil moisture. Between the beginning of June and the end of July, the variation of the total soil water content has been correctly estimated by the OI despite the prescribed zero precipitation. From day 213 onwards, the control is too wet but the bias is limited by the deep drainage and by the "internal" dry bias of the SCM noticed in the unperturbed experiment (Figure 6). As explained in the previous paragraph, the OI remains close to the control. The nudging experiment is too dry with too low evaporation and seems therefore to react too strongly to the errors in specific humidity. As previously discussed, these errors are probably influenced by the warm bias that allows the saturated atmosphere to hold more water than in the observations. Therefore, Figure 10 confirms the spurious behavior of the nudging, especially during the second half of the integration, as well as the consistent and robust behavior of the OI which is able to restore a reasonable soil water content in the

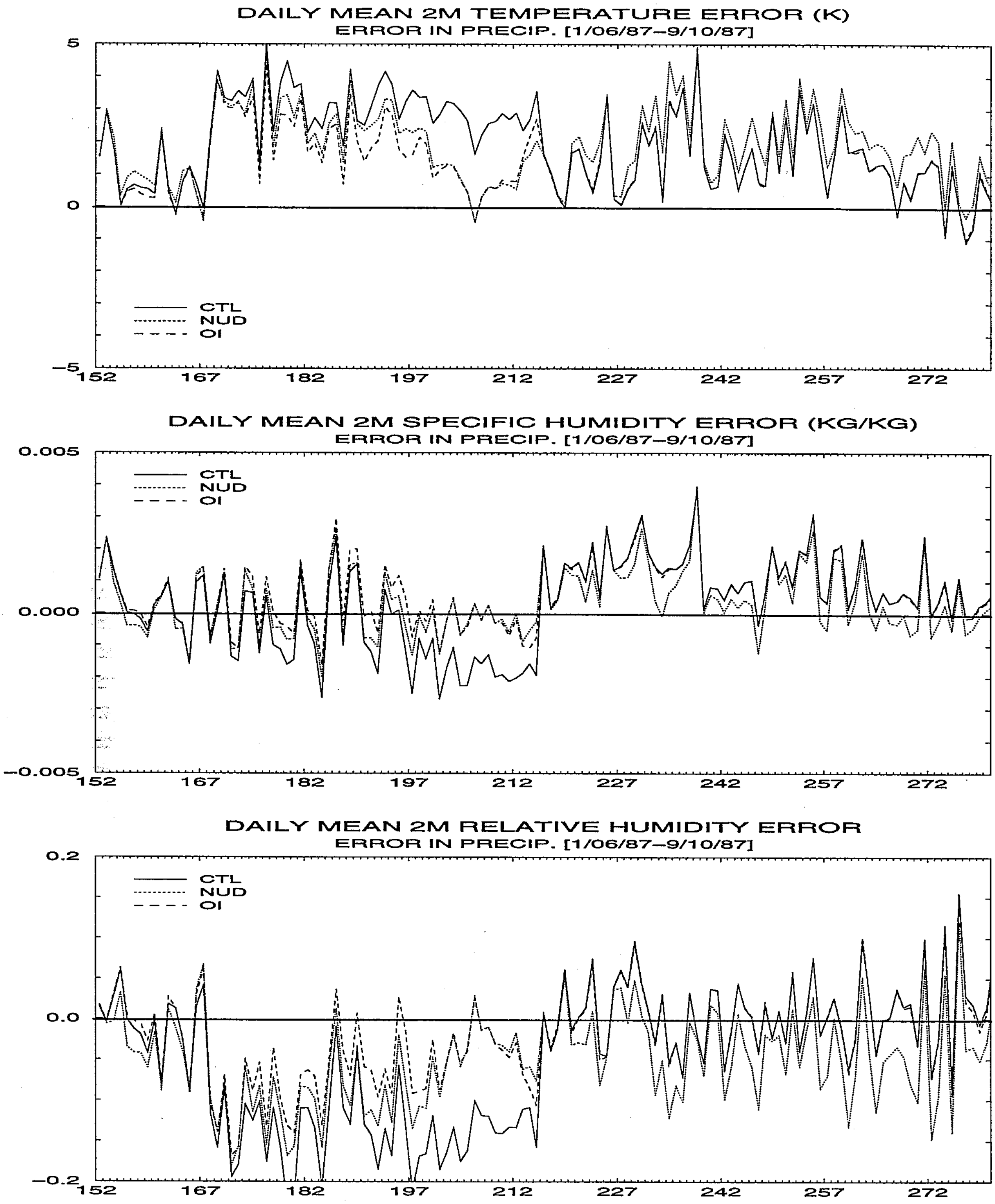


Figure 9: As in figure 4, but all the experiments are forced with biased precipitation.

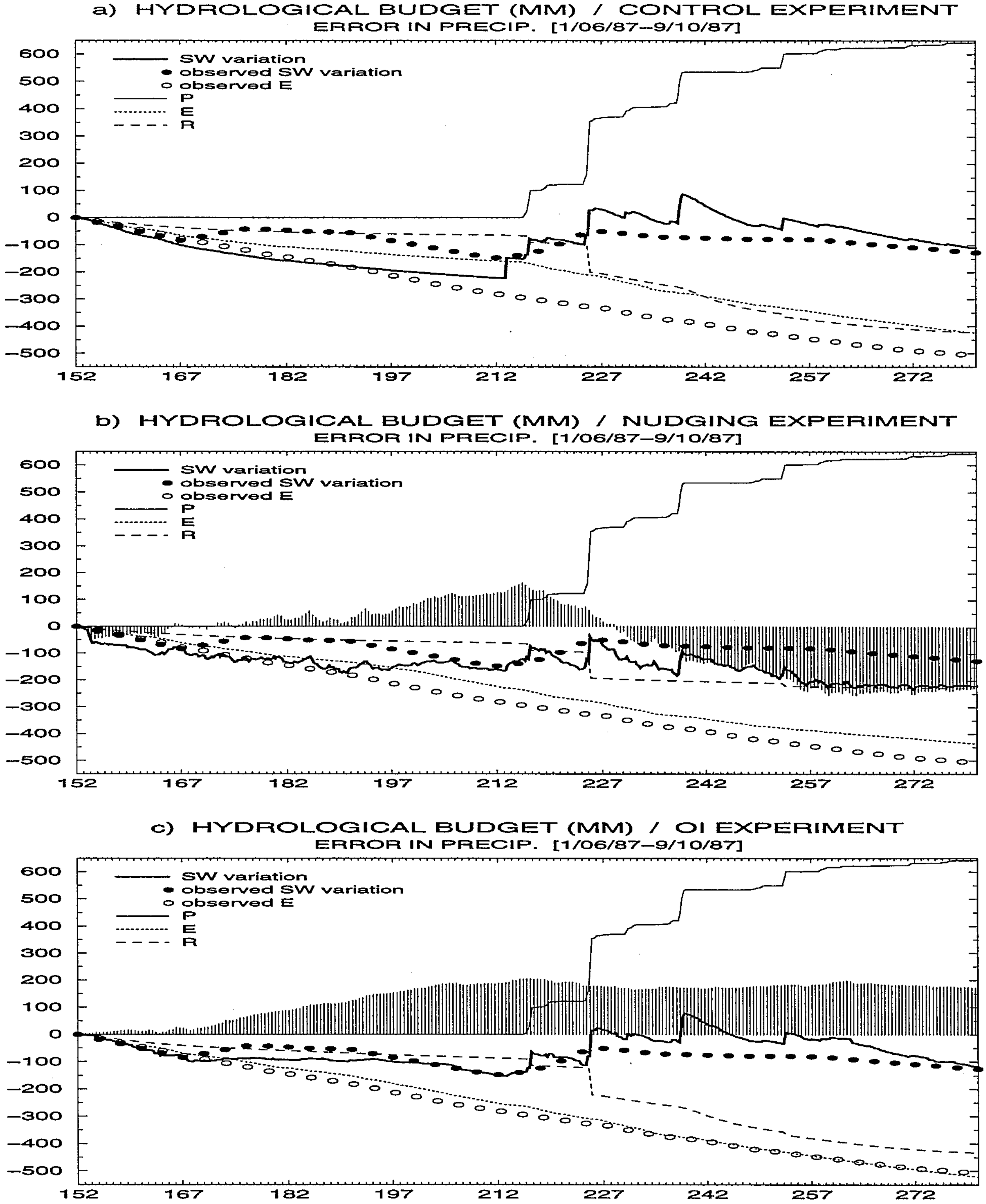


Figure 10: As in figure 6, but all the experiments are forced with biased precipitation. Note that soil moisture is reinitialized to the observed value on 1 August in order to avoid any compensation between the precipitation biases prescribed before and after this date.

total soil depth after a few weeks. This result demonstrates that the OI is likely to compensate efficiently for large precipitation errors in NWP models.

5.4 Biased solar radiation forcing

The last experiment is probably the most difficult test for the soil moisture analysis, especially for the OI. During the first half of the integration, the solar radiative forcing is increased by 25%, while for the second half it is decreased by 25This influences the 2m parameters through evaporation but has also a direct radiative impact on the 2m temperature. Therefore, the 2m temperature errors contain an additional information that could be misleading for the OI analysis, while the nudging could be more robust due to the use of specific humidity errors only.

The errors in the 2m parameters are compared in Figure 11. The warm bias of the model is increased by the radiative bias in the first half of the integration and reduced in the second half. Comparison with Figure 4 indicates that the errors in specific humidity are not much influenced by the radiative biases, whereas the errors in relative humidity are more sensitive. As previously noticed with the biased precipitation forcing, the OI is mainly active during the first half of the simulation, due to the balance between the errors in 2m temperature and relative humidity after day 213. The nudging improves the forecast of specific humidity to the detriment of the other 2m parameters during the second half. Both methods perform well during the dry spell in July.

The hydrological budget is illustrated in Figure 12. In June, the control experiment is too dry but the surface evaporation is fairly consistent with the observations. This is mainly due to the 25% overestimation in the downward solar radiation, which allows the extraction of more water from the soil. Due to the increasing drying of the soil, the evaporation becomes too low during the dry spell in July (which is more obvious when looking at the daily mean latent heat flux). The usual drift towards dry conditions appears during the second half of the simulation, but it remains limited since the downward solar radiation is decreased by 25%. The nudging is close to the control in June. Efficient positive corrections appear in July, but the simulation becomes much too dry after day 213. The OI is too wet in July because it compensates for the direct impact of increased solar radiation on temperature. Due to the balance between the errors in 2m temperature and relative humidity, the OI increments are weak after day 213, and the model is slightly too dry.

These results point out the shortcomings of the OI technique, which uses 2m temperature and relative humidity to drive the soil moisture analysis, and is therefore sensitive to radiative biases. This spurious behavior would not occur in a "perfect" model, but it must be alleviated in the operational framework of NWP models. Possible improvements to the OI soil moisture analysis are discussed in the following section.

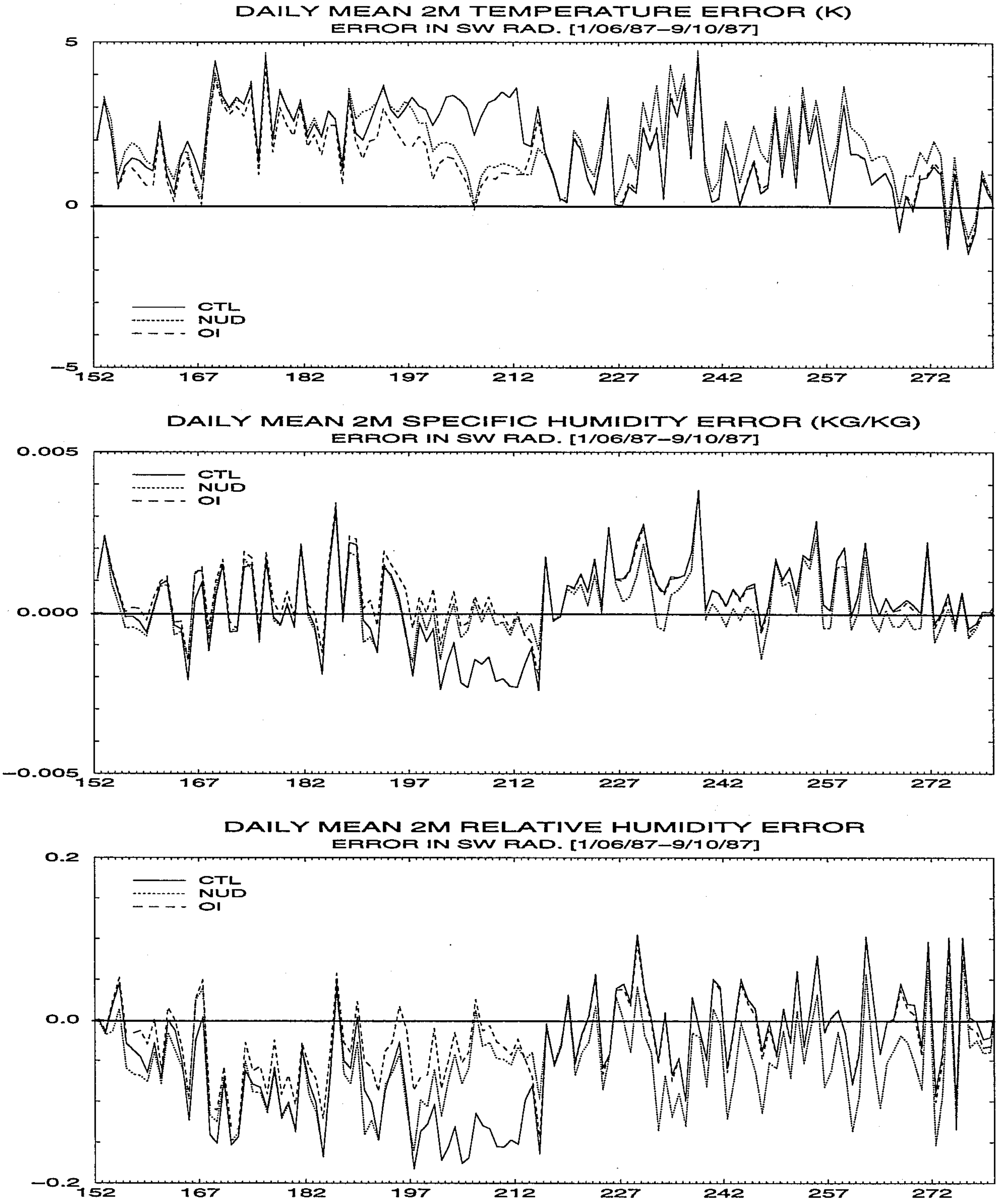


Figure 11: As in figure 4, but all the experiments are forced with biased solar radiation.

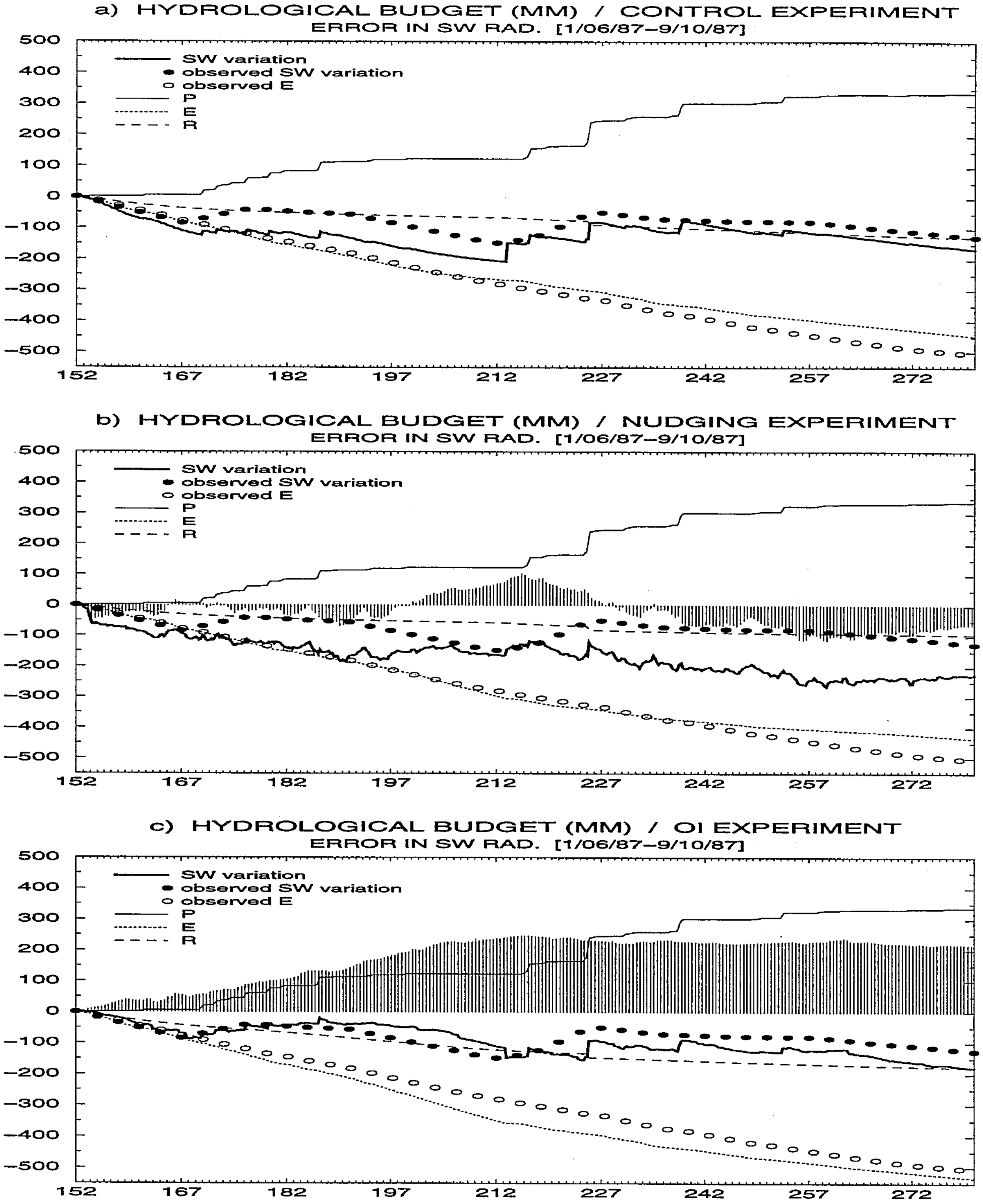


Figure 12: As in figure 6, but all the experiments are forced with biased solar radiation. Note that soil moisture is reinitialized to the observed value on 1 August in order to avoid any compensation between the precipitation biases prescribed before and after this date.

6 Possible improvements to the OI analysis

6.1 Soil temperature analysis

The first possibility that can be explored in order to reduce the 2m temperature biases which are not associated with errors in soil moisture is to perform a soil temperature analysis besides the soil moisture analysis. The OI technique could have been used for that purpose but, in this preliminary study, the soil temperature increments are only expressed as a fraction of the 2m temperature errors :

$$Ts_i^a = Ts_i^f + (1 - F_1) \times \mu_i \times (T^a - T^f) \tag{2}$$

where Ts_i^a and Ts_i^f are the analysed and first guess values of the soil temperature at level i, and μ_i is set to 1, 0.1, 0.01 and 0 from level 1 to level 4 respectively. A similar approach has been proposed by Urban et al. (1985) and Coiffier et al. (1987); The decrease on the coefficients with depth represents a reduced model influence of errors in deeper soil temperatures on the near-surface temperature. T^a and T^f are the analysed and forecast 2m temperature, as explained in section 2.3. F_1 is the empirical function which has been introduced in section 2.3 in order to have a diurnal and seasonal dependency in the soil moisture analysis. The soil temperature corrections are weighted by $(1 - F_1)$ so that the temperature analysis is more effective during the night and in winter, when the 2m temperature errors are not related to soil moisture. In this way, 2m temperature errors are not used to correct soil moisture and soil temperature at the same time.

Measurements of soil temperature at 10 and 50 cm below the surface have been collected during the FIFE field experiment. They can be compared to the temperature of levels 2 and 3 of the ECMWF model, though these levels are more representative of the soil temperature at 17 and 64 cm below the surface respectively. Figure 13 shows the evolution of these temperatures for the control experiment and two OI experiments in the framework of observed ISW and atmospheric forcing (results presented in section 4). Though very simple, the soil temperature analysis allows a reasonable fit between predicted and observed values. While the control experiment and the OI with no temperature analysis (OI1) exhibit a warm bias in the soil (in agreement with the 2m temperature bias), the OI including the temperature analysis (OI2) is much more consistent with the observations. There is now a slight cold bias at level 2, but it might be due to the fact that the model temperature corresponds to a larger depth (17 cm) than the observations (10 cm).

As expected, the soil temperature analysis gives a reduction in the errors of 2m temperature (Figure 13). However, this reduction is not very strong and does not have a large impact on the soil moisture analysis. The soil moisture increments are generally slightly weaker than the ones that had been obtained without the soil temperature analysis. The OI remains in reasonable agreement with the observations when the atmospheric forcing is not perturbed, as well as when a bias is prescribed in the precipitation forcing (not shown). The results are slightly

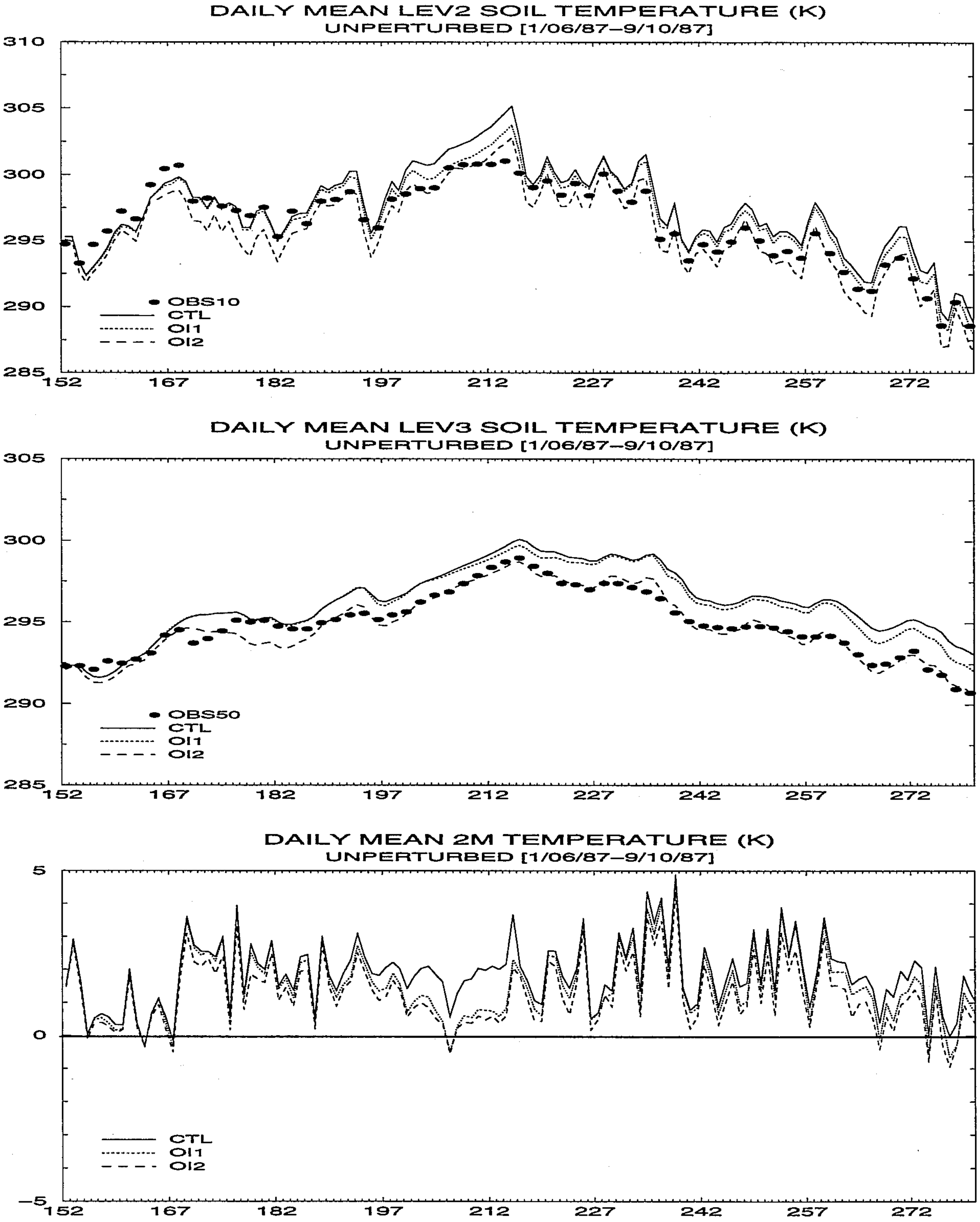


Figure 13: Evolution of the daily mean soil temperatures (K) at levels 2 and 3 (compared with observations at 10 and 50 cm below the surface respectively). Also shown is the simultaneous evolution of the daily mean errors in the 2m temperatures. Three unperturbed experiments are compared : CTL (no soil moisture analysis), OI1 (OI soil moisture analysis), OI2 (OI soil moisture analysis as well as soil temperature analysis).

improved in the simulation forced with the biased solar radiation (not shown). This result confirms that the soil temperature analysis enables the spurious impact of radiative biases on the soil moisture analysis to be reduced. However, the impact is not sufficient to eliminate this problem.

6.2 Filtering of the 2m increments

An additional modification can be introduced in the OI technique in order to avoid spurious corrections due to systematic biases in either the ECMWF land surface scheme or the atmospheric forcing. Every 6 hours, the instantaneous increment of X (2m temperature or relative humidity), $\Delta X = X^a - X^f$, can be replaced by a filtered increment in which an average error is substracted. The average error, ΔX_m, is initialized at a zero value at the beginning of the simulation and is then updated at each analysis cycle :

$$\Delta X_m = \lambda \Delta X + (1 - \lambda) \Delta X_m$$

The effective or filtered increment can be written :

$$\Delta X_e = \Delta X - \Delta X_m$$

The empirical coefficient λ of this simple high pass filter has been set to $0.02 \times F_1 \times F_2$ where F_1 and F_2 are the empirical functions introduced in section 2.3. This technique is quite different from the method used at Météo-France (Giard and Bazile 1998), in which $\lambda = 0.5$ and the relative humidity increments are not filtered. It filters out the low frequency biases which affect the 2m increments during the periods of strong solar radiation, when the soil moisture analysis is performed. However, the filter can have the detrimental side-effect of failing to correct a slow drift in soil moisture.

This alternative method has been tested both with observed atmospheric forcing and biased solar radiation. The experiments will be referred to as OI3. Figure 14 compares the results of the observed forcing experiment with the corresponding control simulation and the initial OI experiment (referred to as OI1). The main impact of the filtering on the daily mean latent heat flux appears during the dry spell in July. As expected, OI3 is better than OI1 which overcompensates the dry bias found in the control experiment because of the systematic warm bias of the model. A similar reduction in evaporation is found in September but does not appear like a real improvement of the simulation. In keeping with the change in evaporation, the root zone soil moisture is better predicted in June and July but is not as good as in OI1 in August and September. This result demonstrates that the filtering implemented in OI3 might be useful to deal with systematic errors in the 2m parameters, but it might also mask a drift in the simulated soil moisture. The hydrological budget of experiment OI3 confirms the slight drying occuring during the second half of the integration and clearly shows that the soil moisture increments are much weaker than in experiment OI1 (Figure 6c).

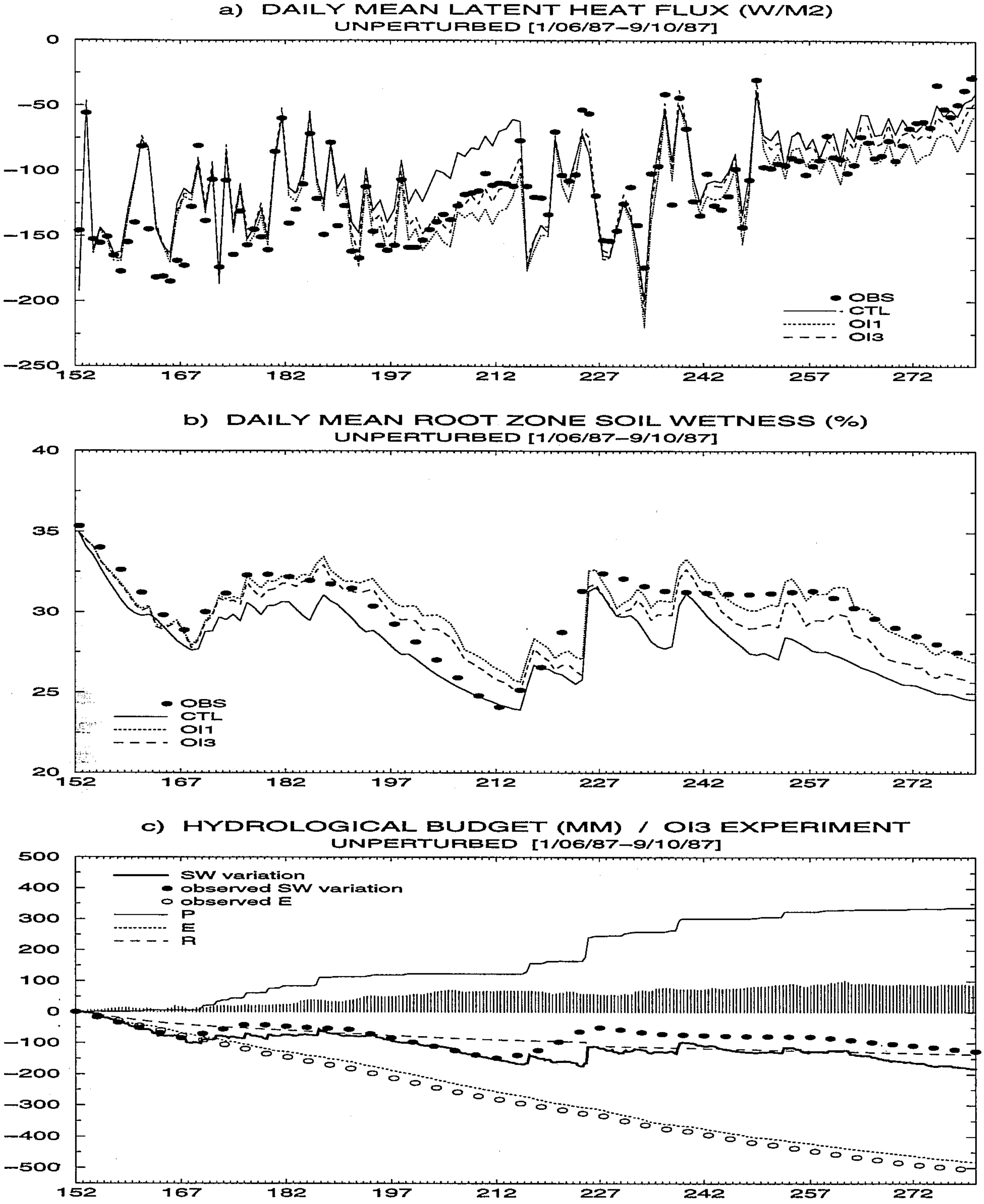


Figure 14: Comparison between the control experiment, the OI soil moisture analysis (OI1) and the modified OI soil moisture analysis (OI3 including the temperature analysis and the filtering) using the unperturbed precipitation and radiative forcing : a) daily mean latent heat flux (W/m^2), b) root zone volumetric soil moisture (%), c) hydrological budget simulated by OI3 (CTL and OI1 are displayed in figure 6).

Figure 15 illustrates the results of the experiments using a biased solar radiation forcing. Again, the filtering has a positive impact on the latent heat flux during the dry spell in July, when the warm bias of the model is reinforced by the overestimated solar radiation. From day 213 onwards, the impact is negligible since the warm bias is counterbalanced by the underestimated solar radiation so that the average systematic bias is rather small. Therefore, the overall performance of experiment OI3 is better than the results of OI1, both for evaporation and soil moisture. A comparison between Figures 12c and 15c confirms the significant reduction of the soil moisture corrections.

7 Conclusions

The ECMWF single column model (SCM) has been used to emulate atmospheric data assimilation and soil moisture analysis on the ERA grid point closest to the site of the FIFE field experiment. The model is cycled on a 6-hourly basis during a 4-month period from 1 June to 9 October 1987. Every 6 hours, the atmospheric profile is updated using the ERA and the soil moisture analysis is performed, using either the operational ECMWF routine (nudging) or an alternative optimum interpolation (OI) technique.

Though not described in the present study, the atmospheric profiles produced by the SCM have been compared to the ERA, showing a reasonable behavior of the model. In all the experiments, the simulated precipitation and downward radiative fluxes have been replaced by the observed fluxes at the Earth's surface in order to force the ECMWF land surface scheme. However, it was checked that the simulated fluxes were consistent with the observations. The agreement was remarkably good for precipitation since both the temporal distribution and the average intensity of the rainfall events were very well predicted. These results gave strong confidence in the SCM as a very useful tool which is much less expensive than a global 3D model.

The present study indicates that the current ECMWF nudged soil moisture analysis is able to restore the model soil water content towards realistic values during a prolonged dry spell like the one occuring in Kansas in July 1987. The nudging is therefore likely to avoid a large drift in summer or dry season conditions. However, only the errors in specific humidity (at the lowest model level in the ECMWF operational model, at the screen-level in the present study), are used to compute the soil moisture corrections, so that the method is very sensitive to model biases. The corrections are performed day and night and, as suggested by Betts et al. (1998 a and b) and Douville et al. (1998), the nudging is strongly influenced by any bias in the diurnal cycle of the boundary layer. For this reason, its behavior is sometimes chaotic and its performance can be poor, especially in wet or rainy conditions.

The OI technique produces smoother increments and generally performs much better than the nudging, due to the use of errors in both 2m temperature and relative humidity and the careful selection of suitable meteorological conditions for the analysis. Table 2 summarises the

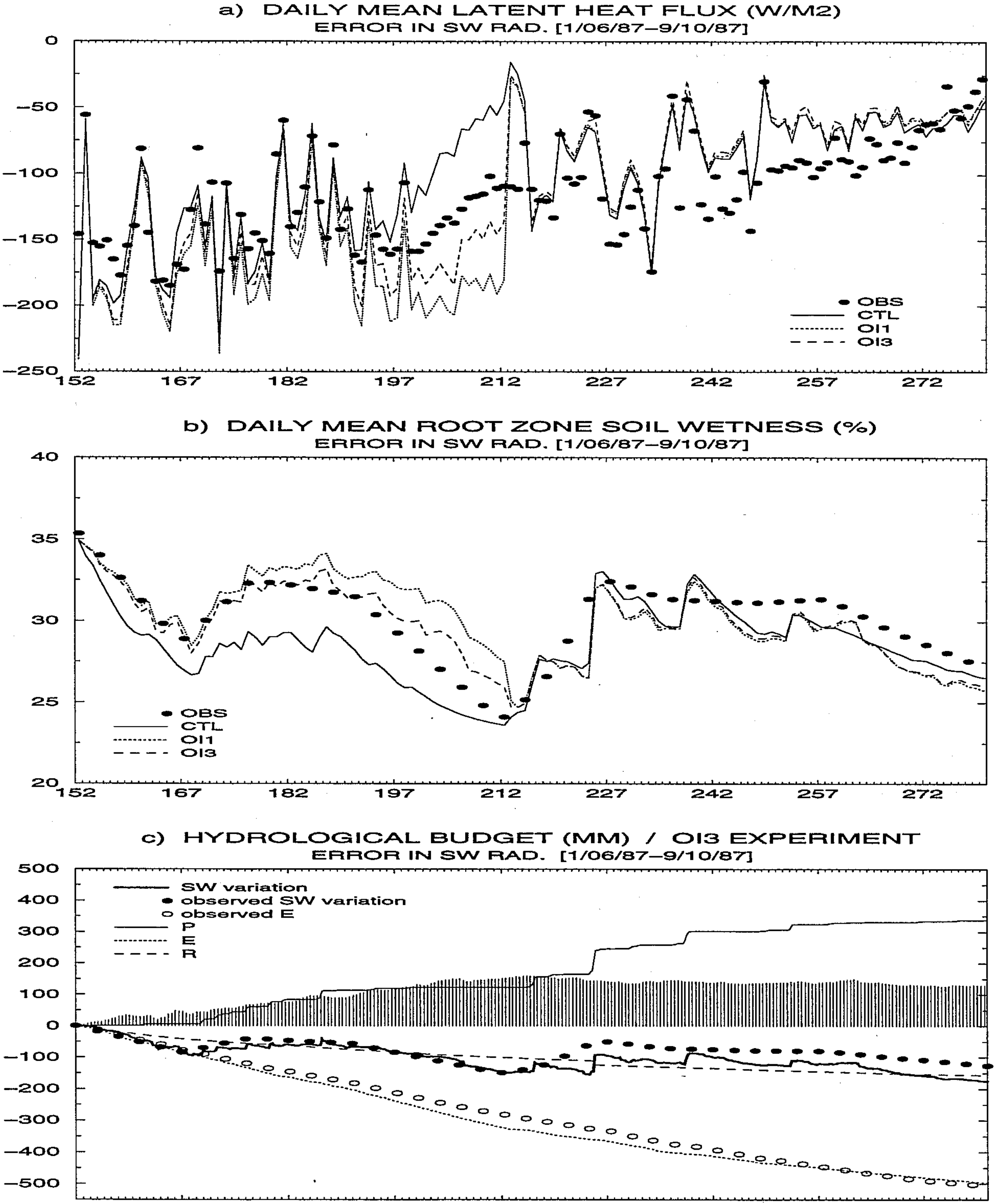


Figure 15: As in figure 14, but all the experiments are forced with biased solar radiation (the hydrological budget of OI3 must be compared to the hydrological budgets of experiments CTL and OI1 displayed in figure 12.

statistics (bias and rms) of the errors in the 2m parameters for the various experiments using the observed precipitation and radiative forcing. As indicated by bold characters, the minimum bias and rms values are generally produced by the OI simulations, mainly by the experiment using filtered 2m increments and a simple soil temperature analysis. The good results of the OI technique are also obvious for the simulations forced with a biased solar radiation, presented in Table 4. However, from Table 3 the OI's superiority does not appear as clearly for the simulations forced with biased precipitation as far as the 2m parameters are concerned, but it was shown in section 5 that the method is able to compensate for the strong biases prescribed in the rainfall rate. The OI also enables the correction of a dramatically wrong soil moisture initialization in a few weeks, and is robust enough to resist an obvious mispecification of the vegetation properties.

However, as suggested by the preliminary study of Hu and al. (1998), the OI analysis remains sensitive to radiative biases. It can wrongly modify soil moisture to give good estimates of the sensible heat flux but poor estimates of the latent heat flux, due to the impact of the radiative biases on the 2m temperature. There is no easy solution to this problem, but it can be mitigated by various modifications of the OI technique. First, the implementation of a soil temperature analysis, besides its intrinsic interest, enables the spurious impact of radiative biases on the soil moisture analysis to be reduced. The filtering of the low frequency component of the errors in the 2m parameters has a similar impact. However, it might be dangerous if the model soil moisture exhibits a slow drift, as this can be masked by this filter. One expects the soil moisture analysis to correct both a low-frequency drift and the high frequency errors related to the poor prediction of the precipitation events.

A possible compromise would be to filter the 2m increments to correct soil moisture in levels 1 and 2 which are strongly influenced by the precipitation, but to use the full increments to correct soil moisture in level 3 which might be more sensitive to a drift associated with a poor estimation of the deep drainage. Moreover, the standard deviations of the forecast errors in soil moisture could have a non uniform vertical distribution so that the corrections would decrease from level 1 to level 3, since any error in the atmospheric forcing should have a stronger impact on the surface than on the deep soil layers. These modifications were tested in perturbed and unperturbed OI experiments and the results (not shown) are basically a compromise between experiments OI1 and OI3.

The best response to the problem of radiative biases would be to implement a cloud analysis. Thanks to the introduction of the empirical function F_2, the soil moisture is not modified by the OI if the model predicts a high cloud cover. On the other hand, the OI is active if the model predicts low cloud cover regardless of the real cloudiness. In this situation, the surface solar radiation may exhibit significant biases, as strong as the 25% errors introduced in these experiments. A cloud analysis based on SYNOP data would allow one to detect poor cloud forecasts, for which the soil moisture analysis could be switched off.

The OI soil moisture analysis described in the present study will replace the current nudging technique in the ECMWF NWP model in a near future. A similar analysis is already used

2m variables	T	(K)	q	(g/kg)	RH	(%)
Statistics	bias	rms	bias	rms	bias	rms
Control / day	1.25	1.42	**-0.13**	1.44	-4.7	5.3
Control / night	2.55	1.78	1.03	1.90	-3.6	**11.8**
Nudging / day	1.47	1.53	-0.35	1.42	-6.4	5.9
Nudging / night	2.62	1.73	1.04	1.89	-4.1	12.5
OI1 / day	0.85	1.48	0.27	**1.32**	**-2.0**	5.3
OI1 / night	2.22	1.50	1.21	1.94	-1.3	14.7
OI3 / day	**0.81**	**1.41**	0.15	1.33	-2.1	**5.2**
OI3 / night	**1.83**	**1.34**	**1.00**	**1.82**	**-0.7**	14.1

Table 2: Day and night mean biases and rms of the errors (model minus observation) in the 2m parameters for the various experiments using the observed precipitation and radiative forcing : temperature (K), specific humidity (g/kg) and relative humidity (%); OI1 refers to the basic OI analysis while OI3 refers to the OI analysis using filtered 2m increments and a soil temperature analysis; the minimum bias and rms values are emphasised by bold characters.

2m variables	T	(K)	q	(g/kg)	RH	(%)
Statistics	bias	rms	bias	rms	bias	rms
Control / day	1.30	1.79	-0.19	1.78	-4.5	8.9
Control / night	2.57	1.45	**0.95**	2.25	-3.4	19.7
Nudging / day	1.34	**1.56**	-0.23	1.45	-5.5	**6.5**
Nudging / night	2.49	1.56	1.07	**1.96**	-3.2	**14.8**
OI1 / day	0.83	1.59	0.28	**1.41**	**-1.7**	6.6
OI1 / night	2.17	1.37	1.21	2.06	-0.8	18.0
OI3 / day	**0.82**	**1.56**	**0.13**	1.51	-1.9	7.1
OI3 / night	**1.86**	**1.21**	0.99	2.07	**-0.5**	18.5

Table 3: As in Table 1 but for the experiments using a biased precipitation forcing.

2m variables	T	(K)	q	(g/kg)	RH	(%)
Statistics	bias	rms	bias	rms	bias	rms
Control / day	1.14	1.85	-0.16	1.64	-4.0	7.8
Control / night	2.51	1.41	0.95	2.04	-3.4	16.1
Nudging / day	1.34	1.65	-0.35	1.44	-6.0	6.3
Nudging / night	2.53	1.38	1.01	1.87	-3.9	14.2
OI1 / day	0.75	**1.64**	0.23	**1.34**	-1.8	**6.0**
OI1 / night	2.17	**1.36**	1.17	1.85	-1.4	14.7
OI3 / day	**0.52**	1.75	**0.08**	1.36	**-1.3**	7.3
OI3 / night	**1.41**	2.71	**0.73**	**1.21**	**-0.8**	**12.0**

Table 4: As in Table 1 but for the experiments using a biased downward solar radiation forcing.

operationally at Météo-France and gives satisfactory results. The implementation in a 3D model requires an efficient analysis of screen-level temperature and humidity. A preliminary version of such an analysis has been recently developed at ECMWF and tested off-line in order to compute statistics about the 2m temperature and relative humidity errors in the ECMWF model (Douville et al. 1998). Some comparisons with in situ observations show the accuracy of this 2m analysis in areas with a dense network of SYNOP observations. In some specific areas (very sparse network, coastlines and mountainous regions), it might be wise not to use the soil moisture corrections until the 2m analysis has been further validated and can deal with the land-sea contrasts and the uncertainties related to orography. Further work is also needed to specify the OI coefficients on the global scale, and particularly the standard deviation of the forecast errors in soil moisture, which probably have both a geographical and seasonal distribution.

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