Soil moisture assimilation using satellite derived surface fluxes

Bart van den Hurk, KNMI, PO Box 201, 3730 AE De Bilt, The Netherlands, email: hurk@knmi.nl

1. Introduction

Treating soil moisture in Numerical Weather Prediction (NWP) models as a prognostic variable introduces the risk of serious model drifts, as errors in the model's parameterization of the hydrological cycle tend to accumulate in the soil moisture reservoir.

Attempts to control soil moisture drift using observations of near surface quantities have been developed and reported by Mahfouff (1991) and Bouttier *et al.* (1993a, b). Since then, various meteorological institutes have introduced a (semi-)operational soil moisture assimilation scheme based on observed near-surface quantity biases (e.g. Viterbo and Courtier, 1995; Giard and Bazile, 1996; Rhodin *et al.*, 1997).

Additional information on soil moisture may be provided by various types of satellite data. Houser *et al.* (1997) tested various data assimilation methods for combining remotely sensed microwave data into an atmospheric model. Calvet *et al.* (1998) derived an assimilation scheme to transport information on top layer soil moisture towards deeper layers. Jones *et al.* (1997) use surface heating rates as observed from geostationary satellites for soil moisture corrections.

Van den Hurk *et al.* (1997) use the variability of surface temperature and surface albedo to calculate surface energy balance components from satellite images. Their work is based on the so-called Surface Energy Balance Algorithm for Land (SEBAL), developed by Bastiaanssen (1995) and co-workers. They successfully applied the SEBAL algorithm to adjust surface evaporation rates over the Iberian peninsula during the first week of July 1994 in a limited area atmospheric model called RACMO (Christensen and van Meijgaard, 1992). Soil moisture corrections induced by differences between RACMO and SEBAL surface evaporative fractions were compatible with RACMO errors of near surface temperature and specific humidity, indicating that SEBAL as applied there contains useful information on turbulent surface fluxes.

In this paper, a description is given of subsequent activities of combining SEBAL and RACMO evaporative fraction calculations. In the next section, a brief description is given of the working principle of SEBAL, followed by a few results of the Iberian test case. These are followed by the description of a new test case and modifications to the SEBAL algorithm. After evaluating some preliminary results, directions for future research are listed.

2. The SEBAL algorithm

SEBAL is designed as an algorithm for a pixelwise solution of all components of the surface energy balance equation with a minimum of in situ observations. Instead, a certain degree of empiricism is allowed, combined with an explicit use of the horizontal variability of the surface temperature and surface albedo. Downward shortwave and longwave radiation components are calculated using a (given) constant atmospheric transmissivity and an empirical function of air temperature, respectively. Soil heat flux G is calculated as fraction of net radiation depending on (among others) Normalised Difference Vegetation Index (NDVI).

Surface sensible heat flux is calculated from a series of steps. The first step is to make a scatterplot of the surface albedo vs the surface temperature (figure 1a). When applied to a limited area, such a scatterplot often shows an evaporation controlled branch, where surface temperature increases as evaporation decreases, and a radiation controlled branch for pixels where evaporation LE can be assumed zero. There an increase of albedo α leads to a decrease of available energy $Q_* - G$ (Q_* being net radiation), and thus of a decrease of sensible heat flux H, shown as a decrease of surface temperature.

For these dry pixels the derivative of H with respect to surface temperature T_s can be written as

$$\frac{\partial H}{\partial T_s} = -K\frac{\partial \alpha}{\partial T_s} - \frac{\partial L^\uparrow}{\partial T_s} - \frac{\partial G}{\partial T_s} = \rho c_p \left[\frac{1}{r_a^{dry}} + \Delta T^{dry}\frac{\partial}{\partial T_s}\frac{1}{r_a^{dry}}\right] \tag{1}$$

where ρ is the density of dry air, c_p the specific heat of dry air, K is the downward shortwave radiation, $L^{\uparrow}$ the upward longwave radiation and r_a^{dry} the characteristic aerodynamic resistance for the dry pixels. ΔT^{dry} can be calculated once a given reference temperature T_a is specified.

In the wet extreme (that is, the cool pixels with low albedo values) it is assumed that all available energy is used for evaporation, $H = 0$. Then, by definition the vertical temperature gradient can be set to zero.

The next, crucial step is to specify a linear relation between the surface temperature and the vertical temperature gradient ΔT (figure 1b). This relationship implicitly assumes that variations of T_a are small compared to variations in T_s, and follow the surface temperature variations in a consistent damped manner.

Finally, latent heat LE is calculated as a residual term in the surface energy budget equation.

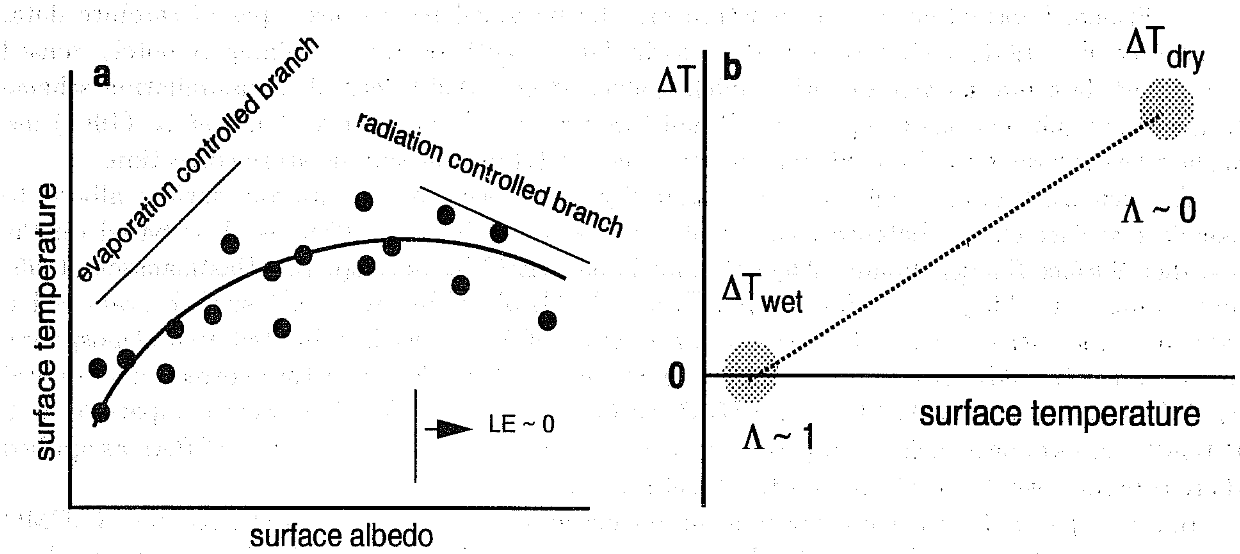

Figure 1: (a) principle of evaporation and radiation controlled branch in scatterplot of surface albedo vs surface temperature, and (b) quasi-linear representation of ΔT as function of satellite derived surface temperature T_s. The encircled areas represent the special cases for $LE = 0$ (right) and $H = 0$ (left).

3. Description and results of a preliminary test case

As a first attempt to evaluate the applicability of SEBAL for soil moisture assimilation in RACMO, a small test case was designed. Simulations were carried out for the Iberian peninsula during the first week of July 1994. Two sequences of RACMO runs were started from a similar soil moisture field for 1 July, generated by forcing RACMO to calculated evaporative fractions close to a SEBAL estimate. In one of the sequences, the *control* no further adjustment of soil moisture was carried out anymore. In the *experimental* run soil moisture was also adjusted using two later SEBAL estimates.

Figure 2 shows results of temperature and specific humidity bias of the two sequences of runs. The *experimental* run succesfully avoids a positive temperature bias shown in the control run, and also produces smaller specific humidity biases. An extensive description of the test case and the results is given by Van den Hurk *et al.* (1997).

4. A new test case, and modifications to SEBAL and RACMO

Inspired by these preliminary results, a new, more extensive test case was designed. This time, the target is a complete growing season for the entire European domain. The period between 1 March and 15 November 1995 was selected.

As described above, SEBAL is designed as a *regional* retrieval algorithm. Many of the underlying assumptions impossibly hold when the target area is increased to the European scale. Therefore, some modifications were applied to SEBAL.

The baseline of the modifications was to replace as much as possible assumptions about forcings

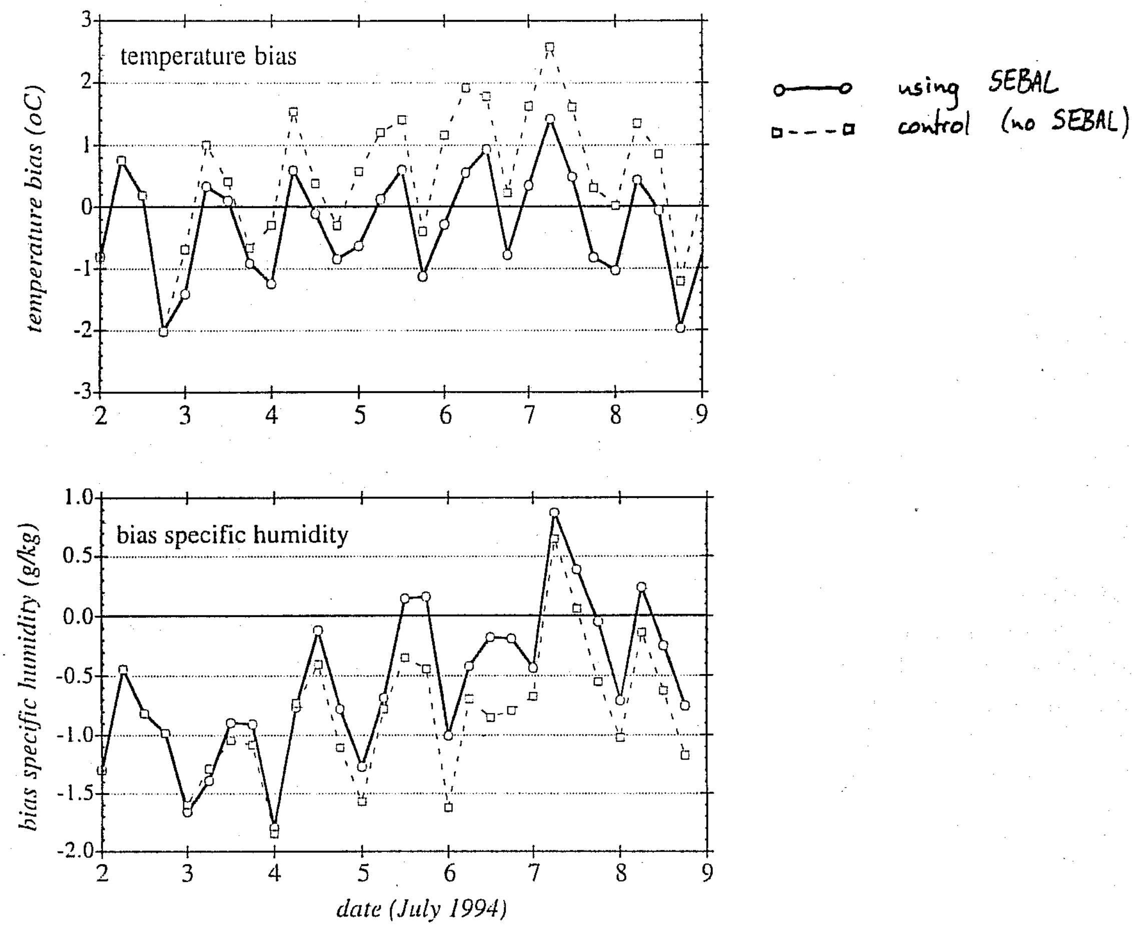

Figure 2: Bias of 2m temperature (top) and specific humidity (bottom) for the control run (dashed lines) and the run with soil moisture updated using SEBAL evaporation estimates (solid lines). Shown are +24 - +42 hour forecasts for the Iberian peninsula in the period 2 - 8 July 1994.

and empirical formulations by RACMO first guess calculations. The first group of modifications concerns the direct use of RACMO clear sky shortwave turbidity and downward longwave radiation as radiative forcing. Furthermore, assumptions about constant wind speed and reference temperature are replaced by RACMO values at the lowest model level, approximately 30m high.

The second modification is the replacement of the SEBAL principle of anchoring extremes of the evaporation regimes by a *pixelwise calculation of surface sensible heat flux.* This avoids the determination of r_a^{dry} and the empirical regression between surface temperature and ΔT. The price to be paid is the need to specify a turbulent exchange coefficient C_H, used to calculate H from $T_{a,RACMO} - T_{s,sat}$. C_H is a function of the roughness length for momentum z_{0m}, the roughness length for heat z_{0h}, and atmospheric stability. Recently, Chen *et al.* (1997) succesfully applied a formulation of z_{0m}/z_{0h} as function of the turbulent Reynolds number Re:

$$\frac{z_{0m}}{z_{0h}} = exp\left(\kappa C\sqrt{Re}\right) \tag{2}$$

in which Re is given by $u_* z_{0m}/\nu$, u_* being the friction velocity and ν the kinematic molecular viscosity of air. κ is the Karman constant, and C an empirical coefficient. Chen *et al.* (1997) found good results with $C = 0.1$.

We have adopted this formulation for use in SEBAL. For z_{0m} at the satellite pixel scale, we used an empirical regression on NDVI, while u_* was calculated from RACMO first guess wind speed.

NOAA AVHRR satellite data were available for 15 days between 23 March and 15 November 1995. Until now, first results have been prepared for data collected on 23 March and 2 April. From the satellite observations in the 5 spectral regions of the AVHRR sensors, cloud-free georeferenced images of broad band surface albedo, NDVI, and surface temperature (corrected for atmospheric effects using a split window technique) were prepared.

In RACMO, the original surface scheme consisted of a single soil moisture reservoir. This scheme was replaced by the 4-layer soil scheme from the ECMWF model (Viterbo and Beljaars, 1995).

A sequence of RACMO runs was initiated on 1 March 12 UTC, with soil moisture set to field capacity. Every day at noon a new 48-hour run was started from ECMWF analyses. Soil moisture was treated as a prognostic variable. No further adjustments to soil moisture were employed. The complete seasonal cycle showed a clear increase of the near-surface temperature and humidity biases from May onwards, reducing to small values again in Autumn (not shown). This pattern clearly shows a drifting soil moisture budget.

For both 23 March and 2 April 1995, first guess results were derived from the 24 hour RACMO forecast from this sequence of runs. The modified SEBAL was used to calculate pixelwise surface fluxes. These fluxes were averaged to RACMO grid box values, and transformed into evaporative fractions.

5. Results

On the 2 selected days in spring, the European average of the RACMO bias of near-surface temperature and humidity was limited. We therefore hypotise that RACMO estimates of surface fluxes are not too far from reality. In the following we will use RACMO surface flux calculations as reference for choosing an optimal value of the parameter C in eq. 2.

Figure 3 shows the difference between RACMO and SEBAL evaporative fractions $\Delta\Lambda$, calculated for 2 April, 12 UTC, for three different values of C. In all three cases a clear pattern of $\Delta\Lambda$ is shown, RACMO being wetter than SEBAL in the South-Eastern part of the area, and the reverse being true in the North-West. On the average, the smallest difference occurs using $C = 0.2$, which will be adopted below.

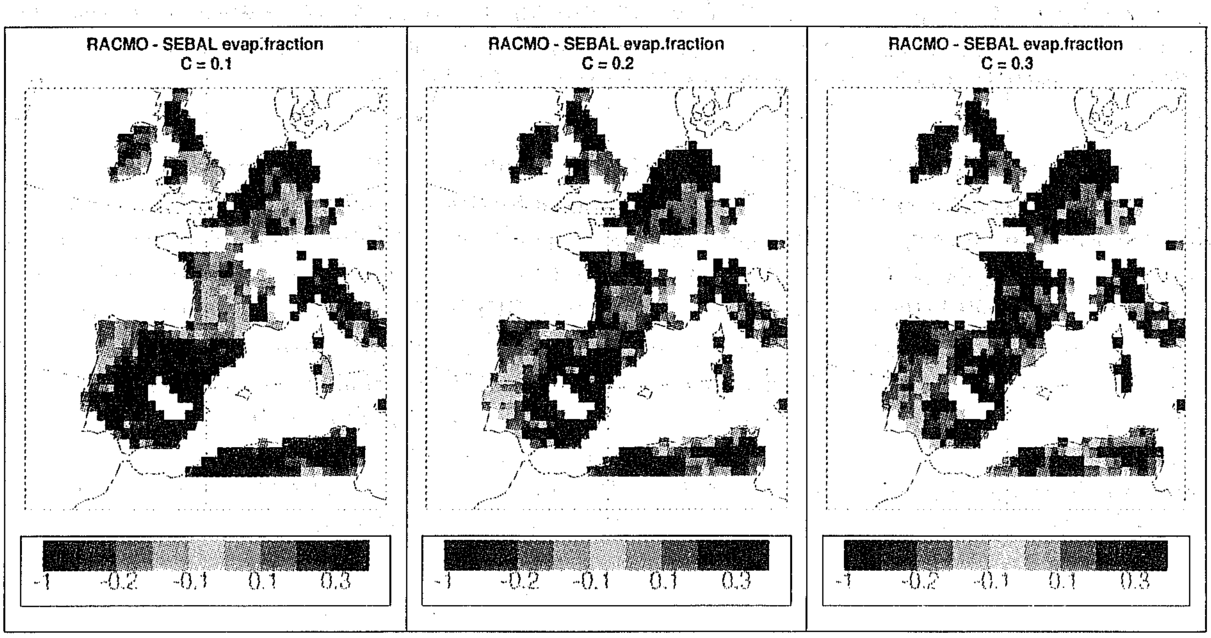

Figure 3: Difference between RACMO and SEBAL evaporative fraction for 2 April 1995, 12 UTC. SEBAL results are calculated using $C = 0.1$ (left), 0.2 (middle) and 0.3 (right).

The clear geographical organization of $\Delta\Lambda$ suggests a strong correlation with the surface temperature. This indeed is evident from Figure 4, where $\Delta\Lambda$ (using $C = 0.2$) is plotted as function of the NOAA AVHRR surface temperature, averaged for each RACMO gridbox. We will come back to this feature later.

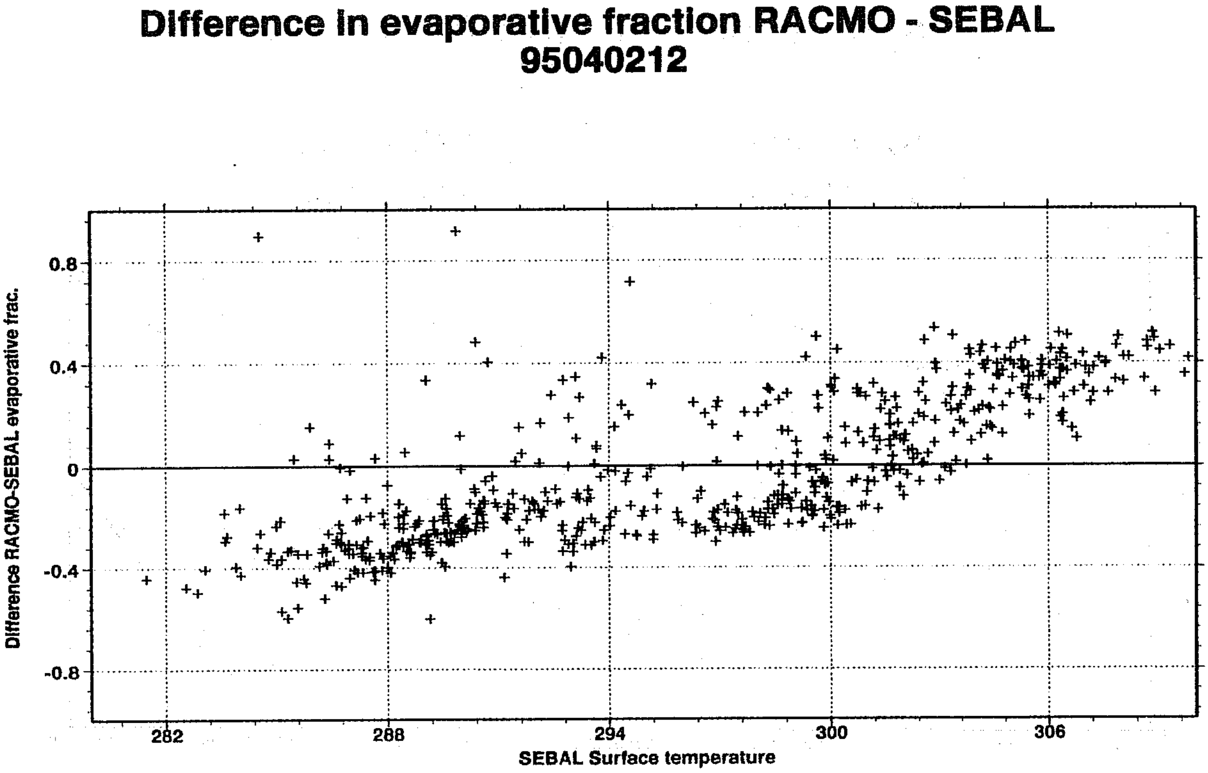

Figure 4: Difference between RACMO and SEBAL evaporative fraction for 2 April 1995, 12 UTC as function of SEBAL surface temperature. SEBAL calculations are carried out using $C = 0.2$.

In an Optimum Interpolation (OI) assimilation scheme, the SEBAL estimates of Λ were used to adjust the soil moisture field in RACMO in order to reduce $\Delta\Lambda$ to a minimum. For each of the two days, a new experimental RACMO 72-hour run was started with soil moisture initialized as indicated. As in the previous test case, synops near-surface observations from the cloud-free target areas were used as validation tool.

Figure 5 shows the bias and root-mean-square (rms) error of specific humidity from both the control and experimental RACMO runs, started on 23 March. A small reduction of the average bias during daytime is visible, but the rms-value is worse. The same picture for near-surface temperature from 2 April is shown in Figure 6. The average bias during daytime is sligtly increased, and impact on the rms is small. Similar results are found on 2 April for humidity, and 23 March for temperature.

6. Discussion and further research

On the selected days surface fluxes in most of the European area are relatively small, owing to the low radiation. The effect of surface fluxes on near-surface quantities is therefore only limited, and the results shown in the last two figures are not very conclusive. If any conclusion is to be drawn here, it would be that the SEBAL evaporative fraction averaged over the whole domain is in correspondence with synops information, but that its distribution over the area is wrong.

The sensitivity of the SEBAL results to the specification of z_{0h} via the choice of C is obvious, and not surpising. Many attempts of defining a universal formulation of z_{0m}/z_{0h} have been proposed in literature, but a clearly superior parameterization has not been found so far. On the other hand, figure 4 suggests that a formulation in which surface temperature appears could be successful.

Future activities will focus on this issue. As a first search direction, we will return to one of SEBAL's original principles, which is to apply an internal calibration by assuming the presence of extreme evaporation regimes in the image. For the pixels in which the difference between surface and reference temperature is largest, evaporation will be assumed to be minimal. Since this assumption

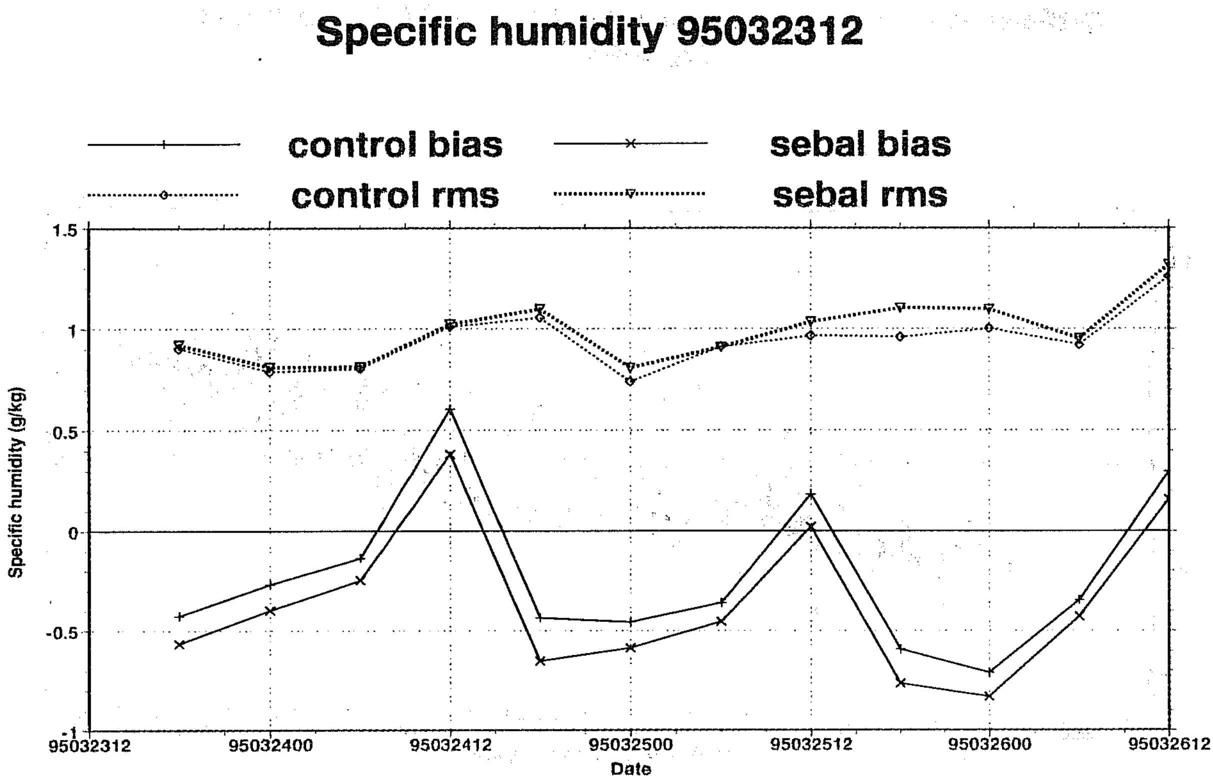

Figure 5: Specific humidity bias and rms error for the control run and the run with soil moisture updated using SEBAL calculations for 23 March 1995. Shown are results for the cloud-free (West European) area.

gives an estimate of H, z_{z0h} (or the coefficient C) can be calculated for these dry pixels. The reverse is done for the pixels were the temperature gradient is small. Rather than interpolating a temperature gradient between these two extremes, an interpolation of z_{0h} (or C) will be addressed.

A second future activity is the implementation of a variational assimilation scheme, along the lines as presented by Rhodin *et al.* (1997). This enables the optimalization of soil moisture fields from a mixture of data sources collected at different times, including synops near-surface quantities *and* SEBAL evaporation estimates from NOAA AVHRR or other (future) satellites.

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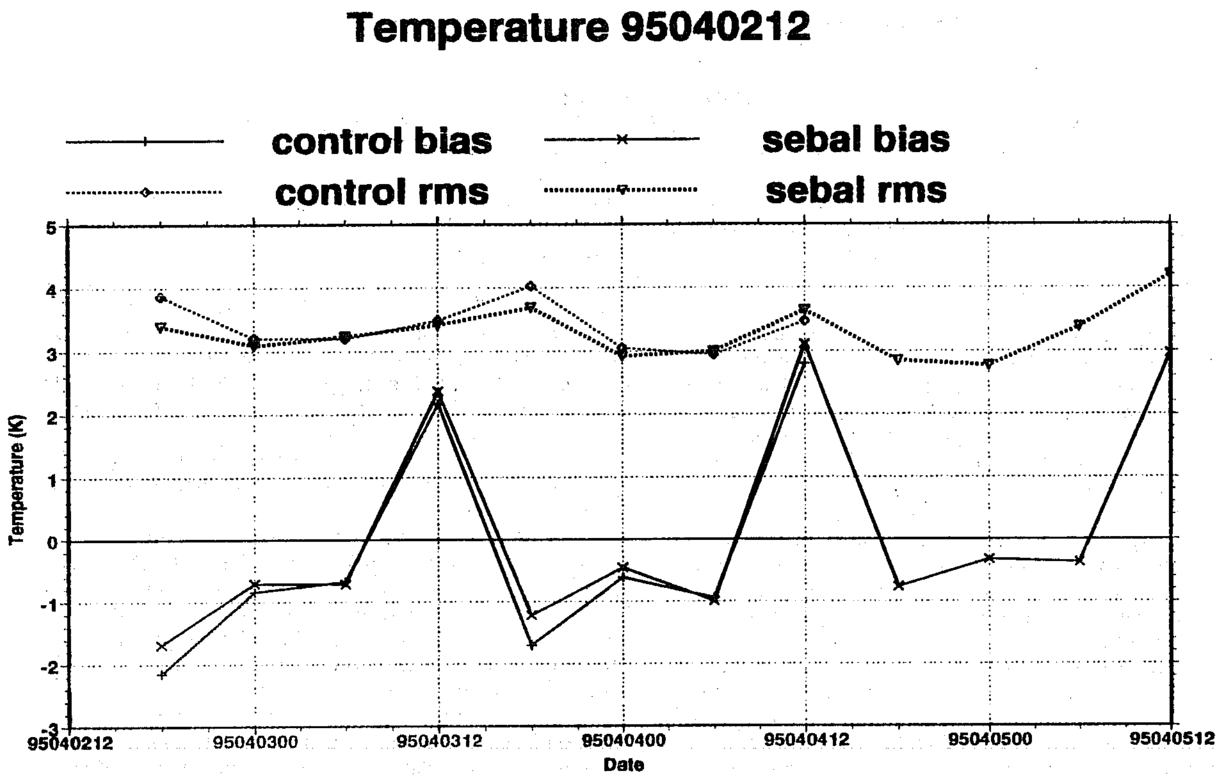

Figure 6: Temperature bias and rms error for the control run and the run with soil moisture updated using SEBAL calculations for 2 April 1995. Shown are results for the cloud-free (West European) area. The control run lasted only 48 hours.

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