Analysis of soil moisture from screen-level atmospheric observations using a variational method

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Initial soil moisture values η in M model layers, are to be retrieved for all grid points eventually leading to the best prediction of atmospheric temperature and relative humidity at screen-level height. A cost function measuring the deviations of predicted screen level temperatures $T_n(\eta)$ and relative humidities $RH_n(\eta)$ from observed values T_n^o, RH_n^o at times n is minimized. The deviations of initial soil moisture from a previous forecast η^b may be penalized by the background term. Suitable observational errors σ_T^o, σ_{RH}^o and background error $\sigma_{\eta_k}^b$ must be prescribed:

$$J(\eta) = \frac{1}{2}\sum_n \left[\frac{(T_n^o - T_n(\eta))^2}{{\sigma_T^o}^2} + \frac{(RH_n^o - RH_n(\eta))^2}{{\sigma_{RH}^o}^2}\right] + \frac{1}{2}\sum_{k=1}^{M}\left[\frac{(\eta_k - \eta_k^b)^2}{{\sigma_{\eta_k}^b}^2}\right] \qquad (1)$$

Variational analysis of soil moisture from atmospheric observations of screen level temperature and humidity was proposed by Mahfouf, 1991 and compared to the sequential method based on optimal interpolation. Both methods retrieved soil moisture contents close to neutron probe estimates. The variational approach was found to be more efficient but it is much more involved because it requires repeated model integrations using an iterative optimization algorithm to find the minimum of J. Thus this method has not been used up to now by operational forecast centers.

The variational method was applied to the regional weather forecast model (DM) of the Deutscher Wetterdienst (DWD) using analyzed fields of 2 m atmospheric temperatures T^o and relative humidities RH^o (Rhodin *et al.*, 1998). In order to reduce the computational load, the modeled impact of soil moisture variations on atmospheric screen level observations remains restricted to the respective local grid column; a cost function J (Equ. 1) is minimized at each grid point independently from the others.

A 1-column model consisting of the complete soil model but a simplified description of processes in the atmospheric boundary layer (lowest model levels) has been designed to calculate $T_n(\eta)$ and $RH_n(\eta)$ at observational times n in the optimization procedure. Stability dependent vertical turbulent diffusion of heat, moisture and momentum as well as Coriolis and pressure gradient accelerations are taken into account in the atmosphere. Advection, diabatic heating and convection are neglected. Radiative forcing and conditions at the top of the boundary layer are prescribed from a DM reference run. The contribution of the missing terms in the prognosting equations due to the neglection of the above processes is determined by comparing the trajectories of the two models (started with identical initial first-guess soil moisture η) in 1/2 hourly intervals. These terms are added in the simplified model equations to prevent a deviation from the DM trajectory. The same values are added even if initial soil moisture is changed during the optimization procedure.

A feasibility study at one model grid-point (Callies *et al.*, 1998) gave insight in the sensitivities of screen level atmospheric parameters on soil properties: The effect of changed soil moisture accumulates during the course of the day as long as the ground is heated by incoming radiation. Thus the start of the assimilation interval should lie at or before sunrise in order not to underestimate the impact of soil moisture on screen level parameters. Initial soil temperature has a weak impact on atmospheric parameters during the day. Only a certain linear combination of vertical soil moisture distribution can be retrieved by this method. The sensitive linear combination depends mainly on the soil-model parameters 'root depth' and 'vegetation cover'.

During a period of five days in spring 1994, each day initial soil moisture values η at 6 UT (7 h local time) were adjusted in the upper (most sensitive) layer, minimizing the differences between predicted and analyzed (on model grid-points) screen level temperature and relative humidity at 12 and 15 UT.

Retrieved soil moisture values turn out to be considerably lower than in the operational reference run. They can be doubted to be realistic for this time of the year but should be considered as being mere effective parameters to be tuned with respect to the specific soil model in order to provide correct lower boundary conditions for the atmosphere. The method can also be regarded as a procedure to assimilate screen level temperature and humidity observations into the atmospheric model, consistently with the boundary-layer dynamics.

Numerical experiments have been conducted in order to estimate the influence of possibly misspecified radiative forcing on the retrieved soil moisture fields. It is shown that soil moisture values being derived from observations of atmospheric relative humidity are much more stable than those derived from temperature observations.

Soil moisture values retrieved without a background term show a strong temporal and spatial variability due to differing radiative forcing conditions. During overcast situations the inverse problem to derive soil moisture from atmospheric properties is ill posed, consequently the expected errors of the analyzed parameters are large. A background term reduces the variability considerably. It must be used in an operational implementation to make the method more robust with respect to model errors as misspecified radiative forcing.

The forecasts of screen level atmospheric parameters on subsequent days (after the assimilation interval) was considerably improved with retrieved initial soil moisture values. The cold and moist bias present in the operational forecast was largely removed.

A positive impact on operational forecasts can be expected if variational soil moisture retrieval is used, although further investigations (within other seasons) are required in order to assess the long term stability of the method.

References

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