2ELDAS comparison of three different algorithms for soil moisture assimilation in the HIRLAM system

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1. Introduction. The ELDAS project.

This work has been carried out in the context of the ELDAS project (European Land Data Assimilation System, see http://www.knmi.nl/samenw/eldas) (Van der Hurk et al., 2002), which was supported by the European Union in the context of the Fifth Framework Program. ELDAS was designed to develop a general data assimilation system for estimating soil moisture fields on the continental (European) scale, and to evaluate the impact of these fields in meteorological and hydrological applications. Moreover, a set of accurate databases of precipitation, radiation and surface heating rates at high spatial and temporal resolution was also created for forcing and verification purposes.

The specific task of INM's contribution was to assessing the impact of the ELDAS generated soil moisture fields, provided by the ARPEGE global model (Courtier et al. 1991), when applied to the soil water content initialization in Numerical Weather Prediction (NWP) simulations (see Parodi et al., 2005). Three different soil moisture assimilation schemes have been compared using the operational HIRLAM model (Unden et al., 2002).

Three experiments were conducted using the same HIRLAM system set-up, and differing only in the soil moisture assimilation algorithm, in order to evaluate the impact of different soil moisture initialization methods on the forecast skills of screen-level variables and also on the soil water balance.

2. Description of the HIRLAM system set-up within ELDAS

The same common set-up was used in all the experiments carried out in this study. HIRLAM version 6.2.0. was used, with 31 levels in the vertical and a horizontal resolution of 0.2 x 0.2 degrees over a rotated grid domain covering all Europe and North Atlantic area (see Fig. 1). A semi-Lagrangian advection scheme is used, with a time-step of 300 s. The forecasting range is 48 hours from 00 UTC analysis only, and ECMWF analysis were used for the lateral boundary conditions. Each experiment has its own 6-hour assimilation cycle both for upper air based on 3D-VAR and for surface variables. The estimation of screen-level parameters is provided by a vertical interpolation between the surface and the lowest atmospheric model layer (about 30 meters above ground) (Geleyn, 1988).

The integration period covers 6 months of year 2000, from May 1 to October 31, but the comparison starts on June 1, leaving the first month (May) for soil moisture spin-up.

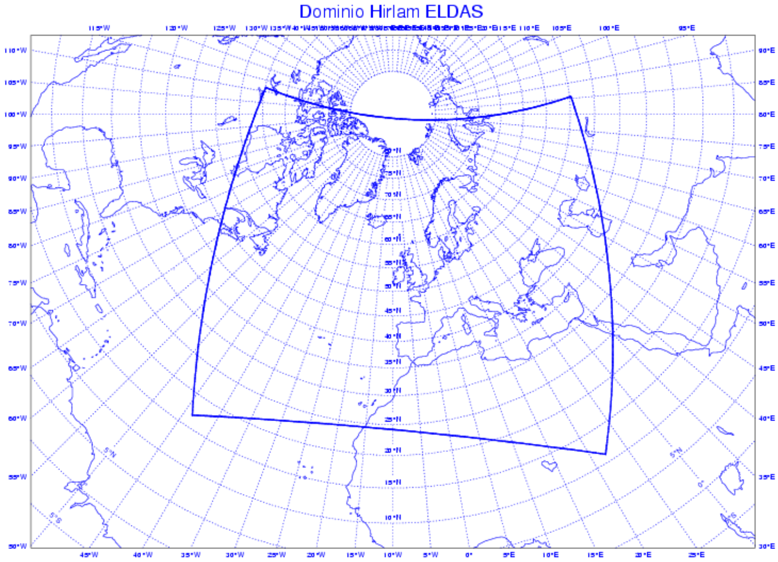

Fig. 1. ELDAS domain in HIRLAM

The land surface scheme used in the HIRLAM system is based on the ISBA (Interaction Soil Biosphere Atmosphere) scheme (Noilhan and Planton, 1989, Noilhan and Mahfouf, 1996, Rodríguez et al., 2003). A number of modifications were introduced in the HIRLAM reference system and applied to the three experiments, in order to minimize the transfer problems of soil moisture fields.

The ECOCLIMAP physiographic database (Masson et al., 2003) was implemented for both soil description and vegetation parameters. The following parameters were accordingly changed: orography, land fraction, vegetated fraction, leaf area index (LAI), soil depth, soil texture, roughness length, emissivity, albedo, and minimum stomatal resistance.. In addition, the ISBA-HIRLAM tiled structure (Rodríguez et al., 2003) used in the reference HIRLAM surface scheme was also modified to only one land tile within each grid box. The predominant land tile is assigned, covering the whole grid land fraction.

These modifications were introduced to approach the land surface scheme formulation of the ARPEGE and HIRLAM models (in the ELDAS version of the ARPEGE model the ISBA surface scheme has no tiling structure and also the ECOCLIMAP database was implemented). In this way, both models share the same physiographic description and surface model in order to facilitate a cleaner exportation from the soil moisture fields assimilated/generated in the ARPEGE model to the HIRLAM system (ELD experiment), and also to make an easier interpretation of results.

3. Description of the compared soil moisture assimilation algorithms

A description of the three algorithms used for soil moisture assimilation is presented below:

3.1. Optimal interpolation analysis (REF) algorithm

The algorithm used to initialise the surface and total water content in this experiment (hereafter referred as REF algorithm) is the same as used in the HIRLAM reference system, which is based on the sequential assimilation developed by Mahfouf (1991) with optimum coefficients approximated analytically by Bouttier et al. (1993 I,II) and rewritten by Giard and Bazile (2000). The HIRLAM implementation is based on this last algorithm (Rodriguez et al., 2003), with fixed optimum coefficients, which depend on the local solar time (LST) and on surface parameters (veg fraction, LAI, Rsmin, soil texture).

SYNOP data are used to analyze both 2-meter temperature (T_{2m}) and relative humidity (RH_{2m}). Results from this analysis are used for soil moisture corrections, which are linearly calculated by an optimum interpolation (OI) algorithm. This method assumes a linear relationship between screen-level variables analysis increments and soil moisture errors. Therefore, the soil moisture analysis is based on the minimization of forecasted errors of near surface parameters (T_{2m} and RH_{2m}), see Navascués et al., (2001) for more details.

The soil moisture analysis is performed in this experiment at the synoptic hours 00, 06, 12 and 18 UTC, with a 6-hour cycling assimilation window.

3.2. Simplified variational method (VAR) algorithm

The algorithm implemented in the HIRLAM system for this experiment (referred as VAR) is based on Balsamo et al. (2004), and consists of a variational method to initialise soil water content. This method is based on the idea of minimizing a cost function (**J**) which combines information from the forecast model and screen-level observed parameters (T_{2m}, RH_{2m}).

The cost function is formally written as:

$$J(x) = ½ (x – x^b)^T B^{-1} (x – x^b) + ½ (y – H(x))^T R^{-1} (y – H(x))$$

Where $\boldsymbol{x}$ is the vector containing the control variables to be analyzed, $\boldsymbol{x^b}$ is the vector representing the background state, and $\boldsymbol{y}$ is the observation vector. $\boldsymbol{B}$ and $\boldsymbol{R}$ denote, respectively, the background and the observation error covariance matrices, and $\boldsymbol{H}$ is the observation operator that transports the model state vector (**x**) into the observations space.
Assuming a tangent linear (**TL**) hypothesis, which is compatible with the case of the analysis of soil water content, as the total water content in the soil evolves with long time-scales (several days), and applied to the soil moisture analysis produces an important simplification (simplified 2D-VAR), making this technique similar to the optimum interpolation method (OI), but with the main difference of using a dynamical estimate of the gain matrix instead of a statistical evaluation (with fixed coefficients) used in the OI technique, (see Balsamo et al., 2004 for further details).

An extra integration of the forecast model from an initially perturbed soil moisture field is needed to estimate the TL observation operator. The set-up for this simplified variational method makes use of the full HIRLAM model to infer the sensitivity of the forecasted 2m screen-level variables (T_{2m} and RH_{2m}) to the soil moisture perturbations.

Thus, this method keeps count of the full physics of the model performing dynamic corrections, soil moisture corrections are adapted to the current meteorological conditions and to the grid point characteristics.

In the VAR experiment, two model integrations were run at each 4 synoptic hours (00, 06, 12, and 18 UTC):

- A reference forecast, with the initial guess of total soil water content.
- A forecast with a perturbation on the initial soil moisture guess (δW_d)

The value of the perturbation is a fixed fraction of the soil wetness index amplitude (ΔSWI, ranging from 0 to 1). In this experiment, ΔW_d has been tuned to be 20% of ΔSWI, to be of the same order than the model error,

$$\Delta W_d = 0.2 \text{ x } \Delta SWI \ [0, 1]$$

A chess-type perturbation of the initial soil moisture guess was used, changing the sign of the perturbation (+/- ΔW_d) each day for each grid-box within the land domain. The soil moisture analysis is performed at 00, 06, 12 and 18 UTC with a 6-hour assimilation time-window.

Some masking conditions have been taken into account to avoid undesired non-linear effects in the perturbed forecast which would lead to an inaccurate analysis correction (see Balsamo et al., 2004),. This masking of the analysis will set K matrix to 0, either under specific meteorological conditions or when the resulting increment in the screen-level variables from the perturbed forecast is of the opposite sign to the expected correlation. Thus, soil moisture assimilation is switched off when:

- for the perturbed forecast:
  - ΔT_{2m} and ΔW_d are positively correlated.
  - ΔRH_{2m} and ΔW_d are negatively correlated.

- $(T_{2m}^a - T_{2m}^f)\ (RH_{2m}^a - RH_{2m}^f) > 0$, where *a* denotes analyzed values and *f* denotes forecasted values.
- Exceeding given threshold values of differences (reference minus perturbed guess) in forecasted variables (precipitation, wind, cloud cover)

3.3. Variational assimilation by an external model (ELD)

This experiment (labelled ELD hereafter) was conducted to assess the added value of an ELDAS soil moisture analysis when applied to an operational NWP model (HIRLAM). The total soil water content is initialized in HIRLAM once a day (at 00 UTC) with the soil moisture fields provided by the soil moisture assimilation system of the global ARPEGE model (at Meteo-France), which also implements the ISBA soil parameterization scheme. The assimilation of soil water content in the ARPEGE system was also based on the same variational approach implemented in HIRLAM in the context of the ELDAS project and described by Balsamo et al. (2004).
However, there are some differences between the variational implementation in ARPEGE and HIRLAM (VAR experiment) system. The length of the ARPEGE assimilation time window was 24 hours (while VAR uses a 6 hour assimilation

window). In order to compensate errors coming from the forcing by model precipitation, the daily assimilation of indirect data of screen-level temperature and relative humidity in ARPEGE is combined with a complementary correction based on precipitation error (from the analysed ELDAS precipitation dataset (Rubel et al., 2004)). Two opposite-phase perturbations for soil moisture were used to estimate the tangent linear of the H matrix and a smaller size of the soil water content perturbation was assigned. Differences are also referred to the magnitude of soil moisture background error variance and the masking algorithm. Moreover, additional differences comes from the different model and analysis systems between ARPEGE and HIRLAM models.

4. Results

The impact of the different soil moisture assimilation experiments will be shown hereafter. Two different set of results will be presented, one set concerning the three experiments for the time period covering the first 18 days of June, and another set where the comparison between the REF and the ELD experiment results will be evaluated for the period starting on June 1 up to October 31 of year 2000.

The VAR experiment was run mainly to ensure that no special problems were present in the exportation of soil moisture fields in the ELD experiment, and also, to evaluate the soil moisture evolution when a variational code for soil moisture assimilation is implemented in the HIRLAM model, thus making possible a comparison with the soil moisture fields supplied by the ARPEGE system.

Furthermore, the VAR experiment with some retuning might be the base of the future soil moisture assimilation package in the HIRLAM system. This new frame would allow the assimilation of soil moisture sensitive satellite information, which is not currently assimilated.

4.1. Single point diagnostics of soil moisture analysis increments for REF, VAR and ELD soil moisture assimilation algorithms.

The study of soil moisture analysis increments provides a valuable source of information on model deficiencies. Ideally, for an optimum model performance the soil moisture increments should be significantly smaller than any of the terms involved in the water budget equation. The real picture, however, is far from this idealistic situation and frequently soil water increments are comparable with each of the hydrological components of the land surface scheme. Soil moisture analysis increments are introduced to compensate soil moisture drifting originated by different types of errors. The study and discussion of such increments will shed light on deficiencies coming either from the surface scheme parameterizations or from external forcing.

Diagnostics for a single grid point, corresponding to the ELDAS validation site located in Sarrebourg (Germany), and for the time period from 1 June up to 18 June 2000 are presented for the three different experiments.

Fig. 2 (top), represents the daily evolution of the soil wetness index (SWI) for the three experiments, it can be seen that REF experiment shows a SWI evolution very different compared to the ELD and VAR profiles. REF presents bigger SWI variations than the other experiments. The soil moisture evolution corresponding to the VAR experiments shows, as expected, an evolution close to the ELD experiment. The soil wetness index for ELD and VAR evolve with a similar behaviour although VAR shows a big variation on day 14, possibly as a consequence of its larger size of the assigned soil moisture perturbation (ΔW_d) compared with ELD experiment, the perturbation used in HIRLAM was 5 times bigger than the corresponding in the ARPEGE implementation.

Fig. 3 (top) represents the accumulative soil moisture increments (in mm of water) for the 18 days period, taking into account the sign of the increment. Fig. 2 (middle) represents the soil moisture increments in absolute value, and Fig 2 (bottom) shows the total amount of the soil moisture increments compared for the three experiments. The first noticeable feature is a clear difference in the total water amount implied in the assimilation algorithm used in the reference experiment (REF) compared with VAR and ELD experiments. REF experiment shows bigger soil moisture corrections than ELD and VAR experiments. This fact is due to the excessively large corrections of the optimum interpolation (OI) method, which were originally computed by a Monte-Carlo approach and they should have been further retuned in the frame of the HIRLAM system. This aspect was already known and the comparison with the other assimilation experiments has allowed a quantification of the magnitudes involved.

4.2. Differences on soil moisture fields between REF and ELD soil moisture assimilation algorithms.

Fig. 4 (top) represents the mean soil water content (mm) differences between REF and ELD experiments, computed for July 2000. It shows that, in general, for Southern areas the ELD algorithm provides more soil water content than the reference (REF), also for the North-Eastern region. On the other hand, it is appreciated that over Scandinavia, the REF experiment shows the opposite behaviour, it produces a larger soil water content compared with the ELD experiment. Fig. 4 (bottom) represents the mean soil water content (mm) differences between REF and ELD experiments but computed for October 2000. It shows a general pattern of soil water content being larger for the ELD algorithm than for REF, except for Scandinavia and Northern areas. Differences in mean soil water content between REF and ELD for July and October are difficult to interpret due to the concurrence of many counteracting factors. Among these factors, it can be mentioned: (i) the ELD correction of precipitation which is suppose to be more important in the case of October. This correction is however linked to the ARPEGE precipitation error; (ii) the different ways to explore sensitivity by REF and ELD to soil moisture changes; (iii) the different initial soil moisture conditions which could dramatically affect the July value in northern latitudes due to their poor coupling between screen variables and soil moisture, etc.

4.3. Differences on forecasted screen variables between REF and ELD soil moisture assimilation algorithms.

Fig. 5 (top left) shows the 36-hour forecasted 2-metre temperature bias for the REF experiment, and averaged for the whole period (5 months). The bias is computed against all SYNOP stations in the model domain. All runs start at 00 UTC and verify at midday (12 UTC). In term of bias, the reference system is able to maintain values generally between +/- 1 degree. A slight cold bias is noticeable over some regions of Europe, being more systematic over Scandinavia and Northern Russia. Fig. 5 (top right) shows the corresponding bias for the ELD experiment. The bias is also well controlled, with a predominance of colder biased regions. However, biased regions do not exactly match in both experiments. ELD shows a clear trend to cold bias over France and Eastern Europe, which is not so notorious in the REF experiment. On the other hand, the REF cold bias over Northern Europe is not present in the ELD experiment. A possible explanation of the Nordic bias in REF could reside on the masking conditions prescribing when screen variables are coupled or not to soil moisture. These "summer-like" conditions frequently show a latitudinal dependence, reducing the number of active cycles for soil moisture corrections as latitude increases (see Navascues et al. 2003).

The overall effect of the soil moisture assimilation in REF and ELD experiments can be estimated by computing the rms error differences for the 36-hour forecasted screen variables and for the whole period. Fig. 5 (bottom left) depicts the difference (REF-ELD) of rms error for 2-metre temperature. It is appreciated that differences are almost negligible. The corresponding map for 2-metre relative humidity (Fig. 5 (bottom right)) shows also very small differences between both experiments. Therefore, both soil moisture assimilation algorithms have a comparable performance in terms of screen-variables scores. It should be taken into account that errors of 2-metre temperature and relative humidity are not always sensitive to soil water content for the whole long period of 5 months. This fact will attenuate the differences between ELD and REF experiments. On the other hand, both experiments, ELD and REF, have used the same source of information (i.e. 2-metre temperature and relative humidity observations) to correct soil moisture, although with different algorithms.

5. Conclusions

Three different soil moisture assimilation schemes have been compared using the operational HIRLAM model. In terms of impact on screen-level temperature and relative humidity, no big differences were found among the three soil water assimilation schemes. This is not surprising as all three schemes are based on the minimization of screen-level variable errors.

About the impact on soil moisture fields, it was demonstrated that the default Optimum Interpolation scheme in the HIRLAM system (REF experiment) showed a marked tendency to overcorrect soil moisture. The ELDAS generated soil moisture field (ELD experiment) showed lower soil moisture analysis increments (corrections). The variational method implemented for soil moisture assimilation within the HIRLAM system (VAR experiment) showed a similar behaviour than ELD but sometimes VAR produces larger soil moisture analysis increments, which are out of the tangent linear approximation, due to the excessively large soil moisture perturbations used by the computation of the perturbed integration. This can be palliated either by decreasing the size of the soil moisture perturbation and introducing more restrictive masking conditions or running a second perturbed integration with opposite sign. Moreover, ELD experiment has a longer assimilation window (24-hours) and incorporates precipitation analysis corrections, which results in lower soil moisture corrections and in a more realistic soil moisture evolution.

From the operational point of view, the comparison has stressed the necessity of further tuning of the OI scheme in order to have a more realistic soil moisture fields maintaining the same soil moisture assimilation scheme. The implementation of the variational soil moisture approach within the HIRLAM model would be a first step to the assimilation of IR (infra-red) and MW (micro-wave) satellite information by the HIRLAM system.

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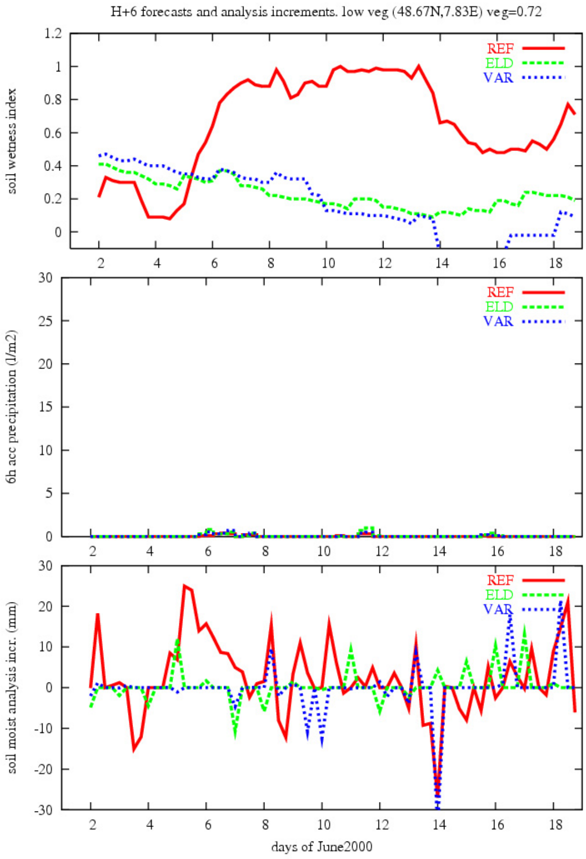


Fig. 2. Daily evolution of Soil Wetness Index (top), 6-hours accumulated precipitation (in mm) (middle), and soil moisture analysis increments (mm of water) for REF (red), ELD (green) and VAR (blue) experiments at Sarrebourg (Germany).

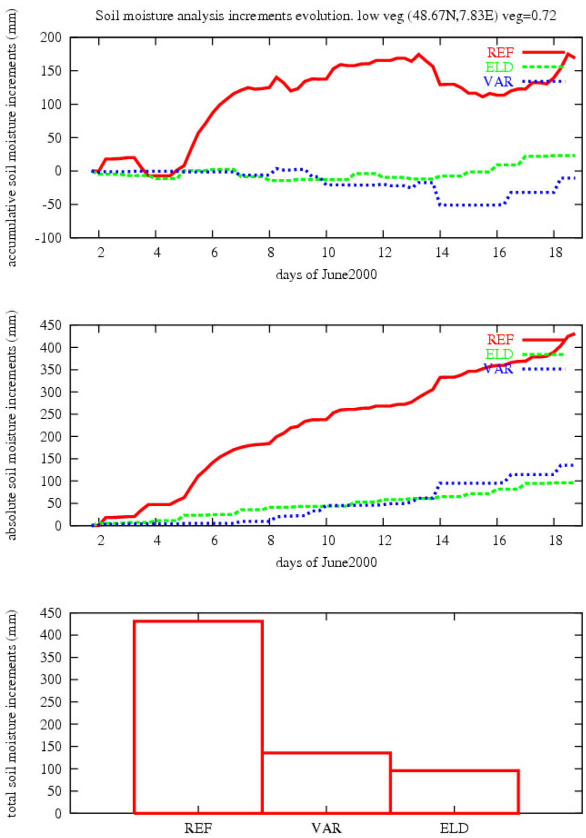
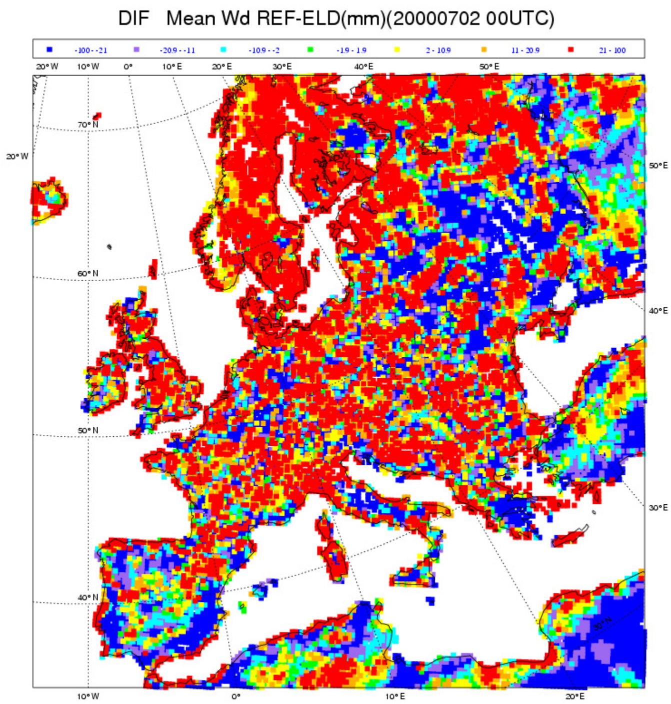


Fig. 3. Daily evolution (at Sarrebourg, Germany) of accumulative soil moisture analysis increments (top), absolute soil moisture analysis increments (middle) and comparative boxes of the total amount of soil moisture increments (bottom) for REF, ELD and VAR experiments.



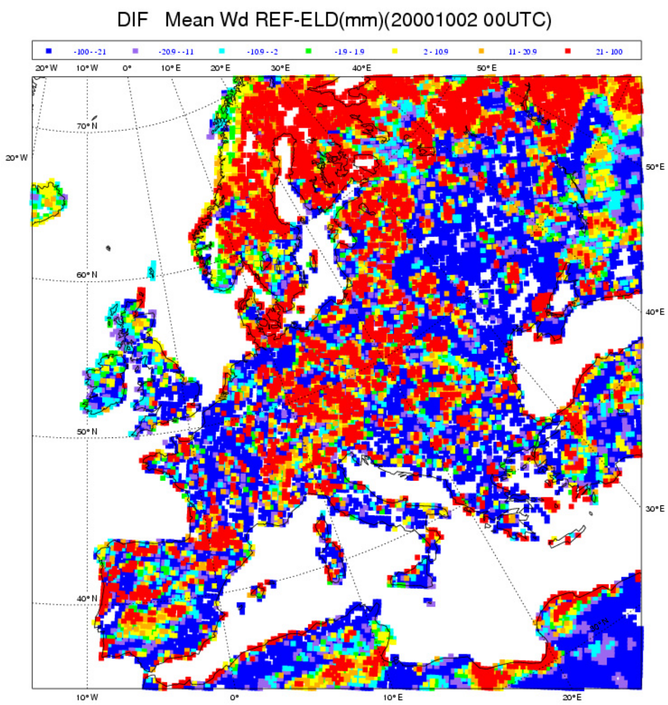


Fig. 4. Mean soil water content (mm) differences between REF and ELD experiments (REF-ELD), for July (top) and for October (bottom) of year 2000. Yellow and red colour correspond to positive differences, while blue colours correspond to negative differences.

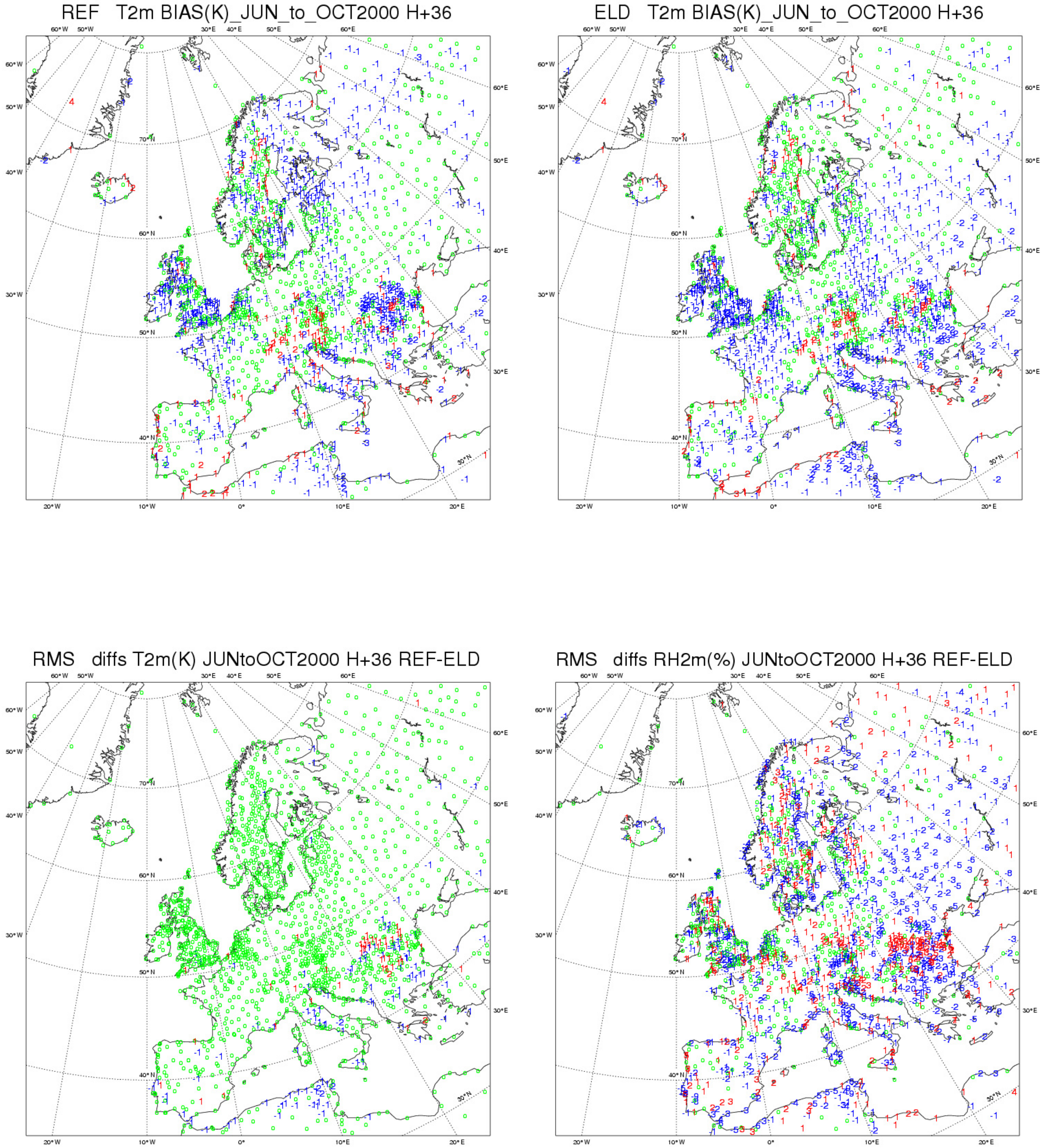


Fig. 5. T2m bias (forecast minus observations) in H+36 forecasts valid at 12 UTC. All daily integrations averaged from June 1 up to October 31 for REF (upper left) and ELD (upper right) experiments. Difference of rms error (REF minus ELD) for T2m (bottom left) and RH2m (bottom right)