Significance of ELDAS soil moisture products for NWP

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ABSTRACT

The analysis of soil moisture for the initialization of numerical weather prediction (NWP) models is discussed subjected to the constraints imposed by an operational environment. Three different techniques are compared within the HIRLAM forecasting system. The first method is the HIRLAM default option based on optimal interpolation (OI) analysis with optimal coefficients analytically formulated. It makes use of 2-metre temperature and relative humidity errors. A second method is based on a simplified variational approach to assimilate also 2-metre observations of temperature and relative humidity. The estimate of tangent linear of the observation operator is obtained here from an extra integration of the numerical model. Finally, a third method is based on the assimilation of soil moisture by a parent (global) model and *a posteriori* corrected by the forecasted precipitation error. The soil moisture produced is then imported to the HIRLAM system.

1 Introduction

The use of land-surface parameterization schemes in NWP models with increasing complexity implies the introduction of additional prognostic variables which in principle need to be initialized. Most land-surface schemes are based on simplifications of the equations for soil water transfer and for heat transfer. The prognostic variables introduced by these equations are usually soil water content and soil temperature. The major problem of specifying the initial conditions of these variables is the lack of routine observations. This is specially true in the case of soil water content. For soil temperature the climate network exists, but observations are not exchanged routinely via the GTS at the time of measurement. Consequently, in practice most stations performing observations at least daily can only be used, in delayed mode, for verification purposes. Another additional problem is the large spatial variability of soil water content and soil temperature, mainly inherited from the high heterogeneity of soil and vegetation properties. This large spatial variability associated with surface properties poses the added problem of using statistics of forecasts errors to spatially distribute the local increments. Such statistics are not known for soil variables.

Despite the sensitivity of short range forecasting to initial conditions of soil water content, few methods are currently available to estimate soil water in NWP models. The ground-based techniques include gravimetric method, neutron scattering, electromagnetic method, and tensiometer method. None of the above techniques is adequate for routine measurements due to a number of reasons: lack of representativeness of point measurements, excessive cost, human intervention needed, etc. The only feasible alternative is the use of satellite-based estimates of soil water content. Both infrared and microwave channels are informative about soil water content (see review in (Schmugge and Becker, 1991)). While the infrared frequencies are sensitive to the evaporative fraction and therefore can be a proxy to soil water content values (van den Hurk *et al.*, 1997), the microwave sensors directly provide information on water content in the top few centimetres of the soil. As satellite-based methods do not supply soil water content in the root zone, some assimilation scheme is needed to extend surface information to deeper soil layers (see *e.g.*, (Calvet *et al.*, 1998)). However, most of the current operational systems make use only of the screen variables information, which is sensitive to the Bowen ratio, to estimate soil water content.

Two methodologies are currently applied in forecast/data assimilation systems for initializing soil water content. Mahfouf (1991) and Bouttier *et al.* (1993a, 1993b) proposed an optimal interpolation scheme for the assimilation of soil water using the information of both temperature (T_{2m}) and relative humidity (RH_{2m}) at the heigth of two meters, which can be formally written:

$$W_a - W_f = \alpha^T (T_{2ma} - T_{2mf}) + \alpha^H (RH_{2ma} - RH_{2mf}) \tag{1}$$

The optimal interpolation coefficients α^T and α^H are analitically formulated. They were once computed by minimizing the analysis variance. The subscripts a and f refer to the analyzed and forecast values, respectively. This method assumes a linear relationship between screen variable increments and soil moisture corrections, which is a rather crude approximation. Therefore, the major disadvantage of this method is that errors in screen variables that are not related to soil moisture effects could lead to soil moisture corrections. In reality, the signal in the bias of near-surface temperature and humidity is only related to soil water content under restricted synoptic conditions: small horizontal advection, no snow cover, absence of precipitation, daytime, etc. A set of masking conditions is additionally imposed to guarantee coupling between screen variables and soil moisture.

Another alternative is the variational method (or variants thereof), which seems more appropriate to treat the non-linear dependence between screen variables and soil moisture, and to assimilate measurements distributed in time. Mahfouf (1991), Hess (2001) and Balsamo *et al.* (2004) have used a 2D-Var approach to estimate the initial soil moisture best fitting to observations of temperature and relative humidity during a diurnal cycle. Therefore, the optimal soil water content minimizes a cost-function which typically consist of background and observation distance terms. This method keeps count of the full physics of the model and the corrections are dynamically adapted to the current meteorological conditions.

Model soil moisture tends to drift in long integrations for various reasons. First, due to the imperfect parametrizations of soil processes and soil-atmosphere interactions, and second, because of errors in the forcing, in particular precipitation and radiation. The usage of realistic forcings close to the observations would, in principle, imply a reduction in soil moisture drift and consequently in soil moisture increments introduced during the analysis phase. Therefore, a third alternative for assimilating soil moisture would consist of an off-line assimilation making use of observed precipitation and radiation (Seuffert *et al.*, 2003).

The main purpose of this contribution is to compare and discuss three realizations of the aforementioned methods of soil moisture assimilation in the context of ELDAS project (European Land Data Assimilation System, see http://www.knmi.nl /samenw/eldas). All testing has been done in the frame of the HIRLAM system using a set-up very close to the current operational versions of the system. For the comparison three parallel experiments were run covering a whole summer period (June-October 2000) agreed within the ELDAS project. The comparison was mainly focused on near surface variables, using the routine scores computed against SYNOP data. No attempt has been done so far to compare the assimilated soil moisture against point observations. As the precipitation and radiation forcing is a frequent source of errors, a comparison between the model and ELDAS produced forcing terms was also conducted. ELDAS daily precipitation analysis were produced using more than 20000 gauges. The daily values were disaggregated in 3 hourly intervals using radar backscatter data (see (Rubel, 2004) for details). ELDAS surface longwave and shortwave downward radiation (ELDORADO) was calculated using the ECMWF radiative transfer code, adjusting the atmospheric profiles of cloud cover and water vapour content in order to match top of the atmosphere reflectances with METEOSAT satellite data (Meetschen *et al.*, 2004).

2 Validation of soil moisture

The lack of an extensive soil moisture observation network represents not only a problem for the initialization of NWP models, but also for the validation studies. As a matter of fact, most studies are therefore restricted either to a reduced number of validation points or to average values at catchment scale.

With these restrictions, the only remaining way of evaluating soil moisture is by using an atmospheric forecasting model and comparing the forecasted fields which are sensitive to soil moisture (usually 2-metre temperature and humidity) against the corresponding observations. This method has the obvious advantage of its globality. The usage of parallel runs with alternative formulations (in this case of soil moisture assimilation) and the comparison of scores is the basic tool in operational NWP to evaluate competing formulations. However, it must be always born in mind that models usually have compensation mechanisms to minimize errors usually coming either from observations or from other parts of the model. This is the case of the assimilation of soil moisture. Most operational soil moisture assimilation algorithms are designed to minimize forecasting errors in soil moisture sensitive fields, like *e.g.*, screen variables, radiometric surface skin temperature, or microwave brightness temperature. Consequently, it may happen that soil moisture can reach some unrealistic values and at the same time provide a robust way of minimizing errors of soil moisture sensitive variables.

An ideal module for land surface parameterization would only show a slight drift of soil moisture, provided that errors in forcing are negligible. The real situation is rather far from this idealistic picture. Operational systems frequently exhibit inadmissible soil moisture drifts originated by a conjunction of errors coming from the hydrological components of the land surface scheme, from the external forcing (singularly precipitation and radiation) and from an inaccurate assignation of vegetation and soil properties. As a consequence, the soil water increments needed to palliate this undesired drifts are rather big compared with the magnitude of forcing terms (*e.g.*, precipitation) and of single hydrological components (*e.g.*, runoff).

3 Description of the HIRLAM system set-up

The HIRLAM system is a complete NWP system including 3D variational assimilation of observations and a limited area short-range forecasting system (Unden *et al.*, 2002). It is currently used operationally by seven European Weather Services (Denmark, Finland, Iceland, Ireland, The Netherlands, Norway, Spain and Sweden).

The HIRLAM set-up used for all experiments here described has a rotated grid domain covering all Europe and North Atlantic. Horizontal resolution is 22 km with 31 levels in the vertical. The number of grid points is 406 x 324. The advection scheme is semi-Lagrangian with a time-step of 300 s. Each experiment has its own assimilation 6 h cycle both for upper air and for surface variables. ECMWF analyses are used for the lateral boundary conditions. The forecasting range is 48 h from 00 UTC analysis only. The simulated period covers a growing season from May 1 to October 31 of the ELDAS agreed year 2000. The comparison starts on June 1, leaving the first month (May) for the adaptation of soil moisture from its initial value (climatological for REF and homogeneous for ELD).

The physics package includes a surface scheme based on the ISBA scheme (Noilhan and Planton, 1989) without the tiled structure formulation used in the reference HIRLAM implementation. This modification was introduced to approach the surface formulation of the ARPEGE and HIRLAM models. The rest of the physics is based on Unden *et al.* (2002). The vegetation and soil description is based on the ECOCLIMAP database (Masson *et al.* 2003). The common physiographic description of ARPEGE and HIRLAM models will also facilitate a cleaner exportation from the soil moisture fields assimilated in the parent ARPEGE model and updated once a day (at 00 UTC) in the HIRLAM system.

4 Description of the compared soil moisture assimilation algorithms

The experiments described below differ only in the algorithms for soil moisture assimilation. The three algorithms used for soil moisture assimilation are briefly described below.

The default algorithm (REF) used in the HIRLAM system to initialize the surface and total water content is based on the sequential assimilation developed by Mahfouf (1991), with optimum coefficients approximated analytically by Bouttier *et al.* (1993a,b). The algorithm was totally rewritten for operational implementation in the ARPEGE model by Giard and Bazile (2000). The HIRLAM implementation follows this last algorithm and is fully compatible with the HIRLAM surface tiled scheme (Rodriguez *et al.*, 2002). Soil moisture corrections are linearly calculated by means of an optimum interpolation (OI) analysis from the analysed 2-metre temperature and relative humidity. Only conventional data is used to analyze 2-metre temperature and relative humidity.

The variational method (VAR) to initialize soil water content is based on the idea of minimizing a cost function which combines information from the forecast model and observed parameters. The algorithm implemented in the HIRLAM system is based on Balsamo *et al.*(2004). The cost function is of the form:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}(\mathbf{y}-H(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}-H(\mathbf{x})) \tag{2}$$

where $\mathbf{x}$ is the vector containing the control variables to be analized, $\mathbf{x}^b$ is the background state and $\mathbf{y}$ the observations vector. $\mathbf{B}$ and $\mathbf{R}$ are , respectively, the background and the observation error covariance matrices, and H is the observation operator that transports the model state vector, $\mathbf{x}$, into the observation space. Assuming a tangent linear (TL) hypothesis the H operator can be simply expressed by its first-order Taylor expansion, allowing to estimate the TL of the observator operator by mean of an extra integration of the forecast model from an initially perturbed soil moisture field. The gain matrix, relating the innovation vector (*i.e.*, the difference between the observation and the forecast model) and the analysis increment, can thus be explicitely calculated from $\mathbf{B}$, $\mathbf{R}$ and the TL observation operator matrix $\mathbf{H}$. In the variational analysis of the total soil water content, the linear hypothesis produces an important simplification that make it similar to the OI technique. Here however, due to the estimation method of H, a dynamical estimate of the gain matrix replaces its statistical evaluation (see Balsamo *et al.* (2004) for further details).

The so-called ELDAS (ELD) method to initialize soil water content will explore the utility of total water content assimilated by the global ARPEGE model and imported once a day to the HIRLAM system. This method poses the non-trivial question of the transferability of soil water fields among different models and for different applications. The assimilation of soil water content in the ARPEGE system was also based on the same variational approach implemented in HIRLAM and described by Balsamo *et al.* (2004). In order to compensate errors coming from the forcing by model precipitation, soil water content was corrected once a day by the difference between model and observed gridded precipitation. A number of modifications was introduced in the HIRLAM reference system in order to minimize the tranfer problems of soil moisture fields. Both systems, HIRLAM and ARPEGE, shared (i) the same resolution - although geometry is slightly different-; (ii) the same physiographic description based on the ECOCLIMAP database and (iii) the same scheme for surface processes based on ISBA. The new physiographic fields and the suppresion of tiling systems are the most relevant changes with respect to the HIRLAM reference system. The correction of soil moisture based on precipitation error is a compromise solution instead of forcing directly with observed ELDAS precipitation, allowing not to alter the structure of the ARPEGE code. There are, however, some differences in the final implementations of the VAR and ELD experiments. These differences are mainly referred to the size of the soil water content perturbations, the magnitude of soil moisture background error variance, the number of perturbations used to estimate the TL of H, the making algorithm and the length of the assimilation time window (6 h in VAR, 24 h in ELD).

5 Results

5.1 Impact of different soil moisture assimilation algorithms on forecasted screen variables

Most of the results shown here will be restricted to compare REF and ELD experiments. The VAR experiment was run only a few days mainly to ensure, first, that no special problems were presented in the exportation of soil moisture fields in the ELD experiment and, second, that the implementation of the variational code for soil moisture assimilation in the HIRLAM frame was supplying a soil moisture evolution comparable to that in the ARPEGE system. The VAR experiment with further retuning will be the base of the future soil moisture assimilation package in the HIRLAM system. This new frame will allow the assimilation of soil moisture sensitive satellite information, which is not currently assimilated.

Figure 1 (top left) shows the 36 h forecasted 2-metre temperatures bias for the reference experiment, REF, and averaged for the whole 5 months period. The bias is computed against all SYNOP stations in the model domain. All runs start at 00 UTC and verify at midday. In term of bias, the reference system is able to maintain values generally between +/-1 degrees. A slight cold bias is noticeable over some regions of Europe, being more systematic over Scandinavia and Northern Russia. Figure 1 (top right) shows the corresponding bias for the ELD experiment. The bias is also well controlled, with a predominancy also of colder biased regions. However, biased regions do not exactly coincide 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 cold 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 *e.g.*, 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 for the 36 h forecasted screen variables and for the whole period. Figure1 (bottom left) depicts the difference (REF-ELD) of rms error for 2-metre temperature. It is readily appreciated that differences are almost negligible. The corresponding map for 2-metre relative humidity (Figure 1 (bottom right)) shows also very small differences between both experiments. It can be therefore concluded that 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 5 months long period. 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.

5.2 Impact of different soil moisture assimilation algorithms on soil moisture fields

The biggest difference among the three soil moisture assimilation algorithms here compared appears when one looks into soil moisture evolution.

Figure 2 represents point evolution for some selected sites chosen from the list of ELDAS agreed evaluation sites. They correspond to Flevoland (Netherlands), Badajoz (Spain), Bordeaux (France) and Norunda (Sweden), respectively. The middle graphic from each point depicts the evolution of soil wetness index (SWI). SWI is defined by $(w-w_{wilt})/(w_{fc}-w_{wilt})$, where w_{fc}, w_{wilt} and w are the field capacity, the wilting point and actual soil water content, respectively. It takes the value 1 for soil water content at the field capacity, 0 for soil water content at the wilting point, negative values for soil water content below the wilting point and values bigger than one for soil water content between the field capacity and the saturation point. Values of SWI show in some cases a rather big discrepancy depending on the chosen soil moisture assimilation procedure. The first noticeable feature is that REF experiment tends to show bigger soil moisture corrections than ELD experiment. This fact is due to the excessively large corrections of the 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 feature was already known and the comparison with the other assimilation experiments has allowed a quantification of the magnitude of the problem.

The soil moisture evolution corresponding to the VAR experiment shows in general, as expected, an evolution close to that of ELD experiment. However, some of the points here selected (*e.g.*, Badajoz, Bordeaux and Norunda) show a clear divergence between VAR and ELD. A further analysis allows to interprete such difference as due to the difference in size of the soil moisture perturbation used by the ARPEGE and HIRLAM implementations. The perturbation used in HIRLAM was 5 times bigger than the corresponding in ARPEGE.

This too large perturbation causes excessive soil moisture corrections which are possibly not compatible with the tangent linear approximation in the variational approach. To palliate this behaviour, the size of perturbation should be reduced and either some more restrictive masking conditions may be imposed or a second perturbed integration with opposite sign can be additionally run. This last alternative, however, is too costly in an operational implementation.

Figure 3 shows the monthly averaged soil moisture increments (analysis minus first guess, expressed in mm/day) for the REF experiment. There is a clear predominance of water addition in particular for June and July. Figure 4 shows the corresponding figure for the ELD experiment. Water addition is also the general trend, although this feature is reversed over the most Nordic regions. In general, the pattern tends to be more noisy for the REF experiment than for the ELD experiment, consistently with the REF overcorrection already mentioned.

Figures 5 represent the July and August rms error of soil moisture increments for REF (top) and ELD (bottom) experiments, respectively. The clear bigger magnitude of REF rms error is a further confirmation of the REF overcorrection.

5.3 Soil moisture analysis increments and water balance

The study of soil moisture analysis increments provides a valuable source of information on model deficiencies. Ideally, soil moisture increments should be significant smaller than any of the terms 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.

Figure 2 provides some hints on the usage of soil moisture increments for some particular points. All selected points shown here have a positive contribution of the soil moisture analysis which is consistent with Figs. 3 and 4. However, how soil moisture increments are distributed among different hydrological terms change from point to point.

The Flevoland (Netherlands) point (Fig. 2 (upper left)) has a contribution of soil moisture analysis which is rather comparable with model precipitation, at least until the end of September. The variation of soil moisture stored in the soil is a significantly smaller term. The accumulated evapotranspiration approximately compensates the added contribution of model precipitation and analysis increments. The runoff term -not represented here- is also a minor term. The analysed precipitation is subtantially bigger than the modelled one. Therefore, it can be hypothesized that here the positive soil water analysis increment is added to compensate the insufficient model precipitation. In fact, difference between analyzed and modelled precipitation is approximately of the same order than soil moisture increment.

The Badajoz (Spain) point (Fig. 2 (upper right)) has almost no contribution from precipitation. Also the variation of soil moisture in the soil is rather small and it evolves around the wilting point. Therefore, the only two remaining terms are the accumulated soil moisture increments and the accumulated evapotranspiration. They roughly compensate each other. This behaviour is very representative of many Mediterranean regions and of most of the Southern part of the Iberian peninsula. Several explanations could be advanced, however the most plausible one is the absence of some irrigation term in the budget. Many Mediterranean regions lack of precipitation during the summer season and nevertheless they get the necessary supply of water for crops from ground water reservoirs or from dams. This water management is not at all contemplated by models. Another alternative explanation could be the lack of representativeness of screen level observations. SYNOP temperature and relative humidity are frequently measured over grassy terrain. As a consequence, the modelled atmosphere is drier and warmer than the corresponding analysis and this fact is compensated by adding water during the soil moisture assimilation step.

The Bordeaux (France) point (Fig. 2 (bottom left)) shows many similarities with Flevoland. However, the main contributor of water here is the analysis increment. The difference between the analized and modelled precipitation does not absorb the total amount of the analysis increment, although it contributes substantially to it. Another factor playing a role here is the difference between the observed (ELDORADO) and modelled accumulated downwards short wave radiation. The model short wave radiation term is bigger than the corresponding observation, implying bigger evapotranspiration and therefore more water comsumption which has to be compensated by the analysis increment.

Finally, the Norunda (Sweden) point (Fig. 2 (bottom right)) has a relatively small contribution from the accumulated soil moisture increments (close to zero for ELD experiment) and from the variation of soil moisture in the soil. The major terms here are the accumulated precipitation and evapotranspiration. It is noticeable here the big difference appearing in terms of SWI bewteen both experiments. This can be probably due to the very different initial conditions and to the poor coupling between soil moisture and screen variables preventing big soil moisture corrections.

6 Conclusions

Three different soil moisture assimilation schemes have been compared using the operational HIRLAM model. The comparison has covered a whole growing season from June to October 2000. In terms of impact on screen level temperature and relative humidity, no big differences were found among the three schemes. This is not surprising as all three schemes are based on the minimization of screen variable errors.

In terms of impact on soil moisture field, it was demonstrated that the default OI scheme in the HIRLAM system (REF experiment) showed a marked tendency to overcorrect soil moisture. The ELDAS generated soil moisture field (ELD experiment) showed a more realistic soil moisture evolution and soil moisture analysis increments. The variational method (VAR experiment) implemented for soil moisture assimilation within the HIRLAM system also showed overcorrection due to the excessively large soil moisture perturbations used by the computation of the pertubed integration.

The analysis of water balance and of forcing terms (precipitation and short wave radiation) for the studied specific points seems to indicate that no substantial differences appear between REF and ELD experiments. The accumulated soil moisture increments and their assignation to the different hydrological terms show big similarities between both experiments.

In general, it can be concluded that for the growing period here discussed there is a net contribution of soil moisture coming from the analysis increments. Some systematic behaviour requiring further study has been observed over certain regions, *e.g.*, the huge demand of water supplied by the soil moisture analysis and converted directly to the evapotranspiration. This behaviour suggests the existance of water sources not contemplated by the model or problems of representativeness.

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 scheme. Some of the major defficiencies associated to the surface scheme itself appear consistently in both REF and ELD experiments. The implementation of the variational soil moisture approach within the HIRLAM system will pave the way for the assimilation of IR and MW satellite information by the HIRLAM system.

Acknowledgements. The authors are very grateful to Gianpaolo Balsamo (Environment Canada) and Francois Bouyssel (CNRM/Météo-France) for providing the variational code and for the fruitful discussions. Thanks go also to Bart van den Hurk for his useful comments on the comparison results. We would like to mention the inspiring influence of our ELDAS colleagues and finally we ackwnoledge the persons and institutions making possible the precipitation analysis, which was of paramount importance for the success of the ELDAS project.

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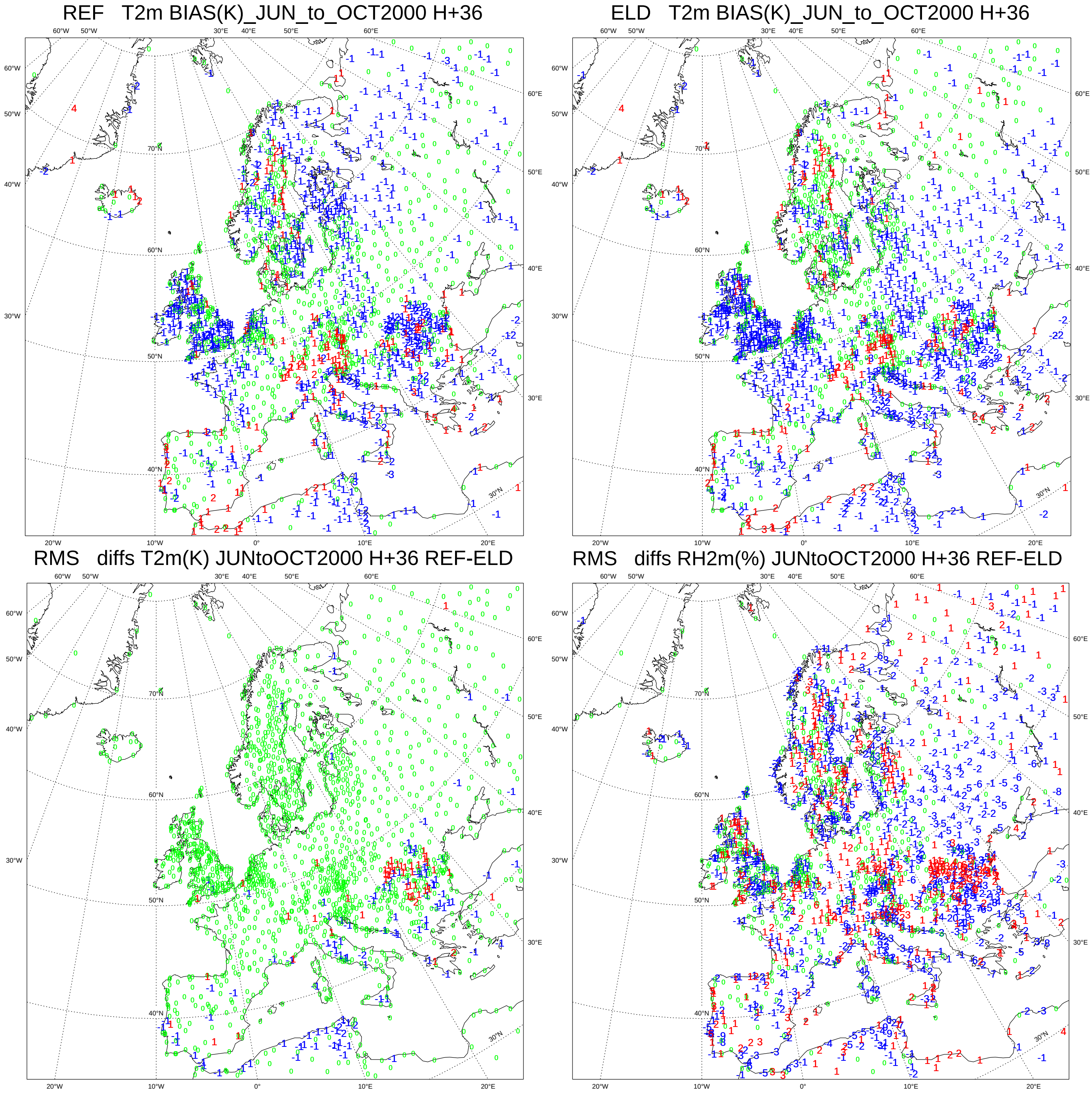


Figure 1: 2-metre temperature bias (forecast minus observation) in H+36 forecasts valid at 12 UTC. All daily integrations from June 1 up to October 31 are averaged for REF (upper left) and ELD (upper right) experiments. Difference of rms error (REF minus ELD) for 2-metre temperature (bottom left) and 2-metre relative humidity (bottom right).

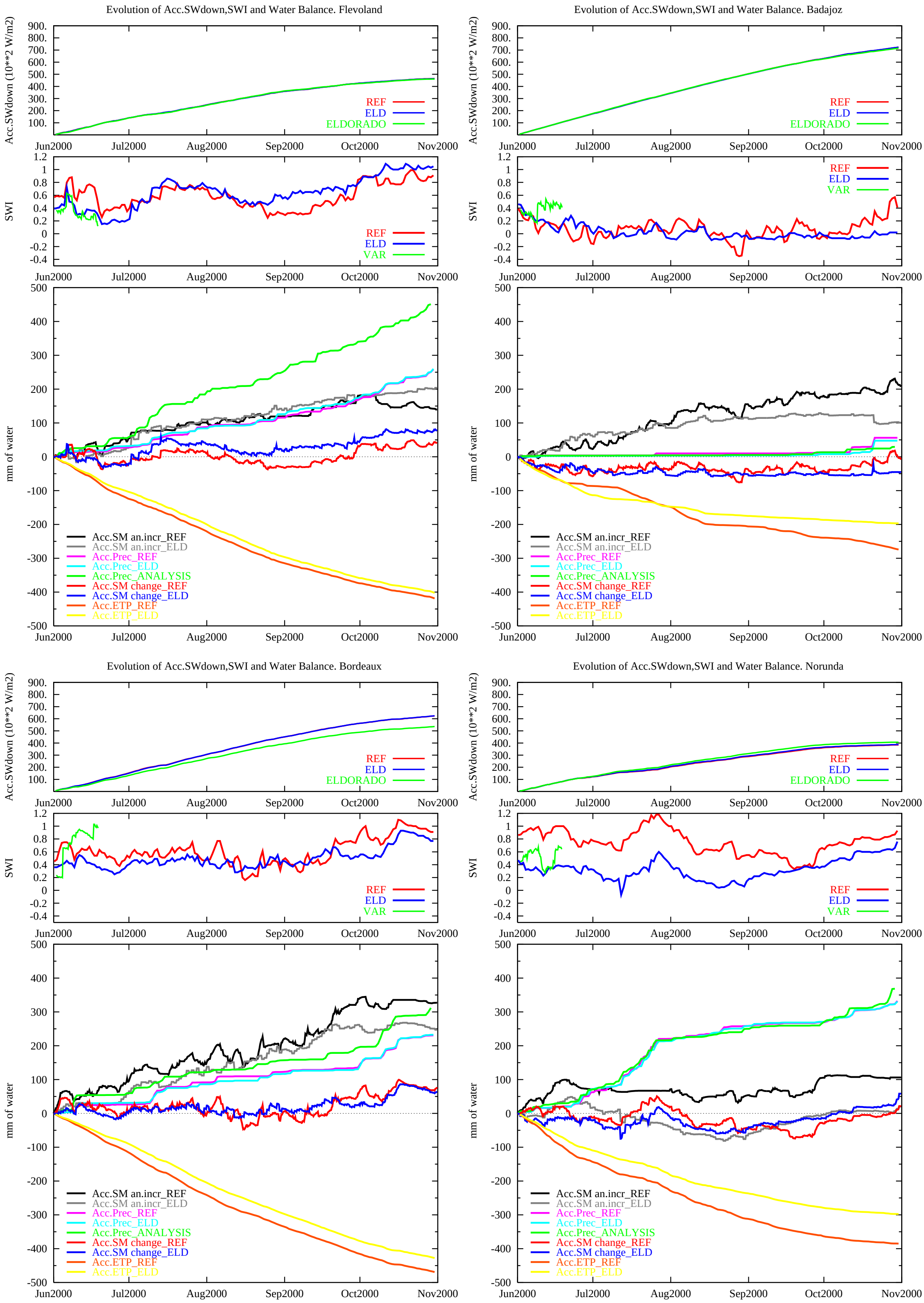


Figure 2: Evolution of the accumulated daily averaged (from 06 to 18 UTC) short wave radiation downwards (REF, ELD and ELDORADO), of Soil Wetness Index (REF, ELD and VAR) and of accumulated water balance terms (REF and ELD) for the following points: Flevoland (Netherlands), Badajoz (Spain), Bordeaux (France) and Norunda (Sweden)

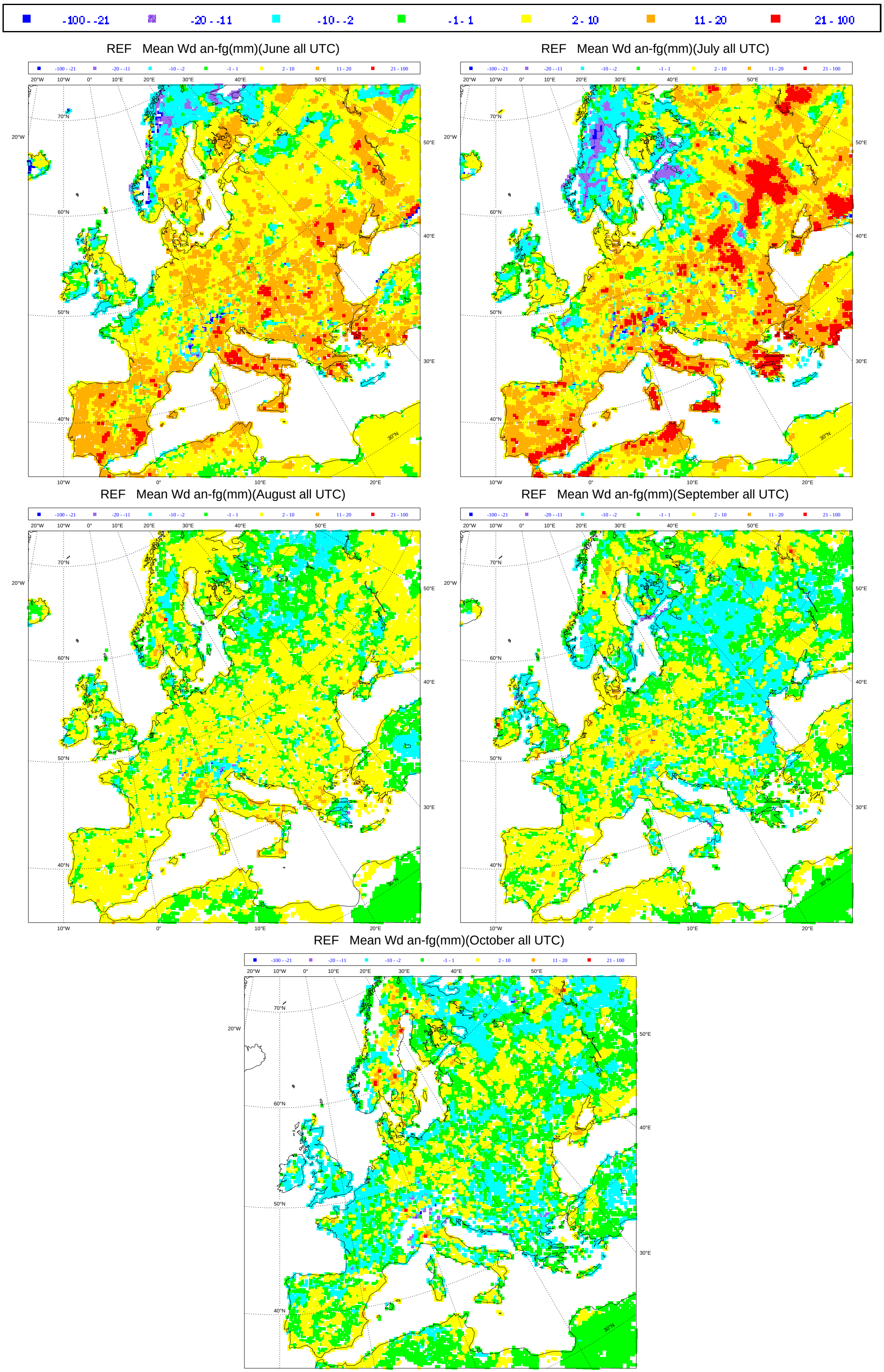


Figure 3: Monthly averaged (from June to October 2000) soil moisture increments (analysis minus first guess, expressed in mm) for the REF experiment.

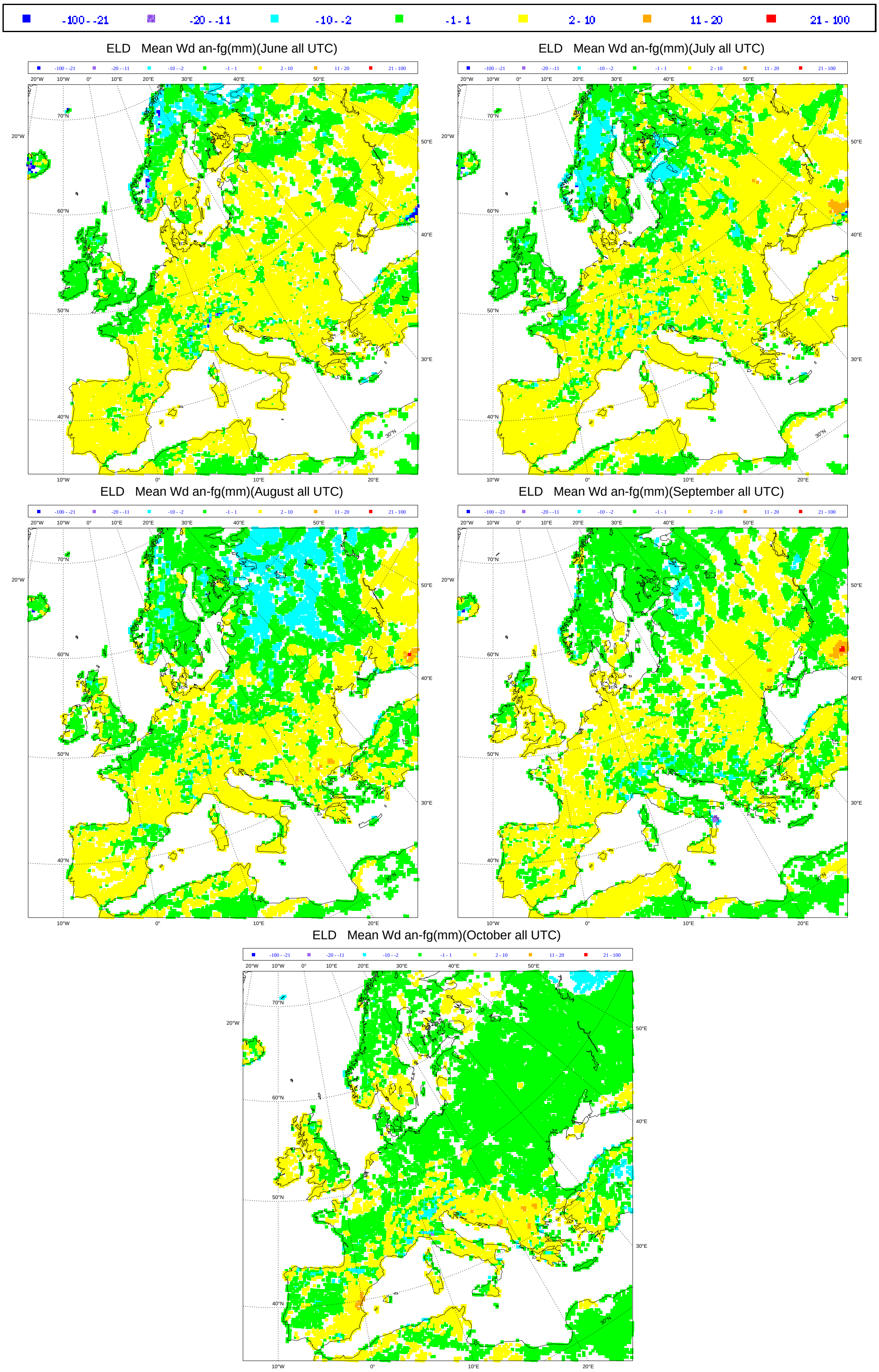
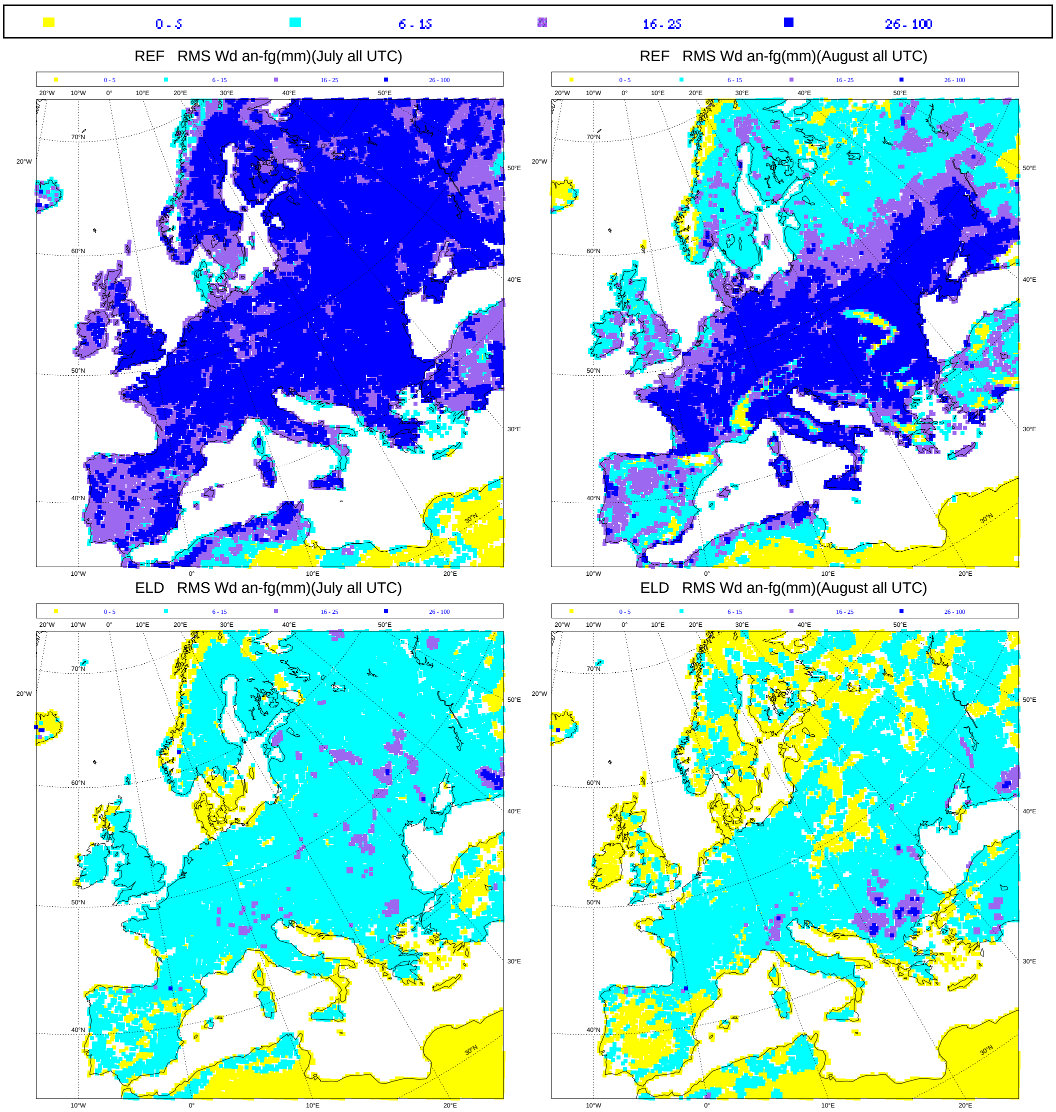


Figure 4: Monthly averaged (from June to October 2000) soil moisture increments (analysis minus HIRLAM first guess, expressed in mm) for the ELD experiment.



REF RMS Wd an-fg(mm)(July all UTC)

REF RMS Wd an-fg(mm)(August all UTC)

ELD RMS Wd an-fg(mm)(July all UTC)

ELD RMS Wd an-fg(mm)(August all UTC)

Figure 5: Monthly averaged (July and August) rms error of soil moisture increments (analysis minus HIRLAM first guess, expressed in mm) for REF (top) and ELD (bottom) experiments.