TECHNICAL MEMORANDUM

258

The ECMWF surface analysis: Diagnostics and prospects

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Part I

Current status of the ECMWF operational soil moisture analysis

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1 Introduction

The purpose of this short note is first to describe the diurnal and seasonal behaviour of the ECMWF operational soil moisture analysis. This analysis was implemented in December 1994 (Viterbo and Courtier 1995) and is based on the low level specific humidity increments which are used to correct soil moisture in the top three layers of the ECMWF land surface scheme (Viterbo and Beljaars 1995). Recent comparisons of the ECMWF reanalysis (ERA) 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 deficiencies in the model's climatology. 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 a negative and positive nudging 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. (1998) suggested that the absence of an annual cycle in the ECMWF model vegetation might be partly responsible for the systematic seasonal behaviour of the soil moisture analysis. They also demonstrated that the nudging was a non-negligible component of the soil water budget.

The second half of this note compares the ECMWF vegetation properties and the ERA surface water balance with inputs and outputs of the international Global Soil Wetness Project (GSWP). In this project, state-of-the-art land surface schemes using prescribed soil and vegetation properties have been forced with meteorological observations and analysis provided on the ISLSCP Initiative I CD-ROM. The objective was to produce a global soil wetness climatology at a $1^\circ \times 1^\circ$ horizontal resolution between January 1987 and December 1988. The monthly mean surface evaporation from the ERA are validated against the GSWP simulation performed with the ISBA scheme of Météo-France. This simulation may be considered as a reference though some analysis suggest that the evaporation might be overestimated in this data set (Douville 1998).

Coming back to the ECMWF operational forecast, the third and last section of the present study compares first guess precipitation errors with soil moisture increments on a monthly basis, in order to check if the increments compensate for the precipitation errors or respond to other model biases. Forecast errors were estimated on the global scale by using the CAMS-OPI monthly mean precipitation data set (1979-1997) from NCEP, derived from station gauges and satellite estimates. The original data available at a 2.5° horizontal resolution is interpolated onto a T42 Gaussian grid. The first guess precipitation was interpolated onto the same grid in order to compute difference maps. The precipitation forecast (48-72h) was also compared with both the observations and the first guess, in order to check if the forecast is significantly better than the first guess, once the initial spin-up period is over. These comparisons are based on January, April, July and October 1996 and 1997, which are supposed to be representative of the three years since the implementation of the current soil moisture analysis.

2 Diurnal and seasonal cycles of the soil moisture increments

2.1 Diurnal cycle

Figures 1 and 2 show monthly mean soil moisture increments for each 6-hour analysis cycle, respectively in January and July 1997. The maps indicate that the conclusions drawn by Betts et al. (1998) about the ERA deficiencies over the FIFE domain (Kansas) are also valid on the global scale. The soil moisture increments are generally positive between 4 pm and 4 am LT and negative between 6 am and 2 pm LT, which is consistent with the overestimated midmorning peak and overestimated late afternoon minimum of specific humidity emphasised in this previous study.

Due to the low surface temperatures and to the presence of snow, the soil moisture analysis is rarely activated in the high-latitudes of the winter hemisphere, which is more obvious in July than in January because of the geographical distribution of the continents. Though it was shown only for January and July 1997, the systematic diurnal cycle of the increments is found in both hemispheres for any season of any year. The monthly mean increments rarely reach more than 5 mm per 6 hours for 1 metre of soil, but they often reach 2 mm, which means more than 60 mm per month. The daily standard deviation within a month is of the same order of magnitude.

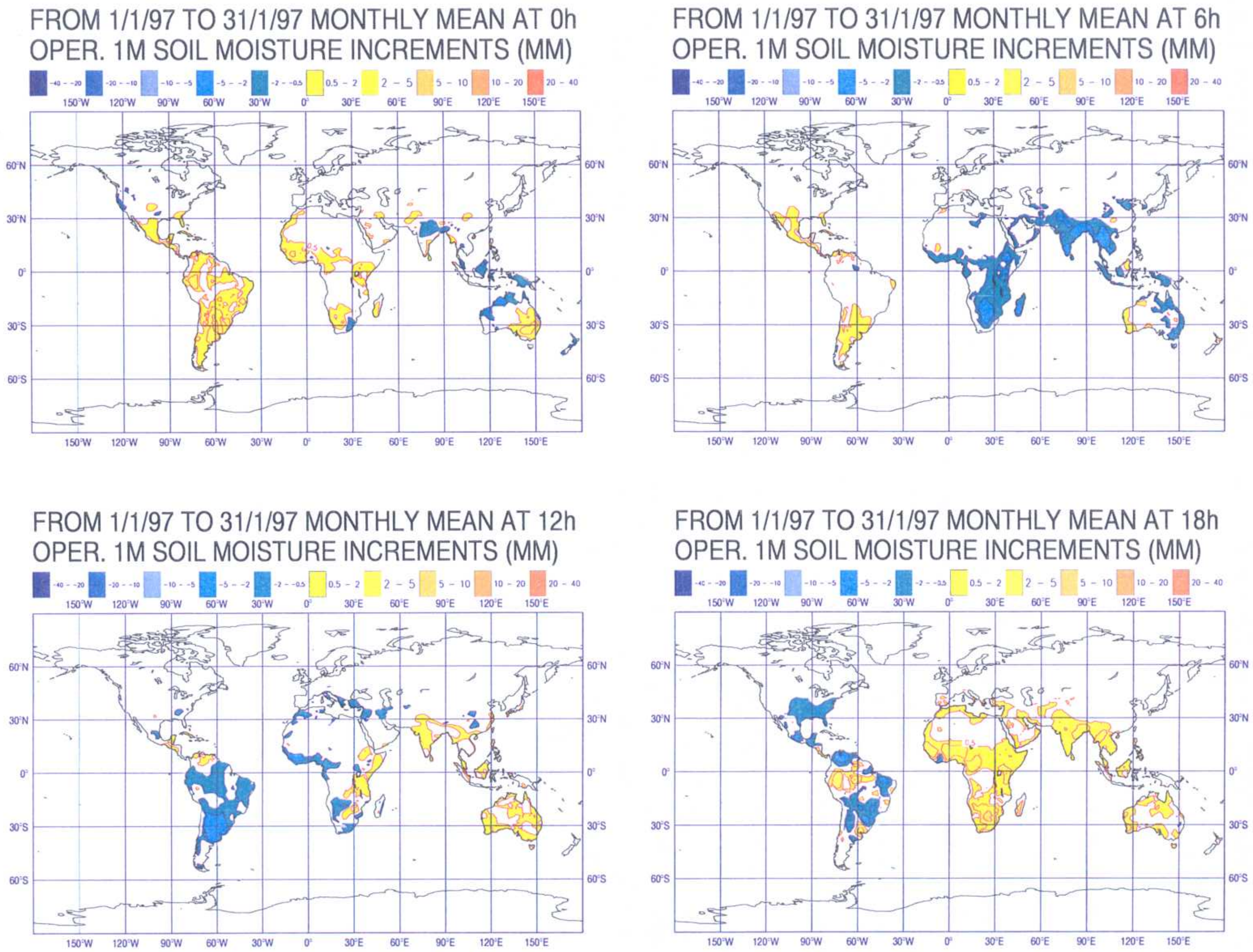


Fig. 1 January 1997 monthly mean soil moisture increments (mm per 6 hours) at 0, 6, 12 and 18h.

2.2 Seasonal cycle

Figures 3 shows the global monthly mean distributions of the daily soil moisture increments (sum of the four 6-hour analysis cycles) for January, April, July and October 1997. Globally averaged, the increments are always positive (between 0.32 and 0.52 mm/day) with a spatial standard deviation exceeding 1 mm/day (Table 1). There are large scale patterns of either positive or negative values instead of a noisy distribution, suggesting that the soil moisture analysis exhibits a systematic seasonal behaviour to compensate for model biases in the low atmosphere.

This is even more obvious when looking at the difference maps between July and January 1997, both for the soil moisture increments and the analysed first metre soil water content itself (Figure 4). The seasonal cycle of the soil water content seems to be reasonable on the global scale, with strong positive and negative patterns in the tropics, due to the seasonal shift of the ITCZ. The seasonal cycle is less clear in the Northern Hemisphere mid-and-high latitudes and seems to be questionable even qualitatively in some areas, which will be further discussed in the next section. But the most striking feature in Figure 4 is that the soil moisture nudging tends to damp the seasonal cycle in most areas and especially in the tropics, as indicated by the opposite patterns between the two maps. Though a more detailed analysis would need inspection of the monthly evolution of the soil moisture increments, the July minus January difference is a strong evidence that the nudging does not only compensate for biases in the diurnal cycle but also in the seasonal cycle. This is consistent with the conclusions of Betts et al. (1998) which therefore apply to most of the continental areas. The damping of the seasonal cycle is found in 1996 as well. Some possible reasons for that systematic behaviour will be provided in section 3.

Table 1 gives a few statistics about the spatial distribution of the increments. The global mean increments, averaged over all land grid points, are always positive, suggesting that the nudging compensates for a systematic bias in the soil water budget, which might be due to an overestimated surface evaporation (see section 3). This hypothesis is reinforced by higher positive values in July than in April, suggesting that the bias is stronger when it is summer in the dominant Northern Hemisphere. The standard deviation of the monthly mean increments is around 1.5 mm/day in 1996, but is 20% lower in 1997. The global mean increment also shows a decrease of about 0.2 mm/day between the two years. This result could suggest an improvement in the first guess forecast, but further results (section 4) indicate that it is not true as far as precipitation is concerned. The decrease in increments might be rather due to a better description of the boundary layer, possibly related to several improvements introduced at the end of 1996 in the operational forecast model (soil freezing and enhanced turbulent fluxes under stable conditions, Viterbo et al. 1998, boreal forests' albedo, Viterbo and Betts 1998).

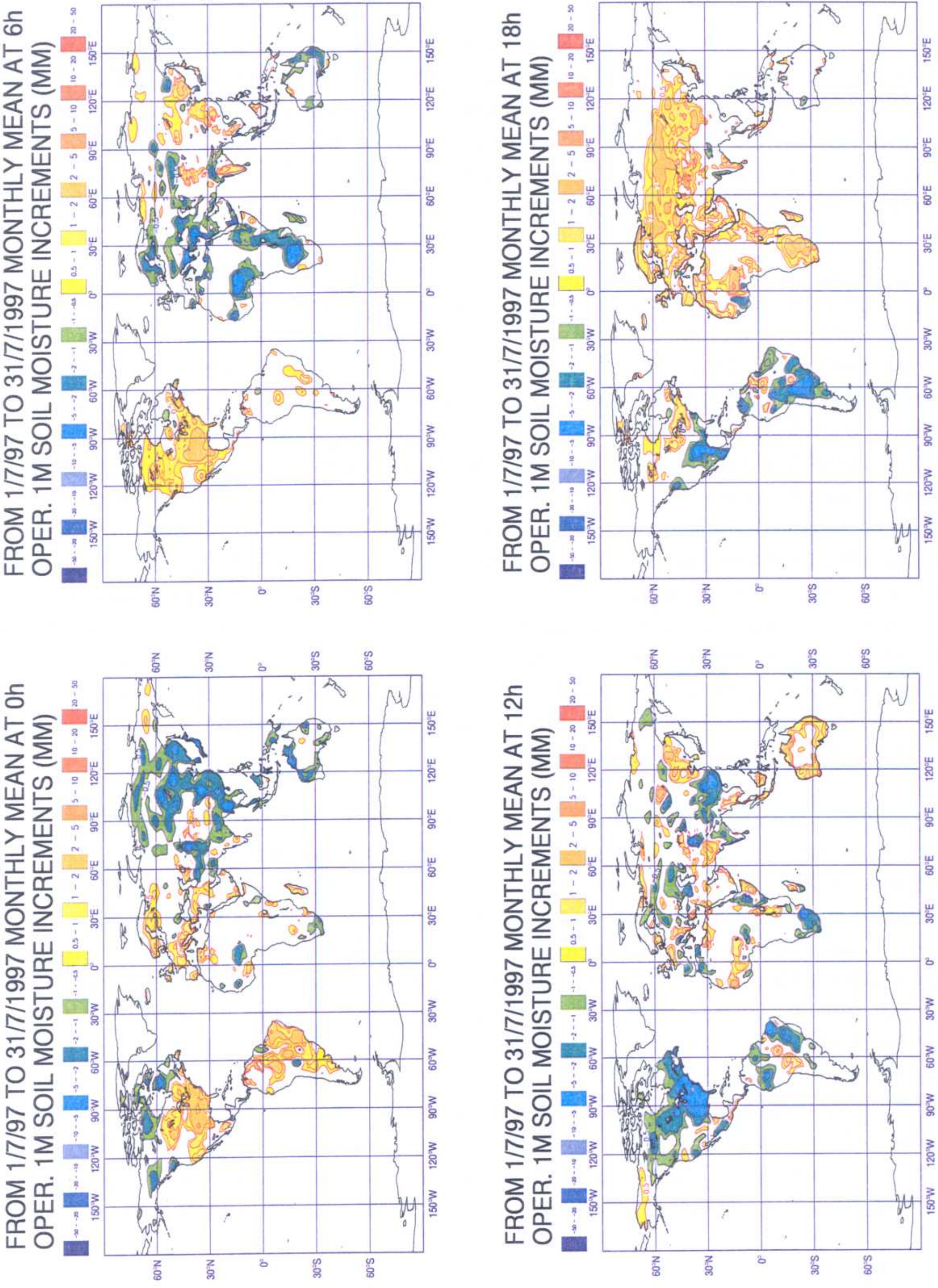


Fig. 2 July 1997 monthly mean soil moisture increments (mm per 6 hours) at 0, 6, 12 and 18h.

Month	Jan	Apr	Jul	Oct	All
1996 mean	0.41	0.39	0.90	0.58	0.67
1996 stdev	1.58	1.52	1.59	1.35	1.51
1997 mean	0.32	0.46	0.52	0.34	0.41
1997 stdev	1.16	1.41	1.40	1.15	1.28

Table 1: Global land mean and standard deviation of monthly mean soil moisture increments (mm/day); the last column gives the 4-month average of the monthly statistics.

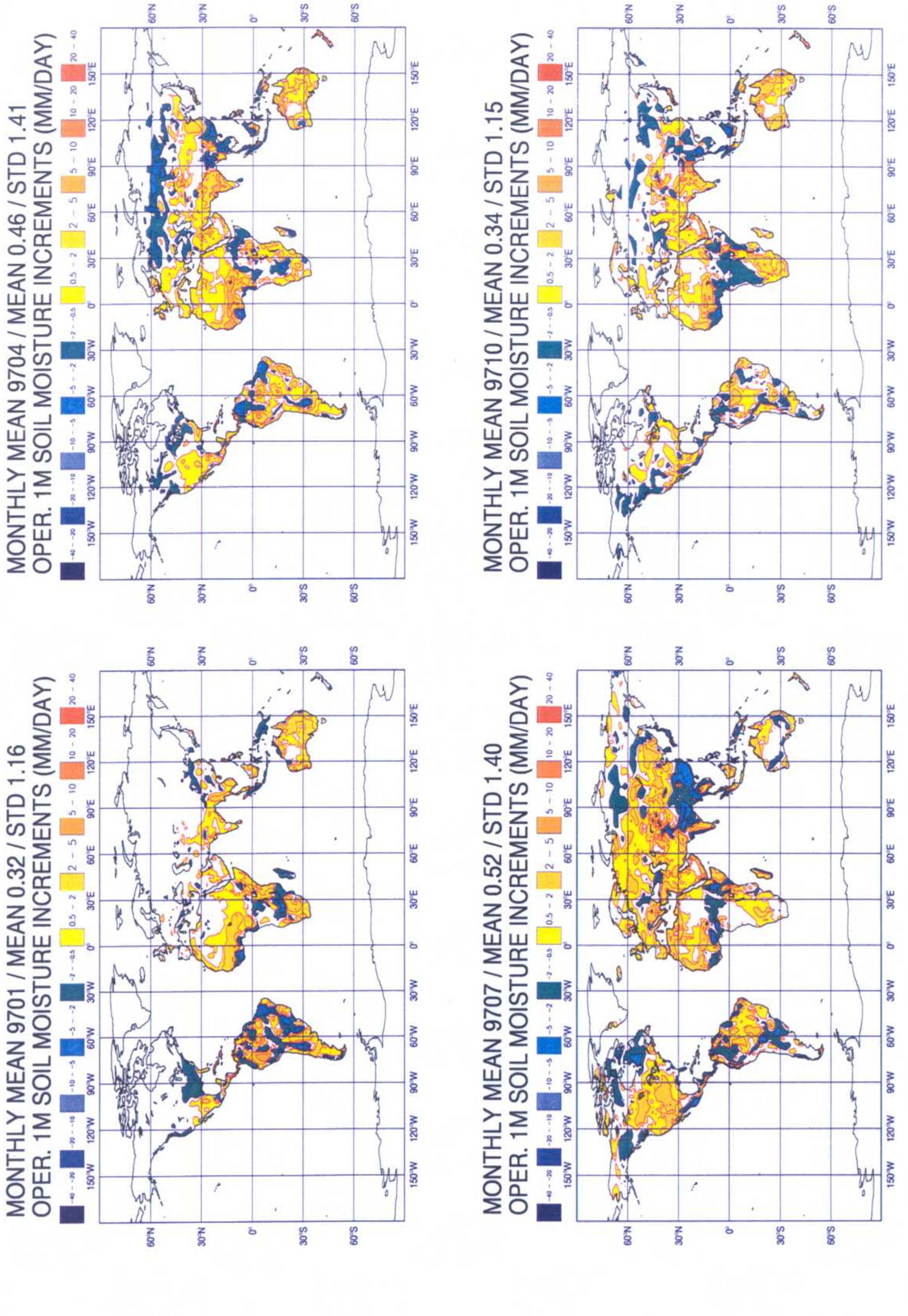


Fig. 3 Monthly mean of the daily soil moisture increments (mm/day) in January, April, July and October 1997.

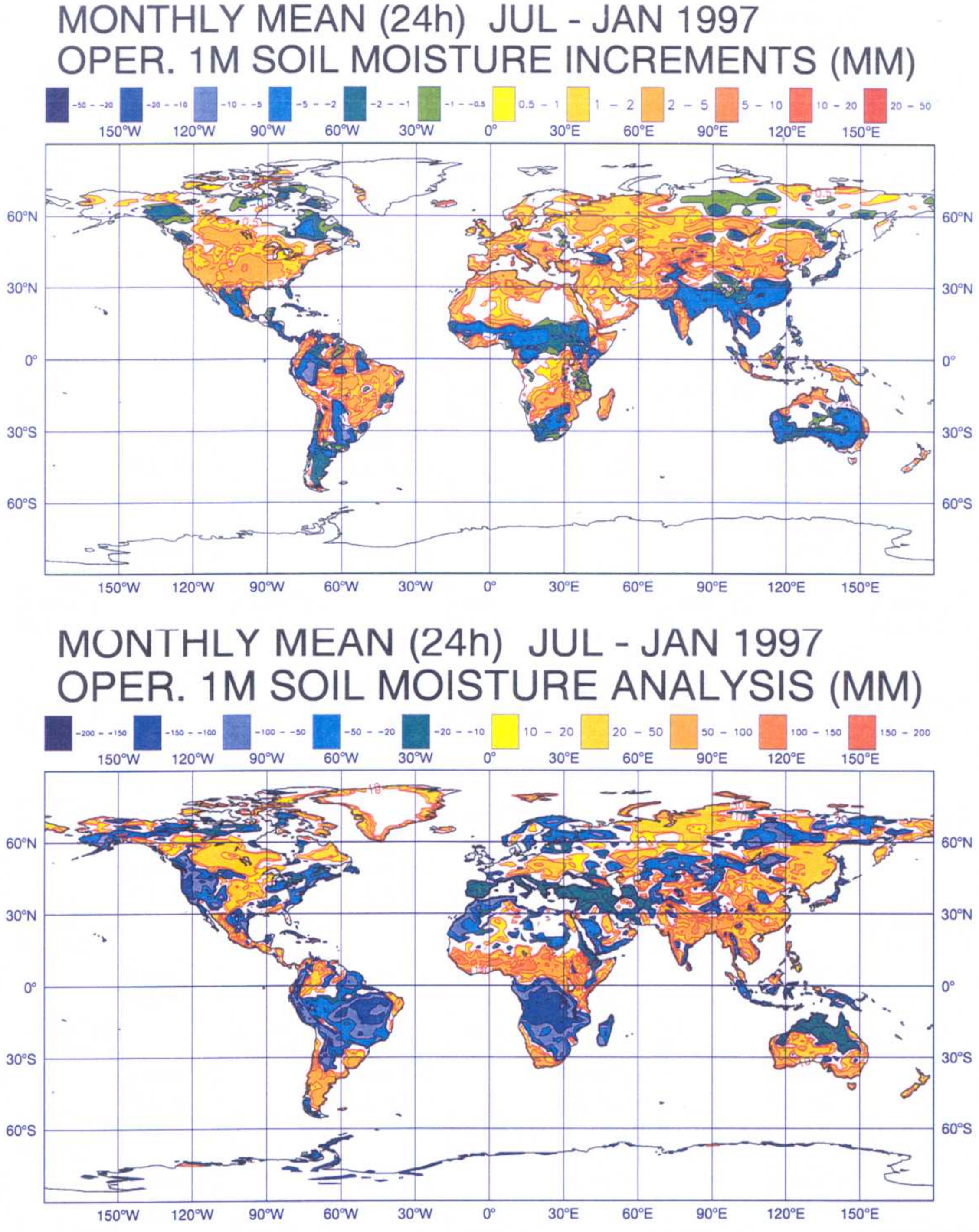


Fig. 4 Seasonal cycle (July minus January 1997) of the soil moisture increments (mm/day) and the analysed first metre soil water contents (mm).

3 ECMWF/ERA versus ISLSCP/GSWP

3.1 Surface water balance

The aim of this section is to compare the surface water balance between the ERA and the GSWP inputs and outputs of Météo-France. This data set covers only the period 1987-1988. It has been derived from a stand-alone simulation forced by observed precipitation (GPCP) and downward radiation (ISCCP) as well as analysed meteorological near-surface parameters (ECMWF analysis). Figure 5 compares the GPCP precipitation forcing with the ERA precipitation (derived from the 12-24h forecasts starting at 0 and 12 UTC) for January and July 1987. Generally, the reanalysis is quite close to the GPCP climatology, which indicates that the comparison of surface evaporation between ERA and GSWP is meaningful.

Figure 6 shows that the ERA evaporation is globally consistent with the GSWP results. However, some discrepancies are noticeable, both in January and July. On one hand, the maximum evaporation seems to be underestimated over the tropical forests during the rainy season despite an overestimation of rainfall. On the other hand, evaporation seems to be overestimated over semi-arid areas, over each side of the ITCZ, and at the transition between the tropics and the winter mid-latitudes. This mid-latitudes positive bias is more obvious in spring and autumn (not shown), which seems to confirm Betts' hypothesis that the absence of an annual cycle in the model vegetation might be a significant limitation to the realism of the simulated surface hydrology.

Figure 7 shows the 1987 seasonal cycle of the soil wetness index ($SWI = (\theta - \theta_{pwp})/(\theta_{cap} - \theta_{pwp})$, where θ, θ_{pwp}, and θ_{cap} represent the root zone soil wetness and its value at the permanent wilting point and field capacity, respectively), summarised by the difference between July and January. In the tropics, where the precipitation and radiative forcing is very strong, the ERA SWI shows reasonable seasonal variations. But it is much less consistent with GSWP in the mid-and-high latitudes. The most striking deficiency appears in the high latitudes and mountainous regions of the Northern hemisphere, where the springtime snow melt does not lead to a maximum soil wetness in summer, as noticed in the GSWP data set whose snow cover was shown to be quite realistic (Douville 1998). This problem has already been raised by Douville (1998) who has compared the normalized annual harmonic vectors between the ERA and GSWP monthly mean SWI in 1987 (Figure 8). Whereas the GSWP vectors exhibit large scale patterns showing a time-lag between the melting season in the mid and in the high latitudes, the ERA vectors point in many directions, suggesting that the snowmelt forcing is wrong or too weak to mask the spurious effects of the soil moisture analysis.

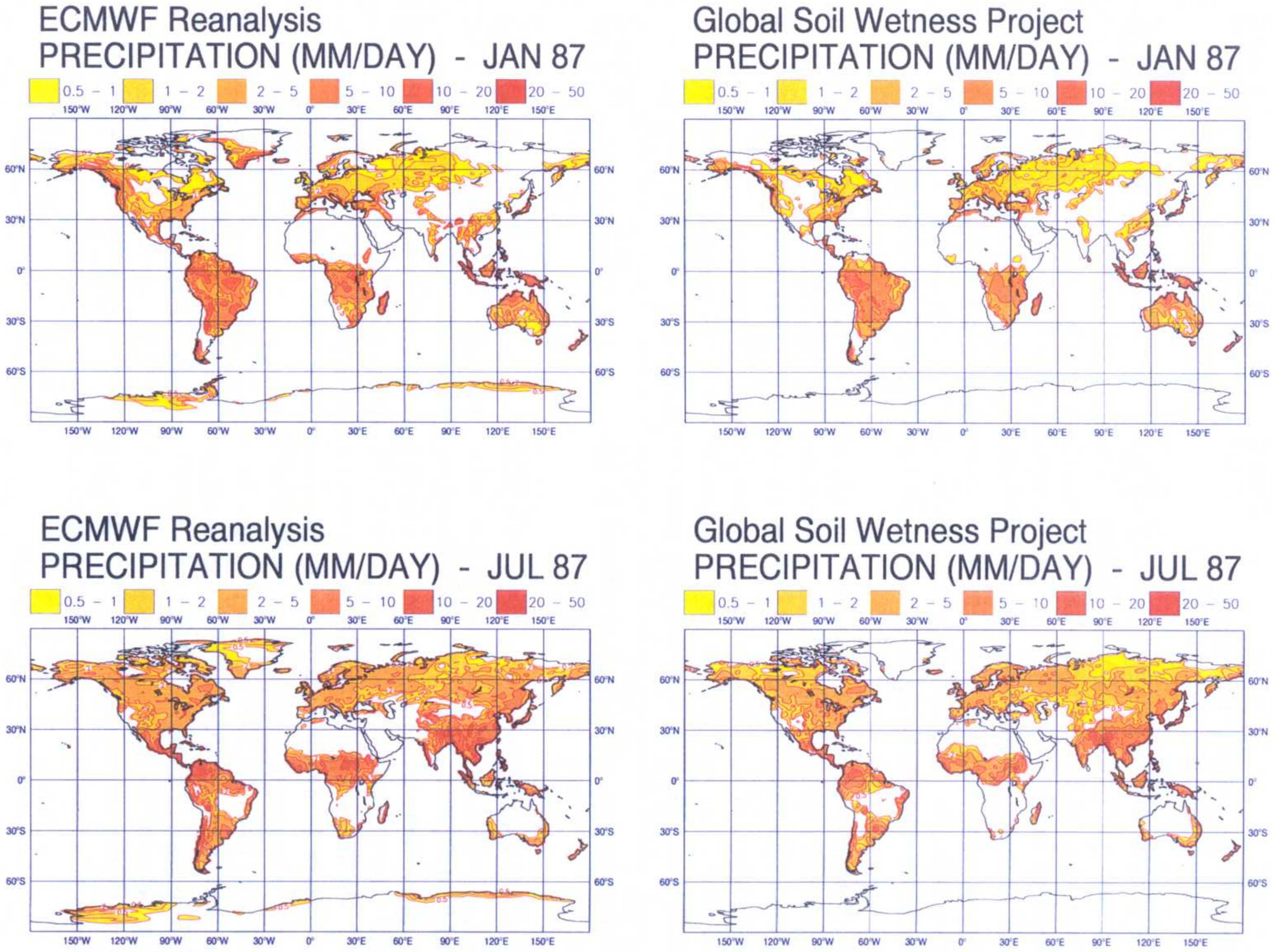


Fig. 5 Monthly mean total precipitation (mm/day): comparison between ERAand GSWP in January 1987 (left) and July 1987 (right).

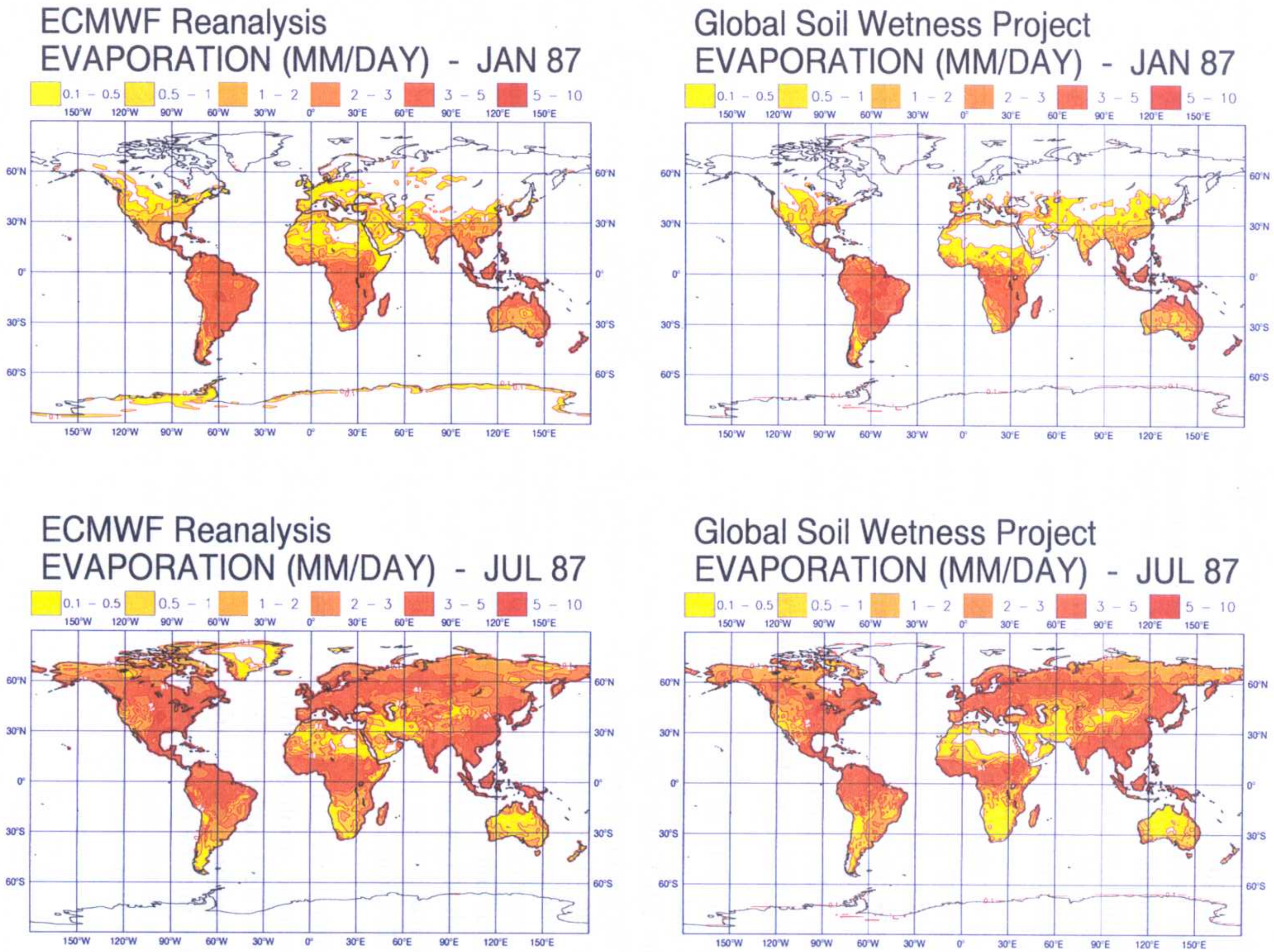


Fig. 6 Monthly mean total surface evaporation (mm/day): comparison between ERA and GSWP in January 1987 (left) and July 1987 (right).

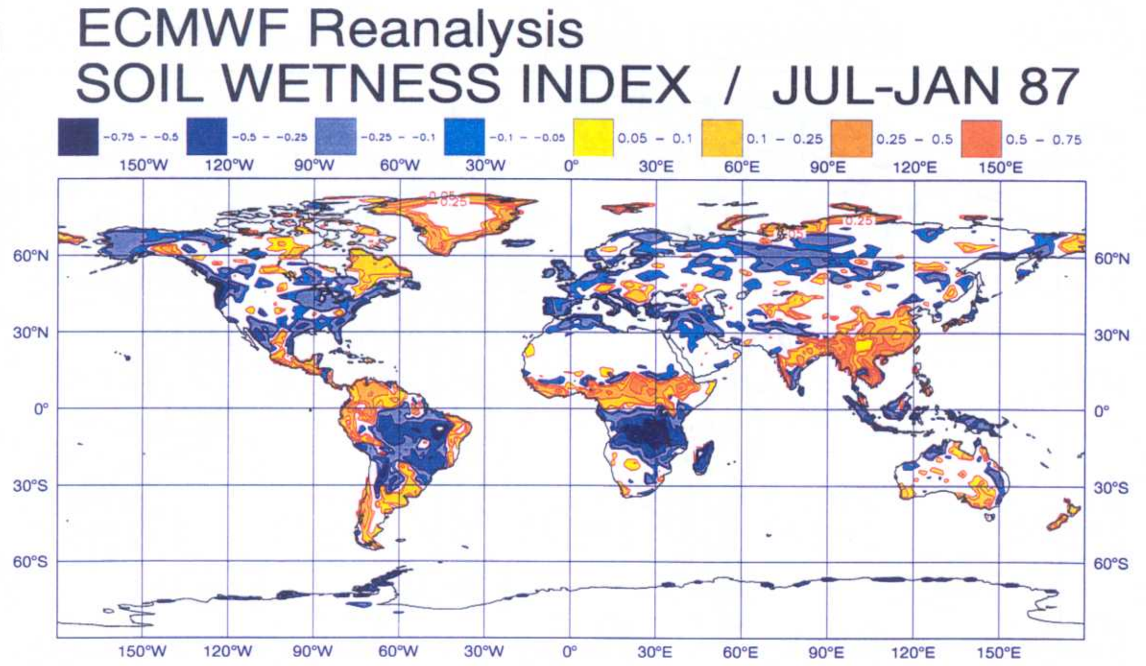
3.2 Land surface properties

The vegetation properties in the ECMWF model are fixed and sometimes uniform, a strong approximation likely to generate substantial biases in the surface fluxes. Figure 9 shows difference maps between the fixed ECMWF vegetation cover and observed monthly vegetation covers provided by the ISLSCP/GSWP data set and derived from satellite measurements. The ECMWF values are much higher than the satellite estimates almost everywhere, except over some desert areas and the tropical forests. The overestimation is greater in winter than in summer in the mid-latitudes where the observations indicate a strong annual cycle.

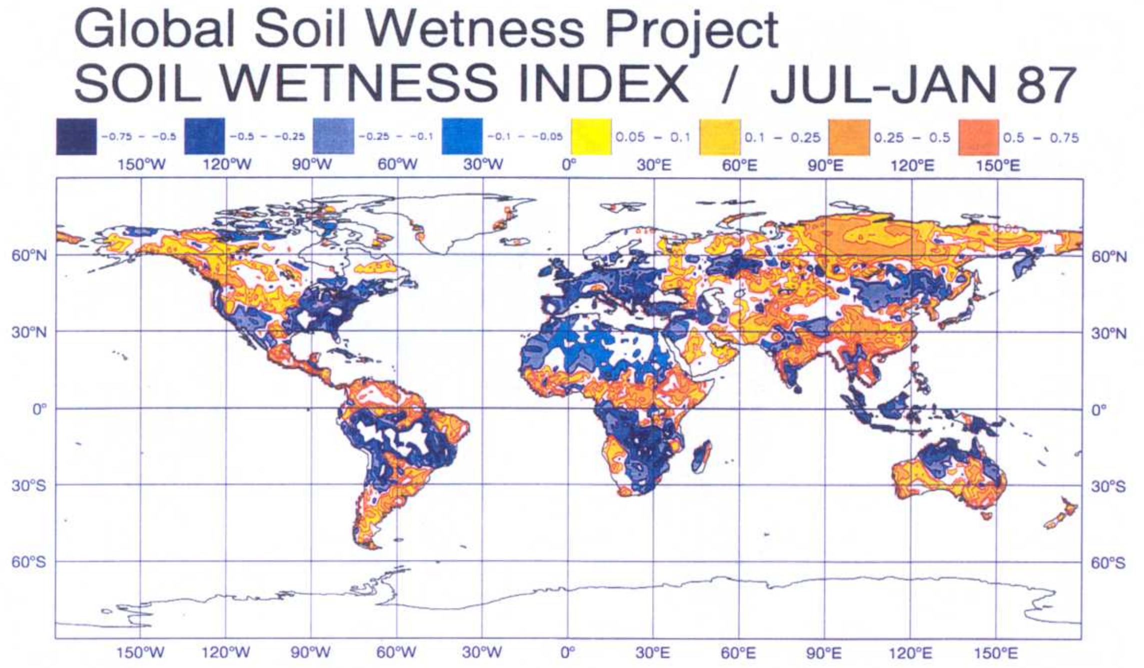
Figure 10 shows similar difference maps for the ratio R_{smin}/LAI, which represents the canopy conductance that partly determins the plants' transpiration and is fixed and uniform in the ECMWF model (60 s/m). Comparison with the ISLSCP data set reveals that this value is much too weak over most areas, especially in winter when the leaf area index (LAI) is low, and over arid areas where the ISLSCP values are so high that the canopy conductance is close to zero. On the other hand, the ECMWF value is too large for the tropical rain forests, as well as for the temperate and boreal forests in summer.

The lack of realism in the description of the vegetation properties in the ECMWF model is obvious and its apparent deficiencies are quite consistent with the discrepancies noticed between the ERA and GSWP surface evaporation. The evaporation is generally too strong due to an overestimation of both the vegetation cover and the canopy conductance. It is too low during the rainy season over the tropical forest due to a reasonable vegetation cover but an underestimated canopy conductance. It is correct over the mid-latitudes forests in summer due to the counterbalance between an overestimated vegetation cover and an underestimated canopy conductance. Note finally that another vegetation parameter may be relevant, namely the rooting depth, which is 1 metre everywhere in the ECMWF model, which may be too low for tropical forests and too deep for low vegetation and may reinforce some of the biases previously described.

These possible errors in the surface evaporation could be partly compensated for by the soil moisture nudging, applied with a weaker relaxation in the ERA than in the operational forecast. Moreover, the land surface evaporation is not the only source of error in the low level humidity, so that the nudging may change the evaporation in the wrong direction in some cases. The soil moisture increments shown in section 2 suggest that this actually happens in summer in the Northern Hemisphere where the increments are often positive, but the surface evaporation seems to be either reasonable or overestimated.



ECMWF Reanalysis
SOIL WETNESS INDEX / JUL-JAN 87



Global Soil Wetness Project
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Fig. 7 Seasonal cycle (July minus January 1997) of the total soil wetness index: comparison between ERA and GSWP.

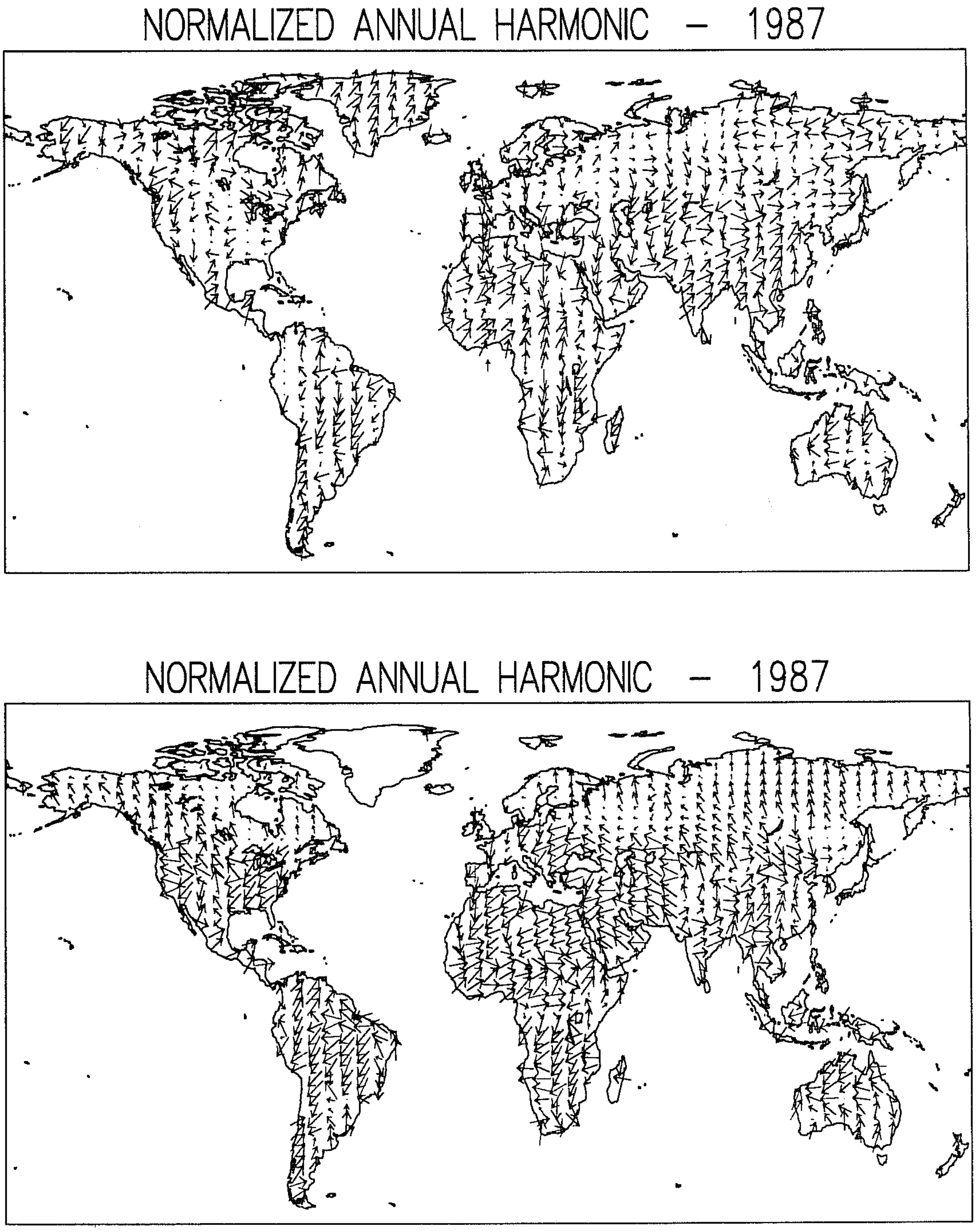


Fig. 8 Normalized annual harmonic vectors computed from the 1987 monthly mean SWI: comparison between ERA (top) and GSWP (bottom) (the vectors follow the phase convention of January pointing down and April pointing to the West and their module gives the % of variance explained by the 1st harmonic).

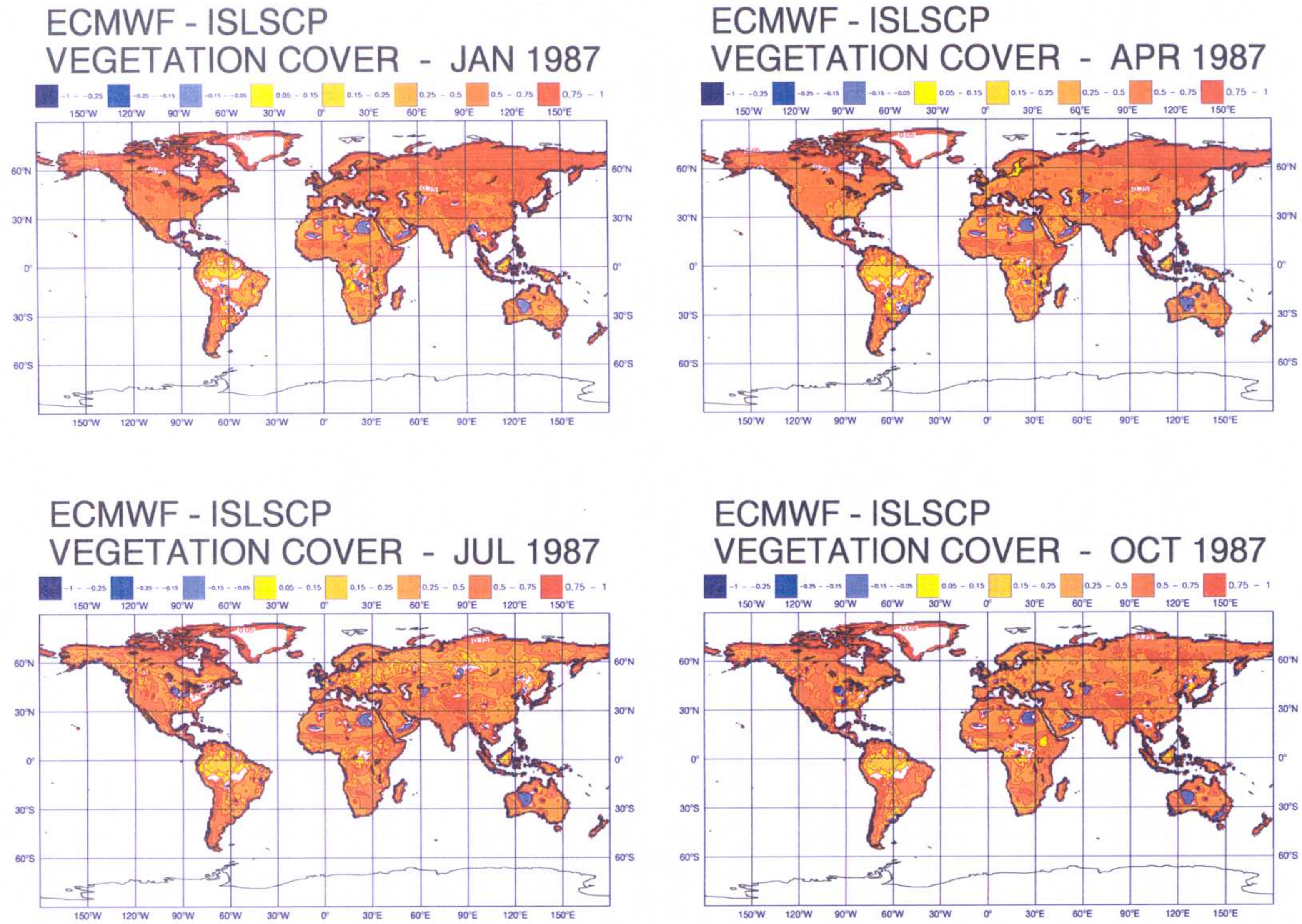


Fig. 9 Vegetation cover : difference between the ECMWF model (fixed) and the ISLSCP data set (monthly means observed in January, April, July and October 1987.

4 Precipitation forecast errors

4.1 First guess errors

In this section, the CAMS-OPI monthly precipitation from NCEP are used to estimate the precipitation errors in the operational ECMWF model and verify if they are consistent with the soil moisture increments since the aim of the nudging is mainly to compensate for these errors.

Figure 11 shows the CAMS-OPI precipitation as well as the precipitation forecast errors over land for January 1997. The first guess has globally too high precipitation, but there are also areas with underestimated precipitation and the RMS over land is 2.67 mm/day (2.63 over both land and sea). The corresponding monthly mean soil moisture increments have been shown in Figure 3. The nudging seems to be able to add (withdraw) water where the precipitation has been underestimated (overestimated). This is particularly true over parts of South and North America but this is far from being systematic.

Similarly, Figure 12 shows the precipitation forecast errors over land for July 1987 and can also be compared with Figure 3. In July, the first guess also tends to overestimate the precipitation globally. Again, the RMS is higher over land (2.98 mm/day) than over sea (2.87 over both land and sea), despite observations that could be considered less reliable over oceans since they are derived from satellite measurements only. Like in January, the precipitation is overestimated along the ITCZ, whereas the errors are randomly distributed in the mid-and-high latitudes. Figure 3 confirms the ability of the nudging to compensate for some of the forecast errors in the tropics. This is not true in many areas of the mid-latitudes even if the increments are consistent over Europe.

More results are summarised in Table 2, concerning January, April, July and October in 1996 and 1997. When averaging these 4 months, the mean error in the first guess precipitation is 0.40 mm/day in 1996 (0.55 mm/day in 1997) while the RMS is 2.28 mm/day (2.55 mm/day). The global bias is systematically positive over land, and is generally lower in 1996 than in 1997. The RMS shows the same interannual variation, which may suggest that first guess precipitation did not improve during that short period.

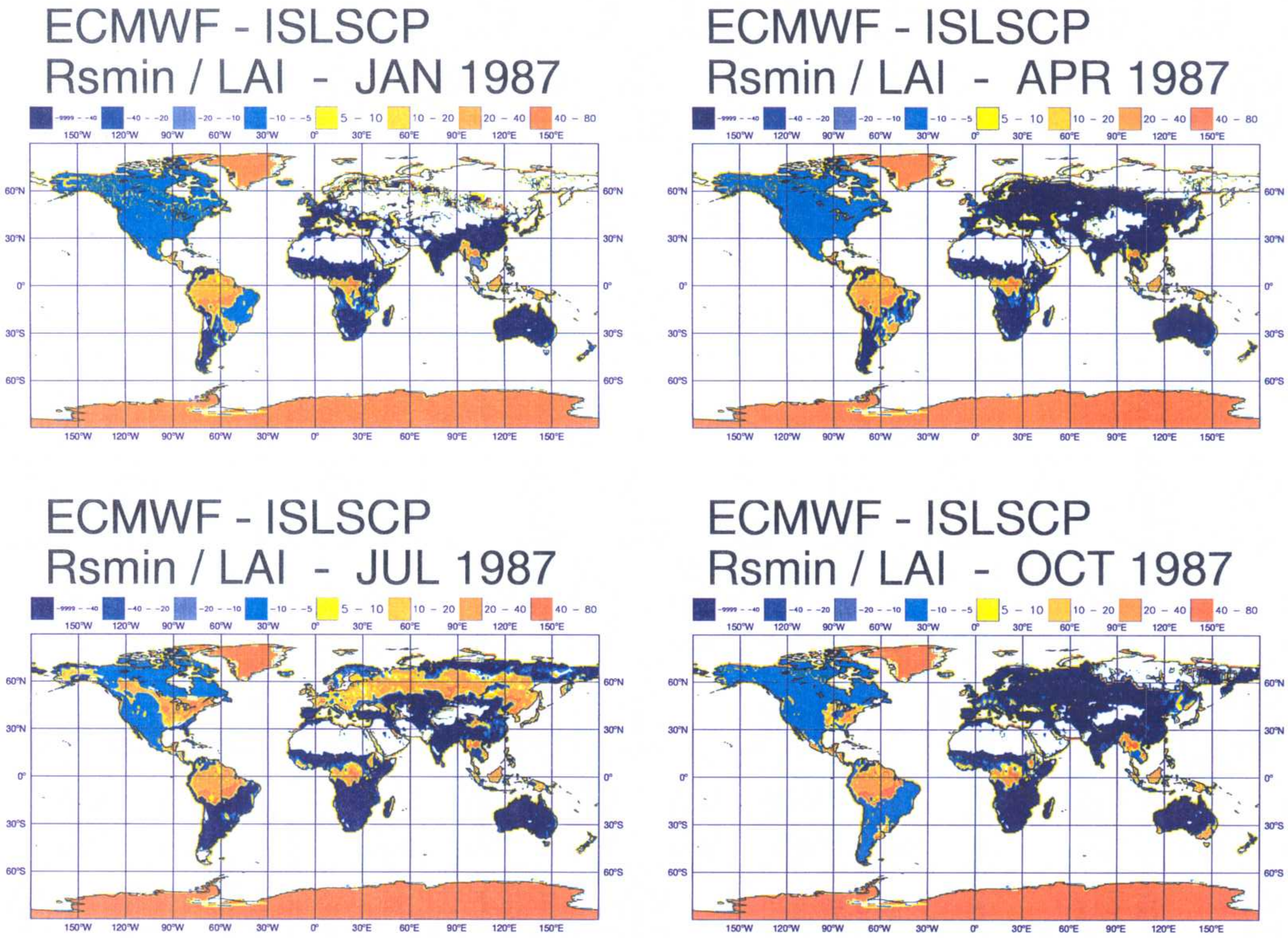


Fig. 10 Ratio R_{smin}/ LAI: difference between the ECMWF model (fixed at 60 s/m) and the ISLSCP data set (monthly means derived from observed LAI in January, April, July and October 1987).

First guess - obs	Jan	Apr	Jul	Oct	All
1996 mean	0.23	0.35	0.47	0.53	0.40
1996 stdev	1.94	2.31	2.43	2.45	2.28
1997 mean	0.41	0.52	0.53	0.74	0.55
1997 stdev	2.67	2.44	2.98	2.11	2.55

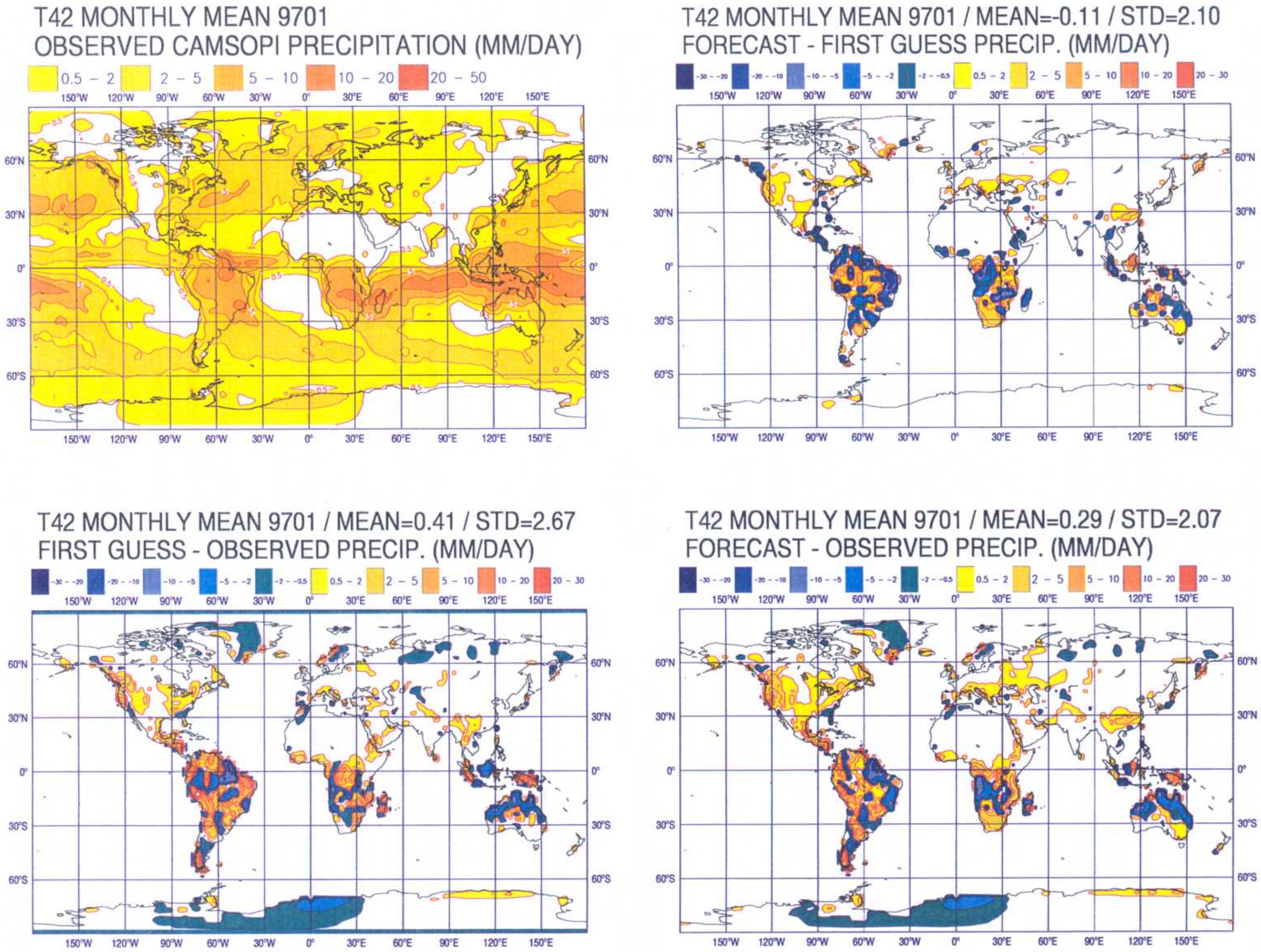
Table 2: Global land mean and standard deviation of monthly mean differences between ECMWF first guess precipitation and CAMS-OPI observed precipitation (mm/day); the last column gives the 4-month average of the monthly statistics.

4.2 Forecast (48-72h) errors

Figure 11 and 12 also show the difference between forecast and first guess precipitation and the difference between forecast and observed precipitation. These are interesting in order to assess the efficiency of the analysis cycle and the relevance of the spin-up in the first guess. The maps indicate that the forecast precipitation is globally improved compared to the first guess. This is not true for all seasons and there are locations where the first-guess fits better the observations. However, some spurious corrections are also noticeable and the improvement might be hopefully more important.

Results for January, April, July and October in 1996 and 1997 are summarised in Tables 3 and 4. When averaging the 4 months, the global mean difference between the guess and the forecast is positive but close to zero. Therefore the significant spin-up in precipitation noticed by Betts et al. (1998) over the Arkansas is not systematic. The spatial standard deviation of the corrections in precipitation is about 2 mm/day which is of the same order of magnitude as the first guess RMS. The precipitation is significantly improved when comparing the forecast and the first guess RMS : 1.99 against 2.28 mm/day in 1996 and 2.28 against 2.55 mm/day. The increase in the first guess RMS between 1996 and 1997 is also seen in the forecast, but the period is probably too short to draw firm conclusions on these variations.

Finally, the accuracy and reliability of the CAMS-OPI monthly mean precipitation may be questionnable. However, a quick comparison of the derived precipitation forecast errors with the verification performed at ECMWF against SYNOP measurements shows similar patterns and gives confidence in this NCEP product.


T42 MONTHLY MEAN 9701
OBSERVED CAMSOPI PRECIPITATION (MM/DAY)

T42 MONTHLY MEAN 9701 / MEAN=-0.11 / STD=2.10
FORECAST - FIRST GUESS PRECIP. (MM/DAY)

T42 MONTHLY MEAN 9701 / MEAN=0.41 / STD=2.67
FIRST GUESS - OBSERVED PRECIP. (MM/DAY)

T42 MONTHLY MEAN 9701 / MEAN=0.29 / STD=2.07
FORECAST - OBSERVED PRECIP. (MM/DAY)

Fig. 11 January 1997 observed CAMS-OPI precipitation as well as first guess and 48-72h forecast errors and difference between forecast and first guess (mm/day).

Forecast - first guess	Jan	Apr	Jul	Oct	All
1996 mean	0.09	0.06	0.05	0.06	0.07
1996 stdev	1.86	1.95	2.00	1.87	1.92
1997 mean	-.11	0.22	0.05	0.02	0.05
1997 stdev	2.10	2.29	1.91	1.50	1.95

Table 3: Global land mean and standard deviation of monthly mean differences between ECMWF 48-72h forecast precipitation and ECMWF first guess precipitation (mm/day); the last column gives the 4-month average of the monthly statistics.

Forecast - obs	Jan	Apr	Jul	Oct	All
1996 mean	0.32	0.41	0.52	0.59	0.46
1996 stdev	1,80	1.91	2.26	1.98	1.99
1997 mean	0.29	0.74	0.58	0.76	0.59
1997 stdev	2.07	2.13	2.82	2.10	1.76

Table 4: Global land mean and standard deviation of monthly mean differences between ECMWF 48-72h forecast precipitation and CAMS-OPI observed precipitation (mm/day); the last column gives the 4-month average of the monthly statistics.

5 Conclusions

The main conclusions of this brief and non-comprehensive study may be summarised as follows :

- The diurnal and seasonal behaviour of the soil moisture analysis identified by Betts et al. (1998) are not only found over the United States but over most continental areas, and are due to systematic biases in the ECMWF model's surface climatology.
- The crude description of the vegetation properties in the ECMWF model is likely to be responsible for biases in the surface evaporation.
- The soil moisture nudging is a non negligible contribution to the soil water budget in the ECMWF model, and is likely to jeopardize the realism of the annual cycle of soil moisture in the model, at least in the mid-and-high latitudes.
- Deficiencies in the runoff associated with snow melting might also contribute to the anomalous soil moisture annual cycle in the high-latitudes and mountainous areas.
- Due to the interaction between the biases in the diurnal and seasonal cycles of the low level humidity, a better estimation of the surface evaporation is necessary but not sufficient to improve the efficiency of the soil moisture analysis; other parameterizations, such as the turbulence in the boundary layer, are also relevant.

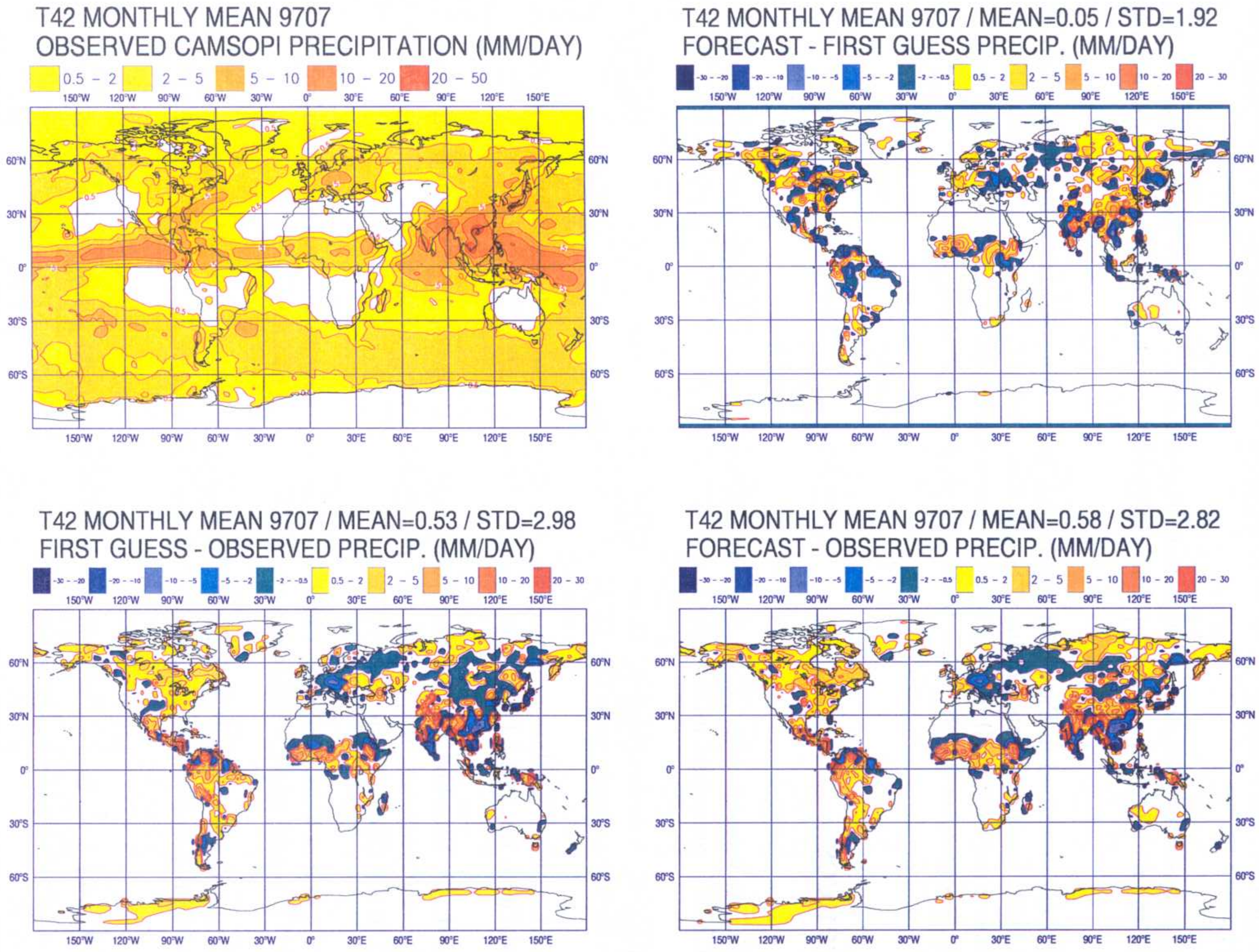


Fig. 12 July 1997 observed CAMS-OPI precipitation as well as first guess and 48-72h forecast errors and difference between forecast and first guess (mm/day).

- The nudging, by compensating for biases in the low level humidity, probably contributes to the significant improvement in the predicted precipitation between the first guess and the forecast, but it is difficult to assess its impact versus other contributions in the analysis cycle.
- The improvement in the precipitation remains rather limited, perhaps due to the fact that the nudging is less than optimal because it compensates mainly for model biases.

The next step, described in Part II of this report, is the comparison of the two-metre temperature and humidity increments produced by the new ECMWF screen-level analysis. In the near future, these increments will be used to drive a new soil moisture analysis (Douville et al. 1998) based on the optimum interpolation technique proposed by Mahfouf (1991).

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Part II

Results from off-line analysis of screen-level temperature and humidity

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1 Introduction

The ECMWF operational soil moisture analysis, implemented in December 1994 (Viterbo and Courtier 1995), is based on the low level specific humidity increments which are used to correct soil moisture in the top three layers of the ECMWF land surface scheme (Viterbo and Beljaars 1995). This so-called "nudging" is not really an additional contribution in the prognostic equations but a correction added at each analysis cycle (every 6 hours) in the following way :

$$\theta_a = \theta_g + C_v D \Delta t \times (q_a - q_g) \quad (1)$$

where θ_a and θ_g are the analysed and first guess values of the volumetric soil water contents, q_a and q_g 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 is an empirically determined constant which is applied globally.

This analysis is therefore a simplification of the method proposed by Mahfouf (1991) in which the soil moisture corrections are expressed as a linear combination of near-surface temperature and relative humidity increments. This method could not be implemented in 1994 because ECMWF did not perform a screen-level parameters analysis at the time. A screen-level analysis has recently been developped at ECMWF, using either a simple Cressman interpolation or an optimal interpolation (O.I.) technique.

In the present study, the two-metre analysis has been used "off-line" on several monthly periods. The O.I. option has been selected with standard deviations of background and observation errors of 1K for temperature and 10% for relative humidity. The interpolation scheme uses up to 50 observations in a circle area whose radius has been set up at a value of 1000 km. A few sensitivity tests to the number of observations or the choice of the radius have been performed, showing that the results are quite robust, even if the patterns of increments are obviously more local when the radius is less than a few hundreds of km. The number of observations to be considered is influent mainly over Europe where the observation network is extremely dense so that there is a lot of observations in a radius of 1000 km.

The aim of this part of the report is to describe the global two-metre increments produced by the surface analysis. In the near future, the two-metre analysis should be implemented in the operational ECMWF model, and the two-metre increments should be used as inputs for a new soil moisture analysis based on the optimum interpolation technique (Mahfouf 1991, Giard and Bazile 1998, Douville et al. 1998).

2 Two-metre temperature increments

2.1 Number of observations

Table 1 gives a few statistics about the number of surface observations (land stations, buoy and ship measurements) which are available and actually used by the surface analysis. In January 1997, the total number of observations is around 12500, with slightly more observations at 12 GMT than for the other analysis cycles. However, more than half of these observations are not used since the ratio of active against total observations is only 41.2%. The statistics are very similar in July 1997, with a slight increase in the total number of observations (around 13000) but a slight decrease in the ratio of active against total observations (40.5%). This fairly low ratio is mainly due to the redundancy check. Rejection occurs if a stationary platform reports several times in the 6-hour analysis period, or if slowly moving platform (drifting buoys or ships) remains in a limited area during the whole analysis period. A small number of observations (less than 5%) is rejected because of the interpolation (orography mismatch or strong mismatch between observation and first guess).

Month	0h00	6h00	12h00	18h00	daily mean
Jan 1997 : total	12446	12564	12940	12043	12498
Jan 1997 : used (%)	41.2	41.0	40.7	42.0	41.2
Jul 1997 : total	12852	13106	13440	12409	12952
Jul 1997 : used (%)	40.7	40.2	40.1	41.1	40.5

Table 1: Statistics on the number of two-metre temperature observations available and actually used by the surface analysis.

2.2 Diurnal cycle

Figures 1 and 2 show monthly mean two-metre temperature increments for each 6-hour analysis cycle, respectively in January and July 1997. Due to the low number of in situ observations over the oceans, the increments are mainly found over the continents and in coastal areas. There are sometimes contrasted increments along the coasts since the observations are used separately over land and over sea. In the following, the study will concentrate on the continents since the ultimate aim of the two-metre analysis is to initialize soil moisture (and possibly skin and soil temperatures) over land.

In January, the ECMWF model is too warm in the Northern Hemisphere high latitudes, but generally too cold in the mid-latitudes and the tropics. The large and continuous pattern of negative increments (analysis minus first guess) in the Northern Hemisphere shows an overestimation of the surface temperature over snow covered areas. The overestimation is stronger

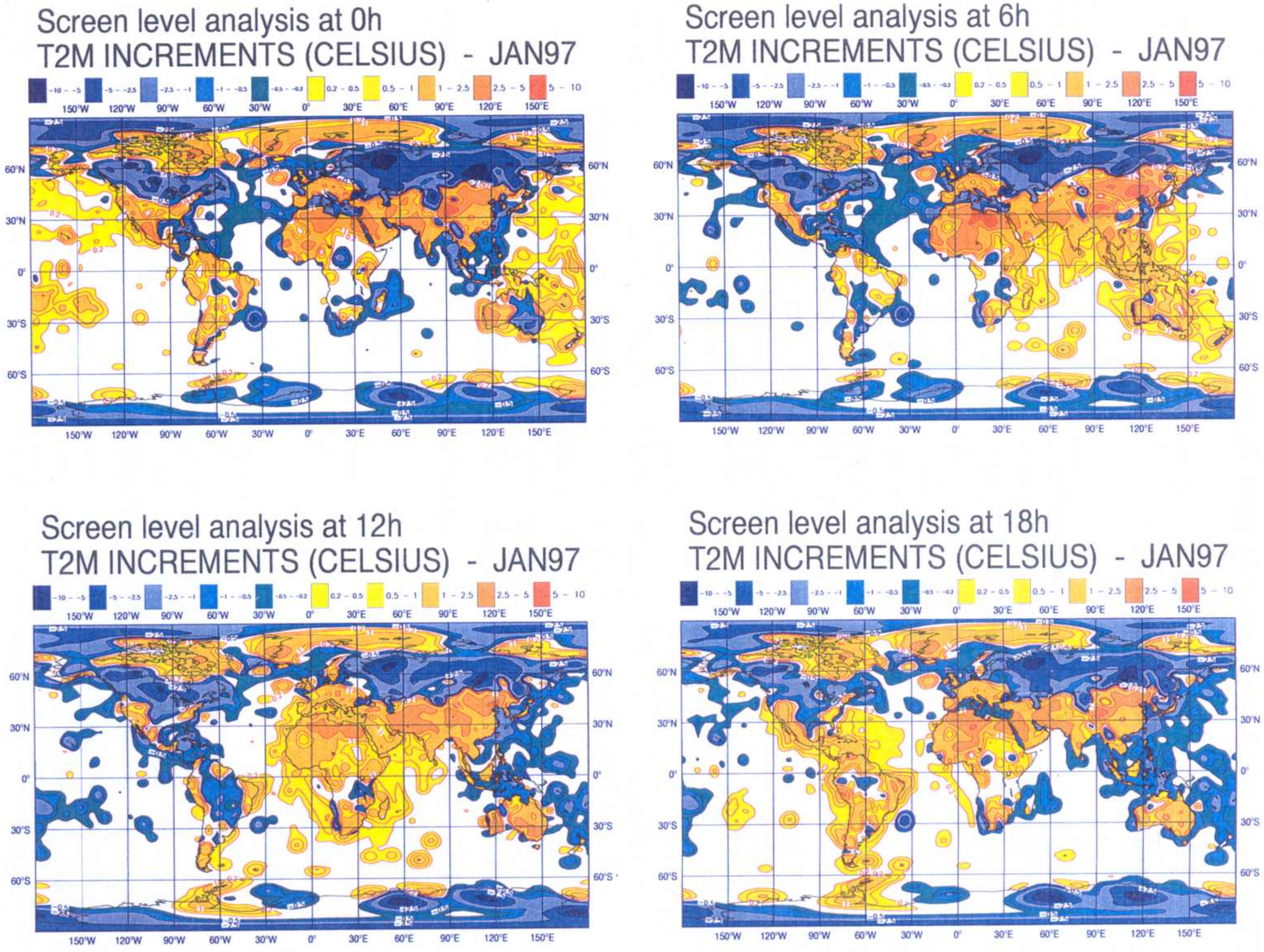
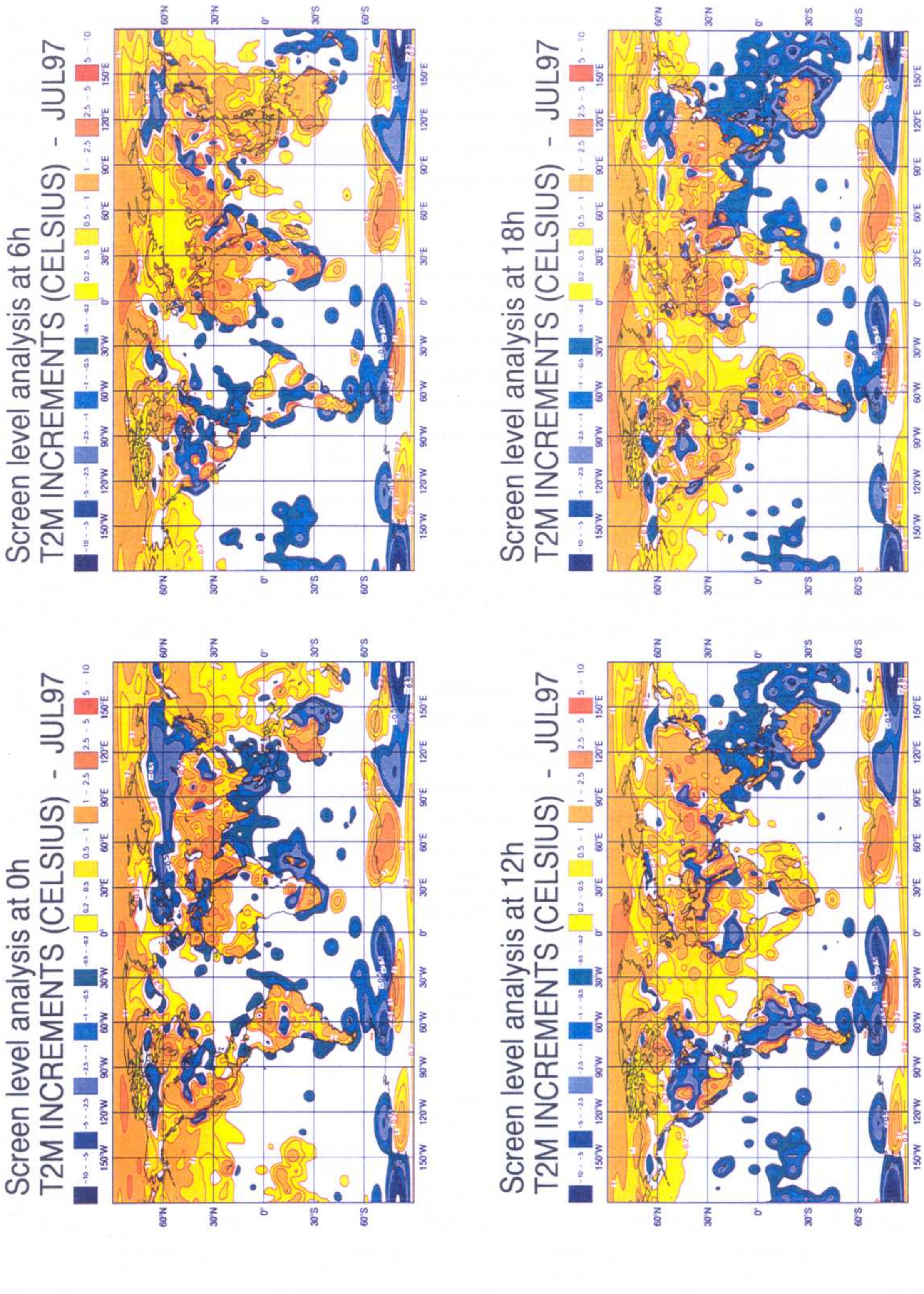


Fig. 1 January 1997 monthly mean two-metre temperature increments (degrees) at 0, 6, 12 and 18h.

during the night than during the day, which indicates errors in both the daily mean temperature and the amplitude of the diurnal cycle. Many reasons may be proposed for these biases, including the relative simplicity of the ECMWF snow scheme which does not take account of the time variations of the snow density and probably overestimates the snow heat capacity. In the mid-latitudes and the tropics, the amplitude of the diurnal cycle is also underestimated and the cold bias is stronger during the day time than during the night.

In July, the model is generally too cold. Like in January, the amplitude of the diurnal cycle is underestimated, so that the maximum errors occur during the afternoon. This underestimation might also be related to an overestimation of the soil heat capacity, especially over arid areas since the heat capacity does not depend on soil moisture in the ECMWF land surface scheme. However, this hypothesis is difficult to confirm when looking at the maps since no specific pattern appears over dry areas. There are of course many other sources of error in the two-metre temperature, which may partly hide the influence of the prescribed heat capacity.

Figure 2 also shows some negative increments in July, especially over the mid-latitude forests of the Northern Hemisphere continents. In this area, the model is too cold at 12 LT but is too warm during and at the end of the night. Nighttime negative increments also appear over the Amazonian forest. These results suggest that both evaporation and heat capacity may be responsible for the two-metre temperature biases. On one hand, the ECMWF model does not account for the low heat capacity of the forests, which again may explain the weak amplitude of the simulated diurnal cycle. On the other hand, Part I of the present report about the operational soil moisture analysis has suggested that the surface evaporation might be overestimated over most areas in the ECMWF model, except over the forests where the maximum canopy conductance is underestimated and the vegetation fraction is reasonable. This could explain that the daytime cold bias is weaker over the forested areas, so that the overestimated heat capacity may lead to a warm bias during the night.



Screen level analysis at 0h
T2M INCREMENTS (CELSIUS) - JUL97

Screen level analysis at 6h
T2M INCREMENTS (CELSIUS) - JUL97

Screen level analysis at 12h
T2M INCREMENTS (CELSIUS) - JUL97

Screen level analysis at 18h
T2M INCREMENTS (CELSIUS) - JUL97

Fig. 2 July 1997 monthly mean two-metre temperature increments (degrees) at 0, 6, 12 and 18h.

Month	Jan	Apr	Jul	Oct	All
1996 mean	2.12	-	1.17	-	-
1996 stdev	1.96	-	1.22	-	-
1997 mean	0.26	0.83	0.53	0.45	0.52
1997 stdev	1.74	1.13	0.84	0.85	1.14

Table 2: Global land mean and standard deviation of monthly mean 2m temperature increments (degrees); the last column gives the 4-month average of the monthly statistics.

2.3 Seasonal cycle

Figures 3 shows the global monthly mean distributions of the 2m temperature increments averaged over the 4 daily analysis cycles for January, April, July and October 1997. Globally averaged over land, the increments are always positive (between 0.26 and 0.83 degrees) with a spatial standard deviation around 1 degree (Table 2). The maps show large scale patterns of homogeneous increments, indicating systematic biases at the land surface and in the low atmosphere.

The snow problem already discussed for January in section 2.2 is confirmed by the increments obtained in October, but is less obvious in April. Despite a significant amount of snow in spring 1997 in the Northern Hemisphere high latitudes (Figure 4), the warm bias found in January has vanished in April. This could be due to an albedo effect, since the snow albedo is much lower at the end of the winter season than at the beginning due to the ageing of the snow pack which is not represented in the model. The significant cold bias found in April may be also explained by an overestimation of the springtime surface evaporation in the Northern Hemisphere mid-latitudes, as revealed by the comparison between the ERA (ECMWF reanalysis) outputs and the results of the GSWP (Global Soil Wetness Project) simulations performed at Météo-France (cf. part I of the present report).

Table 2 gives a few statistics about the two-metre temperature increments obtained for several months in 1996 and 1997. When averaged over all land grid points, the global mean increment is always positive, and even more positive in 1996 than in 1997, showing the impact of the modifications introduced at the end of 1996 in the ECMWF model (soil freezing and increased turbulent fluxes under stable conditions, Viterbo et al. 1998, boreal forests' albedo, Viterbo and Betts 1998). The most striking change occurs in winter, since a strong cold bias is found over the snow covered surfaces in January 1996 (not shown) while a warm bias was found in January 1997. Generally speaking, there seems to be a significant improvement in the first guess two-metre temperature between 1996 and 1997. In January, the improvement is likely due to the soil freezing scheme and the modification of the turbulent fluxes, which limit the winter cooling of the high latitude continents.

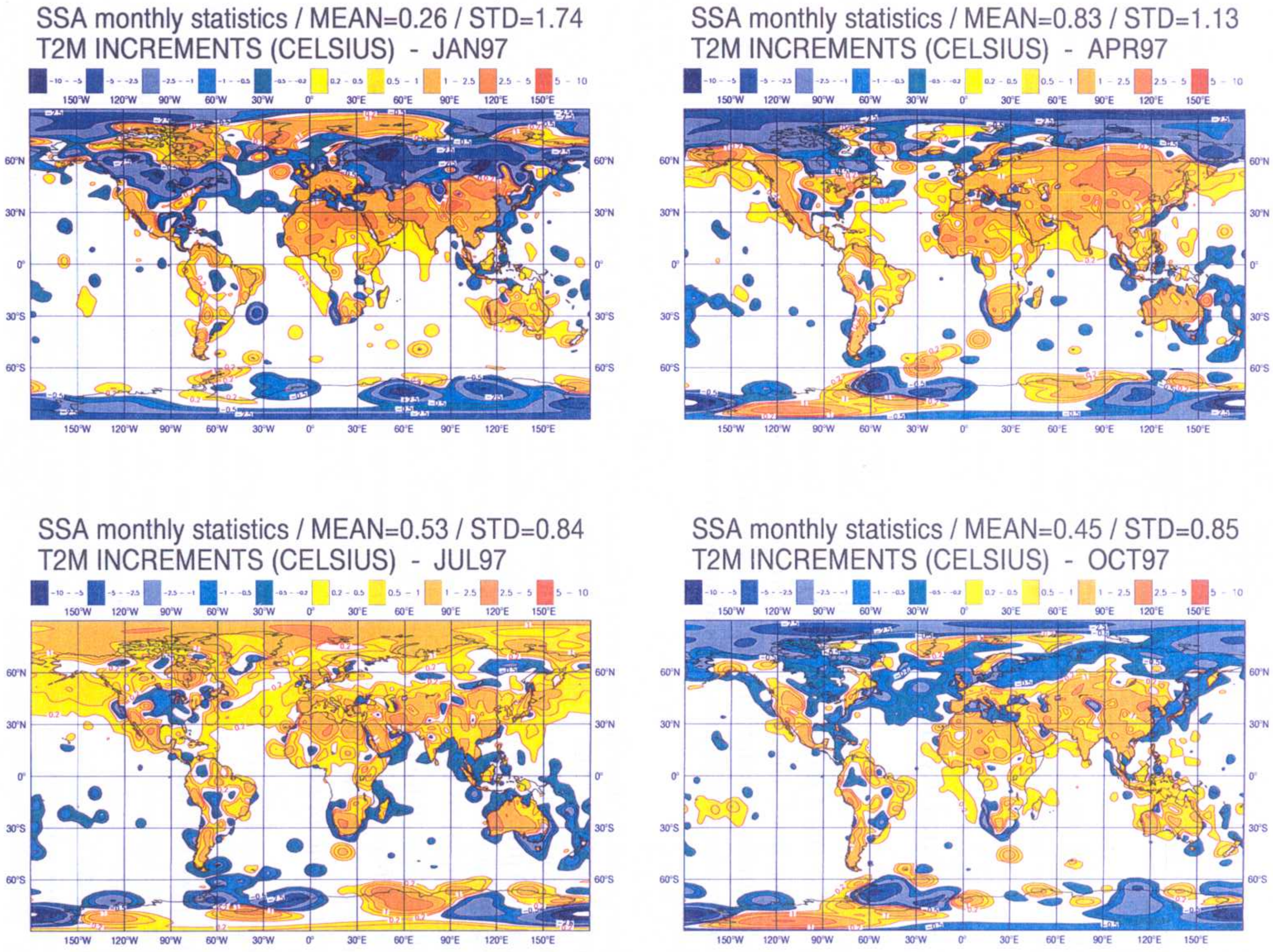


Fig. 3 Monthly mean of the daily mean two-metre temperature increments (degrees) in January, April, July and October 1997.

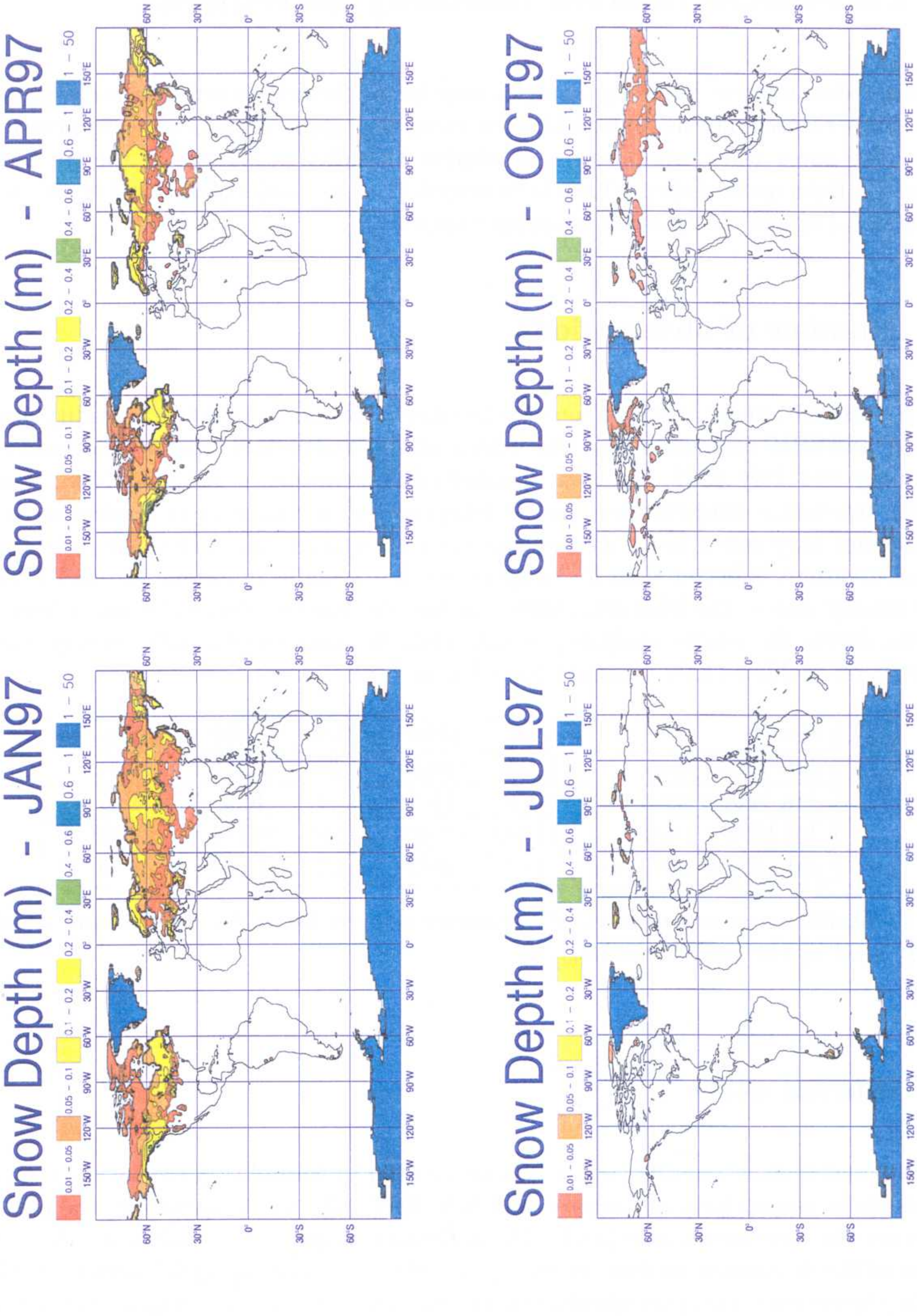


Fig. 4 Monthly mean snow depth (m) in January, April, July and October 1997.

3 Two-metre relative humidity increments

The two-metre relative humidity analysis may be performed either separately from the two-metre temperature analysis (option 1) or by using the analysed two-metre temperature instead of the first guess when computing the relative humidity predicted by the ECMWF model (option 2). Both methodologies have been tested, but the results of option 2 are presented only in section 3.3 about the monthly mean increments.

3.1 Number of observations

Table 3 presents some statistics about the number of two-metre relative humidity observations (SYNOP and SHIP measurements) which are available and actually used by the surface analysis. In January and July 1997, the total number of observations is around 11000, which is less than for two-metre temperature. As for temperature, the number is maximum at 12 GMT but does not vary much from one analysis cycle to another one. The ratio of active against total observations is better than for temperature but remains quite low (around 45%). Again, this is mainly due to the high redundancy in the observations (several reports from the same platform during the 6-hour analysis period), while the number of rejected observations due to interpolation problems only accounts for a few percent.

Month	0h00	6h00	12h00	18h00	daily mean
Jan 1997 : total	11087	11021	11378	10511	10999
Jan 1997 : used (%)	44.9	45.6	45.1	46.6	45.5
Jul 1997 : total	11446	11408	11747	10753	11338
Jul 1997 : used (%)	44.5	45.0	44.7	45.9	45.0

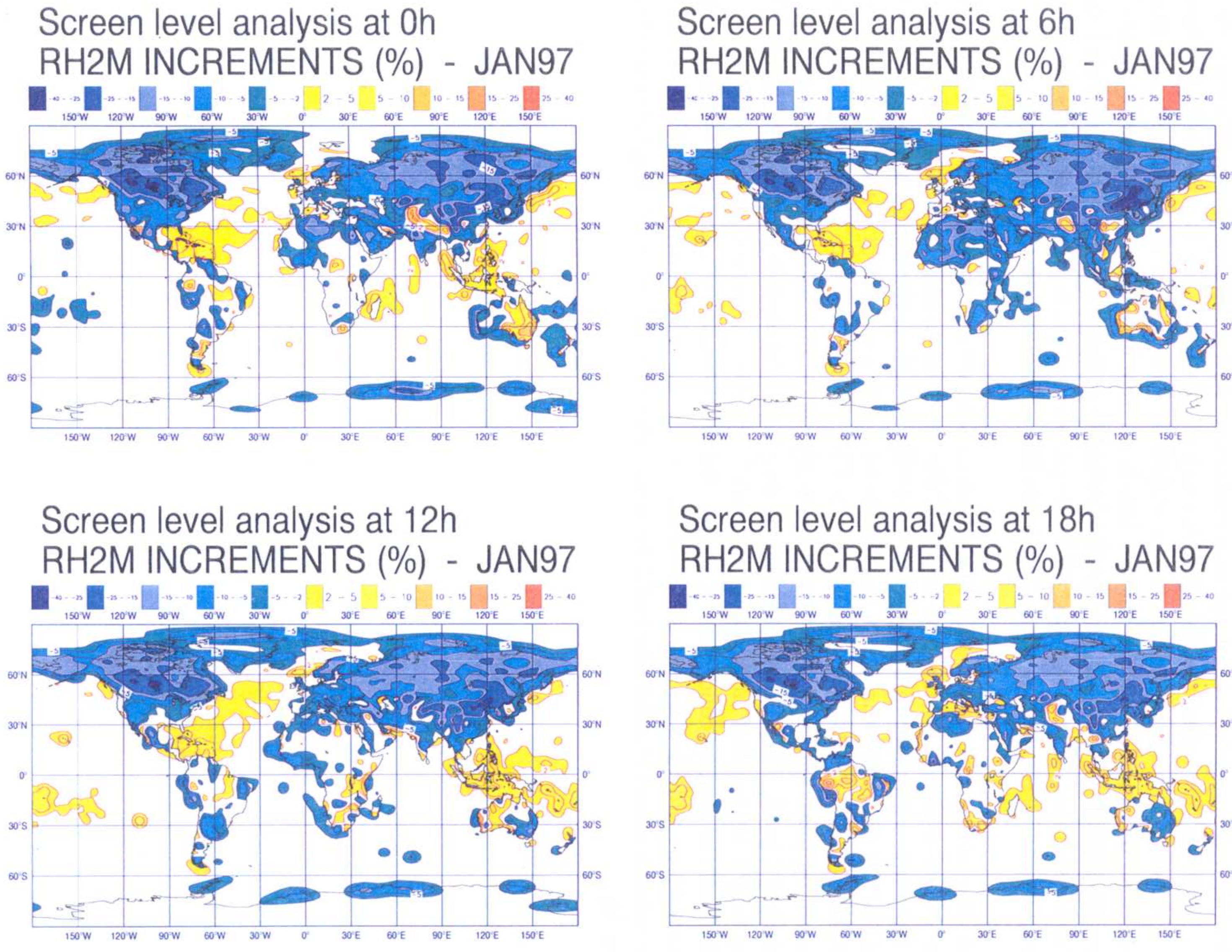
Table 3: Statistics on the number of two-metre relative humidity observations available and actually used by the surface analysis.

3.2 Diurnal cycle

Figures 5 and 6 show monthly mean two-metre relative humidity increments for each 6-hour analysis cycle, respectively in January and July 1997. Like for temperature, the present study focuses on the increments over land. The observations are quite scarce over the oceans and the aim of the two-metre analysis is to improve the soil moisture initialization. Note that the humidity increments are generally slightly positive over the oceans, both in January and July.

In January, the ECMWF model is too wet in the Northern Hemisphere mid-and-high latitudes, while the increments are either positive or negative and generally rather weak in the tropics and the Southern Hemisphere. The large and continuous pattern of negative values exceeding 10% in the Northern Hemisphere high latitudes suggests that humidity is trapped in the boundary layer in winter, despite the change in the turbulent fluxes under stable conditions. Since the model is also too warm in winter, the wet bias in relative humidity should also be quite obvious for specific humidity. However, the specific humidity remains quite low in winter and, anyway, the soil moisture analysis is switched off in the presence of snow. The increments do not exhibit a strong diurnal cycle, except over a few areas like Australia and the Himalayas.

In July, the increments are generally lower than in January and the wet bias is much less obvious on the global scale. Both negative and positive increments are found at each analysis cycle, but they show a stronger diurnal cycle. Generally speaking, the model tends to be too wet at the end of the night but too dry in the afternoon. This is consistent with the study of Betts et al. (1998) about the ERA features over the FIFE domain (Kansas), showing an overestimated mid-morning peak and an overestimated late afternoon minimum of specific humidity at the lowest model level. The surface evaporation might be responsible for this oscillation. The soil drying might be too fast in the morning, partly due to an overestimation of the vegetation fraction and the canopy conductance, so that the soil becomes too dry in the afternoon despite the corrections provided by the soil moisture analysis. This is only a possible scenario and single column model simulations could be a valuable tool for investigating this question more thoroughly.



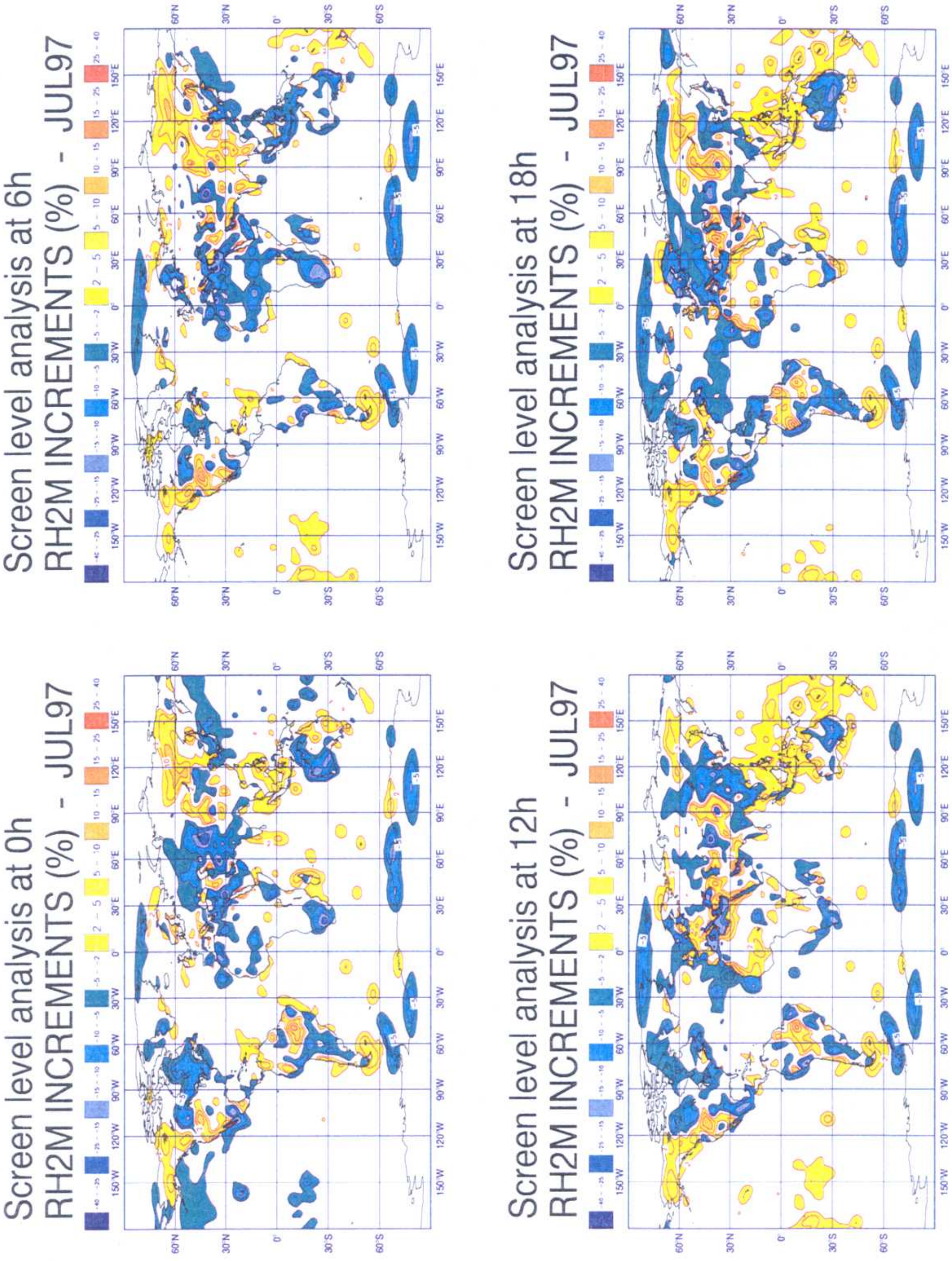
Screen level analysis at 0h RH2M INCREMENTS (%) - JAN97

Screen level analysis at 6h RH2M INCREMENTS (%) - JAN97

Screen level analysis at 12h RH2M INCREMENTS (%) - JAN97

Screen level analysis at 18h RH2M INCREMENTS (%) - JAN97

Fig. 5 January 1997 monthly mean two-metre relative humidity increments (%) at 0, 6, 12 and 18h.



Screen level analysis at 0h RH2M INCREMENTS (%) - JUL97

Screen level analysis at 6h RH2M INCREMENTS (%) - JUL97

Screen level analysis at 12h RH2M INCREMENTS (%) - JUL97

Screen level analysis at 18h RH2M INCREMENTS (%) - JUL97

Fig. 6 July 1997 monthly mean two-metre relative humidity increments (%) at 0, 6, 12 and 18h.

3.3 Seasonal cycle

Figure 7 shows the global monthly mean distributions of the two-metre relative humidity increments averaged over the 4 daily analysis cycles for January, April, July and October 1997. These results have been obtained with option 1, namely when the relative humidity analysis does not use the analysed two-metre temperature. Globally averaged over land, the increments are always negative (between -5 and -0.5%), but this wet bias exhibits a clear seasonal cycle. The strongest negative increments (more than 15 or even 25%) are found in January and April over snow-covered areas (cf Figure 4). In the tropics and the summer hemisphere, both positive and negative increments appear, but their magnitude is generally less than 5%.

Figure 8 is similar to Figure 7 except that option 2 of the new soil moisture analysis has been chosen. It means that the first guess relative humidity has been computed by using the analysed instead of the first guess two-metre temperature. In other words, the relative humidity analysis is performed after correction of the model's temperature biases. When the model is too wet and too warm (like in January over the Northern Hemisphere snow cover), the negative relative humidity increments are increased. On the other hand, when the model is either too wet and too cold or too dry and too warm, the relative humidity increments are decreased. This remark may have important consequences for the soil moisture analysis, since option 2 of the relative humidity analysis decreases the relative humidity increments when they are consistent with temperature increments as far as the soil moisture errors are concerned (and vice-versa). Since the temperature increments are generally positive (over snowfree areas), option 2 generally reduces the negative relative humidity increments, so that the wet bias obtained with option 1 is now weaker.

This result is confirmed by Table 4 which summarises some monthly statistics about two-metre relative humidity increments. Option 2 has been used only for the months selected in 1997, while option 1 has also been used in January and July 1996. In 1997, the results confirm that the global mean increment is always negative, and is more negative with option 1 than with option 2. On the other hand, the standard deviation of the increments increases with option 2. Note also that the increments obtained in January and July 1997 are still better than similar statistics for 1996, although the improvements are smaller than those shown in Table 3 for two-metre temperature. This result indicates that the modifications of the ECMWF model introduced at the end of 1996 have affected much more the near-surface temperature than the relative humidity.

Month	Jan	Apr	Jul	Oct	All
1996 mean (op.1)	-5.68	-	-1.36	-	-
1996 stdev (op.1)	6.50	-	2.91	-	-
1997 mean (op.1)	-4.82	-3.83	-0.48	-1.56	-2.67
1997 stdev (op.1)	5.68	5.33	3.14	2.96	4.28
1997 mean (op.2)	-4.90	-1.43	0.90	-0.42	-1.46
1997 stdev (op.2)	12.35	5.81	3.48	3.56	6.30

Table 4: Global land mean and standard deviation of monthly mean 2m relative humidity increments (%); the last column gives the 4-month average of the monthly statistics; option 1 : use of first guess two-metre temperature; option 2 : use of analysed two-metre temperature.

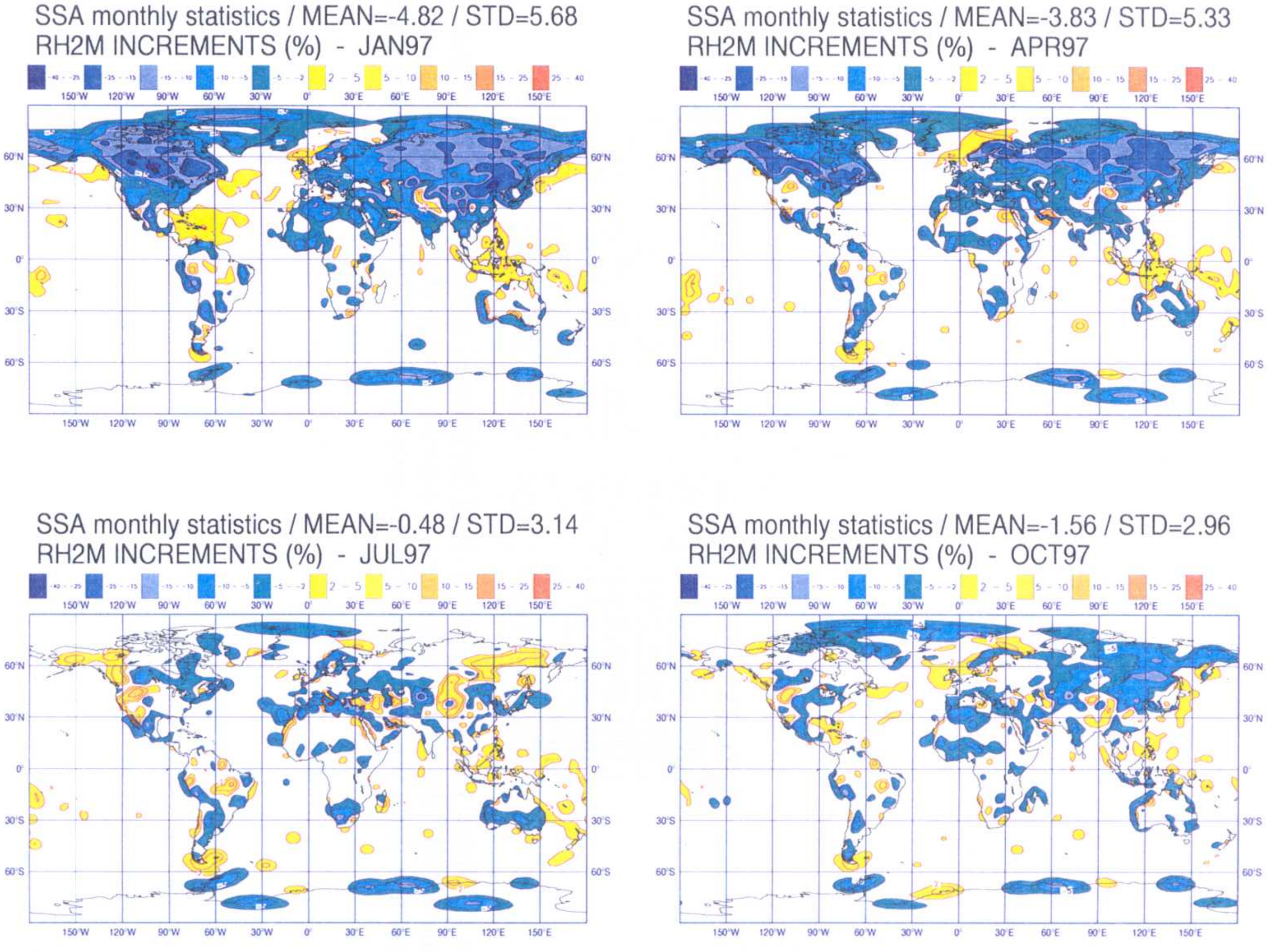
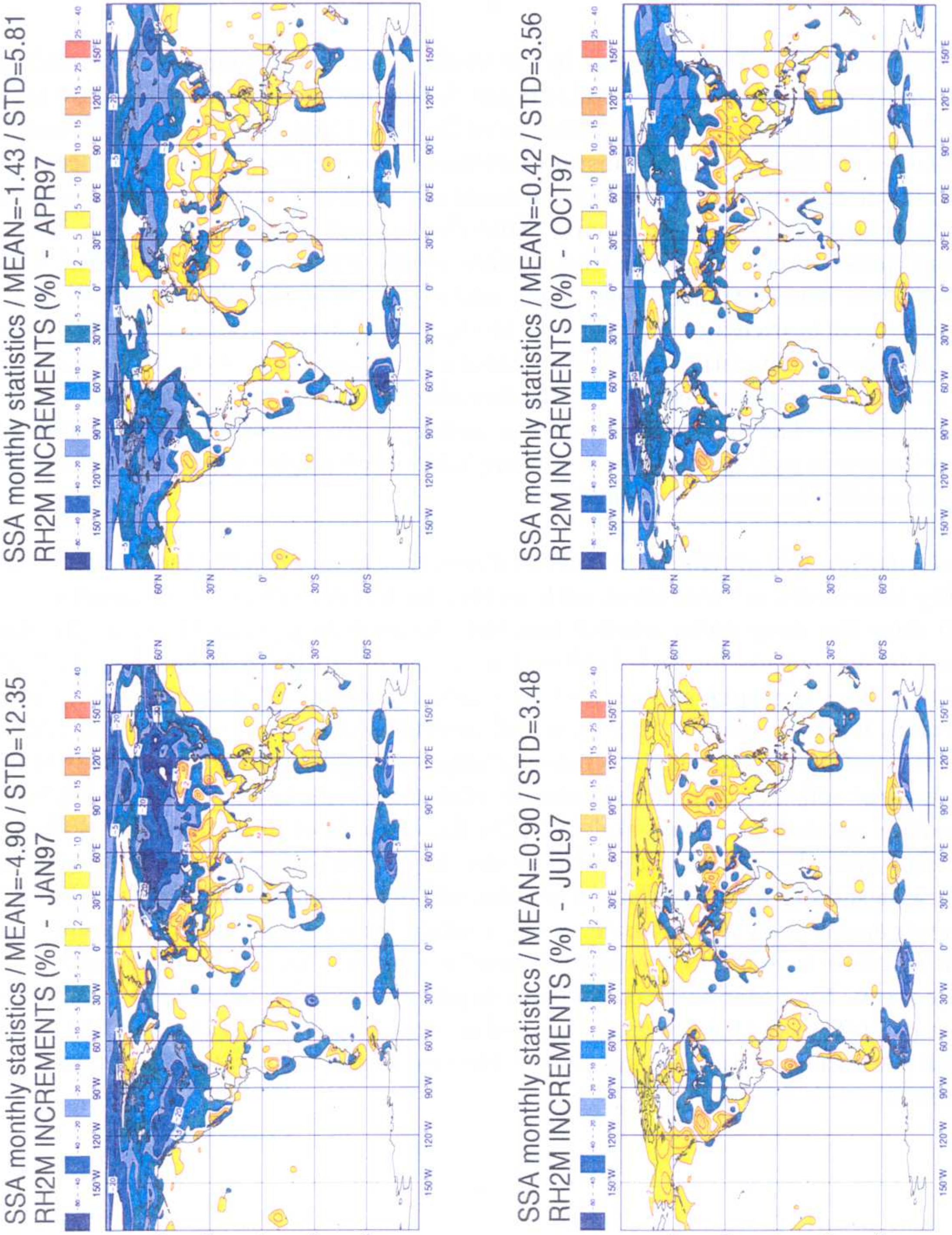


Fig. 7 Monthly mean of the daily mean two-metre relative humidity (%) in January, April, July and October 1997; option 1 : use of first guess two-metre temperature.



SSA monthly statistics / MEAN=-4.90 / STD=12.35
RH2M INCREMENTS (%) - JAN97

SSA monthly statistics / MEAN=-1.43 / STD=5.81
RH2M INCREMENTS (%) - APR97

SSA monthly statistics / MEAN=0.90 / STD=3.48
RH2M INCREMENTS (%) - JUL97

SSA monthly statistics / MEAN=-0.42 / STD=3.56
RH2M INCREMENTS (%) - OCT97

Fig. 8 Monthly mean of the daily mean two-metre relative humidity (%) in January, April, July and October 1997; option 2 : use of analysed two-metre temperature.

4 Remarks about the future soil moisture analysis

Following the methodology proposed by Mahfouf (1991), the two-metre temperature and relative humidity increments may be used as inputs for analysing soil moisture in the 3 first levels of the ECMWF land surface scheme (Viterbo and Beljaars 1995). The method is a simple optimal interpolation in which the soil moisture increments are expressed as a linear combination of the two-metre increments. The statistical calibration (Monte Carlo) of this linear relationship is not described in the present report. Note that no soil moisture correction is done in the following cases : snow covered ground, surface temperature less than 0°C, weak atmospheric solar radiation transmittance (night time, winter or strong cloudiness), 6-hour precipitation and wind speed in excess of 0.6 mm and 10 m/s, respectively. Compared to the operational system, the new soil moisture analysis performs a better selection of the atmospheric situations where the low level parameters are informative about soil moisture, thereby avoiding some spurious corrections. The optimal interpolation technique also allows an explicit representation of observation errors and the possibility of using both observations of two-metre temperature and relative humidity to correct soil moisture.

The new analysis will provide large soil moisture corrections when the temperature and relative humidity increments are consistent with respect to possible errors in soil moisture. Figures 9 and 10 show the daily mean relative humidity increments (option 1) versus the daily mean temperature increments for each land grid point of the Northern Hemisphere in January and July 1997. The hemisphere is divided in 4 latitude bands (of unequeal area), leading to 4 scatterplots for each month. The new soil moisture analysis is expected to have a strong impact for grid points showing increments of opposite signs (warm/dry or cold/wet biases). In January, large soil moisture increments are expected in the tropics and mid-latitudes, where the model is generally too cold and wet. On the other hand small increments should appear in the high latitudes, which might also be due to the fact that most of these grid points are covered with snow in winter so that no analysis will be performed. In July, the relative humidity increments do not show a systematic wet bias, while the model is generally too cold. Therefore, the soil moisture increments should be generally negative but they could remain rather small in many areas. Note that these preliminary hypotheses must be considered with caution, since the diurnal cycle of the increments is ignored and the new soil moisture analysis will hopefully feedback onto the atmosphere and reduce the two-metre temperature and relative humidity increments.

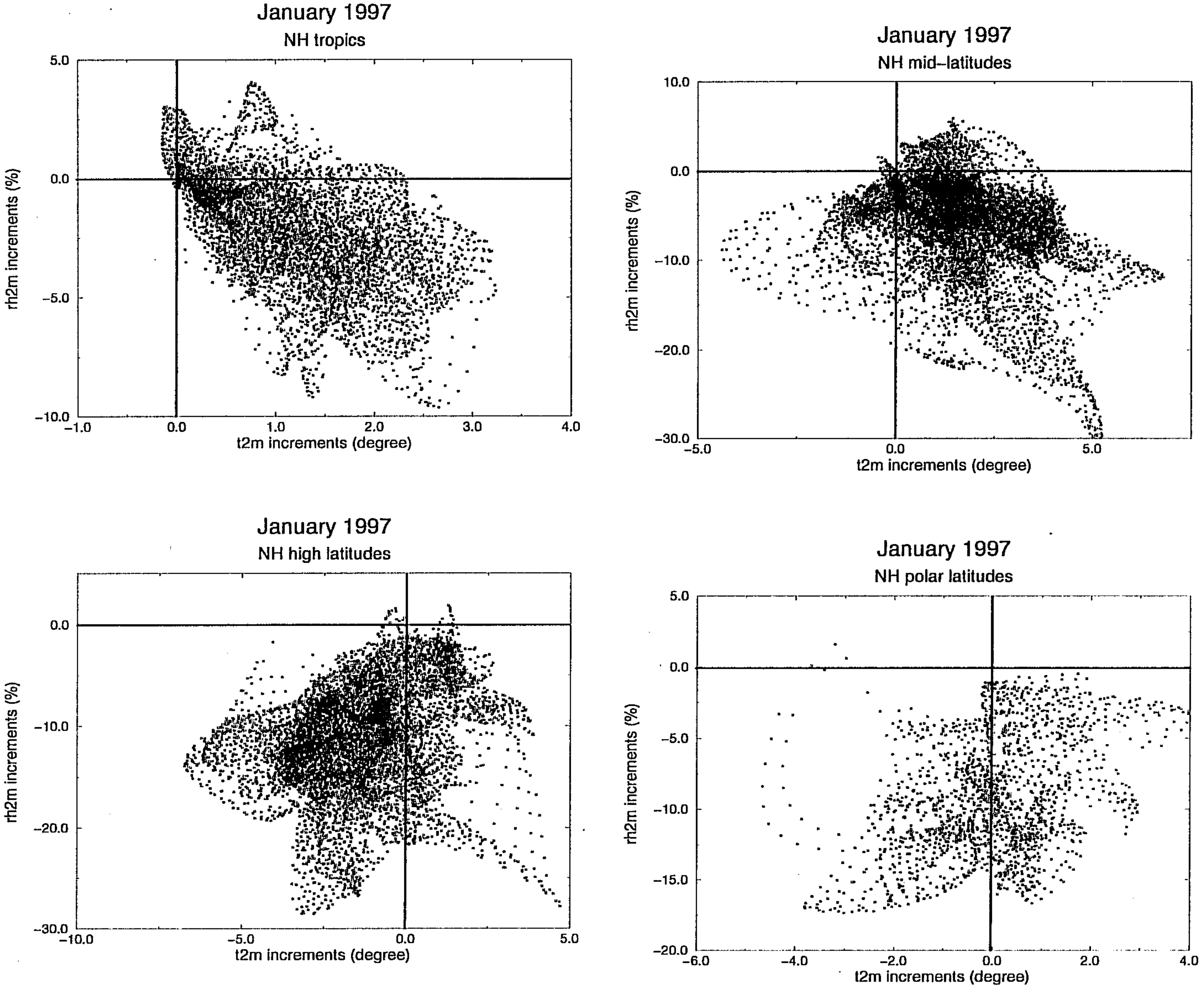


Fig. 9 Relative humidity increments versus temperature increments in January 1997. Each land grid point is represented by a circle for various domains in the Northern Hemisphere: tropics (0-22.5°), mid-latitudes (22.5-45°), high-latitudes (45-67.5°), polar latitudes (67.5-90°); option 1: use of first guess two-metre temperature.

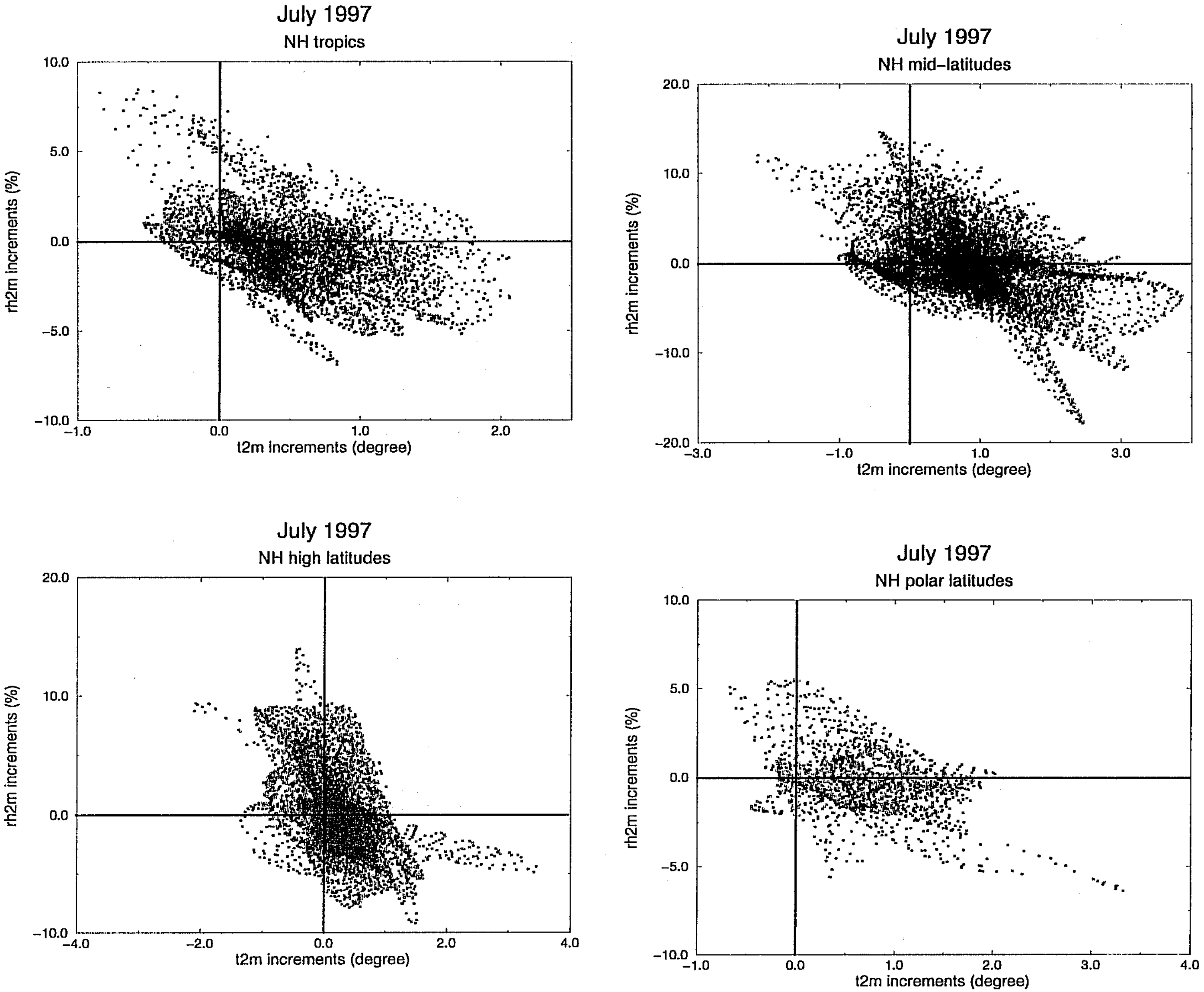


Fig. 10 Relative humidity increments versus temperature increments in July 1997. Each land grid point is represented by a circle for various domains in the Northern Hemisphere: tropics (0-22.5°), mid-latitudes (22.5-45°), high-latitudes (45-67.5°), polar latitudes (67.5-90°); option 1: use of first guess two-metre temperature.

In order to illustrate the relevance of the option chosen for the relative humidity analysis, Figures 11 and 12 show the similar scatterplots of temperature against relative humidity increments, but using option 2 instead of option 1. The shape of the scatterplots is strongly modified since the relative humidity increments are now computed after replacing the first guess temperature by the analysed temperature. In January, the scatterplots show a strong correlation between the relative humidity and temperature increments in the mid-and-high latitudes. This is due to the fact that the sensitivity of relative humidity on temperature is much stronger for low than for high temperatures. Correcting a warm bias in winter induces a strong increase in the first guess relative humidity and may therefore lead to a strong wet bias. This indicates that it is important to switch off the soil moisture analysis under cold conditions. In the tropics, the correlation between the relative humidity and temperature increments vanishes. The model is too cold and the relative humidity increments are slightly biased towards positive values (too dry). Option 2 should therefore lead to weaker soil moisture increments than option 1. In July, the scatterplots are less sensitive to the analysis option (except in the polar latitudes) due to warmer atmospheric conditions. Nevertheless, because of the cold bias in the model, option 2 generates more positive relative humidity increments and should again lead to weaker soil moisture increments than option 1.

The choice of the standard deviations of observation errors will also be particularly relevant since it will determine the sign and the size of the soil moisture increments. They were first set to 2K for temperature and 15% for relative humidity. Such errors considered separately provide increments of same magnitude which nearly cancel each other when they are combined. However, the monthly statistics obtained about relative humidity errors suggest that the value of 15% is too high and will make the soil moisture analysis mainly driven by the temperature increments. Therefore, another set of standard deviations of observation errors was also tested, namely 2K and 5%. As an outlook of future work, an off-line soil moisture analysis was tried out in stand-alone mode, based on the results of the two-metre screen-level analysis presented above. The daily mean soil moisture increments (not shown here) were found to be of the same order of magnitude of the operational increments, but a very different diurnal cycle. Note that, when fully coupled with the atmospheric analysis, the increments are expected to be weaker, since the soil moisture corrections will improve the forecast and reduce the errors in the near-surface parameters.

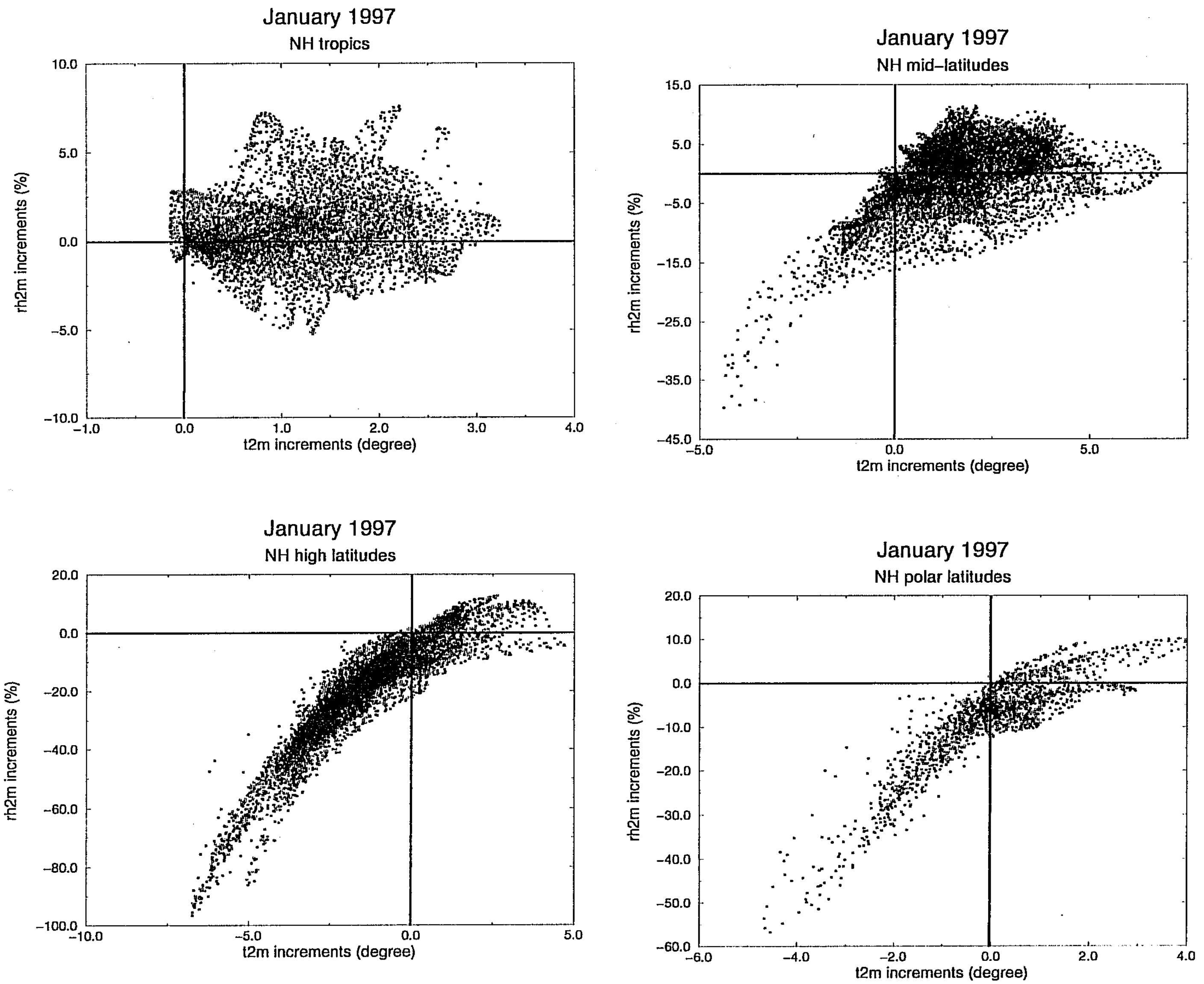


Fig. 11 Relative humidity increments versus temperature increments in January 1997. Each land grid point is represented by a circle for various domains in the Northern Hemisphere: tropics (0-22.5°), mid-latitudes (22.5-45°), high-latitudes (45-67.5°), polar latitudes (67.5-90°); option 2: use of analysed two-metre temperature.

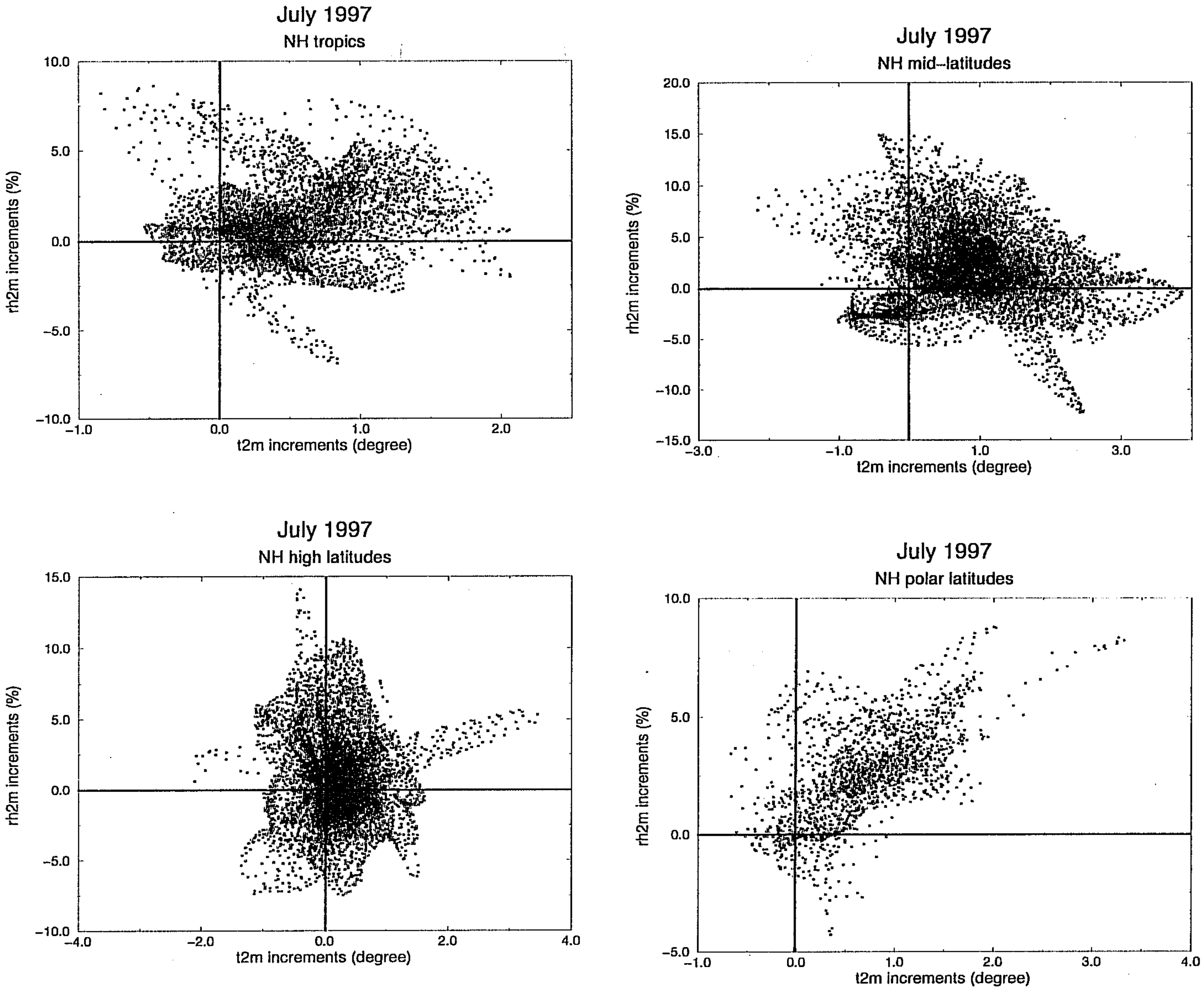


Fig. 12 Relative humidity increments versus temperature increments in July 1997. Each land grid point is represented by a circle for various domains in the Northern Hemisphere: tropics (0-22.5°), mid-latitudes (22.5-45°), high-latitudes (45-67.5°), polar latitudes (67.5-90°); option 2: use of analysed two-metre temperature.

5 Conclusions

A two-metre analysis of temperature and relative humidity has been recently developed at ECMWF. It is an extension of the snow analysis routine and it uses either a simple Cressman method or an optimal interpolation (O.I.) technique. The O.I. option has been used to perform an "off-line" two-metre analysis for several months in 1996 and 1997.

The two-metre temperature increments show significant changes between 1996 and 1997, due to changes in the physical parametrizations of the ECMWF model. The model exhibits a large cold bias in 1996, especially in the winter mid-latitudes. In 1997, there is a warm bias in winter over snow-covered areas, which vanishes in spring, while the model is generally too cold in the tropics and the summer hemisphere.

The two-metre relative humidity increments have not been significantly modified by the changes in the ECMWF model between 1996 and 1997. There is a strong wet bias in the winter hemisphere. The increments are much smaller in the summer hemisphere, which is primarily due to the warmer surface air temperatures but might also suggest that the operational soil moisture analysis based on the lowest model's level increments of specific humidity does a reasonable job in preventing the model from drifting wet or dry. The increments are significantly modified if the analysed two-metre temperature (instead of the first guess) is used to compute the first guess relative humidity. This option creates some artificial correlations between temperature and relative humidity increments in winter and is probably more difficult to implement in the operational system, but it might be useful for the soil moisture analysis in order to avoid spurious corrections.

Some comparisons have been made at KNMI (Robert Mureau, personal communication) between the operational and the new "off-line" temperature analysis, and some in-situ observations in Netherlands. Figure 17 shows the results for Maastricht. Not surprisingly, the new analysis, taking account of the SYNOP measurements, is much closer to the observations. Therefore, the screen level analysis presented in this study provides a much better representation of the surface atmosphere and has a value on its own for verification purposes. It would be useful to implement it in the operational system and in the future reanalysis projects of ECMWF. However, some improvements could be useful, such as taking account of the strong anisotropy induced by land sea contrast in coastal areas (Navascues, 1997).

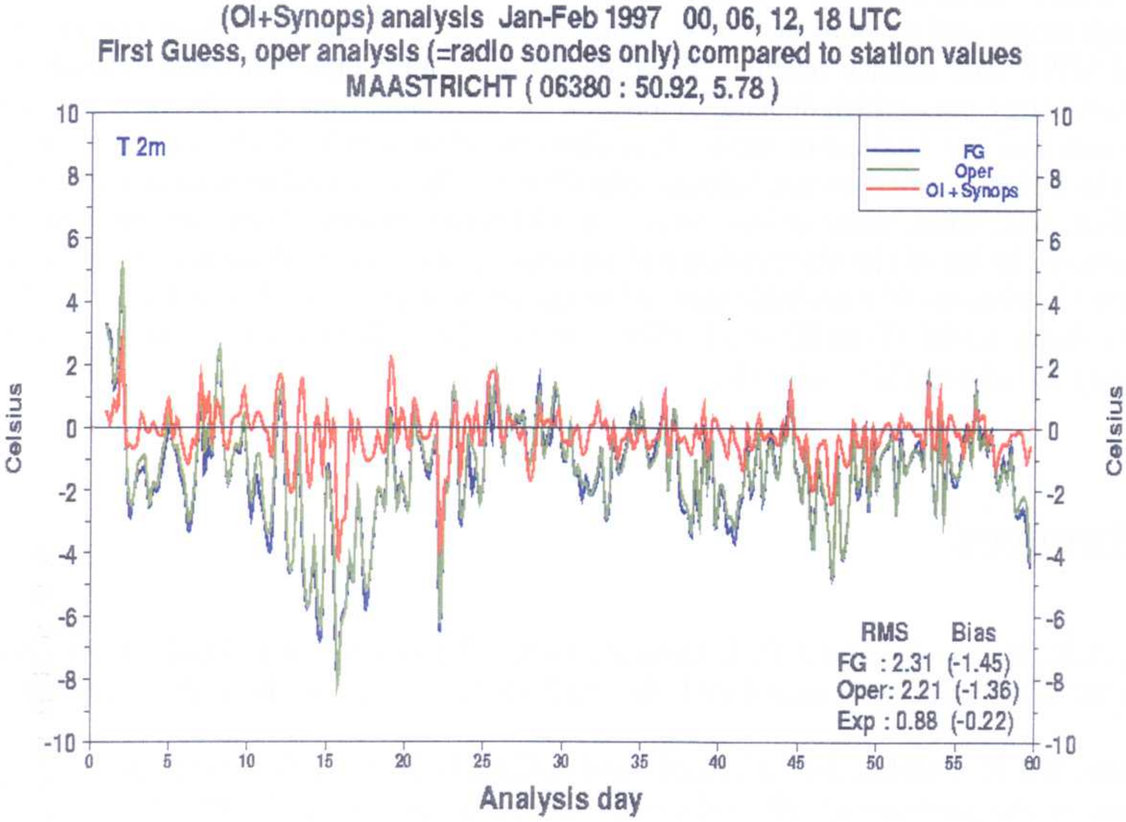


Fig. 13 Deviations from the Maastricht station values for the first guess, the operational analysis and the "off-line" experimental analysis (from R. Mureau at KNMI).

The ultimate objective of the screen-level analysis is to update the soil variables in the ECMWF model. Such a surface analysis has already been implemented at Météo-France (Giard and Bazile 1998) and tested in a single column model at ECMWF (Douville et al. 1998). The soil moisture increments are estimated as a linear combination of the two-metre increments of temperature and relative humidity. Some work has been done to adapt this technique to the ECMWF land surface scheme. The difficulty is to find some "universal" estimates of the optimum coefficients, which depend not only on the local solar time, but also on the atmospheric conditions and the land cover types. It is also crucial to switch off the soil moisture analysis when the soil moisture does not influence significantly the near-surface parameters : weak solar radiation, rain, wind, snow at the surface or cold temperatures. Moreover, the tuning of the standard deviation of the observation and forecast errors must be done very carefully in order to obtain increments of reasonable size. After the promising results obtained with the ECMWF single column model (Douville et al. 1998), several global 3D sensitivity tests are likely to be necessary to achieve this calibration.

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