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A Hydrology Correction Scheme for the Mesoscale Model using observed precipitation rates

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Abstract.

This paper describes the design and testing of a hydrology correction scheme (HCS) for the mesoscale model. The study was motivated by experience with the unified model, in which the soil moisture field has shown a tendency to dry out unrealistically because of a deficiency in rainfall during assimilation. During a week of continuous assimilation, this drying in the UK area amounted to around 20%, depending on season. The current solution operationally is to reset the soil moisture field to climatology each day.

The HCS uses observed rain rates during the assimilation to correct soil moisture, canopy water and snow depth. The derivation of the scheme is outlined, and the quality of the input precipitation data is assessed. Results are described from an extended trial of the scheme, including the changes made to the mesoscale model in the autumn of 1994. The 'autumn changes' largely eliminate the systematic drying problem and the freely evolving soil moisture deviates realistically from climatology. The HCS provides additional locally significant corrections. The trial performance is judged good enough to warrant dispensing with the use of climatological soil moisture operationally.

Contents.

1. Introduction.

1.1. Influence of Soil Moisture on the Atmosphere.

It is widely accepted that soil moisture plays an important role in the evolution of atmospheric parameters. If soil moisture is high, then evaporation predominates and the atmospheric moisture level is increased. If soil moisture is low, then the surface is warmed more by solar radiation. Thus, soil moisture affects the atmosphere by modulating the partition of total energy between latent and sensible heating.

There are two main categories of effects of soil moisture on atmospheric behaviour - firstly those concentrating on the immediate effects of soil moisture anomalies on the weather of the next day or two, and those concentrating on the effects of soil moisture on climate on seasonal time scales. A brief summary shall be given of both.

Concentrating on immediate effects of soil moisture, it is evident that differential heating either side of a soil moisture anomaly may cause a small scale convective cell, and thus alter the local flow, and hence the local weather, in a manner analogous to sea-breezes. Simple numerical models (eg Ookouchi 1984) have shown that circulations of this sort may be comparable in strength to sea-breezes, and may even produce clouds and rain if the situation is right.

In the long term, soil moisture acts as a cooling reservoir which can absorb heat that would otherwise go into large scale features. Anthes & Kuo (1986) showed that there was a strong correlation between the temperature and wetness of springs over the U.S. Western Plains and the temperatures of the summer - a warm dry spring favoured a warm dry summer and similarly cool, wet springs led to cool, wet summers. Meehl (1984) showed that increased soil moisture may lead to increased precipitation during the Asian monsoon. Snow cover has also been found to have significant effects on surface temperature (Walsh et al 1985).

Some preliminary experiments with the unified model were set up as a sensitivity study to see if the effects of doubling or halving soil moisture content over the mesoscale domain were detectable. Two 18-hour forecasts were produced from 00Z 30/06/93 with soil moisture values uniformly doubled and halved. Compared with a control run, temperatures showed a sensitivity of 1-1.5°C, and relative humidities a sensitivity of 10-15%, with the half soil moisture run being generally warmer and drier. A French group (Mahfouf 1991 and Bouttier, Mahfouf & Noilhan 1993), performed similar experiments to measure the effects of soil moisture initial values on surface parameters in a region in the South West of France. They saw temperature differences of about 2°C and humidity differences of 15%, by using differences to the initial soil moisture of ±17% from the starting value. This sensitivity is greater than found in the unified model experiment described above. The reason for this is thought to be due to the fact that the French soil was dryer initially. Soil nearer saturation will require larger changes to it, to achieve the same sensitivity. There was also less wind, and higher maximum temperatures in the French case.

In conclusion, it is soil moisture *gradients* that initiate mesoscale circulations and influence immediate weather behaviour, and soil moisture *amounts* that absorb energy and influence long term atmospheric development, as well as temperatures on a daily basis.

1.2. Soil Moisture Evolution in the Unified Model.

In the larger scale versions of the unified model, it was found that there was insufficient rain during assimilation (Lorenc, 1992). During continuous assimilation, this led to the problem of insufficient water entering the soil via the hydrology scheme, but with the same amount as normal leaving it via evaporation or transpiration. Hence the soil tended to dry out, which potentially led to larger errors in the forecast.

The current solution to this problem is that, every day, the soil moisture field is reset to climatological values. This only partially solves the problem as it has already been stated that fluctuations in soil moisture that are not represented in the model lead to increased forecast errors, and so while this method prevents the soil drying out too much, actual situations of above or below average moisture content are not catered for. Rowell & Blondin (1990) also found a climatological approach unacceptable.

Experiments were run, using the global model, to calculate the soil moisture average over the mesoscale model domain, for the months of April and August '93. Results showed 10 to 15% drying per week in April, and up to 30% drying per week during August.

When difference charts were plotted of the soil moisture before and after resetting, it could be seen that while there was some variation, particularly in mountainous regions, the drying tended to be fairly uniform across the whole country.

It was found, by looking at one of the cases from the 'four-runs-a-day' trial of the mesoscale model, that the effect of higher resolution was to decrease the drying problem. For the case from 30/04/93, the global model showed drying of 4.7% for the day, whereas the mesoscale dried by just 2.8%.

It is the aim of this paper to devise a 'Hydrology Correction Scheme', (HCS) that uses observed rainfall rates during the assimilation to correct for model precipitation errors in the assimilation, leading to a more accurate distribution of soil moisture values, and helping to ensure that there is no unrealistic drying out of the soil. This will then allow the mesoscale model soil moisture to 'run free', hopefully leading to better short range forecasts, especially of temperature and relative humidity, and also, possibly, the ability to cope with seasonal variations.

2. Outline of Hydrology Correction Scheme.

2.1. Basic Plan.

The aim of the HCS is to provide a system that can run in continuous assimilation mode, without the need to reset soil moisture values every day. Instead of using model first guess rain rates in the hydrology scheme, which may be inaccurate or even systematically deficient, we should use observed rain rates, provided they are of high enough quality.

Rain rate observations are obtained from the Moisture Observation Pre-processing System (MOPS) which carries out analyses of precipitation data. A 3-hour mesoscale model forecast is used as a background field, with radar data from the Frontiers system replacing this within its domain. A successive correction scheme, incorporating a recursive filter, is then used to analyze the data. The rain rates and phases are analyzed separately and then recombined. Phase is stored in the sign of the rate, positive implying 'liquid' and negative implying 'frozen'. MOPS rain observations are available as observation type 506 within the Unified Model.

Figure 1 shows the mesoscale model domain with the extent of Frontiers radar data which are used in producing MOPS rain observations and outside which MOPS data are set to missing data. The areas of land in the South East corner and part of Norway are not covered by the radar system and will not be catered for in our scheme. Here we propose to let the model hydrology scheme 'run free', forced only by model precipitation.

It would be difficult to totally recalculate soil moisture changes from scratch using rain observations. So our proposal is to calculate rain rate *increments* $\Delta R = R^{obs} - R^{fg}$ and use these to calculate soil moisture increments Δm.

The exact partitioning of rain into canopy water content, soil moisture content, and surface runoff depends not only on the rain rate and type (convective or dynamic), but also on the initial state of the canopy water content. Our proposed scheme splits the calculations into two distinct stages : firstly, the existing calculation within the model timestep by the hydrology scheme, and secondly a corrective increment added within the assimilation scheme, based on a linearization of the hydrology scheme equations. As the full relationship is non-linear, then doing a calculation in this way is necessarily an approximation, but we believe that the approximation in our scheme is justified and fairly accurate.

It is worth comparing our general approach with a proposed (not operational) ECMWF soil moisture analysis scheme (Vasiljevic 1989) which employs the same basic assumption that all soil moisture errors are caused by forecast rain rate errors. In this scheme, an analysis of precipitation accumulations over 6 hours is used to derive increments $R^{anal} - R^{fg}$. These are divided into increments per timestep and used as a forcing term in a 6-hour integration of a simplified hydrology scheme (decoupled from the atmospheric model) to obtain a soil moisture increment to be added at analysis time.

Like our scheme, this is a nudging approach using simplified hydrology equations forced by rain increments each timestep. However, in the ECMWF approach, the errors in the evaporative changes to soil moisture are uncorrected over the 6 hour period. Apart from the convenience of integrating our scheme within the Analysis Correction scheme, there is also the advantage that at each timestep, the corrected soil moisture is fed through to the model's evaporation calculations.

Section 2.2 describes the derivation of the equations used in the scheme, from the equations in the existing hydrology scheme. A description of the implementation of the scheme into the Unified Model is included as an Appendix.

2.2. Derivation from Equations of UM Hydrology Scheme.

2.2.1. <u>List of variables.</u>

	usual units.
m = soil moisture	Kg m^{-2}
c = canopy water content	Kg m^{-2}
c_m = canopy capacity	Kg m^{-2}
T_f = throughfall Rate	Kg $m^{-2}s^{-1}$
Y_s = surface runoff rate	Kg $m^{-2}s^{-1}$

ϵ = fraction of grid box rain covers, =1.0 for large scale rain
=0.3 for convective rain

K_{sv} = hydrological conductivity Kg $m^{-2}s^{-1}$

R^{obs} = observed rain rate mm/hr

R^{fg} = model first guess rain rate mm/hr

$\Delta R = R^{obs} - R^{fg}$ mm/hr

2.2.2. Summary of Model Hydrology Scheme.

Rain falls over a fraction ϵ of the grid box. Some is intercepted by the vegetative canopy and goes into the canopy water content, **c**, which has a maximum capacity of c_m. The rest is throughfall, T_f, onto the soil. Here some soaks into the soil and is added to **m**, and some runs off, Y_s, into rivers or lakes. For more detail, see Gregory and Smith (1993).

Hence :

$$\Delta c_o = (R^{fg} - T_f) \Delta t$$

$$\Delta m_o = (T_f - Y_s) \Delta t$$

where subscript **o** refers to values calculated during the model timestep. T_f and Y_s are functions of R, ϵ, **c** and K_{sv} :

$$T_f = R(1-\frac{c}{c_m}) \exp\left(\frac{-\epsilon c_m}{R\Delta t}\right) + R\frac{c}{c_m} \quad (1)$$

$$Y_s = R \exp\left(\frac{-\epsilon(K_{sv}+P_m)}{R}\right) \quad \text{where} \quad P_m = \frac{c_m - c}{\Delta t} \quad (2)$$

which is valid for Y_s, when $K_{sv}\delta t > \mathbf{c}$.

For $K_{sv}\delta t \leq \mathbf{c}$ then :

$$Y_s = R\frac{c}{c_m}\exp\left[\frac{-\epsilon K_{sv} c_m}{Rc}\right] + R\left[1-\frac{c}{c_m}\right]\exp\left[\frac{-\epsilon c_m}{R\,\Delta t}\right] \quad (3)$$

As can be seen in Table 1, $K_{sv}\delta t$ is more often greater than **c**, than less, and so equation (2) is the more commonly used and so is the one that was used when considering approximations to be made.

	$K_{sv}\delta t$	C (April)	C (August)
Max.	2.61	1.00	1.00
Min.	0.045	0.00	0.00
Mean	0.47	0.17	0.06

***Table 1**. Comparison of K_{sv}, and **c** values (all in Kgm^{-2}) for the mesoscale model domain.*

Before we start to suggest some methods of calculating the increments, we should define the objectives and requirements of the scheme. There are three main aims :

(i) The scheme should be simpler, and less expensive than repeating the hydrology scheme calculations for the observed rain rates. Doing this would also introduce the problem of trying to assign values of ϵ to the observations (that is, whether the observed rain is convective or dynamic).

(ii) The increments calculated should not necessarily sum to the total rain rate increment, ΔR, but instead to a value ΔR-ΔY to account for any excess runoff. This is especially important when ΔR is negative as we do not wish to remove water that had run off in the first place. Values of ΔY are significant for large rain rates. If either first guess or observed values (or both) exceed 2 to 3 mm/hr of convective rain, then ΔY can account for more than 10% of the increment ΔR. Rates of 4 to 5 mm/hr can lead to ΔY being over 30% of ΔR.

(iii) The scheme should realistically apportion the increment between the canopy and soil moisture. It is not sufficient to merely place it all in the canopy and hope it drains down next timestep, as this will affect evaporation rates from the canopy.

Approximate equations for our corrective increments will now be derived, where in the following equations subscript **0** refers to values calculated by the current hydrology scheme, and subscript **1** refers to the assimilation scheme's corrections. The aim is to compute Δc_1, and Δm_1 by a linearization of the hydrology equations about R^{fg}, making further, justified, approximations if and when required.

We have :

$$\Delta c_1 = \frac{\partial}{\partial R}\frac{\partial c}{\partial t}\,\Delta t\,\Delta R = \frac{\partial}{\partial R}(\Delta c_0)\,\Delta R \qquad (4)$$

and similarly for Δm_1.

We know, from equation (1), Δc_0 :

$$\Delta c_0 = \Delta t\,(R^{fg}-T_f) = \Delta t\,R\left(1-\frac{c}{c_m}\right)\left[1-\exp\left(\frac{-A}{R^{fg}}\right)\right] \qquad (5)$$

where :

$$A = \frac{\epsilon c_m}{\Delta t} \tag{6}$$

and hence :

$$\frac{\partial}{\partial R}(\Delta c_0) = \Delta t \left(1 - \frac{c}{c_m}\right) \biggl[\left(1 - \exp\left\{\frac{-A}{R}\right\}\right) + R \left(\frac{-A}{R^2}\right) \tag{7}$$

thus :

$$\begin{aligned} \Delta c_1 &= \left(1 - \frac{c}{c_m}\right)\left[1 - \exp\left(\frac{-A}{R}\right)\right] \Delta t \; \Delta R - \left(1 - \frac{c}{c_m}\right) \frac{A}{R} \\ &= \frac{\Delta R}{R} \Delta c_0 - \left(1 - \frac{c}{c_m}\right) \frac{A}{R} \exp\left(\frac{-A}{R}\right) \Delta t \; \Delta R \end{aligned} \tag{8}$$

Hence we can use the simple linear relationship :

$$\frac{\Delta c_1}{\Delta c_0} = \frac{\Delta R}{R^{fg}} \tag{9}$$

as long as we can show that the second term in equation (8) is negligible by comparison with the first. Using values of $\epsilon=0.3$ and 1 for convective and dynamic cases respectively, and also $\Delta t=90$s and $c_m=0.5$ Kgm^{-2} (typical of the mesoscale domain), the ratio of the second term to the first term was calculated over a range of realistic rain rates from 0 to 5 mm/hr :

$$\frac{(2)}{(1)} = \frac{\frac{A}{R}\exp\left(\frac{-A}{R}\right)}{1 - \exp\left(\frac{-A}{R}\right)} \tag{10}$$

For dynamic cases, $\epsilon=1$, this fraction was found to be less than 0.1 for all R^{fg}, and for convective cases, $\epsilon=0.3$, it was found to be less than 0.15 up to $R^{fg} \approx 2$ mm/hr, and less than 0.3 up to $R^{fg} \approx 3$ mm/hr. Equation (9) is therefore a satisfactory approximation.

A similar argument applied to the soil moisture gives :

$$\Delta m_1 = \frac{\partial}{\partial R}(\Delta m_0) \; \Delta R = \frac{\partial}{\partial R}(T_f - Y_s) \; \Delta R \; \Delta t \tag{11}$$

from equations (1) & (2) for T_f and Y_s, we get :

$$\frac{\Delta R}{R}\Delta m_0 + \left[\frac{A}{R}\left(1-\frac{c}{c_m}\right) \exp\left(\frac{-A}{R}\right) - \frac{B}{R}\exp\left(\frac{-B}{R}\right) \right] \tag{12}$$

where :

$$B = \epsilon\,(K_{sv}+P_m) \tag{13}$$

So we can now apply the same linear equation to **m**, again as long as the second term is negligible. This time, the fraction :

$$\frac{(2)}{(1)} = \frac{\frac{A}{R}\left(1-\frac{c}{c_m}\right)\exp\left(\frac{-A}{R}\right) - \frac{B}{R}\exp\left(\frac{-B}{R}\right)}{\left(1-\frac{c}{c_m}\right)\exp\left(\frac{-A}{R}\right) + \frac{c}{c_m} - \exp\left(\frac{-B}{R}\right)} \tag{14}$$

also depends on values of **c**, and K_{sv}, as well as ϵ and R^{fg}. It was found to be small for dynamic cases, as for the **c** equation, and also to be acceptable for convective cases. Errors arising from dropping this second term, in convective cases, were largest when **c** was either a large or small fraction of the canopy capacity (ie. greater than 95% or less than 10%). In these cases the second term could amount to as much as 50% of the first term for as little as 1 mm/hr of rain. For c/c_m values below 20% then the second term was always less than 40%, and less than 30% up to R^{fg}=2 mm/hr. For more average values of **c** (around half of c_m) then this second term was generally below 10-15% of the first term and so we felt it was safe to be neglected.

There is one further modification needed for this scheme, and that is for the case R^{fg}=0, which will obviously cause these equations to fail. The derivation of the equations for Δc_1 and Δm_1 in this case can still be viewed as a linearization of the original equations for Δc_0 and Δm_0 about R^{fg}=0, for small ΔR.

From :

$$\Delta c_0 = \Delta t\, R\left(1-\frac{c}{c_m}\right)\left[1-\exp\left(\frac{-A}{R}\right)\right] \tag{15}$$

then for cases of small R^{fg}, A/R will be large and so the exponential term will tend to zero. For the exponential term to be less than 0.1 then we need $R < A/2.3$. Using values from before, this amounts to :

R^{fg} < 8 mm/hr dynamic
< 2.5 mm/hr convective.

In this case :

$$\Delta c_0 \rightarrow \Delta t\, R\left(1-\frac{c}{c_m}\right) \tag{16}$$

and hence :

$$\Delta c_1 \rightarrow \Delta t \; \Delta R \left(1 - \frac{c}{c_m} \right) \tag{17}$$

Typically **B** is larger than **A** ($K_{sv} \approx 5 \times 10^{-3}$ $Kgm^{-2}s^{-1}$) and so for small rain rates we can neglect both exponential terms in the equation for Δm_0 , as long as $c \,/\, c_m$ is not too small, to leave :

$$\Delta m_1 \rightarrow \Delta t \; \Delta R \; \frac{c}{c_m} \tag{18}$$

So the overall set of equations for calculating the assimilation's correction increments for soil moisture and canopy content is :

$$\left. \begin{aligned} \Delta c_1 &= \frac{\Delta R}{R^{fg}} \, \Delta c_0 = \Delta t \, \frac{\Delta R}{R^{fg}} \, (R^{fg} - T_f) \\ \Delta m_1 &= \frac{\Delta R}{R^{fg}} \, \Delta m_0 = \Delta t \, \frac{\Delta R}{R^{fg}} \, (T_f - Y_s) \end{aligned} \right\} \; R^{fg} \neq 0 \tag{19}$$

$$\left. \begin{aligned} \Delta c_1 &= \left(1 - \frac{c}{c_m} \right) \Delta t \; \Delta R \\ \Delta m_1 &= \frac{c}{c_m} \, \Delta t \; \Delta R \end{aligned} \right\} \; R^{fg} = 0 \tag{20}$$

For $R^{fg} > 0$, then the sum of these increments is :

$$\Delta (c+m)_1 = \Delta t \; \frac{\Delta R}{R^{fg}} \; (R^{fg} - Y_s) \approx \Delta t \; (\; \Delta R - \Delta Y \;) \tag{21}$$

where we are using the same linear scaling of the original values calculated by the hydrology scheme to estimate ΔY as we did for Δc_1 and Δm_1. In the case when $R^{fg} = 0$, then this sum is simply ΔR as there is no previously calculated information about runoff amounts. This means that when $R^{fg} = 0$, the scheme will overestimate the soil moisture increment due to large observed rates, R^{obs}. For $R^{obs} \leq$ 4-5 mm/hr, $Y_s/R \leq 0.3$ and so this error is not too serious.

Whilst the $R^{fg}>0$ scheme calculates increments in proportion to the rain rate increment, ΔR, the $R^{fg}=0$ scheme corresponds to adding water to the canopy in proportion to how much space there is in it.

2.2.3. Snow Scheme.

The snow depth calculations in the hydrology section of the model timestep are perhaps more straightforward than those for rainfall. Snow depth is incremented by the amount of snow that has fallen during the timestep, and then snow melt is calculated based on the ground temperature, and the total snow depth after it has been incremented as above. The total increment is then the snow fall amount minus the snow melt.

We considered a similar treatment for snowfall increments but decided that it would be sufficient to just add an amount equal to the (observed - model) snow fall, and leave any melting to happen during the next model timestep. Calculation of ΔT^* is complicated, requiring knowledge of other parameters such as the heat capacity of the top soil layer which varies geographically with soil type, and so developing an approximate scheme was not felt to be important, as any errors may not be serious enough to justify the extra expense.

Hence we propose :

$$\begin{aligned} &\Delta S=\Delta S_F \Delta t \\ \text{where} \quad &\Delta S_F=S_F^{obs}-S_F^{fg} \end{aligned} \qquad (22)$$

where S = snow depth, and S_F = snow fall rate. S_F^{obs} is set equal to the observed precipitation rate if *either* the model snowfall rate is greater than its rain rate *or* if the model has no precipitation at all and the atmospheric level 1 temperature is below freezing - that is, when any 'missed' precipitation is more likely to be snow than rain. This condition is consistent with the current UM dynamic precipitation scheme. With the advent of the revised mixed-phase precipitation scheme in the next year, it would be possible for dynamic snow to reach the surface when the atmospheric temperature was above freezing, as is currently possible also for convective precipitation. It would probably not be worthwhile, however, to adopt a more complex phase test for a surface hydrology correction.

There is a risk in using this second condition that any observed precipitation not forecast will be treated as snow if the model temperature at level 1 is below freezing, in that a lack of model precipitation is probably caused by a lack of model cloud and this may also cause model temperatures to be lower than observed. Thus there is a chance of adding some snow when in reality the temperature is above freezing and the precipitation is falling as rain. The importance of this issue is investigated in the trial reported in section 5.

3. Quality of precipitation data.

An assessment of the quality of data available from the MOPS precipitation analyses was required. As MOPS precipitation data is heavily based on Frontiers radar data, at least within the radar boundaries, the main area of interest, a study was carried out to compare Frontiers data with data from the mesoscale model, and also MORECS (Meteorological Office Rainfall and Evaporation Calculation System) which is available in the form of monthly accumulations over 40 km squares across the UK (not including Ireland).

Monthly accumulations were collected from the three sources for the months February to August 1994 (February to May for the model), and compared with each other. Accumulations were calculated from Frontiers by using the half-hourly analyses, and from the model by summing T+0 - T+24 forecast accumulations. For the purpose of this study, we consider the MORECS accumulations to be "the truth" (or the nearest we can get to it).

Mesoscale model vs MORECS.

There was a fairly good match between these two accumulations, both in amount and distribution. However, the model tended to underestimate extremes of rainfall in highland areas.

Mesoscale model vs Frontiers.

The Frontiers data were definitely deficient when compared with model data. A factor of 2 was an average, subjective, value, with Frontiers being worse in the far North, and South West of the country.

Frontiers vs MORECS.

This was the most important comparison, as it gave some idea of the accuracy of the radar data, and how best to use it in the correction scheme. Amounts measured by the radars were recorded at and around each radar site, and scaled to take account of how much of the time each radar had been available (On average, the radars are 'down' for around 5% of the month).

Corresponding values were taken from MORECS, and values of radar accuracy (the ratio Frontiers : MORECS), were calculated for each radar, as a function of distance from the radar, up to a distance of about 120km, or 3 MORECS grid squares. Figure 2 shows the results for a good radar, Hameldon, and Figure 3 for a bad one, Predannack. Table 2 shows a month by month summary of the results at each radar. A tick indicates good quality data for that month, a cross implies bad quality, and a question mark is somewhere in between.

The results showed that the radars in general have a slight tendency to under-detect rain, and that this tendency increases with distance from the radar. This result has been known for some time. Kitchen and Jackson (1993) noted a steep decline in detection outside a 100 km range. It was also found that some radars were better than others. Some were very good, but some were considered not good enough to be used in the correction scheme. It would be more accurate to leave the model rainfall uncorrected in areas covered by such radars, rather than risk removing real rain that the radar had failed to detect properly.

Thus it was decided to implement a radar "blacklist" of radars deemed unreliable. The correction scheme then only uses data at model points that lie within a given range of reliable radars. Outside of this limit, the model's soil moisture is allowed to evolve freely, without nudging from MOPS data.

The range decided on was 100km, as beyond this, all radars were prone to miss areas of rain. The radars we decided to call 'good' were : Corse, Hameldon, Ingham, Clee, and Chenies. Those labelled 'bad' are: Beacon, Dudwick, Pembroke, Cobbacombe, Wardon, Predannack. Due to the unavailability of MORECS data for Ireland, we used the mesoscale vs Frontiers comparison here and decided to include Castor Bay and Dublin radars, but not

Shannon. Jersey was also omitted.

It was observed that the quality of data covering the eastern part of East Anglia, was good despite being further than 100 km from the nearest radar. It would be possible to include a 'dummy radar' in the region of Norwich, which would then force the scheme to accept radar data in this region.

Although it may seem at first that we have left out a lot of the radars, it can be seen from Figure 4 that the actual land coverage of the ones omitted is not all that large, and a reasonable proportion of the country is covered (around 60% of UK land points).

4. Parallel Trial of Hydrology Correction Scheme.

4.1 Trial.

A trial was set up at the end of August 1994 to test the HCS. It included not just the correction scheme, but also the package of model and assimilation changes due to be implemented at the end of September. These changes reduced spin-up, increasing analysed rainfall rates appreciably (Lorenc et al., 1994). The trial used operational observation files and boundary conditions. It started at 09Z on the 25^{th}, in order to coincide with the mesoscale model starting to run with continuous assimilation. It ran in parallel with the operational model, using the Cray command "fc_hook" to automatically start each run after the operational run had finished. That is, it ran eight 3 hour assimilations per day, but unlike the operational run, it did not automatically perform any forecasts. These could be run later if desired, from archived trial dumps. From here on, these two runs will be referred to as HCS, and Clim respectively. To assess how much of the drying problem was resolved by the reduced spin-up, and to determine the impact of the HCS alone, a second parallel run was carried out, with no HCS but allowing soil moisture to evolve freely with no daily resetting.

At the start of the trial, not all of the radar quality data was available, and so a slightly different set of radars was blacklisted. The radars used in the trial included Wardon Hill, and Pembroke, but not Corse Hill. The 100 km range was unaltered.

4.2. Soil Moisture Evolution.

The trial was run for 5 months, and Figure 5 shows the evolution of the domain average soil moisture content, along with the climatological value being used in the operational model. It can be seen that there are definite, large, sharp deviations of the trial from climatology, but that the overall trend, and mean value are followed. These results seem both expected and entirely reasonable, and they show that the autumn changes together with the correction scheme have successfully overcome the model's drying problem.

The noHCS run was stopped on the 12^{th} of October (day 48 of the trial), as it was thought to have been running for long enough. Figures 6-11 show the soil moisture field for this day for the three runs at 15Z, and also the differences between HCS and the other two. Some features are immediately obvious. The Clim field is much smoother, whilst the two trial runs show a lot of noise. The period had been very dry, especially in the south-east, and so the much dryer values in that region, in the HCS run, were considered to be reasonable. There were frequent local differences of above 30, and some up to 50 Kgm-^{2}, with the HCS trial almost always being drier. There was a mean difference of 17.4 Kgm^{-2}, which is almost 25% of the UK average.

The HCS and noHCS runs were very similar in pattern, but some differences did show up on the difference map (Figure 11). Over the whole UK, the HCS was, on average, about 3% wetter than the noHCS run. There were no significant differences outside the area covered by radars which we had classed as reliable, and within this area, differences showed up to 50 Kgm^{-2} at places, with the HCS generally being wetter. This shows that, although the reduction of spin-up has drastically reduced the drying problem, the correction scheme can still make an important contribution to local soil moisture values.

The HCS and Clim runs were also compared for the 19th Jan 1995 (day 147), a time when climatological values are reaching a maximum for the year. See Figures 12-14. The Clim field is again much smoother, with less variation across the country than in October. The HCS field now has a lot less noise than before. This is probably because as the soil gets a lot wetter, it approaches saturation, and so it reacts a lot slower to individual rain events, and the resultant field is smoothed. From the difference map, it can be seen that Ireland was generally wetter in the HCS trial, but the east coast of England and Scotland was drier. Local differences are as large as 80 Kgm^{-2}, but the mean over the UK is 0.6 Kgm^{-2} wetter in the trial. These results show that the very dry south-eastern region from October was not due to an excessive and persistent drying problem, as this area has responded to rain since then, and is now near climatology.

It is also important to remember that there is a large area of land in the mesoscale domain (namely parts of France, and Norway) not covered by the radars. The values of soil moisture content in this area were also compared with climatology. In neither of the above cases were there significant differences, with mean differences of only a few percent.

The model surface hydrology parameterisation enforces no maximum 'saturation value' of soil moisture, but relies on enhanced sub-surface drainage to remove large amounts of water from the root zone. There was some concern that perhaps such an upper limit to soil moisture values should be imposed, in order to prevent unrealistically large accumulation of soil moisture during heavy rainfall in the winter. But the way the soil moisture responded to the very heavy rain on the 21st Jan 1995 (Day 149), suggests that this is probably not necessary. Heavy rain was widespread over much of the country, and the domain average rose rapidly to 118 Kgm^{-2}, about 20% wetter than climatology. In the next few days, however, it fell quickly to more normal values.

To try to measure the accuracy of the fluctuations about climatology, the trial results were compared with soil moisture deficit (smd) values calculated weekly by MORECS, for an assumed grass land cover - the main land type used in the model. The smd values are the amount of soil moisture by which a given grid box is below "field capacity", and so weekly variations in smd should correspond to weekly variations in the trial's soil moisture content.

The trial increments correlate much better than the climatological ones with the MORECS changes (Figure 15). The HCS run gives a realistic account of the main wet and dry spells, whereas climatology cannot. (The MORECS area covers approximately 40% of the mesoscale model land points. For a few weeks, model increments over an area more closely corresponding to the MORECS area were computed, but these did not show better correlation than the whole-area figures.)

It is noticeable that MORECS increments are more positive than the HCS values; the MORECS soil moisture reservoir fills up more quickly than the model one. This is probably due to differences between the model and MORECS parametrisations, for example run-off and sub-surface gravitational drainage are included in the model but not in MORECS. Different soil moisture capacities are also assumed in the two schemes, so an absolute comparison cannot be pressed too far. The agreement between MORECS and the HCS is least good at week 1 and week 11. For the first week, this may be because the model was started from an unrealistically moist climatology, causing evaporation to be larger than it was in reality. For the last week, the trial increment indicates a wet spell, but MORECS was already close to field capacity and so was unable to store much more rainfall.

4.3. Impact on Forecasts.

We also wanted to see what impact the correction scheme had on the evolution of forecast parameters, especially temperature, during the course of the day.

Three 18-hour forecasts were produced for the 12^{th} October, from 00Z (Figures 16 and 17), and compared against observed temperatures. There were very few differences between the HCS and noHCS runs. However there were several differences between the HCS and Clim runs. The Clim run was more accurate over East Anglia, North Cornwall and South Ireland, and the HCS run was more accurate near the Isle of Wight, the Pennines and North West Ireland. The differences were of the order of a degree. The HCS also made slight improvements to wind speeds and directions over Wales, and the North Wales coast.

Four other cases were picked, where an 18-hour forecast was produced from 00Z, in order to try to find differences between the HCS and noHCS runs. They included cases where the trial was both wetter and drier than climatology, generally by an amount approximately 20% of climatological values. One case, 16/9, showed no significant differences in the forecast charts, this was probably due to strong winds which reduce the effect of soil moisture differences. The cases from 22/9 and 13/10 showed some small improvements in local temperature maxima at 15Z, in the HCS run, but looked identical in precipitation. The case from 10/9 showed several small differences in 15Z temperature, with more being a decrement than an improvement. There was a also a slight difference made to a line of showers in the Midlands at 12Z where the HCS, incorrectly, had less rain. In none of these cases were any differences seen in the humidity or cloud cover charts.

In conclusion, there are not many changes seen between the forecasts, but this could be due in part to the fact that the initial, climatological, value of soil moisture content for the trial was too high, and it took quite a few weeks for the trial to spin-down to more realistic values, consistent with the rainfall data received. It is reasonable to expect a larger, and more systematically beneficial impact, when we get towards late spring and summer 1995. Then the soil moisture will be at a realistic level, and the conditions are more sensitive to soil moisture values.

5. Impact of the Hydrology Correction Scheme on Snow Depth.

Although the snow depth section of the correction scheme will have less of an impact than the soil moisture section, purely because rain is so much more common in the UK than snow, it is still important to know how this part performs, and to make sure that it is not detrimental in any way. To do this, a couple of case studies were carried out for dates early in 1994.

The procedure was to perform a twelve hour assimilation from 18Z, overnight, when snow fell, followed by an 18-hour forecast until midnight the following day. We were interested in snow depth, surface temperature, soil moisture and relative humidity fields for three separate runs:

i) Control.	Four 3-hour assimilations without the correction scheme, each one starting from the final analysis of the previous one.
ii) HCS.	As for the control, but with the correction scheme providing increments to snow depth (and soil moisture).
iii) No T_1-Test	As HCS, but with the test for freezing level-1 temperatures omitted, so that any observed precipitation not forecast by the model was treated as rain. The reason for this was to see if the full scheme was in any way 'over-enthusiastic' in incrementing snow due to errors in model temperatures caused by the omission of precipitation.

The first period chosen for study was from 18Z on the 14^{th} Feb. 1994. Snow fell over most of Southern England, particularly in Cornwall and the South West, but spreading as far as the North Midlands, mid-South Wales and Southeast Ireland.

The main differences between the control and the HCS, at the final analysis, were in areas of significant snow depth (of the order of 2 or 3 or more cm) where the HCS generally tended to remove snow. The deeper the snow, the more was removed. It is hard to tell whether or not this was the correct action to take as the model precipitation bias (measured against MOPS analyses) was 0.87 for rate, and 1.05 for area. That is, the precipitation in general was too widespread, but not heavy enough. Where snow was less, there was seemingly random removal and addition of small quantities which led to some positional variations in the extremes of the snow covered regions. Most notable was a large removed area in the Midlands. Whether or not the removal of the snow in the Midlands was correct is difficult to say, because the surface observations available only give values to the nearest centimetre, and most of the changes were smaller than this, although judging by the extremities of reports of trace snow, it would seem that the control run did go too far north with its snow cover.

There were also some small differences outside the Frontiers radar area, which obviously should not be caused by the correction scheme as it only uses observations from within the area. These differences were probably caused by a build up of the slight differences in the analyses at the start of each 3-hour run.

For the second 'No T_1-Test' run, the final analysis was very similar to that of HCS. In general, the differences between these two runs were very small both in magnitude and area (there were no large areas of difference, just small 'spots'), and it is impossible to determine which, if either, was the more accurate.

At the start of the 18-hour forecast, at 6Z on 15/2/94, there were differences of up to 1.0°C between the control and HCS runs (with an rms of 0.07°C), and of up to 0.5°C between the two test runs. By the end of the forecasts, these differences were 2.6 and 0.9°C respectively. As can be seen from Figures 18 to 21, of snow depth differences and temperature differences (test - control) for 18Z and 00Z, there is some correlation between the two quantities. That is, where one has more snow, then it is also cooler. The temperature charts are affected by a lot of noise, but there is quite often a patch of the same sign in the same place. Most notable are the areas of significantly less snow in the trial (dark patches in Southeast Ireland and South Wales), which are also warmer.

Other quantities were also looked at, namely level-1 relative humidity and soil moisture. There were observed correlations between the four quantities; as a general guideline, temperature decreases where soil moisture, snow depth and relative humidity increase. Thus the snow depth trials were shown to have an impact of the order of 1°C and 5%, on the forecast of the screen temperature and relative humidity during the next 18 hours.

Contour maps of temperature distribution were drawn for the control and test runs, and were compared with surface observation charts from 0Z on the 16th. In general, the contours were too close together to pinpoint any differences and verify them against observations. The only area where the differences were widespread enough was over central Ireland, where observations are sparse. There was one isolated observation, downwind of significant snow areas on the east coast, where our test had made a positive impact of about one degree, but overall the changes were too small to say which was better.

The differences between the two test runs were small and in no definite pattern. The snow depth differences looked like a random pattern of dots of roughly equal numbers positive and negative. The temperature differences were also without structure, with the more significant differences being over the sea, downwind from areas of snow depth differences.

The second case looked at was 5th April 1994. There was not a large amount of snow for this date except for a patch in the middle of Scotland, but there was a high degree of over prediction of snow by the model, and so it was felt that it might be an interesting case. The trial was run without blacklisting the Scottish radars, so although the data used may not have been of the highest quality, it was still a useful sensitivity study.

At 06Z, after the assimilation, the HCS showed temperature differences of up to 0.9°C with an rms of 0.16°C, with the test analysis generally being the warmer. Between the two tests there was 0.6°C maximum difference. At the end of the forecast period the HCS and control runs differed by up to 0.25°C with an rms of 0.08°C (that is noticeably less than at the start), but during the forecast, at about 15Z the differences were up to 1.5°C, and of 0.9°C for between the two tests. The lack of persistence of these differences was probably due to strong westerlies of around 10ms^{-1} which were more or less constant all day.

As for snow depths, the HCS was always less (by up to an inch) than the control which is what we expected as the case was picked for its over-prediction of snow, although it was mainly snow amount that was reduced rather than the extent covered. The two test runs were again very similar.

When plots of snow depth differences were compared with plots of temperature differences, there seemed to be very little correlation between the two as there was in the 15th Feb case. Again, the reason for this was probably the winds which prevented any given region from developing much of a difference.

6. Future Developments.

There are plans to introduce a new, multi-layer version of the hydrology scheme into the Unified Model (Cox, 1993). The main reasons for doing this are to improve the representation of evaporational and runoff fluxes and to facilitate thermodynamic calculations by having the same number of layers and the same depths for both the soil moisture field and the soil temperature, currently held at surface points and at three deep soil levels.

There is no basic incompatibility between such a scheme and our hydrology correction scheme, as we are dealing with the amount of water entering the soil, whereas the multi-layer scheme deals with the partitioning of the water once it has entered the soil. The only thing that would need consideration is the existence of soil moisture capacities at each new level (where there are currently no maximum values), but this is a minor point. Hence it is felt that the HCS could be interfaced with the multi-layer hydrology quite simply. There is no need, for example, to go to the length of basing the linearised increment calculations in the HCS on the multi-layer scheme.

There are plans to replace the Frontiers system with an automated version as part of the Nimrod project. It is expected that when this happens, the quality of precipitation data received will be higher. Therefore, data from Nimrod, once implemented, should be monitored to see if it is of sufficiently high quality to allow us to either extend the current radar range used in the correction scheme, or to add new radars to the 'reliable' list, thus increasing the land coverage of the scheme.

7. Conclusions.

Before the Autumn 1994 changes to the mesoscale model, a lack of rainfall during assimilation led to a pronounced drying of the soil, of the order of 10-20% per week. The operational solution to this problem was to reset the model soil moisture content to climatological values, on a daily basis.

Since the changes, the spin-up problem, and hence the drying, has been greatly reduced. A prolonged trial of the Hydrology Correction Scheme has shown that drying in the model has been eliminated, and the model's soil moisture field now responds realistically to periods of wetter or drier than usual weather. Approval has been gained to remove the daily resetting to climatology, and to let the model's soil moisture field 'run free', as from Spring 1995.

The trial has also shown that the snow depth part functions satisfactorily, and that sensitivity of forecast parameters is very small.

Although forecast temperatures produced from the trial have shown little sensitivity so far, it is expected that more differences will become evident during the spring and summer when conditions are more sensitive to soil moisture differences - namely on clear, sunny days.

Acknowledgements.

We are grateful to Bruce Wright for the original work to make MOPS rain data available to the assimilation scheme, to Malcolm Kitchen for advice on the quality of radar data and to Brian Hems of the Product Development Branch for supplying the monthly Frontiers accumulations. MORECS soil moisture deficit data were supplied by the Product and Service Provision Branch.

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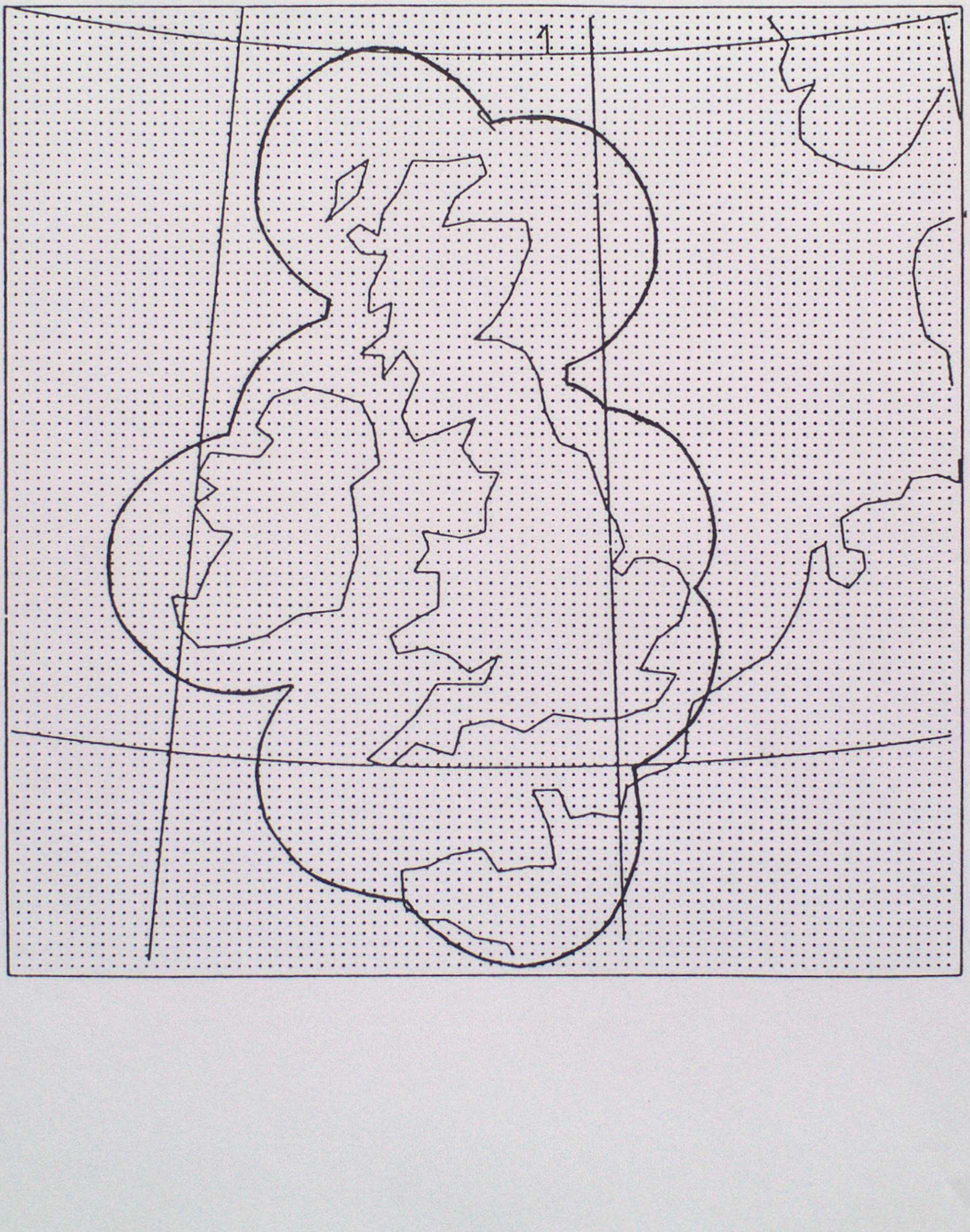
	FEB	MAR	APR	MAY	JUNE	JULY	AUG	**TOT**
Beacon	✓	X	?	X	X	X	X	**X**
Dudwick	X	X	X	?	✓	?	?	**X**
Corse Hill	✓	✓	?	X	✓	?	✓	**✓**
Hameldon	✓	✓	✓	✓	✓	✓	✓	**✓**
Ingham	✓	✓	✓	✓	✓	✓	✓	**✓**
Clee Hill	✓	✓	✓	✓	✓	✓	✓	**✓**
Pembroke	✓	✓	✓	✓	?	✓	?	**?**
Chenies	✓	?	✓	?	X	✓	✓	**✓**
Cobb.	✓	X	X	X	X	X	X	**X**
Wardon	X	X	X	X	X	X	X	**X**
Predannack	X	X	X	X	X	X	X	**X**
Jersey	-	-	-	-	-	-	-	-
Castor Bay	✓	✓	✓	✓	-	-	-	**✓**
Dublin	✓	✓	✓	✓	-	-	-	**✓**
Shannon	✓	X	✓	✓?	-	-	-	**?**

Table 2 - Monthly assessment of each radar.

Note - there was no data available for Jersey, it is included merely for completeness.

Figure 1. Map of the mesoscale model domain, showing the extent of Frontiers data.



Radar Quality as a Function of Range

Figure 2. Hameldon Hill.

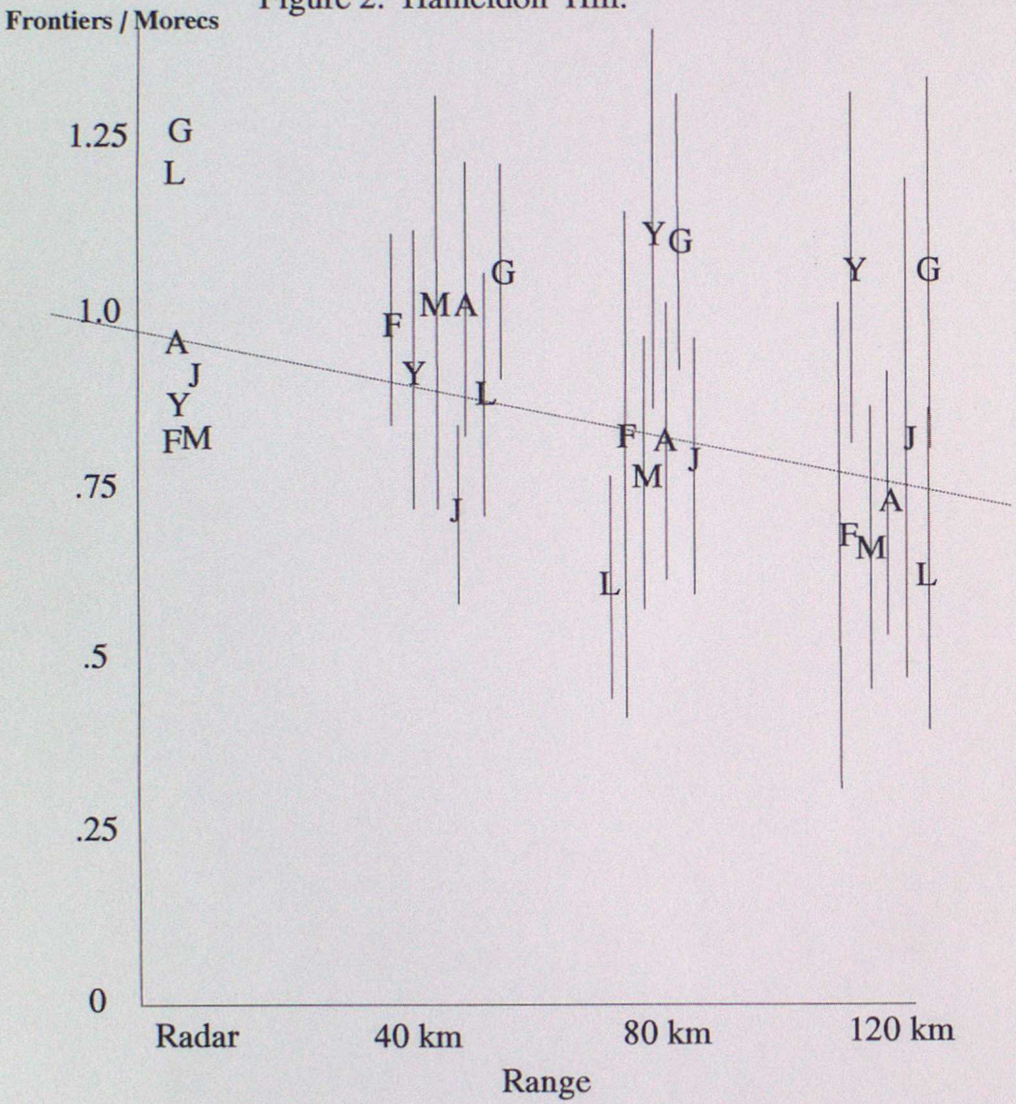
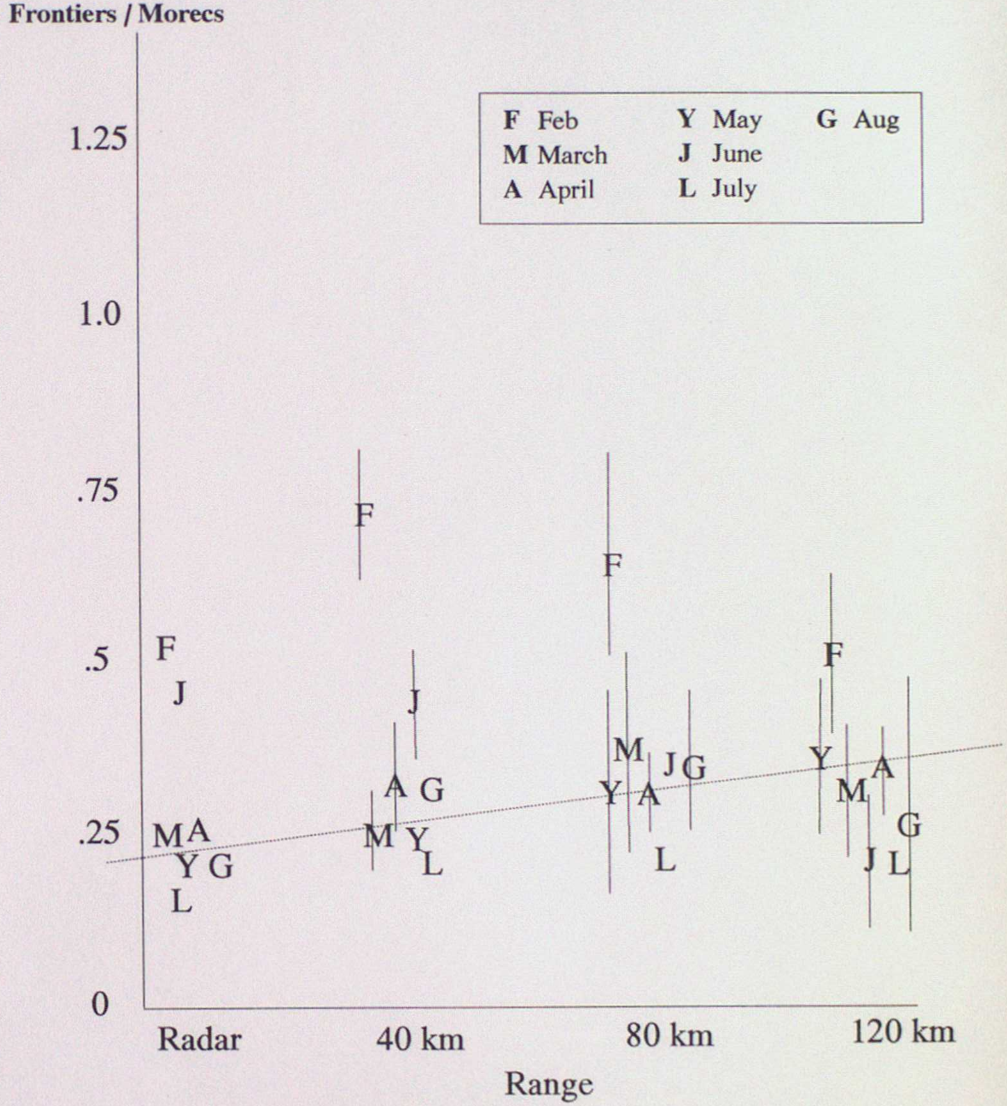


Figure 3. Predannack



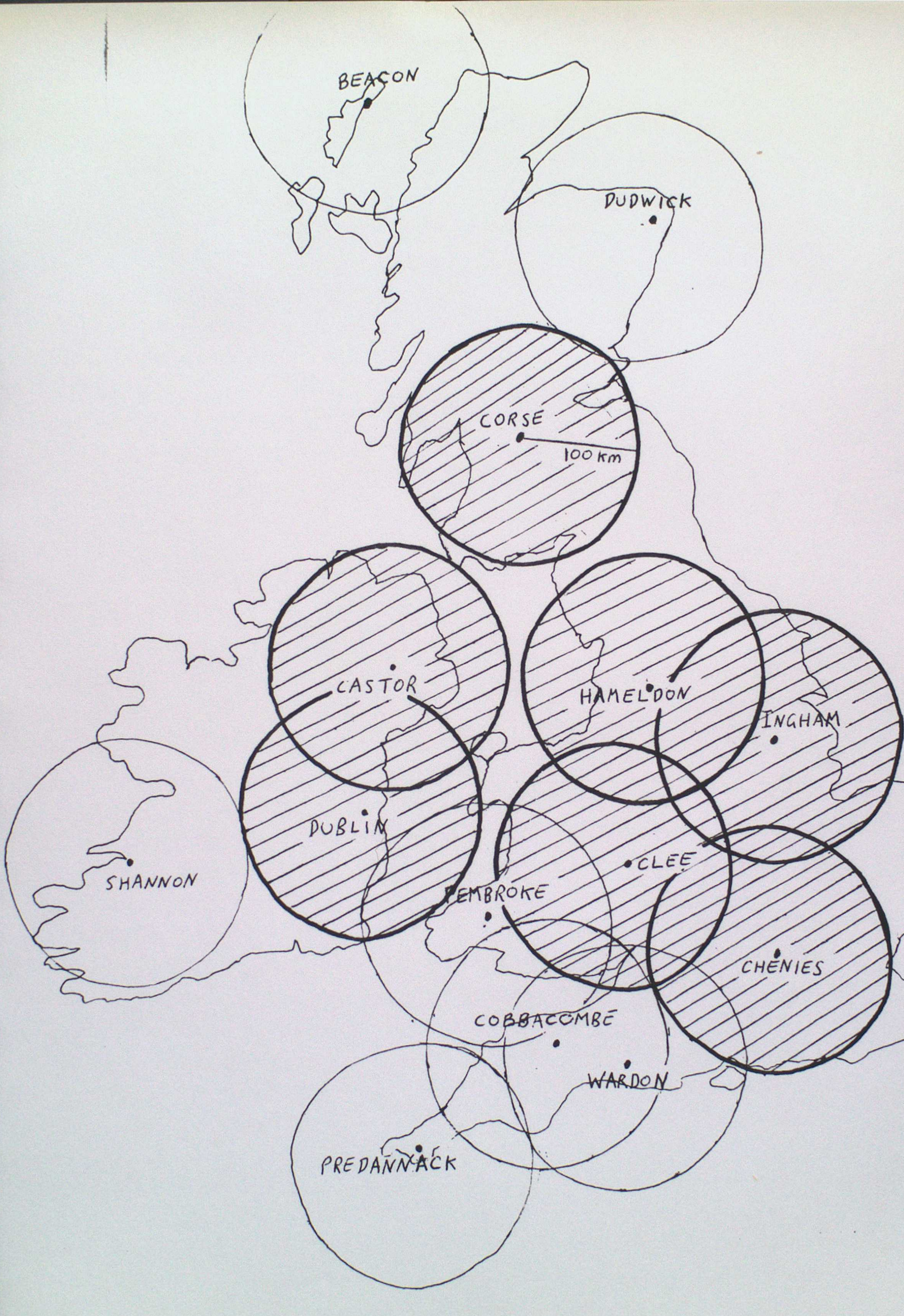
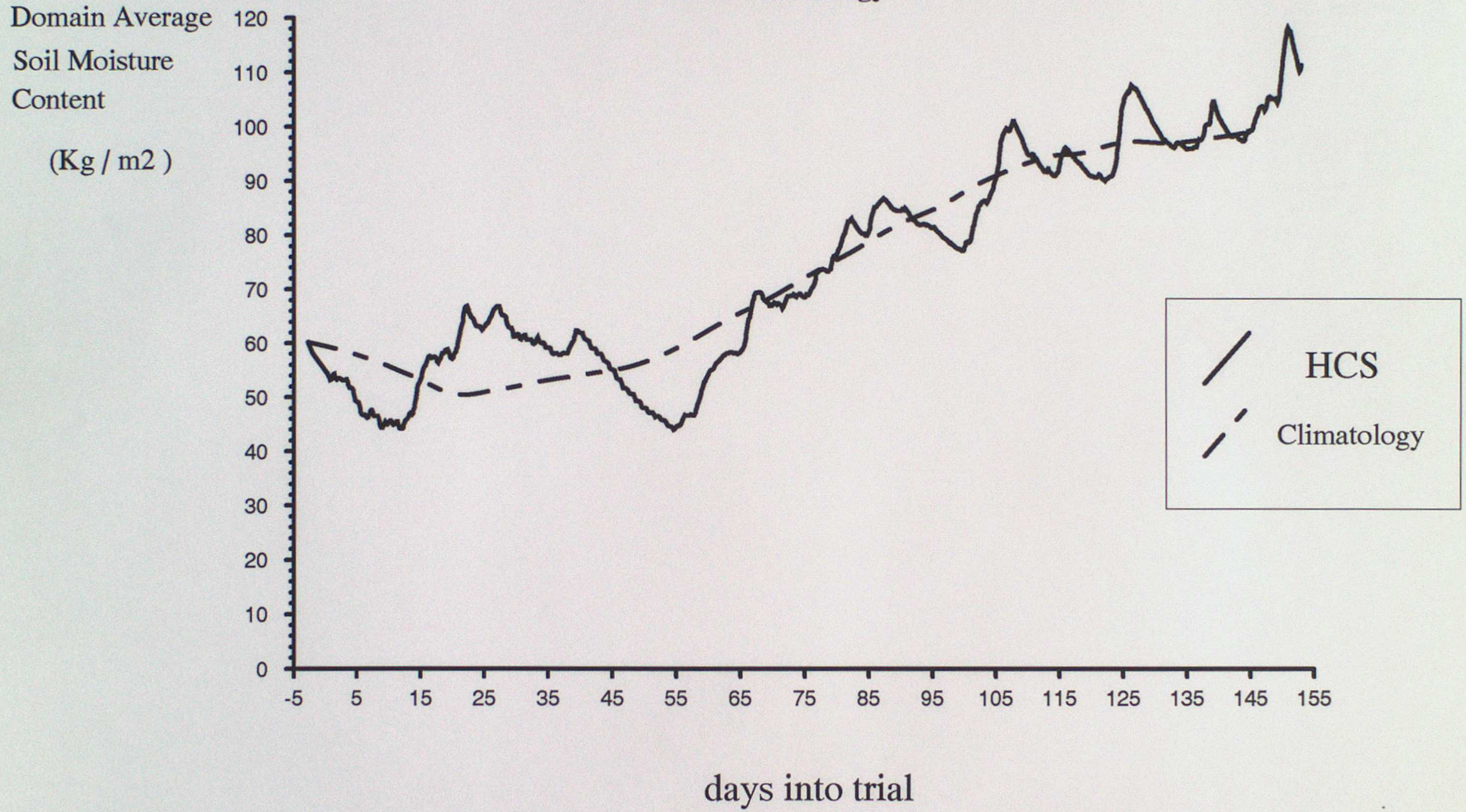


Figure 4. The land coverage of the 100 Km range, from chosen radars.

Figure 5. Soil Moisture Evolution

HCS trial vs Climatology



12th October 1994, 15Z. Soil Moisture Content, Kg m^{-2}.

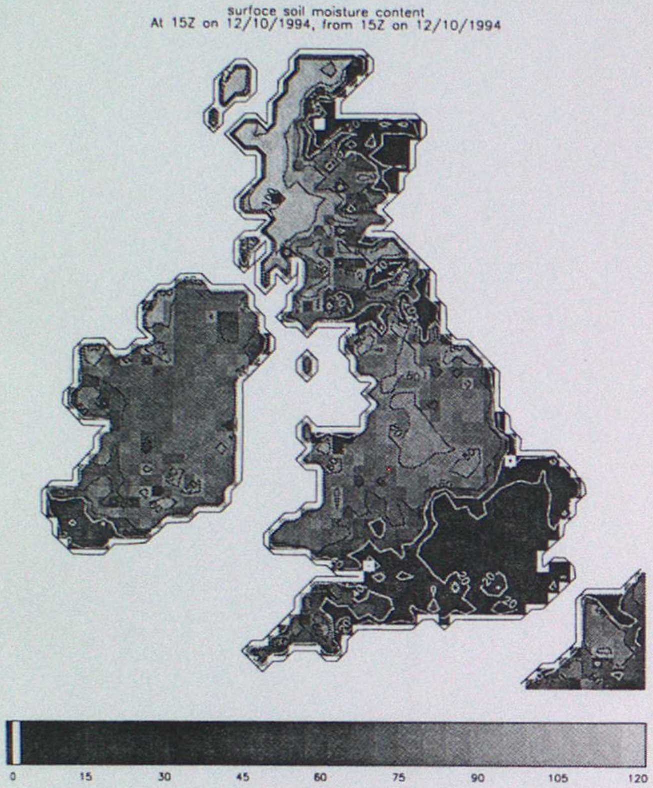


Figure 6. HCS trial.

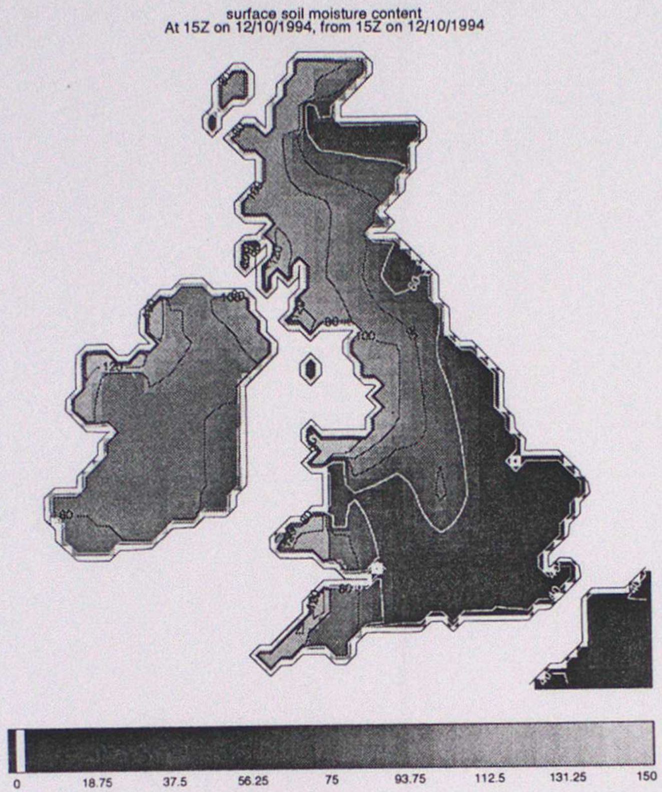


Figure 7. Climatology.

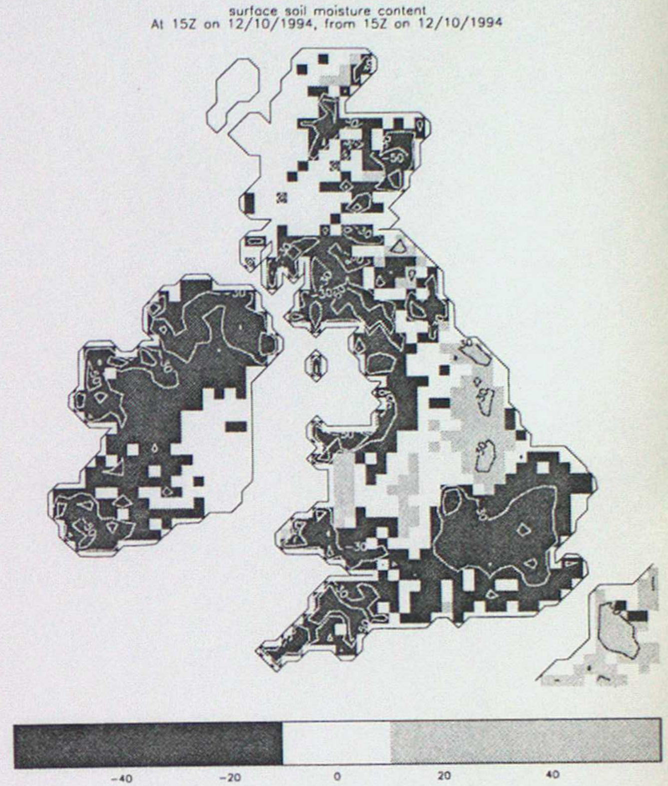


Figure 8. Difference : HCS - Climatology.

12th October 1994, 15Z. Soil Moisture Content, Kg m^{-2}.

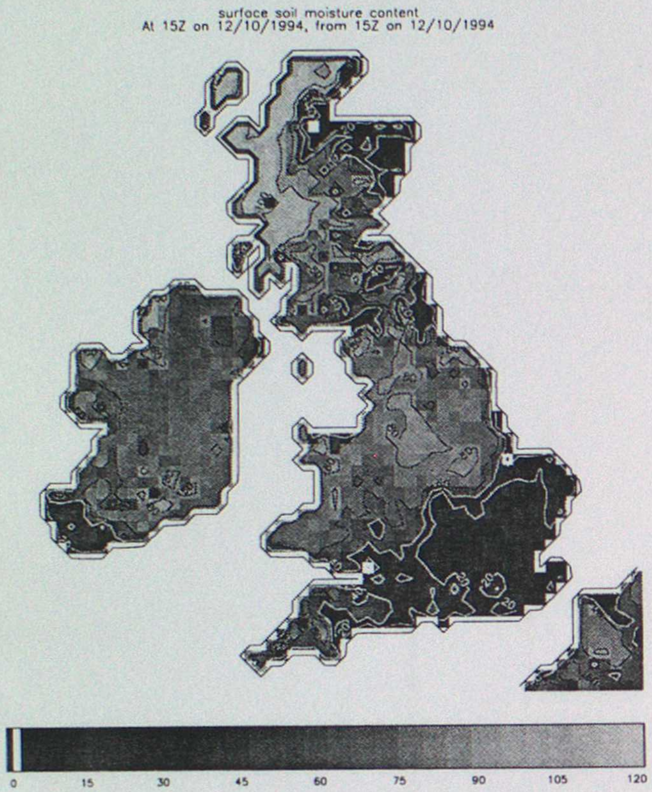


Figure 9. HCS trial (as Figure 6).

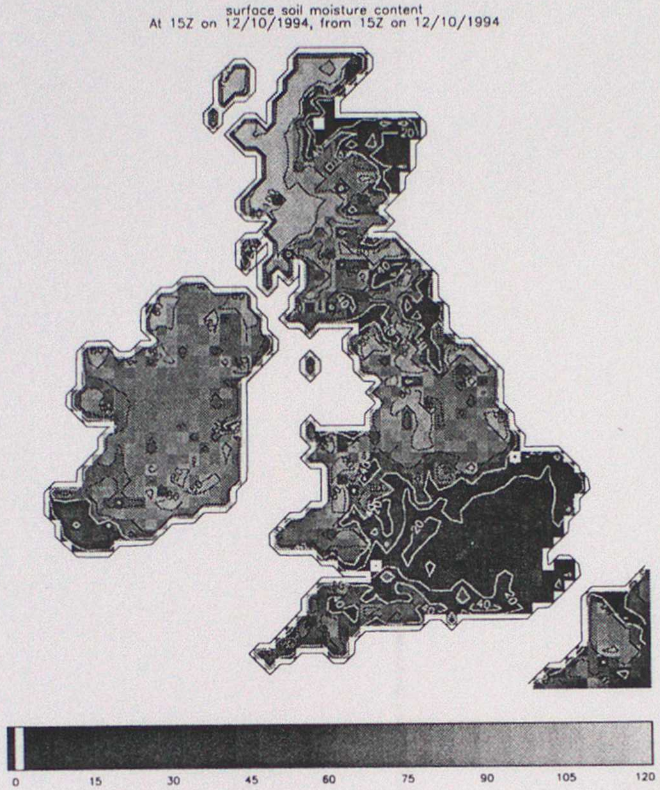


Figure 10. noHCS trial.

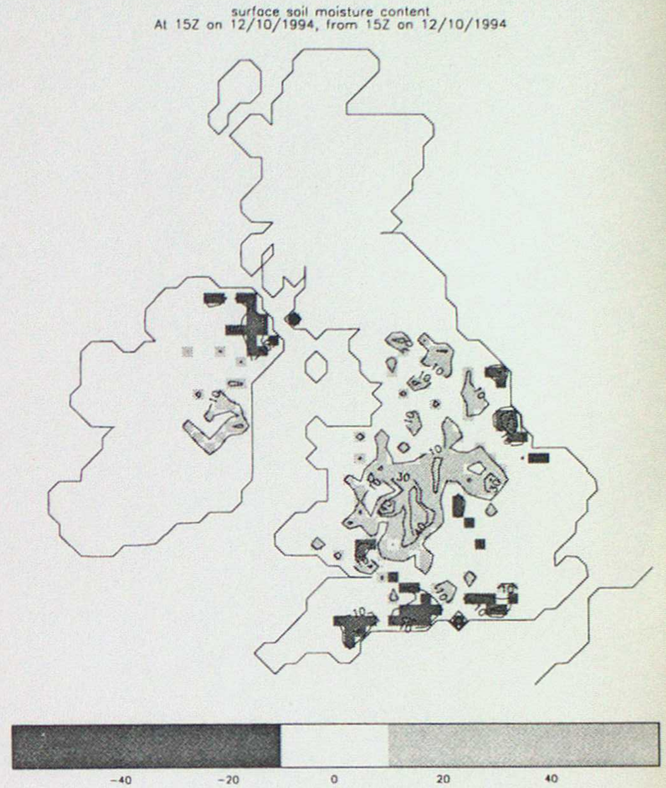


Figure 11. Difference : HCS - noHCS.

19th January 1995, 09Z. Soil Moisture Content, Kg m^{-2}.

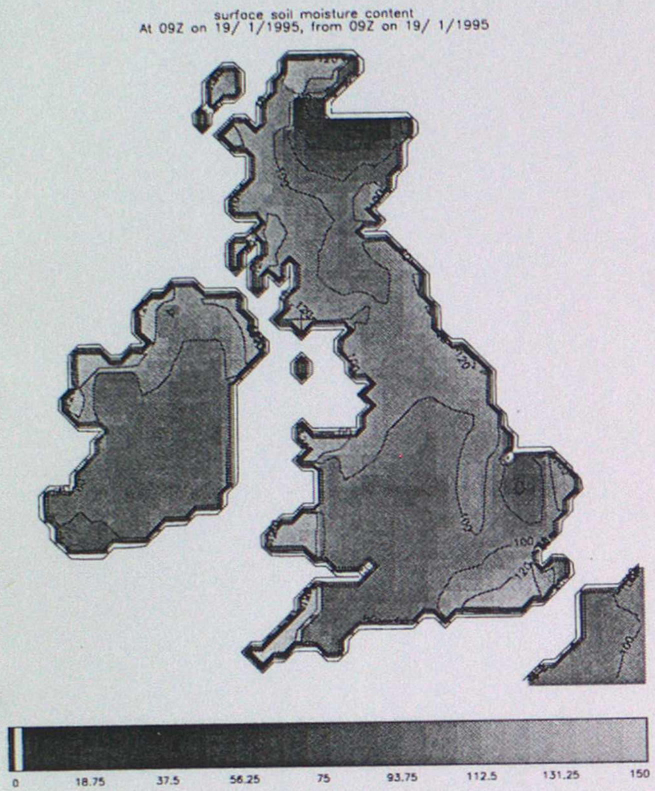


Figure 12. HCS trial.

Figure 13. Climatology.

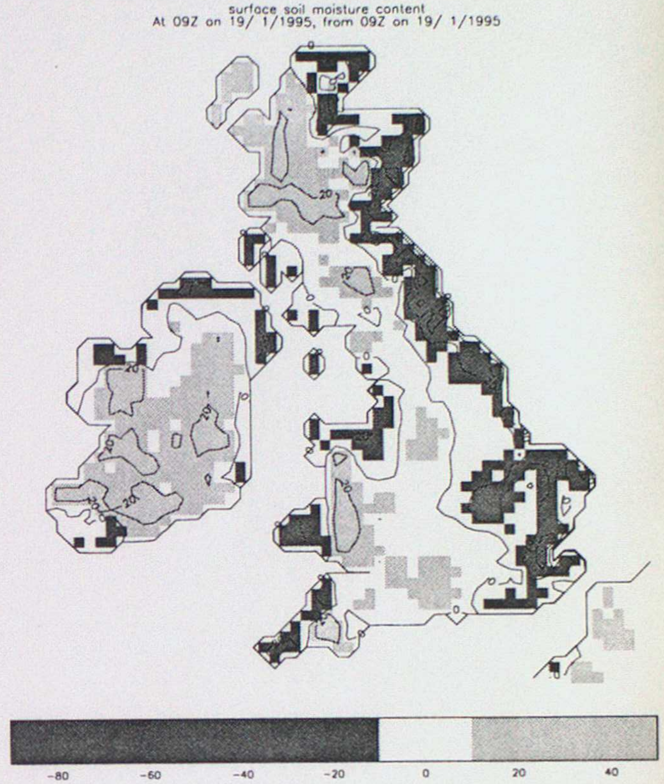


Figure 14. Difference : HCS - Climatology.

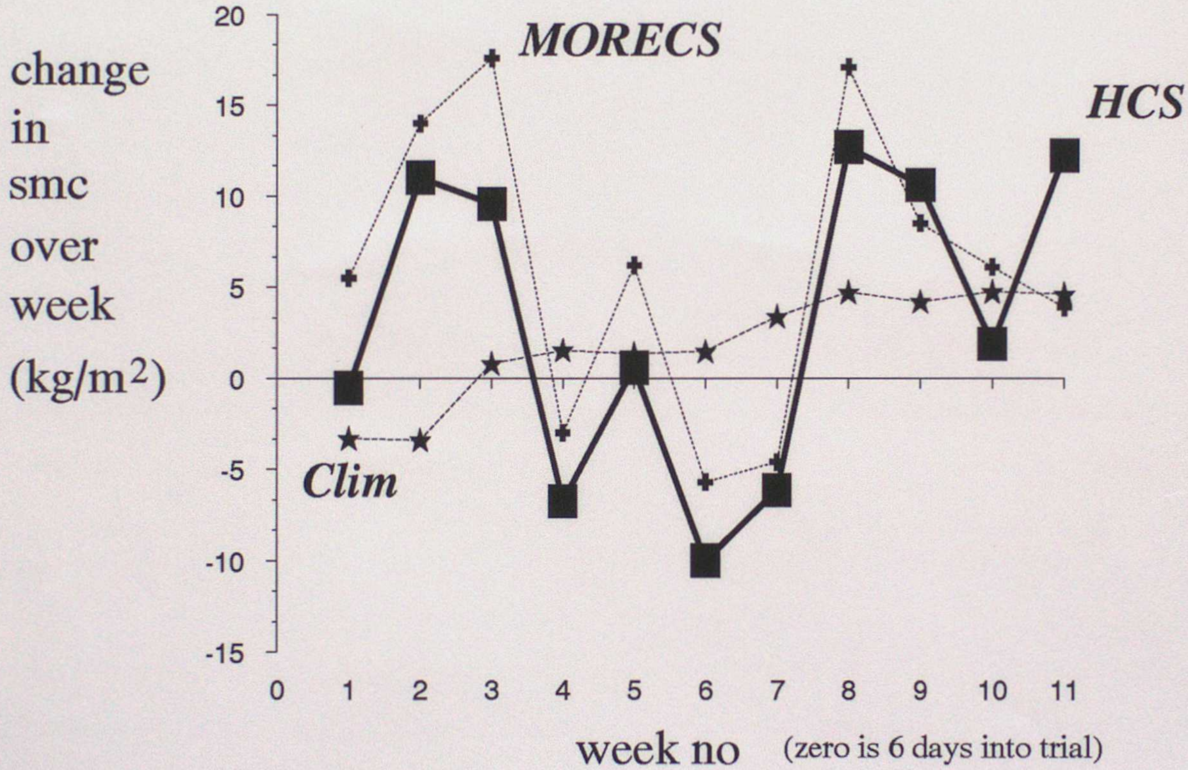


FIGURE 15: comparison of weekly soil moisture changes during the trial. The HCS and Clim values are averages over all model land points, wheras the MORECS values cover England, Scotland and Wales only.

12th October 1994, 15Z. T+15 forecast charts of surface temperature and wind.

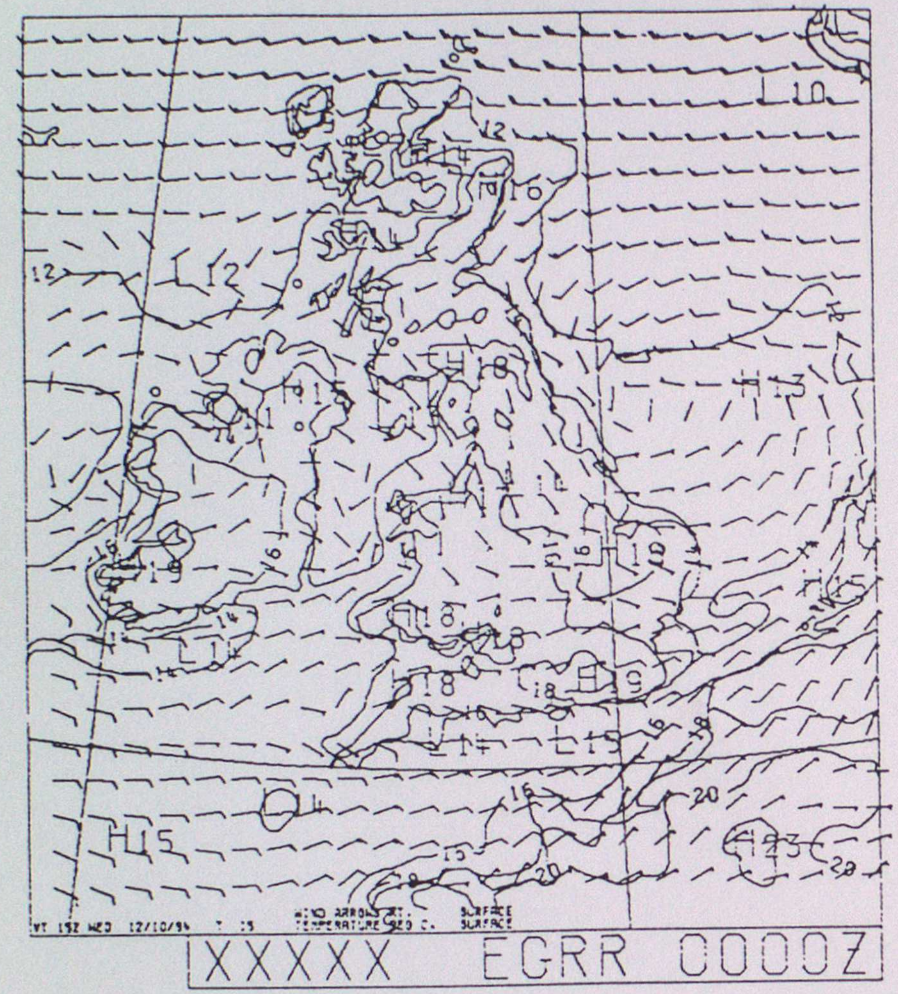


Figure 16. HCS trial.

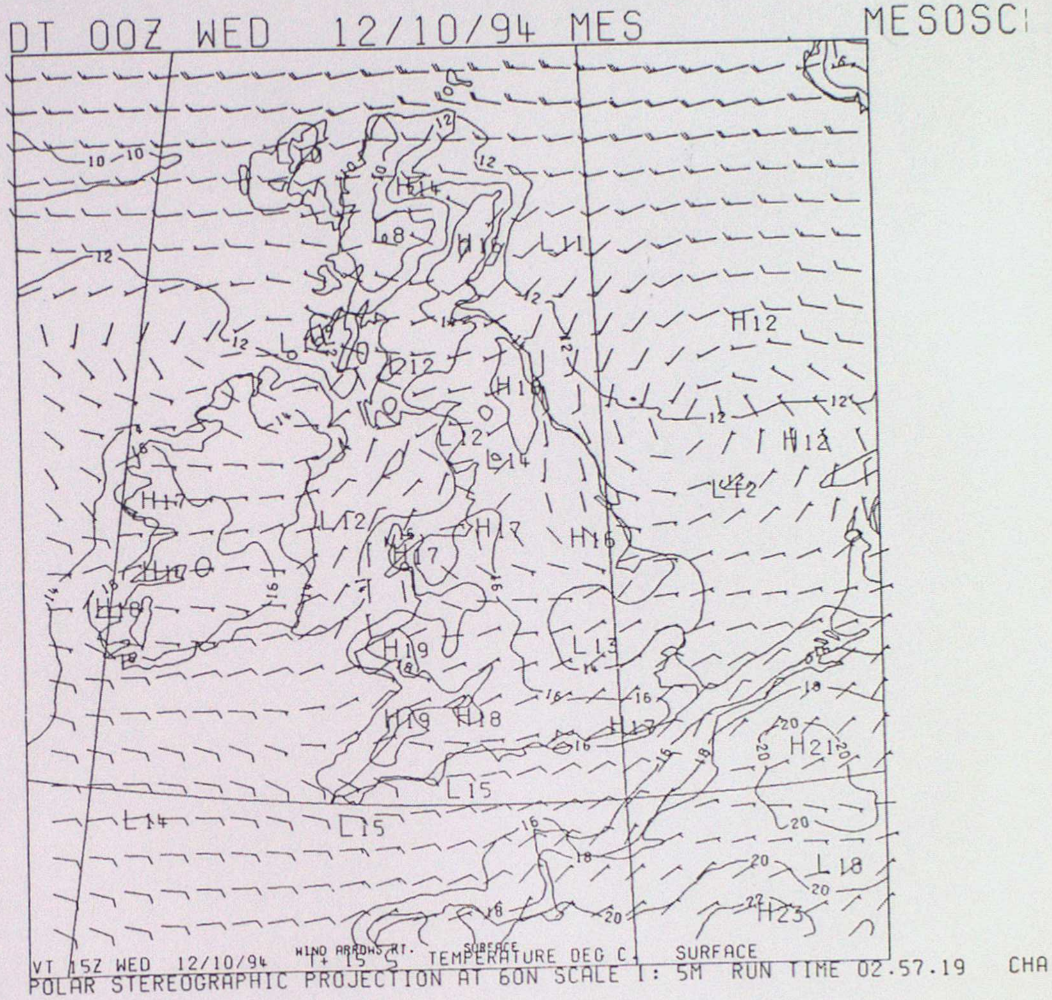


Figure 17. Operational QM00 run.

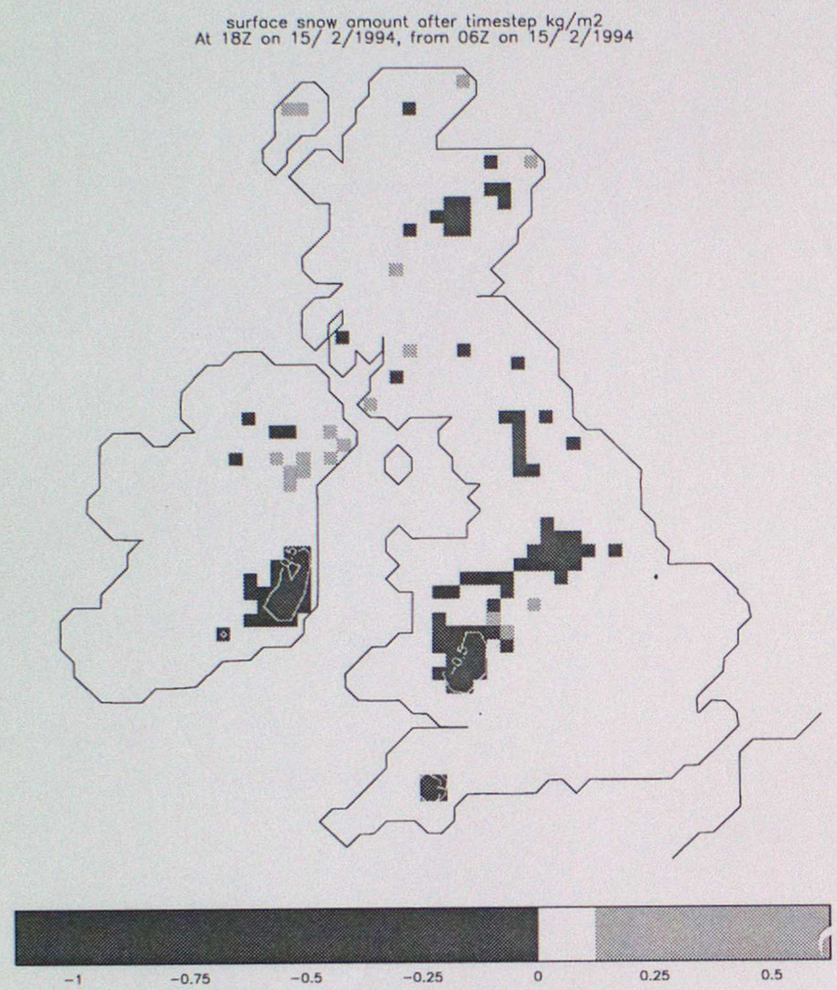


Figure 18. 18Z (T+12) Snow Depth Differences : HCS - Control.

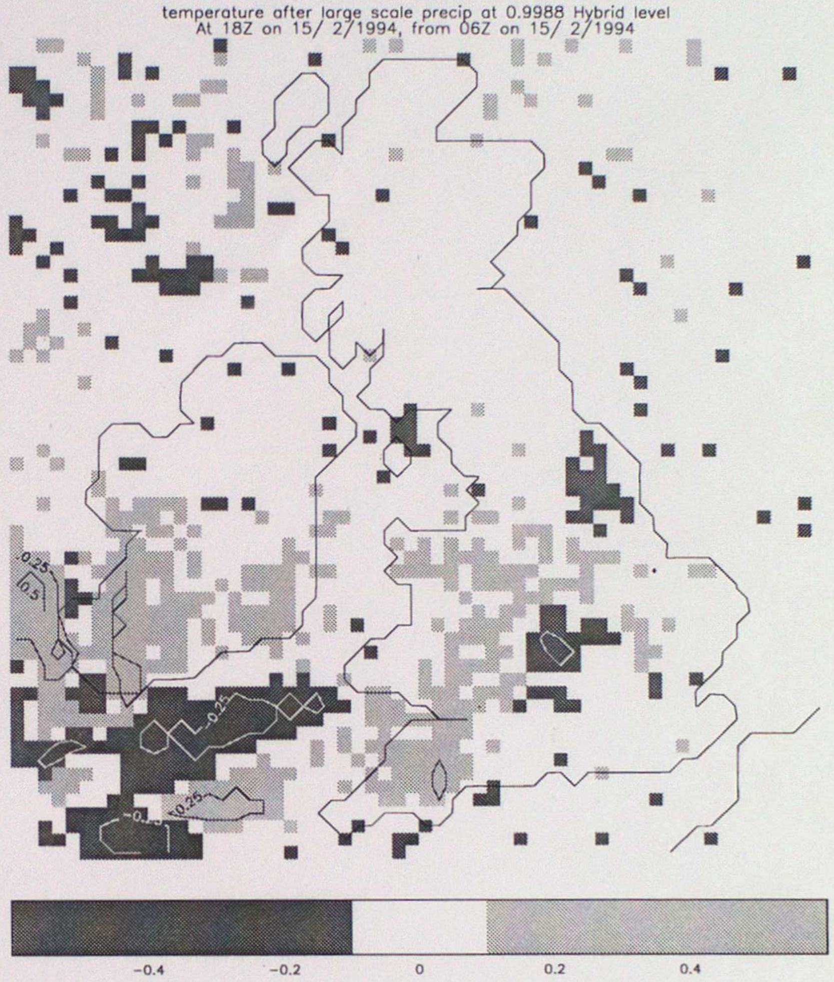


Figure 19. Temperature Differences : HCS - Control.

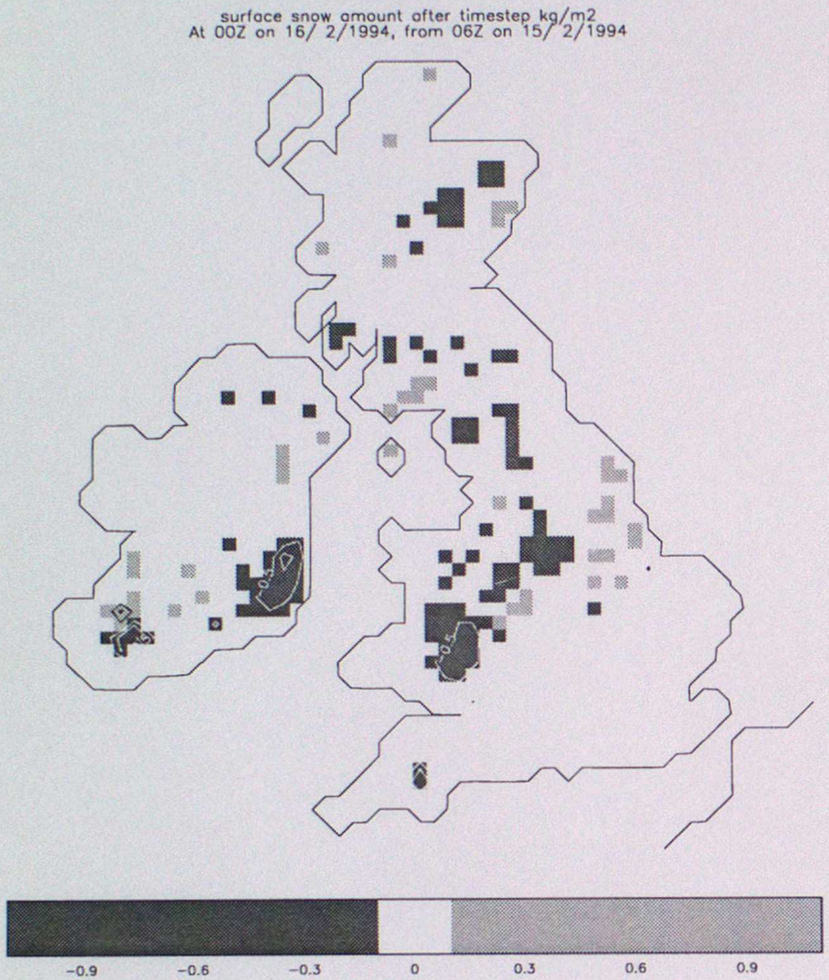


Figure 20. 00Z (T+18) Snow Depth Differences : HCS - Control.

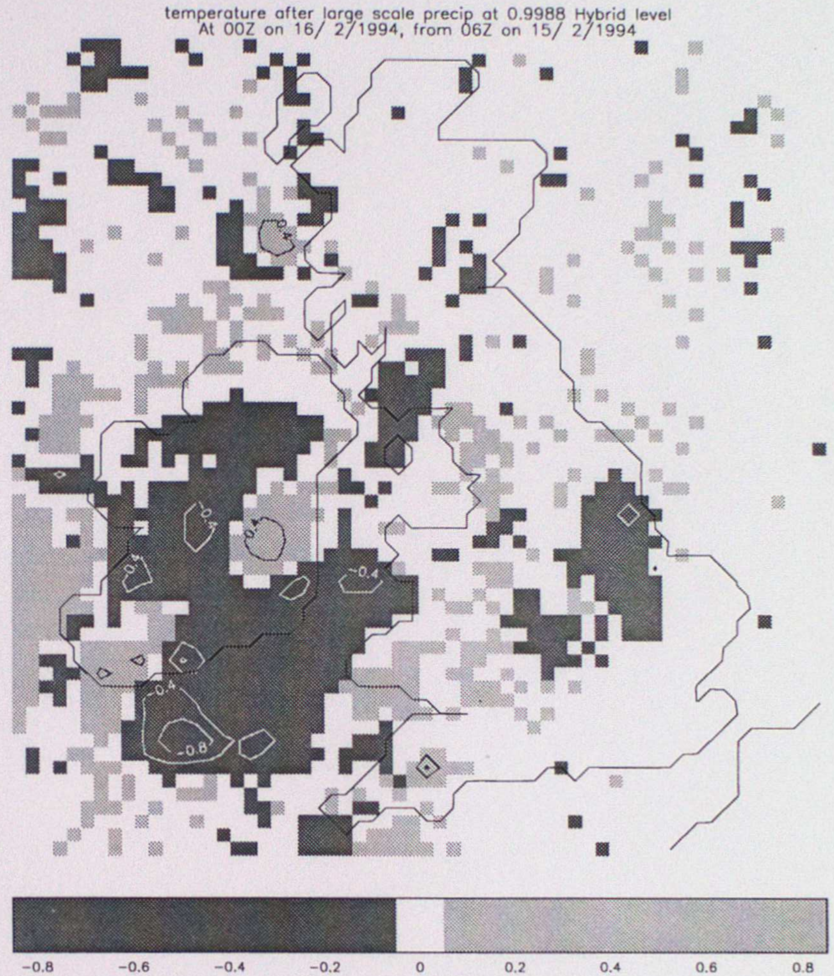


Figure 21. Temperature Differences : HCS - Control.

Appendix.

Implementation in the Model.

A hydrology correction subroutine was written, which is called from subroutine AC2 for rain observations. The structure of the routine is shown in the flowchart in Figure 22 and is described here.

After initializing variables such as soil moisture mean and rms values which are used in the diagnostics, the routine loops over all the land points. If an array is defined at all points in the domain (eg rain rates) then a pointer is used to pick out just the land points in this array.

As the case $R^{obs}=R^{fg}=0$ will be fairly common, often holding at more than half the points, it is a good time saving measure to ignore points where there is no increment to be made, hence the calculations are only performed for $\Delta R\neq 0$. The saving given by this measure can be seen in the subroutine cost summary at the end of this section. Within this main 'IF' block, the code then decides whether to update soil moisture, or snow depth. It does this by considering the total rain and snow rates and choosing the largest. If both model rain and snow are zero, and there is some observed precipitation, then its phase is determined by considering model temperature. The model atmospheric level-1 temperature is calculated, and if it is below T_M (the temperature at which fresh water freezes and ice melts), then precipitation is considered to be snow, otherwise it is considered to be rain.

The snow depth section is straight forward. The snow depth increment is calculated from values of ΔR and the timestep, by equations (22).

In the rain section, as the throughfall amount in the hydrology scheme (from STASH) includes a term due to condensation, which we do not want, then it is recalculated from equation (1) for our correction scheme. Then to calculate soil moisture and canopy water increments, there is a further test for whether R^{fg} is greater than zero. If it is, then the full calculations are carried out, using the throughfall and run-off amounts as described earlier, equations (19). In fact, the actual check is to see if R^{fg} is greater than a very small value, as for small R^{fg}, the run-off may include a non-negligible contribution from condensation. If R^{fg} is nearly equal to zero then the simpler approximations described earlier (equations (20)) are applied. There is then a check that in adding increments to the canopy content, the capacity is not exceeded. If so, then the increments are adjusted accordingly, so that $\mathbf{c}=\mathbf{c}_m$.

Once the increments have been calculated, they are added to the full array, and there is a check on each variable that the value does not fall below zero. If it does, then it is reset to zero, and the increment is also adjusted so that the diagnostics are correct.

The diagnostics produced by the routine are mean and rms values of the increments of soil moisture, canopy water and snow depth. They are calculated as being means over all land points and not just over the points where increments were made. The number of points where increments were made is also counted, but no record is kept of which part of the code the routine used for them - that is, the total number of changes, but not how many relate to snow, and how many to rain.

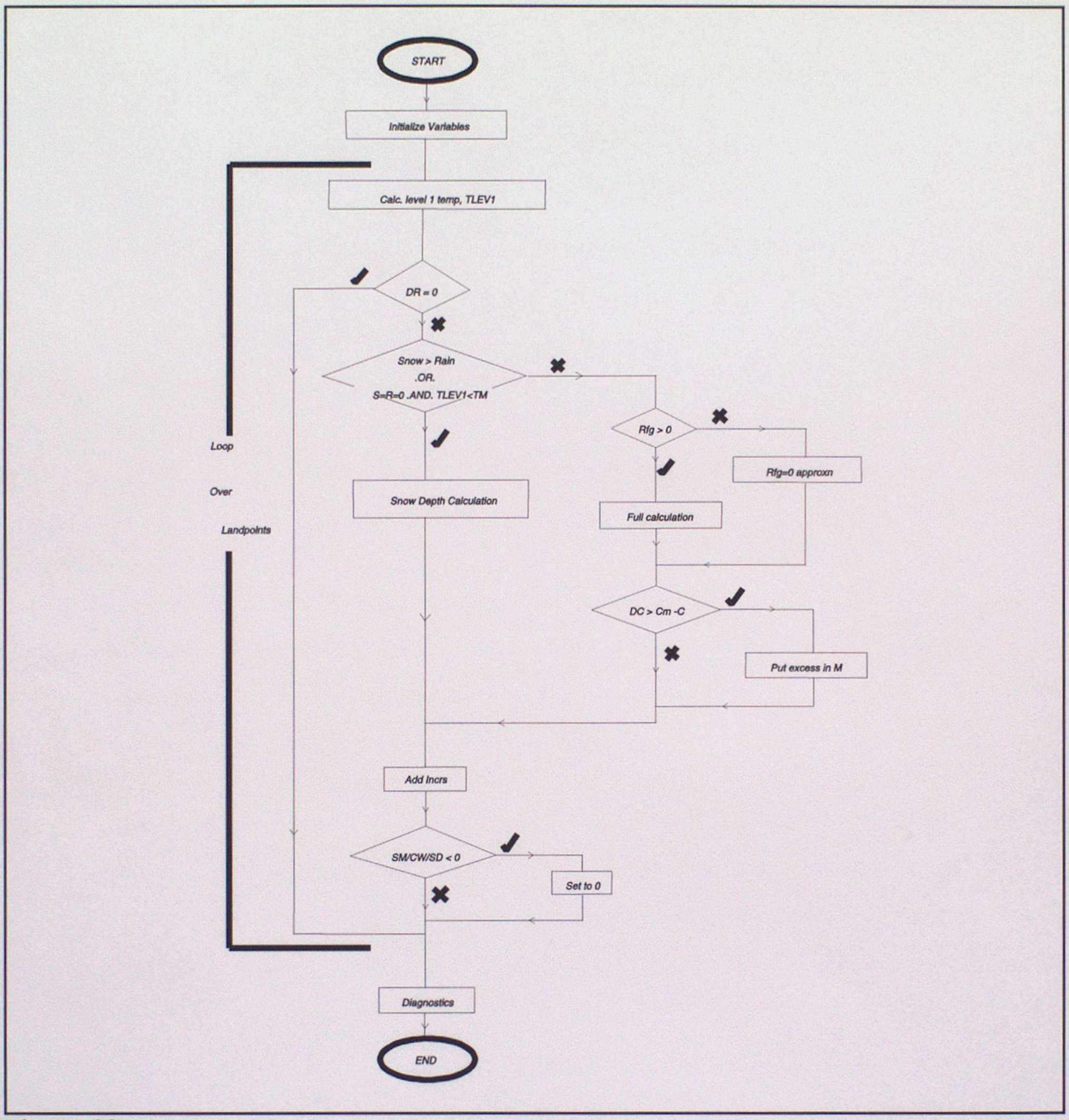


Figure 22.

Subroutine Cost Summary.

To make sure that the new code was not too expensive, the times taken by various parts of the code, were examined. Timing diagnostics, generated during a run from 25th January, are shown here :

End of AC for time step: 36

Group No	1	2	3	4	5	6	7	8	9
No of obs	679	75	576	75	642	7	582	8100	16200
CPU seconds	0.418	0.244	0.177	0.325	0.651	0.085	0.165	0.572	0.550

CPU Time used by AC = 3.194 secs.

Type 506 observations (MOPS data) are group 9. The time spent in AC per timestep was just over 3 seconds. Over 36 timesteps, AC took up 108 s. The whole run took 308 s. It can be seen that roughly one sixth of the time spent in AC is occupied by 506 obs. The number of data is 16200, twice the number of MOPS cloud profiles in group 8, because the rain data from consecutive 3-hourly analyses are used with temporally overlapping insertion periods in the AC scheme.

Other runs were performed without the new code, and showed that the hydrology correction scheme accounts for a small fraction of 506 obs (less than 10%). Presumably, most of the time in processing 506 observations is spent in observation manipulation, and in the subroutines VANRAIN, and DIAGOPR. Another run, using the HCS, but without the test for $\Delta R=0$, showed that it roughly halved the time spent in the correction scheme.