ASSIMILATION OF SATELLITE DATA FOR MESOSCALE ANALYSIS

B.J. Wright, W.H. Hand & B. Macpherson
UK Meteorological Office
Bracknell, England

Summary: The mesoscale data assimilation scheme at the UK Met Office requires satellite imagery as a key ingredient of the Moisture Observation Pre-processing System (MOPS), from which a 3-dimensional cloud analysis is derived and converted into relative humidity profiles for assimilation by the model. The role of imagery within MOPS is described. Problems with cloud detection and cloud top height assignment are explained, along with recent developments to overcome them. Examples are given of the impact of MOPS data on analyses and forecasts.

1. INTRODUCTION

The evolution of mesoscale forecasts is sensitive to the initial humidity distribution, but for mesoscale analysis, the conventional observing network has poor spatial coverage. The operational global and regional models at the UK Met Office (UKMO) receive their main humidity information from radiosondes, which are at least 300km apart. Satellite imagery provides data at the required horizontal resolution, but its direct use in operational models is not yet common. Forecasters use imagery indirectly to check the development of model analyses and short-period forecasts, so enabling them to update their subjective predictions. The forecaster may also construct artificial 'bogus' humidity observations for assimilation by the model in areas where imagery reveals significant errors in the model background fields.

At the UKMO, it is currently only the mesoscale model that makes routine objective use of satellite imagery for cloud analysis. This originated in the development of the Interactive Mesoscale Initialization (IMI) system (*Wright & Golding*, 1990) for an earlier version of the mesoscale model (*Golding*, 1990). The present operational mesoscale model is a version of the unified forecast/climate model (*Cullen*, 1991) with a grid spacing of 0.15 degrees (≈17km) and 30 vertical levels. It employs the same "Analysis Correction" (AC) data assimilation scheme (*Lorenc et al.*, 1991) as the regional and global configurations, but with some extra data not available to the larger scale models.

The assimilation system is shown schematically in Figure 1. Conventional data (including satellite temperature soundings) are assimilated directly into the model. Satellite imagery, radar rainfall imagery and surface cloud reports are combined with the latest 3-hour model forecast in MOPS, the Moisture Observation Pre-processing System (*Wright*, 1993), the output from which is a 3-dimensional

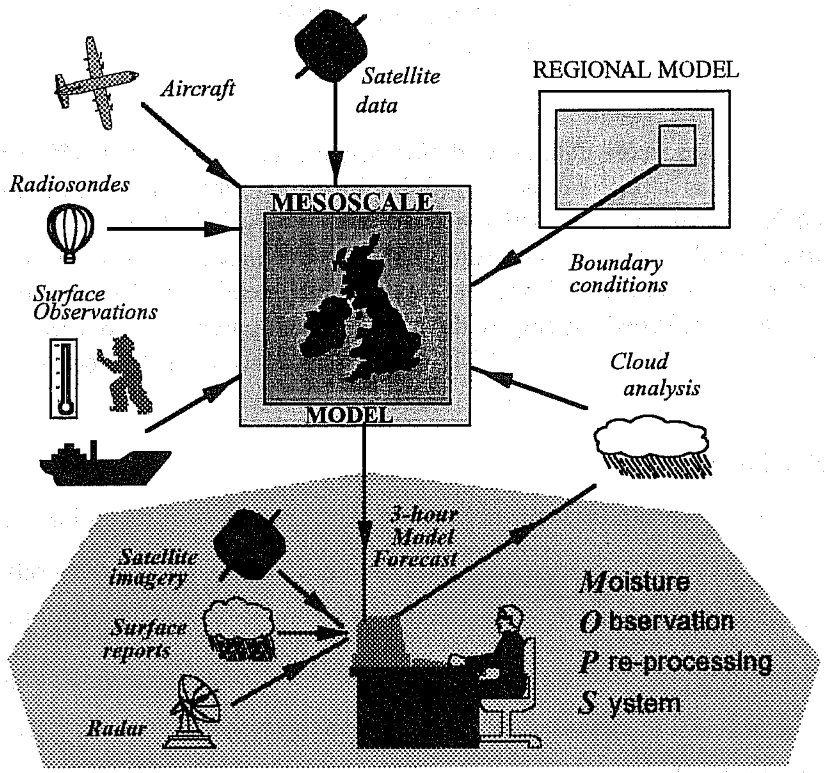


Fig.1 Assimilation system for the UKMO mesoscale model.

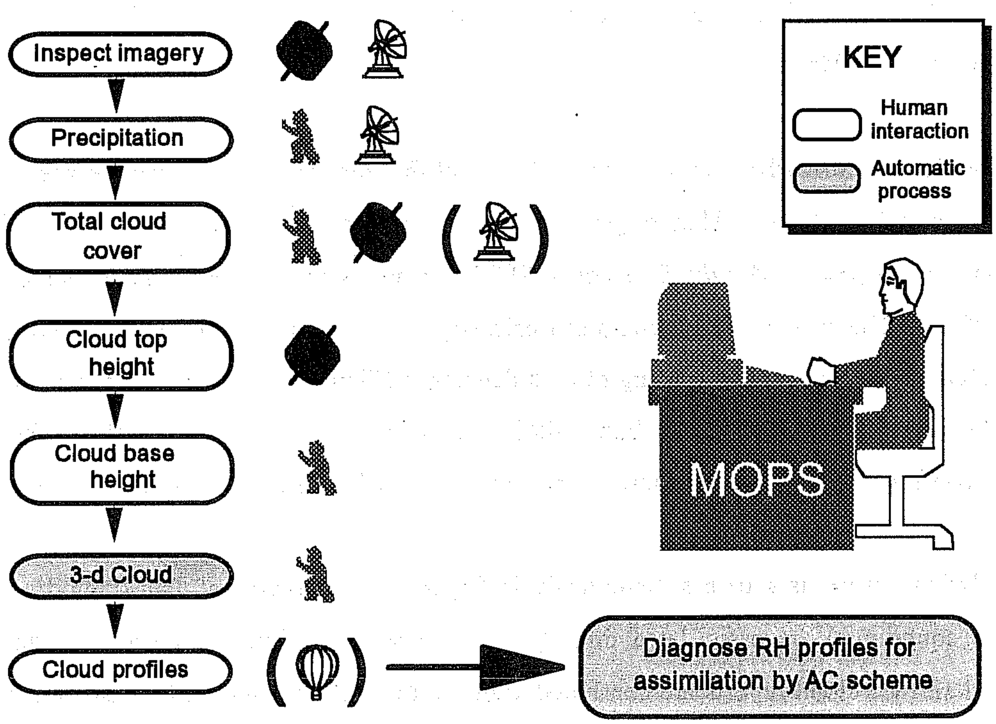


Fig. 2 Sequence of analyses in the Moisture Observation Pre-processing System.

analysis of cloud fraction. For reasons to be explained later, MOPS is run at present under the supervision of a forecaster working at an interactive graphics terminal, although a fully automated version recently developed (see section 5) will remove the need for human intervention. The cloud analysis is converted into a set of relative humidity soundings at each model grid-point, which are then assimilated in much the same way as radiosondes. The conversion to humidity uses a relationship determined by the model cloud scheme. The model is run from 00 and 06 UTC data times daily, starting from an interpolated larger scale analysis at t-6, with two 3-hour assimilation cycles up to t+0. MOPS is run at t-3 and t+0.

2. MOPS

2.1 Preliminaries

The final MOPS cloud analysis is built up through a sequence of 2-dimensional analyses of cloud and precipitation variables (Figure 2). Initially the forecaster checks the available imagery: a Meteosat infrared image (7km resolution), which is displayed as a brightness temperature image, and a radar rainfall image (5km resolution). For reference only, a Meteosat visible image (7km resolution) and a lightning location display are also included. If any of these images are corrupted or unavailable, the forecaster may select one from an earlier time.

Next comes the precipitation rate analysis, constructed from a 3-hour model forecast, a quality controlled radar image, present weather reports and hourly accumulations. It is used to make inferences about total cloud cover and adjustments to the multi-level cloud analysis.

2.2 Total Cloud Cover

In the total cloud cover analysis, the model first guess field is replaced by a cloud cover field derived from a temperature-calibrated Meteosat infrared image over its area of coverage. Satellite pixels colder than the model surface temperature by a specified threshold are assumed to be cloud filled. Counting the cloudy pixels within a model grid-square gives a good estimate of the total cover.

After use of the imagery, the cloud cover field is updated from the precipitation analysis. Where a rain rate of greater than 0.5 mm/hr has been analysed, the total cloud cover is assumed to be 8 oktas. For rain rates below this, a linear relationship between cover and rain rate is assumed. These values based on the rainfall analysis only replace the imagery derived values if they imply greater cover.

Surface observations are then analysed with the cloud cover field from the stages described above acting as a background field. The analysis method involves successive correction by a 2-dimensional recursive filter.

2.3 Cloud Top Height

Before the infrared image is used for cloud top height assignment, it is corrected for ground radiation effects in areas where the analysed cloud cover is only partial. Then, within the image domain, comparison between the corrected image and the model background temperature profile allows the vertical distribution of cloud to be adjusted as follows.

At the bottom level, an initial 'satellite cloud cover' is set equal to the fraction of pixels within the grid-square that are colder than the first-guess temperature (if this does not exceed the analysed total cover). At each level above, a similar satellite cover is extracted (the fraction of pixels colder than the temperature at that level) and represents the cloud above that particular level. The first guess cloud profile is then modified. Where the difference in satellite covers between two levels exceeds the first guess cover at the lower of the two levels, the first guess cover is set to the difference in satellite covers. First guess cloud is reduced where the satellite cover for the level is less than the first guess cover for that level; the new first guess value is made equal to the satellite cover. These changes are based on what is 'seen' by the satellite. No assumptions are made about the cloud at other levels that are hidden.

The cloud top height is taken as the highest model level for which there is at least 1 okta cloud cover in the modified vertical cloud profile.

2.4 Cloud Base Height

Following the analysis of cloud top, surface reports are used to analyse cloud base height, starting with the model forecast as background. This field is then adjusted for consistency with the cloud top: where the cloud base analysis is below about 2.5km, the cloud top height is forced to be at least 150m above the base. Above 2.5km, the satellite-derived cloud top is assumed to be more accurate, so the base is adjusted.

2.5 Multi-level Cloud Analysis

In this stage, surface observations of cloud are interpreted as cloud profiles with values on model levels, using interpolated first-guess profiles from the model (improved by the imagery) to help retrieve 'observed' profiles. The interpretation is sectioned into height regimes of fog, low, medium and high cloud. For example, if the surface report is of medium cloud, then the level with greatest first-guess cloud cover in the height range 2.2-5.6 km has its cloud cover set to the observed total cloud cover. If none is present in the first-guess profile, then the observed value is introduced at the model level lying nearest to the middle of the height range quoted.

Level by level analyses are then carried out, using the observed profiles as point data at each level. Some semi-empirical rules (for example about the depth of particular kinds of cloud) help extract the maximum information from the observations. The total cloud cover, cloud base and cloud top analyses act as constraints.

3. HUMAN INTERVENTION

The forecaster's main priority is to ensure safe use of the imagery by monitoring the cloud cover and cloud top height analyses. Without intervention, these analyses can be grossly in error in situations where, with some straightforward intervention, considerable benefit can be obtained from the data. The profiles in Figure 3 illustrate the problems.

3.1 Cloud cover problems

Cloud is diagnosed where the difference between the satellite brightness temperature and the model background surface temperature exceeds 10K, but this high threshold value can cause problems with relatively warm low cloud over a cold surface. For example, over a cold land surface in winter, the cloud top temperature

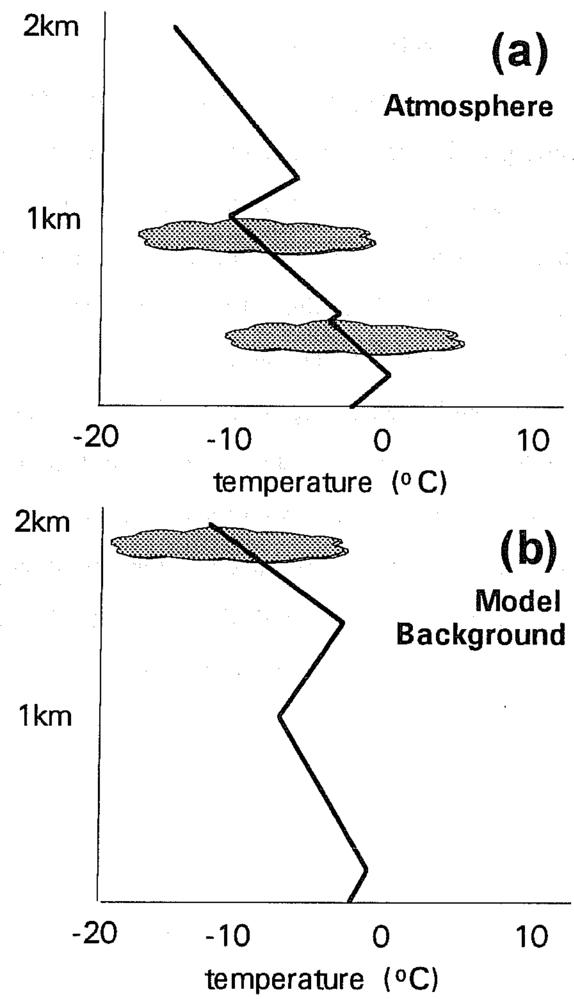


Fig. 3 (a) Temperature profile and observed cloud in the atmosphere.
(b) Temperature profile in model and cloud diagnosed in MOPS.

of a stratocumulus sheet may be similar to that of the ground. With too high a threshold, any cloud correctly present in the model first guess may be removed, and if missing in the model, it will not be added. The lower cloud layer in Figure 3 is an example of this difficulty. In interactive mode, the MOPS forecaster can restore cloud cover in such situations.

With a view to automation of MOPS, the threshold temperature difference has recently been retuned and a value of 5K found optimal. From comparison with independent sea surface temperature analyses, it appears that the Meteosat infrared data have a 4K cold bias when viewing the surface, most of which is believed to be an atmospheric correction effect. The 5K value is therefore to be interpreted as preventing diagnosis of cloud in clear areas by requiring that the satellite cloud top temperature is at least 1K colder than the surface temperature. With this new threshold, the improvement in cloud diagnosis has been significant enough to give confidence that human intervention on cloud cover will no longer be required operationally.

3.2 Cloud top height problems

Cloud top height is assigned by scanning upwards through the levels of the model background temperature profile until a temperature is reached which matches the satellite temperature. Cloud top is often associated with a temperature inversion, which can be very marked for persistent stratocumulus sheets. If the inversion is not well resolved by the model, the matched temperature will not correspond to the cloud deck, but to some point much higher where the cloud-free environment temperature has dropped to the value observed by satellite. This problem is reflected in the treatment of the upper cloud deck in Figure 3. Height assignment errors of 1500m or more can result. The MOPS forecaster can easily detect such a problem in the automatic cloud top height analysis and modify this field interactively to set sensible cloud tops, using available radiosonde ascents as a guide. An alternative to intervening in the cloud top height analysis is provided by the cloud profiles option following the 3-dimensional analysis. Here the forecaster can examine and amend the analysed profiles of cloud cover over a region around the point selected.

4. IMPACT ON ANALYSES AND FORECASTS

4.1 MOPS impact experiments

During the operational trial in late 1992 of the current version of the mesoscale model (*Macpherson et al.*, 1993), 9 cases drawn from a wide range of synoptic types were run with the full mesoscale data assimilation system (CONTROL experiments). As an observing system experiment, they were also rerun without MOPS data supplied to the assimilation (noMOPS runs). For some cases, there were also reruns including MOPS data but omitting radiosonde humidity observations (noSONDE) and, secondly, with neither MOPS nor radiosonde humidity data assimilated (noRH). In a variation of the CONTROL runs, MOPS data were assimilated but were prepared without human intervention. These are the autoMOPS runs.

In assessing the impact from MOPS data, we are looking at the combined impact of the satellite imagery, radar imagery and surface cloud reports. The contribution due to satellite imagery has not been isolated, but is undoubtedly significant. Errors in the model background over the sea areas can only be corrected by the imagery data, except for locations within the radius of influence of coastal radiosondes or ships. Also, while surface reports over land do help the cloud cover analysis, these are sparse in parts of the model domain, especially for analysis times at 0 UTC and 6 UTC as considered here.

Observation errors assigned to MOPS relative humidity soundings are empirically set to 10%, the same value as assumed for radiosondes. Where MOPS has analysed a zero cloud fraction, the assimilation forces the relative humidity to lie below the critical value for cloud formation in the model.

4.2 Impact on cloud cover

Objective verification of cloud cover at UK land stations confirms benefit from MOPS data (Figure 4). The higher rms errors of the noMOPS runs are coupled with a greater negative bias in cloud cover. The signal from MOPS lasts up to t+15-t+18, but is most persistent in anticyclonic cases, of which the case with data time 0 UTC, 4/12/1991 provides a striking example. At t+3 (Figure 5), the CONTROL run with MOPS data has a more realistic coverage than the noMOPS run. There is also significantly more cloud retained to t+18 (Figure 6) with MOPS data included, of benefit to the forecast, although the clear area is predicted too far south.

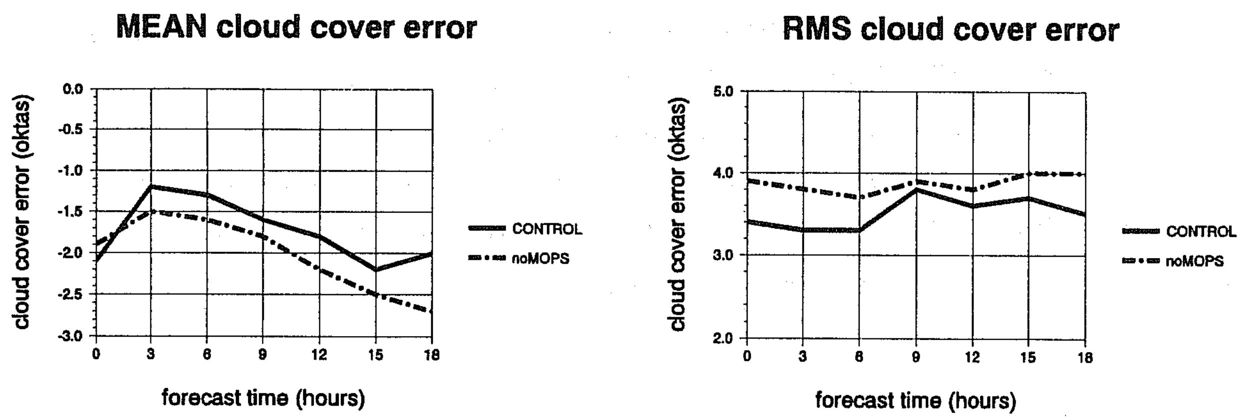


Fig. 4 Verification of total cloud cover for 5 cases from operational trial of mesoscale model.

It is important to note that the benefit from MOPS in this case was only achieved with human intervention. Problems with the automatic use of the satellite image required the addition of cloud over land and the reduction of cloud top heights in the low cloud areas. The results from the autoMOPS run in Figures 5 and 6 are much more like those from the noMOPS run than those from the CONTROL. An analysed ascent from the autoMOPS run (Figure 7) shows a spurious moist layer at 750mb and so betrays the problem with cloud top height assignment when the inversion structure in the model background is unrealistic. The CONTROL run ascent is much better, though it does still display some mismatch between the temperature and moisture profiles around the inversion level. This is to be expected because, even if the intervener achieved exact consistency between the MOPS cloud top height and the radiosonde, the analysis will not fit the radiosonde exactly. Mismatch of this kind disappears in the forecast. The differences in analysed vertical structure and forecast impact between the CONTROL and autoMOPS runs are a clear illustration of the need to analyse cloud at the correct level if the model is to retain the data into the forecast.

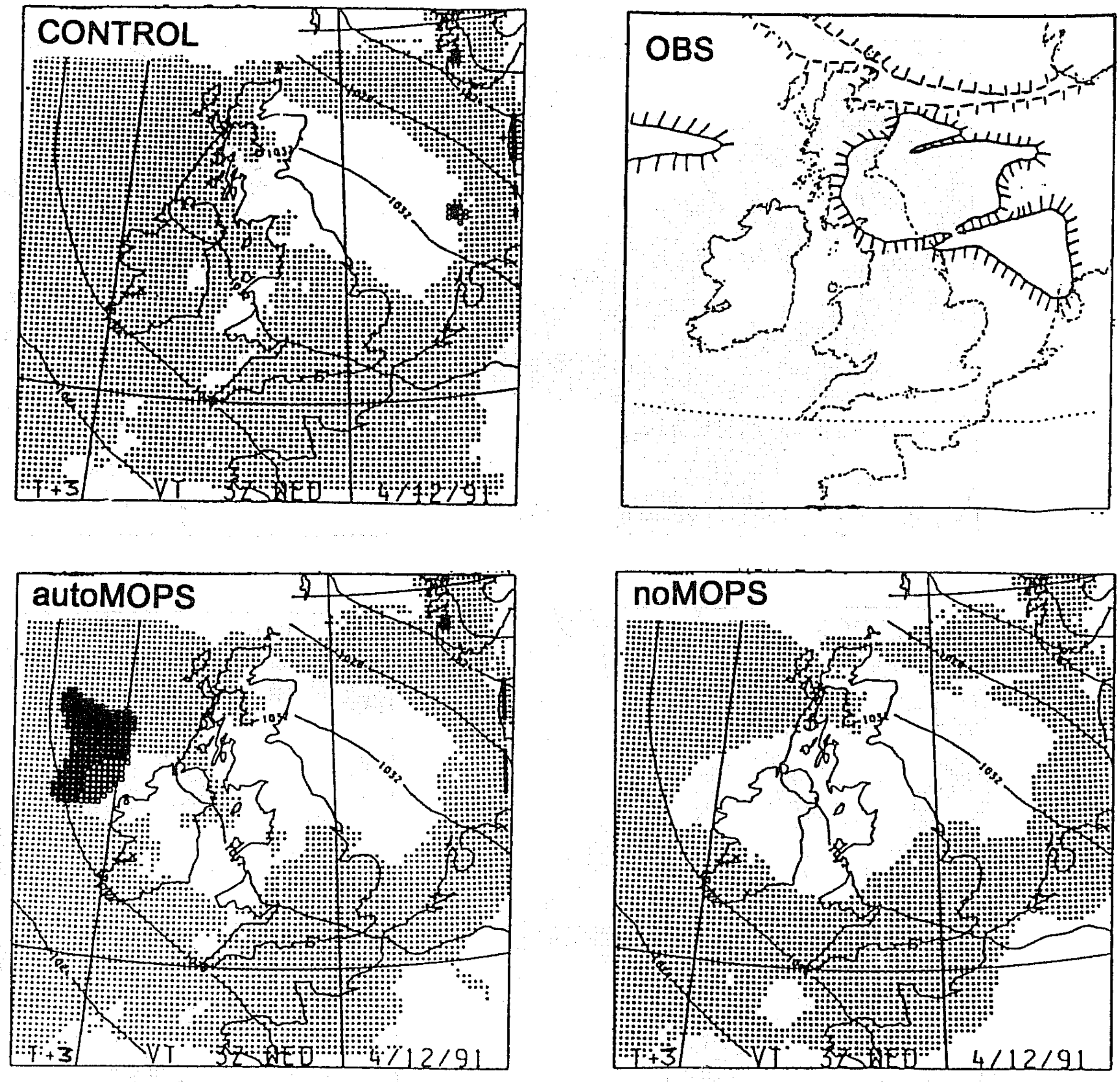


Fig. 5 Schematic of cloud edge from satellite imagery and surface reports at 3 UTC, 4th December 1991 (OBS) and 3-hour mesoscale model forecasts with use of MOPS data as labelled.
The light grey tone indicates low cloud cover of greater than 50%. The darker tone present to the north-west of Ireland in the autoMOPS run indicates medium level cloud, spurious in this case.

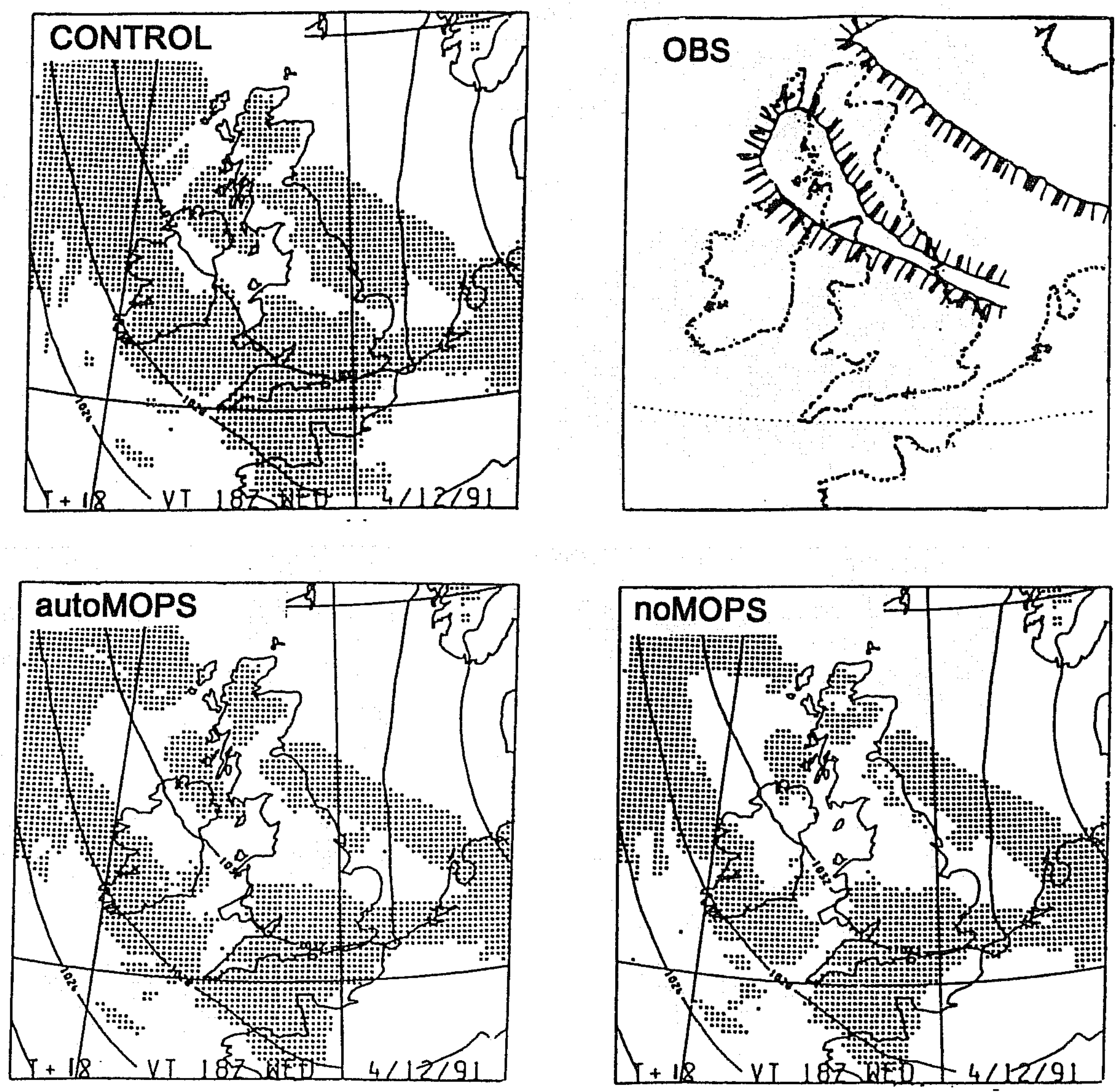


Fig. 6 As Fig. 5, but for 18-hour forecasts verifying at 18 UTC, 4th December 1991.

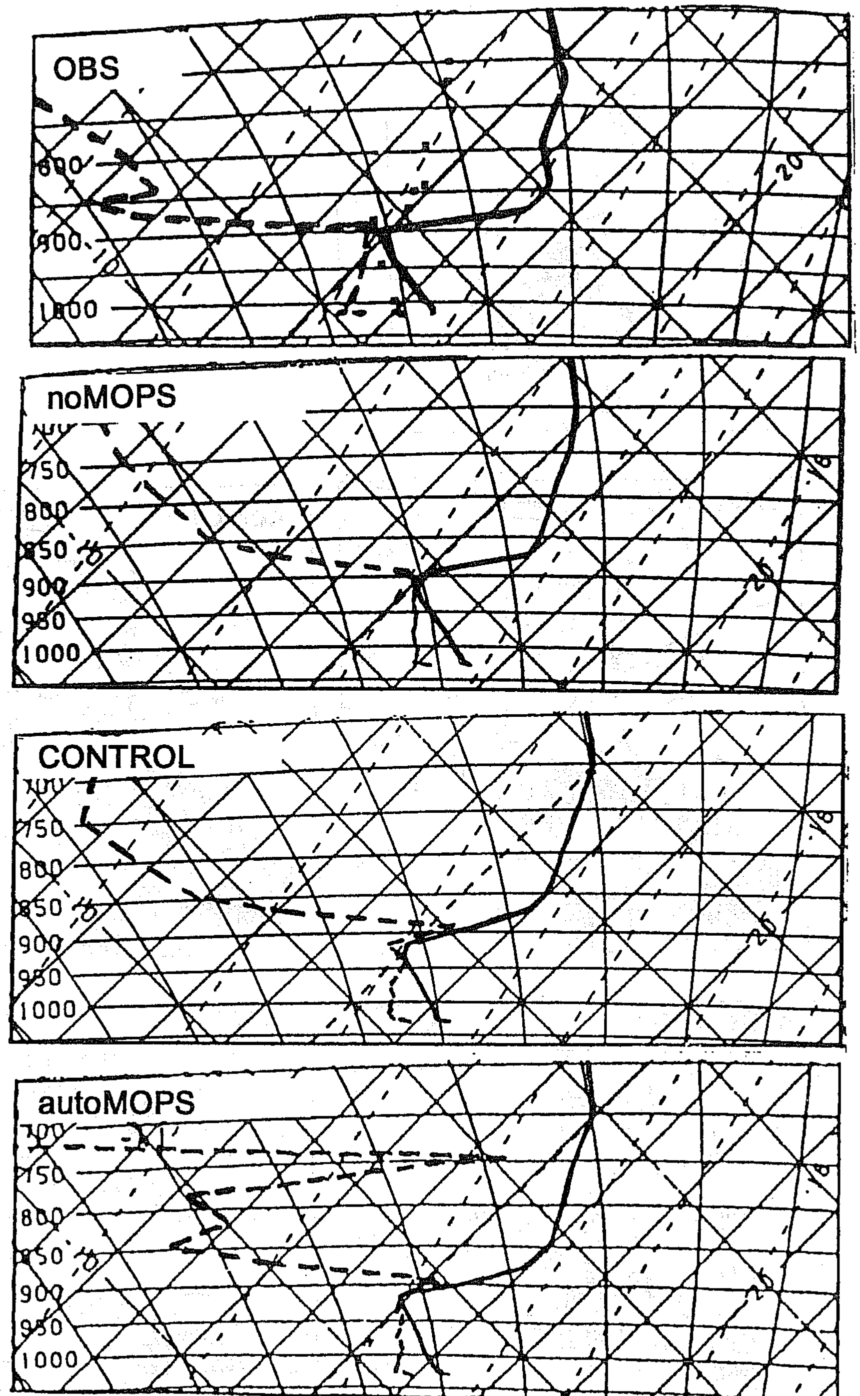


Fig. 7 Observed ascent at Camborne, SW England, at 0 UTC, 4th December 1991, together with various mesoscale model analysed (t+0) ascents, with use of MOPS data as labelled.

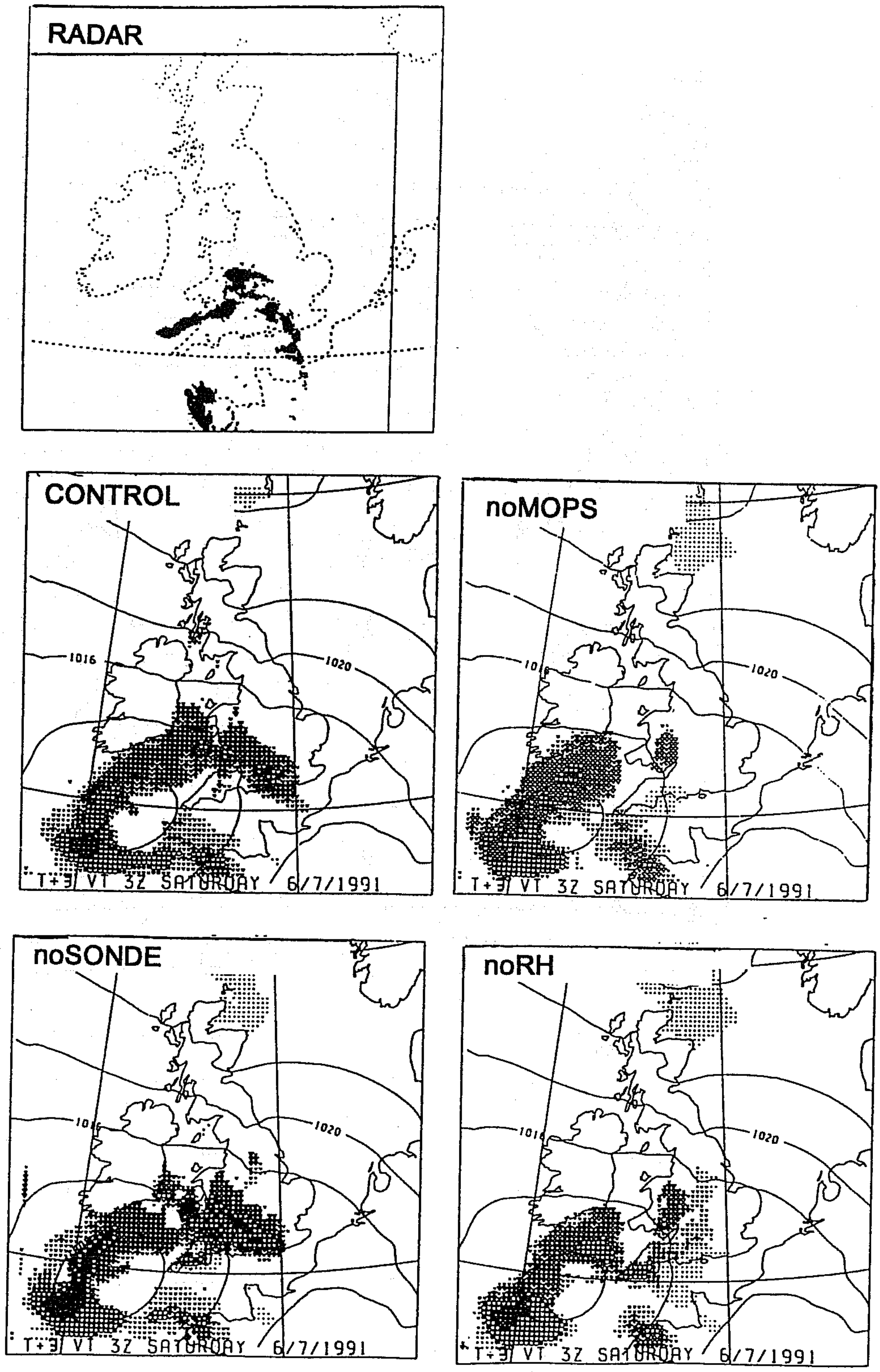


Fig. 8 Radar rainfall analysis at 3 UTC 6th July 1991 and various 3-hour mesoscale model forecasts, with use of humidity data as defined as in the text.

4.3 Impact on precipitation

In most cases with precipitation the impact from MOPS data lasts no more than 6-9 hours, no doubt because of the strong dynamical forcing from intruding boundary conditions. Extra skill in this early period of the forecast is of interest to those developing the UKMO rainfall 'nowcasting' system, which will seek to blend forecasts made by extrapolating radar and satellite analyses with model forecasts to produce the best prediction for the 0-6 hour forecast period.

A case showing worthwhile improvement involved thunderstorms moving north from France. At 3 UTC on 6/7/91 (Figure 8), the t+3 from the CONTROL run produces a reasonable orientation of the rain band over southern England, much of which is lost in the noMOPS run. The noSONDE run has too much rain over southern England at t+3, so the combination of MOPS and radiosonde data gives better results than either data source alone. The noRH run gives poor indication of the rain distribution at 3 UTC. In a second case with data time 6 UTC, 8/11/91 (Figure 9), there is detectable benefit from MOPS data in rainfall accumulations throughout t+0-t+24, but particularly from t+6-t+12, during which period a front moved south-eastward across southern England.

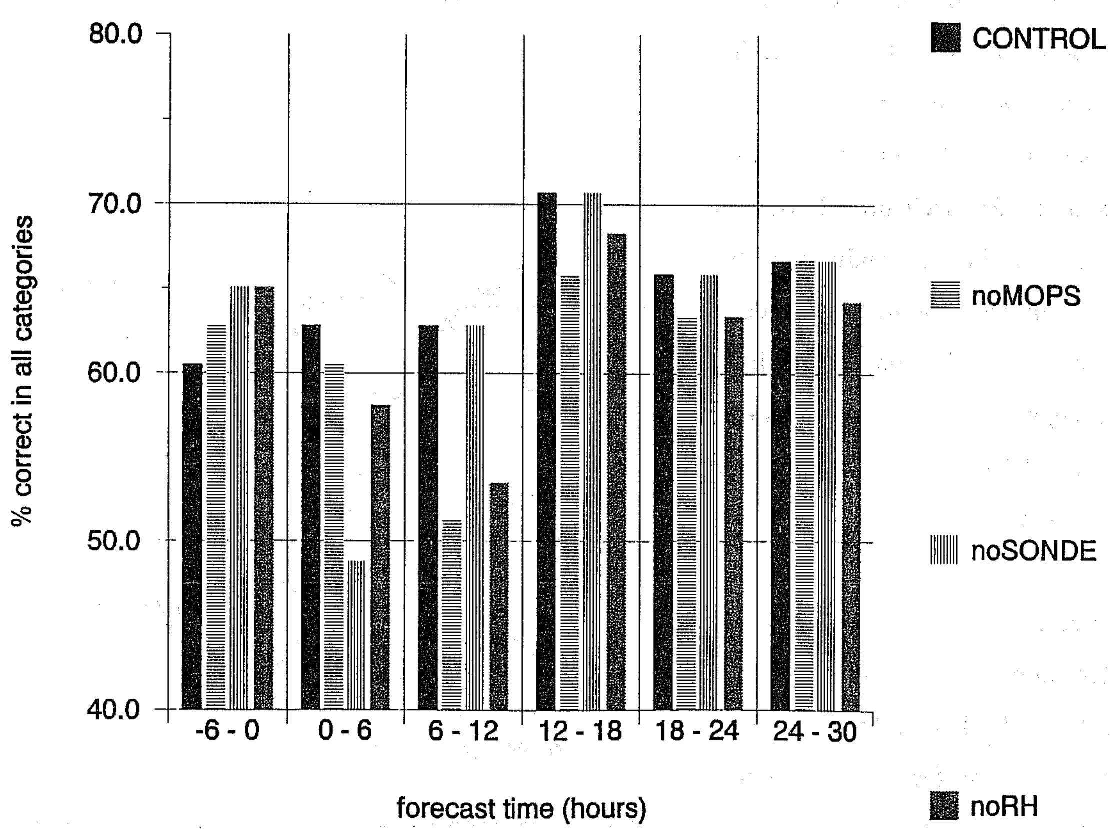


Fig. 9 Verification of 6-hourly rainfall accumulations for case with data time 6 UTC, 8/11/91. Observations at land stations and forecast values for the nearest model grid-point are categorised as 'nil', light, moderate or heavy. Forecasts in the observed category are deemed "correct". The percentage of correct forecasts plotted includes all 4 categories. The use of humidity data in model runs is defined in the text.

5. IMPROVED CLOUD TOP HEIGHT ASSIGNMENT

5.1 Basis of the method

To provide a more reliable automatic method of height assignment, especially in stratocumulus situations, a new algorithm has been developed (*Hand*, 1993). It begins with an idealised vertical profile of temperature and humidity through a stratocumulus layer (Figure 10). Above the cloud the air is warm and dry. At the cloud top there is a marked inversion; the cloud top temperature is that at the base of the inversion. Within the cloud the air is well mixed by turbulence and has a constant wet bulb potential temperature (θ_w). Beneath the cloud the air is also well mixed with the same θ_w as in the cloudy layer, but the relative humidity decreases downwards. The temperature lapse rate approximates the dry adiabatic value and the humidity mixing ratio is constant.

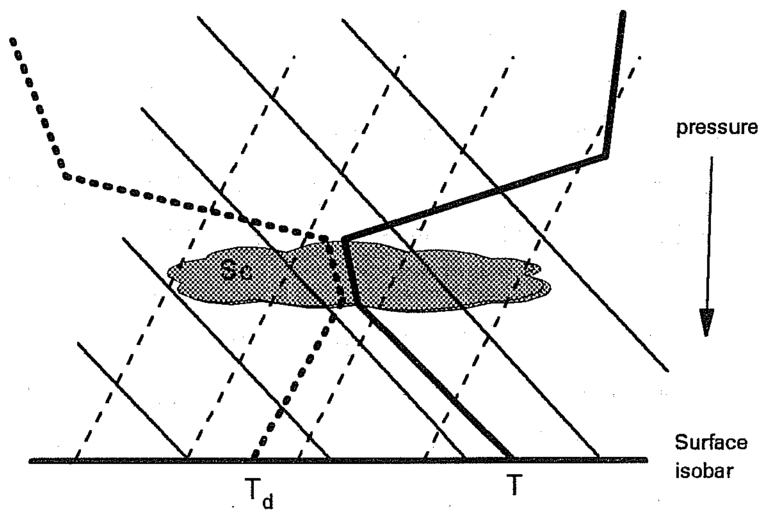


Fig. 10 Idealised tephigram through a layer of stratocumulus (Sc) cloud.

The role of this idealised profile in determining cloud top height is illustrated by Figure 11. At a level near the surface, the model background temperature and dewpoint are selected. Starting from this reference level, the condensation

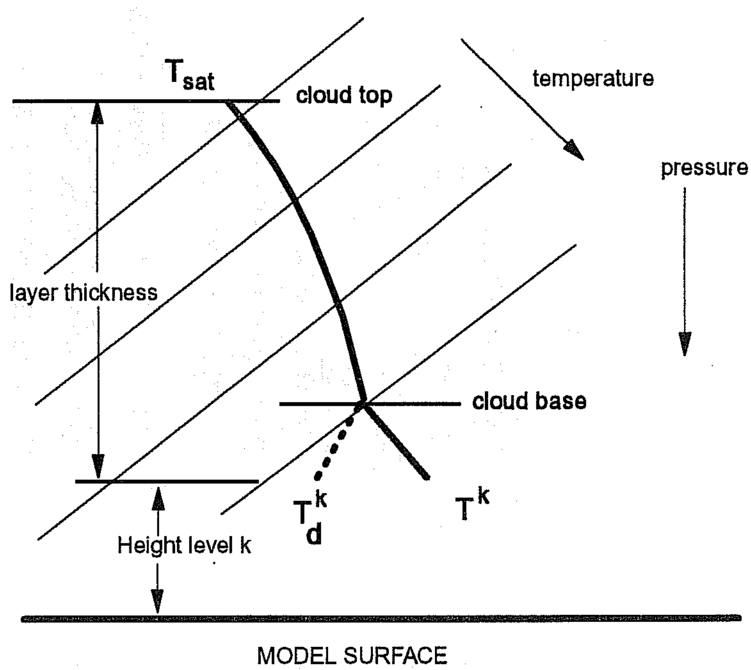


Fig. 11 Tephigram illustrating derivation of cloud top height in new automatic scheme for MOPS.

level (Normand's point) is located by assuming adiabatic cooling from the reference level until saturation. This level is taken as cloud base. From this point the air is allowed to cool at the saturated adiabatic lapse rate until it reaches the temperature, T_{sat}, of the satellite-observed cloud top. Using the temperatures and dewpoints at the cloud top, cloud base and reference level, a layer thickness is calculated from the hydrostatic equation. The height of the model reference level above ground is then added to the thickness to obtain cloud top height.

5.2 Application

Although developed with stratocumulus in mind, this new algorithm can be applied more widely. It has been found to yield sensible cloud top heights in regions where thick multiple layers are present as opposed to just low stratiform cloud. With three provisos (explained below), it has been implemented to calculate cloud top height in every pixel falling within a model grid-square where the analysed total cloud cover is greater than 2 oktas. Grid-squares with less than 2 oktas cover are set as cloud free at the end of the multi-level cloud analysis and so do not require a cloud top height.

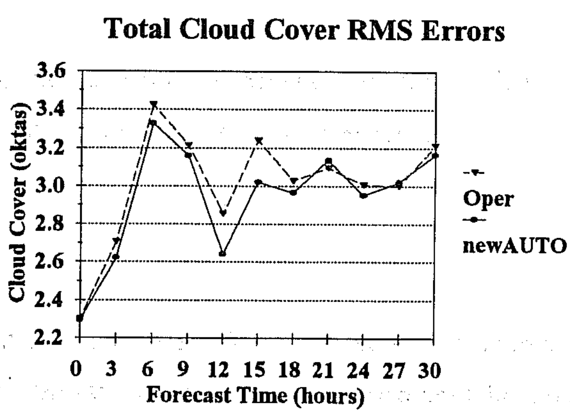
The new scheme encounters a problem when the derived cloud base temperature is lower than the satellite cloud top temperature, as may happen if there are errors in the model reference level temperature and dewpoint values, or in regions of very broken cloud over a warm surface. In this situation it has been judged best to revert to the original technique of scanning the background temperature profile for a value matching T_{sat}. The same action is taken if the model temperature at the reference level is less than T_{sat}.

Also, it would not be appropriate to analyse cirrus heights with this algorithm, so the new method is restricted to pixels with T_{sat} greater than -20 °C. The original method is applied above this level (around 5.5km).

5.3 Performance

The new algorithm has been validated in several stratocumulus cases. The first task was to establish the best reference level from which to choose the model temperature and dew point. Various levels were tested and the cloud top height fields were verified against radiosonde ascents. Most of the cloud top heights for verification were in the region of 600-1200m. The optimal reference level proved to be around 180m. This gave rms cloud top height errors of around 300m and a mean error of about 10m. To put these results in perspective, the average thickness of model layers in the height range 600-1200m is approximately 200m. The new scheme compares very favourably with the operational one that simply matches T_{sat} to model temperature profiles, which returned an rms error of about 900m and a mean error of around 400m.

These results relate to cloud top heights in the MOPS data before it has been assimilated. The impact of this improved automatic preparation of MOPS data on analyses and forecasts has also been tested by assimilation experiments comparing it against the operational system, in which intervention by a forecaster also took place to varying degrees. The new automatic system gives better cloud base height verification early in the forecast, dramatically improving the fit to surface data in the analysis (Figure 12). This indicates that the gross errors typical of the old automatic scheme were still present in the operational runs where some intervention by a forecaster had taken place. It is recognised, however, that the pressure of an operational environment is not conducive to the thorough corrective intervention possible in research experiments after real time. Along with the early improvement in height verification, the new automatic MOPS runs give slightly better cloud cover accuracy from t+3 to about t+15, reflecting better cloud retention from a more consistent initial vertical structure.



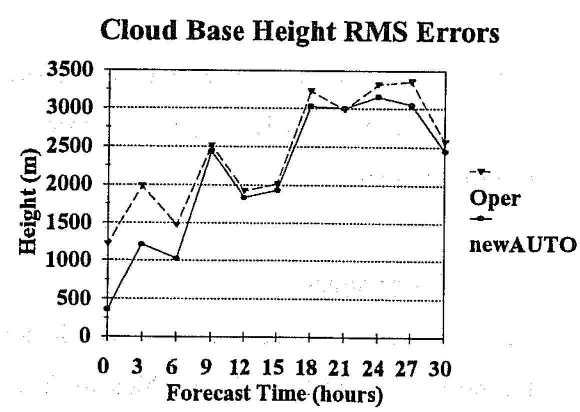


Fig. 12 Results for 4 cases from trial of new automatic MOPS scheme against operational system.

6. FUTURE DEVELOPMENTS

The new automatic version of MOPS is scheduled to replace the current version with human intervention in autumn 1993. Full automation of MOPS is essential for the planned extension of the operational suite to include 12 UTC and 18 UTC mesoscale forecast runs, which are judged to be necessary to give useful guidance on fog and low cloud during the period from evening to early morning.

The imagery used in MOPS comes only from Meteosat. *Whyte et al.* (1993) are developing a cloud top temperature product from AVHRR data for assimilation initially into the UKMO regional model. The horizontal resolution of the AVHRR data is of order 1km, compared with the regional model grid-length of about 50km. This has led to design of the data presentation to the model in terms of a histogram of cloud top temperatures for each model grid-square. The proportion of the model grid-box with cloud tops lying in, for example, 5K bands is derived. The assimilation technique proposed will involve matching each temperature band in the histogram with the model temperature profile for that column, and as with the treatment of MOPS data, nudging the model relative humidity towards a value consistent with the AVHRR cloud cover.

The AVHRR cloud product may also be assimilated in the mesoscale model, perhaps with different temperature resolution in the histogram to reflect the higher vertical resolution relative to the regional model. As an 'off-time' data source, the AVHRR product may complement the Meteosat-derived MOPS data which are available 3-hourly, although for the mesoscale model domain, the AVHRR data have a limited coverage and availability in time.

Looking further ahead, the mesoscale assimilation system may be run on an hourly cycle as part of the 'Nimrod' nowcasting system being developed to provide 0-6 hour forecast guidance for the UK and surrounding waters. Effective assimilation of satellite imagery will be a key to improving the model's contribution to this system.

7. REFERENCES

Cullen, M.J.P., 1991: The unified forecast/climate model. UK Meteorological Office, Short-range Forecasting Research Scientific Paper No.1.

Golding, B., 1990: The Meteorological Office mesoscale model. Meteorol. Mag., 119, 81-86.

Hand, W.H., 1993: A method of improving the analysis of cloud top height for the New Mesoscale Model. UK Meteorological Office, Forecasting Research Division, Technical Report No. 53.

Lorenc, A.C., R.S.Bell, and B. Macpherson, 1991: The Meteorological Office analysis correction data assimilation scheme. Q.J.R. Meteorol. Soc., 117, 59-89.

Macpherson, B., B.J. Wright, and A.J. Maycock, 1993: Performance of the data assimilation scheme in the operational trial of the new mesoscale model. UK Meteorological Office, Forecasting Research Division, Technical Report No. 39.

Whyte, K.W., U.I. De Silva, and N.S. Richards, 1993: An investigation into the use of AVHRR imagery in numerical weather prediction data assimilation. Proceedings of the 6th European AVHRR data users' meeting, Belgirate, Italy.

Wright, B.J., 1993: The Moisture Observation Pre-processing System (MOPS). UK Meteorological Office, Forecasting Research Division, Technical Report No. 38.

Wright, B.J., and B. Golding, 1990: The Interactive Mesoscale Initialization. Meteorol. Mag., 119, 234- 244.