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A report on the performance of an hourly data assimilation cycle for the mesoscale model

by

A.J. Maycock

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Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
United Kingdom

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1. Introduction

The Nimrod project (Golding 1995) has a requirement for high quality mesoscale model analyses, which must be made available at the earliest possible time. This report describes tests of a data assimilation scheme suitable for such a system.

An hourly data assimilation cycle has been designed, and tested on three synoptically different cases. This report describes differences between the current operational 3-hourly assimilation cycle, and the new configuration. A description of the cases used in the performance trial is given, and results are presented for each of these cases.

2. The hourly cycle

The current operational 3-hourly mesoscale data assimilation cycle is a continuous one, with four main forecasts made per day. Each 3 hourly assimilation period provides starting analyses and background fields for subsequent runs. The hourly assimilation cycle is shown schematically in Figure 1. Runs are scheduled to start at 20 minutes after their nominal data time. Each run dumps an analysis at T+0, from which the next run will start, and background fields at T+1 to enable the next set of observations to be processed. Lateral boundary conditions are taken from the Limited Area Model. The most recent set are taken. Only those from the main LAM runs can be used because of the short length of the intermediate LAM runs. The boundary conditions used for each mesoscale model run are shown in Table 1.

2.1 Intermediate update cycle

One consequence of a near real-time assimilation cycle such as this is that the time of receipt of data is a very important consideration. Preliminary studies were made to investigate how long data typically is available after it's "validity time".

For surface data, it was found that the time taken for the data to become available was not going to present any problems for the hourly cycle. Half the surface synoptic reports are received within 7 minutes, and by 20 minutes (when the extraction would be performed), approximately 97% of the reports are available. For satellite observations, which is an asynoptic data type, approximately 90% of the data has been received within 30 minutes. The implication of this is that data for an hhZ run (extracted at hh+20) will contain virtually all observations valid up until hhZ.

A study of the time taken for radiosonde observations to become available has revealed the need for extra data assimilation. Taking main hour sondes only, a study of one years worth of observations showed that even 80 minutes after their observation time, only about 20% were available. By 140 minutes, nearly 100% were available.

As a solution to this problem, the system has been designed to include intermediate update runs, whereby observations are re-extracted before the next run, and the previous run (assimilation only) is re-run so that the late data is fully assimilated. This would obviously be quite an expensive and time consuming process, but due to the fact that nearly all radiosonde data is valid at 00Z,06Z,12Z, and 18Z, we need only have four of these intermediate runs per day. This additional run is shown schematically in Figure 2.
(N.B See also section title "Future developments" at the end of the report)

2.2 Assimilation parameters

In designing the new assimilation cycle, we need to be careful in determining the amount of forcing given to the observations during assimilation. To enable a fair comparison between the hourly and 3-hourly cycles, the aim was to keep the amount of forcing approximately the same for both cycles. This was done based on the following relationship:

Forcing $\propto$ NO_ITER * λ * TIME_WINDOW * FREQ_OF_DATA

where:

NO_ITER is the number of analysis iterations per timestep;
λ is the relaxation coefficient;
TIME_WINDOW is the time window for observation assimilation;
FREQ_OF_DATA is a measure of the data frequency.

The relaxation coefficient λ is related to the nudging coefficient G by:

$$\lambda = \frac{G\Delta T}{1+G\Delta T}$$

where ΔT is the length of the timestep (300s)

For each group of observation types (as defined by the AC scheme groups), the above factors were adjusted so as to keep the amount of forcing the same. The old and new values are shown in Table 2.

3. The cases

The performance of the hourly assimilation cycle was assessed using three synoptically different cases. These were:

13th April 1994:	Cloud
12th July 1994:	Fog
14th September 1994:	Precipitation

Each of these cases, and the configuration of the experiments, are described in this section.

3.1.1 13th April 1994

This was a low cloud case. The period of interest in this case was 06Z to 15Z. At 06Z there was a large area of the UK (Eastern, Central, and Southern England) with extensive cover of stratus and stratocumulus. The cloud generally lifted during the morning period. The operational model T+6 forecast valid at 12Z on the 13th is shown in Figure 3.

3.1.2 12th July 1994

The interest of this case was an extensive area of fog. The period of interest was 00Z to 09Z. During this period, a large area of fog was present over Cornwall, West Wales, Western Scotland and the Irish Sea. The 06Z operational analysis charts are shown in Figure 4.

3.1.3 14th September 1994

Throughout the early hours of the morning of the 14th, there was a prolonged spell of rain. This was in a band which covered the UK south of a line from Central West Wales to Essex. This band moved slowly northwards. The model had precipitation accumulations (6 hours verifying at 06Z) of up to 20mm. The 06Z model analysis charts are shown in Figure 5.

3.2 The method

In each of the cases, the hourly assimilation cycle was run over a 9 hour period. The cycle was started with a one hour forecast, to enable the first observation file to be created. A two hour assimilation/forecast was then run to enable the second observation file to be made. The first of the main hourly runs was then made. A "main" run consists of a one hour assimilation/6 hour forecast. The 9 hour period used ensures that an update run has been included in each case.

3.2.1 The comparison runs

For each of the cases, it was necessary to run the usual 3-hourly cycle for comparison purposes. This was started at the *same time* as the hourly cycle, with a 3 hour assimilation. The cycle was then continued as operationally. The operational assimilation runs, which only run for 6 hours, were extended to 9 hour runs for this experiment. This is their maximum length given the boundary conditions they use.

4. Verification

The aim of the performance trial was to compare the verification statistics from the hourly cycle against *what would be available from the operational forecasts at the same time.* This involves an estimate of what time products are available from both the operational suite and the hourly cycle. For the hourly cycle, an initial estimate is that products will be available 60 minutes from data time. This is based on runs started at HH+20 minutes, and erring on the side of caution in allowing 40 minutes for observation extraction, processing etc., and a 7 hour model run.

A complete list of model runs and their availability times is given in Table 3. Based on this, we can see which runs need to be verified against which. For example, the QM07 hourly run (available at 08Z) would have to be verified against the 3-hourly QM03 run. This would mean that a T+0 from the hourly run is being compared to a T+4 from the 3-hourly run etc.

Most of the verification statistics have been obtained from the mesoscale objective verification package. In addition to this, the model forecasts were also verified against the MOPS cloud and precipitation analyses to obtain scores for cloud in various height bands and precipitation hit rates etc. These precipitation comparisons were made only over the area of radar coverage. Both the hourly and the comparison runs were verified against the same MOPS data (that from the hourly run). Precipitation hit rate and false alarm rate were computed for a threshold of 0.02 mm/hr. The RMS factor is the anti-log of the RMS error in log precipitation rate where both the observed and forecast exceed 0.125 mm/hr.

5. Results

The results are presented in tables 4 to 9. The results from over 150 forecast writeups have been summarised in two tables for each case. For each of three verifying times, the first table shows results of the most recent forecast available from each cycle. For example, at 14Z on the 13th April, the T+1 from the hourly QM13 and the T+5 from the 3-hourly QM09 are the most up to date forecasts available. These tables show the relative usefulness of the products to be used in the image processing and analysis components of Nimrod. In the description below these are termed the analysis products.

The second table for each case shows average verification statistics for the comparable parts of the forecasts. These give a measure of the relative skill over the whole of the forecast period. As an example, the average of the T+1,2,3,4,5,6 from the hourly QM14 is compared with the average of the T+3,4,5,6,7,8 from the 3-hourly QM12. These are termed the forecast products.

Further, more detailed, results are described and presented in Appendix *II*.

5.1 Cloud case

Precipitation verification was not carried out for this case as a negligible amount was observed. The analysis products compared in Table 4 favour the hourly cycle in all scores except for the RMS total cloud cover measured against spot observations at 14Z. Since this is contradicted by the same error computed against analysis (MOPS), its significance is considered doubtful. Most of the comparisons show a substantial benefit in favour of the hourly cycle. This is the only case that shows significant improvement in the wind scores.

The forecast products compared in Table 7 also favour the hourly cycle in most scores. There is little to choose between the wind scores, some being better and some worse in the hourly cycle. Again there is conflict between the two cloud verification methods with the analysis comparisons showing significant gains. The temperature and humidity scores are also substantially better in the hourly cycle.

5.2 Fog case

The precipitation was also very local in this case. For this reason the relatively poor performance of the precipitation in the hourly cycle is not considered significant. There is not a lot to choose between the cloud with some scores better and some worse in both the analysis products (Table 5) and the forecast products (Table 8). However, in both tables the temperature and humidity are substantially improved in the hourly cycle, suggesting that the visibility was also better.

5.3 Precipitation case

The analysis products in Table 6 favour the hourly cycle except at 10Z for the winds - which are almost identical - and for some of the total cloud scores. The precipitation, which is the focus of this case, is substantially better in the hourly cycle. There are also significant improvements in the low cloud and humidity.

The forecast products in Table 9 show mainly small changes in most scores, with a mix of better and worse for the hourly cycle. The precipitation scores are markedly better in the hourly cycle at 07Z and 08Z but close at 09Z with a worse False Alarm Rate.

5.4 Summary

The verification scores from the hourly cycle are better than the 3-hourly scores for the majority of times and parameters. The precipitation scores from the September case and the cloud scores from the April case are particularly encouraging. In all cases, humidity and temperature scores are much improved, whilst 10m wind scores are also generally improved but to a lesser extent. The improvement brought about by the hourly cycle is more noticeable when comparing the analysis products (tables 4-6). Substantial improvements are still found, however, in the comparisons of the entire forecasts.

In nearly every example, low cloud scores (from the MOPS verification) are shown to be improved. The same is true of the RMS screen humidity scores, with up to 2% improvement for the analysis products and 1% in the whole of the forecasts. RMS screen temperature errors are better by about 0.2 degrees in the analysis products. The improvements were larger in the cloud and fog cases.

Future changes

Since the testing of the assimilation cycle was performed on the three cases, the question of minisonde (boundary layer sonde) data has been raised. In the course of a year, the number of these is about one eighth the number of full sondes. They have observation times given as the nearest hour to launch time; e.g a minisonde launched at HH:29 will be labelled as a HHZ sonde, and one launched at HH:31 will be labelled as a (HH+1)Z sonde. The reports from minisondes were found to arrive at the UKMO slightly faster than full main hour sondes, but with the current configuration of the cycle most of the data (about 90%) would arrive after the cut-off time.

Therefore, in order to fully utilise the data from these minisondes, we need to include extra assimilation at intermediate hours also. We could achieve this by having two hours of assimilation for each of the runs. We would then extract observations for the previous two hours (HHZ and (HH-1)Z), remake the (HH-1)Z observation file, make the HHZ observation file, and assimilate both these prior to the HHZ model run. This run would then have to output the analysis for the next run (at HH-1), and background fields for the observation files to be made prior to the next run (at HH and HH+1). The need for the extra update cycle described in section 2.1 would then no longer exist.

Obviously this extra assimilation would add significantly to the time and cost per model run (by about 25%). It may also be worth bearing in mind that of all the minisondes launched, over 70% are done between 01Z and 07Z.

Appendix I - Technical details

The number of technical changes that were required to set up the hourly cycle was fairly small. These are mentioned here.

1) For the observation extraction, new control files were required. These were necessary to enable the extraction time window to be set (HH-59 to HH).

2) The routine *qchknew* was hardwired to recognise existing model run identifiers only. This was modified such that the new model runs were recognised (QM01, QM02 etc.).

3) A number of changes were required to the (Cray) observation pre-processing control files. This was to account for the fact that T+1 (not T+3) background fields are being used.

4) The MOPS restore job was amended to allow the restore of observations and imagery for intermediate hours.

5) The MOPS forward interpolation namelist was changed to account for the fact that the "mesout" fields are T+1 (not T+3).

Appendix II - Detailed results

Tables 10 and 11 contain more detailed verification statistics for each of the cases. The data are arranged as follows. Table 10 has three sections - one for each case. Each of these sections is divided into three sub-sections - one for each of the hourly assimilation runs that could be verified against a 3-hourly run. Within these sub-sections, verification scores are given for each forecast time. Scores are presented for the following parameters:

Relative humidity	(abbreviated RH)	
10m Wind speed	(WS)	
10m Wind vector	(WV)	Verified against surface observations.
Screen temperature	(T)	
Total cloud amount	(CT)	

Precipitation hit rate	(PHR)	
Precipitation false alarm rate	(PFA)	
Precipitation RMS factor	(P)	
Low cloud amount	(CL)	Verified against MOPS data.
Medium cloud amount	(CM)	
High cloud amount	(CH)	
Total cloud amount	(CT)	

So, as an example (12/7/94 case), the T+5 RH RMS error from the 3-hourly QM03 was 8.3%, while the T+1 from the hourly QM07 verifying at the same time was 7.2%.

In this table, the best scores are **bold** (if better by more than 1%), and **<u>bold and underlined</u>** if more than 10% better.

Table 11 should be read in the same way as table 10, and is just a summary of the same data (verification against surface observations and MOPS precipitation only). Here, a '+' indicates that the hourly cycle was more than 1% better, a '++' means more than 10% better. A '-' means the hourly cycle was more than 1% worse, and a '--' means more than 10% worse. These tables indicate that the advantage of the hourly cycle drops with increasing forecast time, with very litte benefit left by T+6.

References

Golding B.W. ,1995. Rainfall - Analysis and short range prediction. *British Hydrological Society Occasional Paper Number* **5**, 1-9.

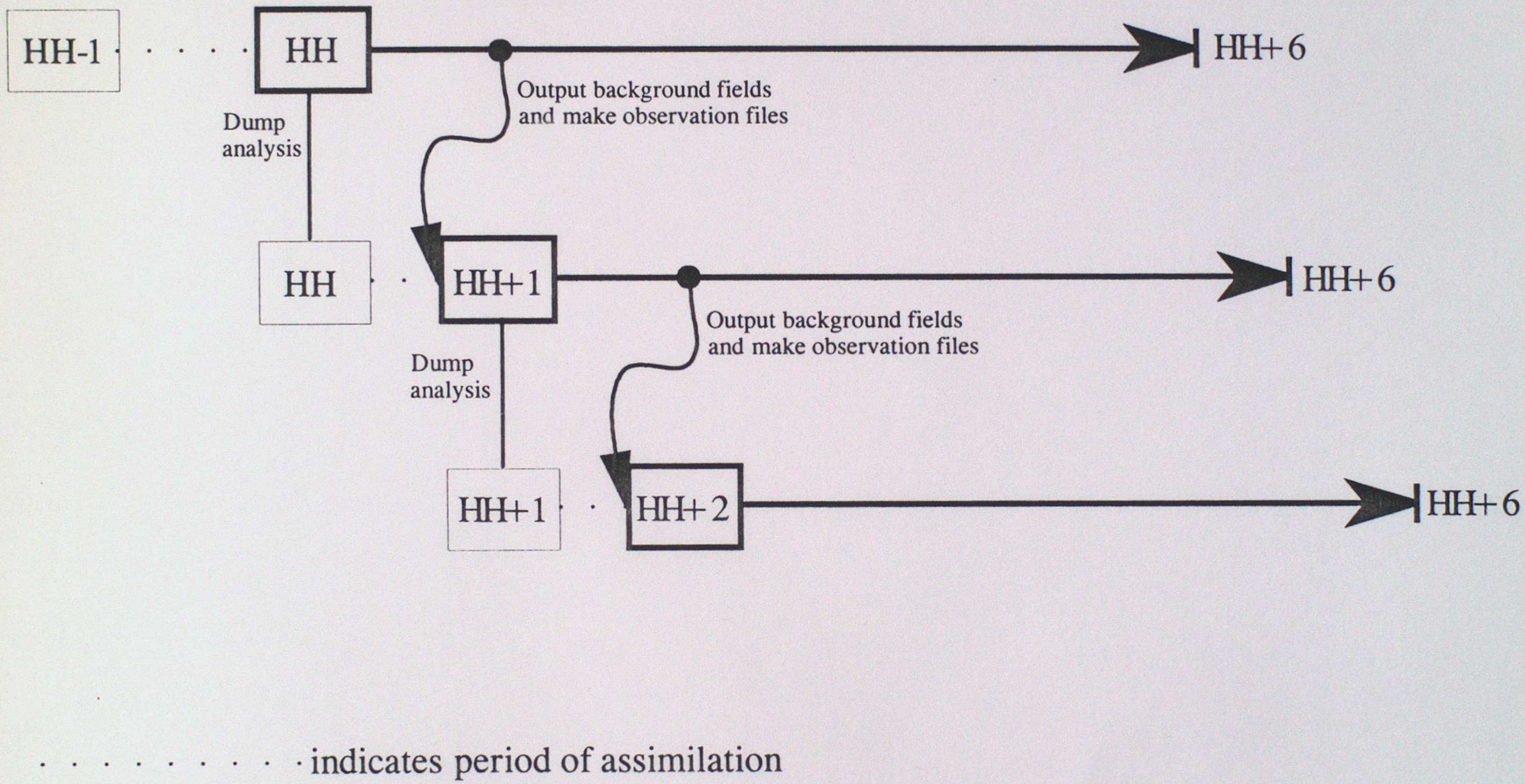

Figure 1. Schematic overview of the hourly assimilation cycle.

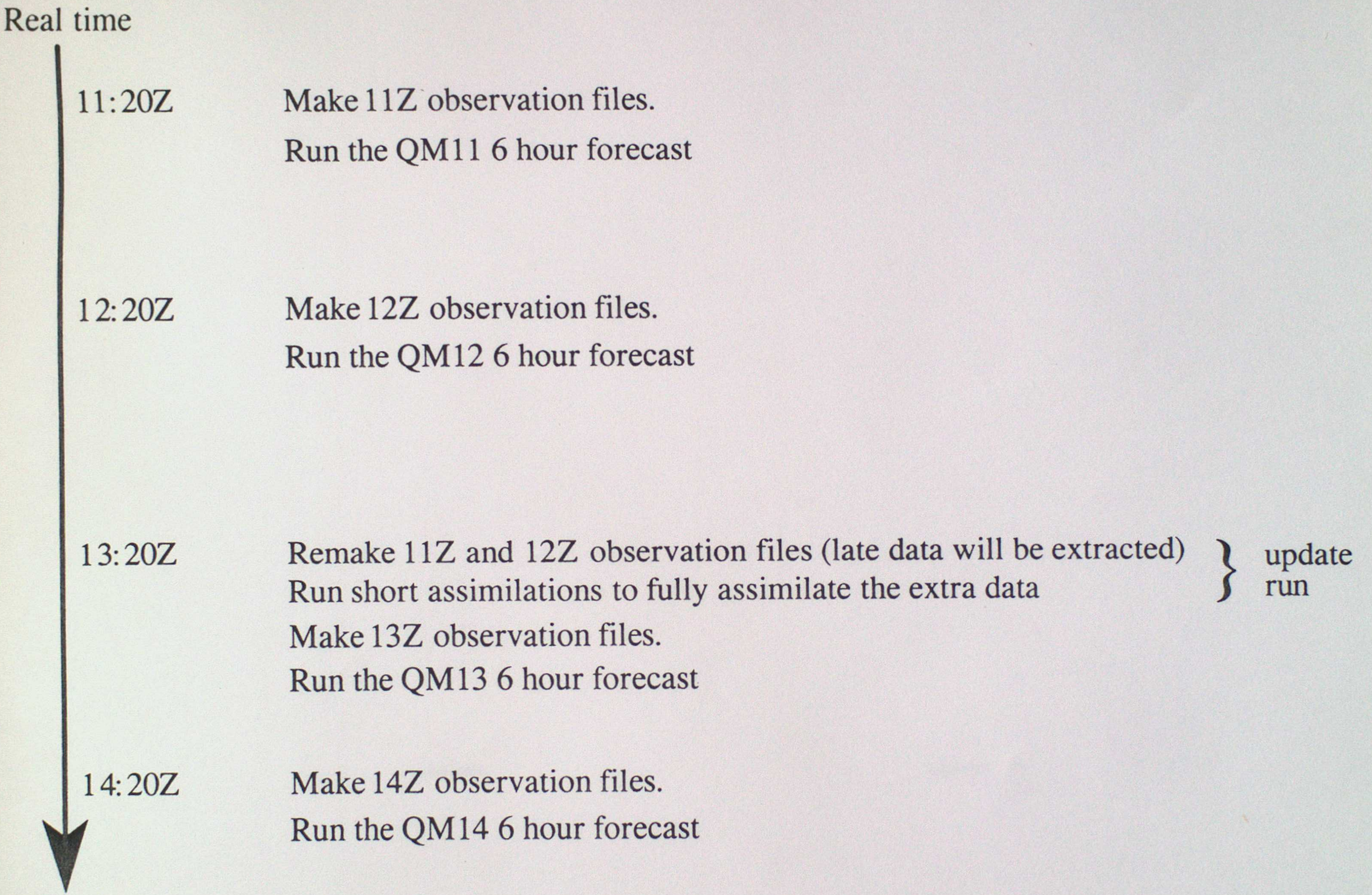

Figure 2. Schematic diagram to illustrate the update runs

Figure 3. T+ 6 mesoscale model charts from the QM06 run 13/04/1994

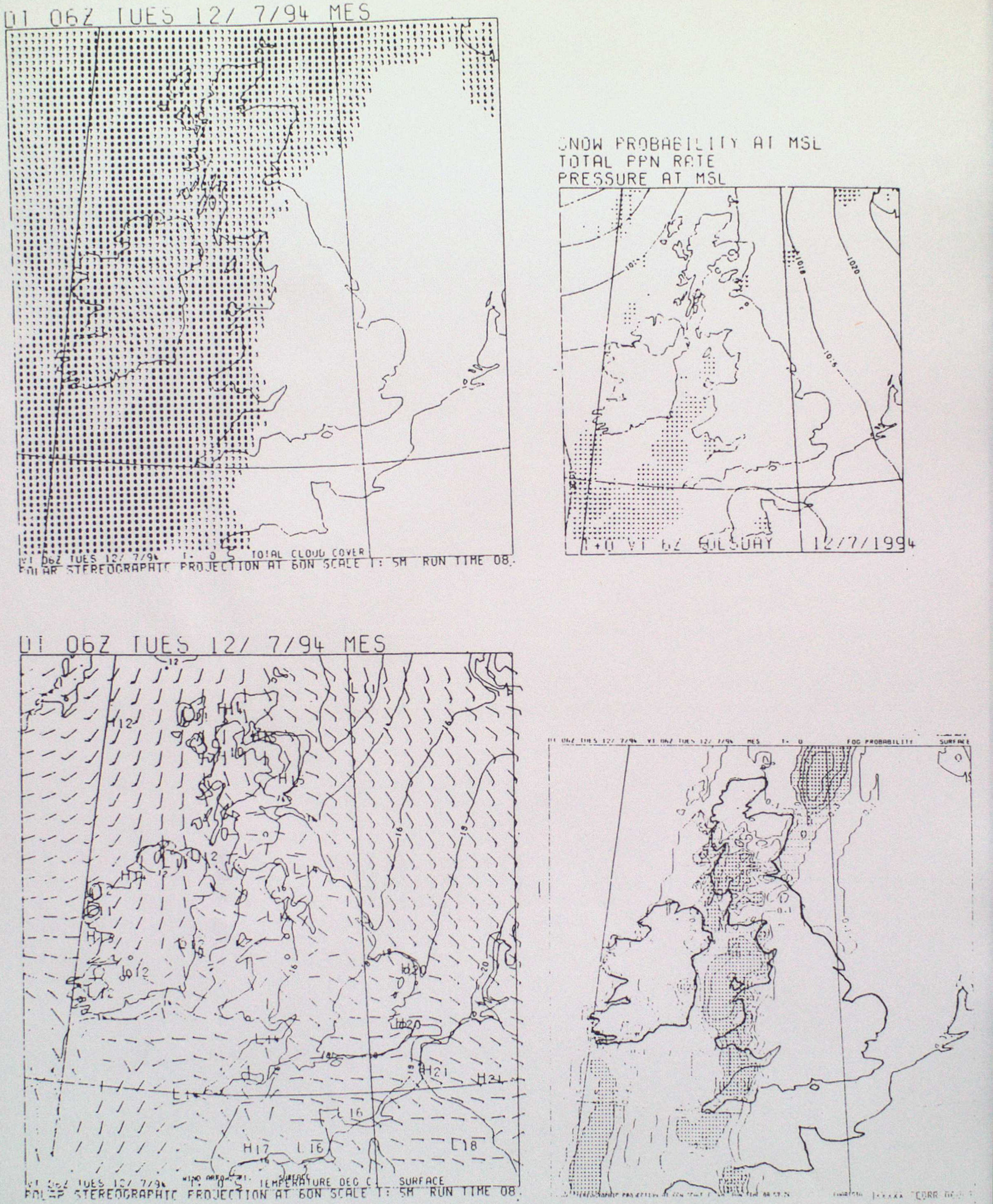

Figure 4. T+ 0 mesoscale model charts from the QM06 run 12/07/1994

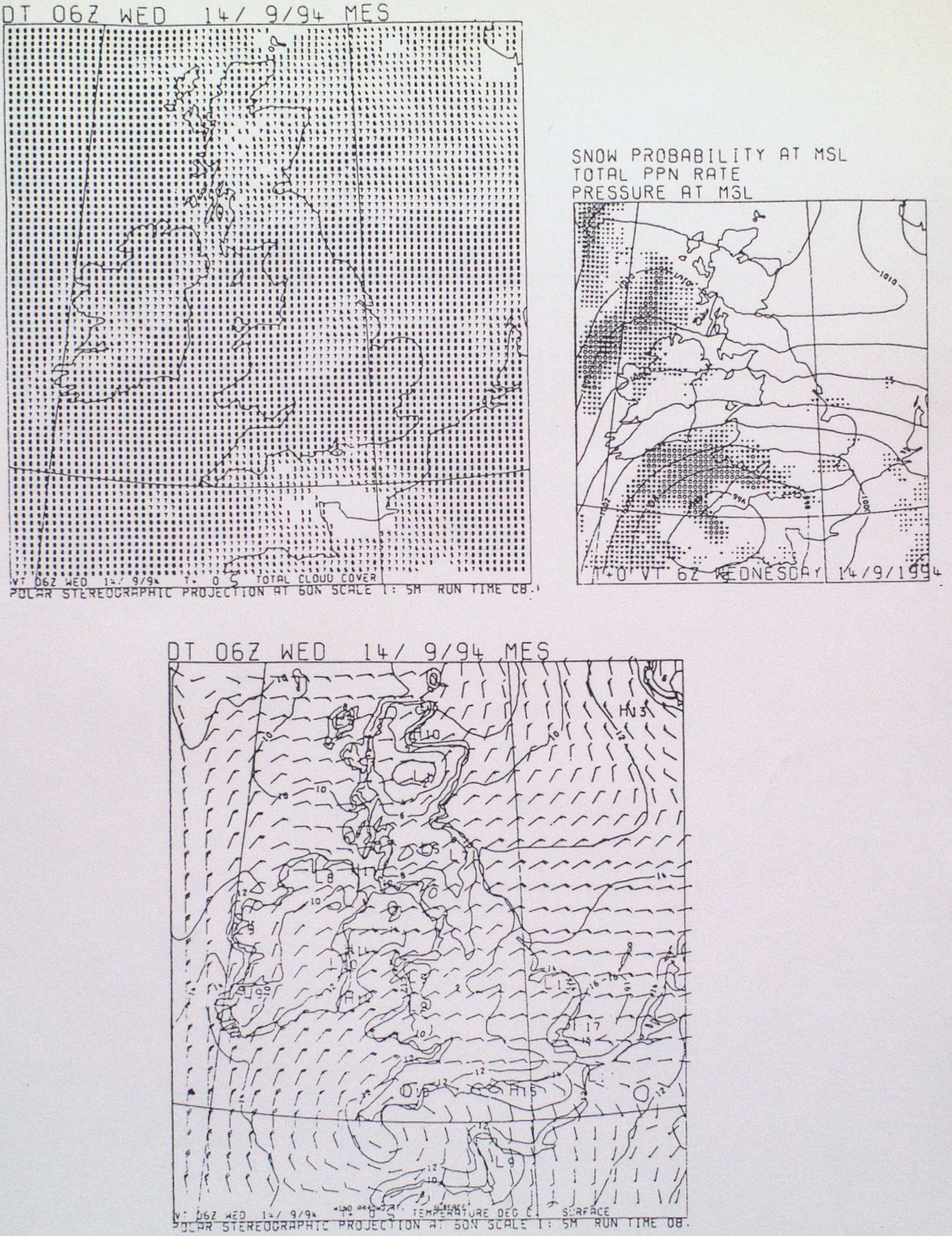

Figure 5. T+ 0 mesoscale model charts from the QM06 run 14/09/1994

Mesoscale run	Boundary conditions from	
	Hourly cycle	3-hourly cycle
QM00	QL18	QL00
QM01	QL18	N/A
QM02	QL18	N/A
QM03	QL00	QL03
QM04	QL00	N/A
QM05	QL00	N/A
QM06	QL00	QL06
QM07	QL00	N/A
QM08	QL00	N/A
QM09	QL06	QL09
QM10	QL06	N/A
QM11	QL06	N/A
QM12	QL06	QL12
QM13	QL06	N/A
QM14	QL06	N/A
QM15	QL12	QL15
QM16	QL12	N/A
QM17	QL12	N/A
QM18	QL12	QL18
QM19	QL12	N/A
QM20	QL12	N/A
QM21	QL18	QL21
QM22	QL18	N/A
QM23	QL18	N/A

Table1. Source of LAM boundary conditions for mesoscale runs

Observation types: Pstar, Surface temperatures, surface RH N_ITER increased from 1 to 2 G unchanged TIME_WINDOW decreased from (-120,24) to (-60,12)
Observation types: upper level temperatures, upper level RH N_ITER increased from 1 to 2 G decreased from 0.0005 to 0.0003 TIME_WINDOW decreased from (-150,30) to (-120,24)
Observation types: upper level winds N_ITER increased from 1 to 2 G decreased from 0.00066 to 0.00038 TIME_WINDOW decreased from (-150,30) to (-120,24)
Observation types: surface winds N_ITER increased from 1 to 2 G unchanged TIME_WINDOW decreased from (-120,24) to (-60,12)
Observation types: MOPS N_ITER unchanged G unchanged TIME_WINDOW decreased from (-150,30) to (-60,12)

Table 2. Assimilation parameters for the hourly assimilation cycle (see section 2.2 for explanation of parameters).

(For the TIME_WINDOW parameter, the two numbers are minutes before validity time followed by minutes after validity time)

Model Run	Time at which products from **hourly** cycle are available	Time at which products from **3-hourly** cycle are available
QM00	01:00Z	03:10Z
QM01	02:00Z	N/A
QM02	03:00Z	N/A
QM03	04:00Z	07:50Z
QM04	05:00Z	N/A
QM05	06:00Z	N/A
QM06	07:00Z	09:10Z
QM07	08:00Z	N/A
QM08	09:00Z	N/A
QM09	10:00Z	13:15Z
QM10	11:00Z	N/A
QM11	12:00Z	N/A
QM12	13:00Z	15:10Z
QM13	14:00Z	N/A
QM14	15:00Z	N/A
QM15	16:00Z	21:25Z
QM16	17:00Z	N/A
QM17	18:00Z	N/A
QM18	19:00Z	21:55Z
QM19	20:00Z	N/A
QM20	21:00Z	N/A
QM21	22:00Z	01:15Z
QM22	23:00Z	N/A
QM23	00:00Z	N/A

Table 3. Product availability times

Verification statistics for 13th April 1994 case - Cloud

Parameter VT	14Z 13/04/94		15Z 13/04/94		16Z 13/04/94	
FT	T+5 (3)	T+1 (1)	T+3 (3)	T+1 (1)	T+4 (3)	T+1 (1)
RMS screen humidity	13.95	10.13	11.78	10.10	12.29	11.04
RMS 10m wind speed	2.37	2.08	2.78	2.50	2.39	2.27
RMS 10m wind vector error	2.93	2.61	3.41	3.21	3.08	3.08
RMS screen temperature	1.81	1.44	1.49	1.14	1.47	1.11
RMS total cloud	2.40	2.62	2.89	2.26	2.97	2.81
Precipitation hit rate	NA	NA	NA	NA	NA	NA
Precipitation false alarm rate	NA	NA	NA	NA	NA	NA
RMS Factor (precipitation)	NA	NA	NA	NA	NA	NA
RMS low cloud (MOPS)	3.79	3.24	3.67	2.85	NA	NA
RMS medium cloud (MOPS)	3.47	3.28	3.37	2.79	NA	NA
RMS high cloud (MOPS)	2.99	2.26	2.47	1.88	NA	NA
RMS total cloud (MOPS)	3.74	3.25	3.57	2.94	NA	NA

Table 4. Verification scores for the cloud case

VT is the validity time of the comparison, FT is the length of forecast with the cycle length in brackets

Verification statistics for 12th July 1994 case - Fog

Parameter VT	08Z 12/07/94		09Z 12/07/94		10Z 12/07/94	
FT	T+5 (3)	T+1 (1)	T+3 (3)	T+1 (1)	T+4 (3)	T+1 (1)
RMS screen humidity	8.30	7.20	8.78	8.78	10.39	8.57
RMS 10m wind speed	1.65	1.57	1.83	1.81	1.71	1.79
RMS 10m wind vector error	2.22	2.22	2.43	2.32	2.32	2.24
RMS screen temperature	1.76	1.49	1.87	1.71	2.18	1.81
RMS total cloud	1.75	1.35	1.81	2.10	2.21	1.58
Precipitation hit rate	87.3	74.5	74.7	62.8	NA	NA
Precipitation false alarm rate	46.3	44.6	52.9	44.8	NA	NA
RMS Factor (precipitation)	2.75	6.05	3.17	4.07	NA	NA
RMS low cloud (MOPS)	2.58	2.12	2.13	2.24	NA	NA
RMS medium cloud (MOPS)	3.13	2.94	2.77	2.61	NA	NA
RMS high cloud (MOPS)	2.14	2.24	2.40	1.96	NA	NA
RMS total cloud (MOPS)	2.55	2.53	2.07	2.27	NA	NA

Table 5. Verification scores for the fog case

VT is the validity time of the comparison, FT is the length of forecast with the cycle length in brackets

Verification statistics for 14th September 1994 case - Precipitation

Parameter VT	08Z 14/09/94		09Z 14/09/94		10Z 14/09/94	
FT	T+5 (3)	T+1 (1)	T+3 (3)	T+1 (1)	T+4 (3)	T+1 (1)
RMS screen humidity	7.19	5.68	7.25	6.80	9.58	7.21
RMS 10m wind speed	2.36	2.18	2.39	2.25	2.26	2.28
RMS 10m wind vector error	3.57	2.99	3.13	3.09	2.90	2.92
RMS screen temperature	1.04	1.02	1.36	1.33	1.68	1.26
RMS total cloud	1.30	1.24	1.39	1.44	1.19	1.12
Precipitation hit rate	59.1	64.4	63.5	70.5	NA	NA
Precipitation false alarm rate	37.6	25.8	36.8	28.2	NA	NA
RMS Factor (precipitation)	4.80	2.91	4.40	3.07	NA	NA
RMS low cloud (MOPS)	3.87	3.30	3.34	3.09	NA	NA
RMS medium cloud (MOPS)	3.64	3.38	3.64	3.31	NA	NA
RMS high cloud (MOPS)	3.85	3.38	3.75	3.22	NA	NA
RMS total cloud (MOPS)	3.01	3.20	2.72	2.88	NA	NA

Table 6. Verification scores for the precipitation case

VT is the validity time of the comparison, FT is the length of forecast with the cycle length in brackets

Verification statistics for 13th April 1994 case - Cloud

Parameter DT	13Z 13/04/94		14Z 13/04/94		15Z 13/04/94	
Cycle	1	3	1	3	1	3
FT	1 - 2	5 - 6	1 - 6	3 - 8	1 - 6	4 - 9
RMS screen humidity	11.09	13.85	12.25	13.00	12.48	13.15
RMS 10m wind speed	2.40	2.61	2.25	2.33	2.26	2.27
RMS 10m wind vector error	2.99	3.20	2.96	2.90	2.89	2.83
RMS screen temperature	1.46	1.77	1.38	1.52	1.30	1.54
RMS total cloud	2.58	2.57	2.89	2.97	3.06	3.07
Precipitation hit rate	NA	NA	NA	NA	NA	NA
Precipitation false alarm rate	NA	NA	NA	NA	NA	NA
RMS Factor (precipitation)	NA	NA	NA	NA	NA	NA
RMS low cloud (MOPS)	3.35	3.75	3.12	3.67	NA	NA
RMS medium cloud (MOPS)	3.23	3.45	2.97	3.37	NA	NA
RMS high cloud (MOPS)	2.67	3.03	2.92	2.47	NA	NA
RMS total cloud (MOPS)	3.24	3.65	2.94	3.57	NA	NA

Table 7. Verification score averages for the cloud case

DT is the start of the comparison period, Cycle is the cycle length in hours, and FT is the range of forecast lengths used in the comparison

Verification statistics for 12th July 1994 case - Fog

Parameter DT	07Z 12/07/94		08Z 12/07/94		09Z 12/07/94	
Cycle	1	3	1	3	1	3
FT	1 - 2	5 - 6	1 - 6	3 - 8	1 - 6	4 - 9
RMS screen humidity	8.13	8.68	10.65	11.67	11.75	12.48
RMS 10m wind speed	1.68	1.69	1.75	1.72	1.93	1.74
RMS 10m wind vector error	2.34	2.26	2.66	2.76	2.84	2.86
RMS screen temperature	1.67	1.89	2.36	2.64	2.60	2.86
RMS total cloud	1.73	1.95	1.82	2.12	1.86	2.09
Precipitation hit rate	66.2	85.7	62.8	74.7	NA	NA
Precipitation false alarm rate	50.1	46.6	44.8	52.9	NA	NA
RMS Factor (precipitation)	4.87	2.95	4.07	3.17	NA	NA
RMS low cloud (MOPS)	2.20	2.54	2.24	2.13	NA	NA
RMS medium cloud (MOPS)	2.88	2.99	2.61	2.77	NA	NA
RMS high cloud (MOPS)	2.30	2.17	1.96	2.40	NA	NA
RMS total cloud (MOPS)	2.39	2.38	2.27	2.07	NA	NA

Table 8. Verification score averages for the fog case

DT is the start of the comparison period, Cycle is the cycle length in hours, and FT is the range of forecast lengths used in the comparison

Verification statistics for 14th September 1994 case - Precipitation

Parameter DT	07Z 14/09/94		08Z 14/09/94		09Z 14/09/94	
Cycle	1	3	1	3	1	3
FT	1 - 2	5 - 6	1 - 6	3 - 8	1 - 6	4 - 9
RMS screen humidity	6.71	7.74	11.43	11.86	12.35	12.95
RMS 10m wind speed	2.27	2.35	2.36	2.30	2.49	2.37
RMS 10m wind vector error	3.06	3.56	3.27	3.05	3.32	3.16
RMS screen temperature	1.22	1.17	2.00	1.99	2.02	2.09
RMS total cloud	1.42	1.35	1.51	1.48	1.45	1.53
Precipitation hit rate	67.2	57.8	70.5	63.5	69.1	68.1
Precipitation false alarm rate	28.1	43.0	28.2	36.8	50.7	44.9
RMS Factor (precipitation)	3.20	4.71	3.07	4.40	3.22	3.21
RMS low cloud (MOPS)	3.33	3.77	3.09	3.34	3.55	3.54
RMS medium cloud (MOPS)	3.51	3.79	3.31	3.64	3.57	3.62
RMS high cloud (MOPS)	3.40	3.87	3.22	3.75	3.57	3.77
RMS total cloud (MOPS)	3.14	2.99	2.88	2.72	3.02	2.97

Table 9. Verification score averages for the precipitation case

DT is the start of the comparison period, Cycle is the cycle length in hours, and FT is the range of forecast lengths used in the comparison

12/7	5	1	6	2								
RH	8.3	7.2	9.06	9.06								
WS	1.65	1.57	1.72	1.79								
WV	2.22	2.22	2.30	2.46								
T	1.76	1.49	2.01	1.84								
CT	1.75	1.35	2.14	2.11								
PHR	87.3	74.5	84.1	57.8								
PFA	46.3	44.6	46.9	55.6								
P	2.75	6.05	3.14	3.68								
CL	2.58	2.12	2.49	2.28								
CM	3.13	2.94	2.84	2.82								
CH	2.14	2.24	2.20	2.35								
CT	2.55	2.53	2.21	2.25								
T+	3	1	4	2	5	3	6	4	7	5	8	6
RH	8.78	8.78	10.39	8.84	10.86	9.11	12.52	11.24	13.27	11.93	14.22	13.98
WS	1.83	1.81	1.71	1.67	1.54	1.54	1.88	1.99	1.64	1.71	1.73	1.79
WV	2.43	2.32	2.32	2.22	2.63	2.54	3.12	3.14	3.01	2.83	3.04	2.88
T	1.87	1.71	2.17	1.85	2.46	2.07	2.99	2.69	3.07	2.75	3.26	3.12
CT	1.81	2.10	2.21	1.59	2.54	1.68	2.49	2.00	2.13	1.77	1.53	1.78
PHR	74.7	62.8										
PFA	52.9	44.8										
P	3.17	4.07										
CL	2.13	2.24										
CM	2.77	2.61										
CH	2.40	1.96										
CT	2.07	2.27										
T+	4	1	5	2	6	3	7	4	8	5	9	6
RH	10.39	8.57	10.86	9.45	12.52	11.52	13.27	12.70	14.22	14.60	13.64	13.63
WS	1.71	1.79	1.54	1.71	1.88	2.13	1.64	1.95	1.73	1.98	1.94	2.03
WV	2.32	2.23	2.63	2.58	3.12	3.19	3.01	2.96	3.04	2.97	3.07	3.12
T	2.17	1.81	2.46	2.05	2.99	2.69	3.07	2.81	3.26	3.16	3.18	3.09
CT	2.21	1.58	2.54	1.71	2.49	1.95	2.13	1.96	1.53	1.97	1.63	2.00

13/4	5	1	6	2
RH	13.95	**10.13**	13.76	**12.05**
WS	2.37	**2.08**	2.84	**2.71**
WV	2.93	**2.61**	3.47	**3.37**
T	1.81	**1.44**	1.73	**1.47**
CT	**2.40**	2.62	2.73	**2.53**
CL	3.79	**3.24**	3.71	**3.45**
CM	3.47	**3.28**	3.43	**3.18**
CH	2.99	**2.26**	3.07	3.08
CT	3.74	**3.25**	3.56	**3.22**

T+	3	1	4	2	5	3	6	4	7	5	8	6
RH	11.78	**11.46**	12.29	**11.44**	12.69	**11.08**	13.36	**12.68**	14.96	**14.31**	12.96	**12.56**
WS	2.78	**2.63**	2.39	**2.25**	2.24	**2.21**	2.23	**2.17**	2.13	2.11	2.20	**2.14**
WV	3.41	**3.33**	3.08	3.07	2.83	2.83	3.01	2.98	2.56	2.56	2.52	**2.47**
T	1.49	**1.37**	1.47	**1.29**	2.04	**1.85**	1.33	**1.19**	1.42	**1.28**	1.39	**1.29**
CT	2.89	**2.44**	2.97	**2.81**	2.96	**2.81**	2.97	**2.89**	3.05	3.07	**2.98**	3.31
CL	3.67	**3.12**										
CM	3.37	**2.97**										
CH	**2.47**	2.92										
CT	3.57	**2.94**										

T+	4	1	5	2	6	3	7	4	8	5	9	6
RH	12.29	**11.04**	12.69	**11.13**	13.36	**12.98**	14.96	**14.54**	12.96	**12.73**	12.63	**12.46**
WS	2.39	**2.27**	2.24	2.25	2.23	**2.20**	2.13	2.15	**2.20**	2.27	2.42	2.44
WV	3.08	3.08	**2.83**	2.87	**3.01**	3.07	**2.56**	2.64	**2.52**	2.64	**2.97**	3.03
T	1.47	**1.11**	2.04	**1.73**	1.33	**1.10**	1.42	**1.15**	1.39	**1.23**	1.59	**1.46**
CT	2.97	**2.81**	2.96	**2.73**	2.97	2.97	3.05	**2.88**	**2.98**	3.22	**3.47**	3.75

14/9	5	1	6	2
RH	7.19	**5.68**	8.28	**7.73**
WS	2.36	**2.18**	2.56	**2.36**
WV	3.57	**2.99**	3.55	**3.13**
T	1.04	**1.02**	**1.30**	1.41
CT	1.30	**1.24**	**1.39**	1.59
PHR	59.1	**64.4**	56.4	**70.0**
PFA	37.6	**25.8**	48.4	**30.3**

P	4.8	2.91	4.63	3.48								
CL	3.87	3.30	3.66	3.36								
CM	3.64	3.38	3.93	3.64								
CH	3.85	3.38	3.88	3.42								
CT	3.01	3.20	2.97	3.08								
T+	3	1	4	2	5	3	6	4	7	5	8	6
RH	7.25	6.8	9.58	7.93	11.52	10.39	12.88	12.48	14.52	15.07	15.38	15.92
WS	2.39	2.25	2.26	2.28	2.25	2.35	2.46	2.56	1.99	2.18	2.45	2.54
WV	3.13	3.09	2.90	2.96	2.87	3.13	3.38	3.60	2.76	3.16	3.29	3.66
T	1.36	1.33	1.68	1.47	2.01	1.91	2.08	2.09	2.18	2.36	2.60	2.81
CT	1.39	1.44	1.19	1.14	1.32	1.56	1.61	1.93	1.69	1.54	1.68	1.55
PHR	63.5	70.5										
PFA	36.8	28.2										
P	4.40	3.07										
CL	3.34	3.09										
CM	3.64	3.31										
CH	3.75	3.22										
CT	2.72	2.88										
T+	4	1	5	2	6	3	7	4	8	5	9	6
RH	9.58	7.21	11.52	9.83	12.88	12.05	14.52	14.47	15.38	15.82	13.8	14.72
WS	2.26	2.28	2.25	2.42	2.46	2.63	1.99	2.19	2.45	2.54	2.78	2.88
WV	2.90	2.92	2.87	3.00	3.38	3.56	2.76	2.94	3.29	3.49	3.74	4.02
T	1.68	1.26	2.01	1.73	2.08	2.01	2.18	2.23	2.60	2.74	1.97	2.17
CT	1.19	1.12	1.32	1.42	1.61	1.64	1.69	1.69	1.68	1.51	1.71	1.34
PHR					64.6	70.8					71.6	67.4
PFA					46.8	49.1					42.9	52.2
P					3.48	2.94					2.93	3.51
CL					3.57	3.54					3.51	3.55
CM					3.71	3.64					3.53	3.49
CH					3.89	3.67					3.65	3.47
CT					2.94	2.99					3.00	3.04

Table 10. Individual verification scores for the hourly and 3-hourly assimilation runs

12/7	1	2				
RH	++					
W	+	-				
T	++	+				
C	+					
P	-	–				
	1	2	3	4	5	6
RH		++	++	++	++	+
W	+	+	+	-		
T	+	++	++	++	++	+
C		++	++	++	++	-
P	-					
	1	2	3	4	5	6
RH	++	++	+	+	-	
W			–			-
T	++	++	++	+	+	+
C	++	++	++	+	–	–
13/4	1	2				
RH	++	++				
W	++	+				
T	++	++				
C	+	+				
	1	2	3	4	5	6
RH	+	+	++	+	+	+
W	+	+	+	+		+
T	+	++	+	++	++	+
C	+	+	+	+		–
	1	2	3	4	5	6
RH	++	++	+	+	+	+
W	+	-		-	-	-
T	++	++	++	++	++	+
C	+	+		+	-	-
14/9	1	2				
RH	++	+				

W	++	++				
T	+	-				
C	+					
P	++	++				
	1	2	3	4	5	6
RH	+	++	+	+	-	-
W	+	-	-	-	-	–
T	+	++	+		-	-
C	+	+	–	–	+	+
P	++					
	1	2	3	4	5	6
RH	++	++	+		-	-
W		-	-	-	-	-
T	++	++	+	-	-	-
C	+	-			++	+
P			+			–

Table 11. Summary of individual verification scores for the hourly and 3-hourly assimilation runs.