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Contents

1 Introduction

The current treatment of boundary layer (BL) turbulent fluxes in the Unified Model (in operational NWP models and in HadAM3 and preceding climate models) uses mixing coefficients (K's) calculated in terms of the local Richardson number, wind shear and a mixing length for all types of boundary layer. Evidence has been accumulating that this approach does not predict turbulent fluxes and boundary layer structure accurately even when (and in some circumstances because) cloud processes are allowed for in the definition of the Richardson number. In particular the local nature of the current scheme leads to unrealistic interactions with other parts of the model such as the convection scheme. The boundary layer is often predicted to be too shallow and moist.

This report discusses the results of trials to test a new boundary layer scheme in the mesoscale version (MES) of the Unified Model (UM). Section 2 gives a description of the main features of the new scheme. Section 3 outlines the model configuration and gives details of the case studies selected for the trial. Section 4 looks at the impact of the new boundary layer scheme on the forecasts (both subjectively and objectively). Section 5 looks at the impact of using 'sharp tailed' stability functions to try and overcome the poor performance of the new boundary layer scheme when a stable boundary layer has been diagnosed. Section 6 looks at four case studies and conclusions and recommendations can be found in section 7.

2 Outline of the new scheme

Motivated by the inadequacies of the current scheme and by insights given by Large Eddy Simulation (LES) studies done by the Atmospheric Processes Research Branch (APR) and others, a "non-local" specification of the turbulent mixing coefficients and fluxes for unstable layers has been developed. (Stable layer mixing coefficients are based on the local Richardson number.) The scheme also includes an explicit parametrization of entrainment into the tops of turbulently mixed layers. The formulation uses moist conserved variables so that both dry and cloudy layers can be treated.

The main features of the scheme are:

(i) Diagnosis of any surface-based or cloud-top-driven turbulently mixed layers.

The starting point and basis of the scheme is the identification of any unstable turbulently mixed layers. Undilute plumes are used to determine the presence and depths of any unstable regions in the boundary layer. Firstly a plume is lifted upwards from the surface layer, allowing for any latent heating effects, and the top of the surface mixed layer (ZH) is taken to be the height (ZHPAR) at which this parcel is neutrally buoyant relative to the environment if below the lifting condensation level (LCL), or the height at which it has maximum excess over the environment if above the LCL. [The use of the height of maximum, rather than zero, excess is usually of little consequence in regions of stratocumulus but it can be necessary in order to identify a capping inversion when cumulus is present (e.g. in the trade wind regions).] If the plume cannot rise at all then ZH is set to the top of the lowest model layer.

The top of any layer cloud in the boundary layer is diagnosed from the model's layer cloud area variable (a threshold of 0.1 is used to indicate cloud in this context). Note that this cloud top may be above the height ZH calculated using the procedure described above. The presence and depth of any mixed layer driven from cloud top is diagnosed by testing the buoyancy of a second parcel as it is moved downwards from the top of the cloud layer. The initial buoyancy of this parcel is perturbed from the mean environment value in order to represent the effects of radiation and entrainment on the parcel over a parametrized time that it has been in the inversion.

The next step is to determine whether cumulus convection is present. This is a crucial feature of the scheme because the mean profiles in cumulus layers are less well-mixed than those in stratocumulus. Thus a different mixing scheme (specifically a mass flux convection scheme rather than an eddy viscosity scheme) is used in order to prevent cumulus layers erroneously evolving into well mixed stratocumulus. Cumulus is diagnosed if the mean gradient of total water content between lifting condensation level (LCL) and the top of the surface-based parcel ascent is greater than some threshold factor (currently set to 1.1) times the mean gradient below the LCL. In this case, the top of the surface mixed layer (ZH) is set to the height of the LCL (rather than to ZHPAR), so that mixing above the LCL is carried out by the model's convection scheme.

Note that any unstable mixed layer driven from cloud top may or may not be coupled (overlap significantly with) any surface-based mixed layer.

The procedure described above leads to the identification of six boundary layer types, as shown diagramatically in Fig. 1 and Fig. 2.

Type I: Stable boundary layer (with or without cloud) - turbulent diffusivities are functions of local Richardson number, wind shear and a mixing length.

Type II: Boundary layer with stratocumulus over a stable near-surface layer - as Type I but with a turbulently mixed cloud layer driven from its top.

Type III: Well-mixed boundary layer - the classic single mixed layer which may be cloud-topped or clear.

Type IV: Boundary layer with a decoupled stratocumulus layer not over cumulus - this is a transitional type between Types III and V; there may be some weak coupling depending on the degree of overlap between the surface-based and cloud-top-driven turbulent regions.

Type V: Boundary layer with a decoupled stratocumulus over cumulus - the cumulus (treated by the model's mass-flux convection scheme) provides coupling with the surface mixed layer.

Type VI: Cumulus capped boundary layer - no turbulent diffusivities are allowed at or above the LCL as the mass-flux convection scheme operates here.

(ii) The parametrization of turbulent mixing coefficients and fluxes within the unstable mixing layers

The approach adopted is an extension of that used by Holtslag and Boville (1992) to allow for top-down as well as surface-based mixing. Non-locally determined profiles of diffusivity with predetermined shapes are applied from the surface to the top of the diagnosed surface mixed layer, and also downwards from the top of cloudy mixed layers (if present). The magnitudes of each are determined from appropriate surface and cloud top turbulence scaling velocities. Also following Holtslag and Boville, "counter-gradient" terms are added to the actual scalar gradients within any surface-based unstable mixed layer before multiplication by the mixing coefficients to obtain the fluxes. The gradient adjustments depend on the standard deviation of the surface layer turbulent fluctuations for the respective scalars. These in turn can be expressed in terms of the surface fluxes.

(iii) The parametrization of entrainment velocities at the top of turbulently mixed layers

Entrainment at the top of turbulently mixed layers resulting from three main processes is parametrized:

(a) Heating from a warmer surface leads to positively buoyant plumes rising from the surface layer. When they reach the vicinity of an inversion they lead to turbulent motions which entrain overlying air into the mixed layer. Thus one term in the parametrization of the entrainment flux is proportional to the surface buoyancy flux. Surface stress also generates turbulence in a surface-based mixed layer which can lead to entrainment at its top and so a term proportional to the rate of t.k.e. generation by wind shear in the surface layer is included.

(b) If a turbulent layer has cloud at its top then the top few tens of metres have net radiative cooling. This has two effects: a direct effect (i.e. not mediated by turbulence generation) whereby air in the inversion is cooled to the extent that it becomes part of the boundary layer and an indirect effect of negative buoyancy causing turbulence close to the cloud top and hence entrainment. There are therefore entrainment terms proportional to the net radiative cooling at cloud top.

(c) Cloud water will evaporate into parcels of dry air entrained from above the inversion. This cools the parcel, sometimes enough to cause it to be negatively buoyant thus providing a positive feedback on entrainment. The entrainment parametrization therefore contains a term involving humidity and buoyancy differences across the inversion to represent this process.

The height at which the surface-based terms are applied depends on the degree of coupling between the surface and any elevated turbulent cloud layer. However, no surface-based entrainment parametrization is applied if cumulus is diagnosed, as the required transports through the LCL are performed by the model convection scheme.

3 Methodology

3.1 Running with MOSES

The new boundary layer scheme works in conjunction with the new Met.Office surface exchange scheme (MOSES). In order to partition the effects of MOSES and the new boundary layer scheme, the following runs were carried out (the naming convention for the runs (3A, 5A etc.) refers to the choice of BL option within the BL section of the UM).

1) 3A - Operational boundary layer scheme plus current surface scheme (OP BL)
2) 5A - Operational boundary layer scheme plus MOSES.
3) 6A - New boundary layer scheme plus MOSES (NEW BL).

MOSES (Cox, 1997) was developed because of a number of deficiencies in the current operational surface exchange scheme (such as the lack of soil moisture freezing). This aspect of MOSES will be briefly discussed to illustrate the large impact such changes can make on surface variables such as 1.5m temperature. In the MOSES scheme, soil moisture can be in either a liquid or ice state (not possible with the current scheme). This means that there can be a phase change to ice when the soil temperatures fall below freezing. The energy associated with this freezing process is released and can help to maintain higher model surface temperatures during winter. Fig. 3 shows the 1.5m temperature at 00z on 06/01/97 for both the OP BL (3A) and OP BL plus MOSES (5A) runs against analysis. The whole of the continent in the MES domain was below freezing at this point in time and there was a warming (mostly beneficial) by MOSES of up to five degrees.

3.2 Model configuration

Testing of the new boundary layer scheme/MOSES commenced in February 1998. The MES was run at the then operational resolution of 92 x 92 gridpoints in the horizontal (16.8km resolution) and 31 levels in the vertical, with 14 levels being boundary layer levels. The current operational resolution is 146 x 182 gridpoints in the horizontal (12.3km resolution) and 38 levels in the vertical (Culverwell and Wilson, 1997). Testing at the higher resolution is currently in progress.

All runs had 6 hours (two cycles) of assimilation, followed by 24 hours of forecast. Deep soil temperatures were initialised from the model analysis while soil humidities were initialised from climatology. Table A summarises some of the physics choices for the runs.

Parametrization/Option	3A	5A	6A
CONVECTION	Local buoyancy closure (not CAPE)		
Convective momentum transport	NO	NO	NO
LARGE SCALE PRECIPITATION	New mixed-phase scheme (*)		
RADIATION	Operational scheme (not Edwards-Slingo)		
GRAVITY WAVE DRAG	NO	NO	NO
VERTICAL DIFFUSION	NO	NO	NO

Table A: Details of the model runs.

(*) Wilson and Ballard (1998).

The 3A and 5A runs had bottom model layer convective parcel excesses set to depend on turbulent fluctuations (as is usual when the 'rapid mixing' BL option is switched on), while the 6A runs had these parcel excesses turned off.

3.3 Case studies

Twelve case studies were chosen from a variety of synoptic conditions

Case study	Synoptic type/poor forecast
19/09/96	Poor wind forecast
13/10/96	Stratus
20/12/96	Frontal passage
05/01/97	Freezing fog
15/01/97	Fog
26/03/97	Frontal passage
12/05/97	Convective
11/06/97	Mesoscale Convective System (MCS)
21/06/97	Convective
24/09/97	Stratocumulus
27/09/97	Stratocumulus
10/12/97	Land gales

Table B: Details of the Case studies.

Verification is performed using the data from model runs and observations from 289 land stations (mainly situated in the U.K, but with a few in Norway and on the near continent). The root mean square (r.m.s) error and mean bias of each forecast were calculated.

4 Results

This section deals with the objective verification of the twelve case studies. The main diagnostics are scatter plots of the OP BL vs the NEW BL for bias and r.m.s. On each figure there are two points marked for each of the 12 case studies (summed over all stations): a triangle representing the mean bias at midday (T+12) and a diamond the error at midnight (T+24). The overall mean bias summed up over all cases and stations is marked in red.

4.1 1.5m temperature

There is an overall negative impact on 1.5m temperatures with the NEW BL scheme (Fig. 4). This negative impact was due to an increase in the warm bias present during night-time. Fig. 5 shows the same data, but with the modulus of the mean bias plotted to emphasize whether the size of the bias is increased or reduced. Only six points show an improvement (four during day-time) with eighteen points showing a degradation (ten of them during night-time). The overall effect on the modulus of the mean bias is to increase it from 0.67 K to 0.75 K (a 12% degradation). The r.m.s errors (RMSE) are displayed in Fig. 6 and they show the same characteristics as the mean bias plot. The overall RMSE is increased from 1.83 to 1.85 (1% degradation).

The most likely cause of the too warm 1.5m temperatures at night-time is the change to the stability dependence of the surface transfer coefficients (following more closely Monin Obukhov theory). This change towards a 'sharper' function reduces the amount of mixing that occurs between the surface and the bottom of the boundary layer in stable conditions. This leads to a reduction in the heat and momentum fluxes between the boundary layer and the surface causing the increase in night-time temperatures.

4.2 10m wind speed

There is a systematic increase in the 10m wind speed throughout the forecast period with the NEW BL scheme. This reduces the daytime weak bias but makes the night-time strong bias worse (Fig. 4). Fig. 5 shows that eight points show a reduced bias (all at midday) while sixteen points show a degradation (twelve at night). The overall effect on the modulus of the mean bias is to increase it from 0.73 to 0.86 m/s (18% degradation) and the RMSE is increased from 2.41 to 2.50 (4% worse) as shown in Fig. 6.

The increase in wind speed is due to the combination of i) more downward momentum mixing as a result of the new way of diagnosing boundary layer types and hence an appropriate mixing profile specification and ii) the change to the stability dependence of the surface transfer coefficients.

4.3 1.5m relative humidity

Overall there is a small negative impact on the 1.5m R.H. Fig. 4 shows that there is a positive bias in the OP BL. Although this moist bias is decreased with the NEW BL (Fig. 5), (15 points showed an improvement and nine points showed a degradation), the degradation in those nine points was sufficient to cause the overall mean bias to be increased from 3.09from 9.43 to 9.97 (6% worse) as shown in Fig. 6.

The cause of the reduction in the night-time 1.5m R.H is probably the combination of the change to the surface transfer coefficients (reducing the moisture flux between the ground and the boundary layer) and the increase in 1.5m temperature causing a reduction in R.H.

4.4 Visibility

There was a negative impact on visibility. The positive bias that was present in the OP BL was increased as can be seen in Fig. 4. Fig. 5 shows that only five points showed an improvement (four of them at midday) with nineteen showing a degradation (eleven of them at midnight). The overall effect on the modulus of the mean bias was to worsen it from 0.23 to 0.28 (22% degradation) and the RMSE was increased from 0.47 to 0.49 (3% worse) as shown in Fig. 6.

4.5 Fog fraction

There was a negative impact on the 1.5m fog fraction. This was due mainly to two points corresponding to T+12 and T+24 from the 15/01/97 fog case as can be seen in Fig. 4 (this case is discussed in more detail in section 6). Fig. 5 shows that seven points showed an improvement, nine points a degradation and eight points no change. These two points worsened the negative bias and caused the overall modulus of the mean bias to be increased from 0.027 to 0.036 (36% degradation). The RMSE was increased from 0.14 to 0.16 (14% worse) as shown in Fig. 6.

4.6 Precipitation

Subjective verification of precipitation against radar imagery was carried out. In three cases the NEW BL was preferred, in seven cases there was no preference and only in one case was the OP BL preferred. The most striking cases were the Summer convective cases when convective precipitation was present in runs with the NEW BL as a result of the removal of low cloud, allowing solar radiation to reach the ground and initiate convective activity. This precipitation was in agreement with radar imagery and was absent in the OP BL runs (see the 12/05/97 case in section 6). The NEW BL scheme also tends to remove light precipitation over sea areas in areas of high pressure. This improves a well known bias in the UM, the so called 'spotty high' situations.

4.7 Cloud amount

Subjective verification of cloud amount was carried out against satellite imagery and surface reports. In ten cases out of twelve, the NEW BL run was preferred and only in one case (the 15/01/97 fog case) was the OP BL run preferred. The NEW BL scheme is particularly effective in removing spurious low cloud in convective situations (see the 12/05/97 case in section 6). However it can also beneficially add low cloud where there was none in the OP BL run (see the 24/09/97 case in the section 6). Another area where the NEW BL scheme performs well is in removing low cloud behind a front (see the 13/10/96 case in section 6).

Finally, the results from figures 4, 5 and 6 are summarised in Tables C,D and E at the end of the paper.

4.8 Summary

The results with the NEW BL scheme are disappointing. The new scheme was designed to improve boundary layer representation in unstable conditions and if just the results at midday are considered then indeed there Is an improvement to the modulus of the bias in 1.5m temperature and 10m wind (and also the RMSE). However, the NEW BL scheme degraded the forecast in stable contions to such an extent that the overall amplitude of the bias in 1.5m temperature, 10m wind, 1.5m R.H, visibility and 1.5m fog fraction were all increased. The RMSE were also increased in these five variables. The conclusion is that without some modification to the NEW BL scheme, particularly in stable conditions, it could not be recommended for operational implementation.

5 'Sharp tailed' stability functions

In the last section, problems with the NEW BL scheme in stable conditions (due to the change to the stability dependence of the surface transfer coefficients) were discussed. This section will discuss the options available to improve the representation of stable BL mixing and the results that were obtained when the 12 case studies were re-run with 'sharp tailed' stability functions.

There are two stability functions which determine the amount of mixing that occurs within the boundary layer and between the boundary layer and the surface in stable conditions:
1) boundary layer stability functions (internal stability functions)
2) surface transfer coefficients, fm

Having changed the stability dependence of the surface transfer coefficients in the formulation of the NEW BL scheme, it might seem logical to reverse the changes that were made. However it was decided that the most physically realistic solution would be to change the stability dependence of the boundary layer stability functions. Fig. 7 (Derbyshire (1997)) shows three different stability dependencies for these functions (plotted as *fm* as a function of the Richardson number, *Ri*). The uppermost curve corresponds to the current UM scheme (also the NEW BL scheme). The middle one corresponds to the 'Louis' function as used by ECMWF (The European Centre for Medium Range Weather Forecasts). The bottom curve corresponds to the 'sharp tailed' function (labelled as 'sharpest') that was used to produce the results in this section. Both Derbyshire (1997) and Dunlop (1998) have compared data gathered from the UKMO Cardington experimental site with UM simulations using these three different functions. The 'sharp tailed' function lies closest to these observations.

5.1 1.5m temperature

There is a positive impact on midnight 1.5m temperatures with the sharp tail run (i.e new BL scheme plus sharp tail) compared to both the NEW BL run (Fig. 8) and the OP BL run (Fig. 9). At midday, the temperatures are not as good as the original NEW BL run, but are still better than the OP BL run. In terms of the modulus of the mean bias, there is a decrease from 0.72 K (OP BL) to 0.68 K with the sharp tail (the original NEW BL run decreased it still further to 0.63 K).

Overall the modulus of the mean bias is reduced from 0.67 in the OP BL run to 0.60 with the sharp tail (an 11% improvement) and the RMSE (Fig. 10) is reduced from 1.83 to 1.81 (a 1% improvement).

5.2 10m wind speed

Fig. 8 shows that relative to the original NEW BL run, the sharp tail run has smaller biases at both midday and midnight. The modulus of the mean bias is reduced from 0.86 m/s (original NEW BL) to 0.68 m/s (sharp tail). Fig. 9 shows that although the sharp tail run only improves 9 out of 24 points with respect to the OP BL run (mostly at midday), the bias is in fact reduced by 7%. There was a 4% reduction in the RMSE compared to the original NEW BL run, although there was no improvement to the RMSE compared to the OP BL run (Fig. 10).

5.3 1.5m relative humidity

There was a negative impact on the 1.5m R.H with the sharp tail run compared to both the NEW BL run (Fig. 8) and the OP BL run (Fig. 9). There was an increase in the positive R.H bias at both T+12 and T+24 (compare with the drying of the night-time moist bias seen in the new BL runs described in the last section). Overall only nine points showed an improvement with fifteen showing a degradation. The effect on the modulus of the mean bias was to increase it from 3.09 to 3.96 (a 28% degradation). (Fig. 10) shows the RMSE which is increased from 9.43 to 10.36 (a 10% degradation).

5.4 Visibility

There is a positive impact on the visibility with the sharp tail run compared to both the original NEW BL run (Fig. 8) and the OP BL run (Fig. 9). With increased relative humidities, the visibility is decreased so reducing the positive bias particularly at night-time. Overall fourteen points show an improvement with only nine showing a degradation. The effect on the modulus of the mean bias is to decrease it from 0.23 to 0.20 (a 14% improvement) while the RMSE is decreased from 0.47 to 0.46 (a 2% improvement).

5.5 1.5m Fog fraction

There is a negative impact on the 1.5m fog fraction with the sharp tail run compared to both the original NEW BL run (Fig. 8) and the OP BL run (Fig. 9). With increased relative humidities, the fog fraction is increased causing spurious fog to occur, particularly at T+24. Overall only six points show an improvement and sixteen show a degradation. The two points corresponding to the 15/10/97 case show an improvement with repect to the NEW BL run (Fig. 8) with the T+24 forecast actually improving on the OP BL run. This is discussed more in the next section. The effect on the modulus of the mean bias is to increase it from 0.027 to 0.050 (a degradation of 89%). The RMSE is degraded by 17%.

The effect of sharp tails on precipitation and cloud forecasts appears to be very small.

5.6 Computing resources

On average, the sharp tail NEW BL was found to take 60% more CPU time than the OP BL. This works out as an increase of 6.5% in total CPU.

5.7 Summary

Overall, the sharp tails improve the performance of the original NEW BL. The results from figures 8, 9 and 10 are summarised in Tables F,G and H at the end of the paper.

6 Case studies

6.1 Convective case: 12/05/97

A low pressure area was centred off the northwest coast of Scotland with south-westerly flow over the U.K. At midday, there was a large swathe of low cloud covering Ireland, Scotland and parts of northern England (Fig. 11). There was widespread organized convection over southern England with heavy thunderstorms. With the OP BL scheme, the model produced too much low cloud over southern Britain (Fig. 12), causing large errors in screen temperature (Fig. 16). With the sharp tailed NEW BL, much of the low cloud was removed from Southern Britain (see Fig. 12) allowing convective activity to occur (Fig. 13) giving a much improved forecast of precipitation (Figs. 14 and 15). The temperature errors were also much reduced (Fig. 16).

6.2 Stratocumulus case: 24/09/97

A high pressure area was centred over the North Sea, just off the coast of England. Much of southern England had a cloudy day with some sunny intervals. Fig. 17 shows a satellite image (visible) for 12z. With the OP BL scheme, the model produced too little low cloud over southern Britain and over the southern tip of Eire (Fig. 18). With the sharp tailed NEW BL scheme, cloud amounts were increased over some parts of southern England and decreased in other parts, for example over East Anglia and Lincolnshire (Fig. 18). This had mixed impacts on the 1.5m temprature errors (Fig. 19) with the large cold bias over Lincolnshire being reduced but other areas with a cold bias in southern parts of England and southern Eire being made worse.

6.3 Fog case: 15/01/97

There was a low pressure area centred in the mid-Atlantic with a warm front stretching all the way over to Southern Scotland and very slack flow over the U.K. The 00z run of the operational mesoscale model cleared widespread freezing fog that persisted in reality. Fig. 20 shows the negative bias in fog probability for the OP BL run in black. The sharp tailed NEW BL run cleared the fog even more quickly (Fig. 21) so increasing further the negative bias in the fog probability (Fig. 20). The sharp tail increased the fog probability at night-time thus reducing the negative bias at T+24. There was a negative impact on the temperature bias throughout the forecast with the warm bias being increased as a result of the removal of low cloud (Fig. 22). However the sharp tailed run has a smaller bias than the original NEW BL run.

6.4 Stratus case: 13/10/96

There was a low pressure area centred off of the west coast of Ireland with a cold front lying north-south over Ireland. The rest of the U.K was in the warm sector with south-easterly flow. The 00z run of the operational MES missed widespread stratus at 09z. Subjective assessment of low cloud amount concluded that the run with the NEW BL scheme with sharp tails was generally preferred to the OP BL run. However, this was as much due to removal of cloud over Western Ireland behind a cold front (Fig. 23) as to the increased production of stratus at 09z (Fig. 24) over parts of Wales and central and SW England.

7 Conclusions

The new boundary layer scheme is a more physically realistic scheme that includes processes such as entrainment that are not modelled in the current operational scheme. Testing of the original NEW BL scheme showed that its performance at night-time in stable boundary layer conditions was sufficiently poor that benefits seen during daytime were outweighed.

With the sharp tailed stability functions, the NEW BL results are much better. The modulus of the mean bias shows an improvement over the OP BL (and the original NEW BL) in 1.5m temperature, 10m wind speed and visibility. Compared to the original NEW BL, the RMSE is improved for all of these variables. The RMSE for 1.5m temperature and visibility is reduced compared to the OP BL. There is also a subjective improvement to precipitation and cloud.

There are drawbacks with the sharp tailed NEW BL scheme - there is an increase in the 1.5m R.H moist bias and an increase in the forecast fog fraction leading to spurious fog, particularly at night-time. The RMSE is increased for both of these quantities compared to the OP BL.

Further work is required to more fully understand the increase in the fog amount and perhaps there is scope for looking at the 1.5m fog fraction diagnostic to see if it can be more finely tuned.

To conclude, the recommendation of this report is for the sharp tailed version of the new boundary layer scheme to be accepted and for a parallel trial to go ahead. This is based on the fact that the scheme is more physically realistic than the current OP BL scheme and the results show on balance the NEW BL is an improvement over the OP BL.

8 Acknowledgement

Many thanks to Byron Chalcraft for performing subjective assessment of cloud cover.

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10 Summary tables

Variable	No. of cases					
	better	worse	no change	better	worse	no change
	T+12	T+12	T+12	T+24	T+24	T+24
1.5m Temperature	4	8	0	2	10	0
10m wind speed	8	4	0	0	12	0
1.5m R.H	7	5	0	8	4	0
visibility	4	8	0	1	11	0
fog	5	5	2	2	4	6

Table C: The number of points in Fig. 5 showing an improvement or degradation in the modulus of the mean bias.

Variable	MODULUS OF THE MEAN BIAS						
	OP BL	NEW BL	OP BL	NEW BL	OP BL	NEW BL	% CHANGE
	T+12	T+12	T+24	T+24	COMB	COMB	COMB
1.5m Temperature	0.72	0.63	0.63	0.87	0.67	0.75	12% WORSE
10m wind speed	0.67	0.52	0.79	1.19	0.73	0.86	18% WORSE
1.5m R.H	3.78	3.97	2.41	2.37	3.09	3.17	3 % WORSE
visibility	0.19	0.25	0.27	0.31	0.23	0.28	22% WORSE
fog	0.02	0.03	0.04	0.04	0.027	0.036	36% WORSE

Table D: The effect of the new BL scheme on the modulus of the mean bias averaged over the 12 case studies. The table gives the breakdown into T+12 and T+24 results and then the combined results.

Variable	RMSE						
	OP BL	NEW BL	OP BL	NEW BL	OP BL	NEW BL	% CHANGE
	T+12	T+12	T+24	T+24	COMB	COMB	COMB
1.5m Temperature	1.84	1.76	1.83	1.93	1.83	1.85	1% WORSE
10m wind speed	2.49	2.44	2.33	2.55	2.41	2.50	4% WORSE
1.5m R.H	10.71	11.12	8.15	8.81	9.43	9.97	6% WORSE
visibility	0.44	0.45	0.50	0.52	0.47	0.49	3% WORSE
fog	0.13	0.14	0.15	0.18	0.14	0.16	14% WORSE

Table E: The effect of the new BL scheme on the RMSE averaged over the 12 case studies. The table gives the breakdown into T+12 and T+24 results and then the combined results.

Variable	No. of cases					
	better	worse	no change	better	worse	no change
	T+12	T+12	T+12	T+24	T+24	T+24
1.5m Temperature	4	8	0	8	4	0
10m wind speed	8	4	0	1	11	0
1.5m R.H	5	7	0	4	8	0
visibility	5	6	1	9	3	0
fog	4	7	1	2	9	1

Table F: The number of points in Fig. 9 showing an improvement or degradation in the modulus of the mean bias.

Variable	MODULUS OF THE MEAN BIAS						
	OP BL	SHARP	OP BL	SHARP	OP BL	SHARP	% CHANGE
	T+12	T+12	T+24	T+24	COMB	COMB	COMB
1.5m Temperature	0.72	0.68	0.63	0.51	0.67	0.60	11% BETTER
10m wind speed	0.67	0.49	0.79	0.87	0.73	0.68	7% BETTER
1.5m R.H	3.78	4.84	2.41	3.07	3.09	3.96	28% WORSE
visibility	0.19	0.19	0.27	0.21	0.23	0.20	14% BETTER
fog	0.02	0.04	0.04	0.06	0.027	0.050	89% WORSE

Table G: The effect of the new BL scheme plus sharp tail on the modulus of the mean bias averaged over the 12 case studies. The table gives the breakdown into T+12 and T+24 results and then the combined results.

Variable	RMSE						
	OP BL	SHARP	OP BL	SHARP	OP BL	SHARP	% CHANGE
	T+12	T+12	T+24	T+24	COMB	COMB	COMB
1.5m Temperature	1.84	1.83	1.83	1.80	1.83	1.81	1% BETTER
10m wind speed	2.49	2.42	2.33	2.40	2.41	2.41	0%
1.5m R.H	10.71	11.82	8.15	8.89	9.43	10.36	10% WORSE
visibility	0.44	0.44	0.50	0.48	0.47	0.46	2% BETTER
fog	0.13	0.15	0.15	0.18	0.14	0.16	17% WORSE

Table H: The effect of the new BL scheme plus sharp tail on the RMSE averaged over the 12 case studies. The table gives the breakdown into T+12 and T+24 results and then the combined results.

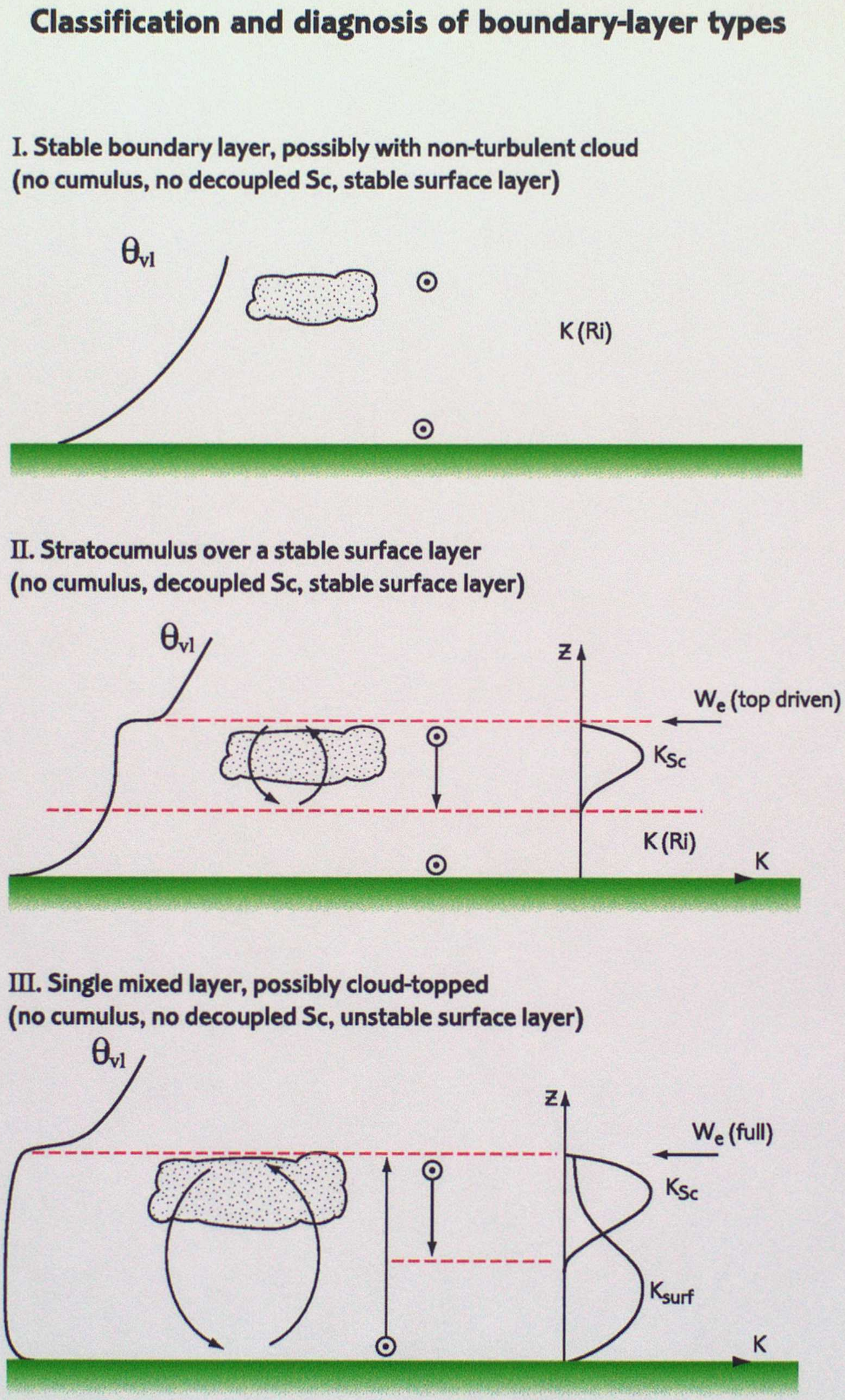

Figure 1: Schematic diagram of b.l types

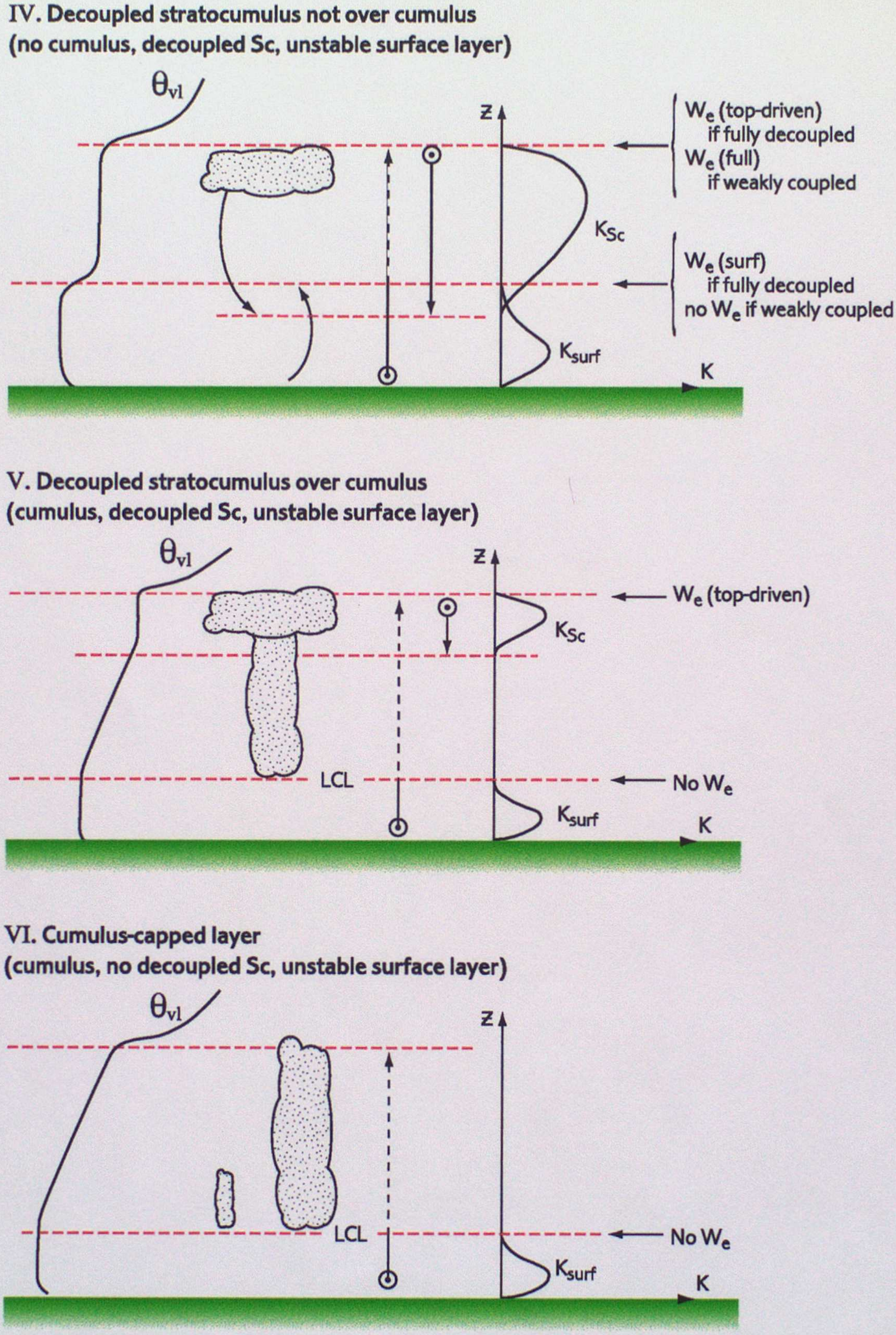

Figure 2: Schematic diagram of b.l types (continued)

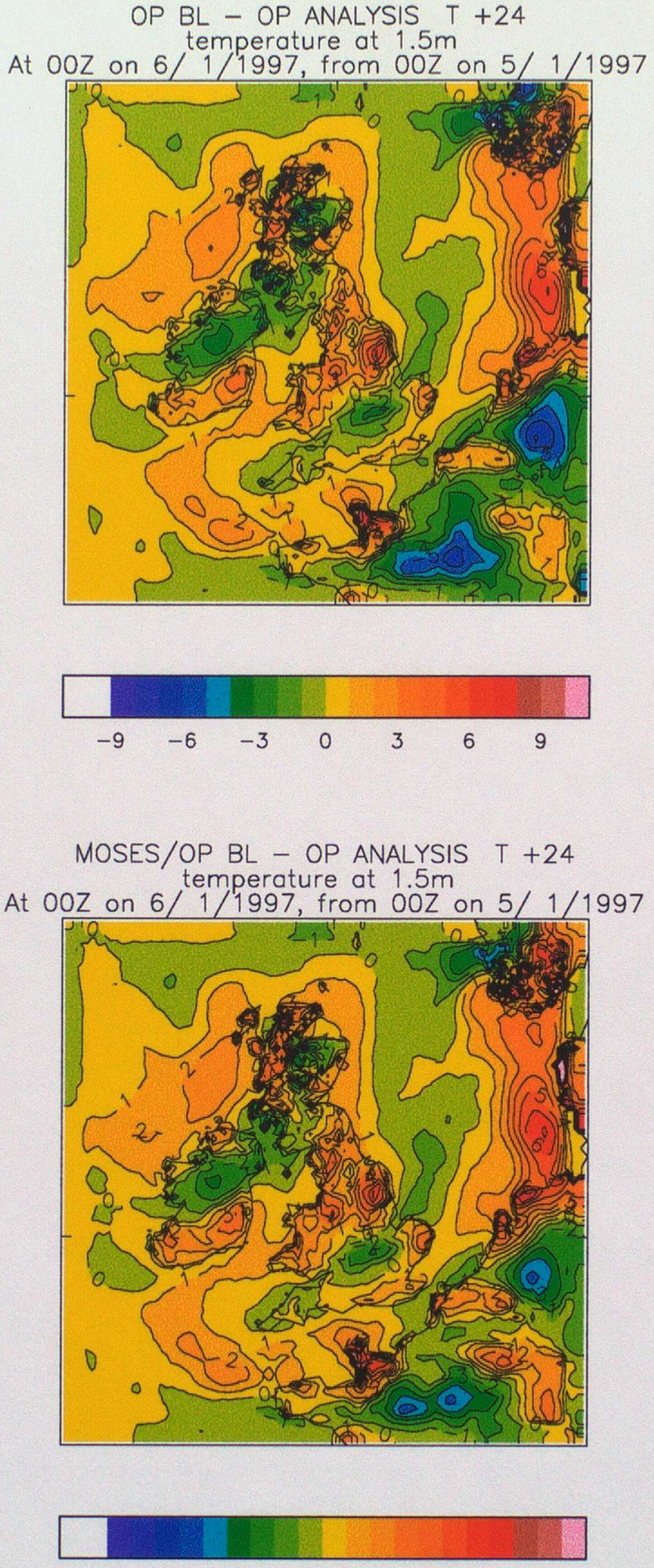

Figure 3: 1.5m temperature against analysis at 00z on 06/01/97

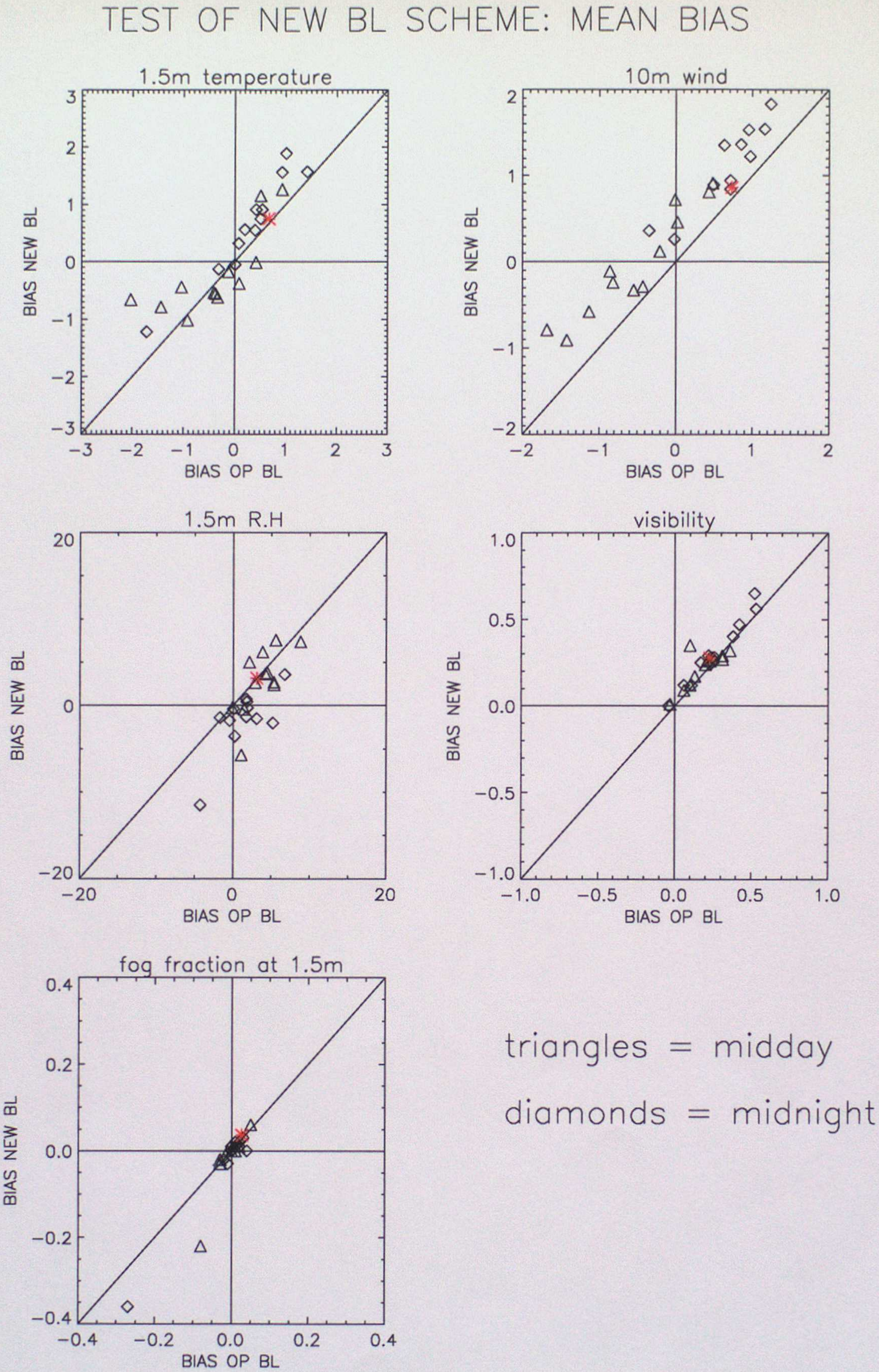

Figure 4: Effect of the new BL scheme on mean biases

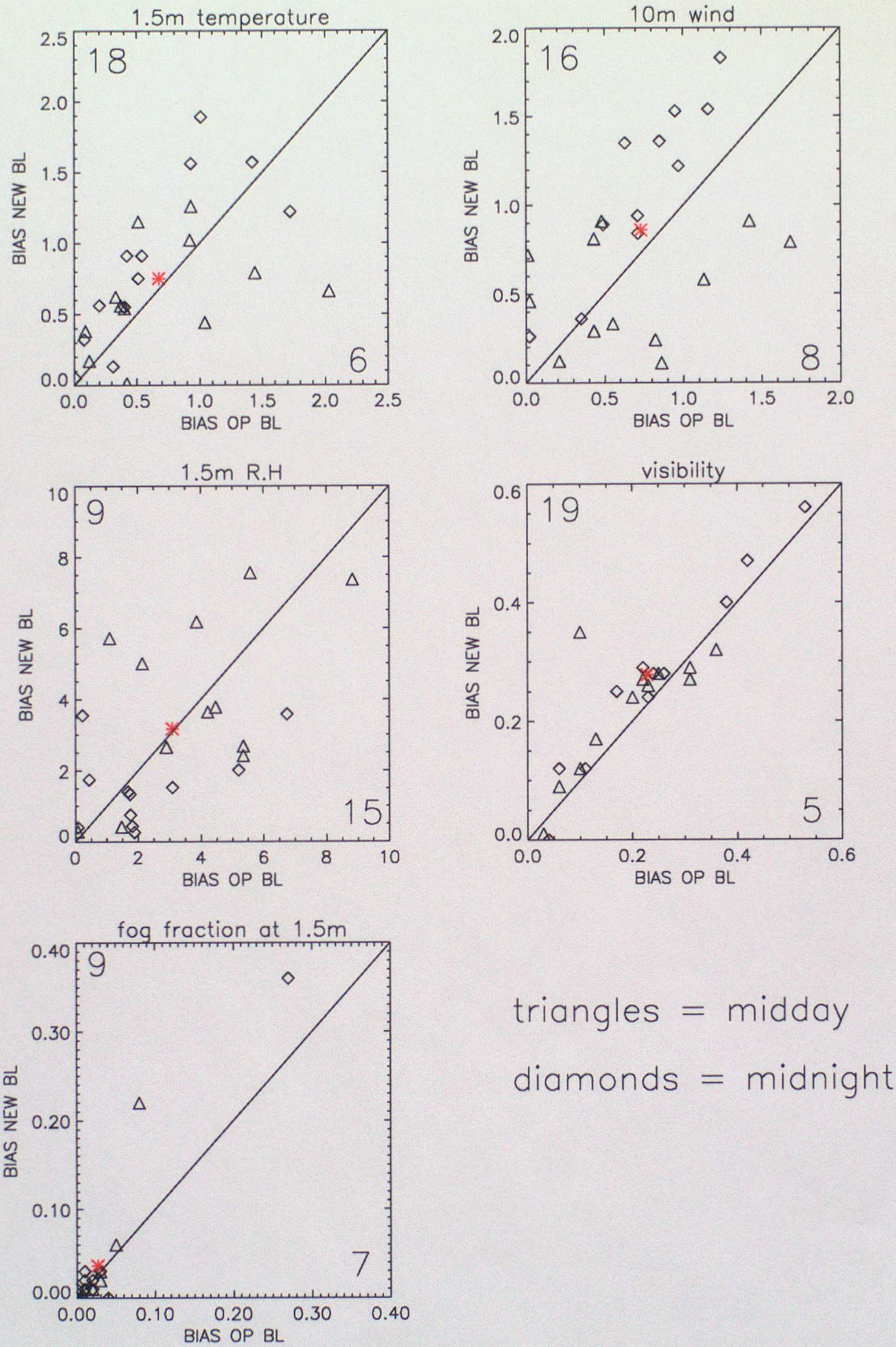

Figure 5: Effect of the new BL scheme on the modulus of the mean bias

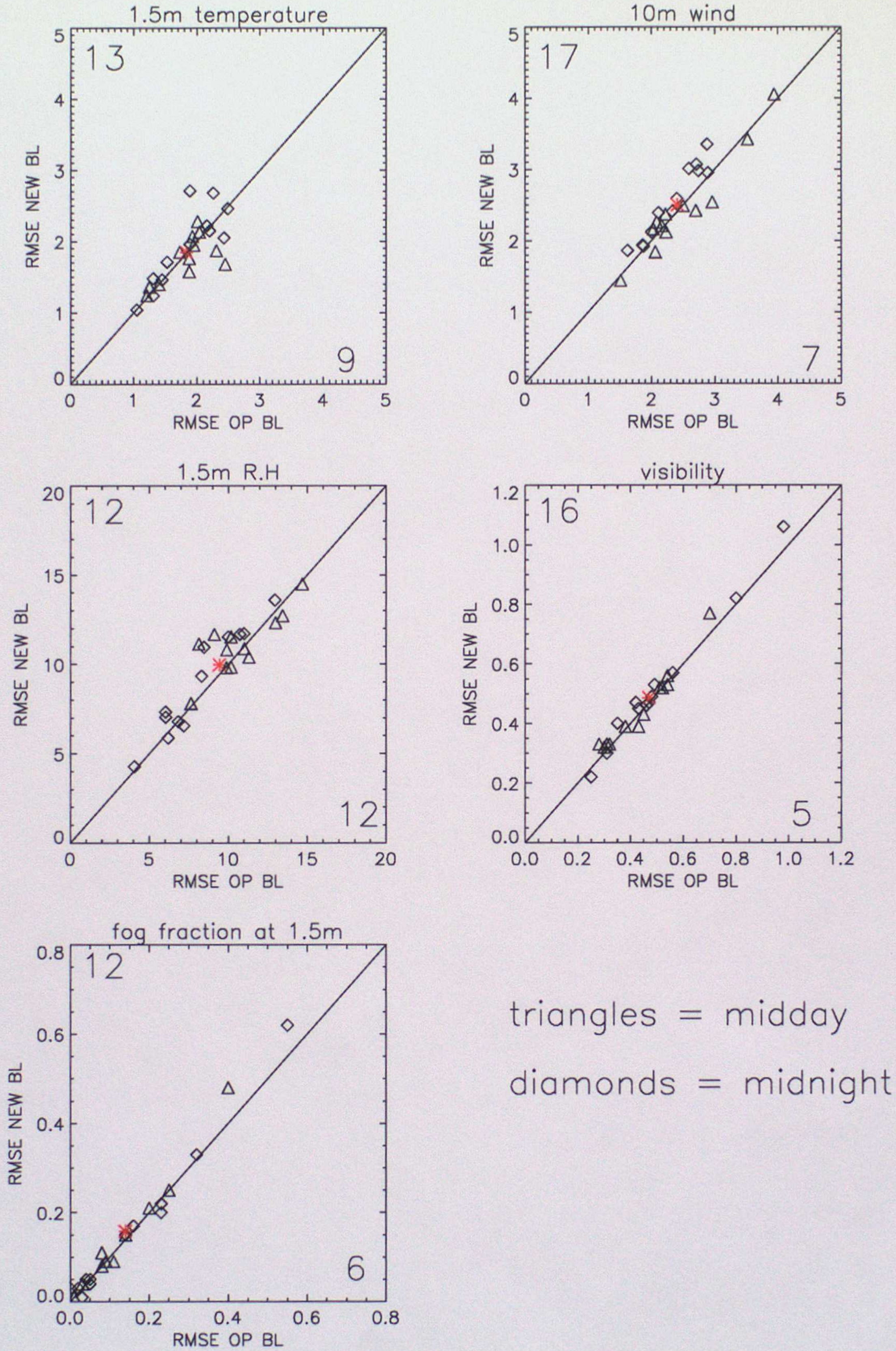

Figure 6: Effect of the new BL scheme on the RMSE

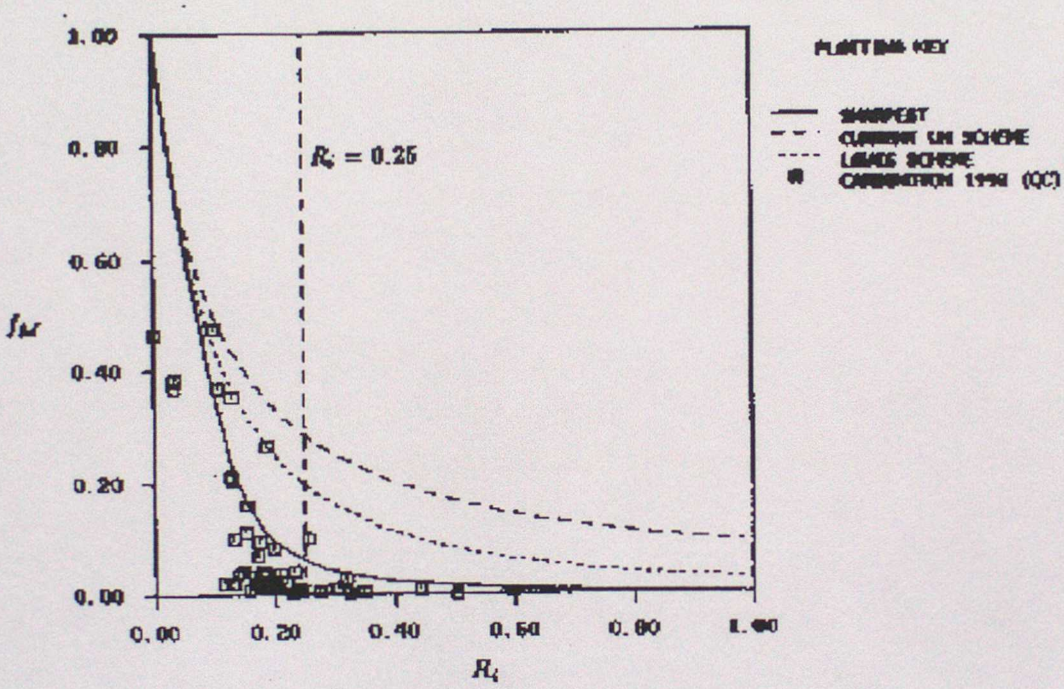

Figure 7: Stability dependence of different BL stability functions

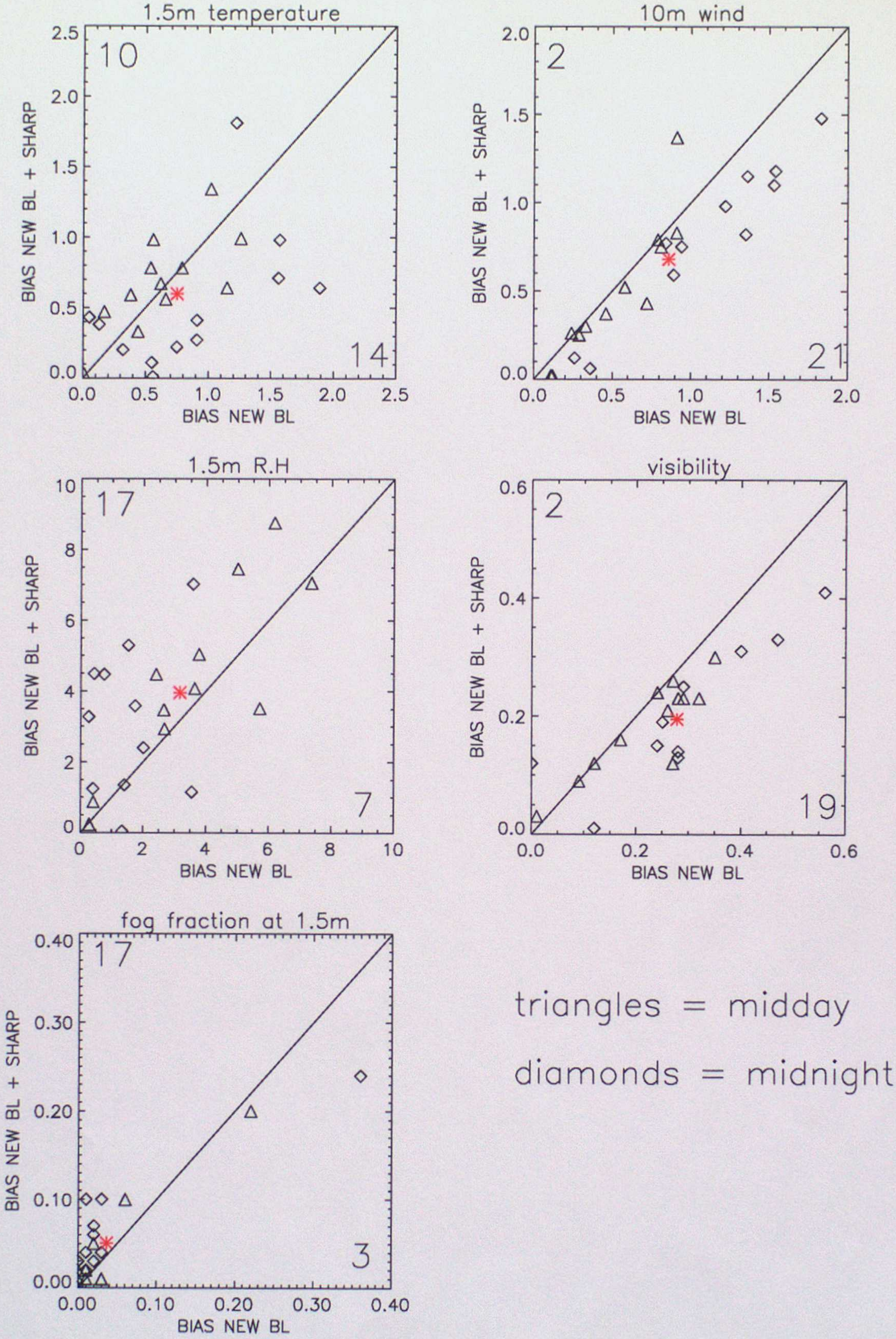

Figure 8: Effect of the sharp tail on the new scheme's modulus of the mean bias

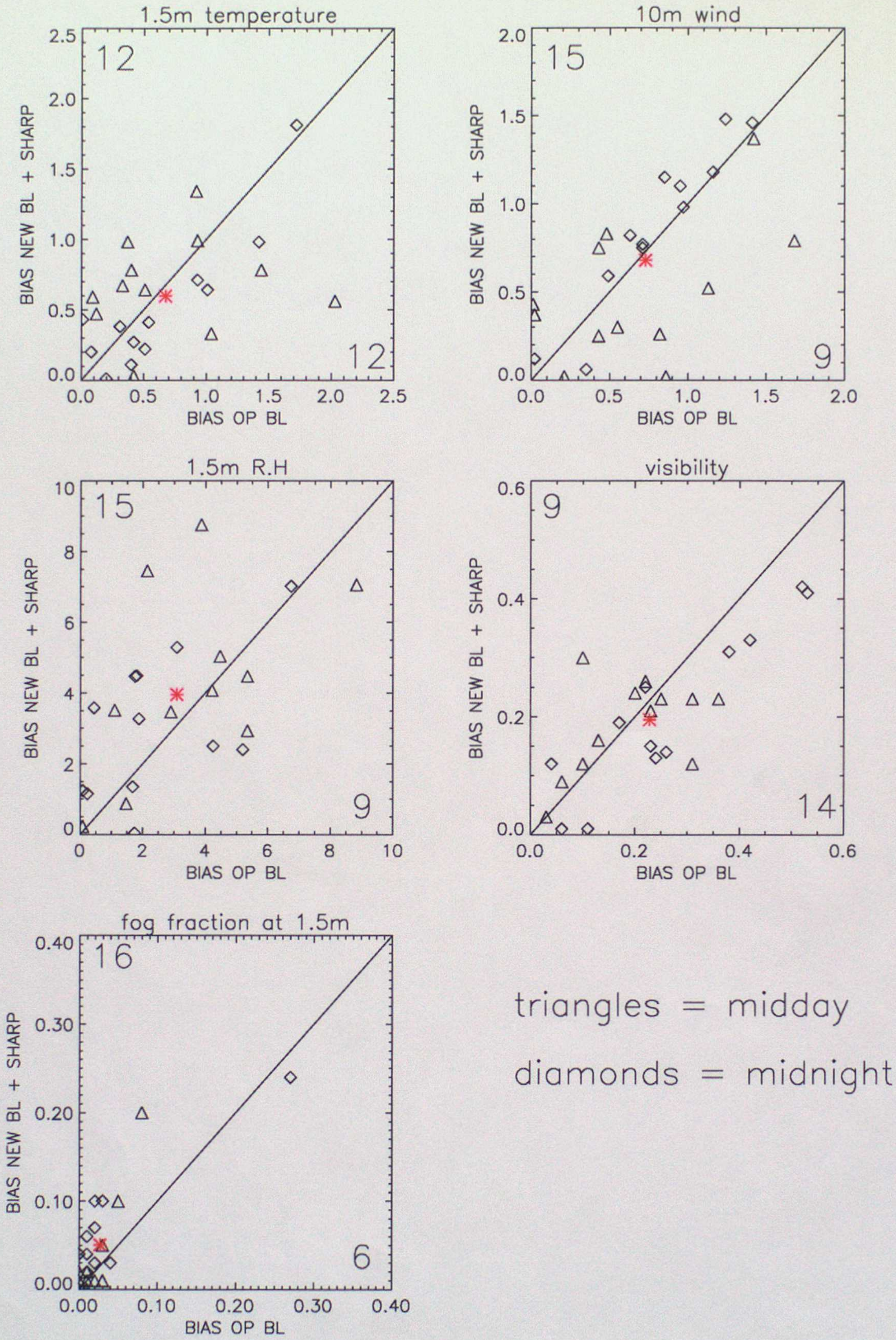

Figure 9: Effect of the sharp tail on the modulus of the mean bias

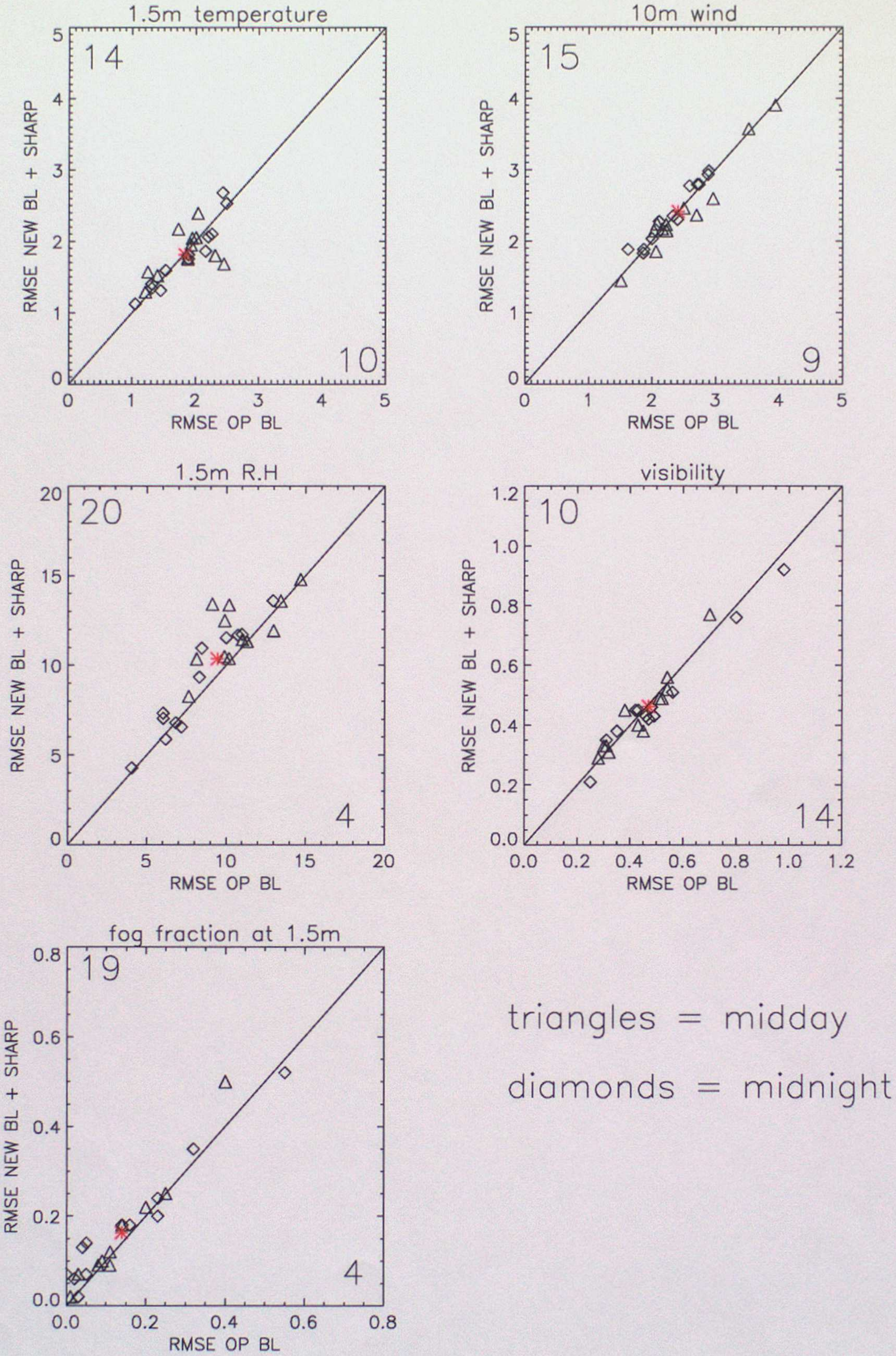

Figure 10: Effect of the sharp tail on RMSE

METEOSAT IR 12 MAY 1997 12:00 UTC

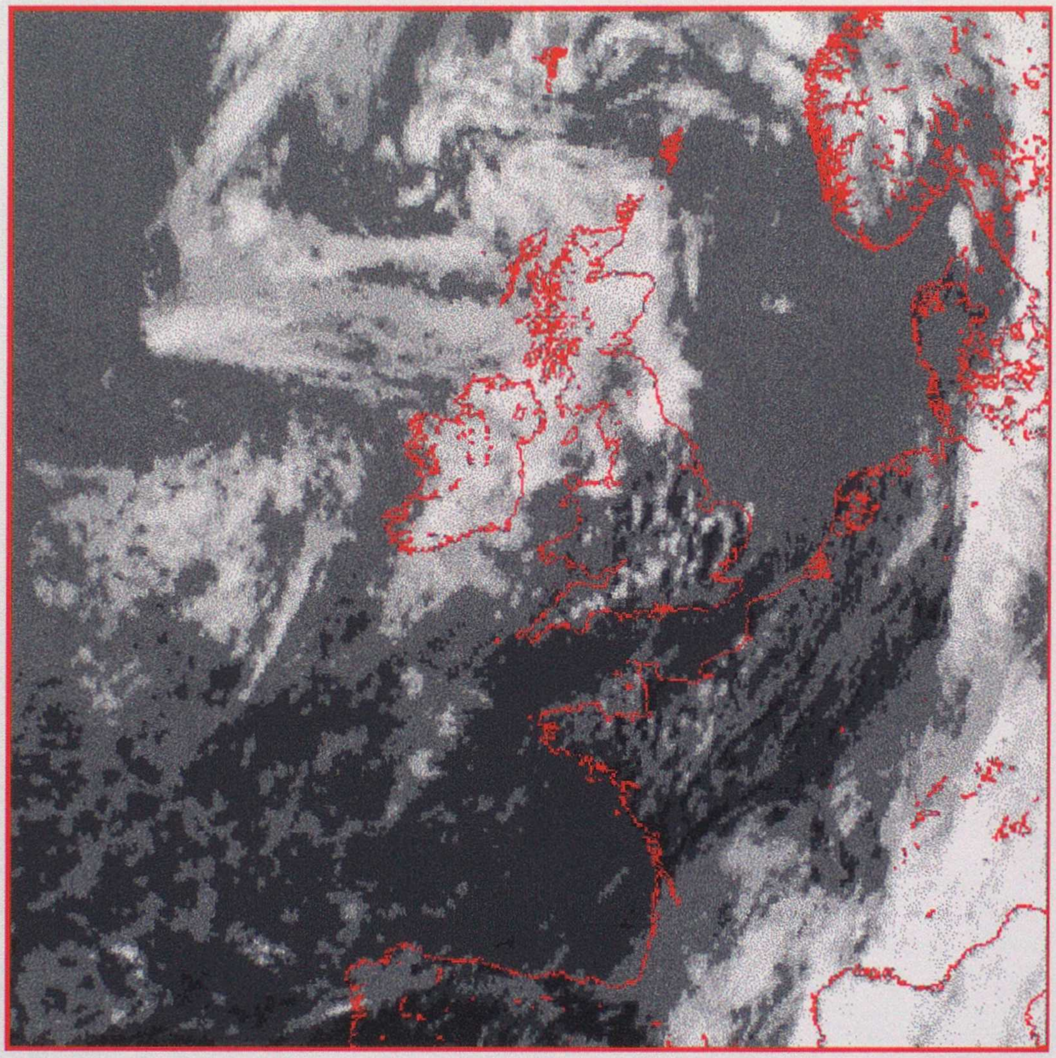

Figure 11: I.R satellite image for 12z on 12/05/97

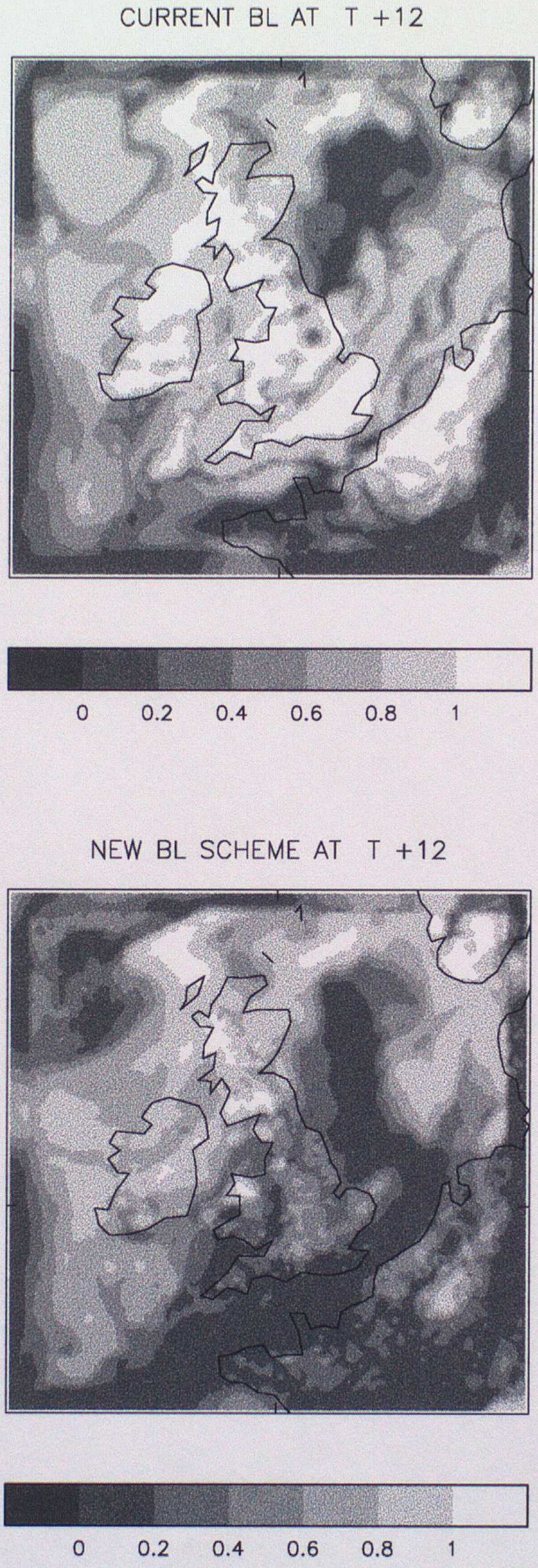

Figure 12: total layer cloud amount at 12z on 12/05/97

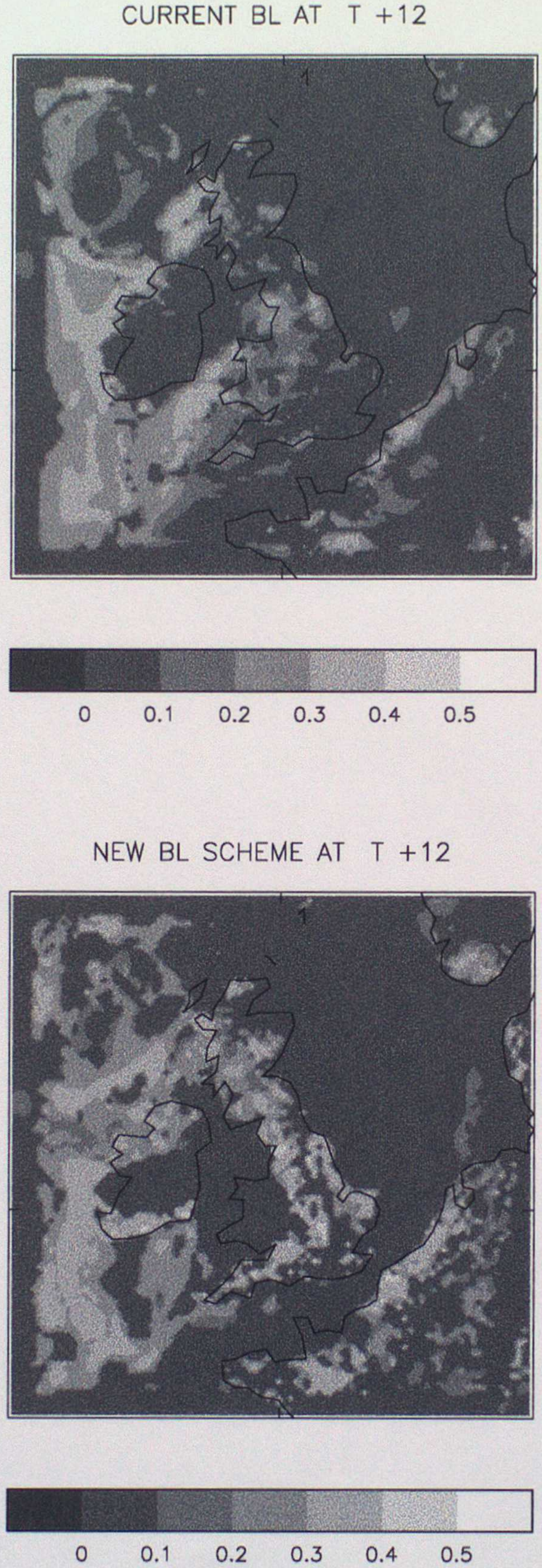

Figure 13: convective cloud amount at 12z on 12/05/97

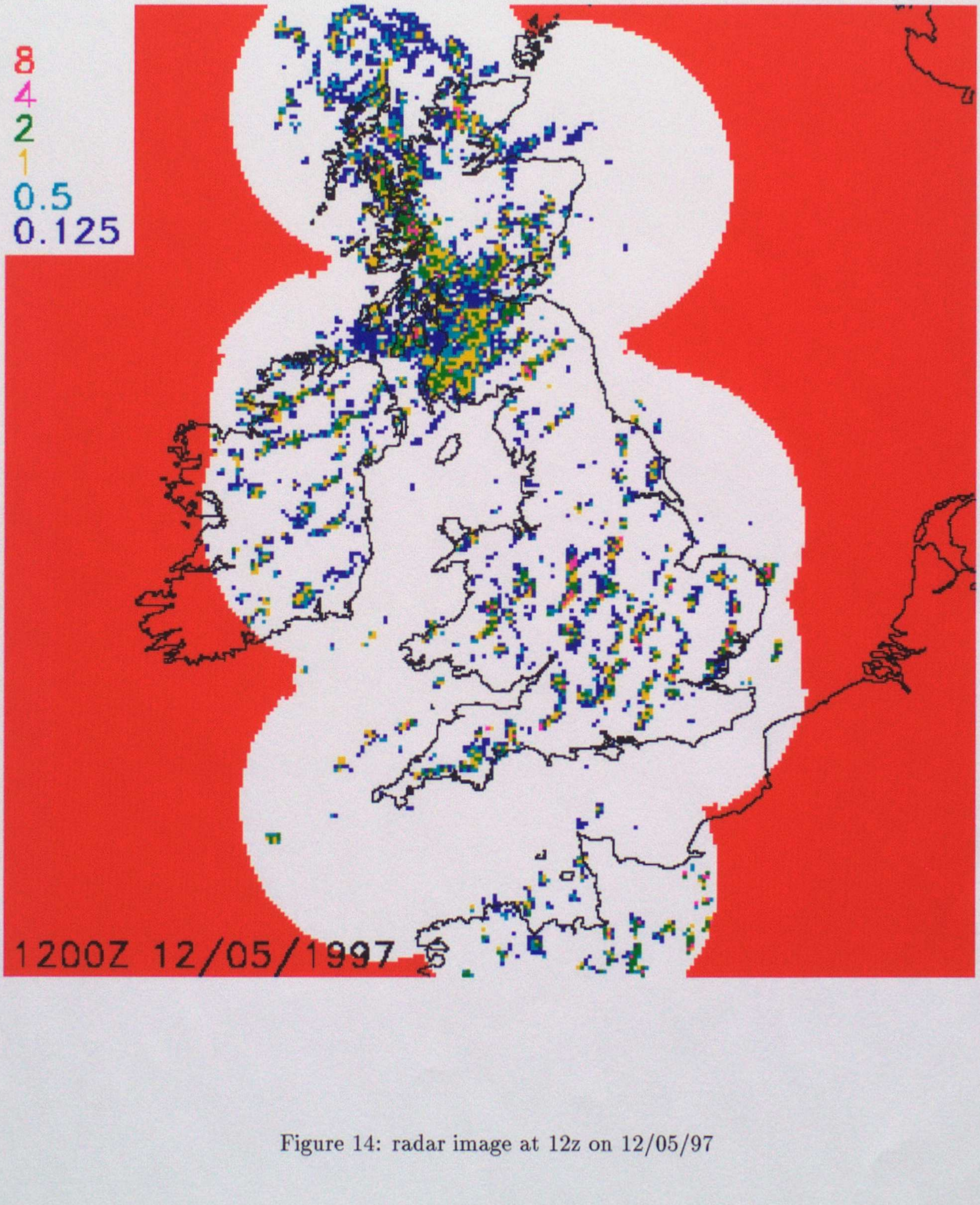

Figure 14: radar image at 12z on 12/05/97

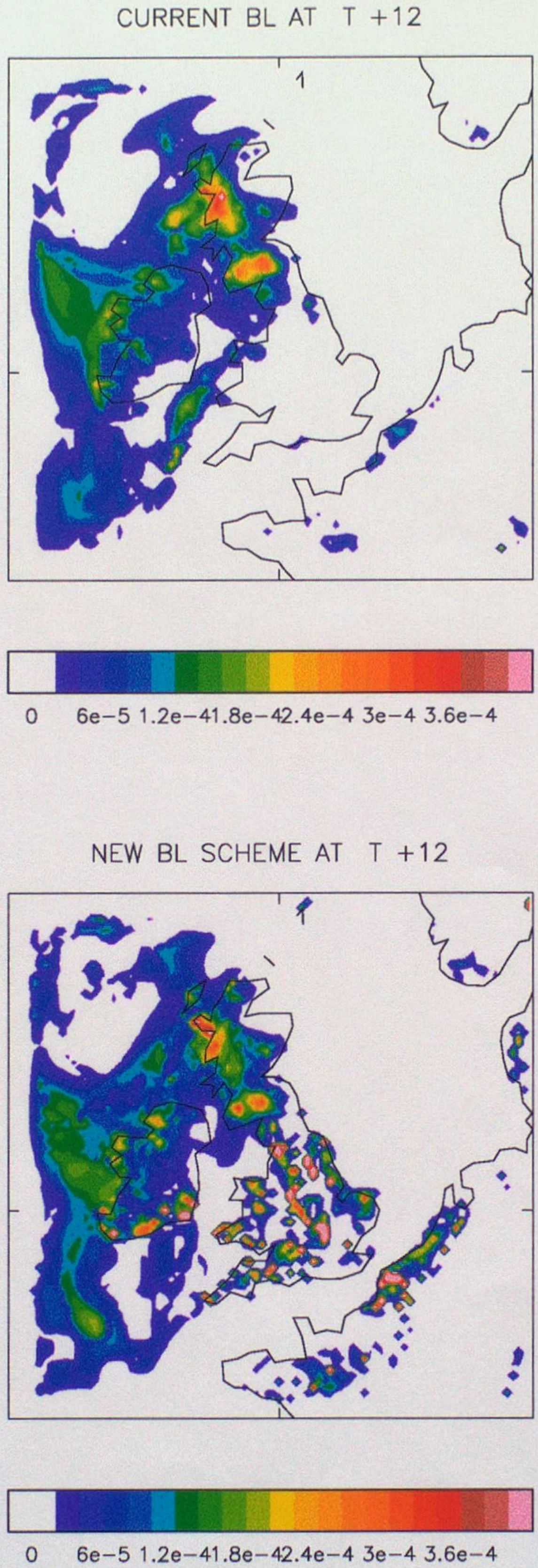

Figure 15: total precipitation rate at 12z on 12/05/97

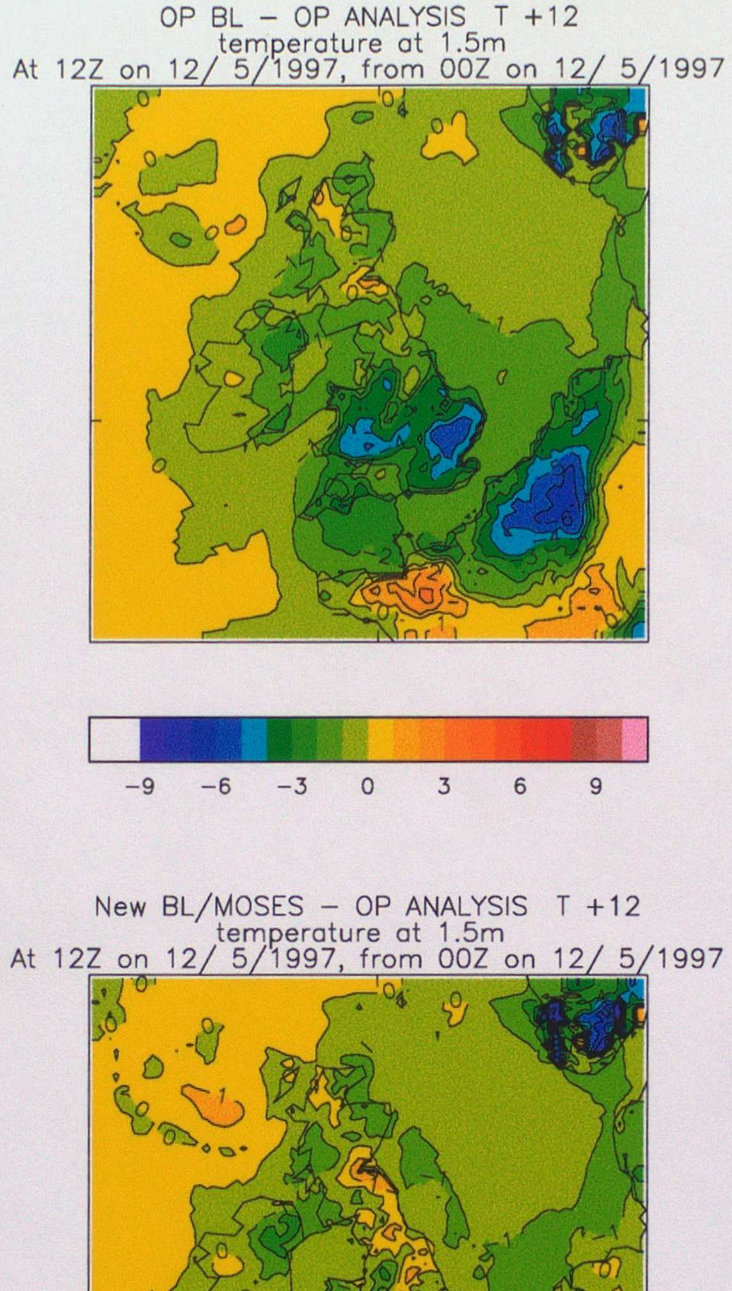

Figure 16: 1.5m temperature against analysis at 12z on 12/05/97

METEOSAT VIS 24 SEP 1997 12:00 UTC

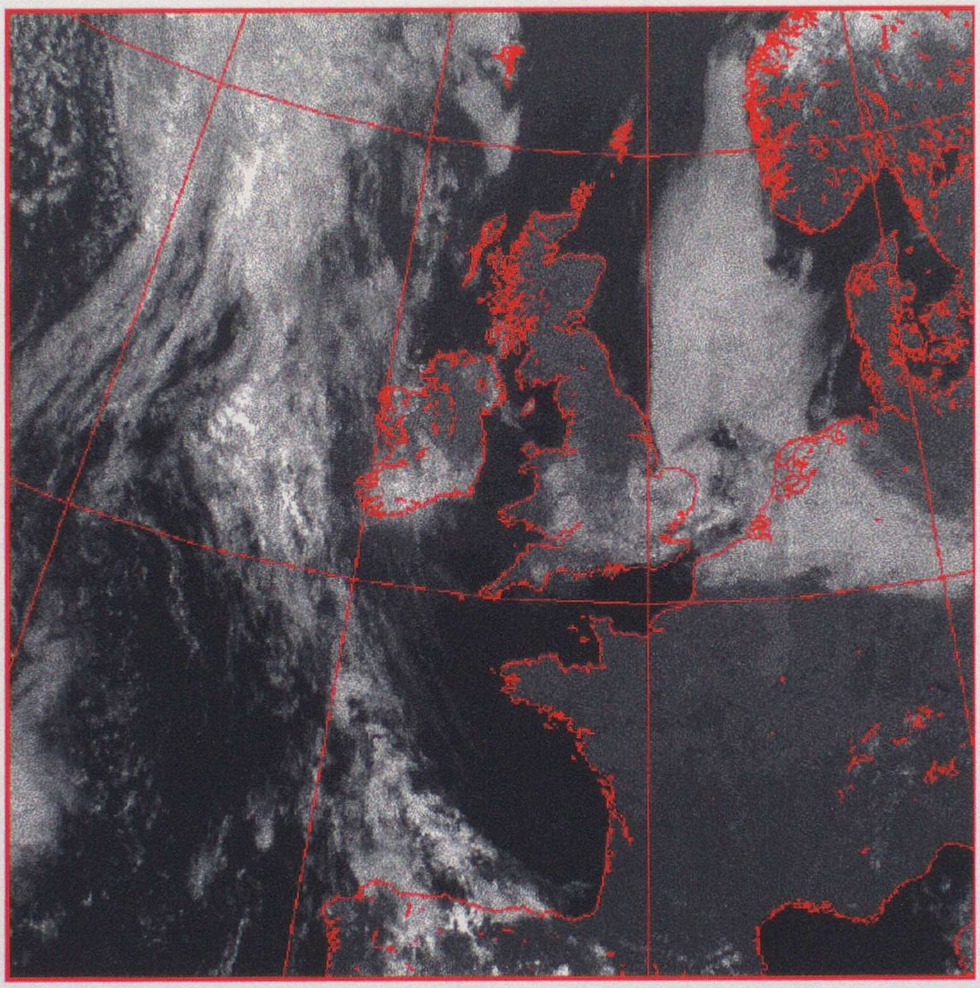

Figure 17: Visible satellite image for 12z on 24/09/97

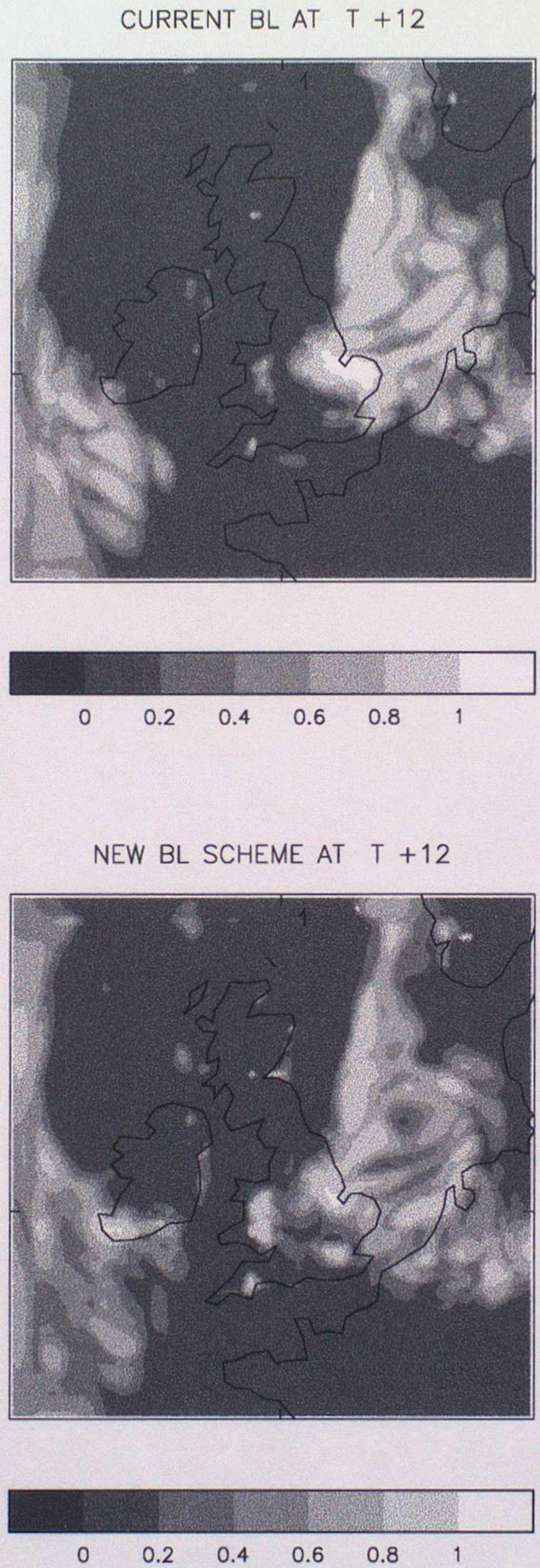

Figure 18: low cloud amount at 12z on 24/09/97

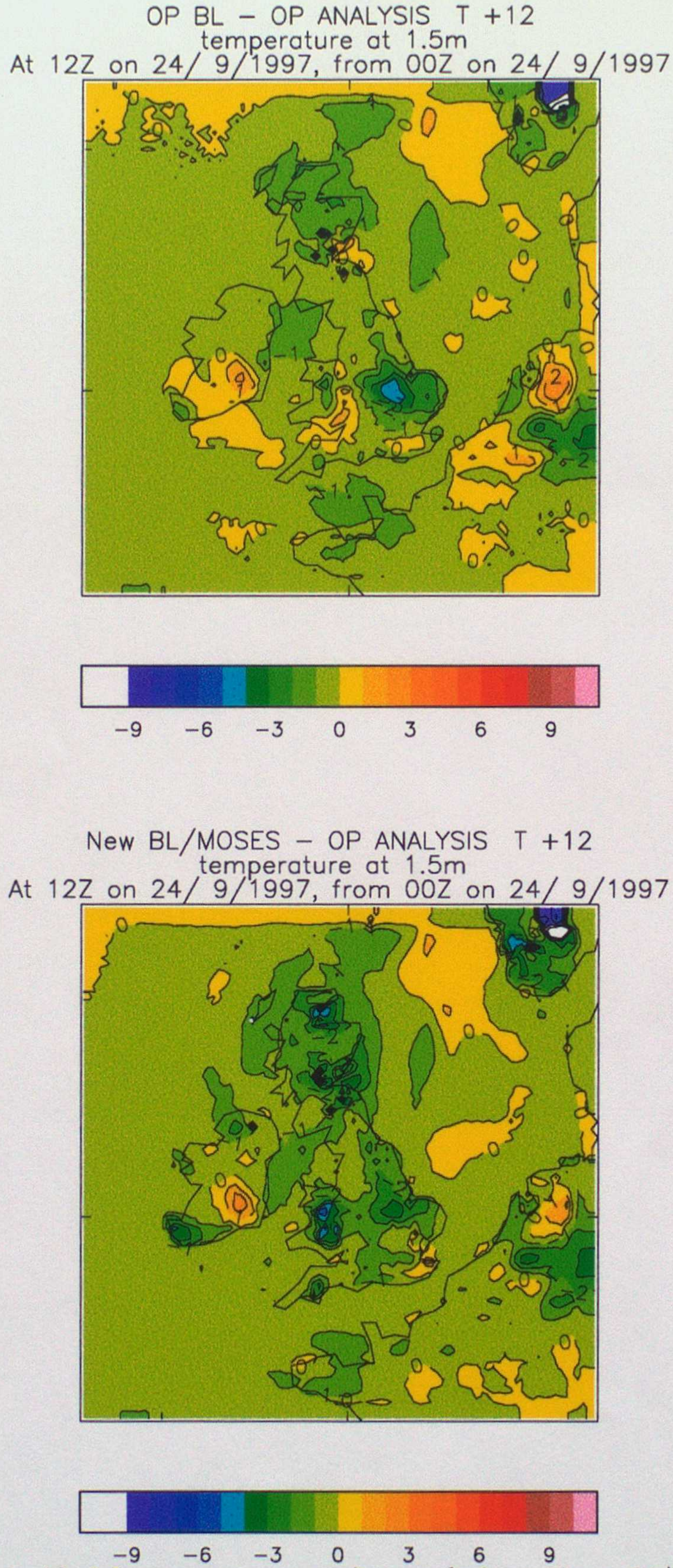

Figure 19: 1.5m temperature against analysis at 12z on 24/09/97

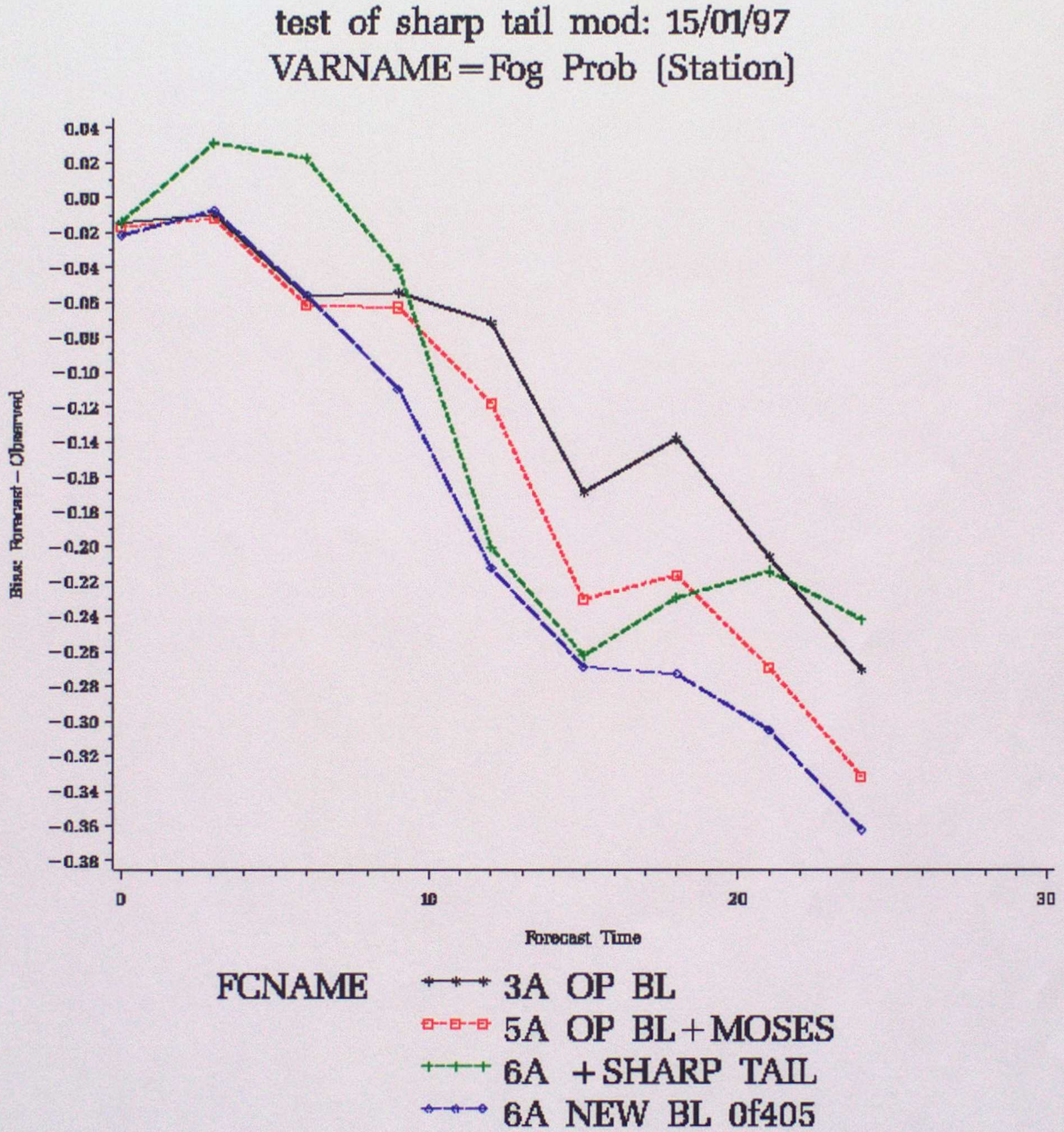

Figure 20: Bias in the fog probability as verified against stations on 15/01/97

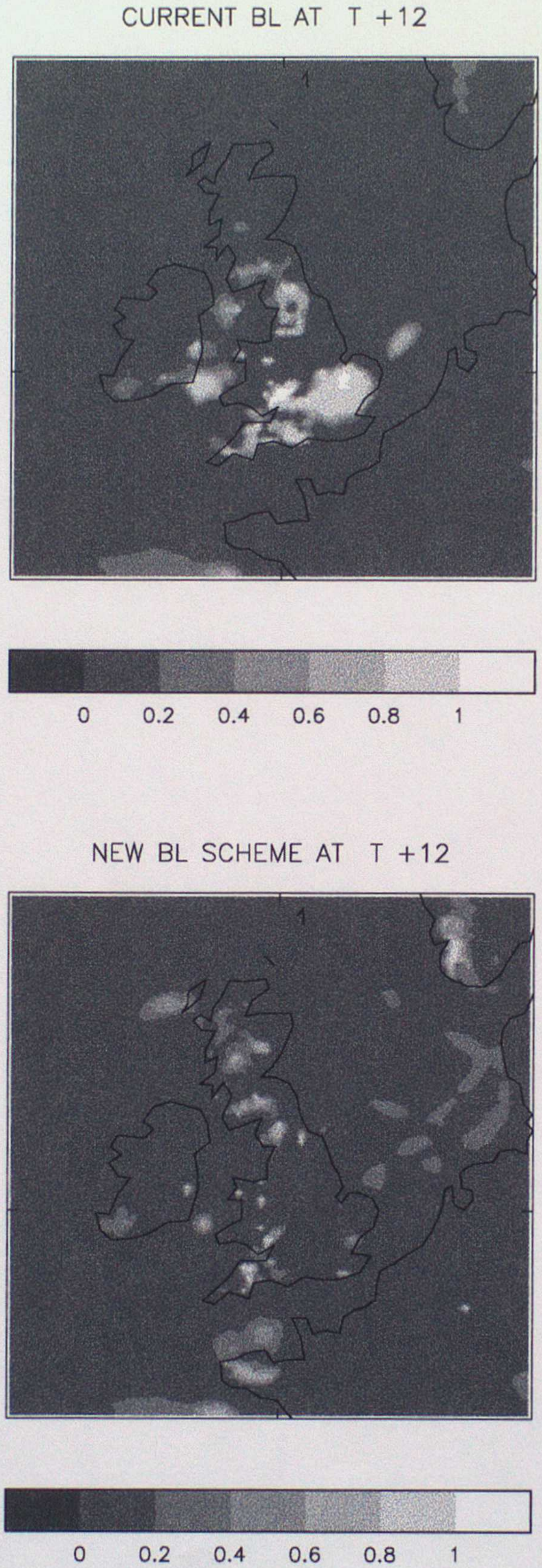

Figure 21: Fog fraction at 1.5m at 12z on 15/01/97

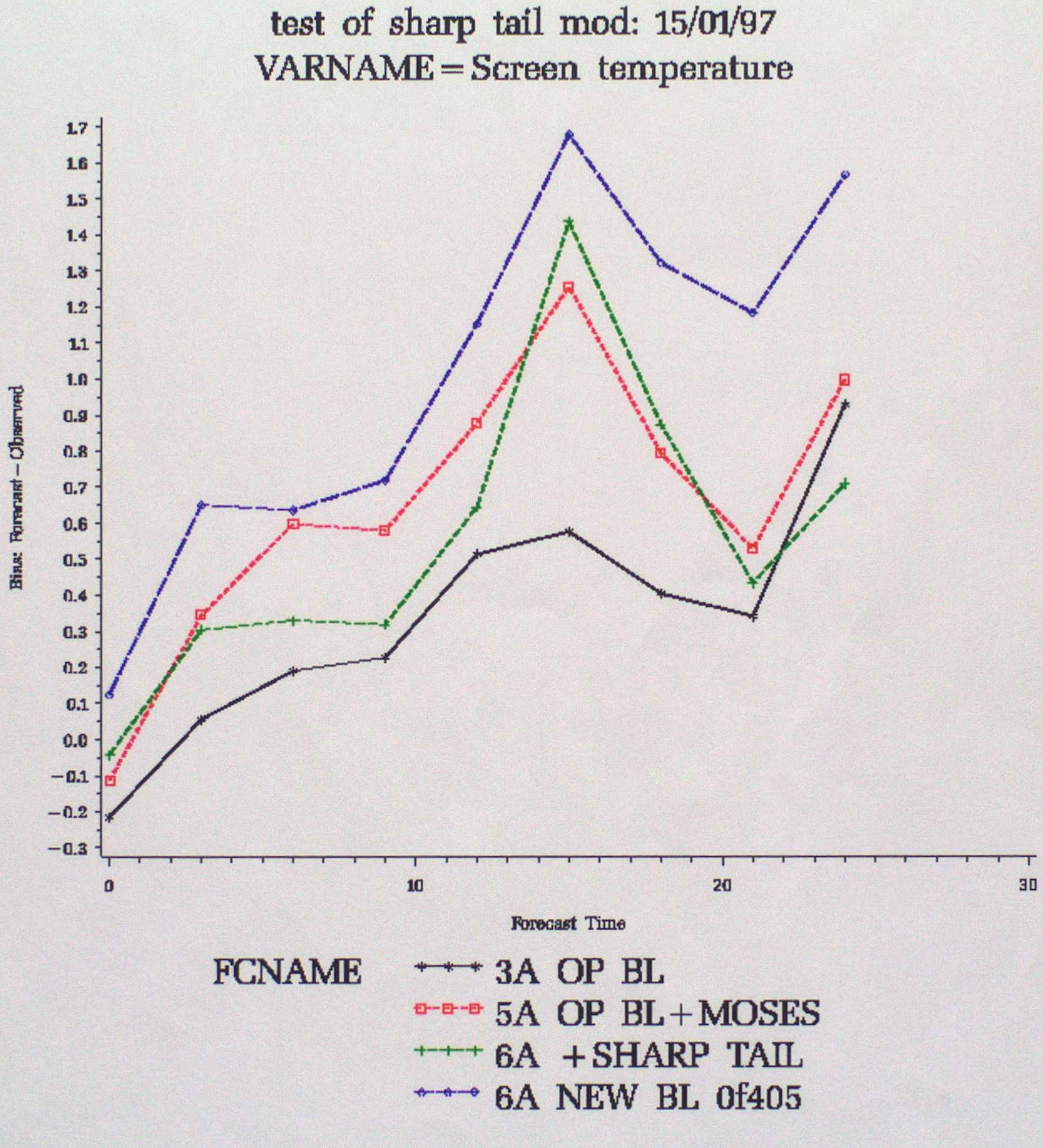

Figure 22: Mes verification of 1.5m temperature on 15/01/97

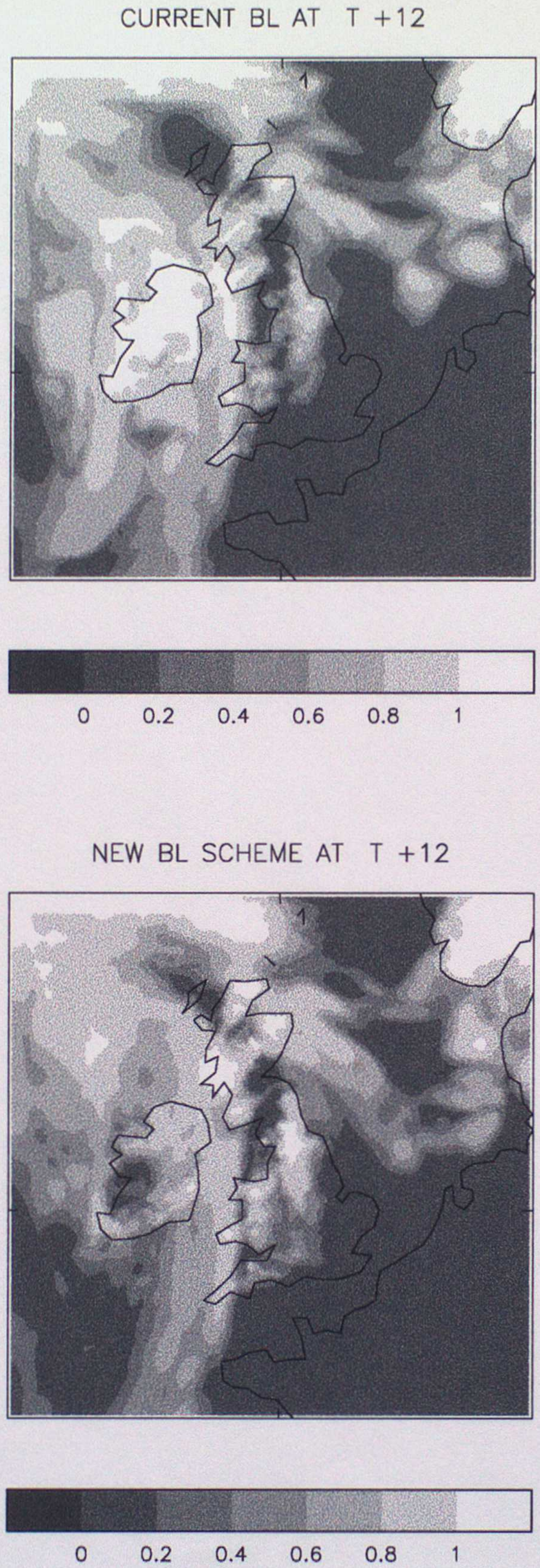

Figure 23: Low cloud amount at 12z on 13/10/96

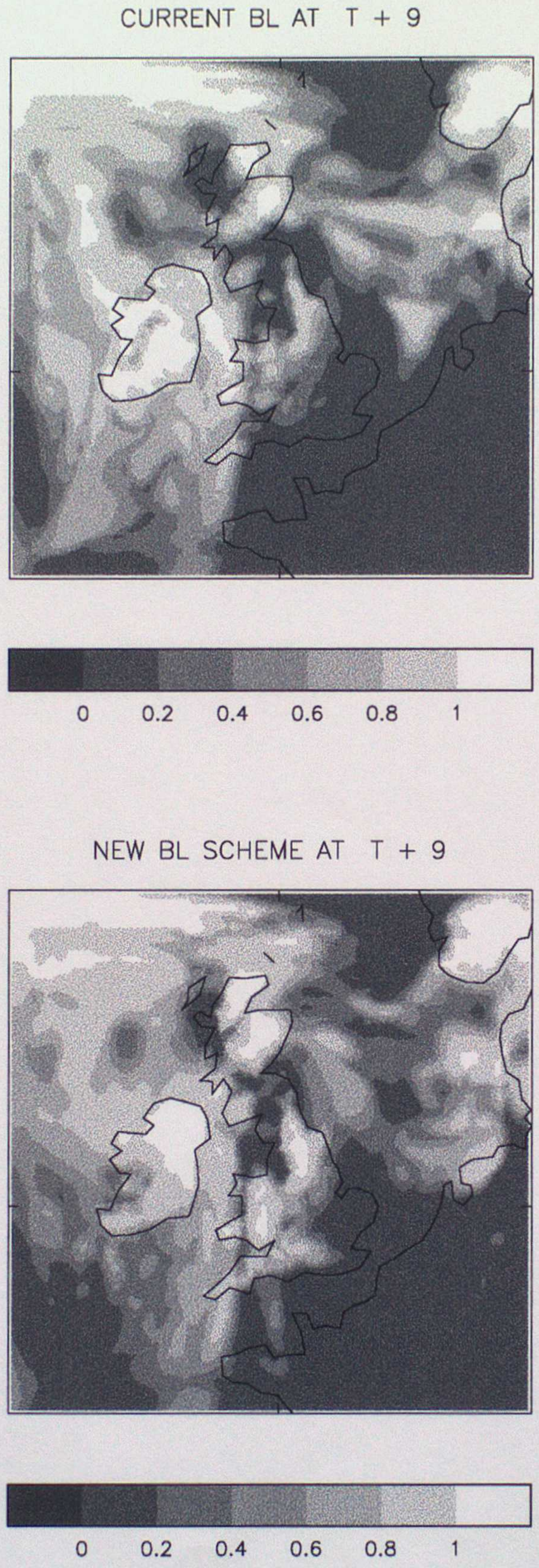

Figure 24: Low cloud amount at 09z on 13/10/96