SHORT-RANGE FORECASTING OF STRATOCUMULUS: INITIALIZATION v PREDICTION

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1. INTRODUCTION

This paper addresses the ability of the UK Met Office NWP models, used for short-range forecasts, to predict stratocumulus and the sensitivity of the forecasts to the initial conditions and physical parametrisations. In section 2 the performance of the models used prior to the unified model is discussed. In section 3 the sensitivity of simulations of the diurnal evolution of marine stratocumulus using a single column version of the nonhydrostatic mesoscale model to resolution and physical parametrisations is described. The results of a case study used to develop the mesoscale version of the unified model are presented in section 4 and in section 5 the results of an investigation of the recent operational performance of the limited area and mesoscale versions of the unified model are discussed. Conclusions are presented in section 6.

2. UK MET OFFICE NWP MODELS PRIOR TO THE UNIFIED MODEL

2.1 Global and limited area models

During the 1980s the UK Met Office operationally ran a global model and limited area model with 150km and 75km horizontal resolution respectively with 15 vertical levels, 4 of which were within the boundary layer (Gadd 1985). Humidity mixing ratio was the only prognostic water variable. The global model did not predict cloud and used a climatological radiation scheme. The limited area model had a diagnostic cloud scheme where cloud fraction was diagnosed from the predicted relative humidity. The only source of humidity data was from radio-sondes and this was included in the model using a continuous 'nudging' type data assimilation scheme, initially using univariate optimum interpolation (Atkins and Woodage 1985) and latterly the Analysis Correction Scheme (Lorenc, Bell and Macpherson 1991).

The model was generally deficient in stratocumulus in the UK area, partly due to dryness and partly due to insufficient vertical resolution. Investigations (Hammon 1988) showed that the prediction of low cloud was sensitive to the assumed location of cloud relative to the model levels. Attempts to bogus in increased relative humidity values were only partially successful (Hammon 1988). In an attempt to improve the prediction of low cloud , the low cloud amount was made dependent on the strength of the inversion and the relative humidity at the base of the inversion as in the scheme developed for the ECMWF model (Slingo 1987).

2.2 Nonhydrostatic Mesoscale Model

From the mid 1980s a nonhydrostatic mesoscale model (OMM) (Golding 1990, Tapp and White 1976) with 15km resolution and domain covering the British Isles was also run routinely. As part of its aim was to provide improved guidance on precipitation, cloud and fog this model had higher vertical resolution within the troposphere (initially 16 levels with 6 levels up to 1510m),a fully prognostic cloud scheme and a 1.5 order (level 2.5) turbulence scheme (Ballard et al 1991) ie including a prognostic equation for the turbulent kinetic energy E. Potential temperature, θ, humidity mixing ratio, q, cloud water/ice mixing ratio, q_l, and cloud fraction, c, were diagnosed from the advected variables of total water, $q_t = q + q_l$, and liquid/ice potential temperature, $\theta_l = \theta - Lq_l/c_p\pi$, following Sommeria and Deardorff(1977) and assuming a "top-hat" probability distribution of the subgridscale super/sub saturation with width, σ_s, determined from the variances of θ_l, q_t which are defined by the turbulence scheme.

The OMM had a three hourly intermittant analysis cycle in which a 3D cloud cover analysis (based on surface reports of cloud cover, base and type and precipitation rate ,a model first guess and forecaster intervention to allow the use of radar data and satellite imagery to provide information on cloud cover and top) and screen relative humidity observations were used to initialise the cloud water and humidity mixing ratio. The model's prediction of low cloud definitely benefitted from the use of cloud observations but forecasts suffered from the advection of erroneously dry air through the boundaries from the limited area model. Otherwise there was a tendency for too much low cloud but the distribution of cloud cover was sensitive to the level and form of the horizontal diffusion.

During 1989 to 1990, in an attempt to improve the prediction of low cloud, the model physics was upgraded and the vertical resolution was increased so that there were 32 levels with 17 levels up to 1550m (Ballard 1989). The initialisation was also changed to use the Interactive Mesoscale Initialisation (Wright and Golding 1990). This allowed automatic use of imagery data and attempted to make other fields consistent with the cloud. Unfortunately this upset the balance of the model and despite good analyses of stratocumulus a lot of the cloud was invariably lost within the first 3 hours of the forecast (Ballard 1991). The model would often reform cloud and hence improve its skill in the later stages of the forecast. Better results were obtained if only the cloud and humidity fields in the model first guess were replaced by those derived in the IMI.

3. SINGLE COLUMN VERSION OF MESOSCALE MODEL

In order to investigate the ability of the physical parametrisations used in the non-hydrostatic model to simulate stratocumulus, sensitivity studies were performed with a single column version which neglected the effects of advection and subsidence so that

$$\partial u/\partial t = f(v - v_g) - \partial(\overline{w'u'})/\partial z \tag{1}$$

$$\partial v/\partial t = -f(u - u_g) - \partial(\overline{w'v'})/\partial z \tag{2}$$

$$\partial \theta_l/\partial t = -\partial(\overline{w'\theta_l'})/\partial z + T_{rad} + T_{precip} \tag{3}$$

$$\partial q_t/\partial t = -\partial(\overline{w'q_t'})/\partial z + Q_{precip} \tag{4}$$

$$\partial E/\partial t = -\overline{w'\vec{v}_H'} \cdot \partial \vec{v}_H/\partial z + g(\overline{w'\theta_v'})/\theta_v - (1/\rho)\partial(\rho\overline{w'E})/\partial z - E/\tau_0 \tag{5}$$

where T_{rad} is the source term due to radiation and T_{precip} and Q_{precip} are source terms due to precipitation and $\theta_v = \theta(1 + 0.608q - q_l)$ is the virtual temperature and the turbulent fluxes are given by $\overline{w'\Phi'} = -K\partial\Phi/\partial z$ with $K = fn(l, E, N^2, S^2)$.

The basic radiation, turbulence, precipitation and subgridscale cloud scheme were as described in Ballard et al 1991 and section 2. above. An implicit time integration scheme was used with 120sec timestep as in the full 3D model.

The model was initialised with data taken from marine stratocumulus field experiments:- North Sea stratocumulus from JASIN 8th August 1978 (Slingo et al 1982) and shear dominated Californian coastal stratocumulus 17th August 1976 (Brost et al 1982). Since there was no other information, the geostrophic wind was taken to be the initial wind profile. Both cloud layers were about 400m thick. The model was run for 24 or 48 hour periods from 12LST to study the diurnal evolution of the cloud.

In the initial runs it was found that the single column model lost cloud at the start of the forecast. This problem was removed by a correction to the vertical mixing coefficient for θ_l and a change to the implicit weighting from α=1 to $\alpha = 2$. The diffusion equation can suffer from a non-catastrophic instability manifested as an oscillation in space and time of the diffusion coefficients K. This is reduced by the increased weighting (Kalnay and Kanamitsu 1988) as used in the unified model scheme (Smith 1993). When implemented in the 3D model these changes improved the retention of cloud in some cases. In both the 1D and 3D models it appears that cloud loss is related to the generation of high turbulent kinetic energy by unbalanced initial conditions. It was also necessary to limit σ_s to prevent unrealistic partitions of q_t into q and q_l in situations with high E.

Initial runs with the JASIN data used 32 levels to 12km with level spacing designed to give good resolution through the cloud layer, especially at cloud top. A bottom level of 10m was used with a spacing of 100m to cloud base at 300m, then a spacing of 50m until 650m reducing to 25m until cloud top at 850m with the spacing then increasing again to the top of the model. The precipitation scheme was switched off and the original 2 level long and short-wave radiation schemes were used which calculated the energy budget at the surface and cloud top only (Ballard et al 1991). In fact the sea surface temperature is held fixed so the only level at which radiative heating/cooling is applied is cloud top. This is a gross simplification of the radiation budget within a cloud where there should be cooling from cloud top and heating of cloud base so the short wave heating rate is limited to the value of the long wave cooling. This means that there is cooling at the cloud top level at night reducing to zero net radiation during the day. The model maintained the cloud throughout the 24 hour period and the top gradually rose and the base lowered with time, see figure 1a, as there was no subsidence to counteract the effect of the moisture flux from the surface and the cloud top cooling. As can be seen from figure 1b, there was greater turbulent mixing at night due to the unstable stratification resulting from cloud top cooling. During the day E is only significant within the cloud layer whereas at night there were periods when there were significant values throughout the boundary layer indicating greater coupling with the surface. From figure 1b it is also evident that there is a 2 timestep ($2\delta t$) oscillation in E.

The model was rerun with the radiation scheme switched off and from figures 1c and 1d it can be seen that the tubulent mixing was greatly reduced and remained mainly confined to the cloud layer. The top did not rise as much but the base gradually lowered. The $2\delta t$ oscillation in E is greatly reduced.

In order to investigate the impact of vertical resolution the model was rerun using the 32 levels of the 3D model which have fine near surface resolution, degrading with height so that the spacing was 100m at cloud base and 200m at cloud top. With the radiation scheme included and the precipitation scheme excluded the cloud base gradually lowered until it reached the surface and there was no rise in cloud top, see figure 2a: ie the model did not reproduce the results obtained when there was better resolution of the cloud layer but poorer resolution of the subcloud layer. Again E increased at night in the presence of cloud top cooling and the $2\delta t$ oscillations were still present. The model was rerun including the precipitation scheme and from figures 2c and 2d it can be seen that the model produces the expected diurnal evolution with cloud base lowering at night and rising during the day as the cloud layer couples and decouples from the surface. Short periods with cloud at lower levels during the day are indicative of the formation of cumulus below the main cloud deck. The inclusion of the effects of precipitation had a similar impact on the runs with the initial vertical levels. The $2\delta t$ oscillations in E

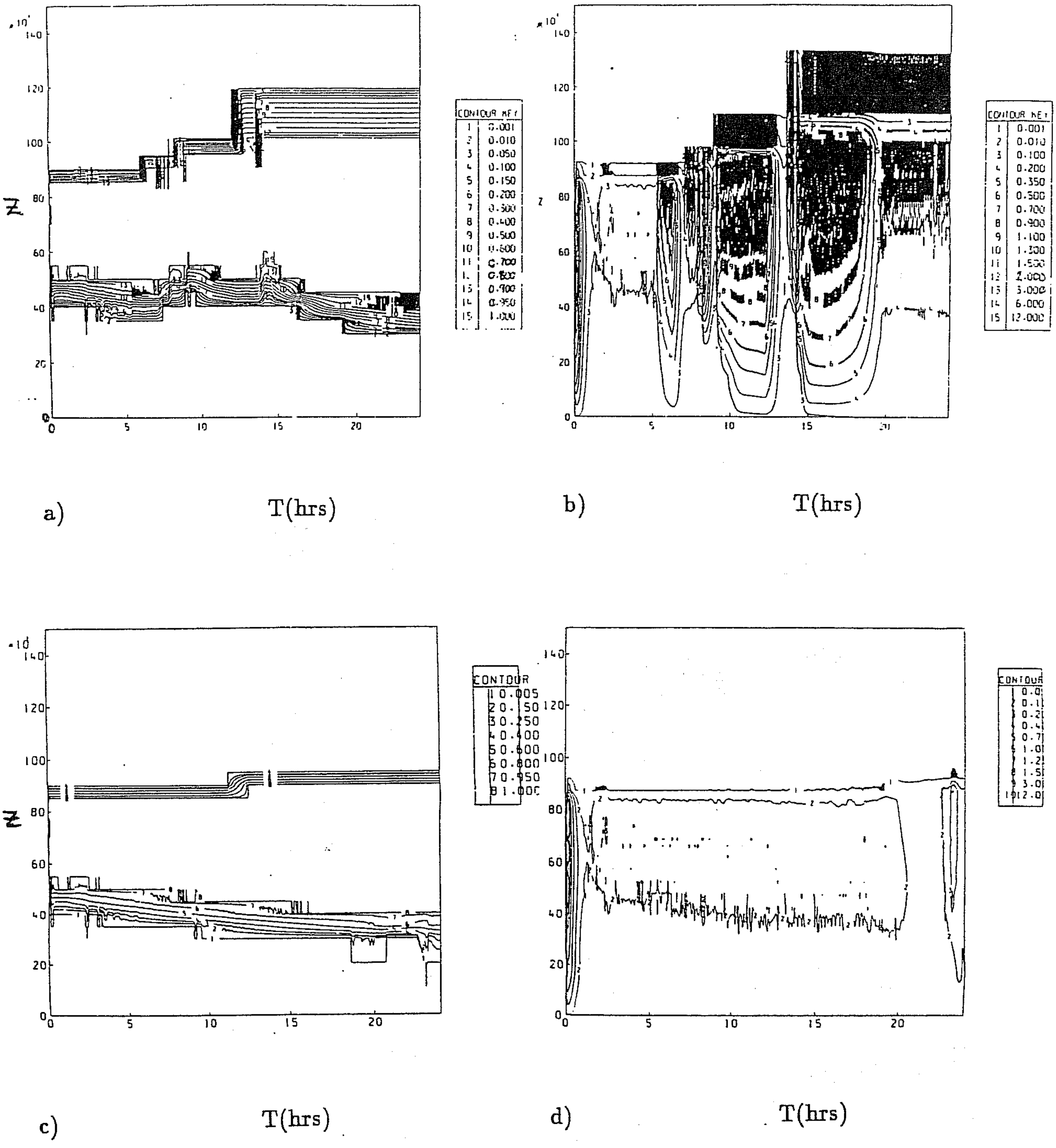


Fig.1 Single column 24 hour simulation of JASIN marine stratocumulus from 12LST 8th August 1978 with 32 cloud resolving levels, no precipitation scheme and δt=120sec. Vertical scale is height in m x 10^1 from 0 to 1500m

a) Cloud amount (decimal fraction) with cloud top radiation budget included.

b) as a) but turbulent kinetic energy (m^2s-2).

c) as a) but no radiation scheme included.

d) as b) but no radiation scheme included.

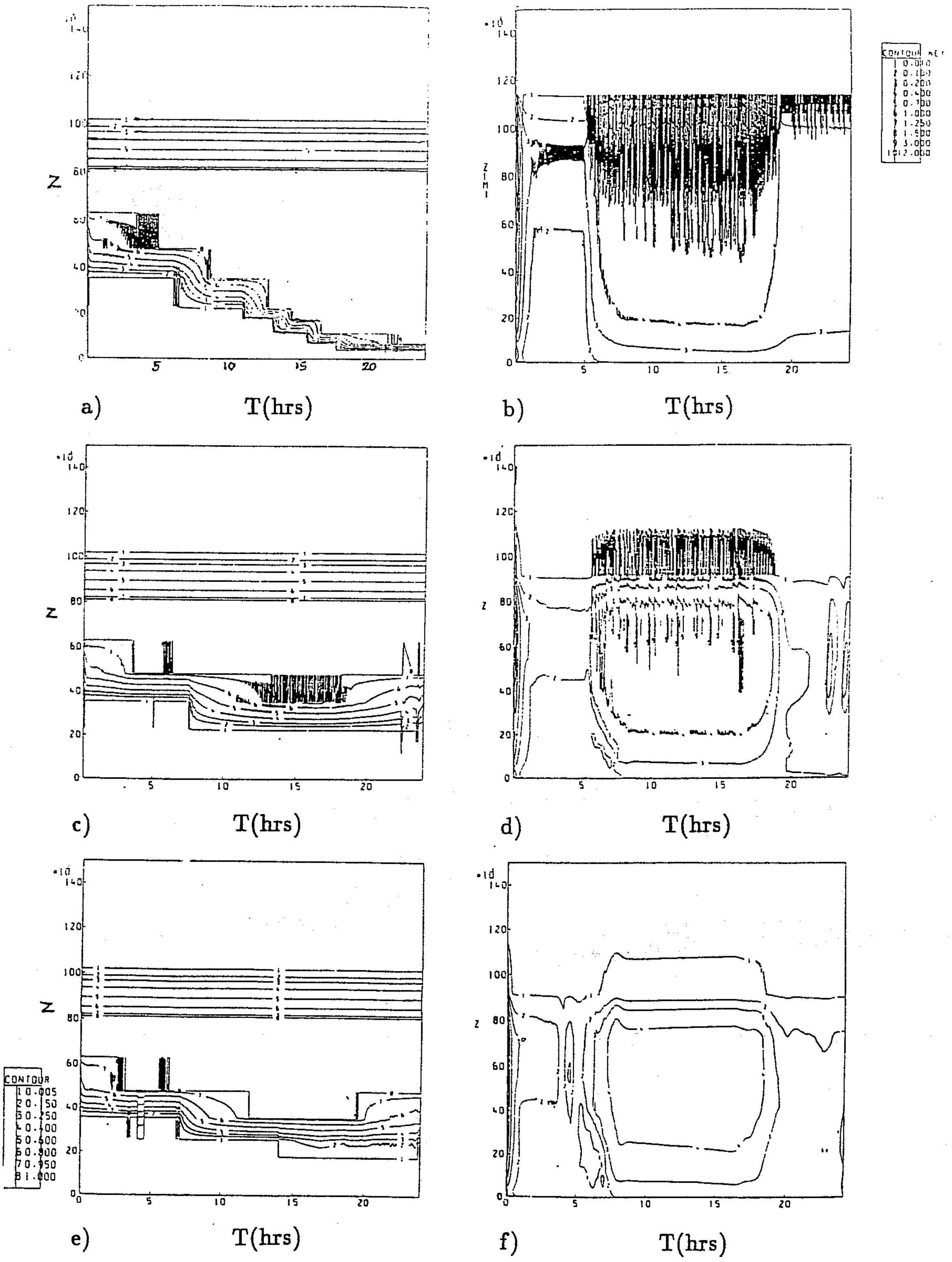


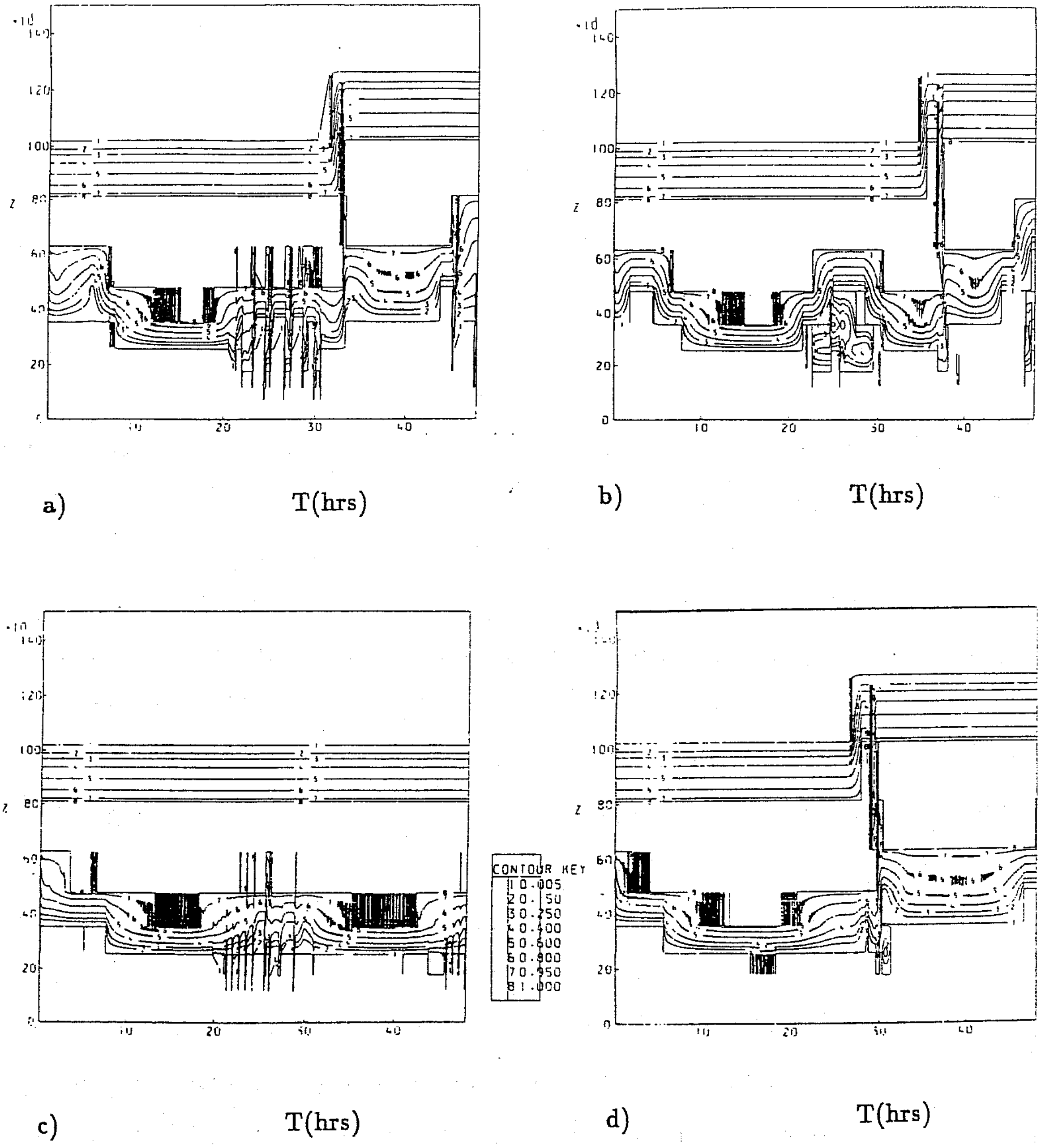
Fig.2 Single column 24 hour simulation of JASIN marine stratocumulus from 12LST 8th August 1978 with 32 operational 3D model levels and cloud top radiation budget. Vertical scale as fig.1
a) Cloud amount (decimal fraction) with no precipitation scheme, $\delta t=120$sec.
b) as a) but turbulent kinetic energy (m^2s-2).
c) as a) but precipitation scheme included.
d) as b) but precipitation scheme included.
e) as c) but $\delta t=10$sec.
f) as d) but $\delta t=10$sec.

were still present and most marked during the period of highest E and cloud top cooling ie night. The model was rerun with a timestep of 10secs and the oscillations disappeared but the general evolution remained the same, see figures 2e and 2f. It is possible that these oscillations are dampened in the 3D model by the use of time-smoothing of the leap-frog time differencing scheme using the Asselin filter.

The sensitivity of these simulations to different radiation schemes was investigated. As well as the original 2 level schemes, a multilevel long wave scheme based on that of Roach and Slingo 1979 (Golding 1993, Ballard 1989) and two multilevel short wave schemes based on those of Slingo and Shrecker 1982 and Somieski 1988 (Golding 1993) were tested, see figure 3. The simulations were extended to 48 hours. The evolution on the second day was similar to the first with the original radiation schemes however when the full long wave scheme of Roach and Slingo was used the cloud top rose during the second night. The diurnal evolution of the cloud was sensitive to which radiation schemes were used. The Somieski scheme produced greater short wave heating than the more detailed Slingo and Shrecker scheme which resulted in greater decoupling from the surface and a greater rise in cloud base and formation of cloud below the main stratocumulus, see figure 3d compared with 3c. The details of the diurnal evolution of the precipitation from the cloud also depended on the radiation scheme but all runs produced maximum rates at night peaking at about .05mm/hr at 5LST and dropping to zero during the day, see figure 4.

Simulations with the Brost et al data showed similar results to the JASIN data, see figures 5 to 7. These were only run with the 32 3D model levels. If the precipitation scheme was excluded the cloud base gradually lowered to the surface but a distinct cloud layer was maintained with diurnal evolution of cloud base when it was included. Again there were $2\delta t$ oscillations in E which were removed by reducing the time-step to 10secs. The magnitude of E was greater than in the JASIN runs, presumably due to the presence of shear and there were longer period (1.5 to 3.5 hour) variations above cloud top which were insensitive to the precipitation scheme and modified slightly but not removed by the reduced time-step, see figure 5.

In figure 6 the diurnal variation of cloud liquid water is shown for different combinations of the radiation schemes. The results are very similar apart from the run using the Somieski scheme where there is a greater thinning of the cloud during the day. In figure 7 the heating rates are shown for the same runs. It can be seen that with the original scheme, with only the cloud top budget, the only radiative effect parametrised is a cooling at cloud top. When the long wave scheme is replaced by the Roach and Slingo scheme it can be seen that not only is there a cooling from the top cloud layers there



a) T(hrs)

b) T(hrs)

c) T(hrs)

d) T(hrs)

Fig.3 Single column 48 hour simulation of JASIN marine stratocumulus from 12LST 8th August 1978 with 32 operational 3D model levels, precipitation scheme included and δt=120sec. Vertical scale as fig.1

a) Cloud amount (decimal fraction) with cloud top short wave and Roach and Slingo longwave radiation schemes.

b) as a) but Somieski short wave and Roach and Slingo long wave radiation schemes.

c) as a) but cloud top short and long wave radiation scheme.

d) as a) but Slingo and Shrecker short wave and Roach and Slingo long wave radiation schemes.

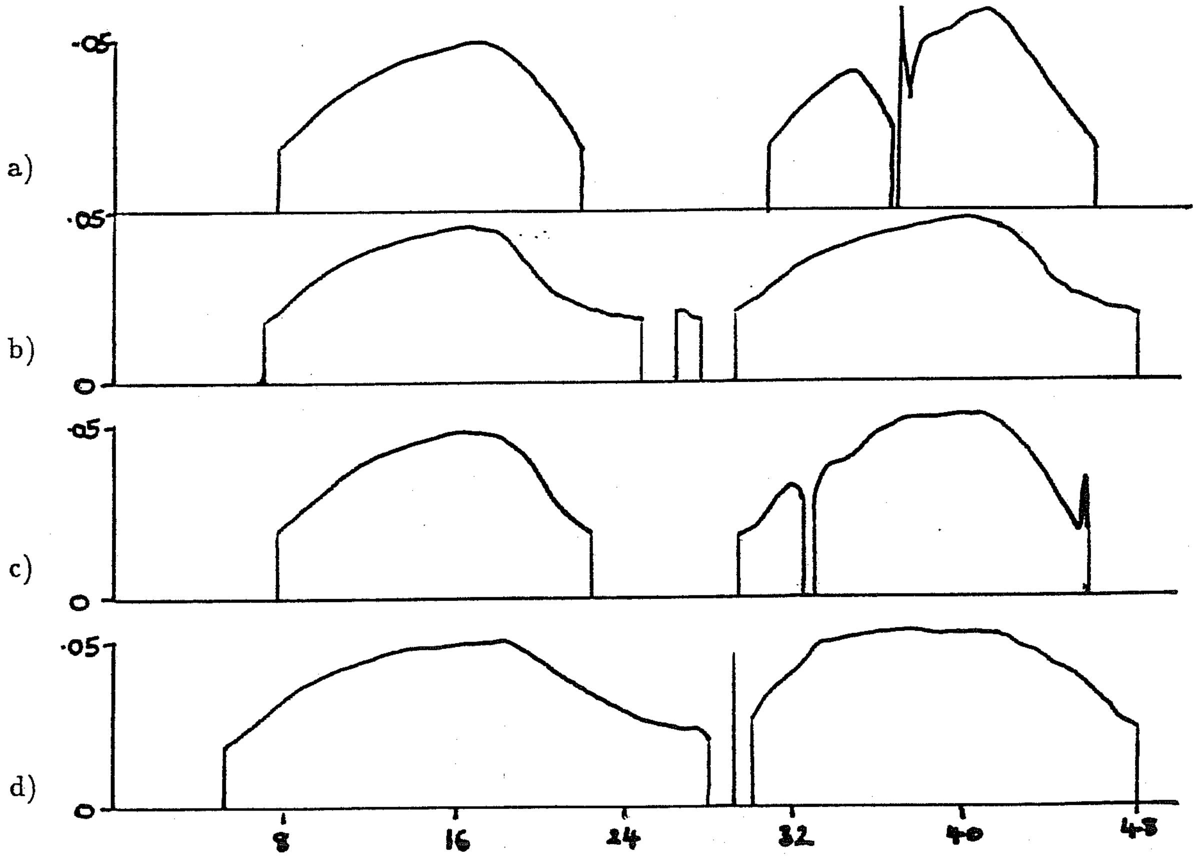


Fig.4 Single column 48 hour simulation of JASIN marine stratocumulus from 12LST 8th August 1978 with 32 operational 3D model levels, precipitation scheme included and δt=120sec.

a) Precipitation rate (mm/hr) with Somieski short wave and Roach and Slingo long wave radiation schemes.

b) as a) but cloud top short and long wave radiation scheme.

c) as a) but cloud top short wave and Roach and Slingo longwave radiation schemes.

d) as a) but Slingo and Shrecker short wave and Roach and Slingo long wave radiation schemes.

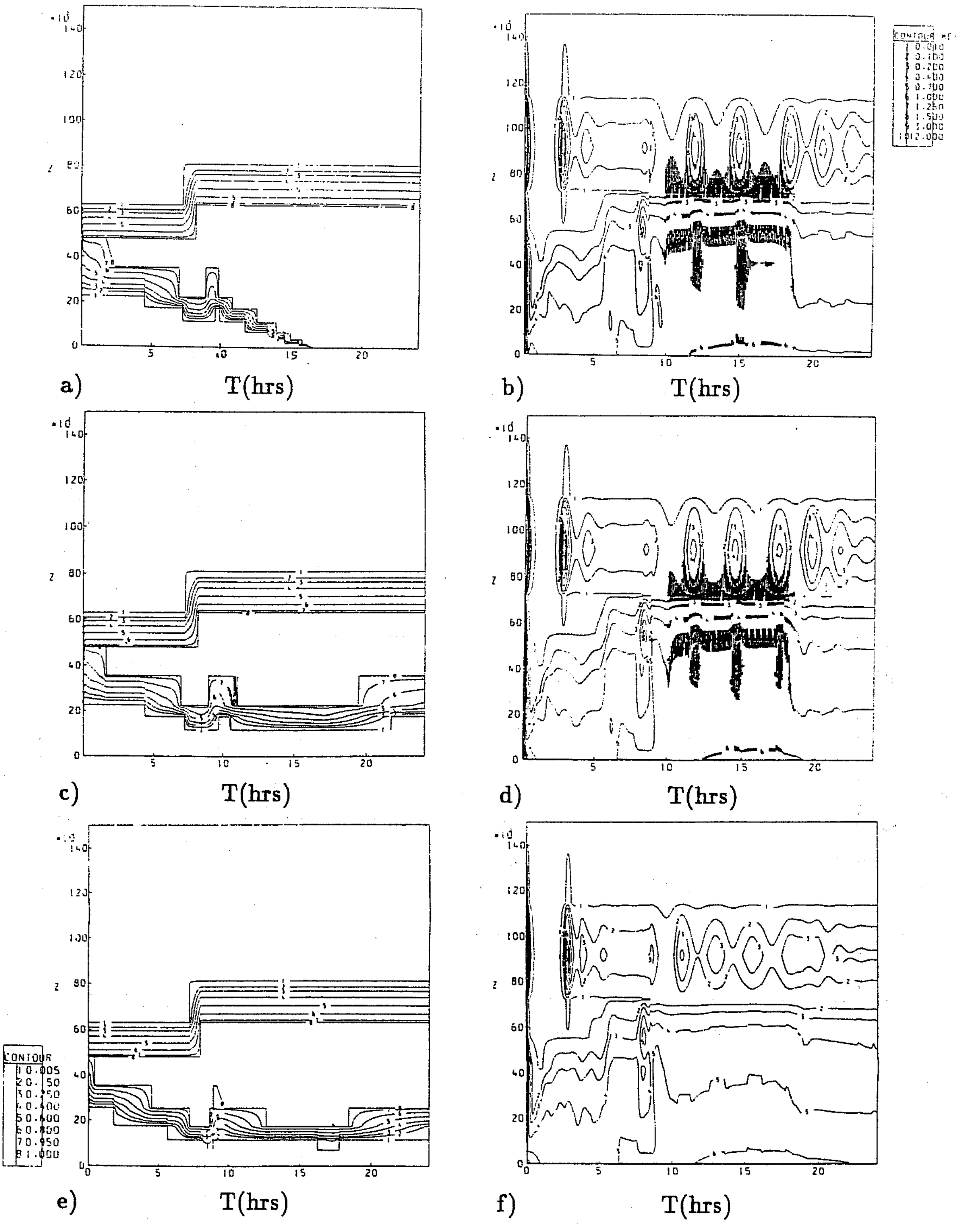


Fig.5 Single column 24 hour simulation of Californian coastal marine stratocumulus from 12LST 17th August 1976 with 32 operational 3D model levels and cloud top radiation budget. Vertical scale as fig.1

a) Cloud amount (decimal fraction) with no precipitation scheme, δt=120sec.

b) as a) but turbulent kinetic energy (m^2s-2).

c) as a) but precipitation scheme included.

d) as b) but precipitation scheme included.

e) as c) but δt=10sec.

f) as d) but δt=10sec.

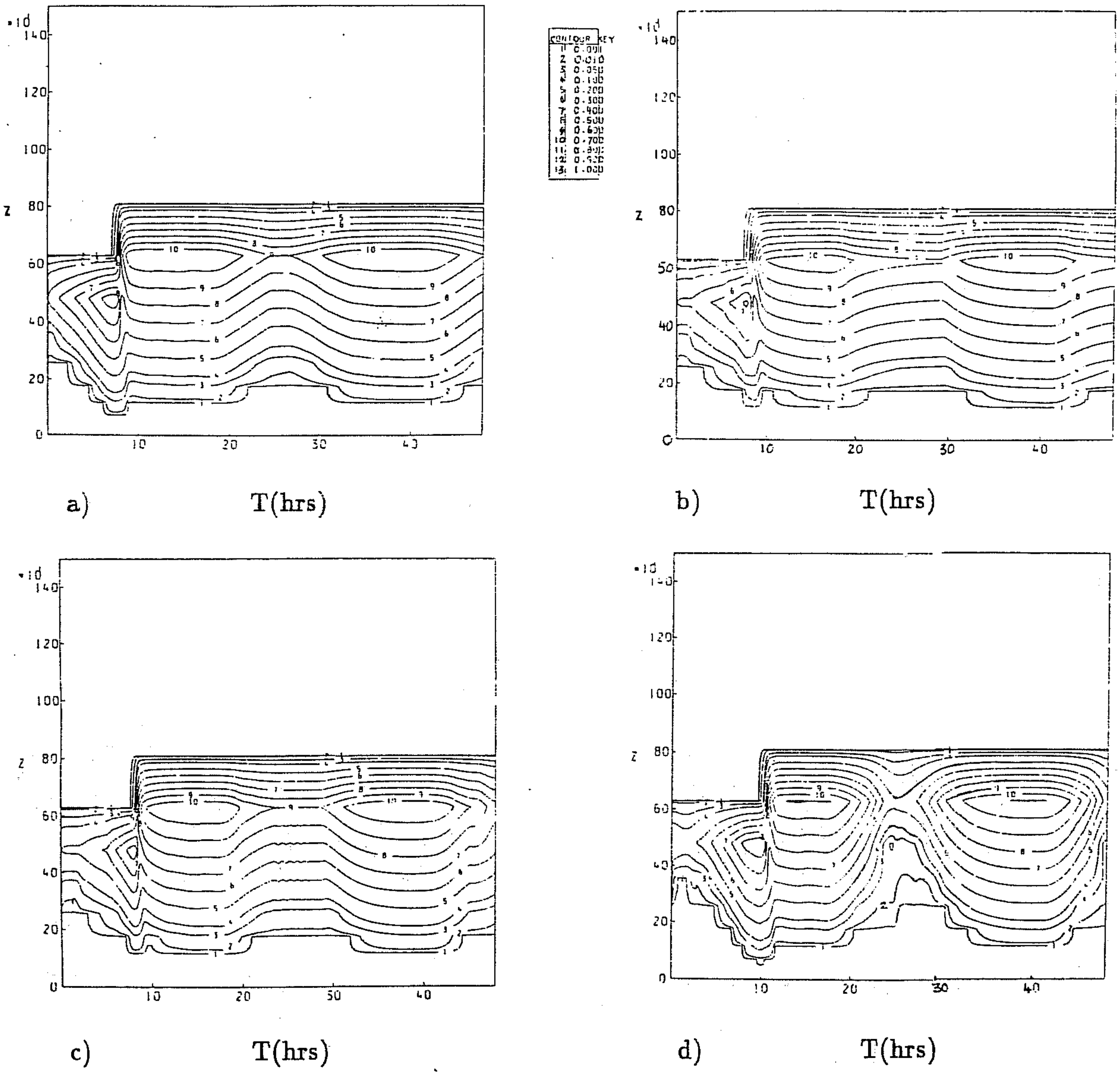


Fig.6 Single column 48 hour simulation of Californian coastal marine stratocumulus from 12LST 17th August 1976 with 32 operational 3D model levels, precipitation scheme included and δt=120sec. Vertical scale as fig.1

a) Cloud liquid water (g/kg) with Slingo and Shrecker short wave and Roach and Slingo long wave radiation schemes.

b) as a) but cloud top short and long wave radiation scheme.

c) as a) but cloud top short wave and Roach and Slingo longwave radiation schemes.

d) as a) but Somieski short wave and Roach and Slingo long wave radiation schemes.

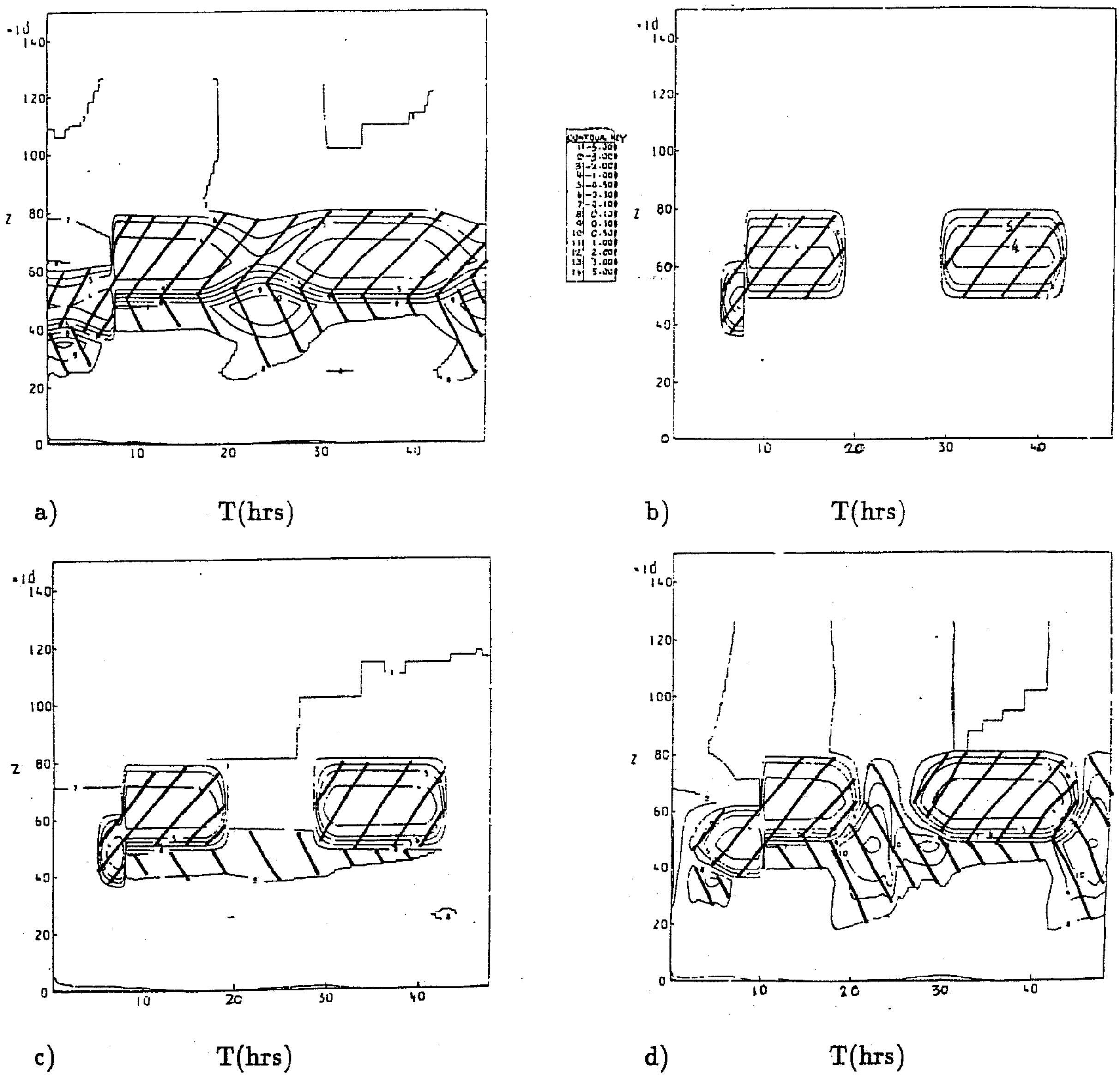


Fig.7 Single column 48 hour simulation of Californian coastal marine stratocumulus from 12LST 17th August 1976 with 32 operational 3D model levels, precipitation scheme included and $\delta t=120$sec. Vertical scale as fig.1

a) Heating rates (K/hr) with Slingo and Shrecker short wave and Roach and Slingo long wave radiation schemes.

b) as a) but cloud top short and long wave radiation scheme.

c) as a) but cloud top short wave and Roach and Slingo longwave radiation schemes.

d) as a) but Somieski short wave and Roach and Slingo long wave radiation schemes.

\\\\= heating, //= cooling

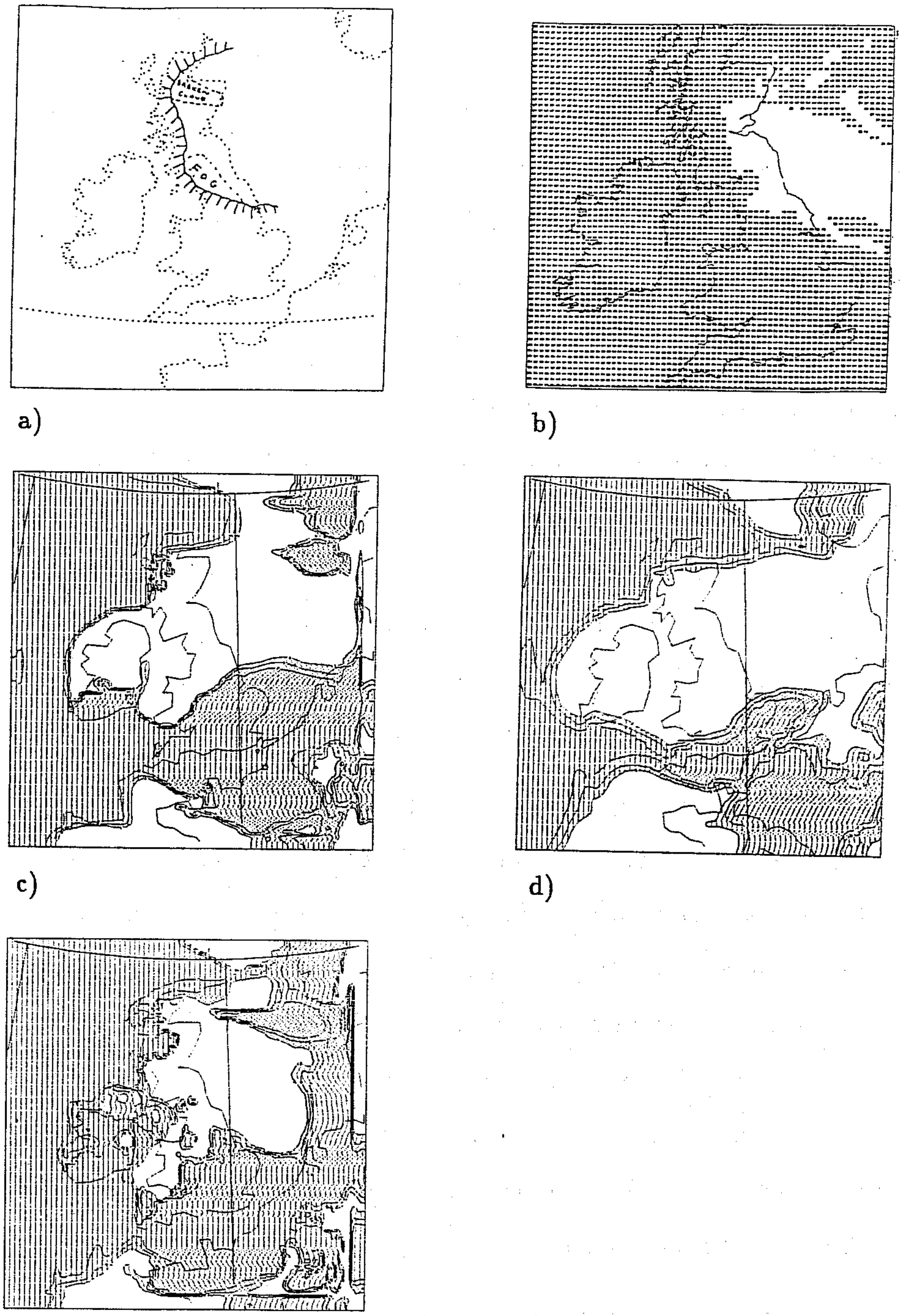
is also a warming of the cloud base solely due to the long wave radiative fluxes. When the Slingo and Shrecker scheme was used with the Roach and Slingo scheme there was cooling from cloud top and warming of the base throughout the 48hrs, a feature which could not be produced with the simple cloud top radiation budget calculation where the long wave cooling and short wave heating were both applied in the same single level at cloud top. It can be seen that the Somieski scheme produces greater short wave heating throughout the depth of the cloud.

4. 3D CASE STUDY USING THE UNIFIED MODEL

In June 1991 the operational global and limited area (LAM) models were changed to versions of the unified model (Cullen 1991 and 1993) with 20 levels and resolutions of approximately 90 and 50km respectively. The boundary layer was increased to a maximum of 5 layers (allowing it to be deeper not providing extra resolution). The unified model has a prognostic cloud scheme similar to the non-hydrostatic model but a first order boundary layer scheme, see Smith 1994. Again the only source of humidity data is the inclusion of radio-sonde relative humidities in the analysis correction scheme.

A mesoscale version (NMM) with 17km resolution was introduced operationally in Dec 1992 (Ballard et al 1993) with 31 levels, 13 within the boundary layer. This used the same data assimilation scheme as the LAM but extended (Macpherson et al 1993) to include relative humidity profiles derived from a 3D cloud cover analysis, MOPS (Moisture Observation Pre-processing System, Wright 1993), produced from an interactive system based on the IMI. The MOPS relative humidity is calculated to be consistent with the model cloud scheme which provides a relationship between cloud fraction and relative humidity as a function of an assumed critical relative humidity RH_c for cloud formation. For relative humidities below RH_c the cloud fraction is zero. The MOPS profiles are derived at every grid-point and assimilated like radio-sonde data.

A stratocumulus case, 0UTC 4th December 1991, was included in the pre-operational trial of the mesoscale model. Initially the NMM was set up as a higher resolution version of the LAM (NMM1) and forecasts from the OMM (run from the IMI and the LAM analysis), the LAM and the NMM were compared. Further developments were made to the NMM before it was introduced operationally (NMM2), these included inclusion of the MOPS data, the modification to the boundary layer scheme for non local mixing (Smith 1994), the inclusion of downdraughts in the convection scheme, modification to evaporation rates and increased surface roughness. Analyses and 15 hour forecasts of total cloud cover are compared with observations in figures 8 and 9. The OMM had a good analysis of total cloud cover from the IMI but lost the cloud over land early in the forecast. The LAM and NMM1



a)

b)

c)

d)

e)

Fig. 8 Comparison of observed and analysed total cloud cover at 0Z 4/12/91. The edge of areas with greater than 3 oktas cover is defined in the observations and areas with greater than 3 oktas cover are shaded in the analyses.

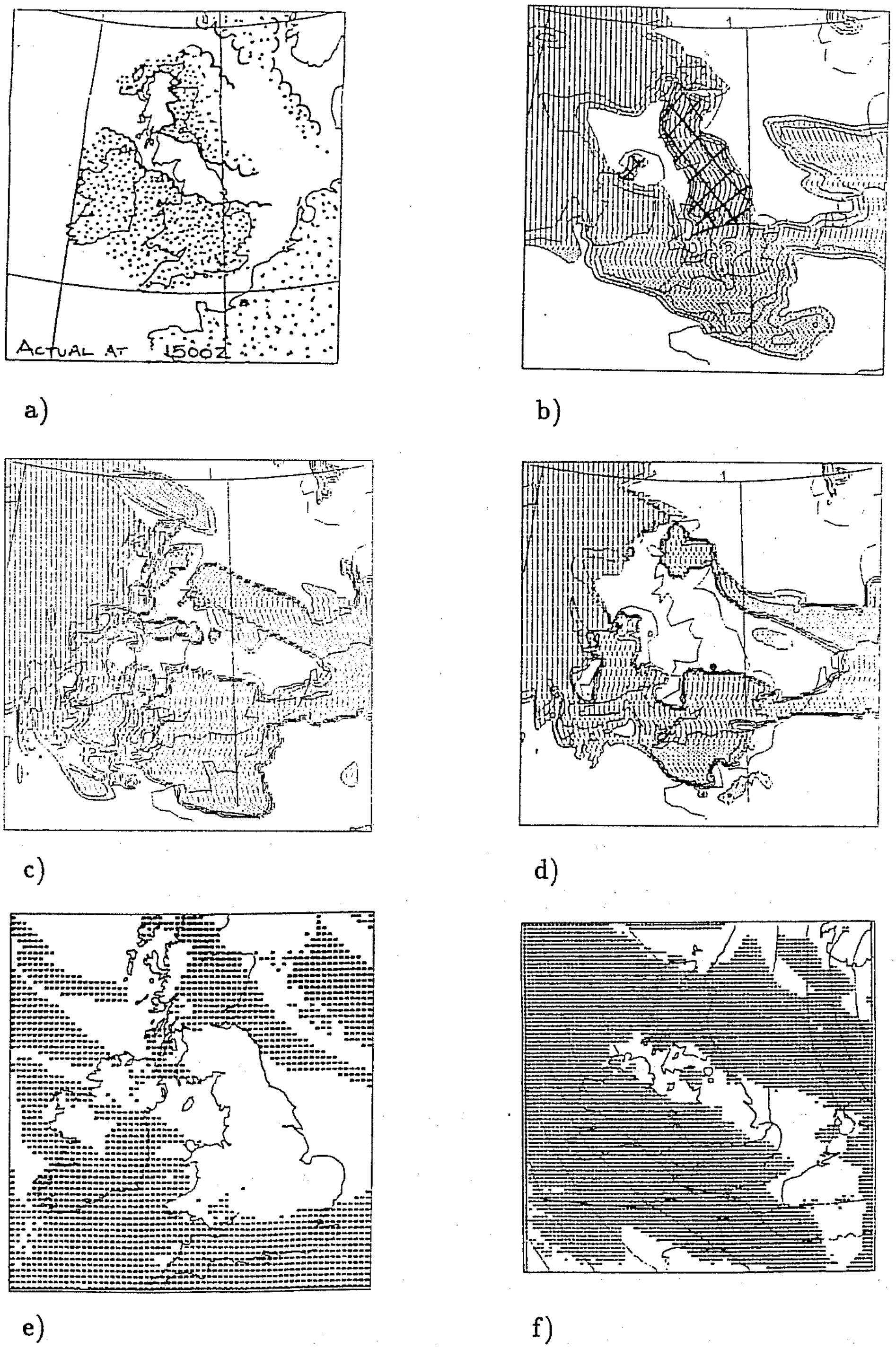
a) observed cloud edge

b) operational OMM analysis with benefit of IMI

c) NMM1 after 6 hours data assimilation

d) LAM after 12 hours data assimilation

e) NMM2 after 6 hours data assimilation including MOPS humidity profiles



a)

b)

c)

d)

e)

f)

Fig.9 Comparison of observed and forecast total cloud cover at 15Z 4/12/91. The edge of areas with greater than 3 oktas cover is defined in the observations and areas with greater than 3 oktas cover are shaded in the analyses.

a) observed cloud edge

b) LAM 15 hour forecast. Hashed area marks cloud at level 1 only,ie fog

c) NMM2 15 hour forecast.

d) NMM1 15 hour forecast.

e) operational OMM 15 hour forecast

f) OMM from LAM analysis 15 hour forecast.

both had a deficit of cloud at analysis time but produced reasonable forecasts by T+15. The NMM1 was better than the LAM which erroneously produced fog. From figure 10 the benefit of the extra vertical resolution in the NMM assimilation of radiosonde data is shown in the definition of cloud top and humidity profile. The OMM run from the LAM analysis provides an excellent forecast showing that the problem in stratocumulus prediction with that model was due to the initialisation and not the model formulation.

The NMM2 benefitted from the inclusion of MOPS data at analysis time which improved the early stages of the forecast. There were problems automatically detecting the cloud top height of low cloud from satellite imagery in the MOPS system and Macpherson et al 1993 found that the NMM2 forecasts were degraded if the MOPS profiles were produced without human intervention to correct the cloud tops. They also found that there was greater impact from the interactive MOPS profiles if the radio-sonde relative humidities were excluded from the assimilation.

The amount of low and convective cloud forecast by the unified model in this case is sensitive to the physical parametrisations, figure 11. Forecasts with the non local mixing scheme included produced more low cloud and less convective cloud resulting in a better forecast of the stratocumulus which was much more like that from the good OMM forecast. This effect was initially inhibited in the NMM2 by the inclusion of modifications to the convection scheme which made it more vigorous and likely to trigger than in the version used by the LAM and climate models. Both the convection and boundary layer schemes perform vertical mixing. Changes to either scheme can alter the relative effectiveness of boundary layer mixing, which produces large low cloud amounts, and convective mixing, which produces smaller convective cloud amounts. When the full set of changes to the physics described in Smith 1994 were tested using the convection scheme as implemented in the climate and LAM models the benefit of the non local mixing scheme was retained and the amount of convective cloud was reduced even further. However the low cloud amounts to the west of the UK were reduced. This was probably a result of the change to the prognostic cloud water scheme which has since been found unsatisfactory as it produces cloud amounts that are too low with 'in cloud' cloud water amounts that are too high.

5. OPERATIONAL PERFORMANCE OF THE LAM AND MESOSCALE MODELS

The results discussed in section 4 showed that the mesoscale version of the unified model could produce good forecasts of stratocumulus that benefitted from the inclusion of the MOPS data. The period 5-10 March 1993 was investigated to see how the model performed operationally (Ballard and Macpherson

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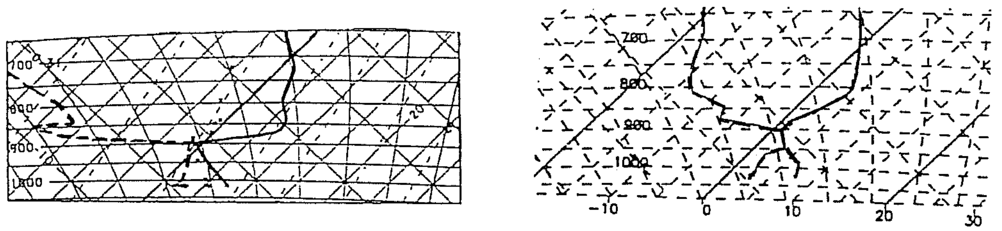
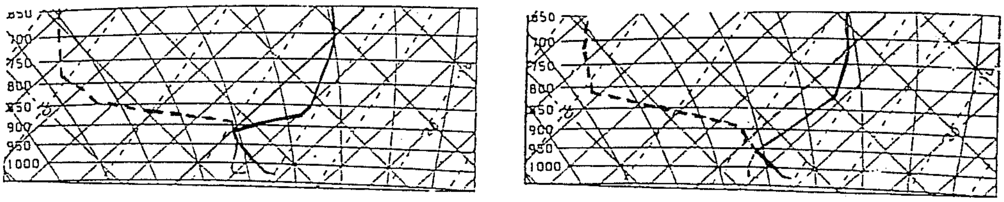


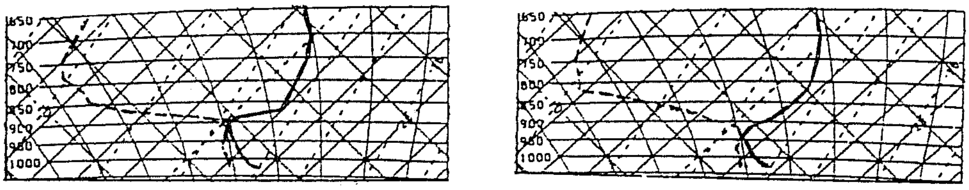
ACTUAL 0Z 4/12/91

OMMIMI T+0 0Z 4/12/91



NMMAC T+0 0Z 4/12/91

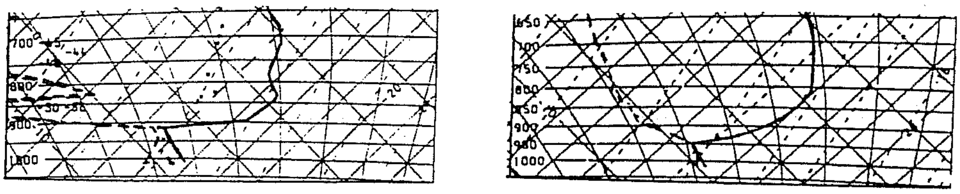
LAMAC T+0 0Z 4/12/91



NMMAC T+6 6Z 4/12/91

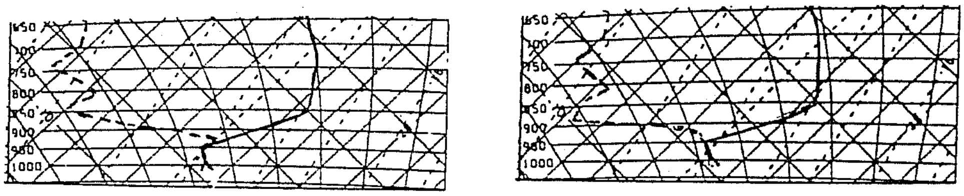
NMMLAM T+6 6Z 4/12/91

CRAWLEY



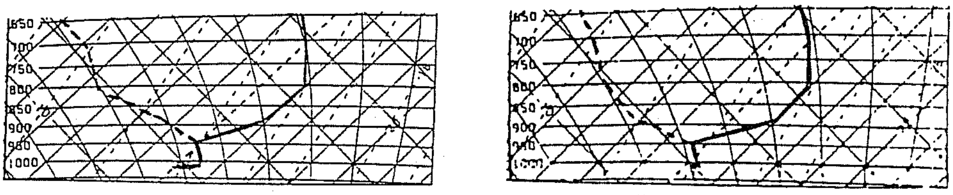
ACTUAL 0Z 4/12/91

NMMLAM T+6 6Z 4/12/91



NMMAC T+0 0Z 4/12/91

NMMAC T+6 6Z 4/12/91

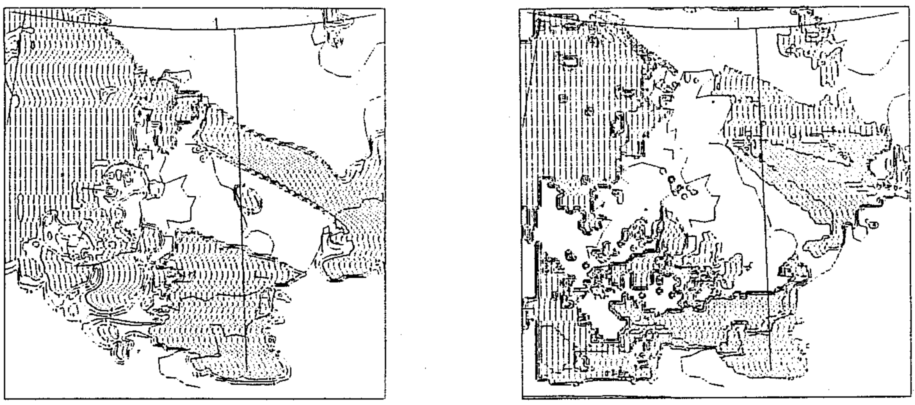


LAMAC T+0 0Z 4/12/91

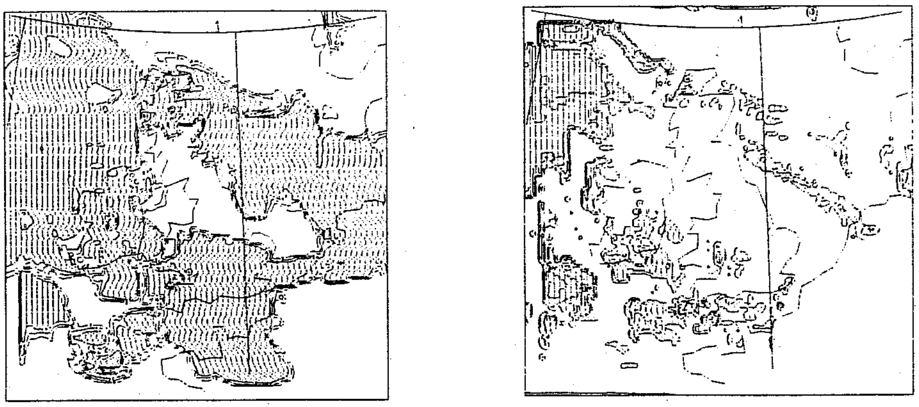
LAMAC T+6 6Z 4/12/91

Fig.10 Comparison of actual and forecast Camborne and Crawley ascents for 4/12/91 case. NMMAC = NMM1, LAMAC = LAM, NMMLAM = NMM run from LAM analysis, OMMIMI = OMM initialisation from IMI.

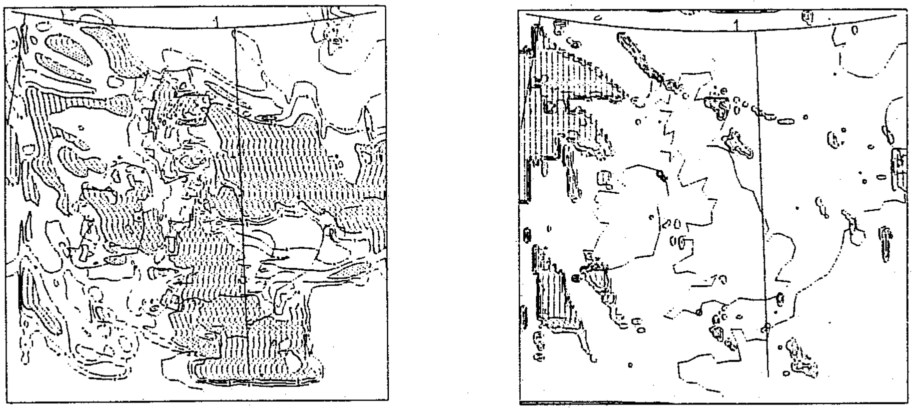
low cloud cover convective cloud cover



a) NMM with original physics as in NMM1



b) as a) but including non local mixing in boundary layer scheme



c) as b) but also including downdraught convection with climate parameters, new evaporation, orographic roughness, 4th order diffusion, revised cloud and precipitation scheme (Smith 1994).

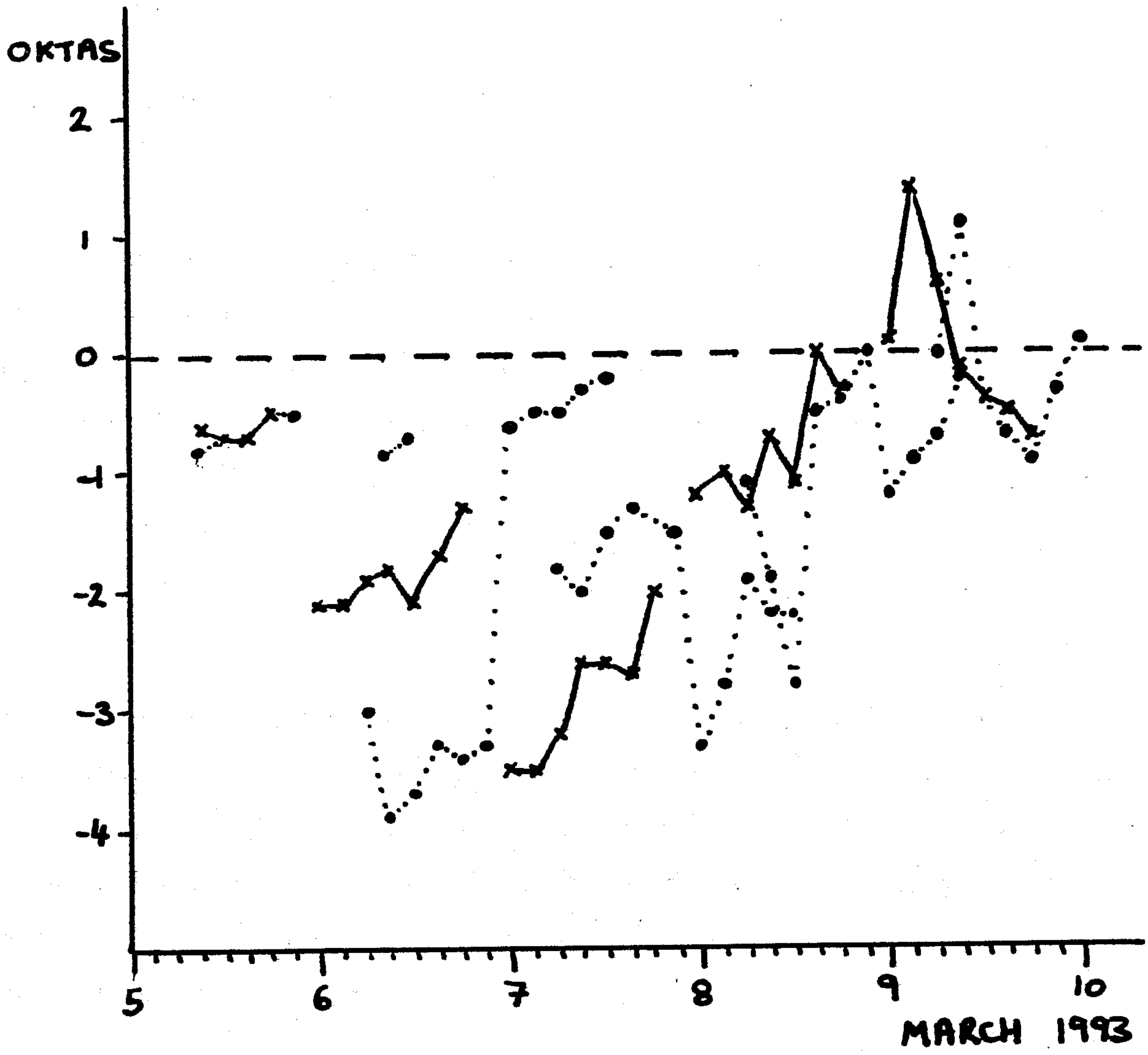
Fig.11 Comparison of 15 hour forecasts of low and convective cloud cover verifying at 15UTC 4/12/91. Areas with low cover greater than 7 oktas are shaded and contour intervals at 3,5,7 and 9 oktas. Areas with convective cloud cover greater than 0.3 oktas are shaded with contour intervals 0.3,1,1.5 and 9 oktas.

1993).

During this period an anticyclone moved eastwards across the country with associated widespread stratocumulus. At the start of the period the forecasts had low and consistent errors in objective verification of total cloud cover, see figure 12. However the analyses and forecasts degraded markedly, with an underprediction of cloud, on the 6th before improving on the 7th and 8th. By the 9th and 10th the errors were low as the cloud had cleared and the model was predicting cloud free conditions. An apparent improvement of skill part way through the 6UTC 6th March forecast was due to the production of fog in erroneously cloud free conditions. By comparing forecasts and analyses verifying at the same time it was apparent that, despite an excellent 24 hour forecast from 6UTC 5th March, see figure 13, in general the analyses were deficient in low cloud which resulted in poor forecasts and results were only marginally better than the LAM. Rather than predicted cloud cover improving as forecast periods reduced the analyses and very short-range forecasts were often worse than the longer range forecasts.

It was found that for some of the poor forecasts no MOPS data had been produced, eg 6UTC 6th March 1993 and for others it seemed unlikely that the cloud top heights had been corrected, thus reducing the impact of the data. The separate contributions of MOPS and radiosonde humidity data to the analyses and forecasts was established by rerunning with these data types separately omitted, eg figure 14. The general conclusion is that the radiosonde humidity data have degraded the analyses and 6 hour forecasts, while MOPS data have been significantly beneficial to the analysis and marginally so to the 6-hour forecasts.

It was found that if the radio-sonde layer averaged relative humidity was used to calculate an effective cloud cover using the unified model cloud scheme there was a negative bias in the derived total cloud cover, even assuming random overlap, compared with the surface observation at that station. For example it was found that for the 0UTC sondes on 8th March there was a bias of -2.7oktas reducing to -2.5oktas if only stations reporting full cover were used. For the 3UTC and 6UTC sondes on the same day there was a bias of -4.4oktas increasing to -6.4 oktas for stations reporting full cover. The 0UTC analysis and forecast was better than those from 6UTC. These biases explain the results of the sensitivity experiments. The MOPS profiles of humidity are consistent with the observed cloud cover, ie the derived relative humidity is high enough for the model to produce cloud. The relative humidity in the sonde profile is too low to produce sufficient cloud in the model. Therefore either the radiosondes are producing relative humidities that are too low compared with reality or there is an

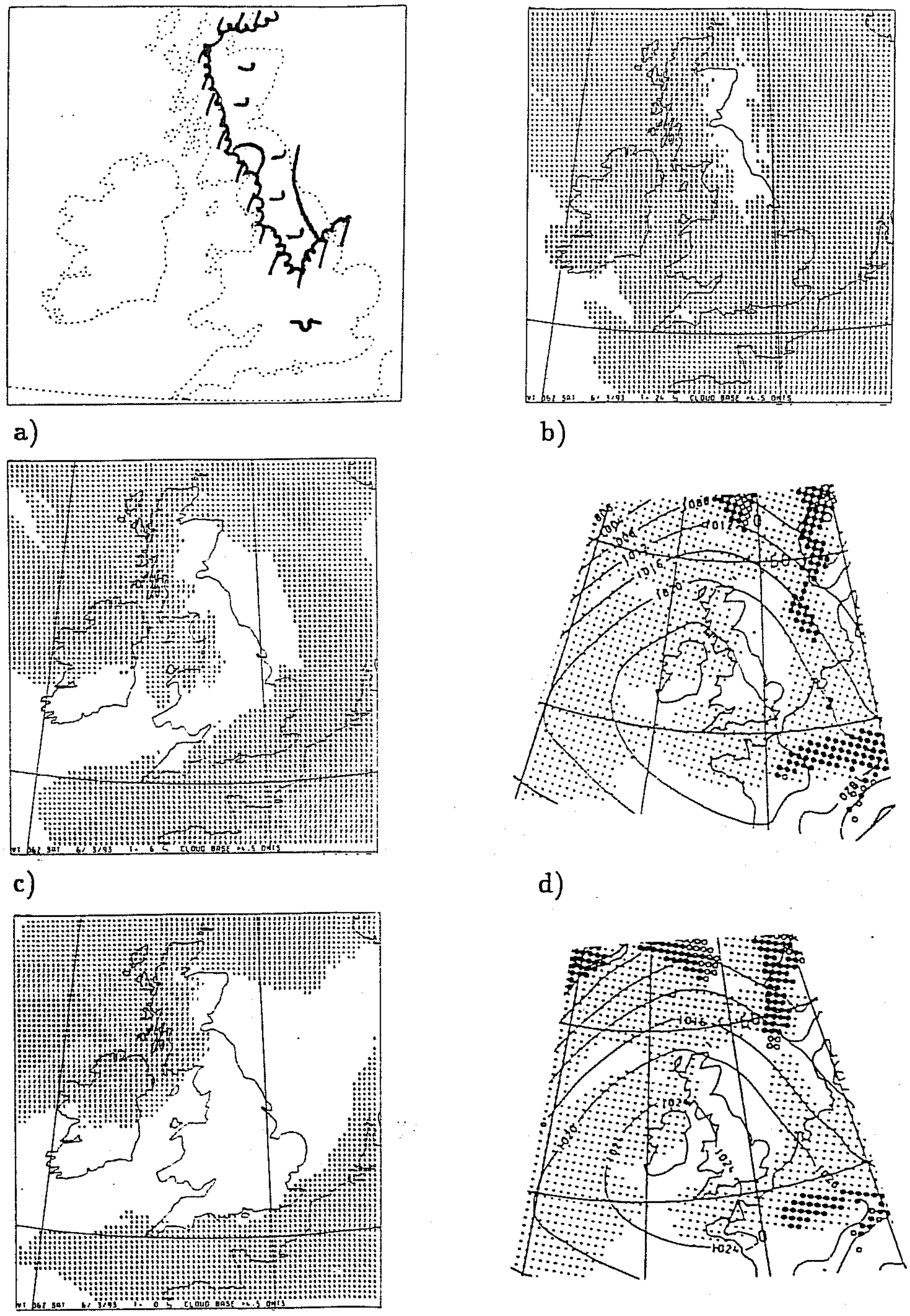


←——— PERIOD OF STRATOCUMULUS ———→ ←—— CLEARANCE ——→

Fig.12 Mean error in total cloud cover from mesoscale model forecasts for period 5/3/93 to 10/3/93. Calculated for surface observing stations in UK area every 3 hours.

—— 0Z forecasts from T+0 to T+18

. . . 6Z forecasts from T+0 to T+30



a) b) c) d) e) f)

Fig.13 Comparison of observed and forecast low cloud cover at 06UTC 6/3/93.

a) Observed cloud . Edge of low cloud, cirrus and clear areas marked.

b) T+24 operational mesoscale forecast from 06UTC 5/3/93. Map shows area of low cloud >4.5 oktas. Figures are code for base height and clear areas are essentially cloud free.

c) as b) but T+6 operational mesoscale forecast from 00UTC 6/3/93.

d) T+6 operational LAM forecast from 00UTC 6/3/93. Map shows mean sea level pressure, low cloud cover greater than 4 oktas as dots, medium cloud as open circles and low plus medium cloud as filled circles.

e) as b) but T+0 operational mesoscale analysis for 06UTC 6/3/93.

f) as d) but T+0 operational LAM analysis for 06UTC 6/3/93.

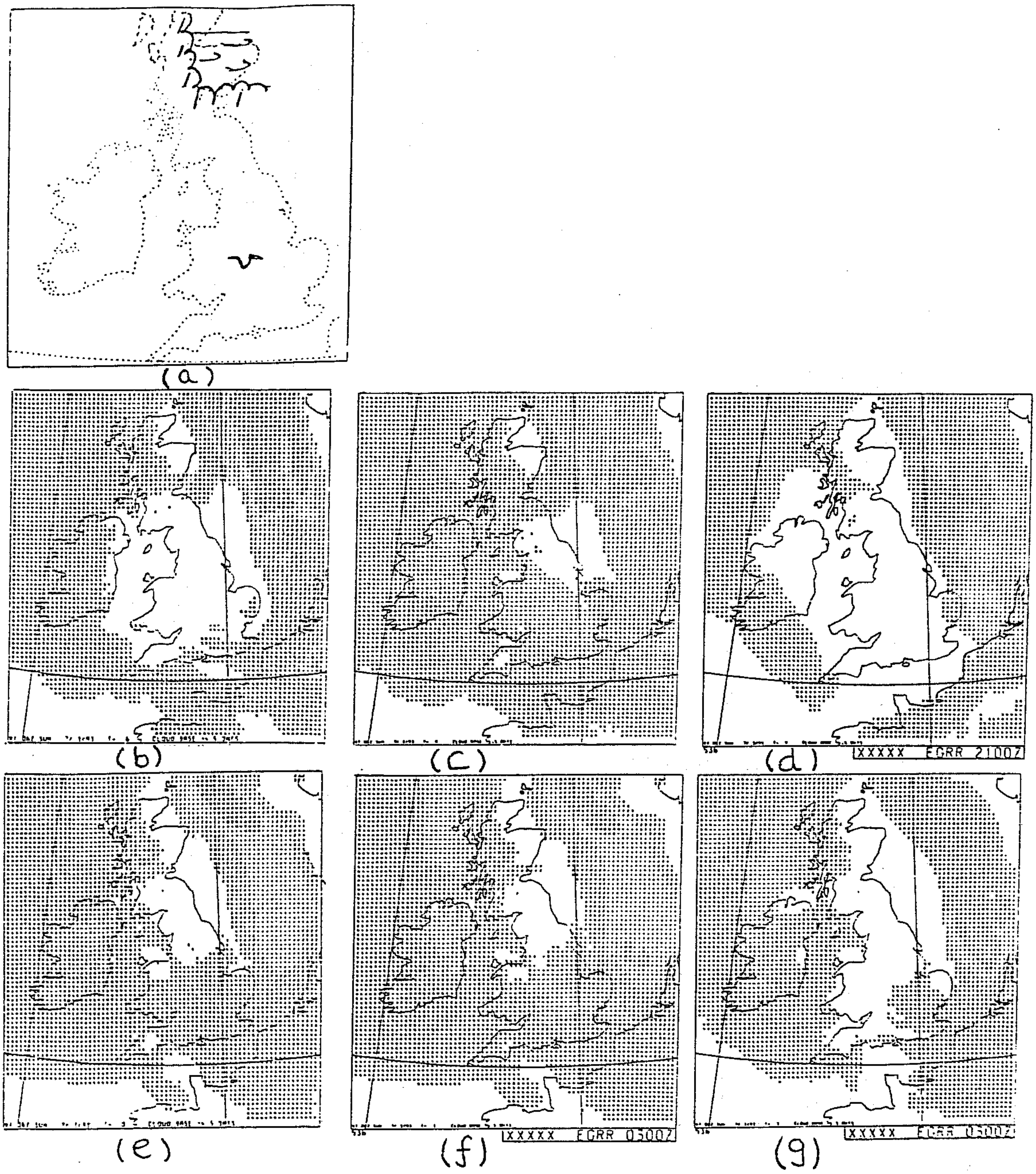


Fig.14 Comparison of observed, analysed and forecast low cloud cover at 06UTC 7/3/93.

a) Observed cloud . Edge of low cloud areas marked.

b) T+6 operational mesoscale forecast from 00UTC 7/3/93. Map shows area of low cloud >4.5 oktas (clear areas are essentially cloud free).

c) as b) but rerun without radiosonde humidity data.

d) as b) but rerun without MOPS data.

e) as c) but T+0 operational mesoscale analysis for 06UTC 7/3/93.

f) as e) but rerun without radiosonde humidity data.

g) as e) but rerun without MOPS data.

error in the model cloud scheme, such as RH_c set too high.

In sensitivity studies with the 6UTC 8th March 1993 assimilation and forecast, see figure 15, it was found that more cloud was produced if the sonde humidity data was removed, the convection scheme was changed so that the non local boundary layer scheme was more effective and/or RH_c was reduced in the low cloud levels (ie RH_c=0.95 at level 1 and 0.85 for other levels as used in the climate model rather than RH_c=0.925 for the bottom 7 levels and 0.85 for the remaining levels).

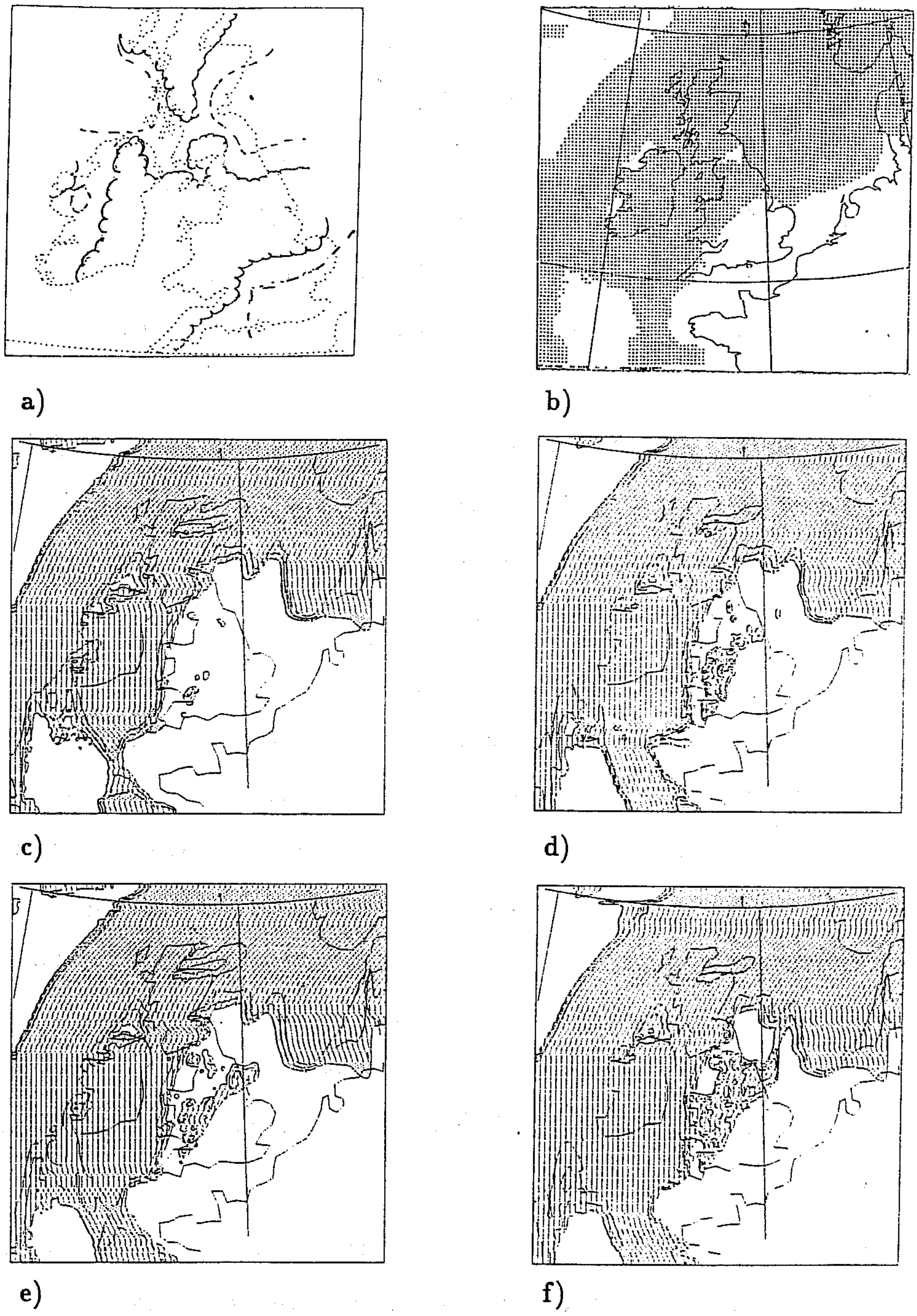
6. CONCLUSIONS

The operational models prior to the unified model were deficient in stratocumulus. The formulation of the nonhydrostatic mesoscale model and its anlaysis scheme, the IMI, was designed to improve the skill of low cloud forecasts. However the difficulty of ensuring balanced initial conditions in the IMI meant that, despite good cloud analyses, the forecasts were unreliable.

Sensitivity studies of the simulation of the diurnal evolution of marine stratocumulus with a single column version of the mesoscale model indicated areas where the parametrisations and finite difference schemes needed to be improved. They also showed that with achievable operational vertical resolution the basic physics of the model was capable of reproducing many of the observed characteristics of stratocumulus such as diurnal variation in thickness and precipitation and decoupling of the cloud layer and generation of a lower cumulus layer. This shows the need for observations of the diurnal variation of stratocumulus to verify the models. In particular information on drizzle rates, cloud water contents, geostrophic forcing and subsidence rates. Since the principal forecasting concern is stratocumulus over land, both directly for aviation and indirectly for its impact on surface temperatures, observations are urgently required over land.

The case study with the unified model showed its ability to predict stratocumulus and the additional benefit of increased vertical resolution. The basic analysis was deficient in cloud over land but this was greatly improved by the use of the cloud observations through the MOPS system. The retention of cloud introduced by MOPS showed the benefit of the 'nudging' technique compared with the IMI. This case also showed the greatly improved skill of the old mesoscale model when run without the IMI. The prediction of low cloud in the unified model is sensitive to changes in the boundary layer and convection schemes and hence to the split of vertical mixing between the two. Should the turbulent mixing scheme or convection scheme produce boundary layer cloud? The inclusion of non local mixing produced more low cloud, more similar to the old mesoscale model.

Operationally, despite some excellent 24 hour forecasts, the LAM and mesoscale versions of the unified



a) b) c) d) e) f)

Fig.15 Comparison of observed and 6 hour forecast of total cloud cover valid at 12UTC 8/3/93.

a) Observed cloud . Edge of low cloud areas marked. Dashed contour marks edge of partial cover.

b) Physics as operational model, ie NMM2, with MOPS data included and radiosonde humidity data excluded. Area of total cloud >3 oktas shaded.

c) as b) but MOPS data excluded and sonde humidity data included. Forecast very similar to operational forecast with both MOPS and sonde humidity included. Area of total cloud >3 oktas shaded with contour intervals at 3,5,7 and 9 oktas.

d) as c) but using climate/LAM convection parameters.

e) as c) but using climate critical relative humidity.

f) as e) but with climate/LAM convection parameters, climate critical relative humidity model were still generally underpredicting stratocumulus and had too little in the analyses. This seemed to be due principally to an inconsistency between the radio-sonde humidity data, surface cloud cover observations and the model cloud scheme combined with problems with missing or poor MOPS data. The problem with MOPS has been resolved by an improvement to the detection of low cloud top (Hand 1993) and introducing an automated system in Autumn 1993.

The radio-sonde humidity problem needs more investigation. The accuracy of the sonde humidities and the ability of the sondes to accurately detect cloud base, top and thickness needs to be defined before any attempt is made to modify the model cloud scheme. At present it seems that sondes are likely to underestimate the layer averaged humidity associated with stratocumulus and hence dry out the model.

The convection scheme was changed in Autumn 1993 to be the same as used in the climate and LAM models so that the non local mixing scheme is more effective and more low cloud is produced as seen in sections 4 and 5.

The unreliability of stratocumulus forecasts may additionally be related to lack of resolution of thin cloud. The cloud scheme does not take account of variations of θ_l and q_t due to sub-vertical gridscale stratification so new parametrisations are being sought. A new cloud and precipitation scheme is also being developed to treat ice and water phases separately, currently between 0°C and -15°C all cloud is part ice and water dependent on temperature. In future the impacts of aerosols on the cloud formation and microphysics will be considered.

Comparisons of a single column version of the unified model with observations and the old mesoscale model will give valuable insight into the ability of the model to predict rather than analyse/initialise low cloud.

REFERENCES

Atkins,M.J. and Woodage,M.J., 1985: Observations and data assimilation. Meteorol. Mag., 114,227-233.

Ballard,S.P.,1989: Enhancements to the mesoscale model and their impact on forecasts, Met O 11 Technical Report No 34

Ballard,S.P.,1991: Assessment of the performance of the 32 level version of the mesoscale model. Short Range Forecasting Research Technical Note No 62

Ballard,S.P.,Golding,B.W.and Smith,R.N.B.,1991: Mesoscale Model experimental forecasts of the Haar of Northeast Scotland. Mon.Wea.Rev., 119, 2107-2123.

Ballard,S.P.,Robinson,R.,Barnes,R.T.H., Jackson,S. and Woltering,S., 1993: Development and performance of the new mesoscale model. Forecasting Research Technical Report No 40

Ballard,S.P. and Macpherson,B.,1993: Operational performance of mesoscale and LAM models in prediction of stratocumulus. Forecasting Research Technical Report No 56

Brost,R.A.,Lenchow,D.H. and Wyngaard,J.C., 1982: Marine stratocumulus layers. Part I:mean conditions. J.Atmos.Sci., 39, 800-817.

Brost,R.A.,Wyngaard,J.C. and Lenchow,D.H., 1982: Marine stratocumulus layers. Part II:turbulence budgets. J.Atmos.Sci., 39, 818-836.

Cullen,M.J.P.,1991: The Unified Forecast/Climate Model. Short Range Forecasting Research Scientific Paper No 1

Cullen,M.J.P.,1993: The Unified Forecast/Climate Model. Meteorol. Mag., 122,81-94.

Golding,B.W.,1990: The Meteorological Office mesoscale model. Meteorol. Mag., 119, 81-96.

Golding,B.W.,1993: A study of the influence of terrain on fog development. Mon.Wea.Rev., 121, 2529-2541.

Gadd,A.J.,1985: The 15 level weather prediction model. Meteorol Mag., 114,222-226.

Hammon,O.M.,1988: Improvements to low cloud forecasts from the mesoscale and fine-mesh models. Met O 11 Technical Note No 20.

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

Kalnay,E. and Kanamitsu,M., 1988: Time schemes for strongly nonlinear damping equations. Mon. Wea. Rev., 116, 1945-1958.

Lorenc,A.C.,Bell,R.S. and Macpherson,B.,1991: The Meteorological Office analysis correction data assimilation scheme. Q.J.R.Meteorol.Soc., 177,59-89.

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

Roach, W.T. and Slingo,A., 1979: A high resolution infrared radiative transfer scheme to study the interaction of radiation with cloud. Q.J.R.Meteorol.Soc, 105, 603-614.

Slingo,A. and Shrecker,H.M.,1982: On the short wave radiative properties of stratiform water cloud. Q.J.R.Meterol.Soc. 108, 407-426.

Slingo,A.,Nicholls,S. and Schmetz,J., 1982: Aircraft observations of marine stratocumulus during JASIN. Q.J.R.Meteorol.Soc., 108, 833-856.

Slingo,J.M.,1987: The development and verification of a cloud prediction scheme for the ECMWF model. Q.J.R.Meteorol.Soc, 113,899-927.

Smith,R.N.B.,1993: Subsurface, surface and boundary layer processes. Unified Model Documentation Paper No 24 version 2 dated 31/3/93, available from Unified Model Librarian, Forecasting Research Division, Meteorological Office, London Road, Bracknell.

Smith,R.N.B.,1994: Experience and developments with the layer cloud and boundary layer mixing schemes in the UK Meteorological Office Unified Model. this volume

Somieski,F.,1988: Mesoscale model parametrisations for radiation and turbulent fluxes at the lower boundary. Oberfaffenhofen, DFVLR-FB-88-48

Sommeria,G. and Deardorff,J.W.,1977: Subgrid-scale condensation in models and of nonprecipitating clouds. J.Atmos.Sci,34,344-355.

Tapp,M.C. and White,P.W.,1976: A nonhydrostatic mesoscale model. Q.J.R.Meterol.Soc, 102,277-296.

Wright,B.J.,1993: The Moisture Observation Pre-processing System. Forecasting Research Technical Report No 38 .

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

Note: all UK Met Office Technical Reports etc referenced above are available from the National Meteorological Library, Meteorological Office, Bracknell, Berkshire, RG12 2SZ, England).