PARAMETRIZATION OF MIXED-PHASE CLOUD AND PRECIPITATION

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1. INTRODUCTION

The UK Meteorological Office uses one basic numerical prediction model, referred to as the Unified Model (*Cullen*,1993) , for climate prediction, global NWP and short range forecasting using high resolution limited area (regional) models. The policy is to keep the parametrization schemes the same in all versions wherever possible. This means that any microphysics scheme needs to be able to cope with the requirements and long time-steps and coarse resolutions of climate simulation as well as those of shorter time-step, high resolution mesoscale modelling. Typical configurations are shown in table 1.

TABLE 1. Configurations of unified model

	resolution	no.of levels	timestep	period of forecast
GLOBAL				
Climate	2.5° x 3.75°	19	30min	decades - centuries
NWP	0.8° x 1.25°	19	10min	7 days
REGIONAL				
LAM	0.442° x 0.442°	19	5min	2 days
Mesoscale	0.15° x 0.15°	31	1.5min	18 - 30 hour

The regional, high resolution configurations are operationally run for a domain covering the North Atlantic and Europe in the case of the LAM (Limited Area Model) and an approximately 1500 km square domain centred on Britain and Ireland in the case of the mesoscale model. However operational and research requirements mean that the model needs to be able to represent global weather systems from extratropical cyclones , arctic stratus, fog and stratoculumulus to tropical convection at both high and coarse resolution.

The treatment of boundary layer cloud in the Unified Model was described in two papers (*Smith* , 1993 and *Ballard et al.,* 1993) in the proceedings of a previous ECMWF workshop on 'Parametrization of the cloud topped boundary layer'. This paper will concentrate mainly on precipitating layer cloud but will touch on the sensitivity of prediction of boundary layer cloud to the treatment of cloud water phase. This paper will also concentrate on the parametrization of cloud variously referred to as stratiform, dynamic, gridscale or layer cloud as opposed to convective cloud parametrization.

In addition to requirements for accurate prediction of precipitation amounts and location the short-range forecasts also need to provide a good indication of regions where the surface precipitation falls as snow rather than rain due to the catastrophic impact of snow on transport, particularly in the UK. Also as well as the requirement for accurate prediction of the location of cloud due to its impact on surface temperature and visibility, eg for aviation, there is a requirement for an accurate prediction of the phase and amount of cloud water. This is because super-cooled liquid water can lead to hazardous build-ups of ice on aircraft which is especially dangerous for helicopters.

The interaction of radiation with cloud water is also sensitive to its phase so accurate simulation of the climate radiation budget and cloud-radiation feed-backs will depend on the accuracy of the description of cloud phase within the model.

Therefore for both NWP and climate simulation a prognostic scheme for cloud water is required which will also predict the proportions of liquid and frozen cloud and precipitation.

2. CURRENT MIXED PHASE PARAMETRIZATION SCHEME IN UNIFIED MODEL

2.1 **Cloud scheme**

The current prognostic cloud water scheme used in the unified model is based on that of *Smith*, 1990. One major difference is that the cloud water content is now advected as part of a total water variable. The prognostic thermodynamic variables which are advected and also transported by the boundary layer turbulent mixing scheme in the unified model are liquid/ice temperature, T_{Li},

$$T_{Li} = T - L_e q_{cl}/c_p - (L_e+L_f)q_{cf}/c_p \quad (1)$$

and total water specific humidity, q_w ,

$$q_w = q + q_{cl} + q_{cf} \quad (2)$$

Where q_{cl} is the specific liquid cloud water, q_{cf} is the specific frozen cloud water and L_e, L_f are, respectively, the latent heats of evaporation and fusion. The liquid/ice potential temperature, $\theta_{Li} = T_{Li}/\Pi$ is actually used for advection. These variables are conserved during changes of state of water, ie during condensation, evaporation, freezing, melting and sublimation of cloud water. However, in order to calculate changes due to other processes such as radiation and the production, evaporation, freezing and melting of precipitation, the actual values of cloud water, specific humidity , cloud fraction and temperature (q_{cl} or q_{cf}, q, c and T) are required. These are diagnosed in the cloud scheme from the grid-box mean values of the 'conserved' variables, T_{Li} and q_w, assuming a subgridscale distribution of those variables comprising local values, T_{Li}^l and q_w^l . This allows some cloud to be formed when gridscale humidity is below saturation. A local supersaturation, Q_s^l, is defined such that

$$Q_s^{\,l} = q_w^{\,l} - q_{sat}(T^l, p) = Q_s + s \quad (3)$$

where $s = a_L(q_w' - \alpha_L T_{Li}')$ and $Q_s = a_L(q_w - q_{sat}(T_{Li}, p))$

and $q_w^{\,l} = q_w + q_w'$

$$T_{Li}^{1} = T_{Li} + T_{Li}'$$

$$a_L = (1+L\ \alpha_L/c_p)^{-1},\ \alpha_L = \partial q_{sat}/\partial T$$

with $q_{sat}(T, p)$ the saturation specific humidity at temperature T.

A symmetric triangular probability distribution function is assumed for the fluctuating part s with a standard deviation equivalent to

$$\sigma_s=(1-RH_c)\ a_L\ q_{sat}(T_{Li}\ ,\ p)/\surd 6 \qquad (4)$$

where RH_c is a specified level dependent critical relative humidity for cloud formation.

In calculation of subgridscale supersaturation the saturation specific humidity is calculated with respect to water at temperatures above 0°C and with respect to ice below 0°C . In the cloud scheme (and model output) the cloud water is diagnosed as liquid above 0°C and frozen below 0°C and this is the distinction used in the definition of the conserved variable T_{Li} and specification of latent heats.

The separate temperature, specific humidity and cloud water fields are also updated due to the processes of production, evaporation and melting of precipitation. The schemes are essentially those described in *Smith* (1990) apart from the parametrizations of evaporation and sublimation of precipitation which are early versions of the schemes derived in *Gregory (*1995). The temperature field is also modified due to radiative heating and cooling which depends on the radiative microphysical properties of the cloud.

2.2 Evaporation, sublimation, melting and freezing of precpitation

The evaporation coefficients are now precipitation rate dependent and separately derived for rain and snow following the method of *Kessler (*1969) to allow more rapid evaporation of snow than rain. Freezing and melting of precipitation is still calculated by assuming that the change of state takes place instantaneously and completely in the model layer containing the 0°C isotherm. For the purposes of evaporation, sublimation, freezing and melting all precipitation falling through levels with temperature below 0°C is assumed to be snow and above 0°C to be rain.

2.3 Production of precipitation

The production of precipitation is essentially as described in *Smith (*1990). The rate of conversion of cloud liquid water to rain is parametrized using the formulation for autoconversion proposed by *Sundqvist* (1978) and (1981) but modified to allow for accretion on precipitation falling from above after *Golding (*1986). As in *Smith (*1993) a lower cloud water content for efficient conversion to rain is used over sea than land.

There is no explicit parametrization of the deposition and aggregation of cloud ice particles to form snow, snow is treated as falling ice cloud . The justification for this is that in liquid water clouds the available condensed water is spread over many cloud condensation nuclei (CCN) and few drops are large enough to fall out . However very few CCN act as ice nuclei so cloud water in ice clouds is spread over fewer, larger particles, all of which quickly develop appreciable fall speeds. The rate of change of cloud ice in a layer is therefore the divergence of the flux of the falling ice particles across the layer.

$$\partial q_{cf}/\partial t = \{ P_* - \rho q_{cf} v_F \}/(\rho \Delta z) \qquad (5)$$

where P_* is the proportion of the frozen precipitation entering the layer (after allowing for changes of state) which is assumed to remain there, rather than fall through it. The fall-out speed of the ice, v_F, is parametrized in terms of the in-cloud water content $q_c=q_{cf}+q_{cl}$ using a formula deduced from observations by *Heymsfield*, 1977:

$$v_F = 3.23\ (\rho q_c/c)^{0.17} \qquad (6)$$

In contrast to the processes represented in section 2.1 and 2.2 above, where all condensed water is treated as frozen below 0°C and liquid above 0°C , in the production of precipitation a very simple parametrization of mixed phase cloud is used to allow for the presence of some supercooled liquid water cloud which has a lower efficiency of precipitation production than ice. Above 0°C all cloud water is assumed to be liquid and below -15°C all frozen. Between -15°C and 0°C the proportion of liquid cloud f_L in a grid box is assumed to be given by a quadratic spline;

$$f_L = \{(T+15)/5\}^2/6 \quad \text{for } -15°C < T < -5°C \qquad (7)$$

$$f_L = 1 - (T/5)^2/3 \quad \text{for } -5°C < T < 0°C$$

2.4 **Radiation**

Simple parametrization of cloud optical properties which depend on the predicted cloud water path are used in both the long-wave (*Senior and Mitchell*, 1993) and short-wave radiation (*Slingo*, 1989) schemes. The long-wave radiation scheme also requires an absorption coefficient for the condensed water and the short-wave scheme an effective radius of its drop size distribution. An attempt is made to allow for the different optical properties of ice and liquid water by using different values of absorption coefficient, k, and effective radius, r_e, for the two phases such that $k=130 m^2kg^{-1}$ and $r_e=7\mu m$ for liquid, $k=65 m^2kg^{-1}$ and $r_e=30\mu m$ for ice. Mixed phase cloud is represented using the the same temperature dependant fraction of liquid cloud as in the production of precipitation to calculate average optical properties.

2.5 **Convection**

The subgridscale convection scheme has very simple microphysics and assumes all cloud produced at temperatures below freezing is ice. It provides increments to the temperature and specific humidity fields only so does not feed directly into the gridscale cloud water fields. However if increments to specific humidity produce subgridscale saturation at the next time the cloud scheme is implemented it may result in production of some gridscale cloud. There is however a direct link to the radiation scheme as a diagnosed convective cloud water and convective cloud fraction is used in the calculation of short-wave and long-wave radiative heating and cooling rates. The calculation of optical properties uses the convective cloud top temperature as opposed to ambient temperature in the parametrisation of f_L to assign the proportion of liquid to ice phase.

3. SENSITIVITY TO PARAMETRIZATION OF MIXED PHASE CLOUD

Smith (1990) states that "The form of the partitioning curve and the lower bound of -15°C have no basis in observation or theory. The form was chosen for its simplicity and smoothness and the lower bound was chosen by 'tuning'. Excessive cloud was simulated if liquid water was assumed to exist below -15°C "
Moss and Johnson (1994) report aircraft measurements processed to determine the ratio of ice to water in mixed phase clouds. The measurements were taken from 11 flights carried out around the British Isles in several different cloud types and air masses including 4 frontal flights but predominantly cumulus and stratocumulus. The ratios were determined from averages of 2 minute horizontal runs in cloud which is equivalent to approximately 10-12km horizontal path length. They compared their observations with the *Smith* (1990) parametrization, see figure 1 and found that the line of best fit to the observations had a similar gradient to the partitioning curve of *Smith* (1990) but approximately 2.5°C warmer so that the model would overestimate the proportion of water at a given temperature. The impact of changing the partitioning curve for ice and liquid has been tested in the unified model.
Moss and Johnson (1994) find that a best line fit to all the data points, as shown in Fig. 1, gives , for T in °C:

$$f_L = 0.091T + 0.832 \quad (8)$$

This implies that ice is present at temperatures above freezing. The current unified model scheme does not allow this to occur so *Gregory and Morris (1995)*, simplified the relationship for f_L to

$$f_L = 1.0 + T/9 \quad \text{for } -9°C < T < 0°C \quad (9)$$

and tested the sensitivity of climate simulations to this modification.

3.1 Sensitivity of climate simulations

Gregory and Morris (1995) tested the sensitivity of cloud fields and radiation budget quantities to this change in the specification of precipitation from mixed phase clouds in a 4 year integration of the Met. Office Unified Model. These experiments used a low resolution version of the model, 5x7.5 deg. latitude-longitude, with 19-levels in the vertical and a timestep of 60 minutes. Fig. 2 shows the zonal mean cloud water, q_c (grid box mean values), from a 4 year experiment with the standard treatment of precipitation from mixed phase clouds and the difference resulting from the modified treatment described above. Cloud water contents are reduced locally by up to 30% in the temperature range 0 to -15 deg. C.

In conjunction with reduced cloud water contents, zonal mean cloud amounts are also decreased in the mixed phase region of both hemispheres (fig. 3). Decreases of up to 8% cloud cover in the zonal mean are found in the summer season of both hemispheres. Other changes to cloud amount are seen outside of the mixed phase region, for example over the south pole , which seem unlikely to be a direct consequence of the modified parametrization.Validation of cloud amounts simulated by models is difficult due to poor

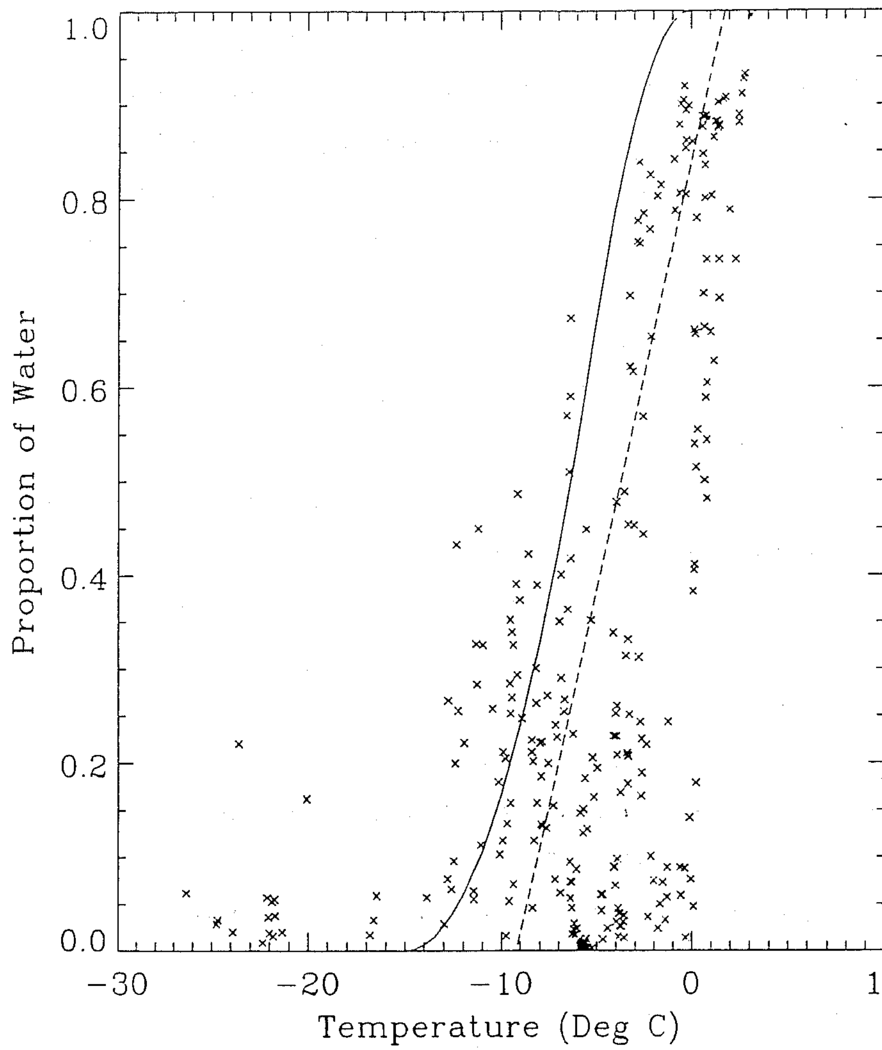

Fig. 1 Plot of the phase ratio (the proportion of liquid water to ice and liquid water) in cloud against ambient temperature (fig 7 from *Moss and Johnson* (1994)) . The aircraft data are shown as crosses, the *Smith* (1990) f_L as a solid line and the linear best fit to the aircraft data as a dashed line.

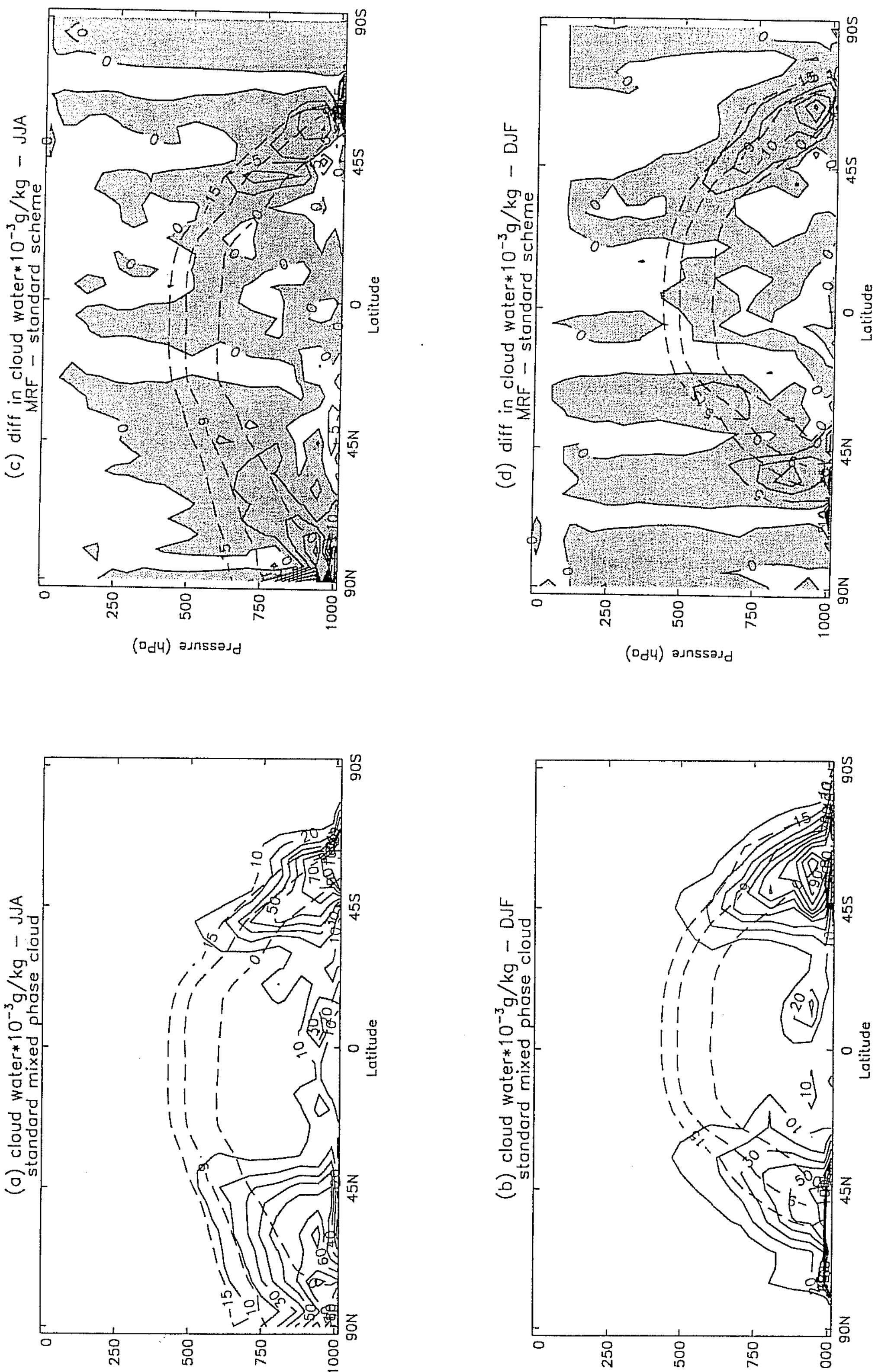

Fig. 2 Plots of zonal mean grid box cloud water contents after precipitation against model level (sigma near surface, pressure at upper levels) for June/July/August JJA and December/January/February DJF averages for standard mixed phase scheme and difference between MRF based parametrisation and standard. The heights of the zonal seasonal mean 0°C, -9°C and -15°C surfaces for the control experiment are also shown for reference. Negative differences are shaded.

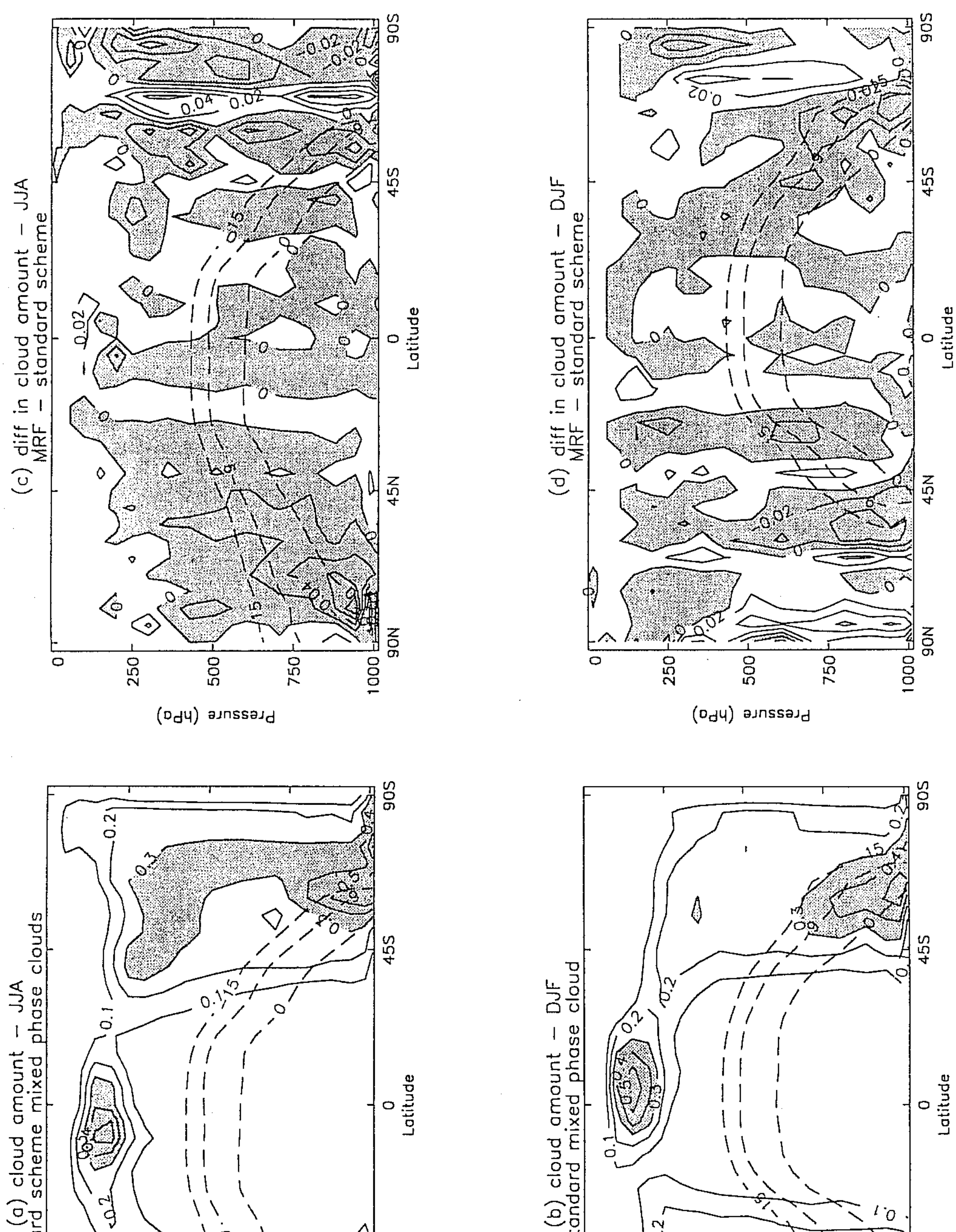

Fig. 3 Plots of zonal mean fractional cloud amount against model level (sigma near surface , pressure at upper levels) for June/July/August JJA and December/January/February DJF averages for standard mixed phase scheme and difference between MRF based parametrisation and standard. The heights of the zonal seasonal mean 0°C, -9°C and -15°C surfaces are also shown for reference. Fractions greater than 0.3 and negative differences are shaded.

observational datasets. However comparison of the model's simulation of the Earth's radiation budget does provide some insight into the accuracy of the model's cloudiness. The difference of model albedo from ERBE satellite data (1987-1991) is shown in fig. 4 for simulations with the standard and MRF mixed phase cloud scheme. With the standard mixed phase cloud scheme, during northern summer albedos are found to be excessive over northern Russia and northern Canada and Alaska. Many of these errors are reduced when the MRF parametrization is introduced, bringing the model into better agreement with ERBE over these regions. Albedos are also reduced over oceanic areas of the northern hemisphere north of 70N and also over the polar regions. Validation in this area is however difficult due to the poor quality of satellite data. The extent of the 0.2 albedo error over the north Pacific is also reduced. During northern hemisphere winter, albedos are reduced over Europe and north America and also over the storm tracks of the north Pacific and north Atlantic, generally bringing the model into closer agreement with the observations, although in the north Atlantic the negative errors are more widespread. In the southern hemisphere an extensive region of excessive albedos is reduced south of 50S through the introduction of the MRF parametrization. However differences from observations are more negative south of 60S, although validation in this region is difficult due to increasing errors in the satellite estimates.

The general improvement on the radiation budget of the mid-latitudes is confirmed when zonal means are studied (fig. 5). Albedos are found to be lower in the mid-latitudes of both hemispheres, with the largest improvements coming in the summer seasons of both the northern and southern hemispheres. These reductions in albedo bring the model closer to the ERBE estimates in these regions. Zonal mean outgoing long wave radiation is little changed through the use of the MRF parametrization, although small increases are found in the mid-latitudes of the northern hemisphere in JJA (fig. 5).

3.2 Sensitivity of mesoscale forecasts

In order to investigate the impact of changes in the f_L parametrization in more detail, to relate the results to the synoptic situation and to compare with observations the sensitivity has also been tested in the mesoscale version of the unified model. Results from three cases are discussed here. These are forecasts from 1800UTC 27/4/92 of a developing frontal wave, 0000UTC 2/11/93 of stratocumulus and frontal cloud and 0600UTC 8/11/93 of an occluded front. For these cases the model was run using the standard version of f_L setting mixed phase cloud between 0°C and -15°C , the MRF based version setting mixed phase cloud between 0°C and -9°C and a third version setting all cloud at temperatures below 0°C to be ice.

3.2.1 Developing frontal wave 1800UTC 28/4/92

In fig.6 results from a 12hour forecast for 0600UTC 28/4/92 are compared. The figures 6c) and d) show domain averages of the model output variables which are the cloud condensed water at temperatures less than 0°C and the cloud condensed water at temperatures greater than 0°C . It can be seen that when a greater fraction of the cloud is treated as ice in the precipitation scheme, ie changing from standard to MRF

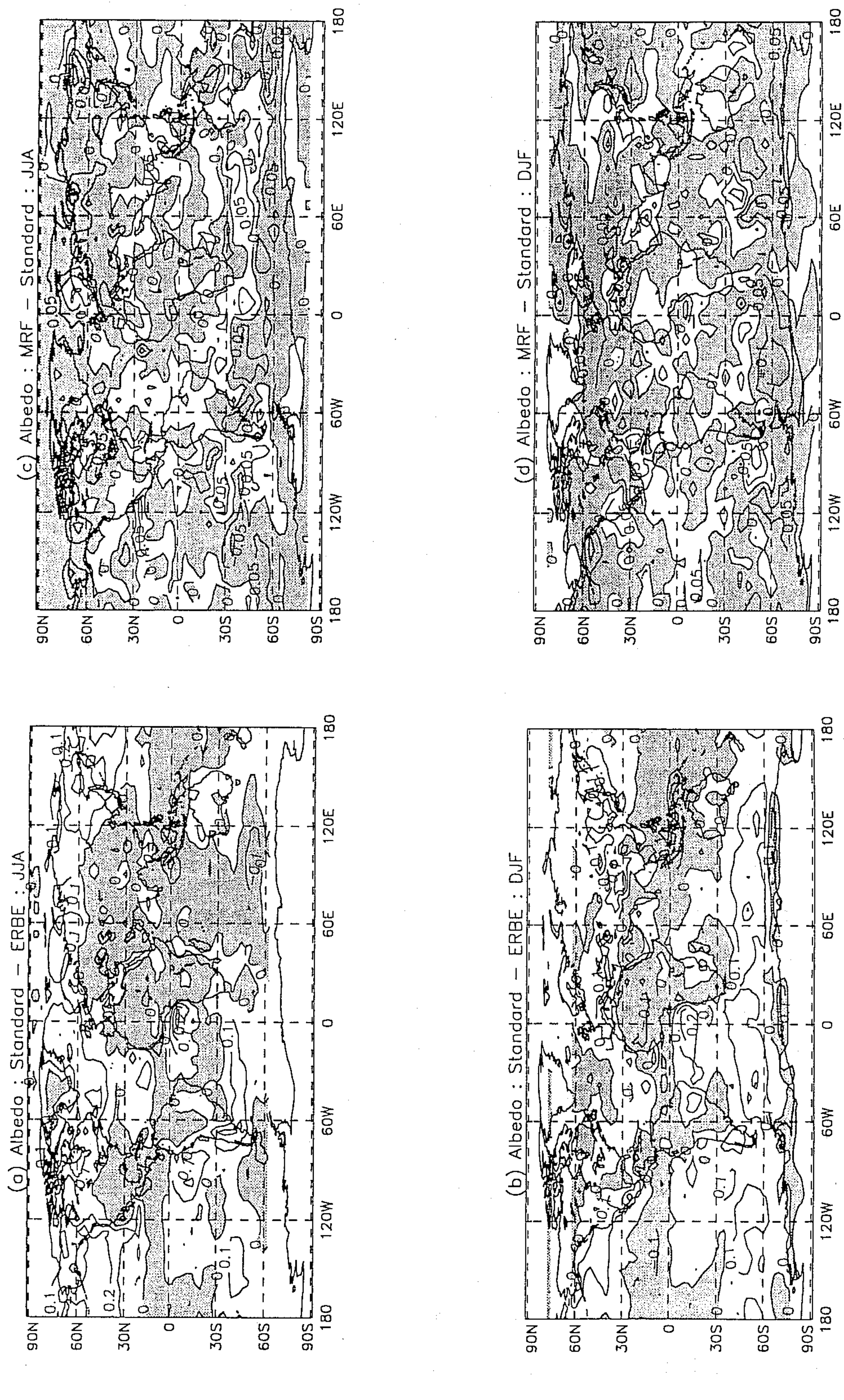

Fig. 4 Plots of difference from ERBE albedo for June/July/August JJA and December/January/February DJF averages for standard mixed phase scheme and difference in albedo between MRF based parametrisation and standard scheme. Negative differences are shaded.

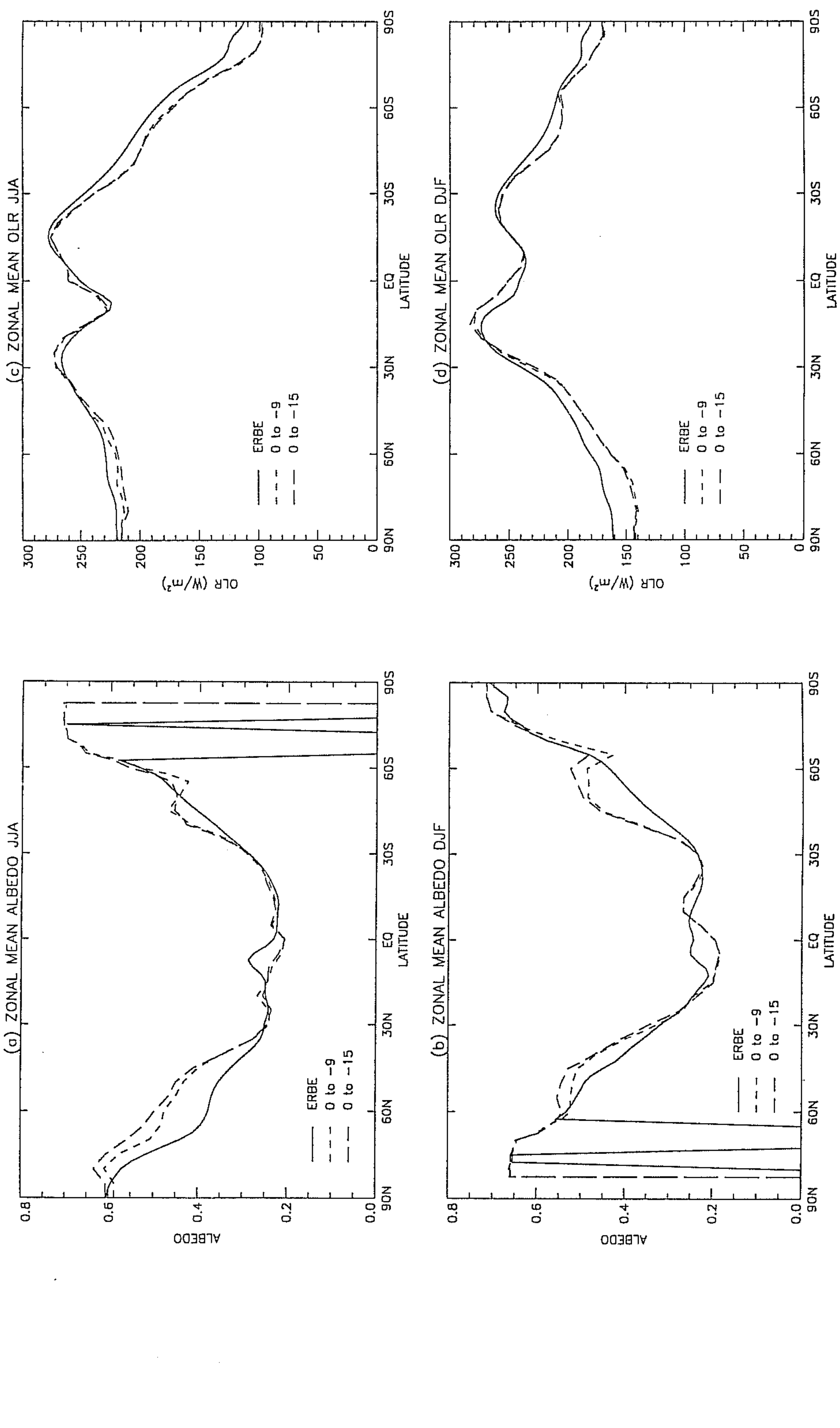

Fig. 5 Plots of zonal mean albedo and outgoing longwave radiation (OLR) for June/July/August JJA and December/January/February DJF averages for standard mixed phase scheme, MRF based parametrisation and ERBE.

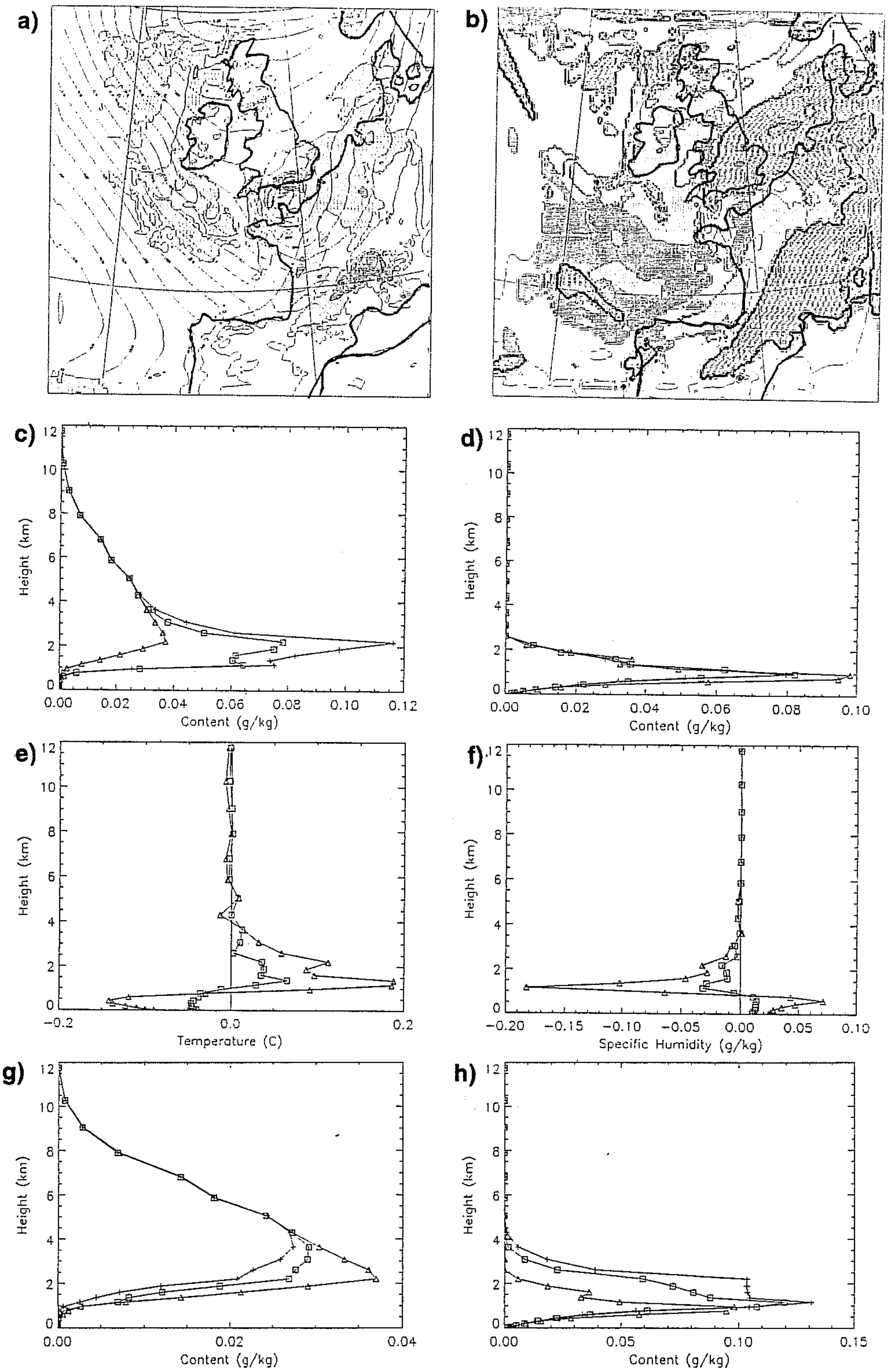

Fig. 6 Comparison of 12 hour forecasts for 0600UTC 28/4/92 . a) forecast mean sea level pressure and surface precipitation rate from standard f_L light shading > 0.05mm/hr, dark shading > 1mm/hr .b) forecast cloud top temperature from standard f_L dark shading tops 0 to 5°C, light shading tops -15 to 0°C, banded shading tops < -15°C. c) comparison of domain average cloud condensed water at temperatures < 0°C. d) comparison of domain average cloud condensed water at temperatures > 0°C. e) difference in mean temperature from forecast with standard f_L. f) difference in mean specific humidity from forecast with standard f_L. g) comparison of domain average condensed cloud water treated as ice. h) comparison of domain average condensed cloud water treated as liquid water. + using standard f_L ie mixed phase cloud 0 to -15°C , □ using MRF based f_L ie mixed phase cloud 0 to -9°C and △ treating all cloud <0°C as ice.

based scheme to all ice, the total amount of condensate at sub-zero temperatures retained in the model is greatly reduced. In the case with no cloud treated as mixed phase there is also an increase in cloud liquid water at temperatures above freezing. Also with a greater proportion of ice there is a slight increase in temperature and decrease in specific humidity in the affected height range and the opposite effect at lower levels. The output cloud condensed water at temperatures less than freezing can be considered to be a mixture of ice and liquid as defined by f_L. f_L can be used with the output temperature to calculate amounts of supercooled liquid water and ice. Figures 6g) and h) show the averages of all cloud treated as ice and all cloud treated as liquid irrespective of temperature. It can be seen that, although peak amounts of cloud ice have increased slightly and there is a greater amount of ice at lower levels, the reduction in sub-zero cloud condensate is through a reduction in supercooled liquid water which is not matched by a corresponding increase in cloud ice. Despite the large changes in cloud water content there was little impact on surface precipitation or mean sea level pressure which were well forecast. The location of precipitation and predicted rates were essentially the same in all runs with only slight changes in the location of the maximum rates.

3.2.2 sub-zero cloud top stratocumulus 0000UTC 2/11/93

One cloud type that may be critically affected by treatment of mixed phase cloud is stratocumulus with sub zero cloud tops. The 2/11/93 case was selected for investigation for this reason. The domain average comparisons for the 12 hour forecast for 1200UTC 2/11/93 are in broad agreement with those for 0600UTC 28/4/92. However they were complicated by the fact that there were three distinct cloud systems within the domain, frontal cloud in the west and south and anticyclonic stratocumulus in the northeast (fig 7a) and b)). The main freezing level was at about 750mb, however the minimum temperature at the top of the stratocumulus below the anticyclonic subsidence inversion was also just below zero at around 900mb. This resulted in double peaks in the cloud water profiles. To simplify interpretation, profiles at a point, 57N 1W, in the stratocumulus were compared as shown in fig. 7c). Here it can be seen that as less cloud is treated as supercooled liquid water the height of the cloud deck is reduced. The inversion height is also reduced. The lowering of the inversion is presumably because the extra ice falls out and significant cloud condensate is only retained below the freezing level so the cloud top with its associated cooling occurs at a lower altitude. Verification can be provided by comparison with the radiosonde ascent at Boulmer at 55.4N 1.6W. At this location the model sensitivity results were basically the same as above. The comparison of model and observed ascents show that best agreement is produced with the standard form for f_L (fig. 8).

3.2.3 occluded front 0600UTC 8/11/93

It is clear from the above results that direct measurements of cloud ice and liquid water contents, particularly supercooled liquid water, would be invaluable for verification and development of the microphysics schemes. On 9/11/93 direct aircraft measurements from the Met Office C130 coincident with 3GHZ dual-polarisation Chilbolton radar(51.13N 1.43W) RHI scans (140km range) were available. The aircraft data provided measurements of the size, shape and number concentration of large water and ice particles (25μm to

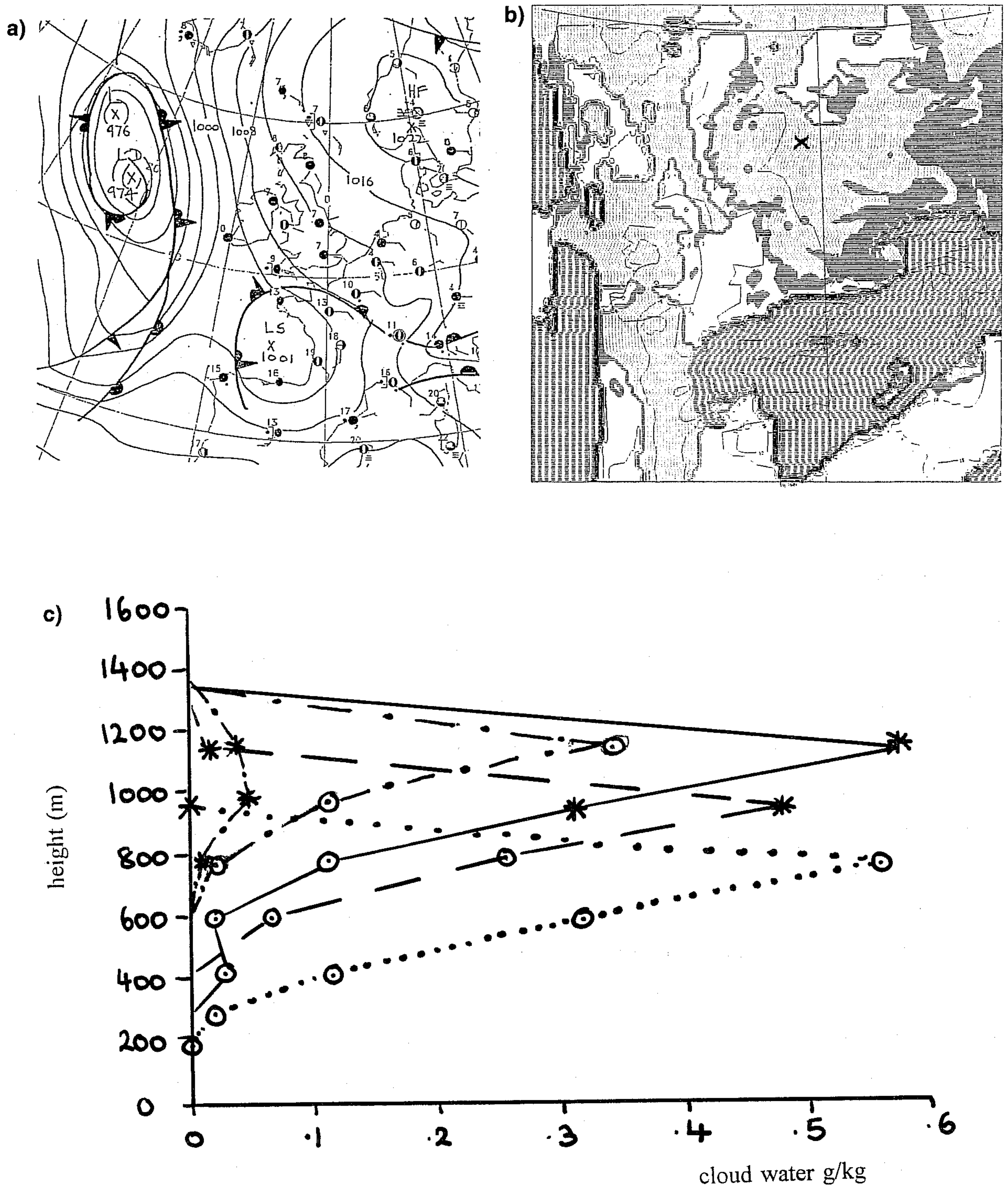

Fig. 7 Comparison of 12 hour forecasts for 1200UTC 02/11/93. a) analysed mean sea level pressure and location of surface fronts. b) forecast cloud top temperature from standard f_L dark shading tops 0 to 5°C, light shading tops -15 to 0°C, banded shading tops < -15°C. c) comparison of forecast profiles of cloud water at 57N 1W in the region of stratocumulus, position marked x in b), solid line using standard f_L ie mixed phase cloud 0 to -15°C , dashed line using MRF based f_L ie mixed phase cloud 0 to -9°C and dotted line treating all cloud <0°C as ice. points where temperature <0°C shown as $*$ and points with temperature > 0°C shown as ⊙. Also shown are the profiles from the new cloud scheme, sections 4 and 5, as the dash-dot lines with the liquid water, ⊙ and ice profiles, $*$ shown separately.

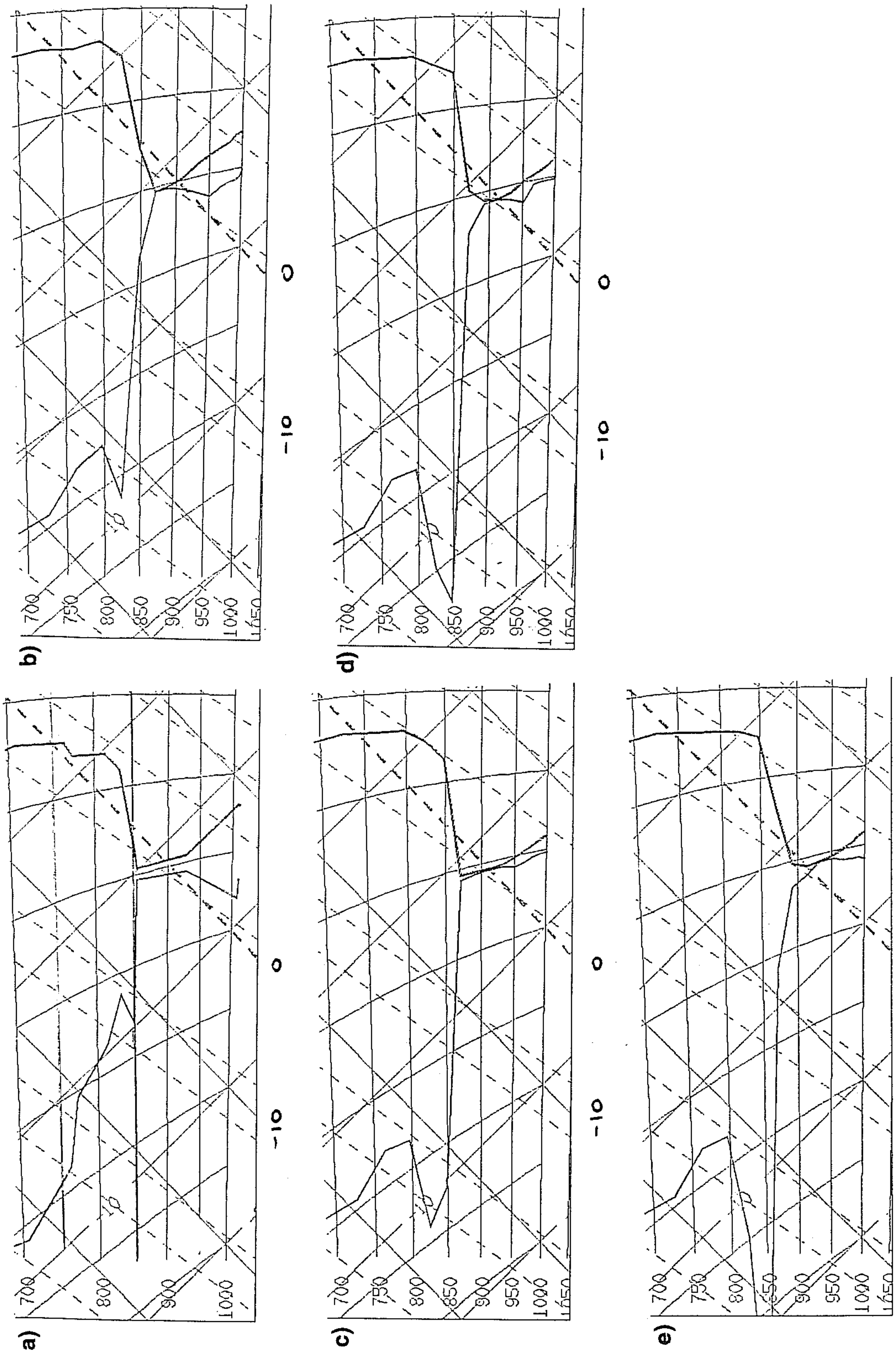

Fig. 8 Comparison of tephigrams for 1200UTC 02/11/93 at Boulmer , 55.4N 1.6W a) actual observed ascent, b) 12 hour forecast from new scheme, section 5, c) 12 hour forecast from original scheme using standard f_L ie mixed phase cloud 0 to -15°C, d) as c) but using MRF based f_L ie mixed phase cloud 0 to -9°C , e) as c) but treating all cloud <0°C as ice.

6400μm) in 8 profiles and 9 levels runs at 1.4°C , -3.8°C , -17.6°C , -19.8°C -26.4°C and 4 near -34°C.

Results from a 36 hour forecast from 0600UTC 8/11/93 were compared with the observations. The general timing and location of the frontal passage across the UK are forecast well, although there are differences in detail, as can be seen in fig. 9.

Again the domain average comparisons for a 30 hour forecast for 1200UTC 9/11/93 were in broad agreement with those for 0600UTC 28/4/92. Despite the large changes in cloud ice and liquid water content, the distribution and magnitude of precipitation rates was hardly affected by the changes to the parametrisation of mixed phase cloud. The mean precipitation rate over the centre of the domain (excluding a rim of 20 points to avoid regions affected by mismatch with boundary conditions) varied from 0.617 mm/hr, standard, to 0.620 mm/hr, MRF, to 0.632 mm/hr, no mixed. The mean accumulated precipitation over the same domain also showed very little change eg 4.36mm, 4.40mm and 4.50mm between 0600UTC and 1200UTC and 3.25mm, 3.28mm and 3.32mm between 1200UTC and 1800UTC for the three schemes standard, MRF and no mixed respectively. There is obviously a slight increase as more cloud is treated as ice but only up to 2 to 3%.

In fig. 10 cross-sections of cloud condensed water at temperatures less than 0°C from the model forecasts for 1400UTC are compared with cloud ice derived from an RHI scan . The radar reflectivity is calibrated in terms of ice water content based on the aircraft data from the run at -3.8°C and some profile data. The observed increase in height of significant reflectivity from the west to the east of the section is well predicted by the model even though it cannot resolve the detailed structure such as the hole in the precipitation and presumably cloud at 70km range from Chilbolton.

It can be seen from fig. 10 that the standard and MRF based schemes gave larger amounts of total cloud water, peak amounts of 0.8g/m^3 at 3km(standard) and 2.5km(MRF) , than the amounts of ice derived from the radar(max 0.3g/m^3 at freezing level but generally 0.1g/m^3) and aircraft data (max ice 0.3g/m^3 at 2.8km, max liquid water 0.1g/kg) . The forecast with all cloud water treated as ice (max ice 0.4g/m^3 at 2.5km) is closer to the radar data. Use of the parameter f_L to estimate the fractions of the total condensate treated as ice and liquid respectively (see fig. 13) give ice water contents from the MRF and standard schemes (max < 0.3g/m^3) in much better agreement with the observations, however the vertical structure seems unrealistic as that forces the maximum in ice content to be above the freezing level at 3.5km and 4km respectively. These schemes also imply high super-cooled liquid water contents (standard 0.75g/m^3 at 3km, MRF 0.7g/m^3 at 2.5km) which are much higher than any amounts derived from the aircraft data, max 0.1g/kg. In interpreting these results differences in model output variables and quantities derived from the observations plus their limitations need to be considered. The model liquid water is essentially the cloud droplets and excludes all liquid water converted to precipitation whereas the model ice water does not distinguish between

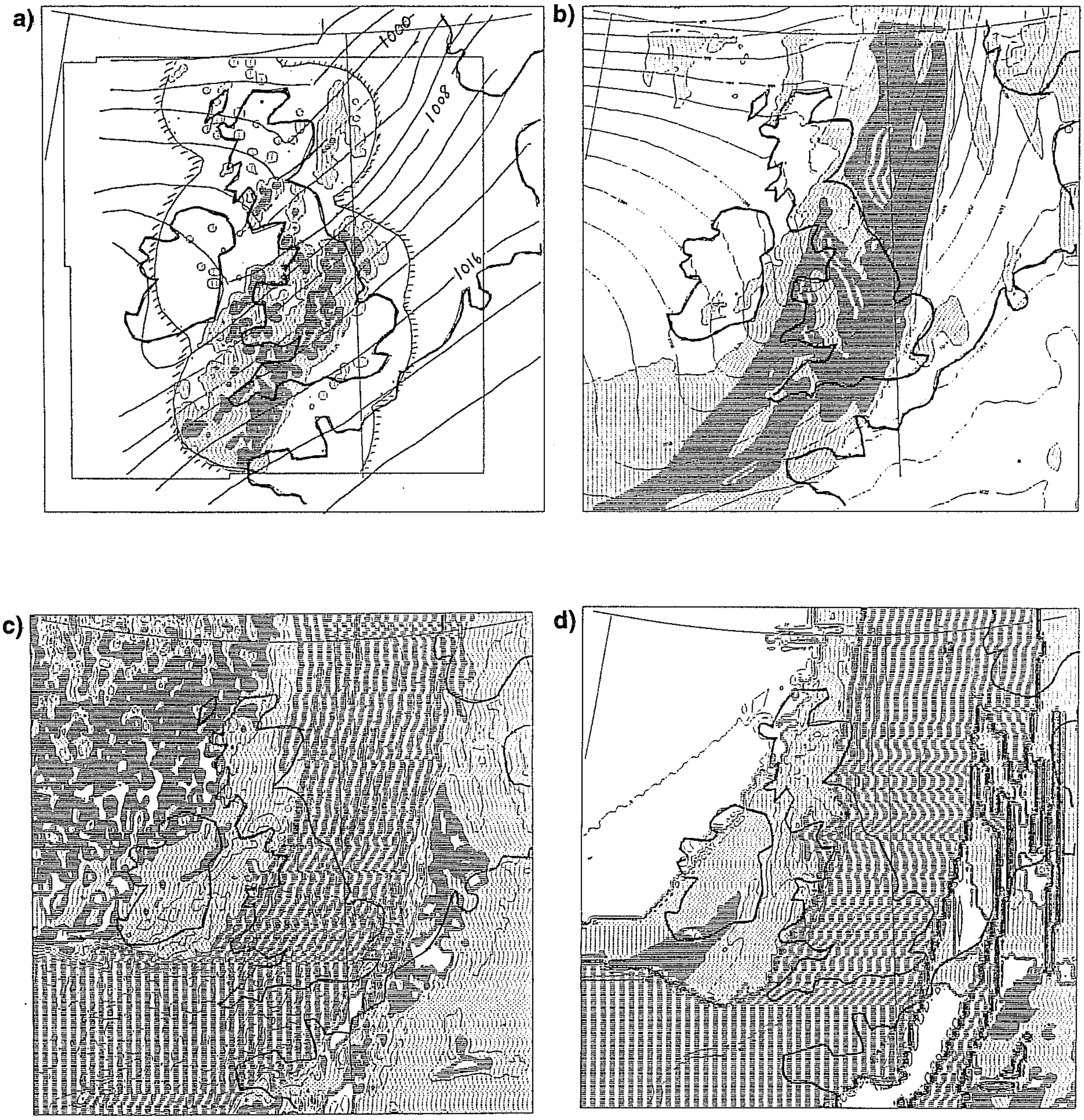

Fig. 9 Comparison of observed and forecast surface precipitation and cloud top temperature from 0600UTC 8/11/93 forecast. a) FRONTIERS radar derived surface rain rate mm/hr and mean sea level pressure analysis at 1400UTC 9/11/93, light shading rates 0.05-1 mm/hr, dark shading 1-2 mm/hr, banded shading > 2 mm/hr. b) 32 hour forecast of surface precipitation rate and mean sea level pressure from forecast with standard f_L shading as a). c) Meteosat IR image for 1230UTC 9/11/93, contours every 5°C , shading as figure 6b). d) 30 hour forecast of cloud top temperature (temperature of highest level with ≥99% relative humidity) shading as figure 6b), note convective cloud is neglected in the model data.

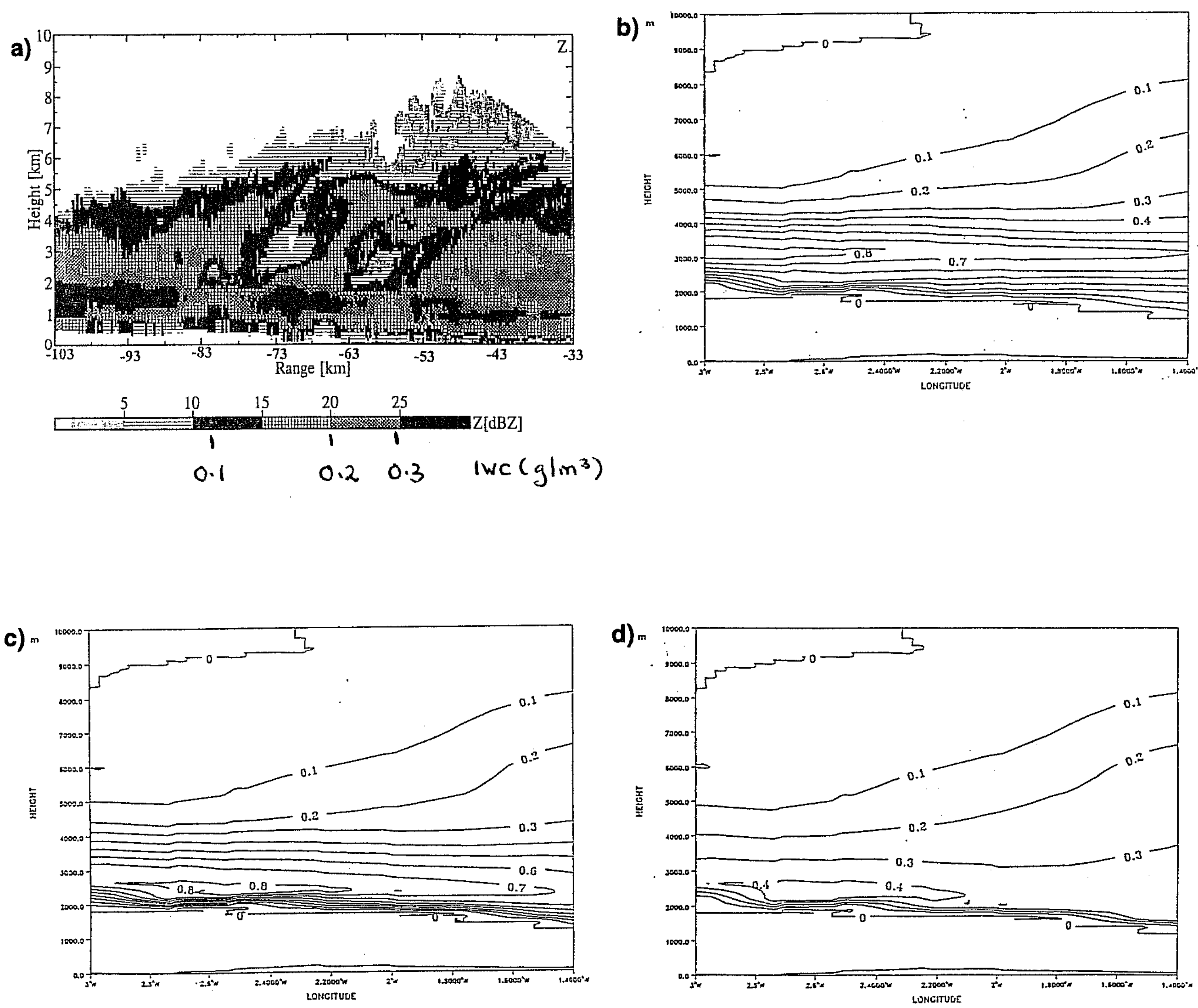

Fig. 10 Comparison of 80km cross-sections of cloud ice at 1400UTC 9/11/93 along 270° azimuth from Chilbolton ie 51°N 3°W to 51°N 1.4°W. a) Chilbolton radar reflectivity calibrated as cloud ice (g/m^3) at 1410UTC. b) 32 hour forecast for 1400UTC of cloud ice (g/m^3) (cloud condensate <0°C) from original scheme using standard f_L ie mixed phase cloud 0 to -15°C, c) as b) but using MRF based f_L ie mixed phase cloud 0 to -9°C , d) as b) but treating all cloud <0°C as ice.

cloud and precipitation and both are included in the diagnosed ice. In contrast the aircraft and radar measurements are biased towards large precipitation size particles. The limitations of the aircraft measurements are discussed in *Moss and Johnson (1994)* and *Bower et al (1995)*. It is important to know whether the difficulties in detecting super-cooled liquid water, particularly the cloud size particles could account for the differences between the forecasts using the standard and MRF schemes and the amount estimated from the aircraft data. It seems unlikely that such high undetected supercooled liquid cloud water contents could be present.

There is another aspect of the precipitation scheme that is important in determining the cloud water contents. This is the treatment of falling ice. In section 2.3 the flux divergence of falling ice was defined in equation (5). The original formulation in the unified model solved this equation implicitly and assumed that P_* was the fraction of precipitation from the layer above that was produced from ice cloud as opposed to supercooled liquid water. However there are problems with this treatment of falling ice. For long timestep integrations it can result in prediction of erroneously high ice amounts at cloud base as the scheme does not allow ice to fall through layers that originally contained no ice. Also it can produce erroneous treatment of evaporation as ice falling into low humidity cloud free layers will be effectively instantaneously "sublimated" by the cloud scheme repartitioning total water into vapour and condensate. One method, now used in the operational versions of the NWP models (global, LAM and mesoscale) to reduce surface fog associated with precipitation and production of spurious superadiabatic lapse rates, is to set P_* to zero, ie assume that all ice falling out of a layer is added to a precipitation flux that falls through lower layers without adding to the cloud ice. The results discussed above all assumed that ice falling out of upper layers added to the cloud ice in the lower layers. The 0600UTC 8/11/93 forecast using the standard parametrisation and all ice parametrisation were rerun with P_* set to zero. As can be seen from fig. 11 this has produced a large reduction in cloud ice and in the case of the standard parametrisation also a reduction in diagnosed supercooled liquid water. Again there is only a slight increase in the average precipitation rate increasing to 0.634mm/hr for the standard scheme and 0.644mm/hr for all ice at 1200UTC.

3.3 Discussion

The change to f_L has not simply repartitioned the initial amount of cloud water between the two phases. The reduction in total sub-zero cloud condensate essentially results from the greater efficiency of the ice fallout processes. Once formed all ice particles are available for precipitation, whereas typical of a wide range of microphysics parametrizations, water condensate has to reach a critical amount for precipitation to form. For a 1km thick cloud this can lead to ice precipitation being about 10 times more efficient than the production of rain at the removal of cloud condensate for cloud condensate in the range of 0.2 to 1.0 g/kg. Despite the large reduction in cloud condensate when a greater proportion is treated as ice there seems to be little impact on the surface precipitation rates; this was seen in the climate runs as well as the mesoscale forecasts. This is in agreement with studies by *Wexler and Atlas (1958)* which showed computed precipitation rates with

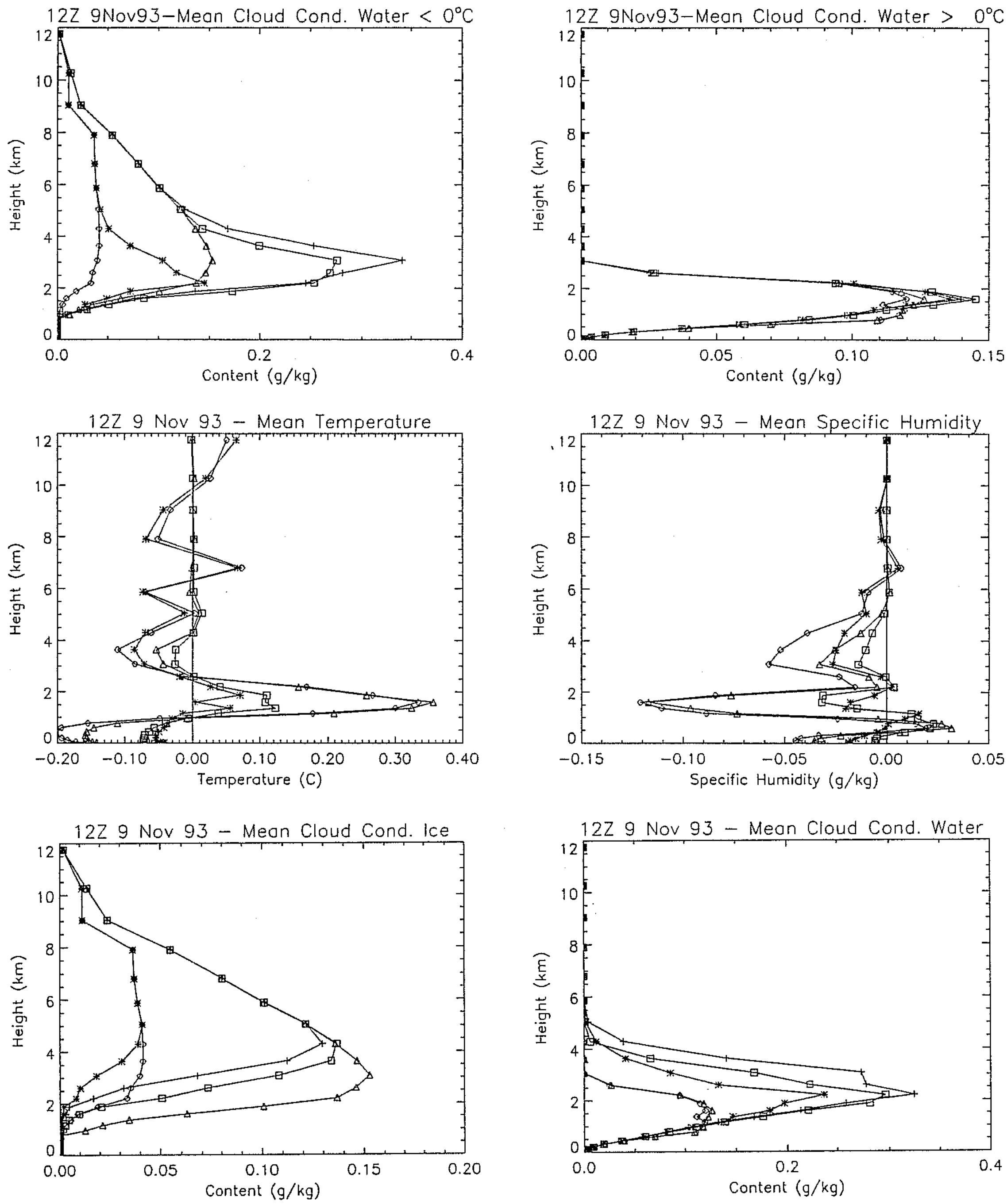

Fig.11 Comparison of 30 hour forecasts for 1200UTC 9/11/93 .a) comparison of domain average cloud condensed water at temperatures < 0°C. b) comparison of domain average cloud condensed water at temperatures > 0°C. c) difference in mean temperature from forecast with standard f_L. d) difference in mean specific humidity from forecast with standard f_L. e) comparison of domain average condensed cloud water treated as ice. f) comparison of domain average condensed cloud water treated as liquid water. + using standard f_L ie mixed phase cloud 0 to -15°C , □ using MRF based f_L ie mixed phase cloud 0 to -9°C , △ treating all cloud <0°C as ice, $*$ using standard f_L ie mixed phase cloud 0 to -15°C with P_*=0, ◊ treating all cloud <0°C as ice with P_*=0,

cloud storage at most 3% above those computed without storage. The precipitation intensity is dominated by the product of the vertical mass transport of air in a layer and the difference in saturation specific humidity between the top and bottom of the layer. There may still be some local differences important in accurate short range forecasting of precipitation but this would need further investigation.

However the amount and phase of cloud condensate is important in the radiative heat budget. For the climate runs the results in section 3.1 using the MRF based parametrization do show improvements over the standard ad-hoc parametrization and demonstrate the sensitivity of cloud and radiation simulations to the specification of precipitation processes in mixed phase clouds.

The results at mesoscale resolution are more mixed. For deep frontal cloud the reduction in cloud condensate from the MRF based scheme is in better agreement with observations but the results using all ice below zero are even better. However for shallow stratocumulus there was a detrimental effect on the height of the cloud deck (see fig. 8).

It can be seen from fig. 1 that there is a wide spread in the observed relationship between the fraction of liquid water and temperature. The best fit line presented by Moss and Johnson (1994) had only a correlation coefficient of 0.56 with the observations and they questioned the validity of a simple parametrization of ice water ratio as a function of ambient temperature. The validity of a scheme based on cloud top temperature, *Golding* (1986) ,was also tested in *Moss and Johnson* (1994) . This scheme assigned all cloud water to be liquid unless the cloud top temperature was less than -15° when the whole cloud was assumed glaciated to just below the freezing level. However there appeared to be no simple relationship between cloud top temperature and cloud phase. The results indicated that over distances of tens of kms it is not valid to assume that a cloud can be all liquid or all glaciated so that some allowance for mixed phase cloud or a more detailed ice parametrization is required.

Moss and Johnson (1994) and *Bower et al (1995)* also suggest slightly different parametrizations for land and sea giving a higher proportion of ice at a given temperature in clouds in maritime rather than continental air masses. This is consistent with differences in aerosol concentrations. However this separation of air mass does not reduce the scatter of the observations.

Bower et al (1995) separate out frontal and convective clouds. For the frontal clouds the results were similar to *Moss and Johnson* (1994) . However there was a clearer indication that frontal clouds were seen to have very low values of phase ratio, f_L, over a wide range of temperature, indicating the presence of high ice fractions even at temperatures just below 0°C. A wide range of phase ratios was only observed close to the freezing level. In contrast, in convective clouds the range of phase ratios was large across the whole temperature range (0 to -30°C).

The solution to the problem of falling ice described in section 3.2 may be adequate as a short term measure for NWP where only the precipitation forecasts are required , the radiative heat budget is not important and accurate forecasts of cloud condensate amounts and phase are not required. However the neglect of the ice precipitation in the cloudiness and radiation calculations is unsatisfactory for climate simulations. This indicates that falling frozen cloud water and cloud fraction should be carried separately from the total water in the model.

The results in section 3.2 and work of *Moss and Johnson* (1994) and *Bower et al (1995)* indicate that a more sophisticated treatment of cloud phase is required both in defining the proportion of liquid and ice phase cloud and precipitation and the treatment of falling ice.

4. NEW MIXED PHASE CLOUD AND PRECIPITATION SCHEME

To avoid the limitations of parametrizations of the ratio of ice to liquid cloud water new cloud and precipitation schemes are being developed for the unified model with more detailed ice microphysics to enable separate prediction of ice and liquid water cloud.

In this the advected variables are liquid potential temperature, θ_L, total nonfrozen water, $q_{nf,}$ and ice/snow, q_{cf}, ie

$$\theta_L = \theta - L_e q_{cl}/c_p \Pi \ , \quad q_{nf} = q + q_{cl} \ \text{ and } \ q_{cf} \qquad (10)$$

and turbulently mixed variables are
$T_L = T - L_e q_{cl}/c_p$ and $q_{nf} = q + q_{cl}$ (q_{cf} should also be mixed but scheme has not been formalised yet).

The cloud scheme is modified to calculate a liquid cloud fraction, temperature, humidity and cloud liquid water from T_L and q_{nf} using subgridscale supersaturation with respect to water at all temperatures.

Changes to the ice/snow variable are calculated within the microphysics routines and cloud fraction is reset to unity if some ice/snow is present at a given point and level. A more detailed ice fraction scheme will be formulated at a later date.

For initial tests the scheme is a modification of one developed for the UK Met office non-hydrostatic model, *Golding* (1992) ,*Golding* (1993) , *Marecal et al* (1994).

The microphysical exchange terms are currently mainly after *Rutledge and Hobbs* (1983) with some modifications based on *Cox* (1988), such as inclusion of a temperature dependence for the ice crystal/snowflake size distribution. Following *Golding* (1992) and (1993), the scheme is simplified to have a combined prognostic ice/snow variable and no separate graupel variable. For implementation in the unified model, which will also run with much longer timesteps, the scheme is further simplified to treat rain as a diagnostic rather than prognostic variable.

The ice/snow fall speed uses the formula of *Heymsfield* (1977). Autoconversion of cloud water to rain does not use the *Rutledge and Hobbs* (1983) Kessler type expression but is as in *Cox* (1988) after the scheme of *Tripoli and Cotton* (1980). The prognostic term for melting of the ice/snow variable uses wet bulb temperature rather than temperature and the melting level is defined as the level where T_W =0°C. This allows for delayed melting in dry air due to evaporation of liquid water from the surface of a melting snowflake, which will cool the snowflake to the wet bulb temperature and delay melting until the wet bulb freezing level is reached, as observed by *Matsuo and Sasyo (1981)*. At present there is no explicit parametrization of secondary ice production such as Hallet-Mossop process, *Hallet and Mossop (1974)*, ice splintering etc.
The processes included are :
fall of ice/snow - uses fall speed after *Heymsfield (*1977)
ice/snow formation - *Rutledge and Hobbs (1983)* with ice nuclei concentration after *Fletcher (1962*)
deposition of ice/snow from liquid water and vapour - as *Rutledge and Hobbs (1983)* but including pressure dependence of diffusivity of water vapour after *Rogers and Yao (1989*)
sublimation of ice/snow to vapour - reverse of deposition
riming of snow from liquid water - *Rutledge and Hobbs (1983)*
evaporation of melting snow - *Rutledge and Hobbs (1983)*
melting - *Rutledge and Hobbs (1983*) but using wet bulb temperature
evaporation of rain - *Rutledge and Hobbs (1983*)
accretion of cloud water onto rain - *Rutledge and Hobbs (1983)* but using fallspeed for rain

$$V_R=33.2\rho_a^{-0.15}q_r^{0.25}$$

autoconversion of cloud liquid water to rain - *Tripoli and Cotton* (1980).

5. IMPACT OF NEW SCHEME IN MESOSCALE FORECASTS

The 0000UTC 2/11/93 and 0600UTC 8/11/93 forecasts have been rerun with the new scheme. The initial and boundary conditions for these forecasts were provided from the operational forecasts using the standard scheme. These were provided as liquid/ice temperature, T_{Li}, and total water specific humidity, q_w . It was assumed that these were equivalent to the initial liquid temperature, T_L and total nonfrozen water, q_{nf}. The initial ice/snow, q_{cf}, was set to zero.

At 1200UTC 2/11/93 the stratocumulus was predicted to be mainly liquid (as can be seen from fig. 7c)), even in the sub-zero cloud top region and the cloud top height was similar to the standard forecast in good agreement with the observations. From fig. 8b) it can be seen that at Boulmer the temperatures within the inversion, and its height have the best agreement with the observations, as does the surface temperature.

However the cloud water contents and cloud depth are reduced. The deep frontal cloud is predicted to be mainly ice at temperatures below the freezing level with ice contents similar to the forecast from the original cloud scheme with all cloud water treated as ice at sub-zero temperatures. The impact on domain average temperatures and humidities are in the opposite sense to those due to changes to f_L in the original scheme. Domain averaged liquid water at all model levels is lower than given by the standard f_L in the original scheme. Average ice amounts are also lower at upper levels but, as with the original all ice T<0°C version, peak amounts occur at lower height, just above the freezing level, than in the standard version. Around 1km there are higher ice amounts in the new scheme than the other versions. This is due to the retention of stratocumulus with sub zero cloud tops which is more glaciated than predicted by the standard f_L. Peak average ice amounts in all schemes are almost a factor of 10 lower than peak average liquid water amounts.

In the 0600UTC 8/11/93 forecast results were similar to those for the frontal cloud in the previous case. Domain average ice and liquid water profiles were similar to those for the original all ice T<0°C version apart from the prediction of some super-cooled liquid water (fig. 12). However, near the freezing level, supercooled liquid water amount was about a factor of 10 lower than the amount of supercooled liquid water diagnosed from the original scheme with standard f_L . Again temperature and humidity variations were in the opposite sense to the f_L sensitivity results. Ice water contents in the Chilbolton cross-section (fig. 13) were also similar to those for the original all ice T<0°C version and it can be seen that the sub-zero cloud is essentially all glaciated . Precipitation rates and their distribution were very similar to the original scheme although the domain average precipitation rate was slightly lower at 0.592mm/hr. From inspection of cross-sections it was apparent that the reduction of cloud water contents in the new scheme was not uniform throughout the domain. Values remained high in areas of greatest ascent, associated with the highest surface precipitation rates, and were reduced preferentially in areas of weak ascent or descent. Pockets of supercooled liquid water at elevated levels were also associated with the regions of greatest ascent.

Using the forecast for 1200UTC 9/11/93 a scatter plot of liquid water fraction against temperature was produced to compare with the aircraft observations from *Bower et al* (1995) (fig.14). The outer 20 rows and columns were ignored to remove boundary effects and only points with greater than 0.1g/kg total water content were included to avoid dominating the results with points with essentially zero cloud water content. The results are remarkably similar to the aircraft observations, particularly the dense cluster of points with high ice ratios between 0°C and -10°C and the wide spread of ratios between about 0°C and -6°C . Both aircraft data and model results show some ice at temperatures above freezing but the model has much higher ice ratios.

6. CONCLUSIONS

From sections 3 and 5 it can be seen that cloud water content, humidity, temperature and albedo are all sensitive to the parametrization of mixed phase cloud. There is some sensitivity in the precipitation rates but,

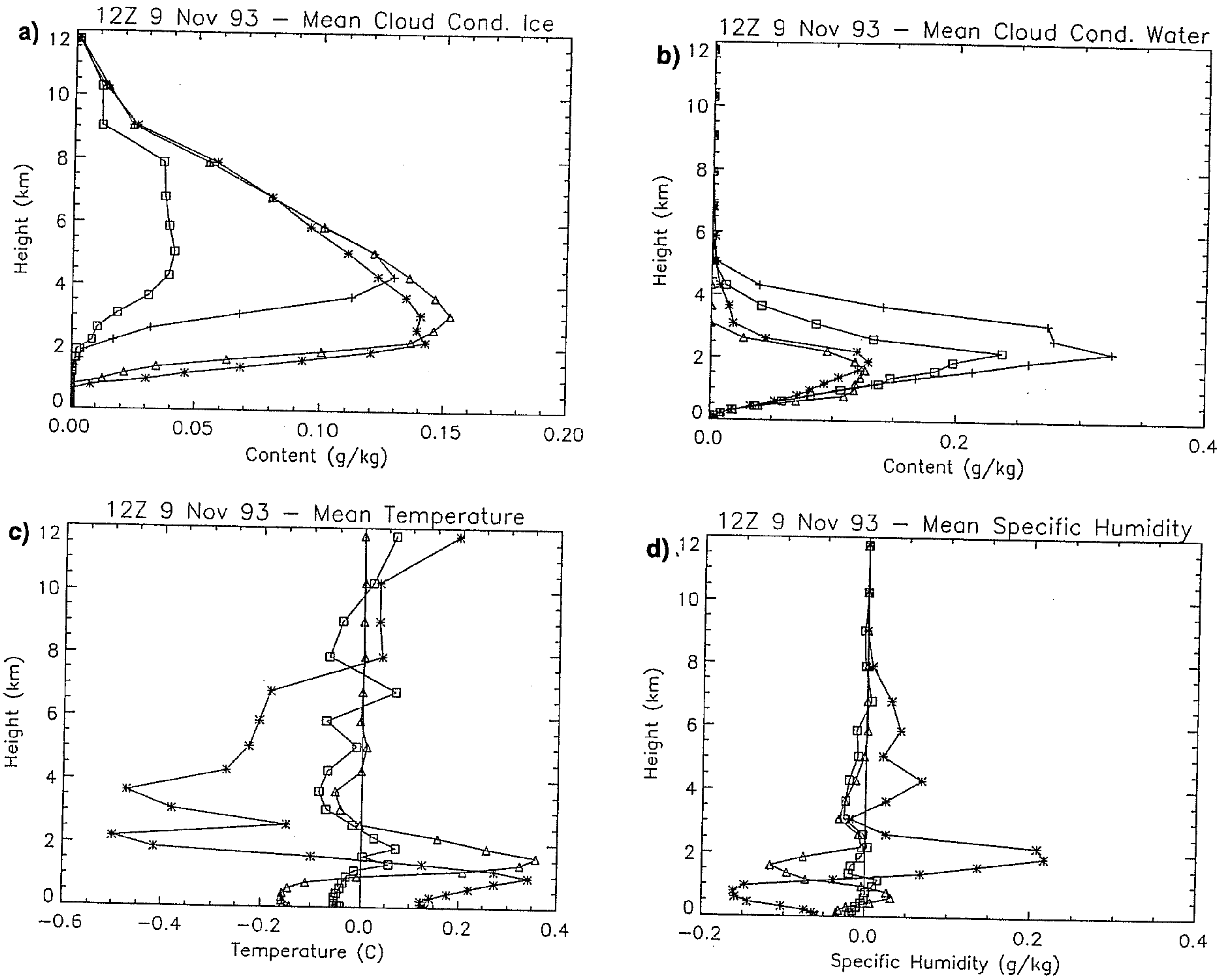

Fig 12. Comparison of 30 hour forecasts for 1200UTC 9/11/93 . a) comparison of domain average condensed cloud water treated or predicted as ice. b) comparison of domain average condensed cloud water treated or predicted as liquid water.c) difference in mean temperature from forecast with standard f_L. d) difference in mean specific humidity from forecast with standard f_L. + using standard f_L ie mixed phase cloud 0 to -15°C , □ using standard f_L ie mixed phase cloud 0 to -15°C with P_*=0, △ treating all cloud <0°C as ice, * new scheme from section 4 and 5.

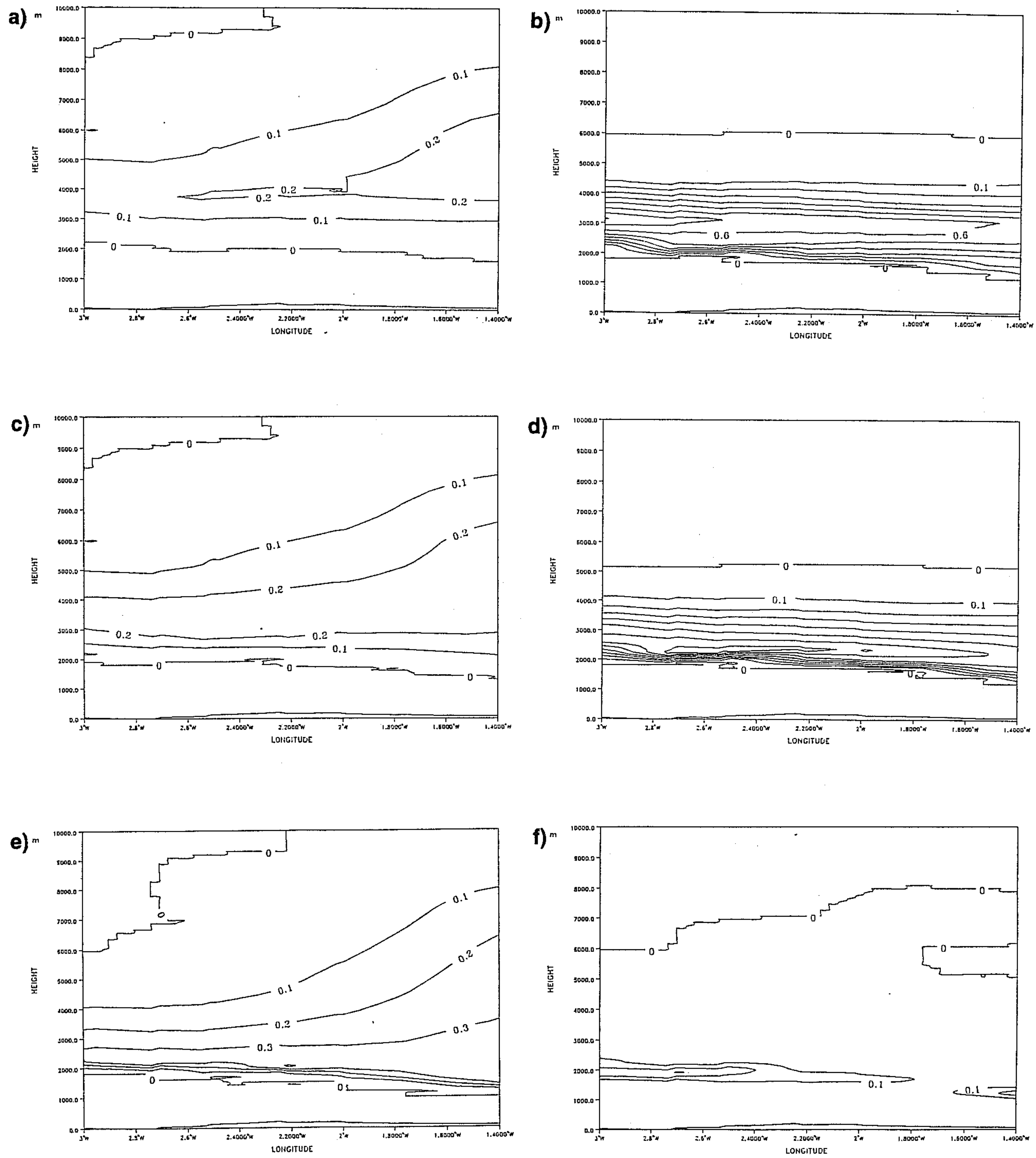

Fig. 13 Comparison of 80km cross-sections of cloud ice and liquid water at 1400UTC 9/11/93 along 270° azimuth from Chilbolton ie 51°N 3°W to 51°N 1.4°W. a) 32 hour forecast for 1400UTC of cloud ice (g/m^3) derived from cloud water <0°C using f_L. Forecast using original scheme with standard f_L ie mixed phase cloud 0 to -15°C, b) as a) but derived supercooled liquid water, c) as a) but using MRF based f_L ie mixed phase cloud 0 to -9°C ,d) as b) but using MRF based f_L ie mixed phase cloud 0 to -9°C, e) cloud ice as predicted by new scheme, f) cloud liquid water as predicted by new scheme.

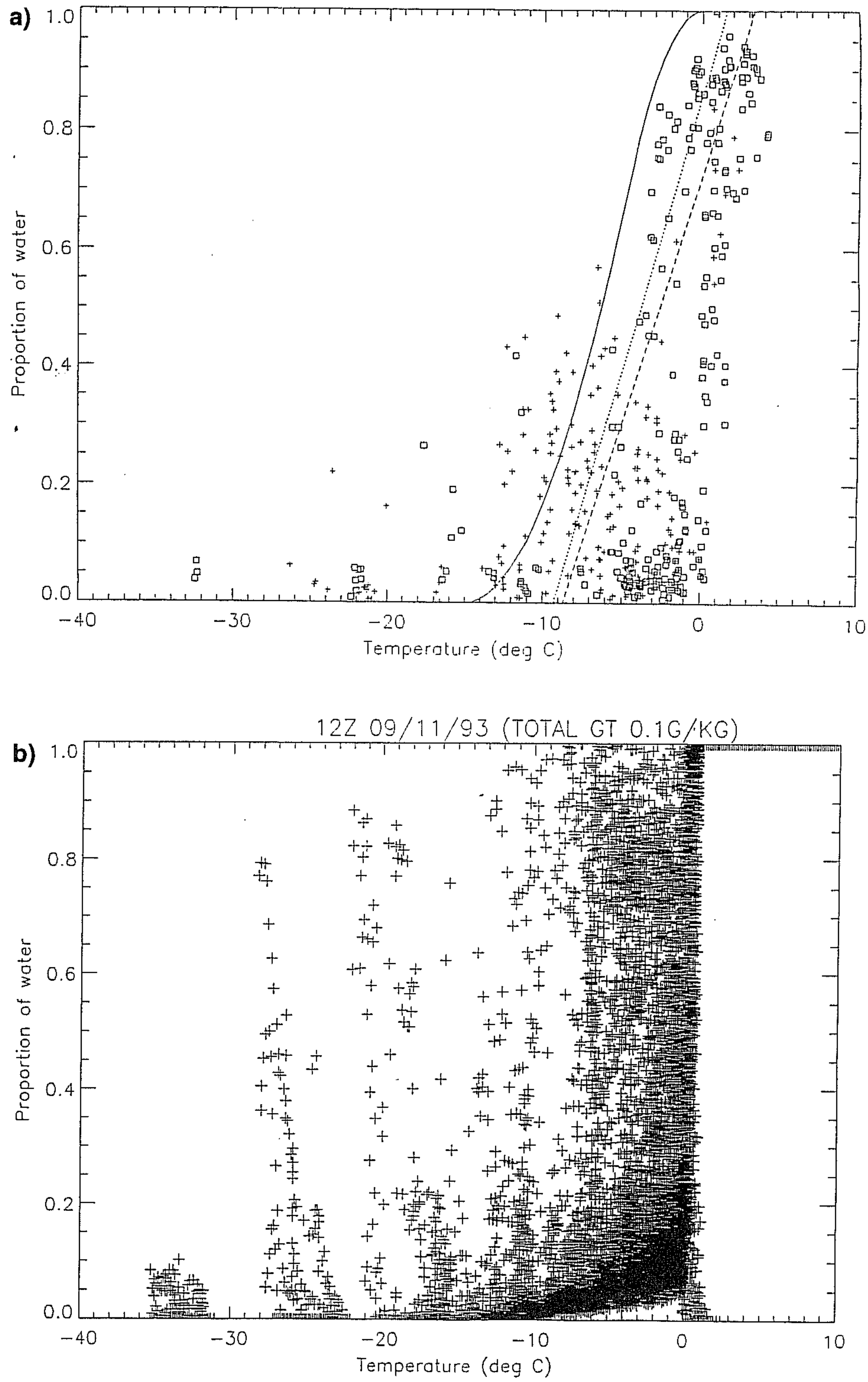

Fig. 14 Plot of the phase ratio (the proportion of liquid water to ice and liquid water) in cloud against ambient temperature. a) from *Bower et al* (1995) . The aircraft data for 11 frontal flights are shown as crosses to indicate clouds in continental airmasses and squares clouds in maritime airmasses. The *Smith* (1990) f_L is shown as a solid line and the linear best fit to the aircraft data for continental cloud as a dotted line and the maritime cloud as a dashed line. b) extracted from the forecast for 1200UTC 9/11/93 with the new cloud scheme where total ice and liquid water contents are greater than 0.1g/kg.

in the case of the mesoscale model, only of the order of 4% in the domain average compared to 50% changes in peak cloud water amounts.

Gregory and Morris (1995) have shown that at climate resolution the MRF based parametrization of mixed phase cloud results in improvements in the global albedo and OLR, important in the radiative heat budget, due to the reduction in predicted cloud water contents. The MRF based parametrization reduces the range of mixed phase cloud from 0 to -15°C to 0 to -9°C. It is interesting that other GCMs parametrize mixed phase cloud over a greater range of temperatures, eg *Rockel et al* 1991 and *Fowler and Randall* and *Tiedtke* in this volume. *Gregory and Morris* (1995) show that even greater improvements to the global albedo are found by treating all sub-zero cloud as ice and worse results are obtained when the range is extended to 0 to -30°C

At mesoscale resolution, from the limited verification data available, it seems likely that the reduced cloud water contents in frontal regions resulting from the MRF based parametrization are also in better agreement with observations. However it is apparent that treating a greater proportion of the cloud as ice can result in poorer representation of stratocumulus. It would be interesting to know whether this is the reason for the increased negative errors in albedo in the climate run in the north Atlantic and south of 60S.

It is obvious that more validation of cloud water contents is required, especially the quantity and distribution of supercooled liquid water. Information on the vertical profiles, variation with ambient temperature and relationship with cloud type/system are necessary for verification of current schemes and the development of improved schemes.

If a simplified, one cloud water variable parametrization is used it is useful to consider whether the current scheme can be improved. At present the same liquid water ratio is assumed irrespective of cloud type or vertical velocity. The assumption is beneficial for boundary layer clouds like stratocumulus but appears to be a problem in frontal cloud. In convective cloud the presence of high concentrations of supercooled liquid water is correlated with strong upward motion. This may also be true for frontal cloud. The magnitude of vertical velocity predicted by a model is related to its grid resolution so that it seems likely that supercooled liquid water is less likely to be predicted explicitly as the resolution decreases from cloud scale to climate model and needs to be parametrized. However this raises the issue of whether the observed presence of supercooled liquid water should be parametrized in the stratiform cloud scheme, as at present, or assumed to come from unresolved subgridscale motions, eg embedded convection and be parametrized in the convection scheme. If it assumed that supercooled liquid water away from the freezing level is from convection it may be possible to produce a new temperature dependence that gives higher ice ratios in the stratiform scheme near freezing. Additional guidance on the existence of supercooled liquid water at low temperatures as a function of cloud type, vertical velocity and whether it exists as uniform stratified regions or just small isolated pockets would be useful for the derivation of parametrizations.

The constraint of zero ice above freezing in the current scheme is not consistent with the observations and the linear relationship between phase ratio and temperature may lead to overprediction of supercooled liquid water at temperatures near freezing and perhaps a more gradual reduction to zero ice phase should be used. However the observations include the effects of precipitation and falling ice rather than just treating the production of ice or liquid water cloud so interpretation of the observations in terms of a simple parametrization is difficult.

The current scheme has an inconsistency between the treatment of cloud phase in cloud diagnosis, melting and evaporation and that used in the production of precipitation and radiation. It may be beneficial to make the treatment the same in all processes if a thermodynamically consistent method can be found. Other schemes, such as those described by *Fowler and Randall* and *Tiedtke* in this volume, use the phase ratio in the definition of the saturation humidity mixing ratio or vapour pressure and it would be interesting to see the impact in the unified model scheme. The concept of an average saturation vapour pressure used to be used in the UK Met Office nonhydrostatic model and previous global and regional models.

The assumption that snow and ice can be treated as a single variable with a mass weighted fall speed causes problems for long time-step integrations. This seems to require that either short timesteps or a full lagrangian type scheme should be used for the treatment of falling snow (even the mesoscale model now uses 5 min timesteps for its physical parametrizations). Implicit schemes have been tried but these seem to be too diffusive or have other failings. It is possible that it may be better to have separate ice cloud (non falling) and snow variables and make the snow a diagnostic variable for long timestep integrations as in *Ghan and Easter* (1992). Work by *Petch* (Reading University, personal communication) indicates that a separate ice variable may result in a better defintion of cloud top which is important in radiative heating and cooling.

This paper has dealt solely with the treatment of cloud phase in the stratiform cloud scheme. It is possible that a more sophisticated treatment of microphysics is required in the convection scheme, especially as it assumes that all cloud below freezing is ice and *Bower et al* (1995) show that liquid water ratios are high down to -30°C. Currently the only interaction between the convective and stratiform cloud parametrizations is through their impact on the environmental temperature and humidity. There may be benefits from a greater coupling of the microphysics and cloud, especially in the tropics for representation of anvil cirrus.

The results from the new scheme at mesoscale resolution are encouraging for both stratocumulus and frontal cloud. The new scheme needs to be adapted so that it is suitable for climate simulations by ensuring accuracy of treatment of microphysical exchange terms and falling snow at long timesteps. The treatment of vertical mixing of ice and calculation of an ice cloud fraction, ie subgridscale cloud ice also needs to be included.

Improvements to the microphysics exchange terms may be required such as the inclusion of the Hallet-Mossop process. However it is interesting that the scheme predicts almost total glaciation of frontal cloud without the need to invoke the Hallet-Mossop process.

The initial formulation of the new scheme uses a Marshall-Palmer type crystal size distribution for snow with the *Cox* (1988) temperature dependent intercept parameter, N_{os}. Chilbolton radar and MRF data have provided information on ice aggregation and spectra (*Marecal et al* 1994) and indicate that N_{os} is dependent on the spectral slope factor λ so that $N_{os} = C \lambda^3$, close to *Passarelli* (1978)'s model. This work indicated that when changes to the dropsize spectra, mass/diameter and fall speed/diameter relationships for ice and snow were included in the nonhydrostatic model they resulted in better agreement between observed and forecast ice water contents. It is planned to test the impact of these modifications in the new scheme in the unified model.

It is hoped that more cases with combined radiosonde , Chilbolton radar, and MRF C-130 microphysical data will be obtained in the next year to provide verification of the cloud schemes. Some new data has already been obtained through collaboration with MRF, Reading University and Rutherford Appleton Laboratory and this with existing data will also be exploited to aid development of improved parametrizations. SSMI or other microwave sounding systems may also provide useful information on water paths.

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