Forecasting Research

Forecasting Research Division
Technical Report No. 102

Study of the meteorological conditions pertaining to the 25th January 1994 PEAC BAe 146 ALF 502 rollback incident

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1 Introduction

On 25th January 1994 at 2100GMT at latitude 2N, longitude 108E a BAe 146 flying at 31000 feet experienced rollback of all four engines. As the aircraft was flying in IMC not very far from a virulent cumulonimbus, it was considered quite likely that the engine behaviour was associated with ingestion of hydrometeors, either liquid (rain or cloud droplets) or solid (snow, small cloud ice particles, hail or graupel). In addition, the True Air Temperature probe indicated a sudden apparent rise just before the first rollback, and it was thought that this was due to the probe icing up. Therefore , using a detailed microphysical model, an investigation was carried out into the likely meteorological conditions at the time. This report describes the findings of this investigation. Section 2 describes the experimental design, section 3 gives the results and section 4 the conclusions. The report is written such that it may be possible to read section 3 without reading section 2, and it may be possible to read section 4 without reading either of the two preceding sections.

It is understood that the aircraft was not flying in the part of the cloud having the strongest radar echoes, i.e. the part of the cloud referred to as the updraft zone, and therefore in the study the emphasis was on examining the conditions in other parts of the cloud.

It is worth commenting that, while in the model there is reference to particular microphysical species, e.g. snow, graupel, these are of necessity somewhat artificial distinctions. In the model the main reason for distinguishing between snow and graupel is because of the different fallspeeds. It is quite plausible that the predominant species predicted by the model did not have the observable physical characteristics of the precipitation encountered by the aircraft. However, there is much greater confidence in the model's ability to distinguish liquid hydrometeors from frozen ones.

2 Experimental design

The study consists of running a two-dimensional bulk water parametrized model (Cox, 1988). In the model the wind flow is fixed for the duration of each simulation, but the temperature, humidity and concentrations of cloud liquid water, cloud ice (small particles), snow, rain and graupel vary with time. Normally the model is run until a quasi-steady cloud occurs, although there is some interest in examining transient fields as well.

In the experiments this model was run with 100 grid points in the horizontal, 500m apart, giving a domain of 50km, and 84 grid points in the vertical 200m apart, covering from the surface of the earth to an altitude of 16600m, or over 54000 feet. Such vertical coverage was necessary because it is important to simulate processes throughout the depth of the cloud (snow at high levels can fall and remove cloud water at lower levels) and there is some evidence that in this case the cloud may have extended to this general altitude.

To initialise the model we require values of temperature, airflow and humidity. Provided within the model domain there is an updraft, a cloud will form and there is no need to specify initial values of the condensed water variables. Although it is reasonable to prescribe initial temperature and humidity fields which are horizontally uniform, in order to generate a cloud with an anvil (outflow region) a horizontally varying windflow field had to be specified. In practice the approach was as follows. The initial temperature and humidity fields (which were horizontally uniform) were obtained by vertically interpolating from the archived fields of Unified Model (Cullen, 1993) analysis data. The horizontal wind flow at the right hand boundary of the domain was also obtained by vertical interpolation from Unified Model fields. This was the wind component parallel in direction to the flow at the level of the maximum wind.

Figure 1 shows the stream function used in simulation 1. In a two-dimensional model the stream function specifies both the horizontal and vertical velocities - the direction of the flow in the x-z plane is shown by the orientation of the contours and the strength of the flow is indicated by the contour spacing. Formally, the gradient of the stream function is equal to the product of the density and the velocity vector in the x-z plane. Also indicated in figure 1 are the various zones of the domain and the critical levels ltop and lbottom, whose significance is discussed in the following.

In order to specify the flow in the domain (apart from at the right hand boundary where it is specified), two levels were defined, ltop and lbottom. In addition, in the horizontal, the domain was split into three zones, an inflow zone, an updraft zone and an outflow zone. Above ltop, the flow is uniform horizontally and the vertical velocity is zero everywhere. Below ltop, in the inflow and outflow zones, the flow is uniform horizontally (but different in the two zones) and the vertical velocity is zero everywhere. In the inflow zone, at levels between lbottom and ltop, the horizontal flow is zero. This is the constraint used to define the flow in the updraft zone between ltop and lbottom: in this part of the model the vertical motion (which is horizontally uniform) is chosen so that at the left hand boundary the flow is zero but at the right hand boundary the flow is that taken from the unified model. In the updraft zone below lbottom the vertical velocity (which is horizontally uniform) varies quadratically with height so that both the vertical motion and its first derivative are continuous at lbottom. The horizontal flow below lbottom in the inflow zone is prescibed to be consistent with the verical velocity in the updraft zone. The vertical velocity at the bottom of the model is of course zero everywhere. Although this flow regime is not necessarily particularly realistic, its virtue is that, given the flow at the right hand boundary, the flow within the model is entirely specified by the positions of ltop and lbottom, and the inflow, updraft and outflow zones. The regime has the advantage that all of the outflow is from left to right in the model and thus, with the updraft well to the left of centre in the model, there is the greatest opportunity to assess what is going on in the outflow region.

For the experiment shown in most detail in the next section, lbottom was 34 and ltop was 74. Other simulations show that the result is relatively insensitive to lbottom, but quite sensitive to ltop (a result using a lower value of ltop will also be shown). From the data from the Unified Model, it appears that the tropopause was at approximately 150mb, corresponding to level 74, and this was the reasoning behind setting ltop to this value. It is generally accepted that the tropopause acts as a lid to convection, although particularly vigorous cumulonimbus may penetrate the tropopause.

In all experiments the updraft zone was centred on the point 20 grid lengths in from the left hand boundary and had a width of 16 gridlengths.

3 Results

Figure 2 shows the rain mixing ratio (figure 2(a)), the snow mixing ratio (figure 2(b)) and the cloud water mixing ratio (figure 2(c)) for simulation 1 after 2000 seconds of simulated time. At this time, as will be indicated by figures showing these variables at later times, the cloud was not in equilibreum. For all fields except temperature, the contour labels are in g/g, whereas in most of the discussion the units used will be g/kg.

As far as rain is concerned, as can be seen the highest values are to be found below 4km and the highest values at the typical altitude the aircraft was flying only occur very close to the updraft, and it is believed that the aircraft was not particularly close to the updraft. Therefore rain is not considered to be important.

The peak value of snow mixing ratio (figure 2(b)) was 0.6 g/kg, which occurred at an altitude of 12km, rather higher than the aircraft altitude. The highest value at aircraft altitude at this time was 0.1 g/kg. However, within the model the snow is falling - this is indicated by the fact that the contours of snow mixing ratio slope downward from left to right in the figure. In the absence of evaporation, and at a constant fall speed, the mixing ratio of snow would remain constant as the snow fell through the model. Thus in those conditions, one would expect a snow mixing ratio of 0.6 g/kg at aircraft altitude at a later time. In the simulations such a value does not occur, mainly because of evapouration, which is rather high because in the initial conditions the humidity was low at these altitudes. While the humidity may have been typical of the undisturbed airmass, the instability of the temperature and humidity profile was such that undoubtedly there was a sequence of cumulonimbi, and for the later clouds the upper level humidity was almost certainly much higher than it was for earlier ones.

At an altitude of 31000 feet the density of air is very approximately 500 g/cu m, so a mixing ratio of 0.6 g/kg would give an ice water content of 0.3 g/cu m.

The peak value of cloud water mixing ratio (figure 2(c)) was 1.8 g/kg, at an altitude of 5km, and therefore of little relevance to the incident. What is relevant on figure 2(c) are the isolated contours indicating the presence of liquid water at approximately 10km altitude in the centre of the domain. The contour corresponds to a mixing ratio of 0.1 g/kg. This feature is definately transient, but indicates that significant liquid water can exist at aircraft altitudes some distance from the updraft, albeit only temporarily.

Figure 3 shows the humidity mixing ratio (figure 3(a)), the graupel mixing ratio (figure 3(b)) and the temperature (figure 3(c)) for simulation 1 at the same time as figure 2. Of these the graupel field is the most significant. The maximum value is 9g/kg, at an altitude of 7km, and at aircraft altitude the maximum value was 6g/kg. However this value occurs right at the edge of the updraft zone, so is not likely to have been relevant to the incident. For values likely to have pertained to the incident, see the discussion of fields at later times (below).

Figure 4 is directly analagous to figure 2, but pertains after 6000 seconds of simulated time. It is notable that there is snow throughout the outflow area between 8km and 13km, although relatively low concentrations - a maximum of only 0.05g/kg. There is no cloud water of any consequence at aircraft altitudes except near in the updraft zone.

Figure 5 is directly analagous to figure 3, but, like figure 4, pertains after 6000 seconds of simulated time. What is of note here is that the high graupel concentrations extend further to the right than was the case at the earlier time. For example the 10^{-3} contour, extends nearly 10km from the updraft zone at aircraft altitudes.

An additional simulation was performed in which ltop was set at 50 (this will henceforth be referred to as simulation 2). This was done to simulate the effects of a relatively low tropopause. Figure 6 is directly analagous to figure 4 for simulation 2. However, in comparing the figures, it is noticeable that in simulation 2 the snow concentrations are much higher and there is significant cloud water at aircraft altitudes in the outflow zone. The highest value of snow mixing ratio is 0.6g/kg and this occurs at aircraft altitude: the highest value of cloud water mixing ratio at aircraft altitude is 0.2 g/kg. These high concentrations are undoubtedly due to the flow being "squeezed" under the artificial tropopause. Although all the indications are that the tropopause (at 00Z on January 26th) at the various radiosonde stations on islands surrounding the incident was much higher than an ltop of 50 would imply, it is possible that locally a temperature inversion occured that had the same effect. Note that, as shown in figure 5(c), the simulated cumulonimbus itself causes a high level temperature inversion, and this could have affected subsequent cumulonimbi.

4 Conclusions

The conclusions are that there were rather high ice water contents near where the aircraft was flying, and possibly there was liquid water present as well. The simulations give ice mixing ratios (either of snow or graupel) of approximately 0.5 g/kg, or ice water contents of 0.25 g/cu m. There is less certainty as to the existence of liquid water, but it is plausible that there were isolated areas with cloud water mixing ratios of 0.1 g/kg, or liquid water contents of 0.05 g/cu m. Whilest this quantity of liquid water by itself is unlikely to cause problems, its effect in conjunction with the ice may be significant. It could act to adhere the ice to parts of the engine and to itself, thereby disrupting the flow.

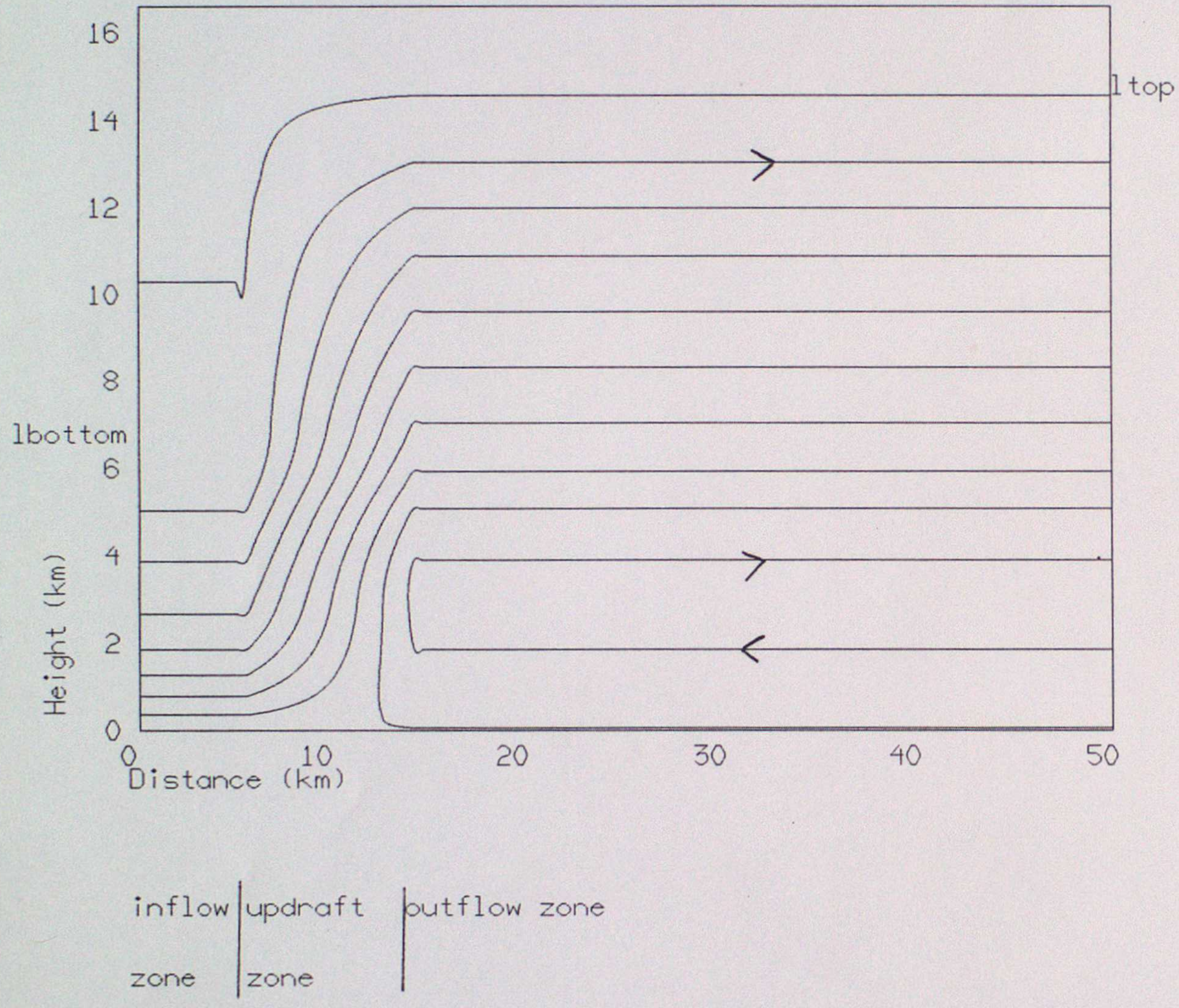
To set the ice water content of 0.25 g/cu m in some perspective, it is worth referring to the UK Defence Standard aircraft design environment (DEF STAN 00-970, leaflet 711/2). The condition for continuous falling snow is an ice water content of 0.8 g/cu m, although interestingly the altitude range for which it pertains is up to 10000 feet, and for temperatures down to -30 degrees C. There is no doubt that, near cumulonimbi, in conditions several degrees above the ISA profile, high ice water contents well above 10000 feet can occur, as the simulations have shown.

5 References

Cox, G.P., (1988) "Modelling precipitation on frontal rainbands", Quarterly Journal of the Royal Meteorological Society, Volume 114 pages 115 to 128.

Cullen,M.J.P. (1993) The unified forecast/climate model. Meteorological Magazine Volume 122 pages 81-94

Figure 1. Shows streamfunction used in simulation 1.



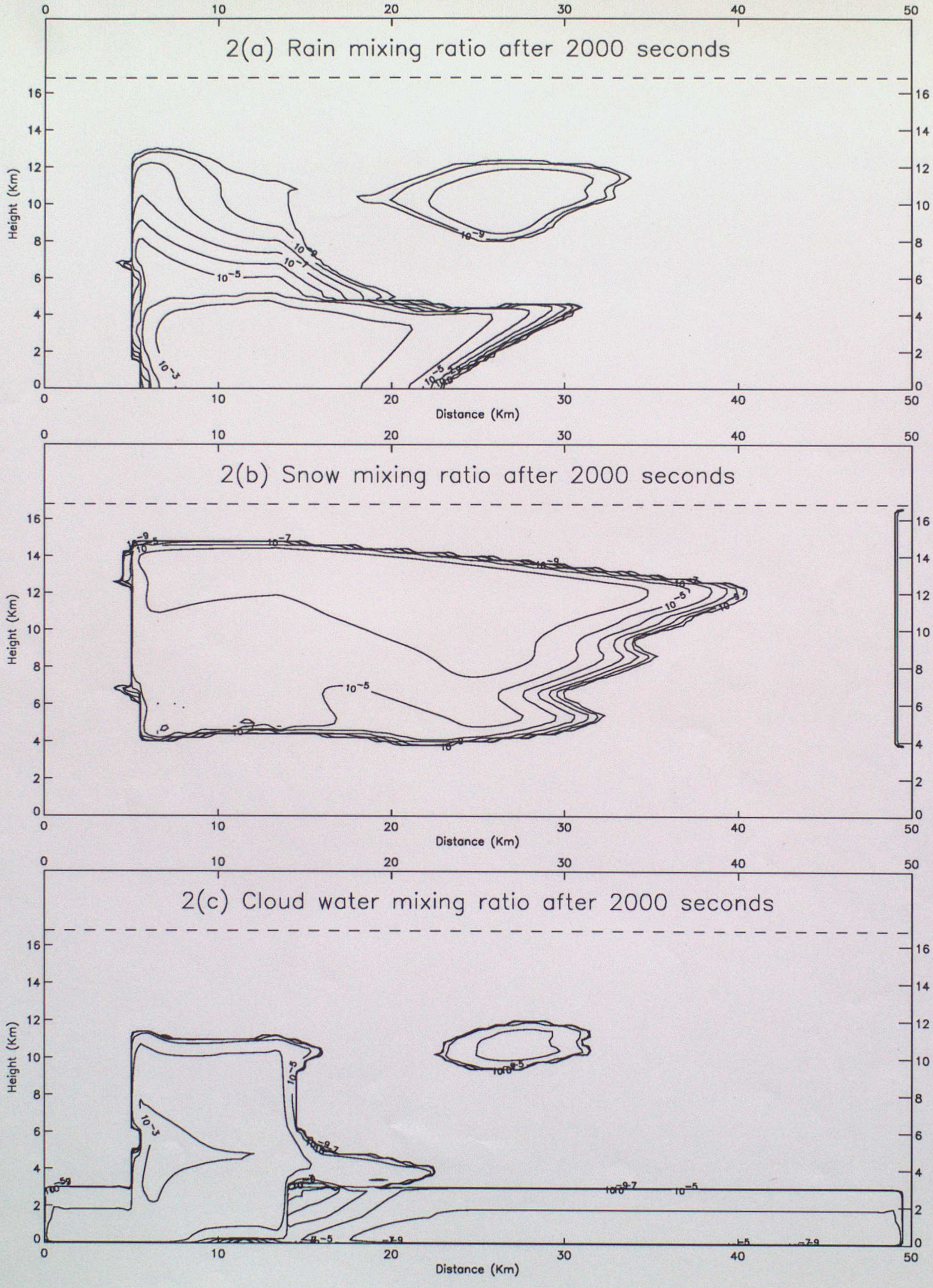


Figure 2. Rain, snow, and cloud water after 2000 seconds, simulation 1

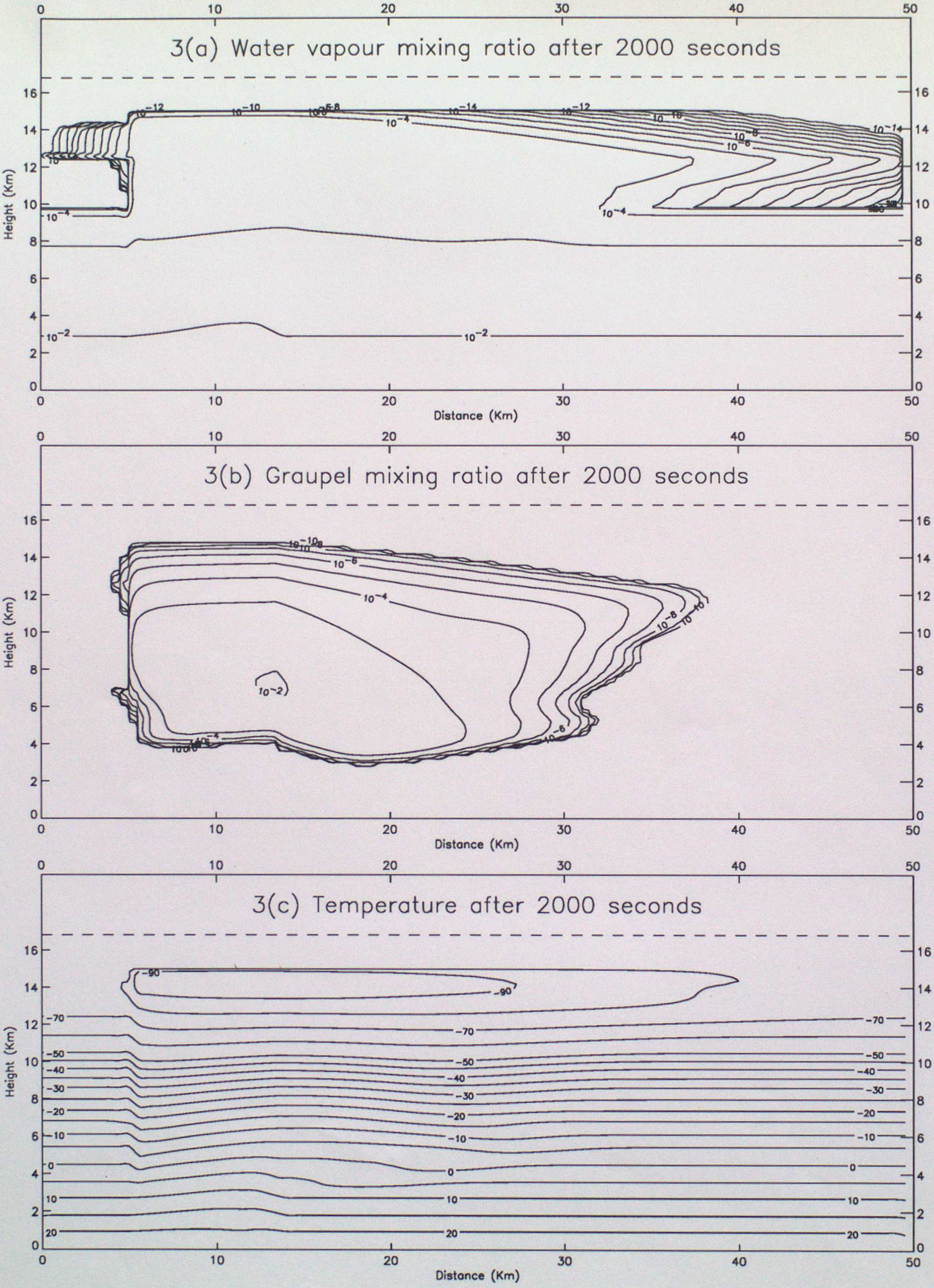


Figure 3. Humidity, Graupel and temperature after 2000 seconds, simulation 1

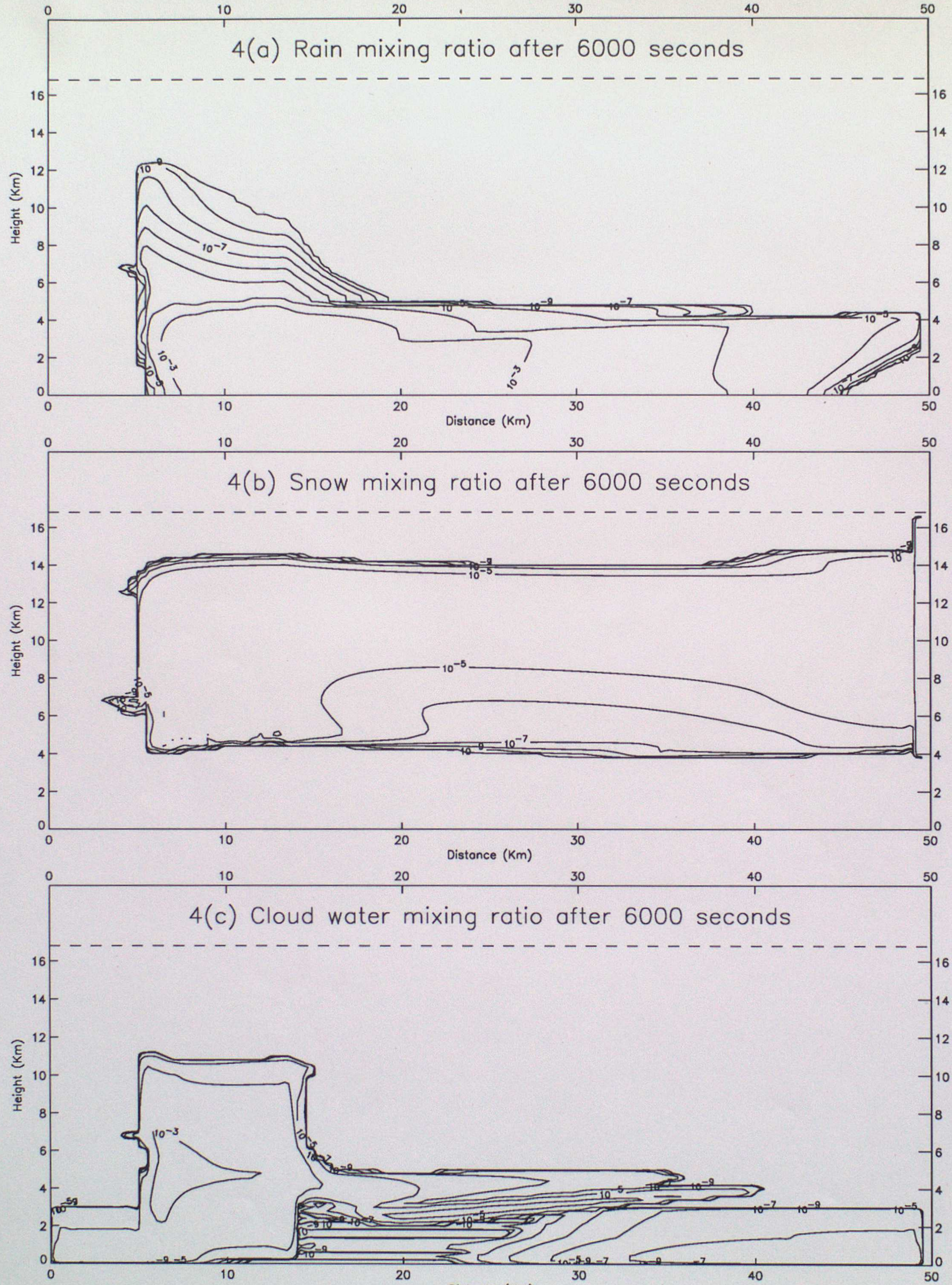


Figure 4. Rain, snow and cloud water after 6000 seconds, simulation 1

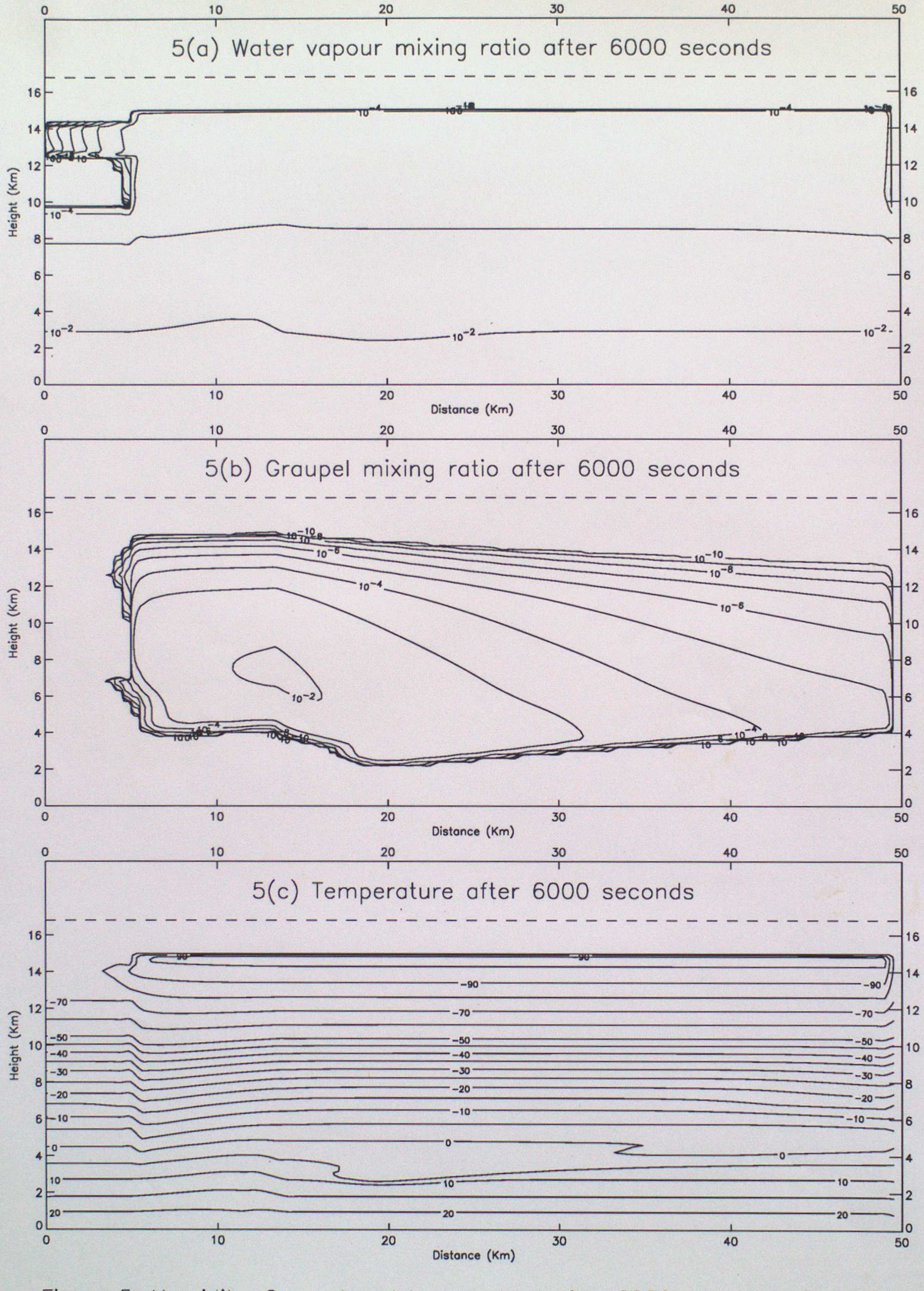


Figure 5. Humidity, Graupel and temperature after 6000 seconds, simulation 1

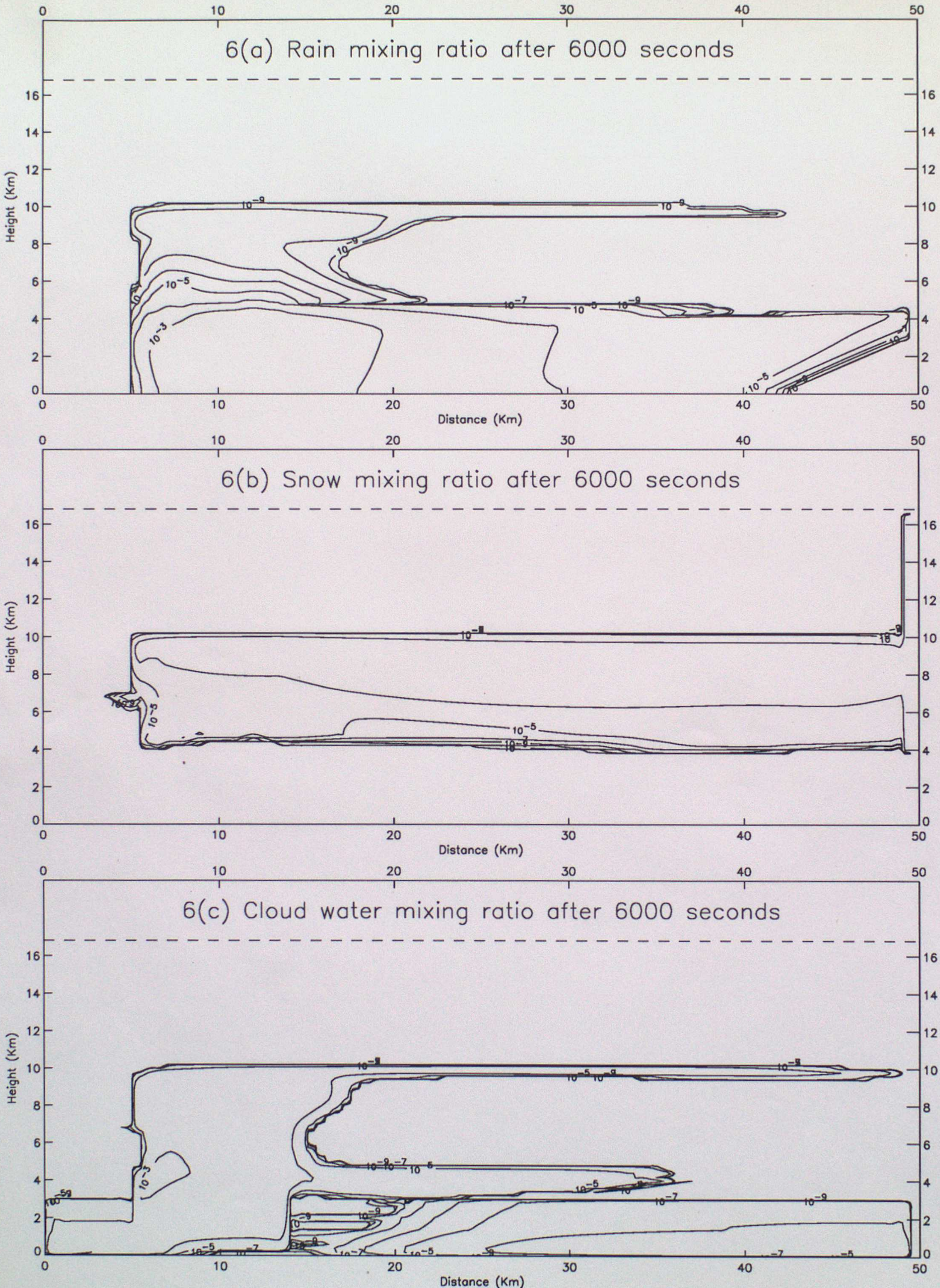


Figure 6. Rain, snow and cloud water after 6000 seconds, simulation 2