The CLARE'98 Campaign and Its Context

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CLARE'98 was the Cloud Lidar and Radar Experiment airborne and ground-based campaign carried out in October 1998. A general introduction on the wider context of this campaign and on the Earth Radiation Mission is first given, followed by a summary of the participating instruments, aircraft, institutes and the structure of the campaign. The most extensively studied flight is presented, together with some of its most relevant results. The major results and conclusions of the overall campaign are then discussed.

Introduction

The governments of most developed countries agreed at Kyoto to reduce emissions of greenhouse gases, in response to disquieting predictions of 21st century climate change resulting from human industrial and agricultural activities. Forecasts of 'global warming' range from 1 to 5 deg, with even greater discord regarding predicted regional temperatures and precipitation changes. Such predictions rely on global numerical models, and the inadequate representation of clouds and aerosols in these models constitutes a major source of uncertainty. To gain more confidence in the climate predictions and thus provide a universally agreed-upon basis for action both by governments and economic decision-makers, a first necessary step is to validate that the current weather and climate are being correctly represented.

Increases in low-level clouds cool the Earth by reflecting more sunlight, but additional high-level cold clouds warm the Earth by reducing infrared radiation losses to space. This 'cloud radiative feedback' can be larger than the original direct radiative forcing by, for example, increased CO_2. Changes in the vertical profiles of clouds lead to important changes in heating rates and atmospheric dynamics, which then feed back to cloud-profile changes. Current satellite measurements can determine incoming and outgoing radiation at the top of the atmosphere, but they cannot provide data on cloud profiles and consequent energy heating profiles. Accordingly, the Second Assessment Report of the Intergovernmental Panel on Climate Change in 1995 stated that:

'The main uncertainties in climate-model simulation arise from the difficulties in adequately representing clouds and their radiative properties'.

These uncertainties arise from shortcomings in the treatment of cloud and aerosol processes in climate models, and from the lack of observations with which to evaluate and improve these parameterisation schemes. The same difficulties bedevil numerical weather-prediction models used for short- and medium-range and seasonal forecasting. All such models divide the atmosphere into grid boxes, typically 20 – 50 km in the horizontal and 500 m in the vertical direction. Clouds are represented for each box by prognostic variables such as fractional cloud cover, ice and liquid-water content, particle size, together with some implied cloud overlap for each vertical stack of grid boxes. The overlap assumptions affect both radiative transfer and precipitation efficiency in the clouds. We have scarcely any observations with which to verify that this representation is correct. A particularly glaring gap is our ignorance of the depth and water content of the widespread tropical ice clouds.

Increases in aerosols directly modify the solar radiation reaching the ground, and also affect biochemical and photochemical processes in the atmosphere and clouds. Aerosols acting as cloud condensation nuclei also affect clouds indirectly by: (i) decreasing droplet size and so increasing cloud albedo, and (ii) increasing cloud lifetime. The indirect effect may be very strong, but in practice its impact is unknown.

The Earth Radiation Mission (ERM) addresses these issues and was one of the candidate Earth Explorer Core missions for ESA. Ultimately, ERM was not one of the two missions chosen in 1999, but ESA's Earth Sciences Advisory Committee and Earth-Observation Programme Board have recommended that a radiation mission be pursued in collaboration with Japan.

In the frame of the preparation work for the Earth Radiation Mission, several activities were carried out. Among these, an airborne and ground-based campaign was found necessary to consolidate the scientific objectives for ERM and to support the development of retrieval algorithms. Of particular interest was the development and validation of algorithms specially for the radar and lidar and mid-layer/mixed-phase clouds. A campaign (CLARA) had already been carried out in The Netherlands, but it had concentrated on ground-based measurements and airborne in-situ measurements of liquid/low-layer clouds. CLARE'98 was therefore implemented involving three instrumented aircraft and several ground-based instruments.

The ESA Earth Observation Preparatory Programme (EOPP) and the Technology Research Programme (TRP) jointly funded the campaign and the associated data analysis for retrieval-algorithm development.

The Earth Radiation Mission

The ERM is extensively described in ESA Special Publication SP-1233(3) (available from ESA Publications Division), but a brief description of its objectives and observational requirements here will allow the reader to better understand the context of the CLARE'98 campaign.

Scientific objectives

The ERM was specifically defined with the scientific objective of determining worldwide the vertical profiles of cloud and aerosol field characteristics to provide basic (and essential) input data for numerical modelling and studies (on a global scale) of:

- the divergence of radiative energy
- aerosol-cloud-radiation interaction
- the vertical distribution of water and ice and their transport by clouds
- the vertical cloud-field overlap and cloud-precipitation interactions.

These objectives were jointly defined by the Japanese and European scientific communities. The cloud and aerosol data available at present are of limited value for the validation of atmospheric models. In these models, the major uncertainty is the representation of clouds and aerosols. Traditionally, cloud parameterisation schemes in numerical models have been validated by comparing long runs of such models with the climatological observations of fluxes. Such validations are, however, rather crude, since for a given flux at the Top-of-the-Atmosphere (TOA) there is more than one possible solution. The ERM addresses this issue by using a 'snapshot approach'. This consists of measuring the vertical profiles of clouds and aerosols (using a nadir-looking radar and lidar) and the constraining TOA radiance (using a broad-band radiometer). To understand the wider context of the measurements (across-track and scene texture), an imager is used.

The mission supports the goals of the World Climate Research Programme (WCRP) and, in particular, of its Global Energy and Water Experiment (GEWEX) sub-programme, which is intended to develop an improved understanding of energy and water fluxes within the climate system, to secure reliable forecasts of weather and climate.

In order to meet the ERM's objectives, the following observations are required on a global scale:

- cloud boundaries (top and base), even for multi-layer clouds, and consequently height-resolved fractional cloud cover
- vertical profiles of ice water content and ice particle size
- vertical profiles of liquid water content
- detection of precipitation and estimation of light precipitation
- detection of aerosol layers and estimates of their optical depth
- short-wave (SW) and long-wave (LW) radiances at the top-of-the-atmosphere.

Observational requirements

The entire set of mission observational requirements (including instrument requirements)

Table 1. Observational requirements for ERM

Parameter	Detectability	Accuracy
Fractional cloud cover	5%	5%
Cloud top/base - Ice	N/A	500 m
- Liquid	N/A	300 m
Ice water content	0.001 g m^{-3}	+40 / -30%
Ice effective radius	N/A	+40 / -30%
Liquid water content (and effective radius)	Optical depth 1	+100% / -50%
Aerosol optical depth	0.04	10%
SW/LW radiances, TOA	N/A	1.5 Wm^{-2} sr^{-1}

Table 2. Summary of requirements for lidar and radar

	Lidar	Radar
Footprint	≅ 100 m	< 1 km
Sensitivity	$\leq 8\mathrm{x}10^{-7}\,\mathrm{m}^{-1}\mathrm{sr}^{-1}$@10 km integration	≤-36 dBZ@10 km integration
	$\leq 2.4\mathrm{x}10^{-6}\,\mathrm{m}^{-1}\mathrm{sr}^{-1}$@1 km integration	≤-31 dBZ@ 1 km integration
		at 8 km height
Signal-to-noise ratio	≥ 2	
Radiometric accuracy		≤ 1.7 dB
Vertical resolution	≤ 100 m	≤ 500 m
Swath	Nadir only, co-located footprints	

were driven by a TOA flux accuracy of 10 Wm^{-2} on a synoptic scale. The sensitivity limits and accuracy required for the key geophysical parameters are listed in Table 1.

The instrument complement consists of two active instruments (a radar operating at 94 GHz and a lidar at 1.06 µm) and two passive instruments (a Multi-Spectral Imager and a Broad-Band Radiometer). Table 2 shows the requirements for the key active instruments. These were also derived from the same TOA flux accuracy requirement.

As will be shown later, CLARE'98 has demonstrated that the scientific objectives can only be met with co-located and simultaneous measurements by the two active sounders with other complementary instrumentation onboard the same satellite. The radar and lidar footprints need to be co-located to better than 500 m to be able to use both active instruments in synergy to retrieve cloud properties with the required accuracy.

CLARE'98 has also demonstrated that cloud properties can be retrieved using the radar and lidar; in particular, ice water content and effective radius can only be retrieved using the two co-located and simultaneous active measurements together.

Owing to the snapshot approach used, the radar and the lidar are required to make observations in only rather narrow fields of view about nadir, with footprint dimensions of less than 200 m and 1 km, respectively.

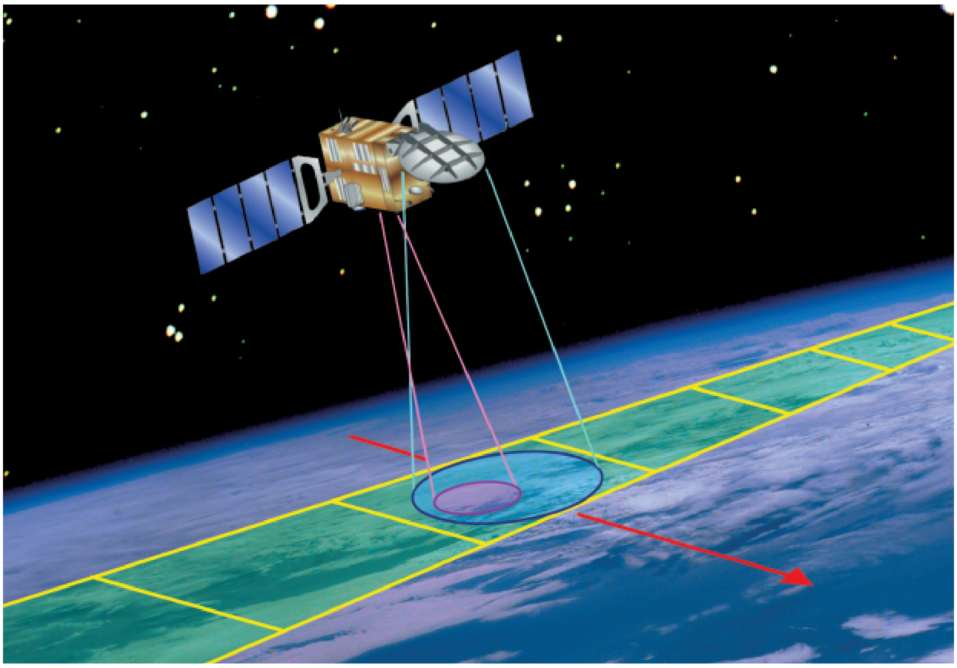
The broadband-radiometer data provides values for the radiance at the top of the atmosphere, and thus the constraining value for the estimates of the vertical radiative flux divergence profiles within the atmosphere.

The multi-spectral imager enables a clear distinction to be made between different cloud types and supplies the context in which the measurements are carried out. The passive instruments need to have larger swaths in the across-track direction than the active instruments. As the typical correlation length for cloud structures sometimes extends beyond the size of the reference cells, the swath widths of the multi-spectral imager and broadband radiometer have been specified as approximately 100 km.

Figure 1 is an artist's impression of the ERM, showing the footprints of the radar, lidar and the multi-spectral imager.

As far as the orbit requirements are concerned, a near-polar orbit ensures that all climate zones will be sampled. A polar (Sun-synchronous) orbit with an equatorial crossing time around noon will ensure a maximal signal in reflected solar radiation for both passive sensors. A preceding orbit is not strictly necessary for the ERM due to the snapshot approach used.

Figure 1. Artist's impression of the Earth Radiation Mission (ERM). The blue and lilac footprints represent the radar and the lidar, respectively. The yellow-delimited boxes depict a single row of pixels as seen by the Multi-Spectral Imager. The footprint of the Broad-Band Radiometer is not represented. The red arrow represents the ground track of the satellite at nadir



The campaign

For the purposes of CLARE'98, three aircraft were necessary. One performed *in-situ* measurements, while the other two made remote measurements from different altitudes. One of the aircraft was required to carry both a lidar and radar with characteristics similar to those proposed to be embarked on the ERM. Complementing the airborne measurements, an extensive set of ground-based measurements was also required. To take advantage of existing ground-based instrumentation and facilities, the Observatory of Chilbolton, Hampshire, UK was chosen. The campaign was carried out during the period from 5 to 23 October 1998.

Figure 2. The UKMO-MRF Hercules C-130 flying over Chilbolton (UK), where all ground-based instruments were sited. CAMRa (3 GHz scanning radar), with its 25 m antenna, and Rabelais (35 GHz radar), with its small dish on the right-hand side of the large antenna, are also shown

Aircraft

Three aircraft were used:

- A UKMO-MRF Hercules C-130, performing in-situ measurements of temperature, wind, humidity, particle-size spectra (FSSP, 2D-C and 2D-P), and bulk water (Johnson-Williams probe). In addition, this aircraft performed radiative measurements (broad-band, narrow-band plus microwave).
- A INSU/IPSL Fokker 27 (ARAT), performing measurements with a 94 GHz cloud radar ('Kestrel' from the University of Wyoming), a lidar ('Leandre') and an array of radiometers.
- A DLR Falcon, carrying out high-altitude measurements with the 'Alex' lidar and the 'Fubiss' spectrometer, as well as short- and long-wave radiometers.

The C-130 and the ARAT were present throughout the period, while the Falcon was present from 12 to 23 October. Seven flights were carried out, using the maximum flying hours allocated to this campaign.

Ground-based data were taken during the flights from radars at 3, 35 and 94/95 GHz, together with radiometers, interferometers, ceilometers, and fluxmeters. For most of these instruments, data was logged continuously throughout the campaign.

The aircraft flew runs with an azimuth of 260 deg towards and away from the Chilbolton site, where all ground-based instruments were placed (Fig. 2), each outbound or inbound flight leg being called a 'run'. The Falcon flew at a high level of about 10 km, with the lidar looking downward and generally above the cloud; the ARAT was generally at its ceiling of around 5 km with its radar and lidar looking downwards to cloud, below which the C-130 was performing in-situ micro-physical measurements. The co-ordination of the aircraft worked very well with a pair of synchronised inbound and outbound legs over Chilbolton, typically every thirty minutes. The start of the inbound run was different for each aircraft, due to their different speeds, so that the over-flight of Chilbolton occurred as much as possible at the same time for all aircraft. For the outbound runs, the latter started at Chilbolton for all aircraft. Table 3 shows the summary for the seven flights.

Ground-based instruments

The ground-based instruments were sited at the Chilbolton Observatory and consisted of:

RAL (UK)

- 3 GHz scanning (CAMRa) and 94 GHz vertically pointing radar ('Galileo', on long-term loan from ESA)
- 22, 28, 78 and 94 GHz zenith-pointing radiometers
- a UV lidar
- CT-75K Vaisala Lidar/Ceilometer (on long-term loan from ESA)
- standard meteorological instruments
- cloud camera.

CRA (F)

- 35 GHz scanning radar ('Rabelais')
- 35 GHz radiometer.

GKSS (D)

- 95 GHz vertically-pointing radar ('Miracle').

KNMI (NL)

- IR radiometers (2)
- video camera
- VIS-IR sensor.

Table 3. Summary of runs per flight

Date	Flight	C–130 runs	ARAT runs	Falcon runs
7 Oct. 1998	1	8	8	–
13 Oct. 1998	2	16	10	10
14 Oct. 1998	3	14	8	8
16 Oct. 1998	4	14	–	–
20 Oct. 1998	5	28	18	18
21 Oct. 1998	6	8	6	6
22 Oct. 1998	7	12	-	-

TU Delft/TU Eindhoven (NL)

- multi-frequency microwave radiometer (21.3, 23.8, 31.65, 51.25, 53.85 and 54.85 GHz, on loan from ESA).

Other scientists, not funded by ESA, joined the CLARE'98 campaign with their instruments on condition that the data collected would be shared. The University of Heidelberg (D) operated a high-resolution A-band radiometer, from which it should be possible to derive the optical depth and photon path-length distribution through the clouds, The University of Bath (UK) participated with GPS receivers to evaluate the path-integrated vapour and a 95 GHz high-performance radiometer, and the University of Portsmouth brought along a 40 GHz radiometer and satellite (Italsat) beacon receiver.

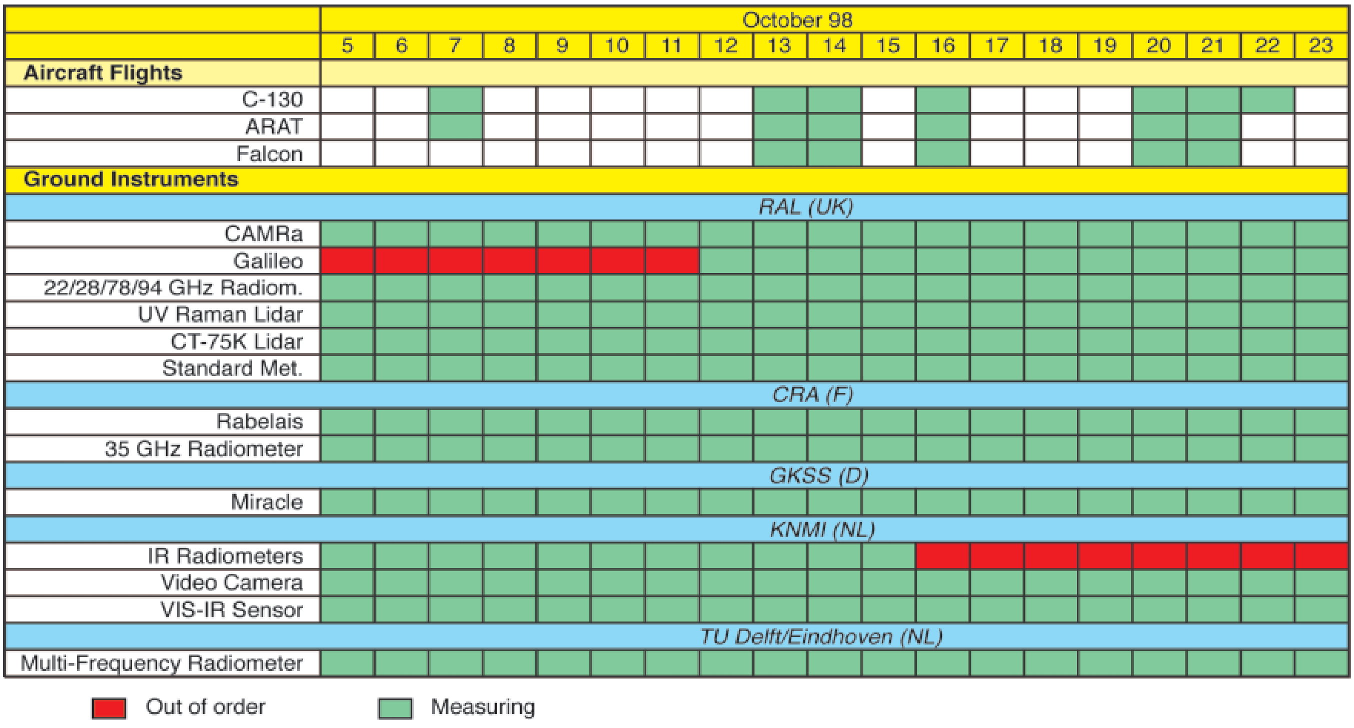
Table 4 summarises the instrument and data status for all ESA-funded instruments during the campaign.

During the flights, the scanning radars performed slow RHIs (Range Height Indicators, i.e. a scan in elevation at constant azimuth), following the aircraft as they flew along a 260 deg-azimuth line to and from the site. Figure 3 shows an example of this mode of operation, with the radar reflectivity measured by the ground-based 3 GHz radar (CAMRa), together with the lidar (ALEX) measurements performed from the Falcon and the in-situ measurements carried out by the C-130.

On other occasions, the radars performed faster RHIs to gain a greater knowledge of the overall cloud environment. At other times the scanning radars joined the other instruments in recording vertical dwells throughout the duration of the experiment.

To avoid the ground-based radars interfering with those on the ARAT, the GKSS radar had its E-field vector at 45 deg to the aircraft azimuth, and the Galileo (RAL) scanning radar had its E-field in the vertical plane.

Table 4. Summary of data availability



	October 98																		
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Aircraft Flights																			
C-130			🟩						🟩	🟩		🟩				🟩	🟩	🟩	
ARAT			🟩						🟩	🟩		🟩				🟩	🟩		
Falcon									🟩	🟩		🟩				🟩	🟩		
Ground Instruments																			
RAL (UK)																			
CAMRa	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Galileo	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
22/28/78/94 GHz Radiom.	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
UV Raman Lidar	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
CT-75K Lidar	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Standard Met.	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
CRA (F)																			
Rabelais	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
35 GHz Radiometer	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
GKSS (D)																			
Miracle	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
KNMI (NL)																			
IR Radiometers	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Video Camera	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
VIS-IR Sensor	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
TU Delft/Eindhoven (NL)																			
Multi-Frequency Radiometer	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

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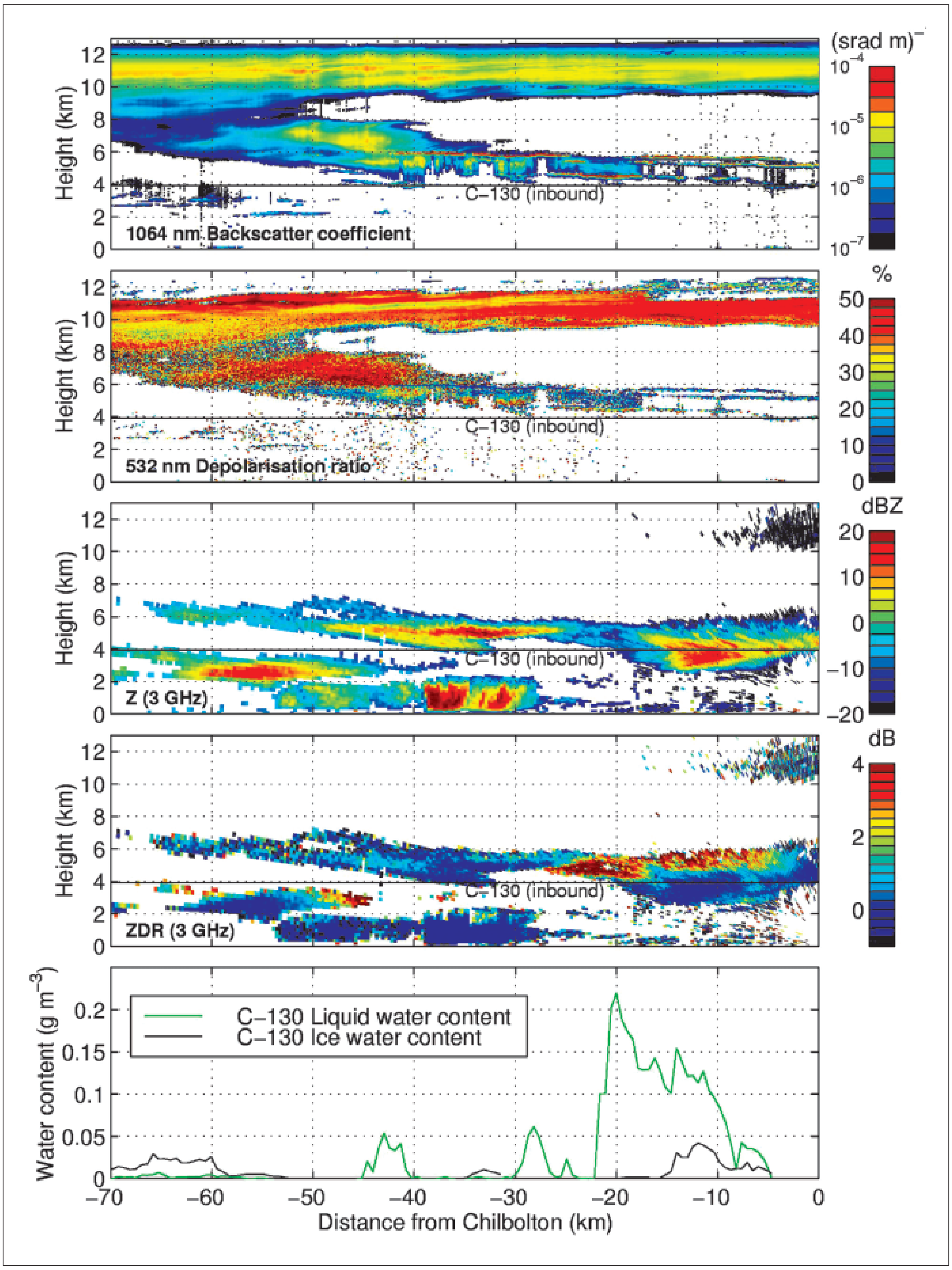


Figure 3. Composite of observations from 20 October 1998 during CLARE'98. The first two panels show measurements by the nadir-pointing lidar (ALEX) onboard the DLR Falcon aircraft flying at an altitude of 13 km. Simultaneous measurements of radar reflectivity (Z) and differential reflectivity (ZDR) by the ground-based CAMRa radar (3 GHz) at Chilbolton are shown in the next two panels. The last panel shows the liquid and ice water content measured by the C-130 aircraft at an altitude of 4 km

The fifth flight, on 20 October 1998

This has proved to be the most intensively studied flight, and therefore serves as a good example of the type of data collected and the results that can be achieved. To document the meteorological conditions, Figure 4 shows the 12:00 UTC routine meteorological (synoptic) analysis. This analysis uses the objective frontal identification of Hewson, in which the isobars are overlaid with the IR satellite data, and warm and cold fronts are shown in red and blue, respectively. Upper fronts are marked in hash shading and the broad black lines represent upper-level jets. Figure 5 shows the radiosonde 12:00 UTC ascent from Larkhill, which is 28 km west of Chilbolton.

Successful co-ordinated flights were made through ice and mixed-phase clouds ahead of advancing fronts in a strengthening south-westerly wind flow (Fig. 4). The ascent (Fig. 5) shows a saturated layer at 650 to 500 hPa. The C-130 remained airborne for 8 hours, but the other two aircraft had to return for refuelling in between. This flight has been the most intensively analysed and is the subject of a number of scientific papers.

Figure 3 shows data from the ALEX lidar looking down from the DLR Falcon for the 14:00 UTC run. The upper cirrus layer between 10 and 12 km is clearly visible, and although the ice attenuates somewhat, some highly reflecting

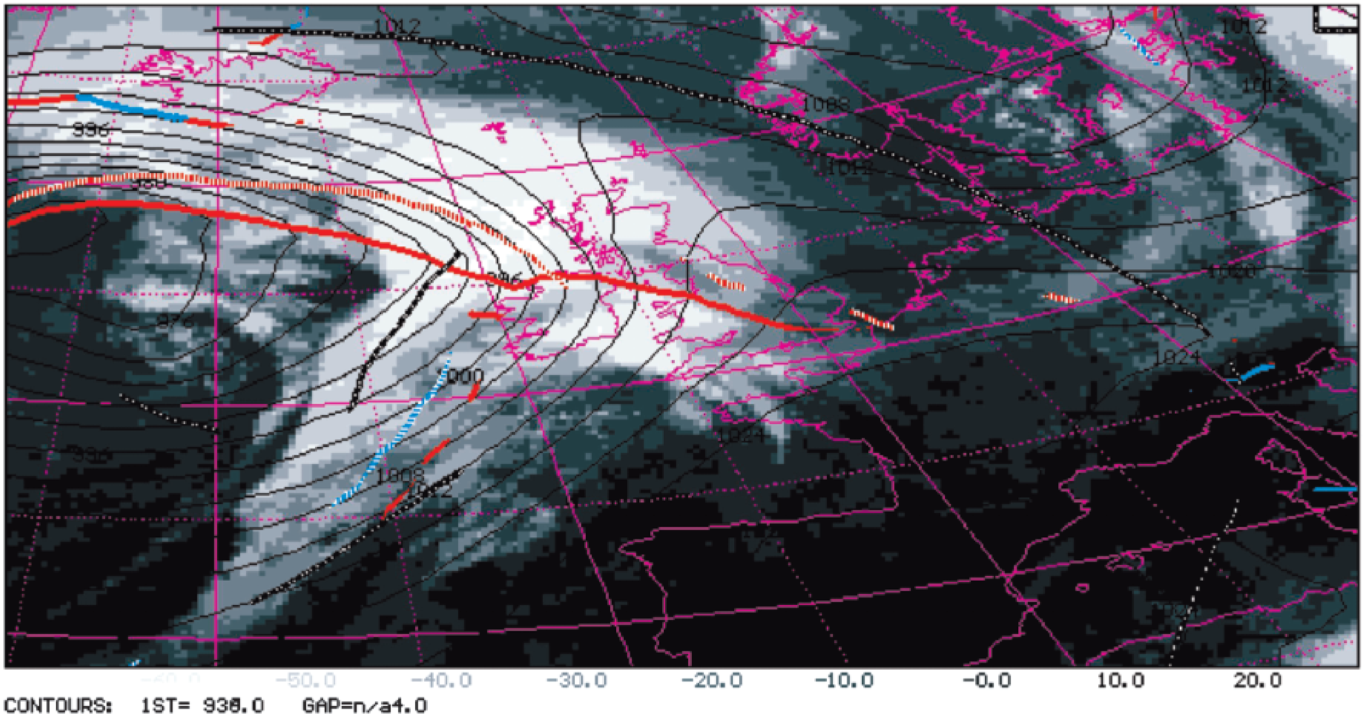


Figure 4. Synoptic situation at 12:00 UTC on 20 October 1998, from IR satellite data. Warm fronts are marked in red, cold fronts in blue, while upper-level jets are indicated by broad black lines

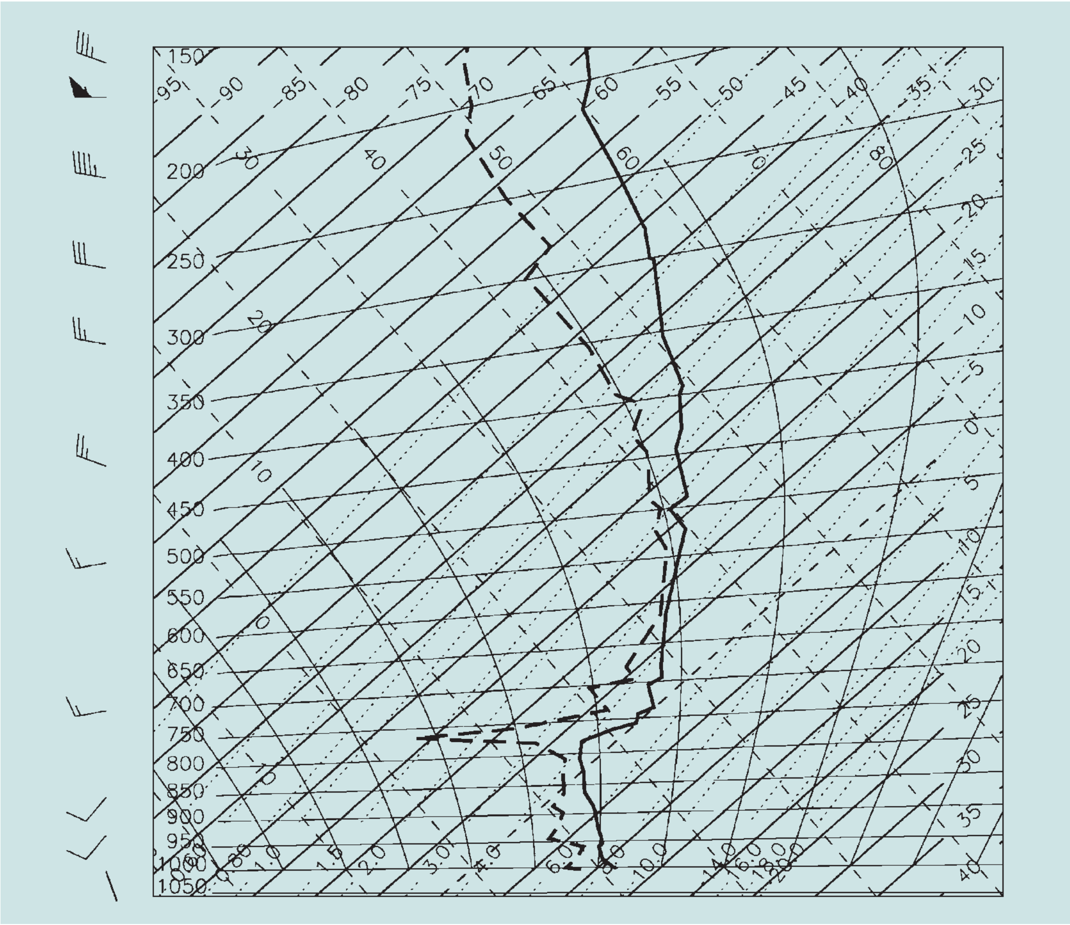


Figure 5. Radiosonde ascent at 12:00 UTC on 20 October 1998 from Larkhill (UK)

layers at a height of 4 to 6 km are evident. The first panel depicts the backscatter coefficient (β) as measured by ALEX. Thin layers of high backscatter coefficient can be seen embedded in the mid-level cloud, and the low depolarisation of these layers as shown in the second panel indicates that they are super-cooled water. This assertion has been confirmed by other in-situ measurements carried out by the C-130. The temperature of the highest super-cooled layer is around -15°C.

The third panel shows the radar reflectivity (Z) in dBZ as measured by the ground-based scanning CAMRa (3 GHz) radar at Chilbolton, and the fourth panel the corresponding

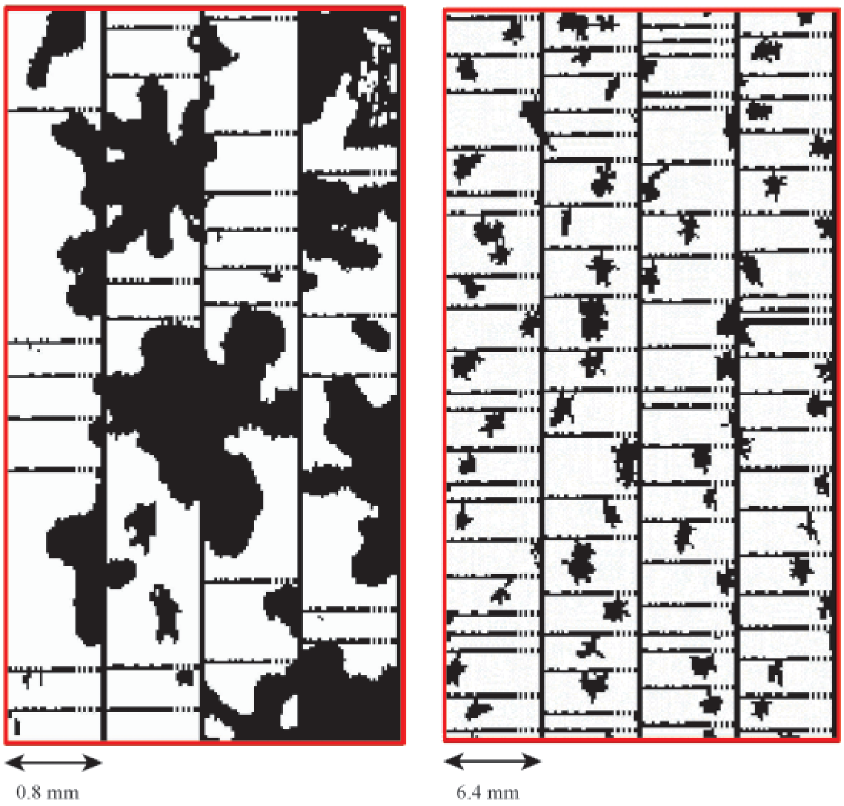
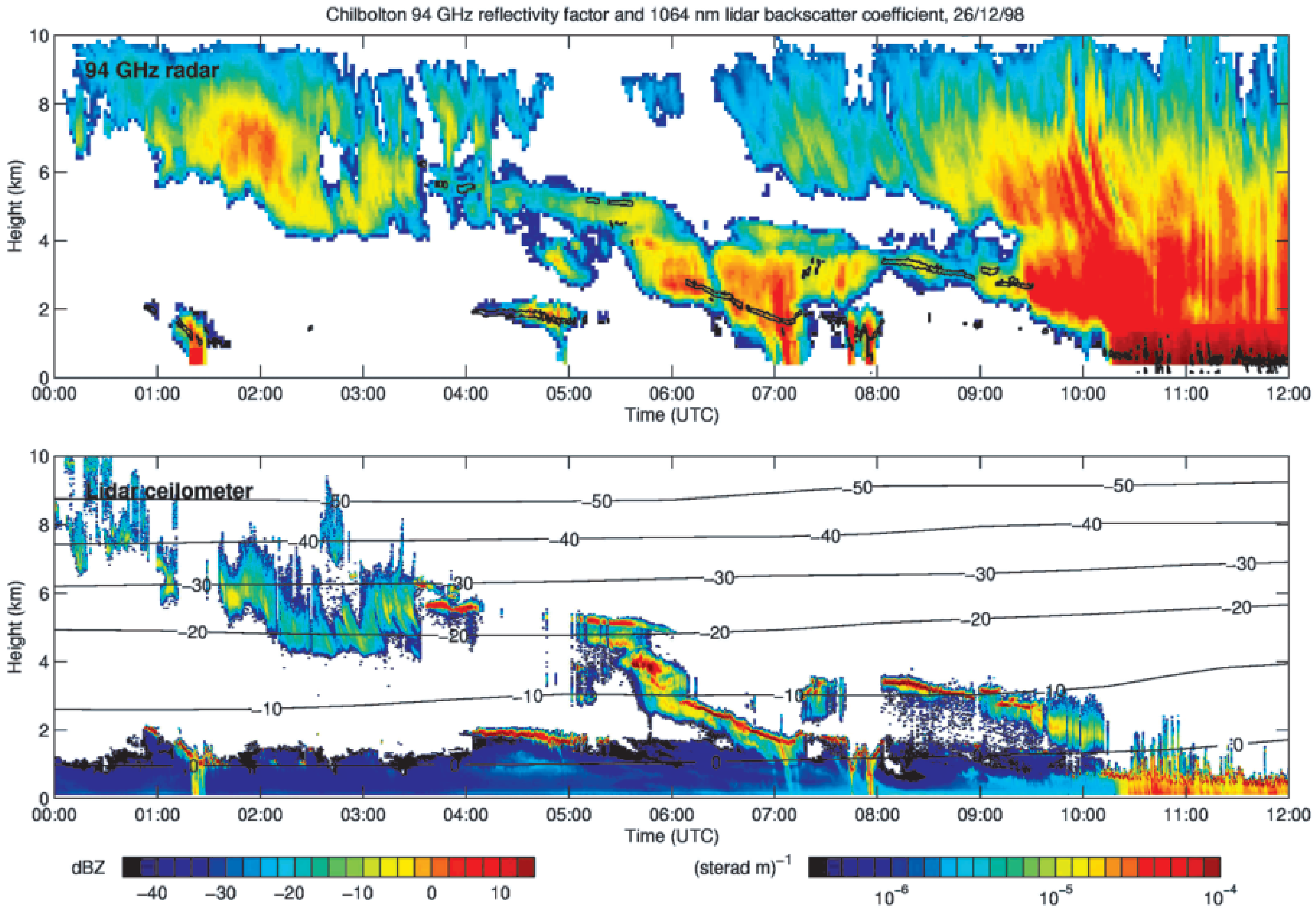


Figure 6. Data from the 2D cloud (left) and precipitation (right) probes, with the array width for each indicated

differential reflectivity (ZDR - difference between the horizontally and vertically polarised radar reflectivities). The cirrus above 9 km is largely below the sensitivity limit of the radar. In the radar-reflectivity data, there is no sign of the super-cooled layers; this is because the much larger ice crystals in the volume of cloud observed dominate the radar signal. For the later runs in this flight, these super-cooled layers have disappeared. The ZDR in the vicinity of these layers is very high, however, indicating a distinct change in ice growth behaviour. The UK Meteorological Office's C-130 was making *in-situ* micro-physical measurements at an altitude of 4 km (indicated in Fig. 3 by a continuous line in all four upper panels) where the temperature was -7°C. The last panel shows the liquid-water content

Figure 7. Continuous ground-based measurements performed by the vertically pointing Vaisala lidar and Galileo radar. The synergy between measurements shows the layers of super-cooled liquid water (marked in black in the upper panel) within the ice cloud. The upper radar plot shows a constant cloud top but a gradually descending cloud base, culminating in rain after about 10:30 UTC. The lidar signal (lower panel) shows the aerosol in the lowest kilometre and after 04:00 highly reflecting and attenuating layers of super-cooled liquid cloud droplets



(LWC) measured by the Johnson-Williams probe, and the ice-water content (IWC) measured by the 2DC and 2DP probes (see example in Fig. 6).

These measurements show that the synergetic use of radar and lidar can reveal the presence of super-cooled layers in mid-level/mixed-phase clouds. This conclusion was further confirmed by continuous ground-based observations using vertically pointing radar and lidar with characteristics similar to those that would be embarked on the ERM. Figure 7 shows an example. This type of continuous observation has also revealed that the presence of super-cooled layers in mid-level clouds is very common.

Figure 8 shows the measurements performed by Kestrel and Leandre aboard the INSU/IPSL ARAT in a subsequent run on this same flight. Using these measurements, techniques were developed and validated for retrieving the micro-physical characteristics of ice clouds. Figure 9 shows the retrieved effective radius (R_{eff}) and ice-water content (IWC).

Figure 10 shows the results of the comparison between the retrieved R_{eff} and IWC (blue lines) and those measured *in-situ* by the C-130 (red lines) that was flying at 4.6 km and under the ARAT. Figure 11 shows that the error between the retrieved and measured quantities is well within the ERM observational requirements (see Table 1, +40/-30% for both R_{eff} and IWC). In this case (Figs. 10 and 11), to ensure that the two aircraft are quasi co-located, their GPS data is used and the data are re-located to ensure that, as far as possible, the same part of the cloud is being sampled. The lowest panel of Figures 10 and 11 shows the horizontal distance between aircraft, and it can be seen that this is always less than 300 m in the area where a cloud is present.

The measurements can also be used to evaluate the co-location requirement for the radar and lidar. For this purpose, since the ARAT and C-130 have different speeds, the comparison can also be performed in terms of time. In this case, the C-130 *in-situ* data is used as a proxy for the data from one of the active instruments. Figure 12 shows the retrieved and

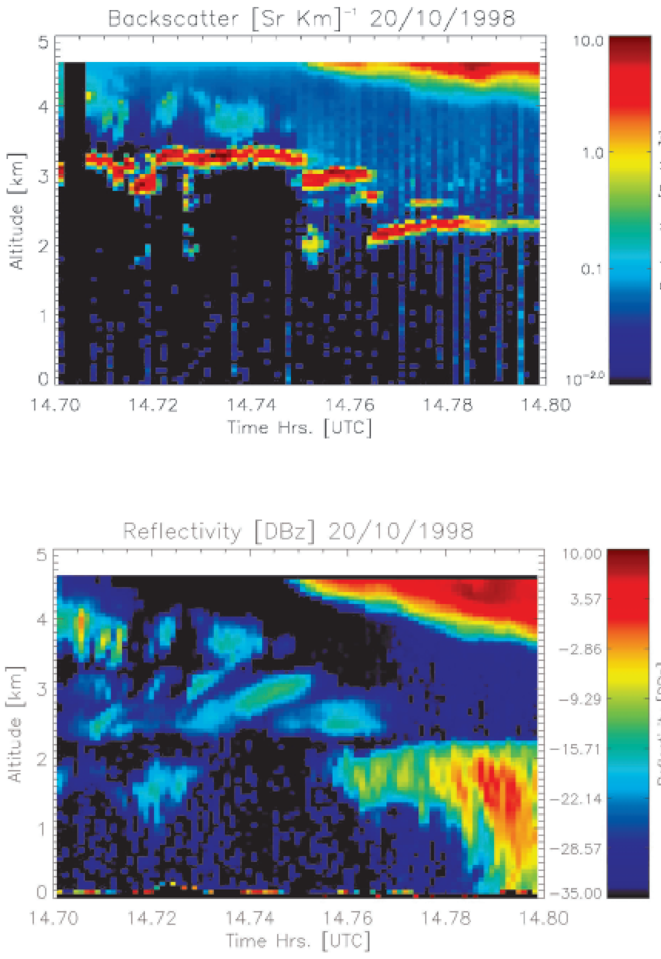


Figure 8. Measurements performed by the nadir-looking lidar (Leandre – upper panel) and radar (Kestrel – lower panel) onboard the INSU/ISPL ARAT aircraft on 20 October 1998

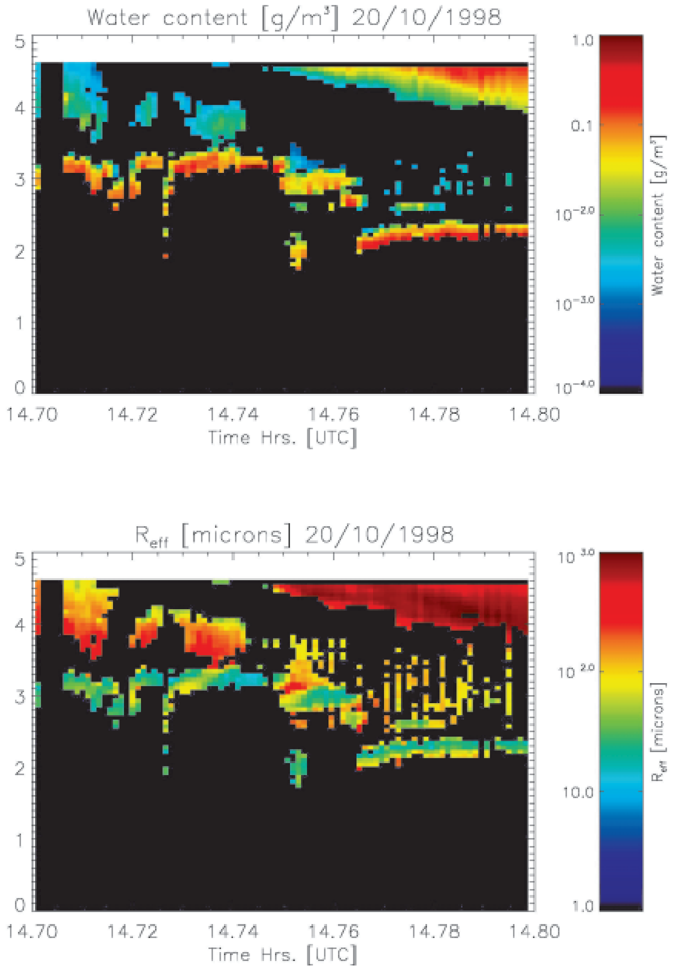
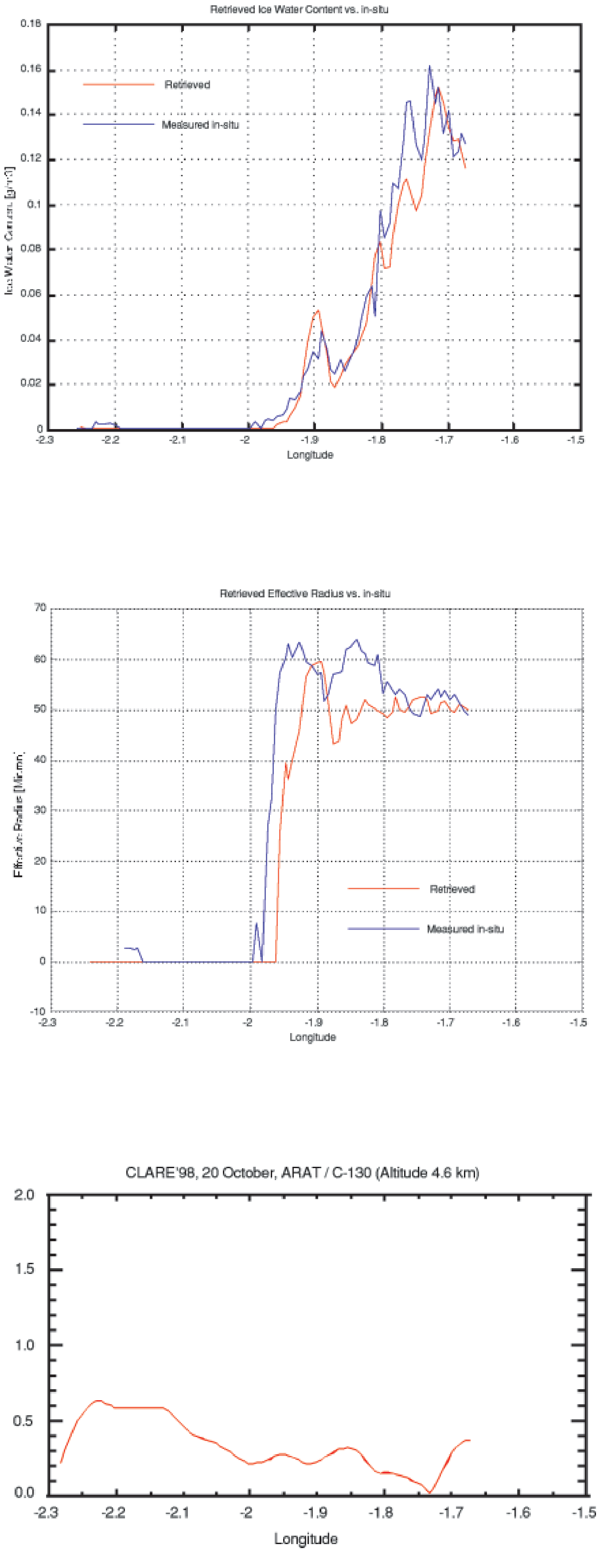


Figure 9. Ice water content (upper panel) and effective radius (lower panel) retrieved from the measurements shown in Figure 8 (after Donovan et al.)



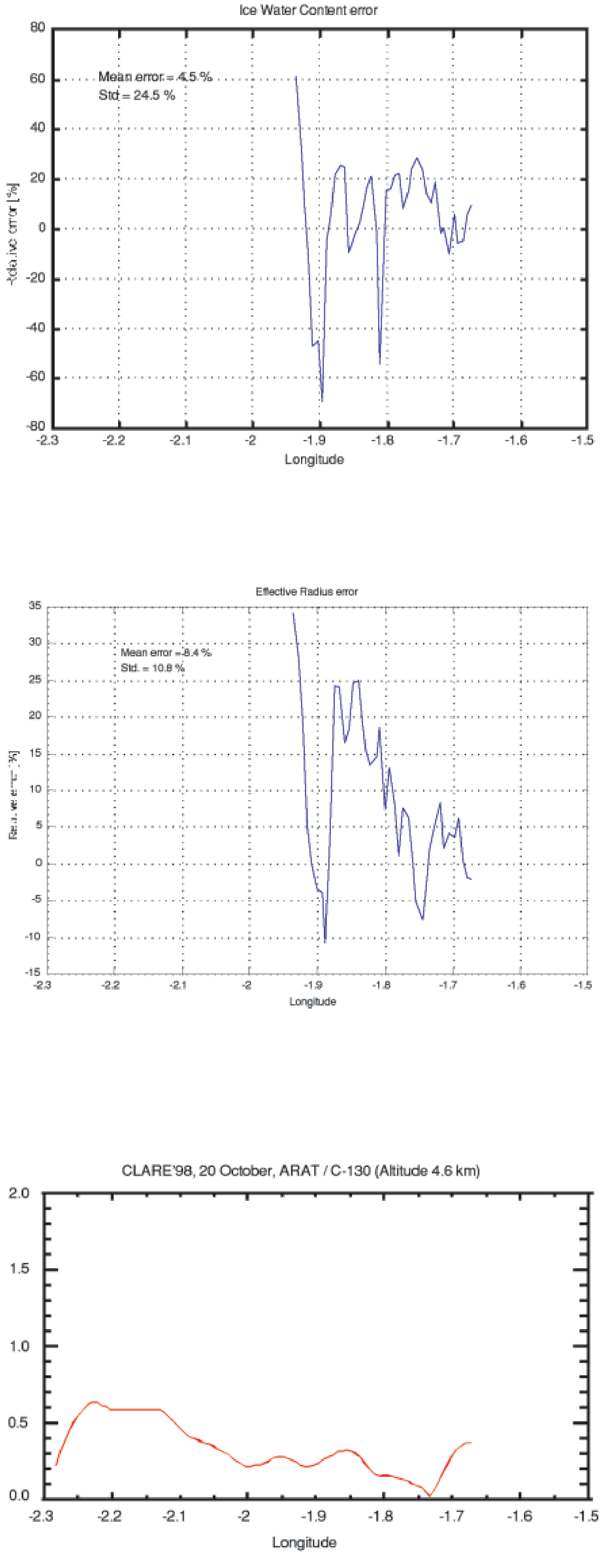


Figure 10. Measured in-situ and retrieved ice water content (first panel) and effective radius (second panel). The third panel shows the horizontal distance between aircraft

Figure 11. Relative error between measured in-situ and retrieved ice water content (first panel) and effective radius (second panel). The third panel shows the horizontal distance between aircraft

measured IWC, as well as the horizontal distance between aircraft. For a 40% error, beyond a distance of around 1 km the retrieval error is unacceptable. In any spaceborne mission, the retrieval error would be even higher due to the attenuation in the signal being simulated by the C-130 data. These results confirm the conclusions arrived at in other studies that use the spectral variability of clouds.

Major results and conclusions of CLARE'98

The major thrust of the data analysis was directed towards the validation and development of algorithms that can be used for a future space mission flying an active radar and lidar. Aspects considered are: instrument sensitivity and cloud detection, the inference of the properties of liquid, mixed phase and ice clouds, and finally the computation of radiative fluxes from the cloud properties.

Detection of clouds and cloud boundaries

The analysis performed on the data confirms that the space-borne radar and lidar proposed for the ERM should have sufficient sensitivity to detect virtually all radiatively significant ice clouds. The radar, however, would miss some thin liquid water clouds, although the lidar should see them. The instruments should detect the multi-level nature of clouds and, for ice clouds, the radar/lidar combination nearly always gave cloud bases with an accuracy of much better than 400 m (ERM requirement). We conclude that the sensitivity of the proposed space-borne instruments is adequate.

Liquid-water clouds

Vertical profiles of drop size, concentration and liquid water content can be derived from ground-based lidar, radar and radiometers on the assumption that drizzle is not present and the total droplet concentration is invariant with height. Optical depth can be derived from ground-based measurements of the oxygen A-band absorption.

These ground-based and short-range aircraft methods of remotely sensing the profiles of water content, drop size and concentrations in liquid-water content show great promise. For space-based remote sensing, a different approach will have to be used since, in liquid-water clouds, the lidar signal would be affected by multiple scattering and attenuation, while the radar would miss some of the clouds due to their very weak reflectivity and the limited radar resolution. However, the cloud boundaries (top and base) can be detected from space, and with some assumptions (e.g. vertical quasi-adiabatic behaviour) and information from passive imagers, estimates of liquid-water content can be made, but further work is needed to refine such techniques.

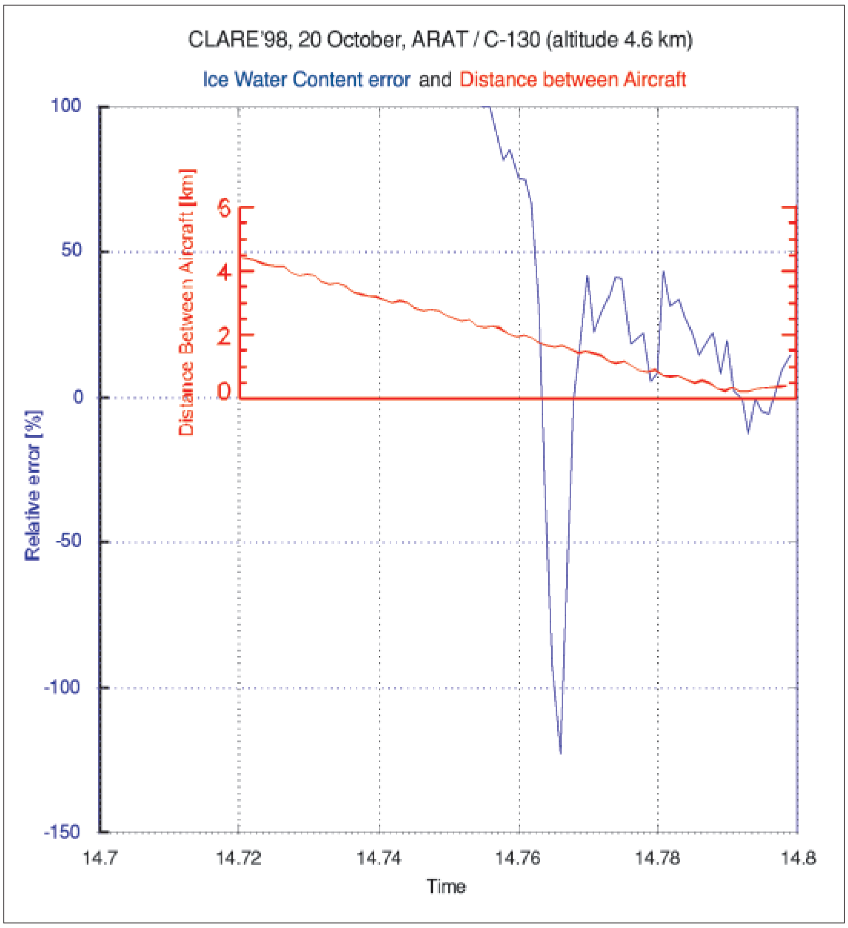


Figure 12. Relative error between measured in-situ and retrieved ice water content when the data are not co-located. The C-130 measured data are being used as a proxy for one of the active instruments. The red graph shows the horizontal distance between aircraft as a function of time. This distance decreases in the direction of Chilbolton where, in each run, the aircraft should pass overhead at the same time. As can be seen, for distances greater than 1 km the retrieval error is unacceptable for the ERM

Mixed-phase clouds

A major advance in our knowledge of mixed-phase clouds was made during the flights on 20 and 21 October, when the presence of layers of super-cooled water was clearly identified by their very high lidar backscatter, which was not accompanied by any increase in the radar reflectivity signal. These inferences were confirmed by the in-situ C-130 measurements; the C-130 aircraft penetrated the thin layer of enhanced lidar backscatter on 20 October.

Analysis of more extensive ground-based radar and lidar observations has revealed that such layers of super-cooled liquid water are quite common and can be easily identified by the combined returns of the two active instruments (Fig. 7). Clearly, the presence of such layers has important implications for the radiative properties of clouds, and also the glaciation and lifetime of cloud, which must be correctly represented in global models. The projected space-borne mission would be able to detect such layers, and this is a very important finding.

Further work is needed – requiring analysis and new observations – to perfect the algorithms for detecting such layers and to define and remove any remaining ambiguities.

Ice clouds

Our lack of quantitative global data on ice clouds is a major gap in the validation of current global-circulation models. The Earth Radiation Mission aims to fill this gap.

The combined radar and lidar should be able to detect virtually all radiatively significant ice clouds and their boundaries, as discussed above. The combined use of radar and lidar has been analysed and a stable method of correcting for lidar attenuation using the radar reflectivity as a first guess has been proposed, which then iterates to a solution for ice particle size and water content. Figures 9 and 10 show an example of the application of this new retrieval algorithm and a comparison of the retrieved Ice Water Content and Effective Radius versus the in-situ measurements. An alternative retrieval approach has also been developed based on the assumption that the normalised ice particle concentration is constant with height, and then using the combined radar and lidar to retrieve ice water content.

The analysis of the data has also demonstrated that the multiple scattering contributions from ice clouds in a space-borne lidar (as opposed to liquid clouds) should be small and should not have a major effect on the retrievals.

The CLARE'98 measurements demonstrate also that, because of the variability of ice cloud properties over short distances, the synergetic radar/lidar retrievals will only operate efficiently if the two instruments are carried on the same platform. It is concluded that the combined use of radar and lidar from space should provide unique data on such ice cloud properties as ice water content and particle size, provided both instruments are indeed embarked on the same platform.

Radiation calculations

The data analysis has demonstrated that the ground-based IR emissivity for water clouds of known temperature can be related to their liquid water path, but that for ice the relationship is less simple. The aircraft measurements show also that for water clouds, the observed radiative fluxes in the visible are consistent with the values of optical depth and albedo inferred for the cloud. As for the ground-based measurements, for ice clouds the situation is more difficult. They have many variable parameters, so that it is impossible to take the measured radiative fluxes and derive a unique cloud profile. The approach to be adopted is the one used in the ERM. Once the profiles of ice cloud properties have been derived from the active sensors, then these values are fed into a radiative transfer model predicting the radiative fluxes. These fluxes can then be compared with the aircraft observations. It is important that this work be carried out as it parallels exactly the approach that will be used in a space-borne radiation mission.

Conclusions

As the results of CLARE'98 demonstrate, a very successful campaign consisting of seven data-collecting flights was carried out probing a variety of clouds. Associated with CLARE'98, techniques were developed and validated to derive the vertical profiles of the characteristics of liquid-water clouds from ground-based measurements. For space-based measurements, however, a different technique will have to be developed, defining cloud top and cloud base of liquid-water clouds and then using information from the passive sensors to infer cloud water content. An assumption based on the quasi-adiabatic behaviour of these clouds may further help in this development, but additional work is needed to refine such retrievals.

The synergetic use of space-borne radar and lidar should prove a powerful tool with which to quantify the occurrence of layers of super-cooled water. The representation of such layers is important in global models because of their effect on cloud radiation and cloud lifetime, but it is only with these new observations that the ubiquity of such layers in clouds has been established. Further work is needed to confirm the efficiency with which lidar and radar can identify such layers.

The synergetic use of radar and lidar is a uniquely powerful tool for quantifying the ice water content and effective radius of ice clouds, provided the two instruments are embarked on the same space-borne platform. The global characteristics of such clouds are urgently needed for validating global circulation models. Further work is needed to refine and perfect the radar and lidar retrieval algorithms.

A more powerful joint European-Japanese Earth radiation mission is being actively pursued. Such a mission would be able to address all of the key issues associated with the role of clouds and aerosols in the Earth's radiation budget.