

Observing cloud properties with ground-based mm-wavelength radar

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1 Introduction

The correct representation of clouds is crucial to models used to provide short term weather forecasts and predict future climate change. Such models now typically have one or two prognostic variables to simulate the clouds, such as cloud fraction and ice/liquid water content. The EU CloudNET project has three aims:

- a) to develop cloud radar and lidar instrumentation and appropriate algorithms to derive the variables used to represent clouds in such models,
- b) to obtain a two year continuous record of these cloud variables over three sites within Europe and then,
- c) to compare these observations with the representation of clouds over these three sites in four operational forecast models of ECMWF, the Met Office, MeteoFrance and Racmo.

The CloudNET project will terminate in the summer of 2005. In this paper we describe the progress made in the first three years of the project.

The instrumentation and sites are outlined in Sect. 2 and a summary of the algorithms development is provided in Sect. 3, the data sets in Sect. 4, and some early results of comparisons with the models are described in section 5. The 17 refereed CloudNET papers are too lengthy to list in this short article but can be found along with the data set quick-looks at <http://www.met.rdg.ac.uk/radar/cloudnet/>.

2 CloudNET remote sensing stations

2.1 Observation Sites

The three sites are located at Chilbolton UK (51.14N –1.44E), Palaiseau, Paris, France (48.24N 2.16E) and

Cabauw, The Netherlands (51.97N 4.92E). At each site a variety of ground based remote sensing instruments is deployed, most of which have been operating 24 h a day and 7 days a week since the start of the two year intensive period of observations on 1 October 2002. The most important instruments are the vertically pointing Dopplerised cloud radars (94/95 GHz at Chilbolton and Palaiseau, and 35 GHz at Cabauw) and 905 nm lidar ceilometers which provide profiles with 60 m vertical resolution every 30 s. In addition there are downwelling broadband SW and LW radiometers, several microwave radiometers for providing water vapour and liquid water information and a 3 GHz radar at Cabauw. Other instruments such as 355 nm UV Raman lidar at Chilbolton and a polarimetric lidar at Palaiseau have been run on an event basis.

2.2 Instrument Calibration

Accurate calibration is crucial when deriving cloud properties from the lidar and radar backscatter profiles.

Lidar Calibration. Traditionally lidars are calibrated by comparison with molecular Rayleigh scattering but this is not possible at wavelengths greater than 600 nm. Instead we use thick stratocumulus clouds to provide a self-calibration technique by adding up the backscatter (in $\text{m}^{-1} \text{sr}^{-1}$) at each gate until the signal is extinguished. This gives us the 'integrated backscatter' which should have a theoretical value of 15 sr in liquid water clouds. The calibration factor is adjusted until this value is achieved and provides an absolute calibration accurate to about 10%.

Radar Calibration. Absolute calibration via link-budget calculations is error prone. Instead we use the fact that at 94 GHz Mie scattering leads to a radar reflectivity in rain above 2 mm hr^{-1} which is virtually constant and close to 19 dBZ. The reflectivity is measured at a range of 250 m to minimise any attenuation affects and provides an absolute calibration to within 1 dB.

3 Data quality and algorithms

3.1 Categorisation and Quality Control

If the products are to be used for evaluating NWP model performance then the data must be rigorously quality controlled to avoid spurious artifacts being falsely identified as cloud.

Categorisation. The first stage is to examine the lidar backscatter and Doppler data together with the temperature profile from the operation models and classify the targets into nine categories of targets: i) aerosols, ii) insects, iii) aerosols and insects, iv) ice and supercooled droplets, v) ice, vi) drizzle/rain and cloud droplets, vii) drizzle or rain, viii) cloud droplets only, and ix) clear sky.

Quality control. This categorisation information is accompanied by a status flag. Firstly, the 94GHz radar must be corrected for attenuation by water vapour and oxygen which is straightforward using the operational model. Cloud liquid water attenuation can be corrected if good radiometer data is present, but is very difficult for attenuating rain. Low level water cloud will extinguish the lidar return completely. This leads to nine status flags: i) Radar ground clutter, ii) Radar corrected for liquid attenuation, iii) No radar echo but known attenuation iv) Good radar echo only v) No radar but unknown attenuation (rain), vi) Good radar and lidar echo, vii) Radar echo but uncorrected attenuation, viii) Lidar echo only, and ix) Clear sky.

3.2 Retrieval Algorithms

The next stage is to derive the products which will be compared to the values held in the operational model output which is available every hour with a vertical resolution ranging from 100 m to 500 m. Below is a summary of some of the algorithms which have been developed. Note the philosophy whereby operational model variables are used in some of the algorithms.

Cloud Fraction. The categorisation information can be used to identify which of the 60 m/30 second pixels contain a cloud, as opposed to, for example, a radar signal indicating drizzle below the lidar cloud base. A typical model grid box will contain over a hundred pixels so cloud fraction can be estimated to a few per cent. The spatial distribution of pixels within the grid box can be used to examine cloud overlap properties.

Ice Water Content from Z and T. The reflectivity values of those pixels within a model grid box categorised as ice can be converted into ice water content (IWC) either by a straightforward empirical IWC-Z relationship, or, for increased accuracy, an IWC-(Z, T) relationship using T from the operational model. A value of mean IWC within a grid box or a pdf of IWC within the grid box can then be derived together with its error. The error has two components, one associated with the IWC-Z or IWC-(Z, T) retrieval, and an additional error arising from the attenuation of Z and the confidence with which that attenuation has been corrected. During heavy rain we reject all data as being too error prone.

Ice Water Content and Size from Radar and Lidar. When the categorisation indicates ice and the quality flag signals that there are good radar and lidar echoes, then a radar/lidar algorithm is invoked which uses the radar signal to correct for lidar attenuation, and then derives the ice particle size from the ratio of the radar backscatter to the attenuation corrected lidar backscatter. Once the size is known then a more accurate IWC can be calculated from the value of Z.

Ice particle Density. The density of ice particles tends to fall with increasing size and the precise form of this density-size relationship can change the IWC derived from Z by 50%. The variation of the ratio of the reflectivities at 35 and 94 GHz as a function of the ratio of the observed mean Doppler at the two frequencies can be used to infer the optimum density-size relationship.

Stratocumulus with and without drizzle. It is difficult to derive liquid water content (LWC) of clouds from Z because the presence of occasional drizzle droplets dominates Z but contributes little to LWC. Techniques have been developed which use the Doppler and reflectivity radar observations with the lidar to isolate the drizzle component and derive the concentration and size of the droplets together with the drizzle flux. In the absence of drizzle the lidar and radar signal are used to derive the size and concentration of the cloud droplets and hence find the LWC and the degree to which mixing leads to subadiabatic values. These findings confirm the validity of assuming a profile with a constant drop concentration in the lower half of stratocumulus clouds.

Turbulence. The rate of dissipation of turbulent kinetic energy (TKE) is derived from a new radar parameter: the variance of the mean Doppler velocities recorded every second over a period of thirty seconds. This new approach uses the wind, U (m s^{-1}), from the operational model, so that the two limits for the spatial scale of the motions sensed by the variance of the mean Doppler are $30U$ m and $(U + \text{beamwidth})$ m. These two limits are within the inertial sub-range, so by integrating an expression involving the variance of the mean doppler between these two spatial scales, we can derive the dissipation rate of TKE in terms of the observed variance in the mean Doppler. The values of TKE in stratocumulus are found to be three orders of magnitude higher than in cirrus.

4 Data Sets

The raw observations taken every 30 s with 60 m resolution are displayed on quick looks for each site every day in near real time together with monthly composite quick looks. The derived model quantities are plotted on the hourly model grid with the appropriate vertical resolution and displayed on the web together with parameters from the four operational models hour-by-hour at each site. All data are recorded in standard netCDF format for ease of subsequent processing.

The raw data plotted are profiles of i) radar reflectivity, ii) mean Doppler, iii) spectral width, iv) variance of the mean Doppler, v) lidar backscatter; integrated values of

vi) rainrate, vii) liquid water path from the radiometers; profiles of viii) the 94 GHz attenuation from oxygen and water vapour, ix) 94 GHz attenuation due to lwp, x) broad band SW and LW downward fluxes. Then the derived profiles of xi) target classification xii) target status, xiii) cloud fraction calculated by area and volume, and for one hour or for a time equivalent to 60 km estimated using the model winds. xiv) Integrated cloud cover computed four ways as for the cloud fraction profiles xv) Profiles of Ice water content from Z and T and associated errors and status xvi) Profiles of Ice water content, ice particle size and extinction coefficient calculated from simultaneous radar and lidar and associated errors xvii) Profiles of dissipation rates of TKE derived from the variance of the mean Doppler and its associated error.

These observed quantities can then be compared with the hourly profiles from the four operational models. The following values are archived for the grid point above the three stations: T , q_v , RH, LWC, IWC, u , v , w , and cloud fraction.

5 Results

The common NetCDF data format makes comparing model and observations relatively straightforward. We now report on three example comparisons.

Fractional cloud cover and ice water content. Analysis of one years data over Chilbolton reveals that the ECMWF and Met Office mean fractional cover for the whole year tended to be overestimated above 6 km and underestimated below 6 km. This was principally due to an error in the fractional cloud cover when cloud was present. The values of profiles of IWC in the two models were about half the value observed, but this difference was within the error of the observed IWC arising from uncertainty in the IWC- (Z, T) relationship. In addition, the data were split up into six weather regimes, depending whether there was ascent at 500 and 700 mb and if the atmosphere was stable at 900 mb. An example of the conclusions is that the Met Office diagnostic cloud fraction scheme found it difficult to produce 100% cloud cover when there was low level stability, whereas such complete cloud cover was frequently observed and well captured by the prognostic cloud cover scheme used by ECMWF.

Climatology of supercooled clouds. Supercooled cloud layers can be easily identified by the very high lidar backscatter leading to total extinction of the signal at cold temperatures which is not accompanied by a significant increase in radar reflectivity. This inference has been validated by simultaneous in-situ aircraft observations of cloud particle type. Analysis of one year's data at Chilbolton and Cabauw reveals that such layers are relatively common, for example on 20% of the occasions when there is cloud at -10°C then a supercooled layer is present. Such layers are often thin and contain relatively low amounts of condensed water but have a large effect on the radiation, but the same amount of water in the form of ice would have a much smaller radiative impact. The models are not able to produce these supercooled layer clouds in a realistic manner.

Parameterisation of ice cloud inhomogeneities. Analysis of the spatial distribution and variability of individual pixels of ice water content within a model grid box has revealed that the pdf of the iwc is well represented by either a log-normal or gamma function. Expressions have been derived on how the fractional variance of the iwc varies within the grid box as a function of grid box size and wind shear. In addition the degree to which inhomogeneities in ice water content overlap in the vertical has been quantified as a function of grid box size and wind shear; currently the ice is assumed fill the grid box uniformly but the degree of overlap influences the radiative transfer.

Defining cloud fraction by volume or by area. Models implicitly assume that the fraction of the grid box filled by cloud is equal to the projected area of the grid box filled by cloud, and use this fraction for computing radiative effects. Analysis of the precise distribution of cloudy pixels within a grid box shows that clouds usually slope to some degree so that the cloud fraction by area is always higher than that by volume. For example, for a grid box with a height of 720 m if the volume is half filled with cloud, then the horizontally projected area of cloud is about 80%. Analytical expressions have been derived for the mean difference between the two values of cloud cover as a function of grid box size and wind shear.

6 Conclusion

A unique quality controlled data set of observed profiles of cloud properties with errors at three ground stations and co-incident profiles of the representation of clouds in four operational models is being obtained. The data is all stored in a common format to facilitate comparison of the observations with the model representation and the first results are being produced. With this infrastructure it is a simple step from comparing one algorithm product at one site with one model output to testing the product at all sites for all models. Such comparisons will be available over the next twelve months.

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