

Ground-based Radar Observations of Visibility in a Radiation Fog Layer

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Abstract

The development of a radiation fog layer at the Cabauw Experimental Site for Atmospheric Research (51.97° N, 4.93° E) on 23 March 2011 was observed with ground-based in situ and remote sensing observations to investigate the relationship between visibility and radar reflectivity. The fog layer thickness was less than 200 m. Radar reflectivity values did not exceed -25 dBZ even with visibilities less than 100m. The onset and evaporation of fog produce different radar reflectivity – visibility relationships. The evolution of the fog layer was modelled with a droplet activation model which used the aerosol size distribution observed at the 60 m altitude tower level as input. The modelling results suggest that the different radar-reflectivity – visibility relationships are the result of differences in the interplay between water vapour and cloud droplets during formation and evaporation of the fog. During droplet activation only a few large cloud droplets remain after successfully competing for water vapour with the smaller activated droplets. These small droplets eventually evaporate (deactivate) again. In the fog dissolution / evaporation stage, only these large droplet need to be evaporated. Therefore, to convert radar reflectivity to visibility for traffic safety products, knowledge is necessary of the state of local fog evolution.

1. Introduction

Visibility is the end result of a complex interplay between aerosol microphysics, chemistry, radiation cooling and the activation of wetted aerosol particles to droplets. Before particle activation occurs, visible extinction is not so large, and range variations in visibility can be observed remotely by lidar. However, when particle activation has occurred, visibility can only be locally observed with traditional in situ visibility sensors while horizontal variations in visibility are undetectable. This makes visibility sensors or lidar as tools for nowcasting of limited use as spatial variations in visibility remain undetected.

The purpose of this paper is to establish the link between visibility and radar reflectivity in order to investigate the feasibility of developing a radar visibility product for use in (air) traffic management. To this end the remote sensing synergy present at the Cabauw Experimental Site for Atmospheric Research (CESAR, <http://www.cesar-observatory.nl>) in the western part of the Netherlands is used to detect fog layers. The strategy of this work was to capture the link between visibility, radar reflectivity from the CESAR observations, and to model this link using a fog – cloud droplet activation model in order to understand the physics of nucleation and droplet formation. Particle nucleation was simulated using a kappa-Kohler model of droplet activation. The nucleation model was coupled to a traditional Mie scattering model to simulate visibility and radar reflectivity in order to gauge whether the observed coupling between visibility and radar reflectivity can indeed be modelled, and thus can be understood in terms of physical processes.

2. Observations

The Cabauw Experimental Site for Atmospheric Research (CESAR) is situated at 51.97° N, 4.93° E in a rural flat grassland region between the cities of Rotterdam and Utrecht in the Netherlands. Cabauw is the meteorological research site of KNMI and was originally established in 1972. The 200 m mast is instrumented at the 2, 10, 20, 40, 80, 140, and 200 m levels. Measurements at these levels include temperature, humidity, wind speed and wind direction. The observations at CESAR are supported by radiosonde that are launched at 12 hour intervals at the WMO-KNMI launch site in de Bilt (52.10°N, 5.18° E) which is at a distance of 22.19 km from Cabauw. The principal modes of cloud observation are a cloud radar at 35 GHz, a ceilometer, and a multi - wavelength microwave radiometer. As the radar is traditionally operated in the zenith direction, this mode of operation would yield no information about fog, as the first range gate of the radar is at 250 m. Therefore a light weight aluminium reflector was procured, and during fog episodes the reflector was placed above the antenna of the cloud radar. The reflector deflects the radar beam in nearly horizontal direction but slightly upwards at an angle of 3.5°. This small angle was chosen for safety purposes and to be able to detect the top of the fog layer. An aerosol inlet was mounted at the 60 m tower level and a TSI Scanning Mobility Particle Sizer (SMPS), was installed to measure dry aerosol spectra and total cloud particle counts. The tower levels 2, 10, 20 were fitted with Biral SWS-100 sensors with a visibility resolution of 10 m and an accuracy of 10% (maximum).

3. Droplet Activation Model

A droplet activation model was developed that allows the calculation of wetted – aerosol / fog droplet spectra as a function observed SMPS dry aerosol spectra. Here a combination of tower-measured temperature and humidity data is used to prescribe particle growth rate and activation. Droplet activation was modelled for three values of the hygroscopicity parameter κ , namely a) $\kappa = 1.30$ (representing pure sea salt NaCl , for example present during north-westerly inflow of clean oceanic air), b) $\kappa = 0.67$ (representative of ammonium nitrate, NH_4NO_3 , a nitrogen salt that is typically formed in the polluted Dutch environment as a result of reaction between ammonia and NO_x), c) $\kappa = 0.33$ (representative of a less soluble organic compound). To convert the computed spectra to visibility the particles were binned at time steps of 1 minute in 150 size bins and Mie-code was used to calculate the scattering properties of the wetted aerosols at a wavelength of 550 nm. Then visibility can be calculated according to standard formulae.

4. Results

The observations and modelling of the radiation fog that developed in the night from 22 to 23 of March 2011 are discussed. Maximum height of the fog layer was at 140 m well below the tower altitude. The fog layer developed late on 22 March and dissolved between 8 and 10 GMT on the next day. As the height of the initial fog layer late on 22 March did not reach the first detection level of the radar (lower than 20 m) these early data are of no consequence for developing visibility – radar relationships. Therefore we only discuss the data of 23 March.

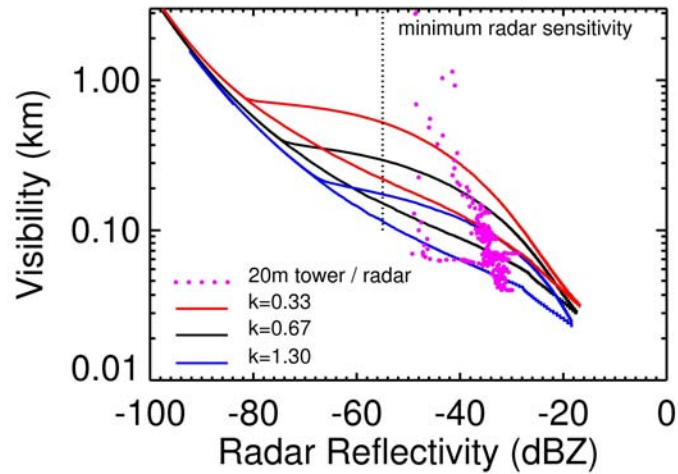


FIG. 1. Modelled relationships between visibility and radar reflectivity (black, red and blue) superimposed on the measured relationship (purple), for 23 March 2011.

Figure 1 shows radar reflectivity versus visibility as the purple dots. Maximum reflectivity values are in excess of -30 dBZ. These values are well below those expected of minor drizzle formation (-10 – 20 dBZ) so it is clear that no precipitation occurred during the fog episode. It appears that for this day there is not a uniform link between visibility and radar reflectivity. There are two branches with the lower branch [purple dots on the lower left] representing the early hours of fog development, and the second steeper branch [upper right] representing the later hours.

The relationship between visibility and radar reflectivity is modelled for the three values of κ . Although there is not a one-to-one relationship between data and model output, for each simulation the two branches are apparent that reflect the process of activation (lower branch) and that of deactivation (upper branch).

Figure 2 shows a plot of the radar reflectivity converted to visibility using a least squares fit through the upper branch of the visibility – radar reflectivity relationship from Figure 1. For this relationship the radar is able to distinguish visibilities of 500m or less at distances of several kilometres away from the observer. It is even possible to discern visibility variation at very high temporal evolution. However, these visibility estimates are always limited by the sensitivity of the radar.

5. Conclusions

The comparison of fog related observations on 23 March 2011 with a simulation using a microphysical model of particle activation shows a number of important points:

1. The link between visibility and radar reflectivity does not follow an unambiguous universal curve. Early on during fog formation the link shows comparative little variation in visibility and large variation in radar reflectivity. Later on as the fog is in its mature stage and show signs of dissolution, the relationship shifts towards large variation in visibility and comparatively smaller variation in radar reflectivity.

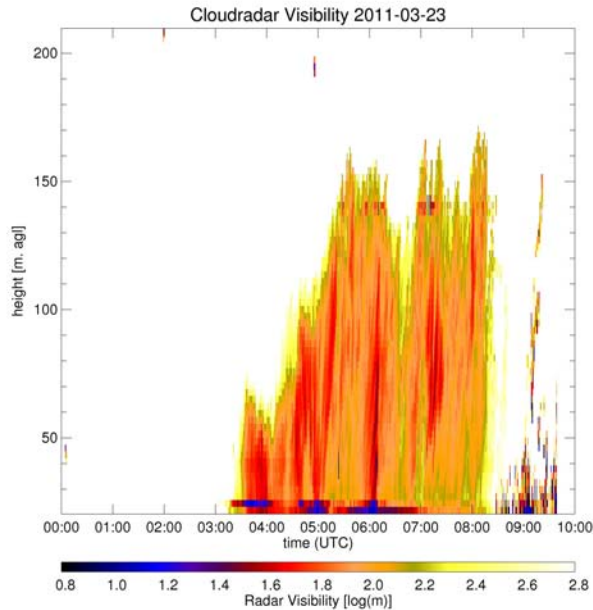


FIG. 2. Colour plot of the time-height cross section of visibility as derived by radar reflectivity converted to visibility by means of the visibility – radar relationship established from FIG. 1, for 23 March 2011 [upper branch of purple dots in FIG 1].

2. A model simulation of this fog episode indicates that one possible reason for the two branches in visibility – radar reflectivity plot is that during condensation a portion of activated aerosol particles evaporate well ahead of their reaching a mature stage as they loose the competition for water vapor with the larger drops.

3. Simulation suggests that only about 1% of available aerosol particles are activated to fog droplets. This is a very small number and entirely due to the fact that the cooling rate for this fog is an order of magnitude less than that of a parcel of moist air moving at an updraft speed of 0.5 m s^{-1} . Thus, the total number of fog droplets is much lower than expected from a typical cloud for which the droplet concentration is controlled by convective motions.

4. The chemistry of the fog layer has a significant impact on the link between visibility and radar reflectivity. The lower the value of k the more dynamic resolution is to be expected in the sensitive transition region where a layer changes from haze to fog to dense fog.

To our knowledge our observations are the first to link radar reflectivity and visibility through direct observations of these two quantities. It is clear that radar reflectivity can be converted to visibility opening the way for a powerful tool to augment the detection capability of reduced visibility at airports or roads. Depending on the chemistry of the dry aerosol and given the fact that $10000 \text{ particles cm}^{-3}$ is a useful number to approximate the typical aerosol concentrations at CESAR, the current radar will yield credible values of visibility from 600 – 800 m downwards to 50m. It would be useful to increase radar sensitivity to -60 to -65 dBZ so that the dynamic range of the radar - visibility product is improved. Further research presently under way will focus on continued analysis of fog episodes with emphasis on chemical composition, different cooling rates and the measurement of fog droplet concentration at the 60 m altitude inlet.