Observing and Forecasting Antarctic Clouds

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Introduction

Forecasting low cloud cover and cloud base height is critical to the support of Antarctic aviation operations. Both the Terminal Area forecast (TAF) and route forecast (ROFOR) are required to provide estimates of low cloud ($<$ 5000 ft, or 1524 m) cover, in oktas and base height (feet) to provide aircrew with minimum safe altitudes for maintaining Visual Meteorological Conditions (VMC). Along with providing forecast of cloud height and extent, observing and forecasting icing conditions within the clouds is also of critical importance to many of the aircraft operating in the Antarctic. In the first section an analysis of cloud observations and forecasting techniques is presented and in the second a case study of an aircraft icing incident. Observational and modelling issues surrounding cloud forecasting and areas for further research are highlighted.

Observing Antarctic clouds

Routine observations of cloud base and cover are made at staffed Antarctic stations and many of the regular ski-ways and landing sites with these observations traditionally provided by trained observers and the accuracy of the cloud base observations dependent on the experience of the observer and availability of reference markers to gauge the cloud height. These observations are also necessarily limited to staffed sites with large sections of the Antarctic continent devoid of any observations of cloud base or cover.

This data void has led to a reliance on Numerical Weather Prediction (NWP) output to provide information on cloud properties over the Antarctic region. Early systems were based on polar-LAPS modeled Relative Humidity (RH) profiles using threshold RH values (Adams 2002) to define the presence of cloud from which cloud top temperature and cloud base height fields could be generated. The threshold values used in the algorithm varied from 99% near the surface to 65% in the upper troposphere and were strongly influenced by mid latitude threshold values and the expectation that the very low clouds at least would be mixed phase clouds and high RH measurements expected from the radiosonde as it passed through the cloud.

However, a study by Inoue et. al. (2010) highlighted some major inadequacies in using RH as a cloud discriminator in the Antarctic. A comparative analysis of radiosonde RH profiles in the lower troposphere and manual observations of cloud base height showed a significant number of observations of low cloud were coincident with very low RH as measured by the radiosonde with some measurements below 50%, and nowhere near the 90 to 100% which would be expected if the radiosonde had passed through a liquid water cloud. In the analysis by Inoue et. al. (2010) radiosonde and surface based cloud observations were compared from Mawson, Davis and Casey (Figure 1) for the period November 2005 to May 2010. In one such comparison the 0000 and 1200 UTC radiosonde data was limited to those occasions where the low cloud layer was observed at 8 oktas and guaranteeing that the radiosonde had passed through the reported cloud. In this analysis it was found that 22% of cloudy events (389 total) at Casey had RH values in the lowest layer (surface to a height 250 m above the reported cloud) of less than 80%. At Davis the figure

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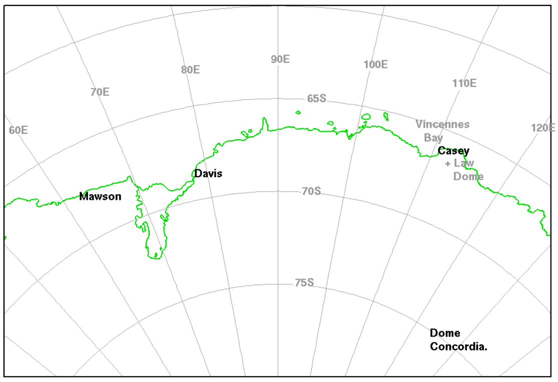

Figure 1: map of East Antarctica highlighting Mawson, Davis, Casey and key features in the Casey area.

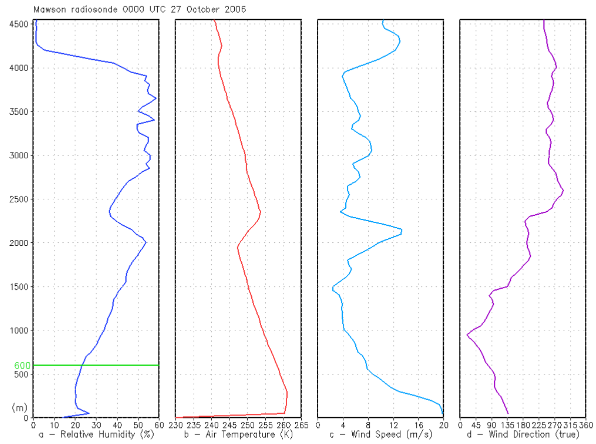

Figure 2: Radiosonde data from Mawson at 0000 UTC 27 October 2006. a) relative humidity, b) air temperature, c) wind speed, d) wind direction.

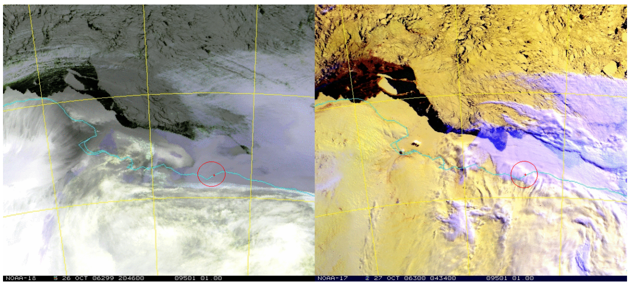

Figure 3: Multi-spectral false colour imagery from around Mawson at: a) NOAA18 2046 UTC 26 October 2006 IR channels, b) NOAA17 0434 UTC 27 October 2006, from visible channels.

was 40% (of 106 total events) and at Mawson the figure was 43% of the 117 total cloud cover events. At Mawson Station 14% of cloudy events had RH values in the lowest layer of less than 50%. At Davis the figure was 7% and at Casey only 0.25% (1 observation).

Figure 2a shows an example RH profile from Mawson Station at 0000 UTC on 27 October 2006 where the observed solid deck of cloud (base at 600 m) went undetected by the radiosonde humidity probe. RH values steadily rose to 53% by 2000 m but it was very unlikely that an observational error of such a magnitude was made given that sunrise was around the time of the radiosonde flight and visibility would have been good. In Figure 3a the infra-red false colour image from the NOAA18 26 October 2006 2046 UTC pass, three hours prior to the balloon flight, showed a solid cover of low cloud over the Mawson area. The same deck of low cloud was still evident in the visible/near visible false colour image from the NOAA17 0434 UTC pass on 27 October 2006 (Figure 3b), some four hours after the radiosonde ascent. The day-time NOAA17 passes do not include the 3.74 micron channel used for liquid water detection, however the NOAA18 pass some nine hours after the radiosonde flight at 0849 UTC (Figure 4) identified the presence of liquid water content in the cloud mass to the east of Mawson which at the time of the radiosonde ascent had been over Mawson. Cloud top temperatures from the 2046 UTC NOAA18 were around 252 K, which from the radiosonde flight (Figure 2b) placed the cloud tops near an inversion at 2200 m, and consistent with the peak in RH at 2000 m.

Satellite imagery and radiosonde data would suggest the cloud over Mawson was mixed phase but predominantly ice in the lower layers where RH values were very low. One possible method of glaciation in the lower part of the cloud is from ice crystals lifted from the surface. At Mawson the near surface flow is dominated by a strong and highly persistent katabatic from the south-east (Adams 2008). At the time of the radiosonde release the reported 10 m wind speed was only around 1 to

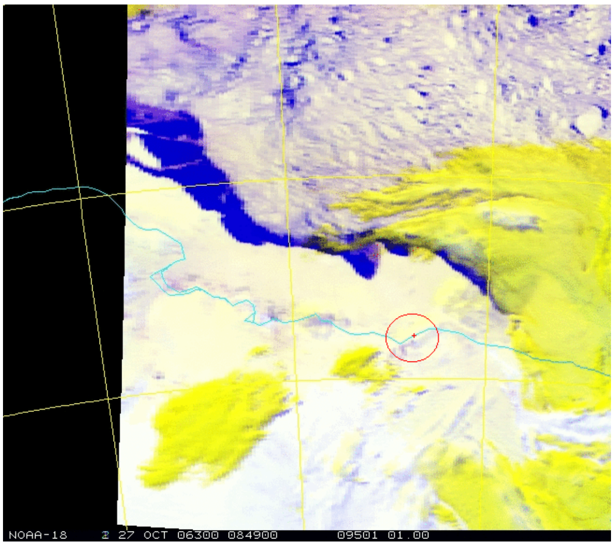

Figure 4: NOAA18 visual false colour image at 0849 UTC 27 October 2006 with cloud liquid water showing as yellow.

2 ms^{-1}. However the wind in the lowest 200 m over Mawson reached 20 ms^{-1} from the south-east and in the preceding 30 hours the 10 m wind speed had been as high as 37 ms^{-1} from the south-east with reports of blowing snow.

With almost no supporting observations inland of Mawson to define the surrounding flow, polar-LAPS NWP output (Adams et. al. 2007) from the run initalised at 1200 UTC 25 October 2006 was used to captured the synoptic situation. Model performance was reasonable, apart from timing issues around the onset of the light surface flow at Mawson. The top panel of Figure 5 shows a vertical cross-section of the down-slope flow in the direction of the south-easterly katabatic some hours prior to the radiosonde flight and highlights the very strong near surface flow just inland of Mawson with the suggestion of a hydraulic jump and strong up-motion in the vicinity of Mawson consistent with the prevailing conditions raising ice crystals into the lower few hundred metres of the atmosphere and seeding the lower cloud levels from the surface.

This process may explain why the level of occurrence of situations where radiosonde traces report very low RH values in low cloud is quite high at Mawson. At Davis the incidence is some what lower

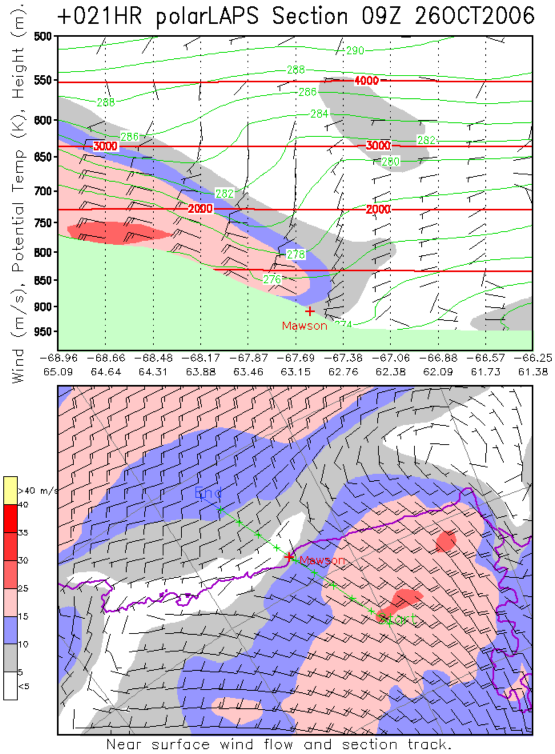

Figure 5: Top: vertical cross-section of wind and potential temperature along the south- easterly flow into Mawson. Bottom: 9 m wind flow with cross-section track marked.

where the prevailing wind is much lighter, although Davis is the most southerly of the three stations at 68^0 35' S and on average cooler than Mawson. Casey has by far the lowest recorded incidences of low RH values in low cloud. However, Casey is the most northerly of the three stations at 66^0 17' S and the cloudiest with significant low cloud developing over the station in the lee of Law Dome in response to a weak near surface eddy over the open waters of Vincennes Bay (Figure 1). The formation process of the low cloud at Casey, coupled to the relative northerly position may be responsible for the higher occurrence of liquid water clouds.

Modeling output

The comparison outlined above highlights the problem in relying on RH as means of establishing cloud parameters such as cloud base height and cloud top temperatures. Fortunately within modern NWP systems fields of cloud liquid water mixing ratio (Q_{lw}), cloud ice water mixing ratio (Q_{iw}) and rain water mixing ratio are generated along with the standard water vapour mixing ratio, giving a complete physical picture of the state of H_2O within the simulated atmosphere. Inoue et. al. (2010) found that using the mixing ratios Q_{lw} and Q_{iw} from polarLAPS provided a reasonably good assessment of cloud properties such as cloud base height when converted to Liquid Water Path (LWP) and Ice Water Path (IWP), where these paths are defined as the total mass of water (or water equivalent in the case of IWP) in a column of atmosphere with:

$$LWP = Q_{lw} * \rho_{air} * \frac{\Delta Z}{cos(\theta)}$$

$$IWP = Q_{iw} * \rho_{air} * \frac{\Delta Z}{cos(\theta)}$$

whereρ_{air} is the air density, ΔZ the thickness of the NWP model vertical level, and θ the solar zenith angle introduced to account for the increased cloud visibility during times of low solar elevation. During the summer time where the Inoue et al. (2010) study was undertaken θ is generally between 45^0 and 90^0 and a fixed value of $\theta = 70^0$ assumed. The LWP and IWP values were then converted to an optical depth,τ , a dimensionless quantity describing the visibility of a cloud and defined as:

$$\tau_{LWP} = \frac{9}{5} * \frac{LWP}{\rho_{water} * r_e}$$

from Wood (2006) where ρ_{water} is the density of water and r_e the effective cloud droplet radius, and:

$$\tau_{IWP} = 0.068 * (IWP)^{0.83}$$

from Heymsfield et al. (2003). In general Antarctic cloud droplets range from 5 to 30 µm (Lachlan-Cope 2010) with a constant value of 20 µm used here. With a threshold value of $\tau \geq 0.1$ used to define when cloud would be visible, the study found reasonably good agreement between modeled and observed cloud base where the NWP system had successfully forecast the synoptic situation as either an onshore maritime flow or offshore continental flow. However, biases under such conditions were still relatively high at around 100 to 200 m at Casey and Davis and 500 m at Mawson, and enough to impact on VMC conditions where cloud base is expected to be above 457 m (1500 ft).

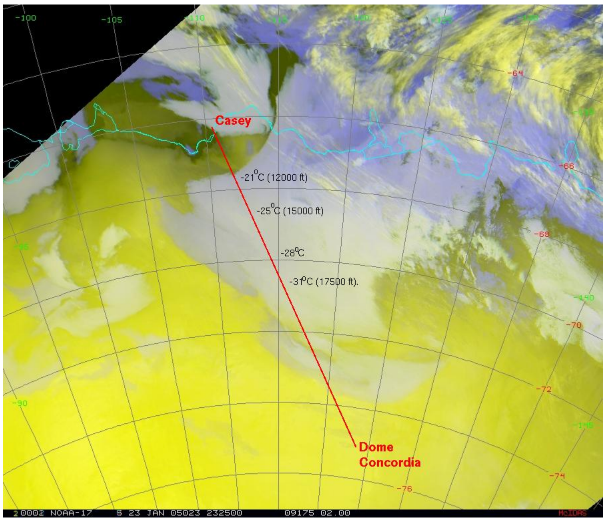

Figure 6: NOAA17 IR composite image at 23:25 UTC 23 January 2005 showing the flight track from Casey to Dome Concordia.

Forecasting cloud icing - a case study

On 24 January 2005 at 00:50 UTC a CASA C212 twin engine aircraft departed Casey Station (66^0 17' S, 110^0 32' E) in East Antarctica for Dome Concordia (75^0 6' S 123^0 24'E). Around 170 to 190 nm south of Casey, at 70^0 S the aircraft encountered significant un-forecast airframe icing. The aircraft attempted to climb out of the cloud but at around 17000 to 18000 ft there was no sight of clearing and the aircraft aborted the flight and returned to Casey.

Conditions at Casey at the time of departure were clear. However, the NOAA17 IR multi-spectral image (bands 3, 4 and 5) from 2325 UTC 23 January showed a substantial bank of cloud inland of Casey and on route to Dome Concordia (Figure 6) . Cloud top temperatures estimated from the IR data are labelled along track with approximate cloud top heights, estimated from the Casey radiosonde flight at 2315 UTC 23 January (not shown). An analysis of the situation over the preceding 36 hours highlighted the existence of a meso-scale low situated near 64^0 30' S 137^0 E at 1500 UTC 22 January that developed and moved westward to be near 64^0 20' S 132^0 E at 0130 UTC

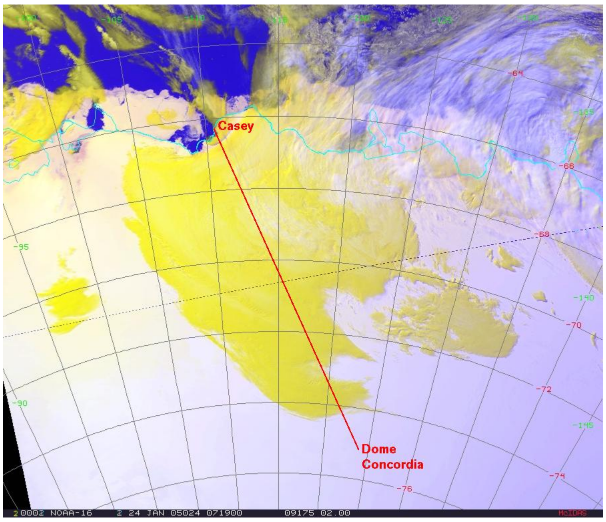

Figure 7: NOAA16 Composite image form 07:19 UTC 24 January 2005.

on 23 January, and by 1500 UTC was on the coast near 123^0E. A substantial bank of cloud associated with the low had pushed inland by this stage, reaching as far south as 72^0S. By 2325 UTC on 23 January the bank of cloud was substantial with the southern edge near 73^0 45' S and much of the flight track covered (Figure 6). The type of cloud (ice or water) was not easily determined from the near IR channel used by NOAA17 during daylight passes. However, a multi-spectral composite image (bands 1, 2 and 3) derived from the NOAA16 pass overhead at 0719 UTC channels (Figure 7) highlighted the extensive area of liquid water cloud inland of Casey and on track to Dome Concordia. Liquid water clouds show up as bright yellow over the blue-white ice surface and dark blue ocean, with the glaciated cirrus cloud to the west also showing as blue-white.

At the time of the incident multi-spectral displays of the NOAA imagery were not routinely used and the presence of liquid water clouds went undetected. Similarly model output fields of cloud liquid and cloud ice content were not available with cloud products generated from model RH values as described above. However, if multi-spectral satellite data had been used and accompanied by model output of cloud liquid and cloud ice content then the flight may have been delayed. Figure 8 is a cross section through a polarLAPS forecast valid

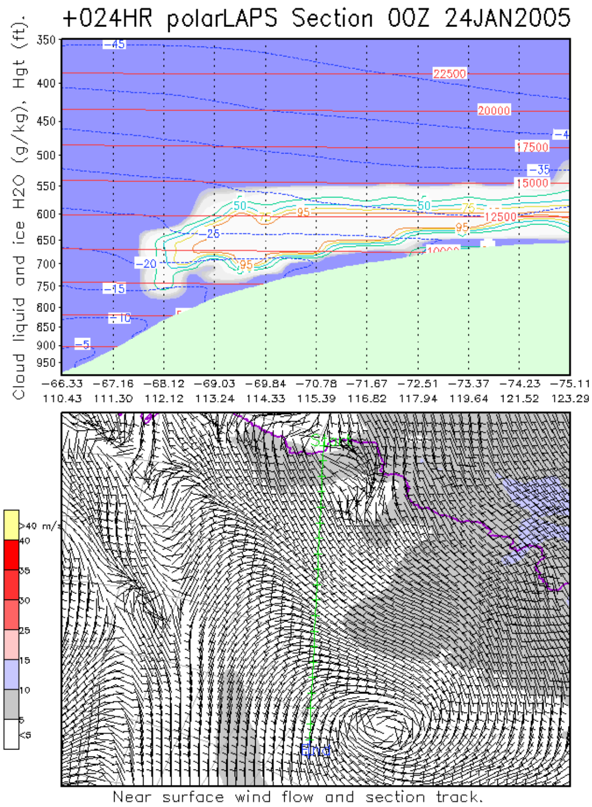

Figure 8: Upper panel: vertical cross section of total cloud mixing ratio (liquid and ice) along the track Casey to Dome Concordia valid at 0000 UTC 24 January; lower panel shows the near surface wind and the track used in the cross section.

at 0000 UTC on 24 January highlighting extensive cloud on route. The forecast cloud tops were not far from the inferred cloud tops from the satellite imagery and the model forecast significant liquid water within the cloud.

Discussion

The use of cloud water and cloud ice mixing ratios from NWP systems provides a more physical basis upon which to define forecast cloud fields such as cloud base height and cloud top temperature/height and also provides the ability to assess icing conditions through an analysis of the percentage liquid water content within the cloud below the freezing level. However, this is predicated on the model effectively calculating these fields. The only assimilated component of the water budget is water vapour mixing ratio, with the cloud water and cloud ice values generated internally to the NWP system. The cloud parameterisation schemes used in this process are not necessarily tuned for the Antarctic and they are not initialised off any physical measurements of the real atmosphere. Observational studies directly measuring cloud liquid and cloud ice water content are needed both for NWP assimilation and to assess the veracity of the cloud parameterisation schemes employed in Antarctic NWP systems. The Bureau is currently developing a new Antarctic limited are NWP system (ACCESS-P) which will be used to assess cloud parameterisation schemes and provide the next generation of cloud forecasting guidance.

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