A Preliminary Assessment of the Simulation of Cloudiness at SHEBA by the ECMWF Model

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Introduction

This report describes a preliminary comparison of cloudiness in the ECMWF forecast model with surface-based measurements at the SHEBA ice camp during 1-24 November 1997. It is the second in a series of preliminary reports focusing on clouds and boundary layer processes in the ECMWF as part of FIRE III (see http://www.atmos.washington.edu/~breth/SHEBA/ECMWF.html).

The report focuses on the following topics: (1) cloud presence; (2) the association of errors in cloud prediction with errors in ECMWF surface quantities (temperature, longwave flux, and sensible heat flux); (3) the vertical distribution of clouds; and (4) the phase of cloud condensate.

The presence and vertical distribution of cloudiness at SHEBA is determined using surface-based cloud radar reflectivity measurements from 1-24 Nov., provided by T. Uttal of NOAA-ETL. Information about cloud phase comes from measurements of the depolarization of lidar backscatter during 1 Nov. - 24 Jan., provided by J. Intrieri of NOAA-ETL. Near-surface measurements of temperature, sensible heat flux, and longwave irradiance were obtained from the SHEBA boundary layer group (Andreas et al.). All observations are averaged on an hourly timescale, if necessary, and compared with hourly model output from the ECMWF.

Cloud Condensate Mixing Ratio

The analysis of cloud radar measurements will eventually provide estimates of the mixing ratio of atmospheric condensate at SHEBA which can be compared directly to model variables in the ECMWF. In order to compare ECMWF cloudiness to available measurements, we have estimated the reflectivity of the model clouds using the following equation: 

$$Z_e = a W r_e^3$$

where \(a\) is a coefficient (49.6 E-6 for liquid, 9.4 E-6 for ice), \(W\) is liquid or ice water content in g m\(^{-3}\), and \(r_e\) is the effective radius of the cloud particles in microns (15 for liquid and 40 for ice). This equation, provided by S. Matrosov at NOAA-ETL, assumes a first order cloud particle size distribution. The time-height plots of observed and modeled radar reflectivity shown in Figs. A1-A3 (in the appendix) indicate that the reflectivity of clouds in the model is smaller than observations by
about a factor of 10. The reflectivity of ECMWF clouds never exceeds -10 dBZ, whereas observed reflectivities occasionally exceed 0 dBZ (Fig. 1). This discrepancy may be explained by the fact that the estimation of ECMWF cloud reflectivity does not include the effect of precipitation, which often has total (ice plus liquid) water contents comparable to cloud condensate (Fig. 2).

**Cloud Presence**

The determination of cloud presence at a given time and height is based on whether the radar reflectivity exceeds a specified background level. The reflectivity plots shown in the appendix suggest that this threshold is larger at greater heights, so the background level is defined as a linear function of height passing through -25 dB at 0.5 km and -15 dB at 10 km. Figure 3 shows where cloud is present when the mask is applied to cloud radar reflectivities measured at SHEBA during 9 - 17 November.

Ice particles are frequently observed precipitating from cloudless skies during the cold season in the Arctic. These events would be reported as clear by surface observers, even though the radar reflectivity of the ice particles might exceed the threshold defined by the cloud mask. The occurrence of clear sky ice crystal precipitation should not affect the comparison of cloud cover statistics from the ECMWF and cloud radar, since a cloud must be present in the model to produce precipitation.

Three categories of cloud cover are compared: lower (< 2 km), upper (>2 km), and total cloud cover. The lowest 8 (of 31) model levels in the ECMWF are in the lower region. A category of cloud is assumed present in the observations if radar reflectivity exceeds the threshold at any level in a the corresponding height range. Model cloudiness is computed using the assumption of maximum overlap for computing upper and lower cloud cover, and using the assumption of random overlap for total cloud cover. A category of cloud is assumed present in the model if cloudiness exceeds 50%. Tables 1-3 show the frequency of occurrence of each possible combination of
Figure 2: Total (ice plus liquid) water concentration of (a) precipitation and (b) cloud condensate in the ECMWF for 9-17 November 1997. An average fall speed of 1 m s\(^{-1}\) is assumed in computing precipitation concentration.

Figure 3: The presence of cloud (red) as produced by the cloud mask using radar reflectivity shown in Fig. A2(b).
The ECMWF correctly predicts the occurrence of cloudy and clear conditions 69% of the time for total cloud cover, 55% at lower levels and 73% at upper levels. There is a bias of +20% in the prediction of low-level cloudiness and virtually no bias at upper levels.

**Association of Low-Cloud and Surface Quantities (T, LW, SH)**

The relationship between the occurrence of low cloud and surface quantities in the observations is assessed using the cloud radar and measurements of 2.5-m air temperature, downward sensible heat flux, and downward longwave irradiance (from Andreas et al.). The results shown in Table 4 indicate that the presence of low-level cloud is associated with higher than average surface temperature and downward longwave irradiance. This probably can be attributed to fact that low clouds typically are close to the surface and high in emissivity. The presence of low cloud is also associated with lower than average values of downward sensible heat flux. One factor behind this is that low clouds make the boundary layer cooler with respect to the surface, which decreases static stability and favors more turbulent transfer.
Table 5 lists the errors in ECMWF for these surface quantities and how they are associated with predicted cloudiness. As noted in the previous report, there are significant positive biases in surface air temperature and downward sensible heat flux, which have been attributed to the modeling of sea-ice thermodynamics and atmospheric turbulent diffusion, respectively, in the ECMWF. Based on the information in Table 4, one would expect model errors in surface air temperature and downward longwave irradiance to be more positive if low-level cloud is incorrectly included, and more negative when low-level cloud is incorrectly omitted. The opposite relationship should hold for downward sensible heat flux. The results shown in Table 5 are consistent with these predictions, indicating that errors in low-level cloud prediction are contributing to errors in surface quantities. In the case of downward longwave irradiance, the average error is made more positive by the over-prediction of low-level cloudiness. This error is compensated by a negative bias in downward longwave irradiance when low clouds are correctly produced in the ECMWF, which leads deceptively small average bias.

Table 4: Observed Surface Quantities

<table>
<thead>
<tr>
<th>Low-Cloud Presence</th>
<th>T (2m)</th>
<th>downward SH</th>
<th>downward LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>253.4 K</td>
<td>+1.0 Wm⁻²</td>
<td>213.4 Wm⁻²</td>
</tr>
<tr>
<td>with low cloud</td>
<td>257.1</td>
<td>-1.3</td>
<td>241.3</td>
</tr>
<tr>
<td>no low cloud</td>
<td>249.2</td>
<td>+3.7</td>
<td>181.7</td>
</tr>
</tbody>
</table>

Table 5: Model Error (ECMWF - Observation)

<table>
<thead>
<tr>
<th>Low-Cloud Presence</th>
<th>T (2m)</th>
<th>downward SH</th>
<th>downward LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>+3.0 K</td>
<td>+5.5 Wm⁻²</td>
<td>-1.1 Wm⁻²</td>
</tr>
<tr>
<td>ecmwf= Y, radar= Y</td>
<td>-0.5</td>
<td>+10.2</td>
<td>-10.3</td>
</tr>
<tr>
<td>ecmwf= Y, radar= N</td>
<td>+6.2</td>
<td>-2.4</td>
<td>+20.9</td>
</tr>
<tr>
<td>ecmwf= N, radar= Y</td>
<td>-0.6</td>
<td>+18.6</td>
<td>-31.2</td>
</tr>
<tr>
<td>ecmwf= N, radar= N</td>
<td>+8.8</td>
<td>-2.4</td>
<td>+0.3</td>
</tr>
</tbody>
</table>
Vertical Distribution of Cloud

The statistics of cloud occurrence (Tables 1-3) and the time-height plots of reflectivity (Figs. A1-A3) suggest that the vertical distribution of cloudiness in the ECMWF is broadly consistent with radar measurements. The main discrepancies in the reflectivity plots are that the upper clouds in the model tend to be higher and have a smaller vertical extent than observed. Consistent with the reflectivity plots, the main differences in the mean vertical profiles of cloud amount between the ECMWF and observations (Fig. 4) are extra cloudiness above 5 km and a local minimum near 2 km. The latter feature may be explained by the fact that precipitation also contributes to the measured radar reflectivity. Since precipitation particles are larger than cloud particles, and radar reflectivity of a given mass of condensate is proportional to the third power of effective radius, a relatively small amount of precipitation is needed to produce a radar reflectivity comparable to cloud condensate. The profile of mean cloud frequency bears a stronger resemblance to the observations when the presence of precipitation (> 10^{-3} g m^{-3}) is considered.

Figure 4: Mean profiles for 1-24 November 1997 of (a) ECMWF cloud and precipitation presence in the ECMWF and (b) observed cloud presence. In the ECMWF, cloud is present if cloud fraction is > 0.5 and precipitate ‘cloud’ is present if its total water content is > 0.001 g m^{-3} and there is no regular cloud present. Cloud is present in the observations if the radar reflectivity exceeds the threshold defined by the cloud mask (~ -20 dBZ).
Phase of Cloud

Lidar depolarization ratio ($\delta$) can be used to obtain information about the phase of atmospheric condensate since ice particles depolarize backscattered lidar more strongly than liquid particles (Sassen 1991). The depolarization ratio of backscattered lidar is typically less than 0.1 for liquid clouds and greater than 0.3 for ice clouds. The existence of two peaks in the distribution of observed $\delta$ (Fig. 5a) indicates that both liquid and ice-phase clouds were present at SHEBA during November - January. Figure 5(b) shows how depolarization is associated with temperature in the observations. Values of $\delta$ between 0.1 and 0.3 are interpreted here as mixed phase cloud, but should simply be regarded as ambiguous; it is possible that Fig. 5b overestimates the actual frequency of mixed phase cloud. For example, it is known that the depolarization ratio backscat-

![Distribution of depolarization ratio](image1)

![Condensate phase from Lidar measurements](image2)

Figure 5: (a) Observations of depolarization ratio of backscattered lidar; (b) the temperature dependence of condensate phase, as interpreted from depolarization ratio (see text).
tered from ice crystals can vary over a wide range (including $\delta < 0.3$), based on factors such as crystal size and geometry (e.g. Sassen 1991). Low values of $\delta$ occur most frequently in the lower troposphere (see Figs. A1- A3), which is consistent with the expectation that liquid clouds are most likely found in a warmer environment, and higher values of $\delta$ are typical in the colder upper troposphere. However, there are many counter-examples to this generalization. Either phase of condensate can occur over a wide range of temperatures, with liquid clouds existing at temperatures as low as 240 K and ice particles (probably snow) remaining quite prevalent near freezing (Fig. 5b). This demonstrates that cloud phase depends on more than just air temperature. Cloud phase in the ECMWF is a diagnostic function of temperature, such that cloud condensate is frozen when the air temperatures is below 253 K, liquid when the air is above freezing (273 K), and mixed phase in between these temperatures (Fig 6). The agreement between the ECMWF and observed cloud phase might improve if the model allowed supercooled liquid to occur at temperatures below 253 K.

Figure 6: Dependence of cloud phase on temperature in the ECMWF output from 1 Nov. until 24 Jan.
Conclusions

Overall, the simulation of cloudiness in the ECMWF forecast model agrees reasonably well with surface-based radar and lidar measurements for the wide variety of weather conditions that occurred at SHEBA during November 1997. The most prominent discrepancies in cloudiness between the ECMWF and observations are the following:

(a) the model predicts too much low-level cloudiness,
(b) the model predicts too much cloudiness at altitudes greater than 5 km, and
(c) the estimated reflectivity of clouds in the model is an order of magnitude lower than measured by cloud radar.

Appendix: Time Series

Finally, hourly time series of several model and observed quantities for 1-24 Nov. 1997 are shown in the remaining figures so the reader may better appreciate the comparison statistics.

Reference:

Figure A1: Time-height plots of cloud radar reflectivity (in dB) (a) as estimated for ECMWF output and (b) as measured at surface; (c) depolarization ratio of backscattered lidar measured at the surface (values > 0.4 are not resolved); and (d) atmospheric temperature in ECMWF.
Figure A2: As in Figure A1, except for 9 - 17 November 1998.
Figure A3: As in Fig. A1, except for 17 - 24 November 1998.