Using ship observations to assess Southern Ocean clouds in a storm-resolving general circulation model ICON

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Motivation

- A new generation of km-scale resolution global climate models are in development as the forthcoming phase of climate modelling.
- One such model is a 5-km version of the Icosahedral Nonhydrostatic Weather and Climate Model (ICON) developed jointly by Deutscher Wetterdienst (DWD) and the Max-Planck-Institute for Meteorology (MPI-M).
- Because of the high resolution, most parametrisations, such as that of convection and clouds, can be avoided.
- Previous studies have identified substantial large-scale biases in model clouds over the Southern Ocean, affecting sea surface temperature and the Earth's albedo overall.

Aims

- Quantify how well the high-resolution ICON model is simulating clouds in the Southern Ocean, particularly in light of the fact that subgrid-scale clouds are not parametrised in this model. This region is mostly dominated by boundary layer clouds generated by shallow convection, and these are problematic to observe by spaceborne lidar and radars, which are affected by attenuation by overlapping and thick clouds and ground clutter, respectively.
- Use a large set of ship-based observations conducted with ceilometers and lidars on board of RV *Polarstern* and other research vessels.
- Analyse about 1500 days of data from 31 voyages and 1 sub-antarctic station covering diverse longitudes of the Southern Ocean.
- Achieve a like-for-like comparison with the model by using a ground-based lidar simulator.
- Contrast the results with the ECMWF Reanalysis 5 (ERA5) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2).

Conclusions

- The ICON model underestimates total cloud fraction by about 10%, with overestimation of cloud below 1 km, and underestimation of cloud above 1 km.
- The reanalyses underestimate total cloud fraction by about 20%. ERA5 overestimates cloud below 1 km but underestimates near-surface cloud or fog.
- We compare radiosonde profiles acquired on the RV Polarstern voyages with ICON. The ICON model exhibits smaller internal variability than observations, and its lifting condensation level tends to be higher.
- This might explain why cloud occurrence is peaking higher in the model (at 500 m) than in the observations (at the surface).
- The results imply that Southern Ocean cloud biases are still a significant issue in a km-scale resolution model, even though an improvement over the lower-resolution reanalyses is notable.
- More effort is needed to improve model cloud simulations in this region.

Methods

Voyages and stations

- We analysed 31 voyages of RV *Polarstern*, RSV *Aurora Australis*, RV *Tangaroa*, RV *Nathaniel B. Palmer*, HMNZS *Wellington* and 1 sub-Antarctic station in the Southern Ocean south of 40°S between years 2010 and 2021.
- A total of about 1500 days of observations were included.
- Ceilometer Vaisala CL51 operating at 910 nm and Luff CHM 15k operating at 1064 nm were used on the voyages.
- Radiosondes were launched at synoptic times and surface meteorological quantities were measured continuously on the RV *Polarstern* voyages.

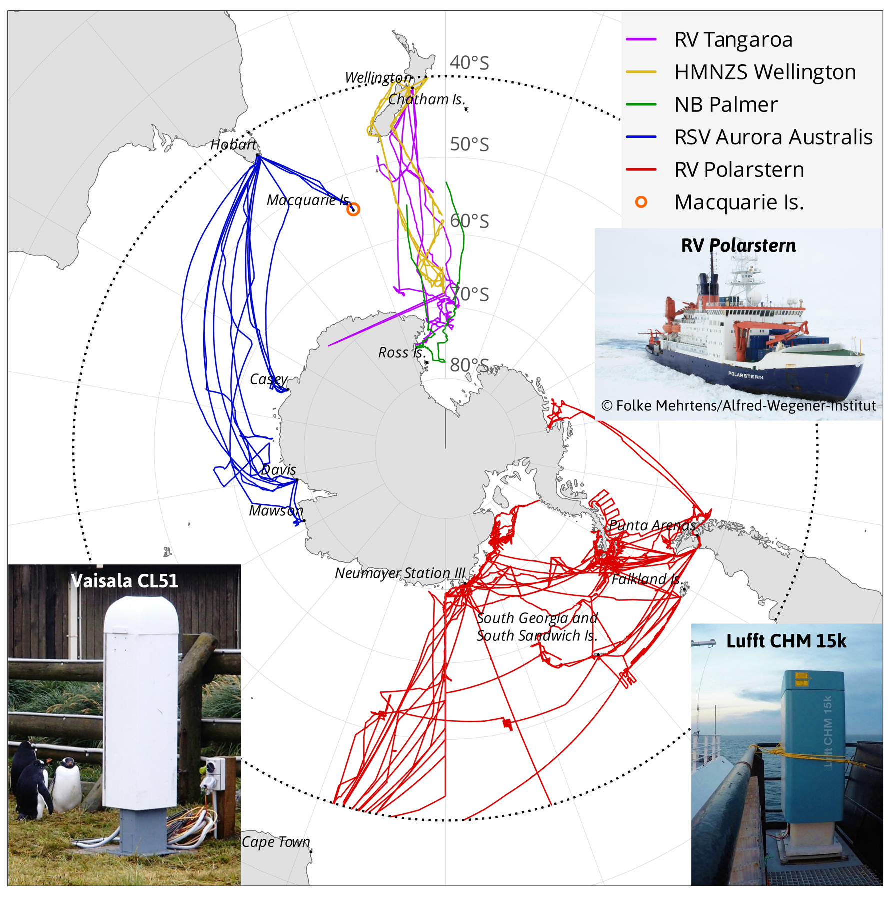
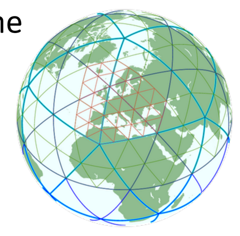


Figure 1 | Tracks of the 31 voyages and 1 sub-Antarctic station between Africa, South America, Australia, New Zealand and Antarctica in years 2010 to 2021, a photo of RV *Polarstern*, and photos of the ceilometers.

ICON



- We used 'Cycle 3' storm-resolving version of the Icosahedral Nonhydrostatic (ICON) Weather and Climate Model in development by the NextGEMS project.
- The horizontal resolution is about 5 km.
- 4 years coupled simulations in 2021–2024.
- Unlike current GCMs, it does not parametrise mass flux, but resolves convection explicitly.
- Turbulence is parametrised.
- Grid box cloud fraction is always either 0 or 100%.
- The model is free running. Therefore, when comparing to observations, we take the same geographical location and time relative to the start of the year.

Lidar simulator

- We used a ground-based lidar simulator Automatic Lidar and Ceilometer Framework (ALCF) to compare the model with observations.
- ALCF is based on the instrument simulator COSP.
- ALCF calculates simulated lidar backscatter from offline model fields of cloud liquid and mixing ratio, cloud fraction, temperature and pressure.

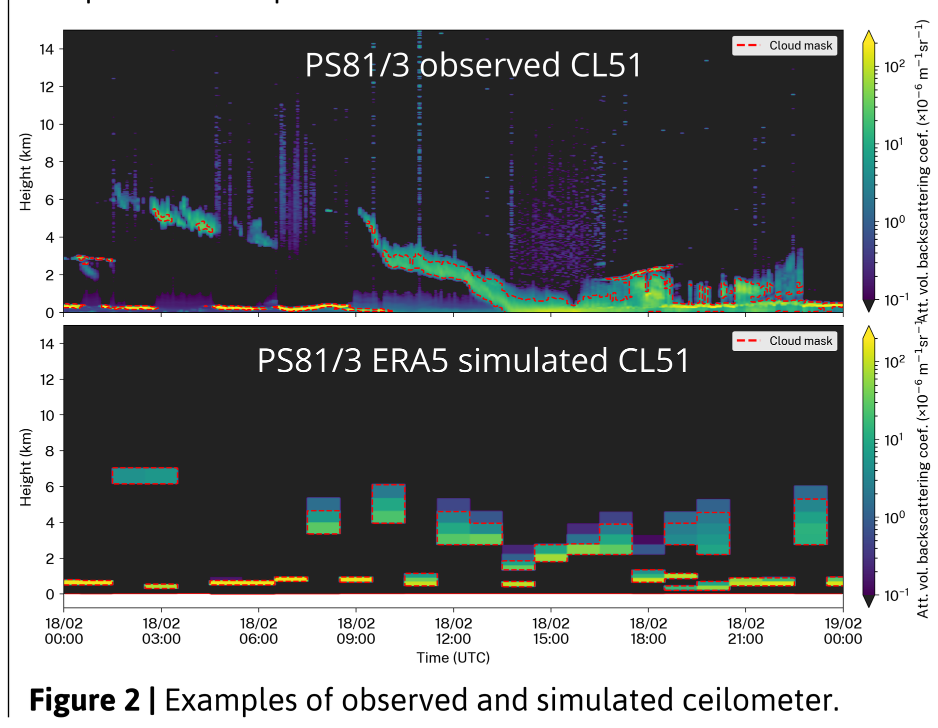


Figure 2 | Examples of observed and simulated ceilometer.

Filtering out precipitation using machine learning

- We need to filter out profiles with precipitation because it cannot be easily distinguished from clouds in observations, and cannot be compared with the model, which does not provide precipitation mixing ratios.
- Instruments such as a rain gauge are not reliable on ships.
- We train a convolutional artificial neural network (ANN) to recognise short time intervals (10 min) of near-surface backscatter (0–250 m) as having precipitation or fog.
- Human-performed observations at synoptic times are used as a training reference for clear, fog, rain and snow conditions near the surface.
- The ANN achieves 65% sensitivity and 87% specificity when the true positive rate (26%) is made to match observations.

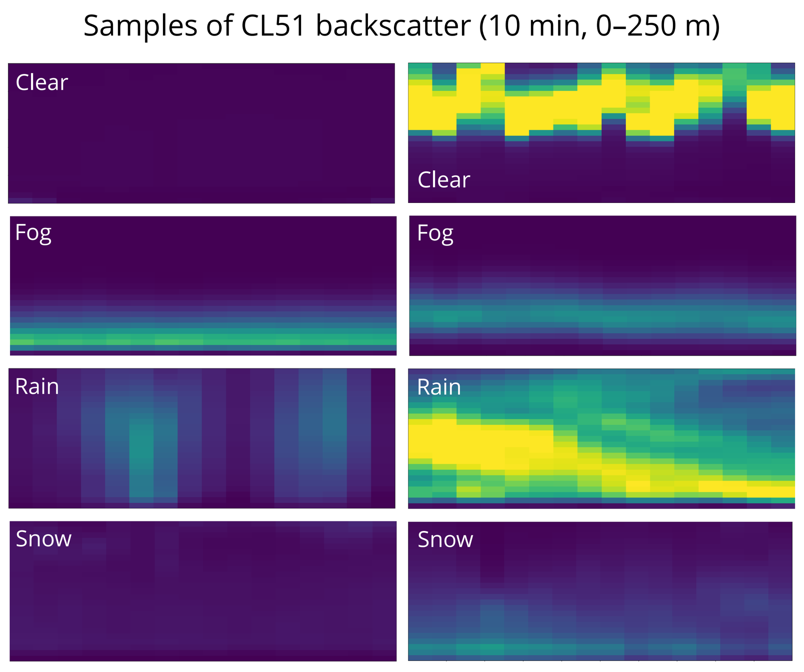


Figure 3 | Near-surface ceilometer backscatter in different weather situations.

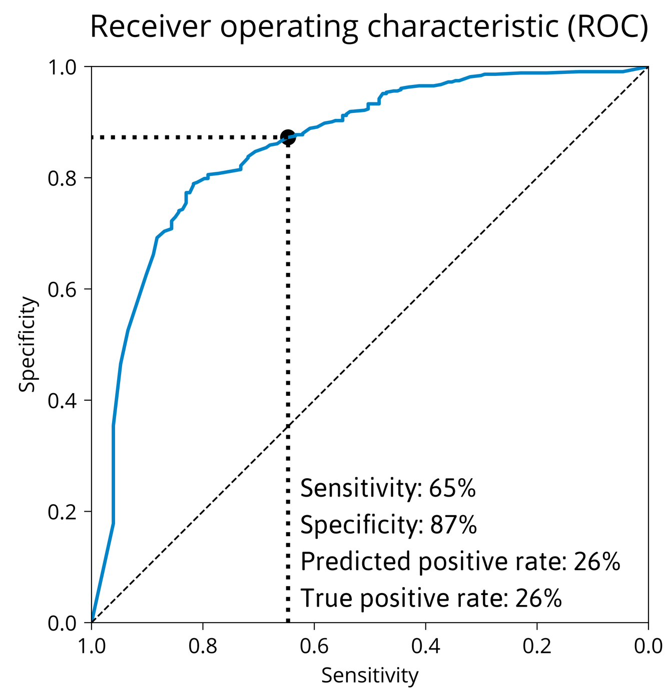


Figure 5 | ANN error statistics.

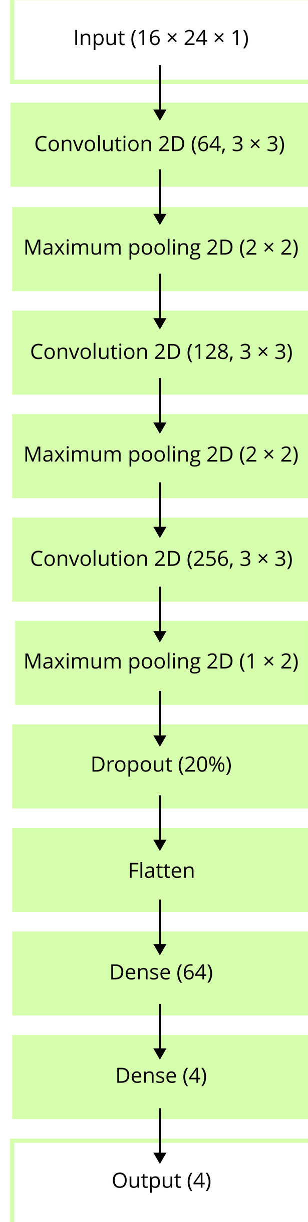


Figure 4 | ANN layers.

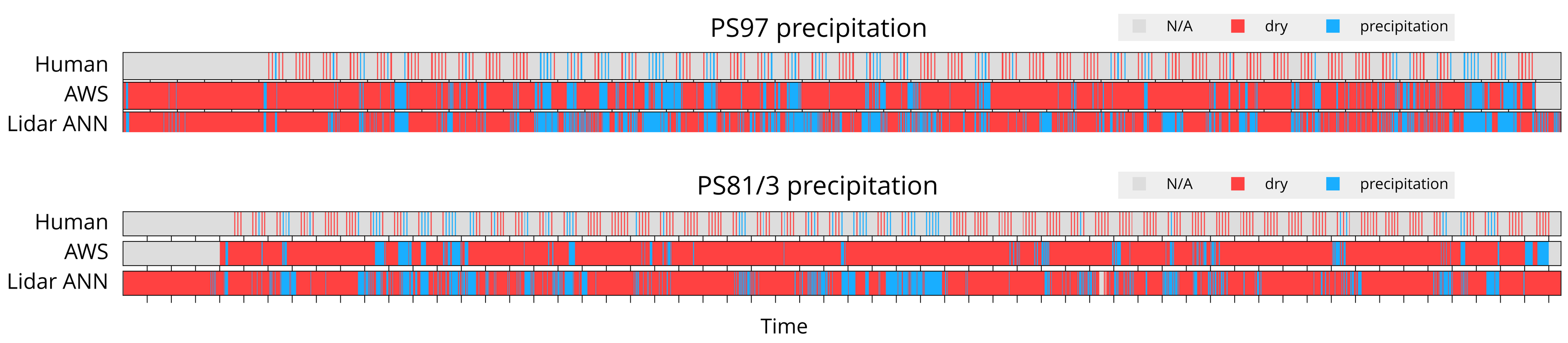


Figure 6 | Precipitation and dry conditions identified by a human, automatic weather station (AWS) rain gauge and the ANN during two RV *Polarstern* voyages.

Results

Cloud occurrence

- We calculated cloud occurrence by height for each voyage and then calculated an aggregate of all profiles (mean and the 16th and 84th percentiles).
- Total cloud fraction (determined as the fraction of profiles with clouds at any height in the lidar cloud mask) is underestimated in ICON and reanalyses by about 10% and 20%, respectively.
- ICON overestimates cloud occurrence below 1 km and underestimates above.
- MERRA-2 underestimates cloud occurrence at all heights, especially near the surface.
- ERA5 simulates cloud occurrence relatively well above 1 km, but strongly underestimates it near the surface.
- Fog or near-surface clouds are strongly lacking in the reanalyses.
- The biases are relatively consistent across voyages and longitudes (Fig. 9).
- ICON results are overall better matching the observations than the reanalyses.
- ICON comparison limitations: The model is free running, thus profiles cannot be expected to represent the same weather conditions. Only profiles with the same sea ice conditions (present or not present) are included.

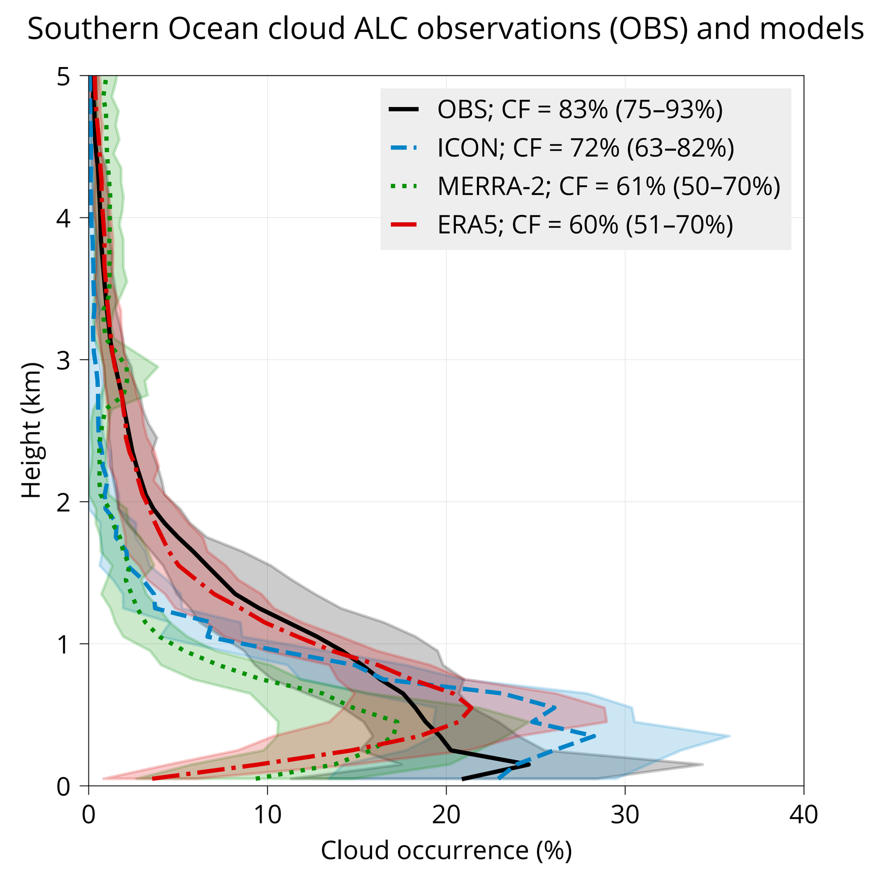


Figure 7 | Cloud occurrence by height aggregated for all voyages/stations. Total cloud fraction is shown in the legend. The ranges are from the 16th to the 84th percentile.

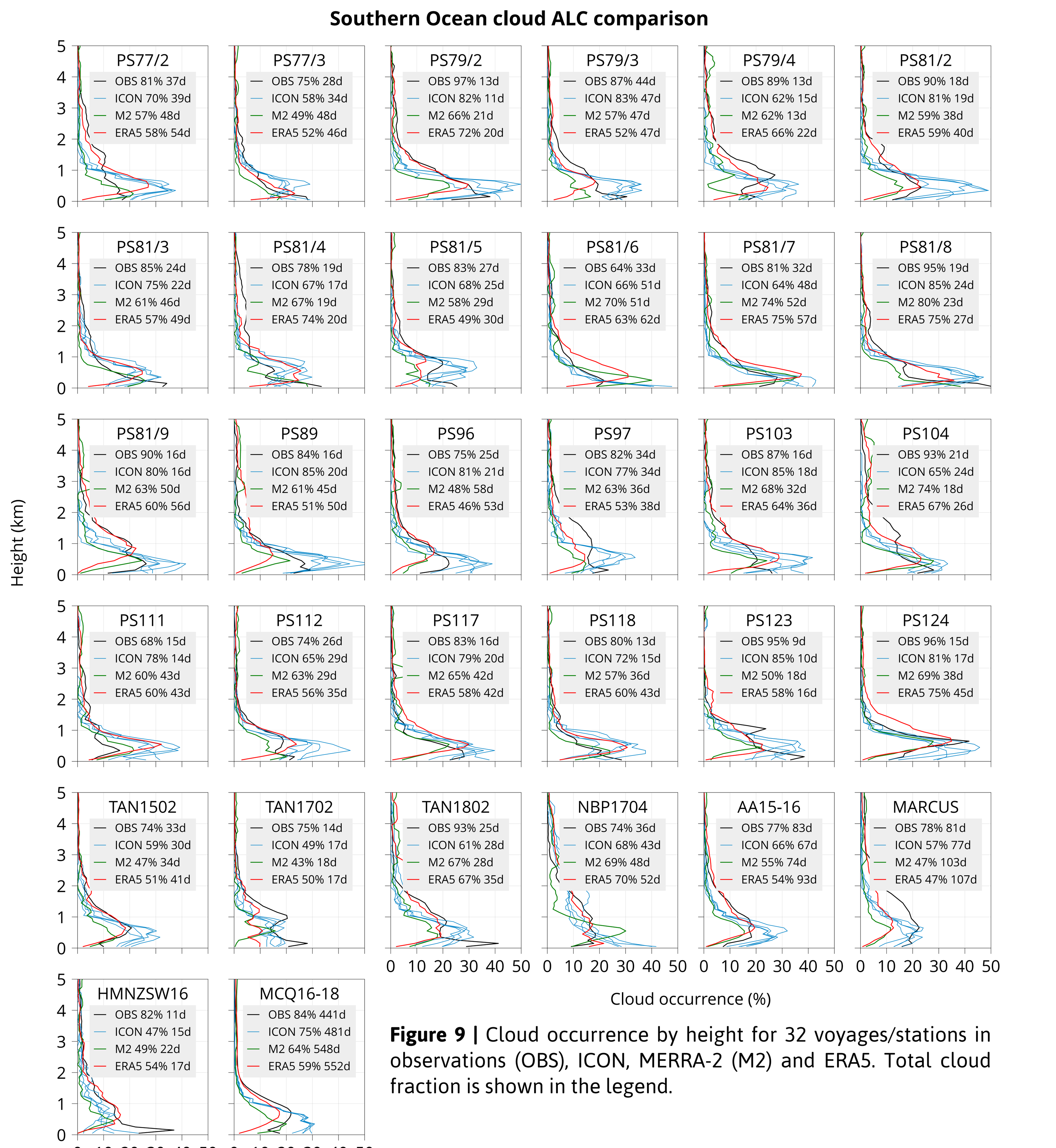


Figure 9 | Cloud occurrence by height for 32 voyages/stations in observations (OBS), ICON, MERRA-2 (M2) and ERA5. Total cloud fraction is shown in the legend.

Thermodynamic profiles

- We compared about 2000 radiosonde profiles from the 24 RV *Polarstern* voyages between the observations and the model.
- Profiles in the model are taken at the same geographical location and time relative to the start of the year.
- Only profiles for which the sea ice conditions (sea ice present or absent) are the same in the observations and the model are included.

Notable findings are:

- Variability of potential temperature in the model is smaller than in the observations. This indicates that the model does not represent entire natural variability.
- The lifting condensation level peaks at the surface in the observations, but the peak in the model is higher (about 200 m). This probably relates to the greater occurrence of fog and peak of cloud occurrence at the surface in observations, whereas in the model the peak is higher.

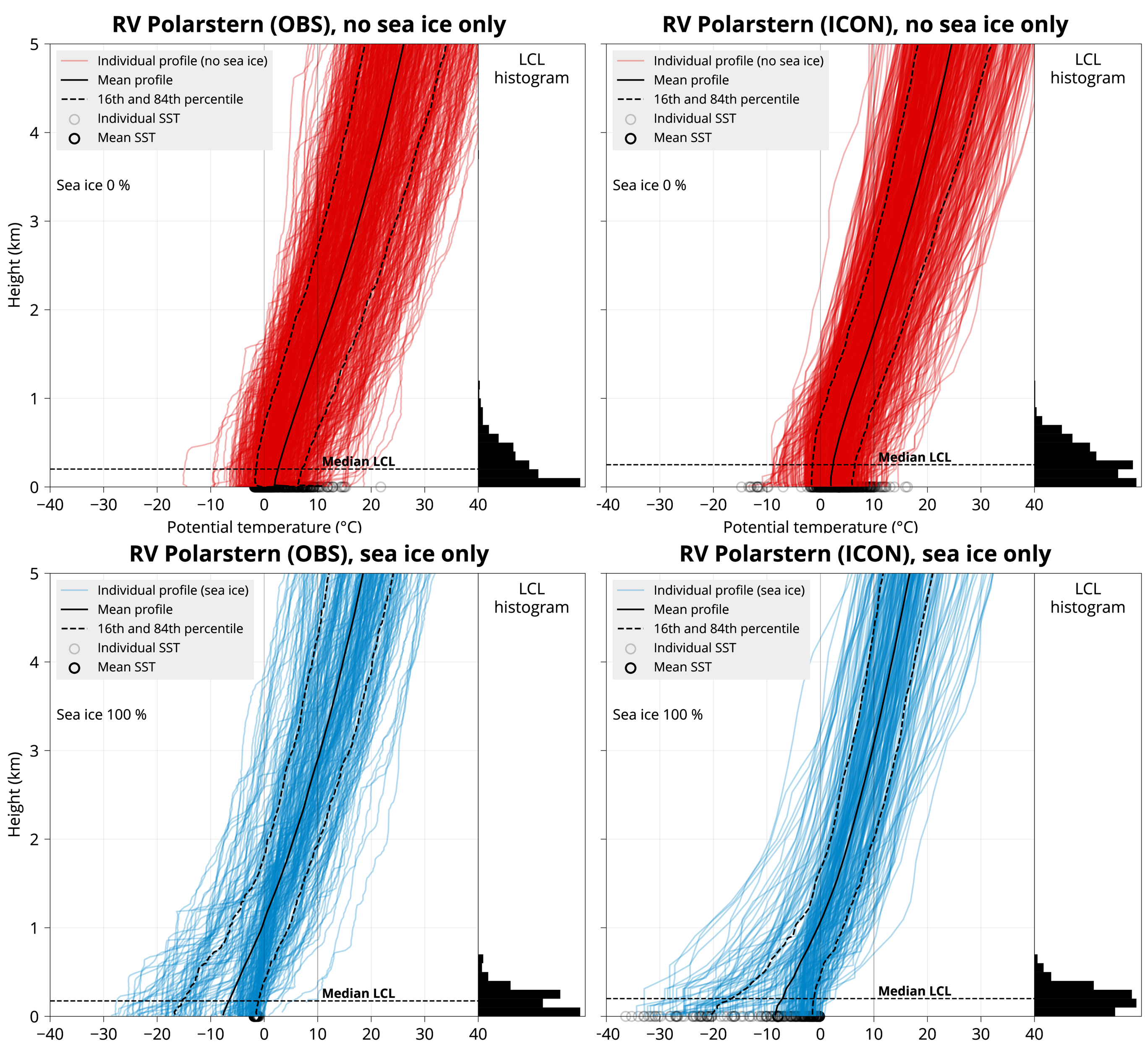


Figure 8 | Radiosonde profiles of potential temperature and lifting condensation level (LCL) on all RV *Polarstern* voyages.

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