# Ship-based lidar evaluation of Southern Ocean clouds in the storm-resolving general circulation model ICON and the ERA5 and MERRA-2 reanalyses

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Peter Kuma[1,2,*], Frida A.-M. Bender[1,2], Adrian J. McDonald[3], Simon P. Alexander[4,5], Greg M. McFarquhar[6,7], John J. Cassano[8,9,10], Graeme E. Plank[3], Sean Hartery[11], Simon Parsons[12], Sally Garrett[13], Alex J. Schuddeboom[3]

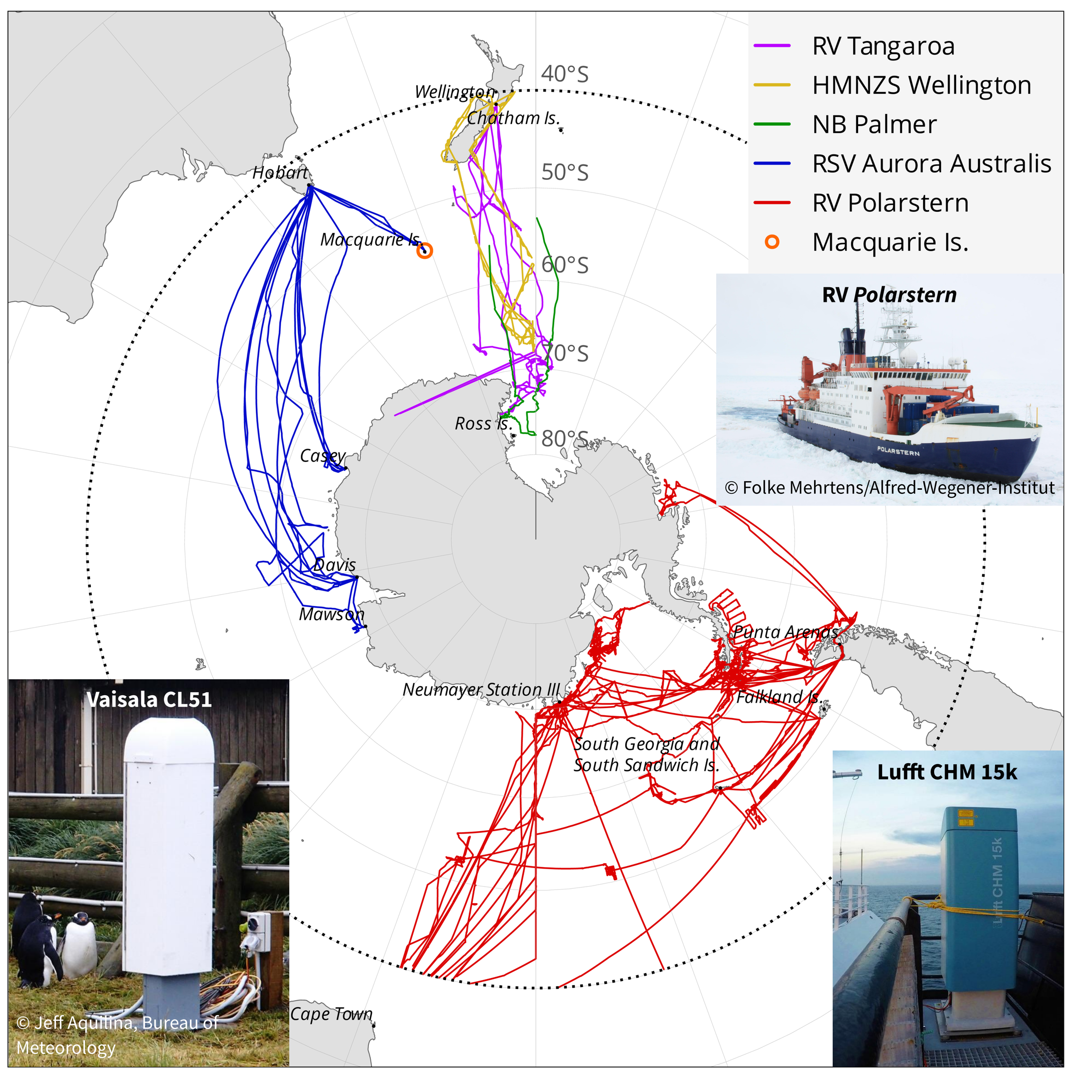
[1]Department of Meteorology (MISU), Stockholm University, Stockholm, Sweden; [2]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden; [3]School of Physical and Chemical Sciences, University of Canterbury, Christchurch, Aotearoa/New Zealand; [4]Australian Antarctic Division, Kingston, Tasmania, Australia; [5]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia; [6]Cooperative Institute of Severe and High Impact Weather Research and Operations, University of Oklahoma, Norman, OK, USA; [7]School of Meteorology, University of Oklahoma, Norman, OK, USA; [8]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA; [9]National Snow and Ice Data Center, University of Colorado, Boulder, CO, USA; [10]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO, USA; [11]Department of Physics & Atmospheric Science, Dalhousie University, Halifax, Canada; [12]New South Wales Department of Planning and Environment, Sydney, New South Wales, Australia; [13]New Zealand Defence Force, Wellington, New Zealand; *E-mail: peter.kuma@misu.su.se; Web: peterkuma.net.

## Summary

- Global storm-resolving models (GSRMs) are the next avenue of climate modelling.
- Due to the high resolution, parameterizations of convection and clouds are avoided.
- Standard-resolution models have substantial cloud biases over the Southern Ocean (SO), affecting radiation and sea surface temperature.
- We evaluated SO clouds in a GSRM version of ICON and the ERA5 and MERRA-2 reanalyses.
- The SO is dominated by low clouds, which cannot be observed accurately from space due to overlapping clouds, attenuation, and ground clutter.
- We analysed about 2400 days of lidar observations from 31 voyages and a station using a ground-based lidar simulator.
- ICON and the reanalyses underestimate the total cloud fraction by about 10 and 20%, respectively. ICON and ERA5 overestimate the cloud occurrence peak at about 500 m, potentially explained by their lifting condensation levels being too high.
- The reanalyses strongly underestimate near-surface clouds or fog.
- MERRA-2 tends to underestimate cloud occurrence at all heights.
- In daily cloud cover, ICON and the reanalyses tend to be about 1 and 2 oktas clearer, respectively.
- Compared to radiosondes, potential temperature is accurate in all, but ICON is too unstable over the low-latitude SO and too humid in the boundary layer.
- SO cloud biases are a substantial issue in the GSRM but are an improvement over the lower-resolution reanalyses.
- Explicitly resolved convection and cloud processes were not enough to address the model cloud biases.

## Voyages and stations

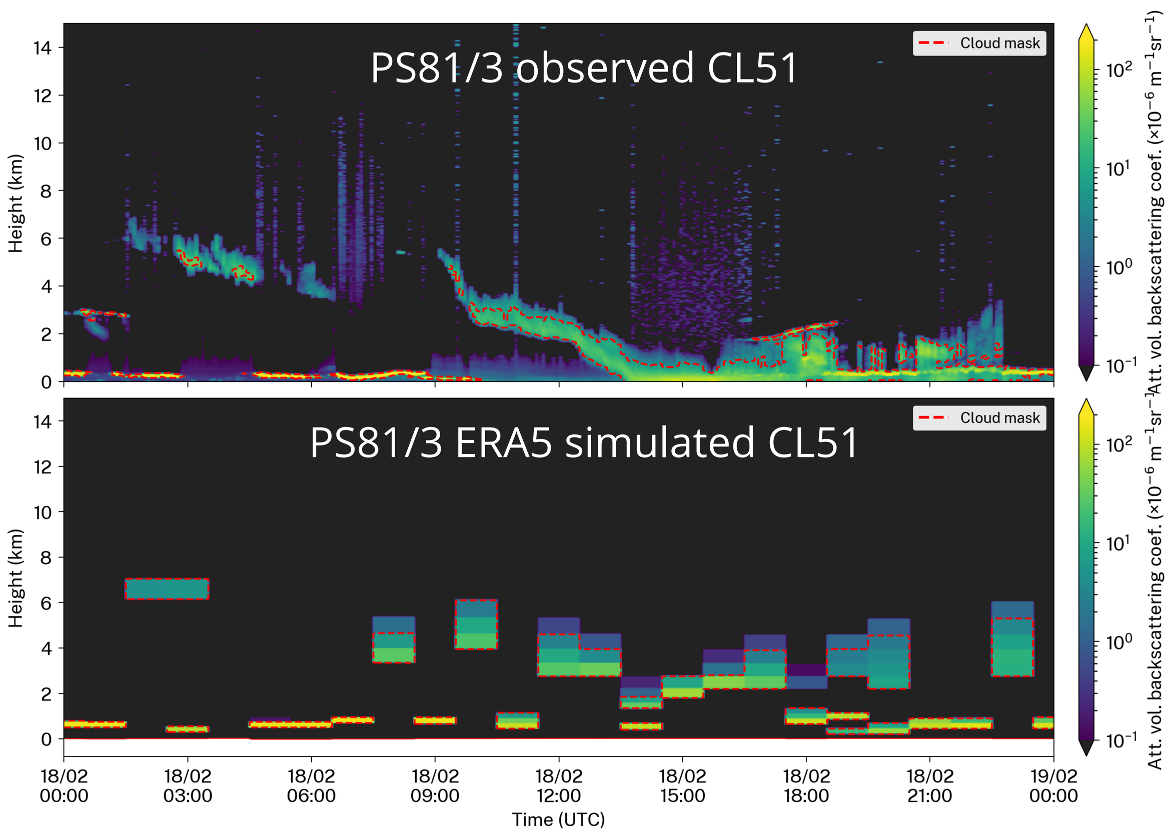
- We analysed 31 voyages of RV *Polarstern*, RSV *Aurora Australis*, RV *Tangaroa*, RV *Nathaniel B. Palmer*, HMNZS *Wellington*, and a station in the Southern Ocean south of 40°S between 2010 and 2021.
- A total of about 2400 days of observations were included.
- Ceilometer Vaisala CL51 and CT25K operating at 910 nm and Lufft CHM 15k operating at 1064 nm were used on the voyages.
- Radiosondes were launched and surface meteorological quantities measured continuously on multiple voyages.
- We subsetted the data by latitude into high- (55+°S) and low-latitude SO (40–55°S), cyclnic activity based on cyclone tracking, and stability using lower tropospheric stability.




## Lidar simulator

ALCF

- An instrument simulator is needed for an unbiased comparison with a model.
- We used the Automatic Lidar and Ceilometer Framework (ALCF).
- ALCF is based on the instrument simulator COSP.
- It calculates simulated lidar backscatter from the model fields of cloud liquid and mixing ratio, cloud fraction, temperature, and pressure.
- Cloud mask is determined based on a threshold.
- Cloud occurrence by height is determined from the cloud mask.

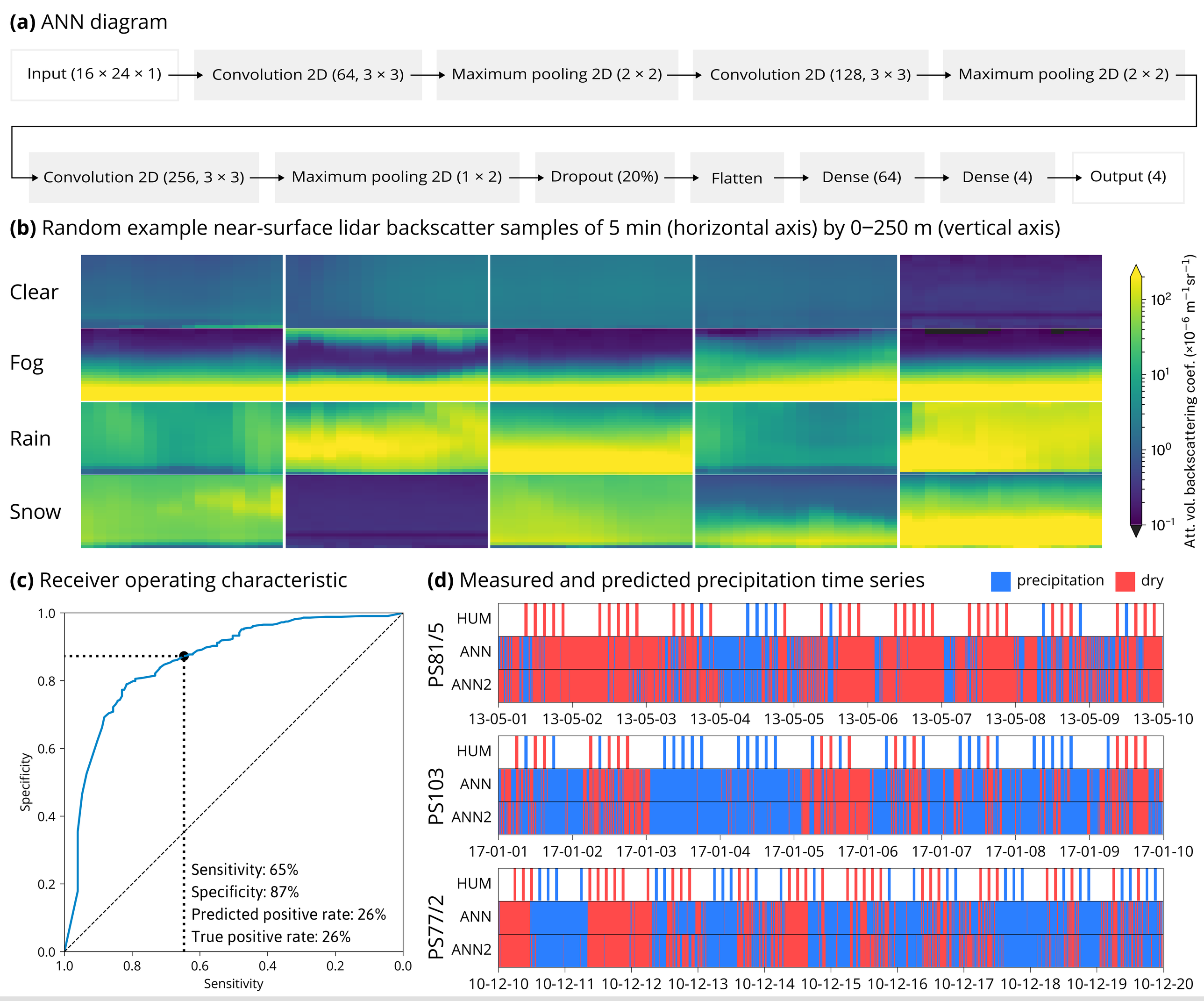



## ICON

- We used Cycle 3 storm-resolving version of the Icosahedral Nonhydrostatic Weather and Climate Model (ICON) in development by the NextGEMS project.
- The horizontal resolution is about 5 km.
- 4 years of 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.

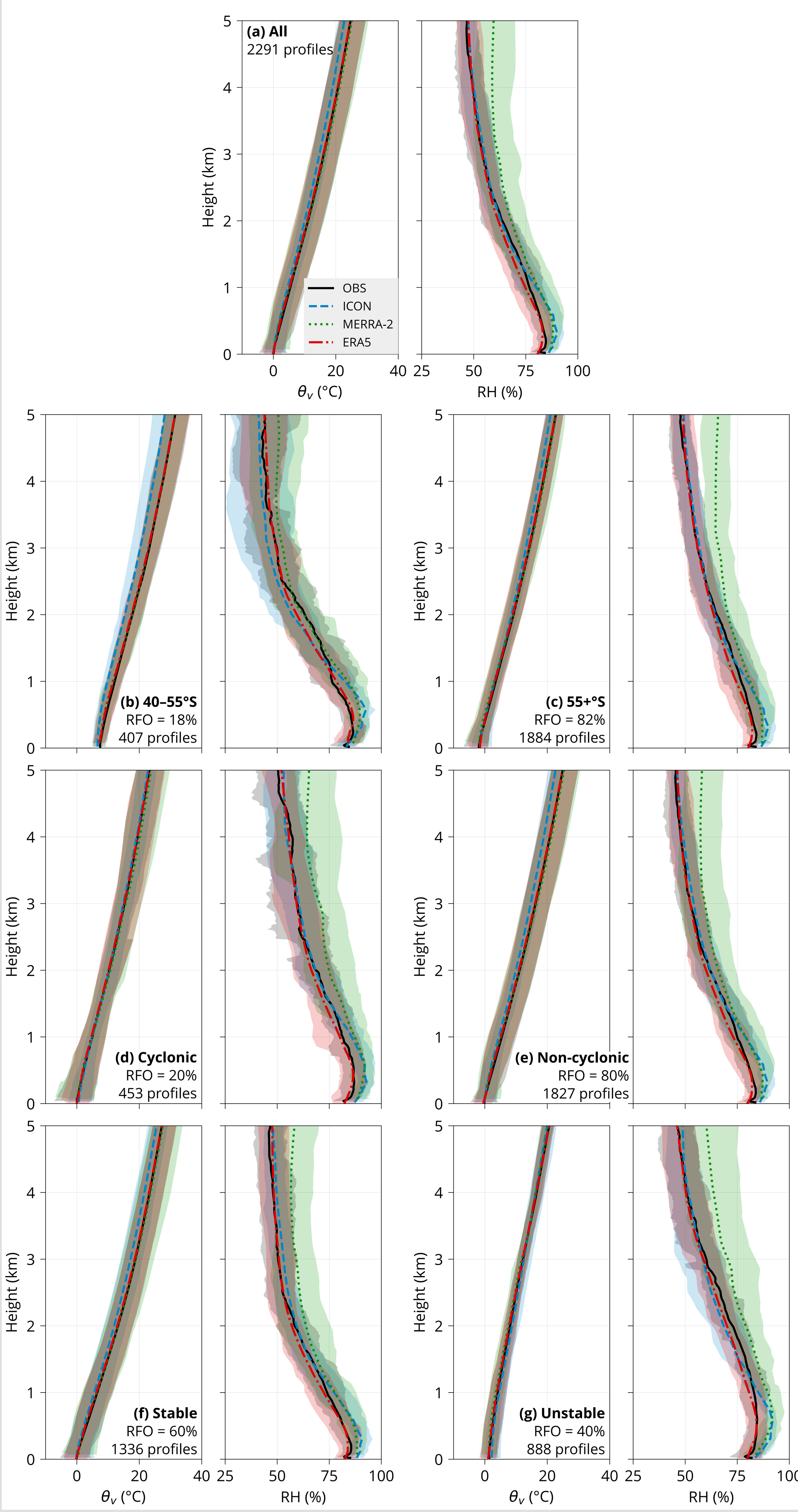
## Filtering precipitation using machine learning

- Profiles with precipitation cannot be easily distinguished from clouds in observations.
- They cannot be compared with the models, which do not provide precipitation mixing ratios.
- Instruments such as a rain gauge are not reliable on ships.
- We train a convolutional U-Net artificial neural network (ANN) to recognise precipitation in lidar backscatter.
- Human-performed observations are used as a training reference.
- The ANN achieves 65% sensitivity and 87% specificity when the true positive rate (26%) is made to match observations.



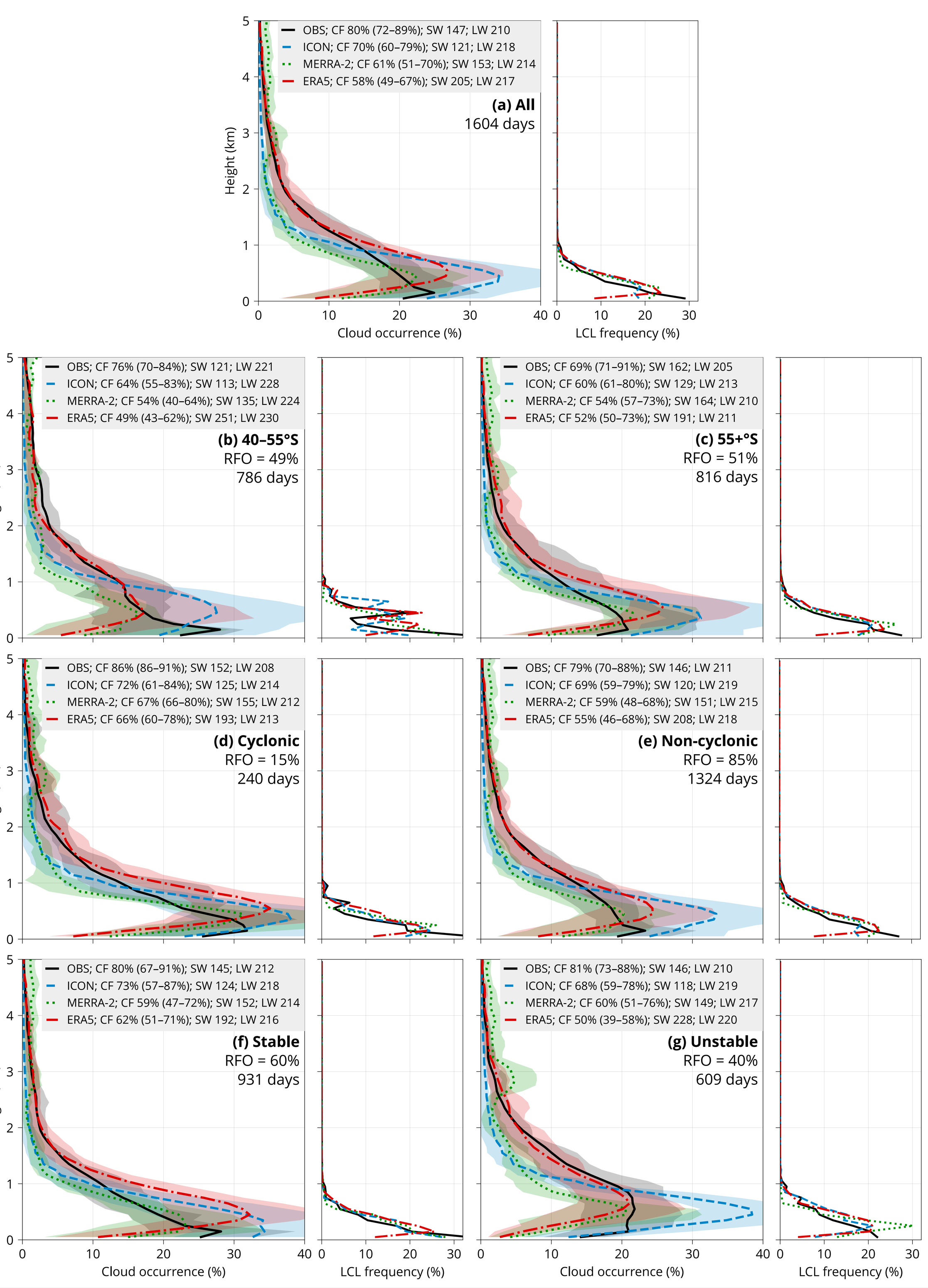

## Thermodynamic profiles

- We analysed about 2300 radiosonde profiles south of 40°S from the 24 RV *Polarstern* voyages, MARCUS, NBP1704, TAN1702, and TAN1802 campaigns.
- Spatially and temporally colocated profiles were taken from ICON and the reanalyses.
- Virtual potential temperature well-represented, except for ICON at 40–55°S, which is too cold at 5 km height. Consequently, it is too unstable.
- Variance of virtual potential temperature is too small in ICON.
- ICON is too humid in the first 1 km.
- MERRA-2 is too humid by up to 20%.



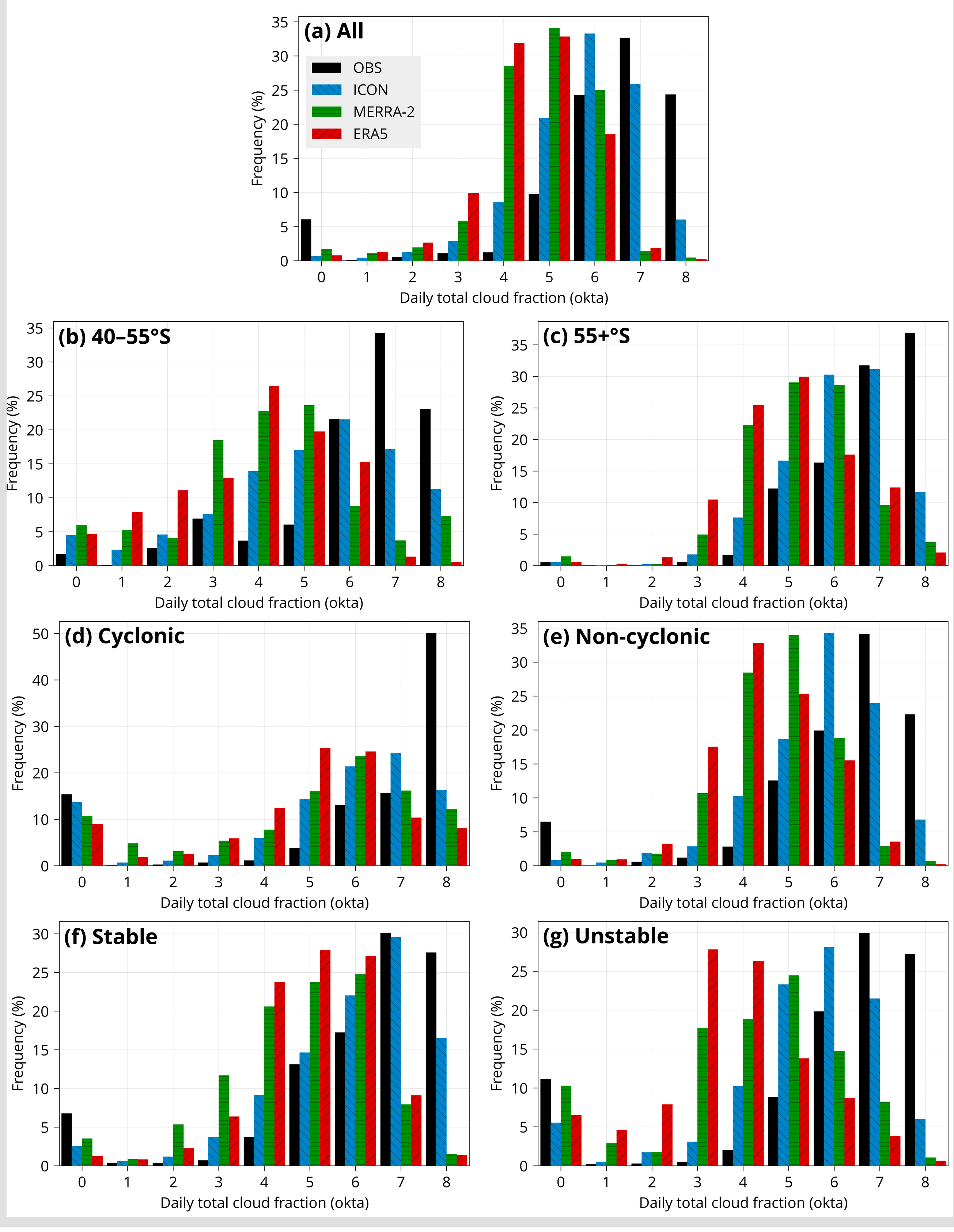

## Cloud occurrence by height

- We aggregated data from all voyages and stations, each weighted equally.
- The total cloud fraction is underestimated in ICON and the reanalyses by about 10% and 20%, respectively.
- ICON overestimates cloud occurrence below 1 km and underestimates it above.
- MERRA-2 underestimates cloud occurrence at all heights.
- 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 models have a higher-altitude peak (at about 500 m) than observations.
- The reanalyses exhibit the too few, too bright bias previously identified in climate models.
- Outgoing top of atmosphere (TOA) shortwave (SW) radiation in the reanalyses is similar to or higher than in the satellite observations, while total cloud fraction is underestimated.
- ICON underestimates both cloud fraction and outgoing TOA SW radiation.
- Unstable sitations are especially problematic for ICON, with a strongly overestimated peak at 500 m.




## Daily total cloud fraction

- Calculated from the lidar cloud mask as the daily total cloud fraction, irrespective of height.
- Observations have the greatest representation of high cloud cover (5–8 oktas), peaking at 7 oktas.
- ICON tends to be 1 okta clearer than the observations, peaking at 6 oktas, and highly underestimating days with 8 oktas.
- The reanalyses underestimate cloud cover by about 2 oktas and strongly underestimate days with 7 and 8 oktas.
- The cyclonic subset has the highest cloud cover, with 8 oktas occurring half the days.
- This is not represented by ICON or the reanalyses at all.
- High-latitude SO tends to have greater cloud cover, peaking at 8 oktas.
- The largest biases are present in ERA5 in the unstable subset, in which ERA5 peaks at 3 oktas, whereas the observations peak at 7 oktas and show negligible cloud cover below 5 oktas.

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