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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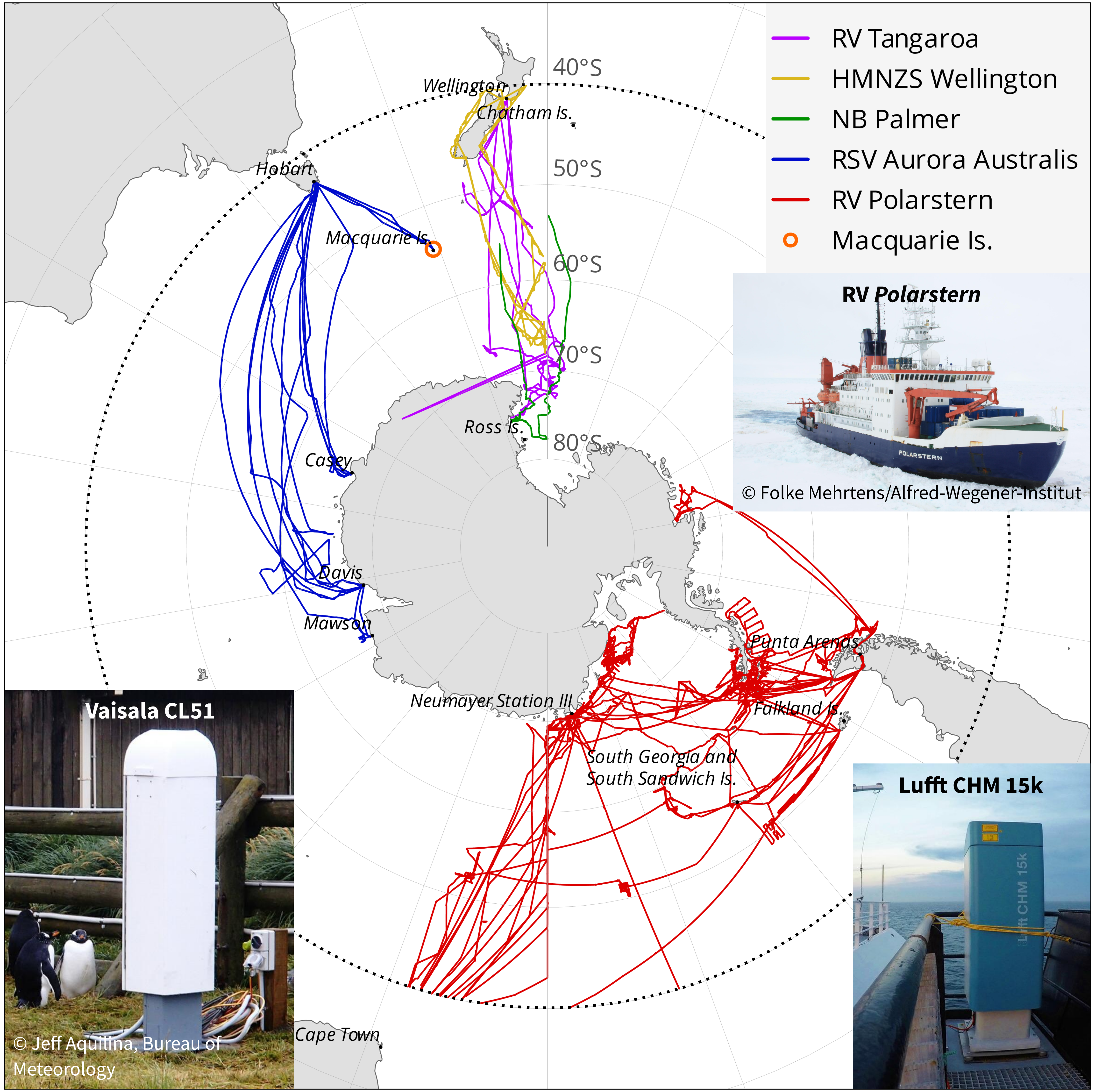
Introduction

- 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.

Voyages and stations

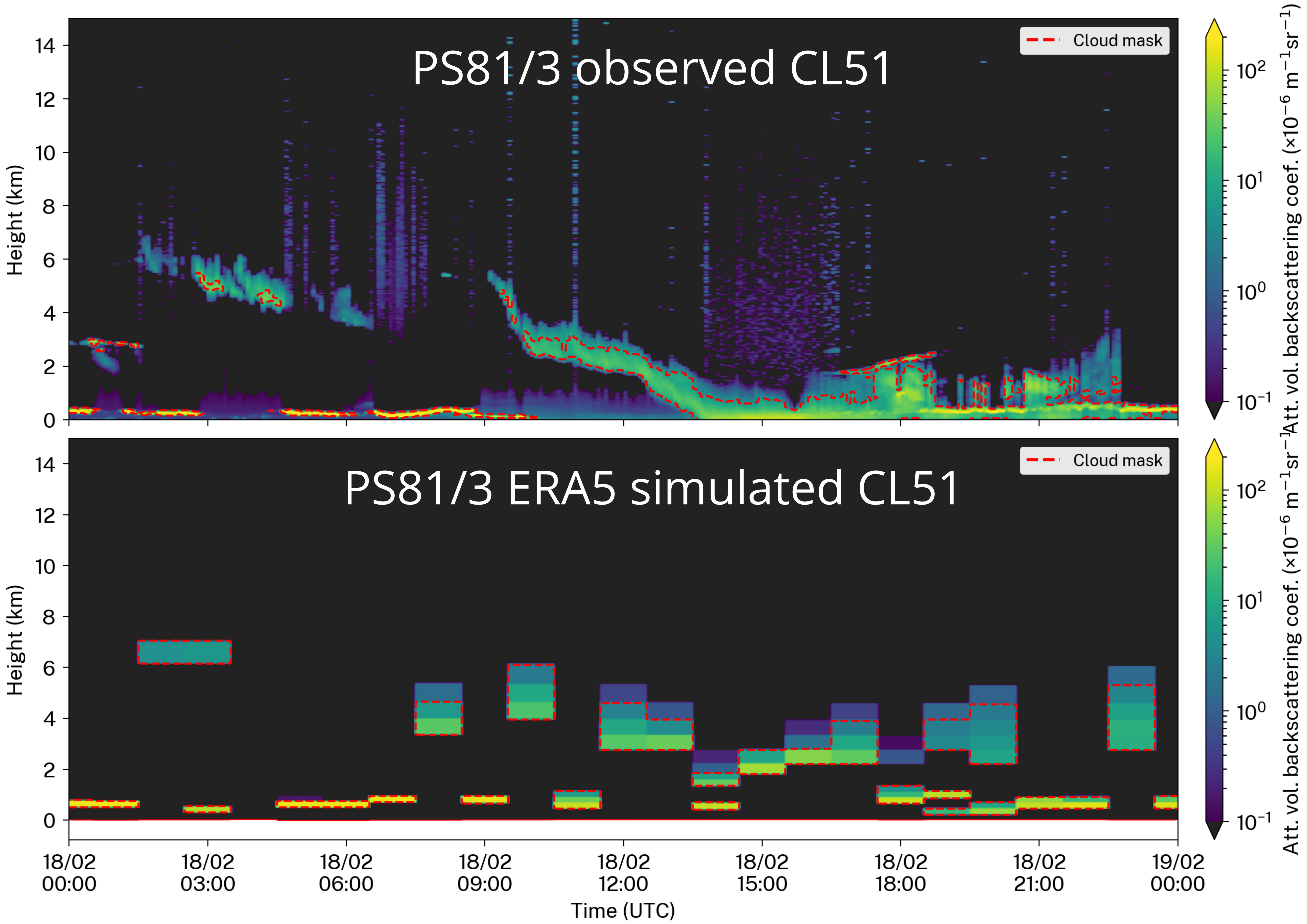
- We analysed 31 voyages of RV *Polarstern*, RSV *Aurora Australis*, RV *Tangaroa*, RV *Nathaniel B. Palmer*, HMNZS *Wellington*, and a station in the Southern Ocean south of 40°S between 2010 and 2021.
- A total of about 2400 days of observations were included.
- Ceilometer Vaisala CL51 and CT25K operating 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

- 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.

ALCF



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.

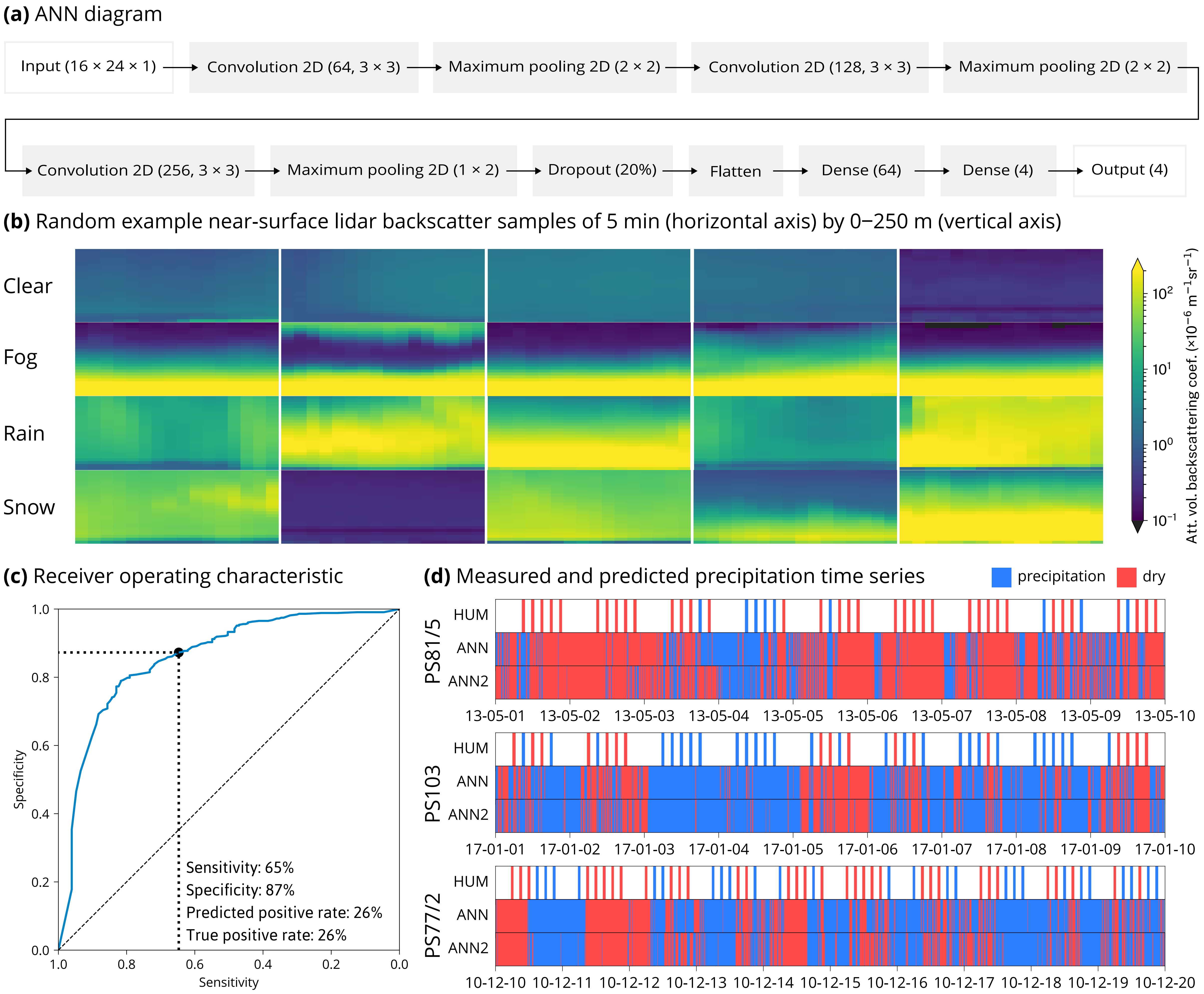
- Turbulence is parametrised.

- 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.

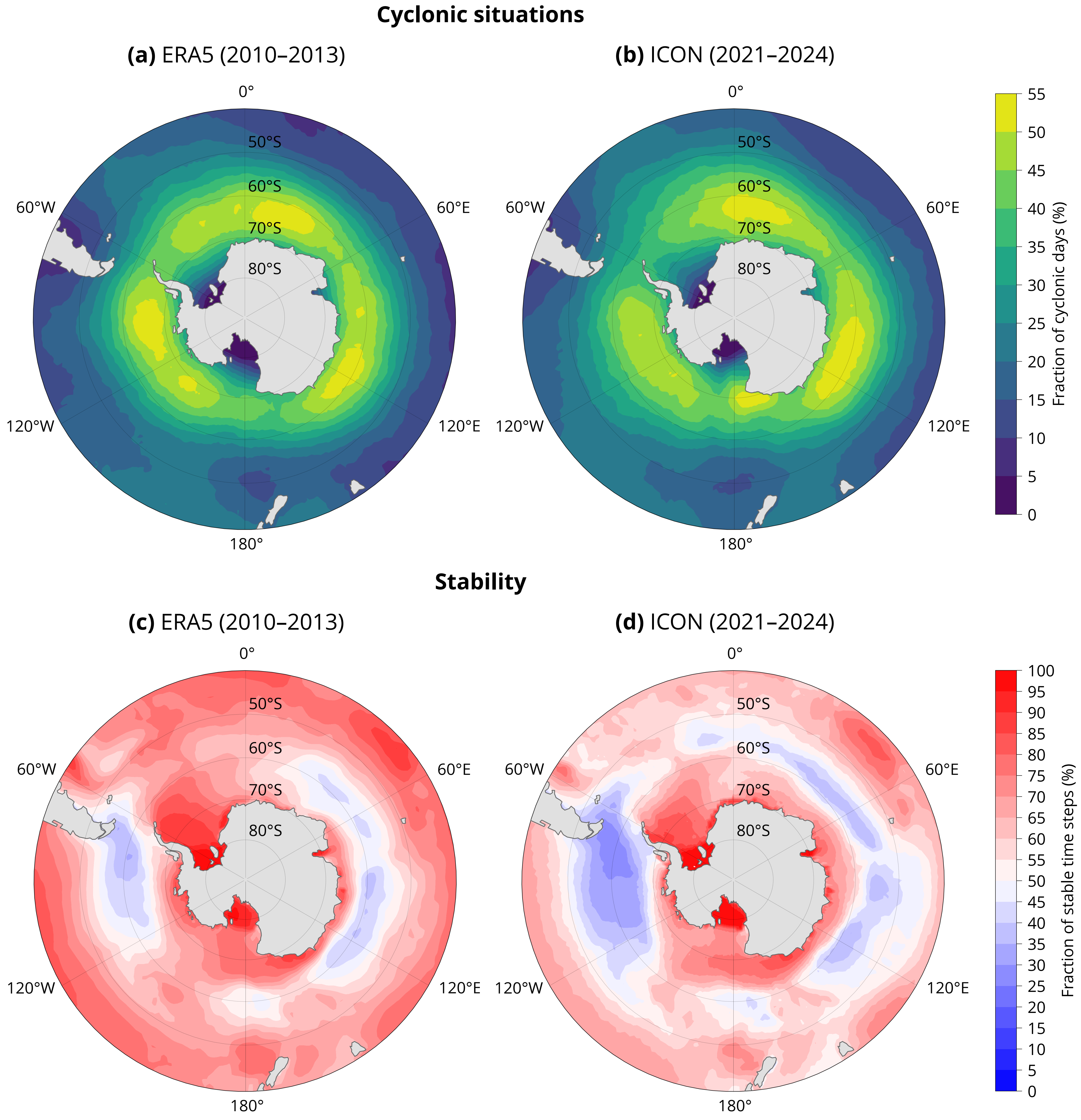
Filtering precipitation using machine learning

- 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 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.



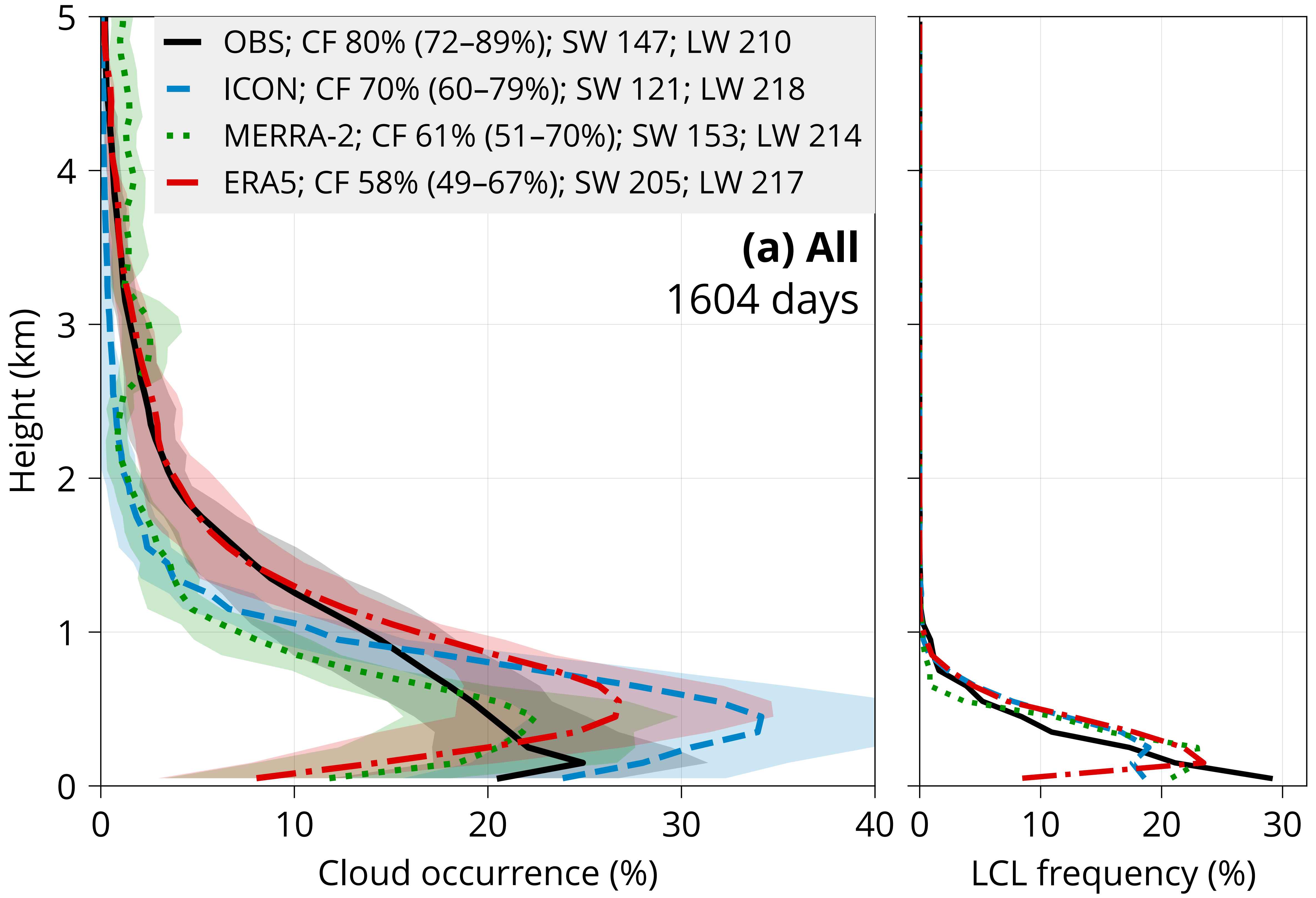
Subsetting by cyclonic activity and stability

- All data subsetted by cyclonic activity using cyclone tracking and by stability using lower tropospheric stability.
- The cyclonic and non-cyclonic subsets and the stable and unstable subsets are mutually exclusive.



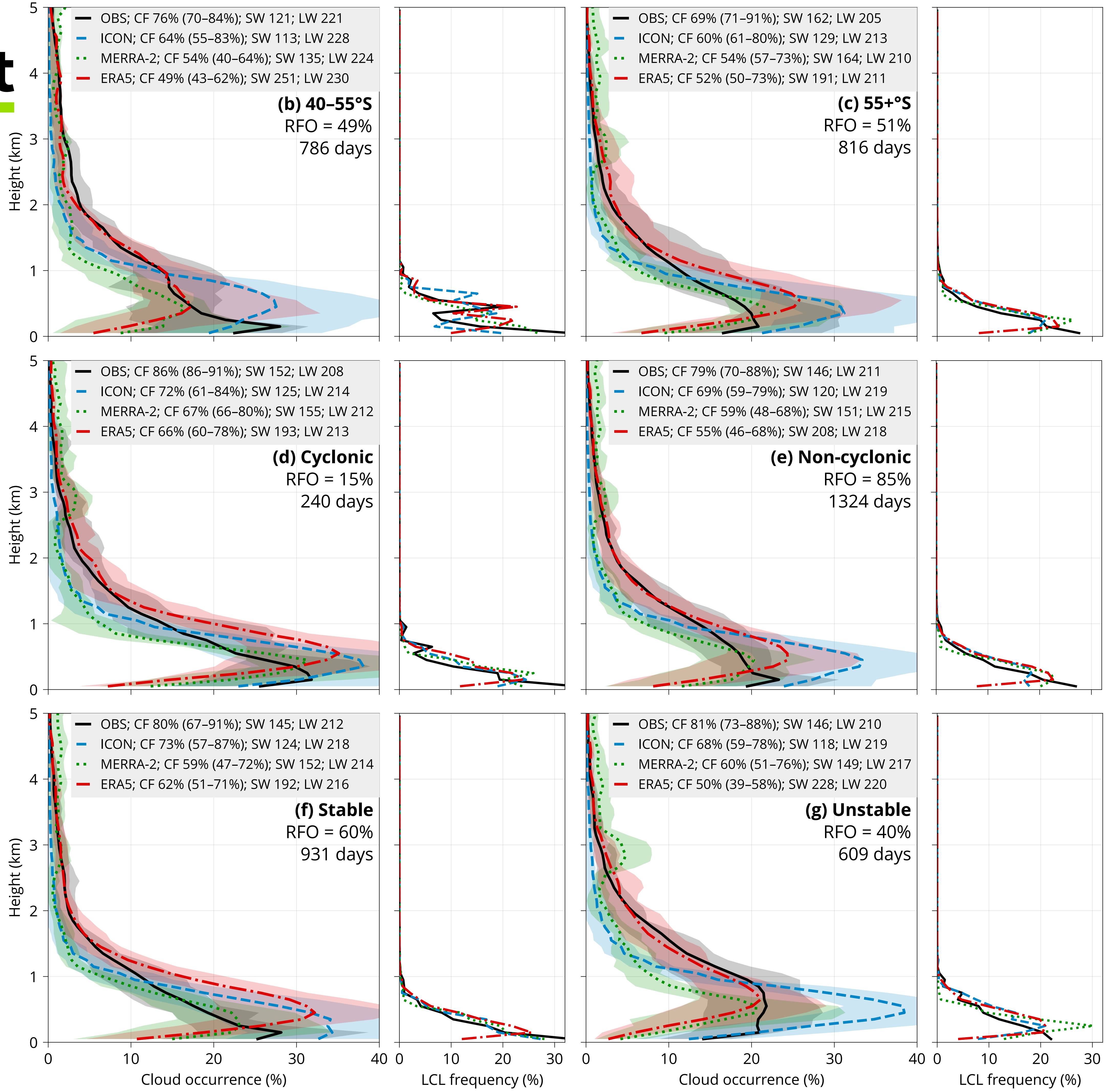
Cloud occurrence by height

- 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%,
- 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.



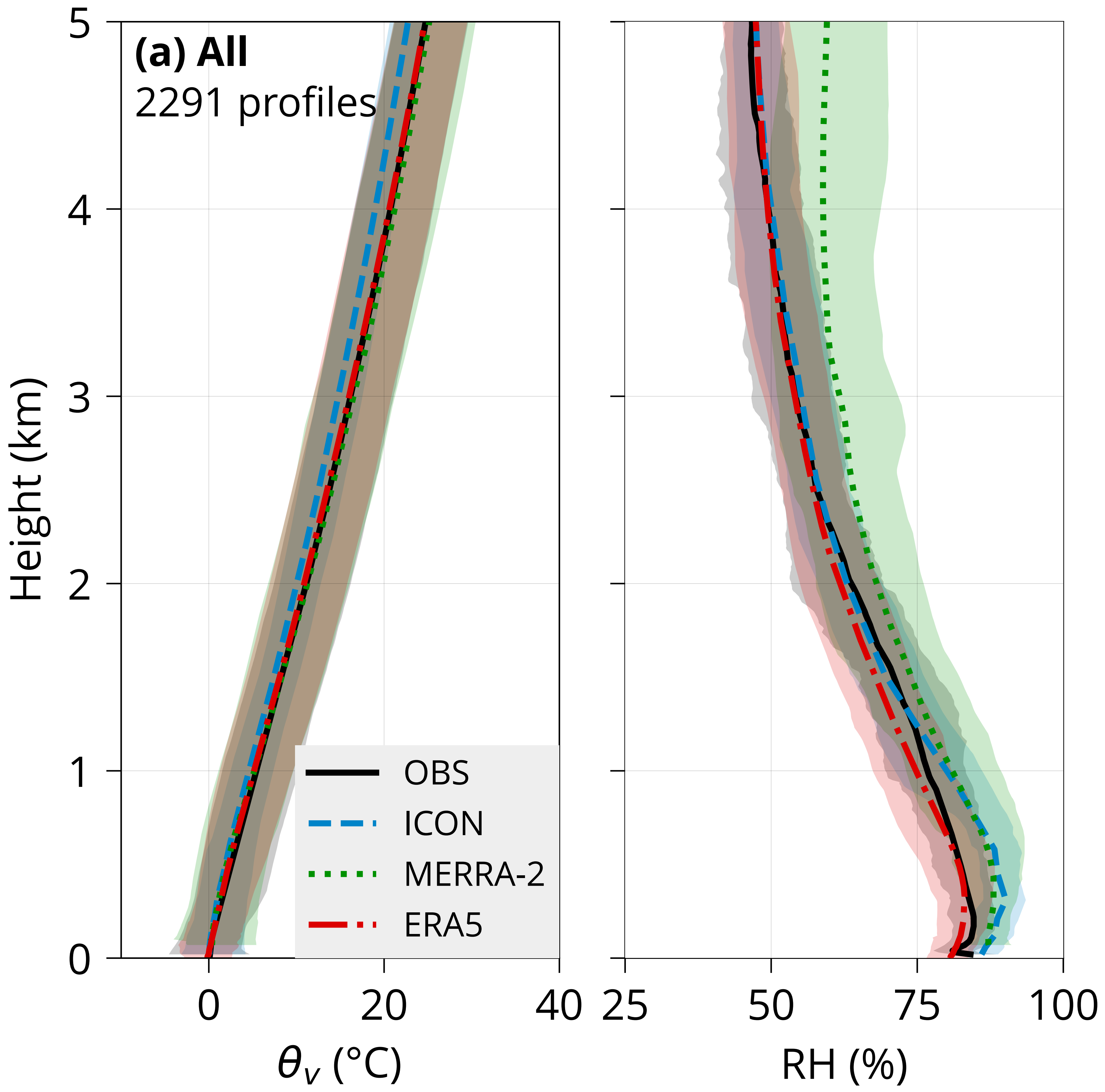
Cloud occurrence by height

- 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
- 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.



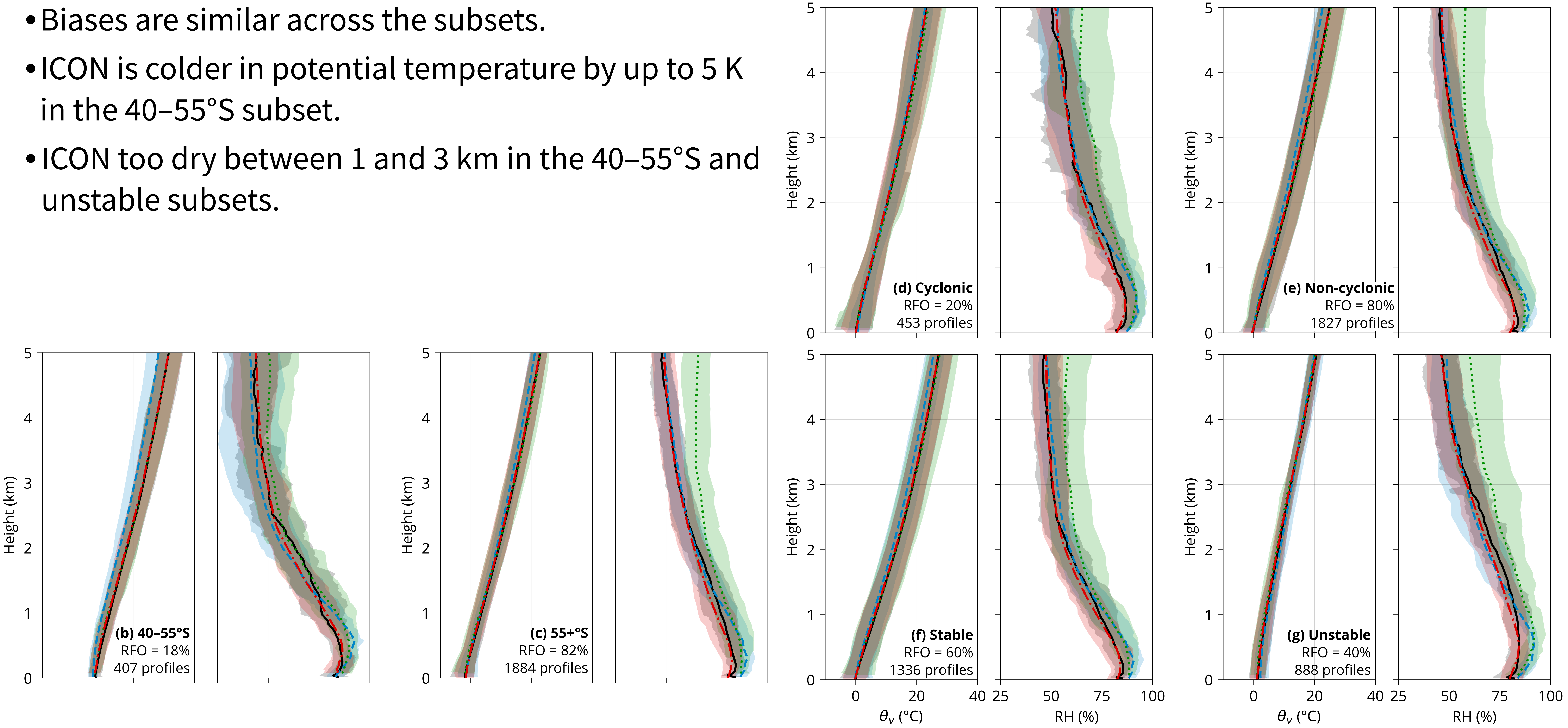
Thermodynamic profiles

- 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%.



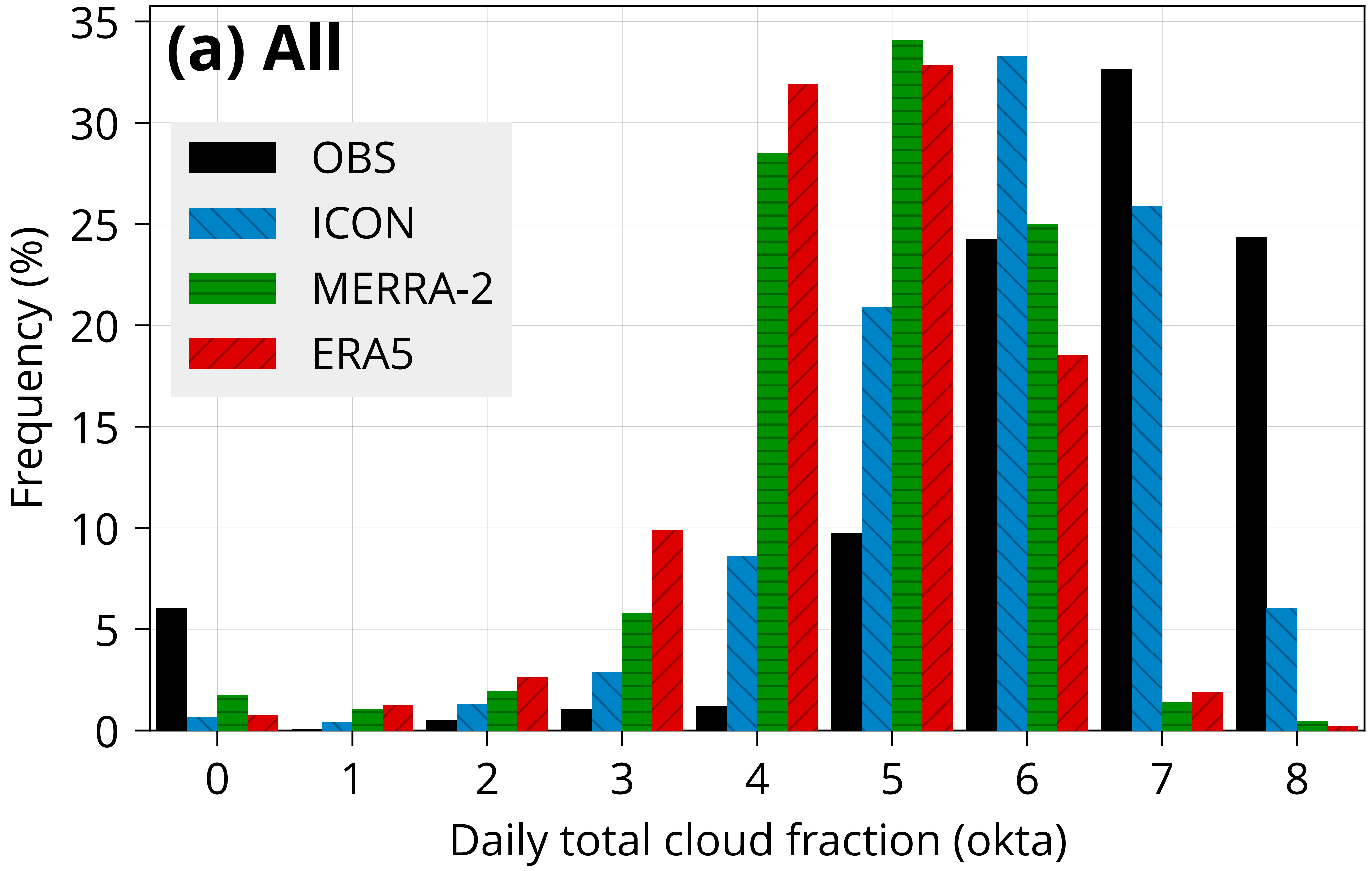
Thermodynamic profiles

- Biases are similar across the subsets.
- ICON is colder in potential temperature by up to 5 K in the 40–55°S subset.
- ICON too dry between 1 and 3 km in the 40–55°S and unstable subsets.



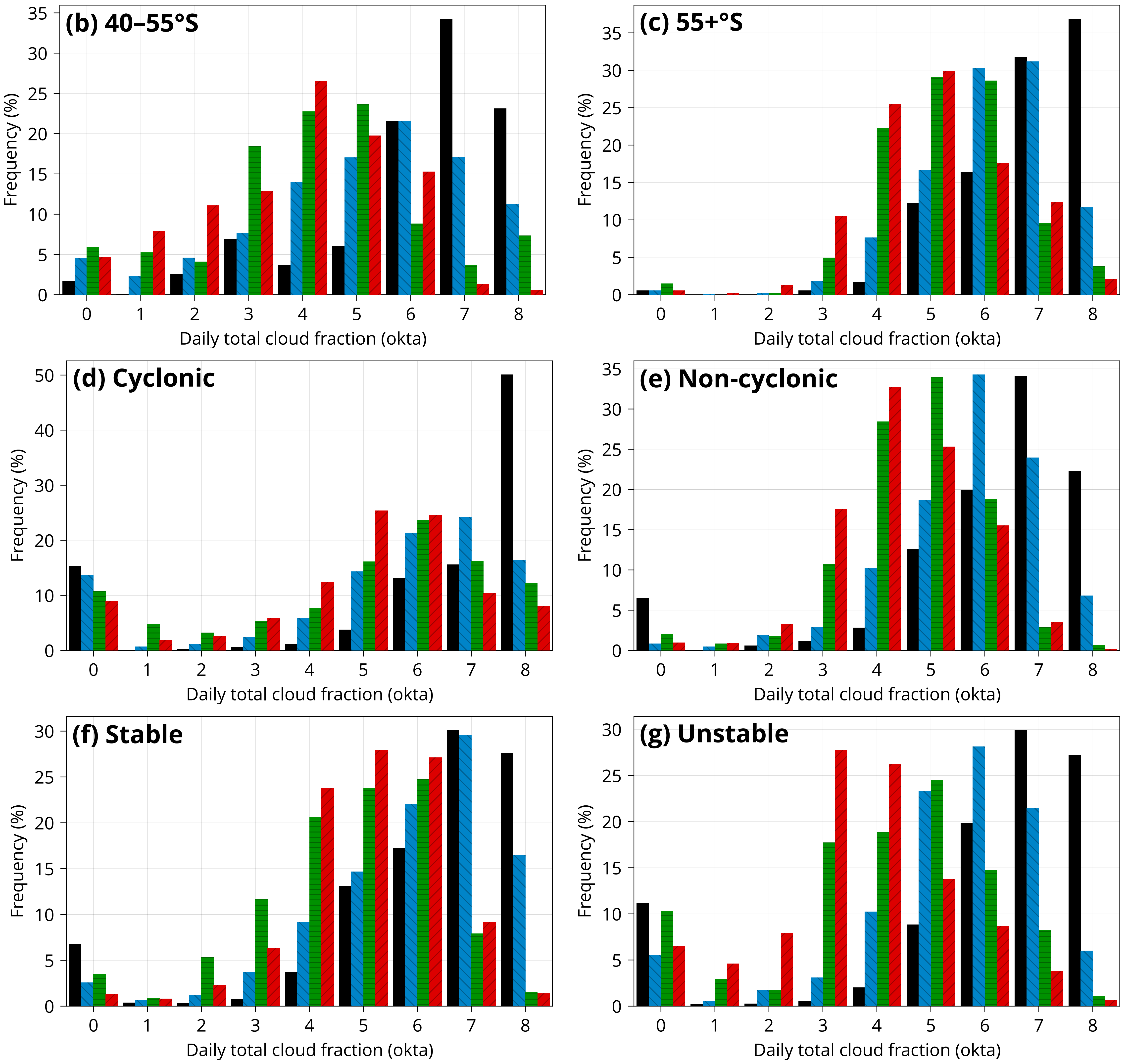
Daily total cloud fraction

- 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.



Daily total cloud fraction

- 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.



Conclusions

- 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.