Presentation of the Degree of Doctor of Philosophy thesis

Comparing remotely sensed observations of clouds and aerosols in the Southern Ocean with climate model simulations

by Peter Kuma[1]

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Presentation outline

Part I: Introduction

Part II: Ground-based lidar processing and simulator framework for comparing models and observations (ALCF 1.0)

Part III: Evaluation of Southern Ocean cloud in the HadGEM3 general circulation model and MERRA-2 reanalysis using ship-based observations

Part IV: Improving Southern Ocean boundary layer cloud parametrisation in the HadGEM3-GA7.1/UM11.4 general circulation model

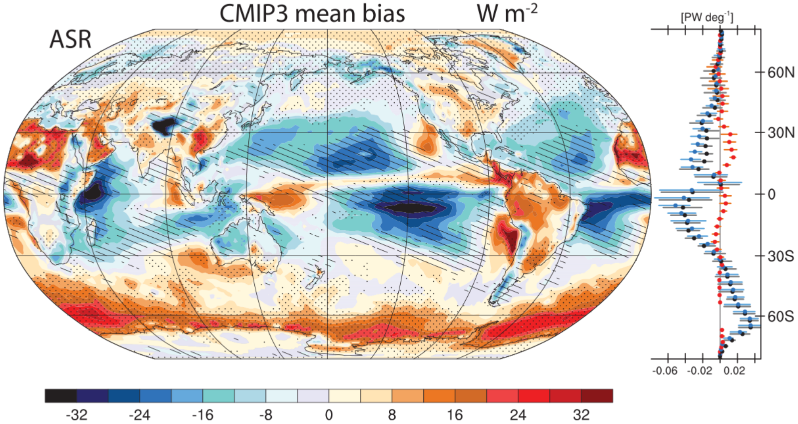
Part V: Conclusions

Part 1

Introduction

Top of Atmosphere biases in the Southern Ocean

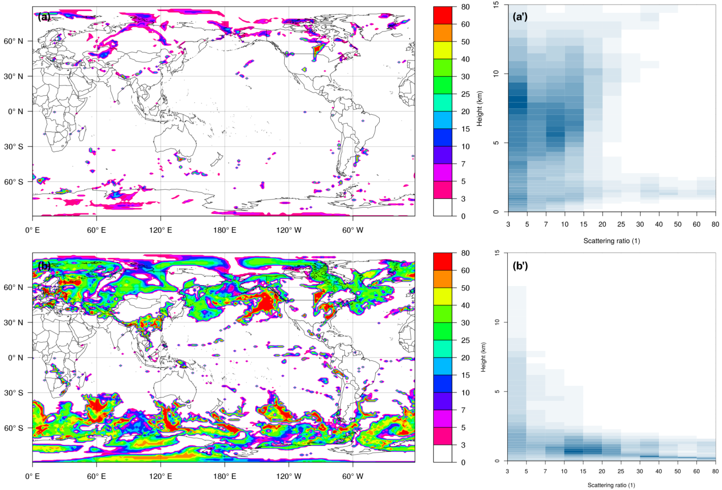
- Shortwave (SW) radiation biases of up to 30 $\mathrm{W\,m^{-2}}$ in the Southern Ocean (SO) are common in numerical weather prediction (NWP) models and general circulation models (GCMs).
- Largely thought to be due to cloud and cloud–aerosol representation, possibly linked to large-scale circulation and boundary layer parametrisation. Cloud cover exceeds 80% in the SO.



Adopted from Trenberth and Fasullo (2010).

Ground based vs. spaceborne lidar

- Passive and active satellite observations are limited in the SO for studying low clouds and fog due to overlapping clouds and ground clutter (CloudSat radar).
- Ground-based observations in the SO are scarce and expensive, but provide better view of low level clouds.
- Spaceborne lidars (CALIPSO, CATS) have proven as extremely useful for studying global clouds. The lidar forward simulator in the CFMIP Observation Simulator Package (COSP) has been used extensively for model evaluation.
- Our aim was to modify this simulator for use with ground-based automatic lidars and ceilometers (ALCs) to study SO clouds.



Objectives

1. Participate on SO campaigns: TAN1702 (2 weeks), TAN1802 (6 weeks); deployments on NBP1704 (NSF) and HMNZS *Wellington* (Royal New Zealand Navy).
2. Post-process existing and new SO voyage data.
3. Modify COSP lidar forward simulator to support ground-based ALCs.
4. Evaluation SO biases in the New Zealand Earth System Model (NZESM), which is based on HadGEM3.
5. Modify the code of the model to improve cloud simulation relative to voyage observations.

TAN1802 voyage

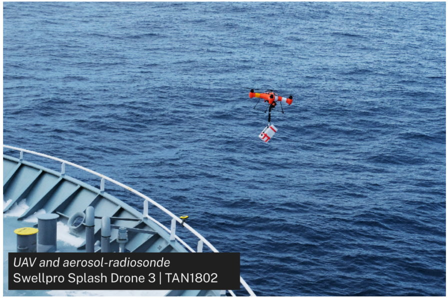
- 6-week voyage of R/V *Tangaroa* from Wellington to the Ross Sea in February–March 2018.
- Atmospheric measurements with a ceilometer, mini micropulse lidar (MiniMPL), micro rain radar (MRR-2), radiosondes, optical particle counters (OPCs) mounted on a UAV and helikite, human weather observations, …(Kremser et al., 2020, manuscript in preparation)


Ceilometer
Vaisala CL51 | Macquarie Is.

Ceilometer
Lufft CHM 15k | TAN1702


Micro rain radar
Meter MRR-2 | TAN1802


Helikite | TAN1802


UAV and aerosol-radiosonde
Swellpro Splash Drone 3 | TAN1802

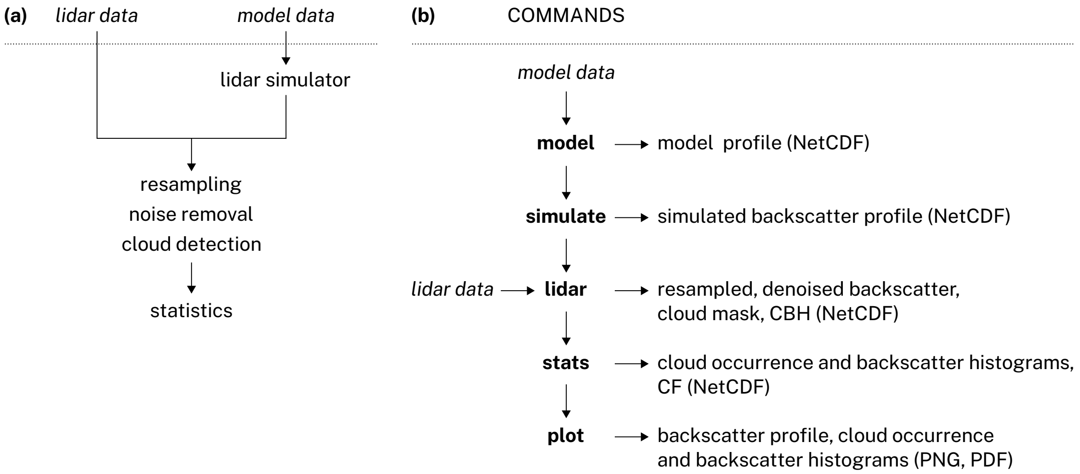

Radiosonde release
iMet-1 ABx | TAN1802

Part 2

Ground-based lidar processing and simulator framework for comparing models and observations (ALCF 1.0)

Overview of the Automatic Lidar and Ceilometer Framework (ALCF)

- The ALCF is a software framework for consistent processing of ALC data and a ground-based lidar forward simulator derived from COSP.
- Processing of data from ALCs: Vaisala CL31, CL51, Lufft CHM 15k, Sigma Space MiniMPL, and atmospheric models and reanalyses: AMPS, ERA5, JRA-55, MERRA-2, UM.
- Models and observations can be compared statistically or based on curtain plots of attenuated volume backscattering coefficient (if model resolution is high enough).



(a) *lidar data* *model data*

lidar simulator

resampling
noise removal
cloud detection

statistics

(b) COMMANDS

model data

model → model profile (NetCDF)

simulate → simulated backscatter profile (NetCDF)

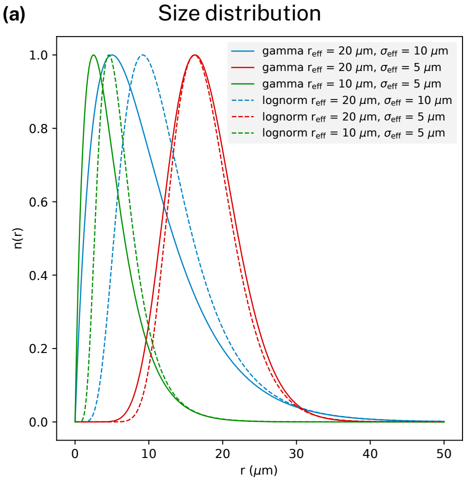
lidar data → **lidar** → resampled, denoised backscatter, cloud mask, CBH (NetCDF)

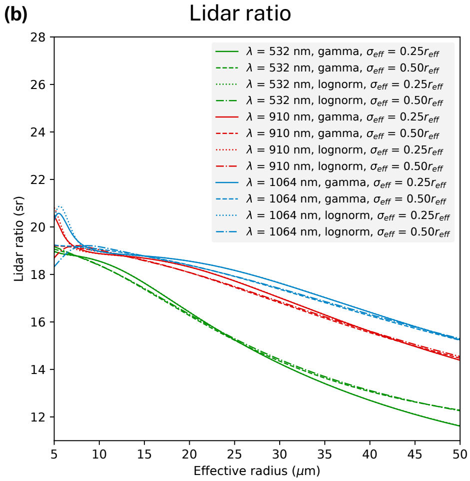
stats → cloud occurrence and backscatter histograms, CF (NetCDF)

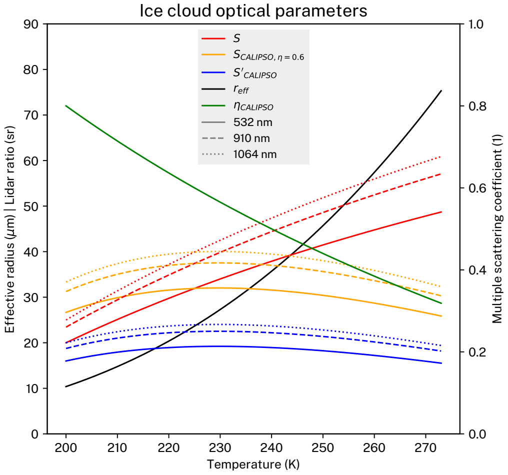
plot → backscatter profile, cloud occurrence and backscatter histograms (PNG, PDF)

Parametrisation of optical properties of cloud liquid water and ice

- Cloud droplet size distribution is approximated by Gamma distribution, lidar ratio (extinction-to-backscattering ratio) is calculated as a function of the effective radius for 532 nm, 910 nm and 1064 nm lidar wavelengths.
- Ice optical properties are parametrised as a function of temperature, derived from global CALIPSO measurements Garnier et al. (2015) and a set of lidar field campaigns Heymsfield (2005).

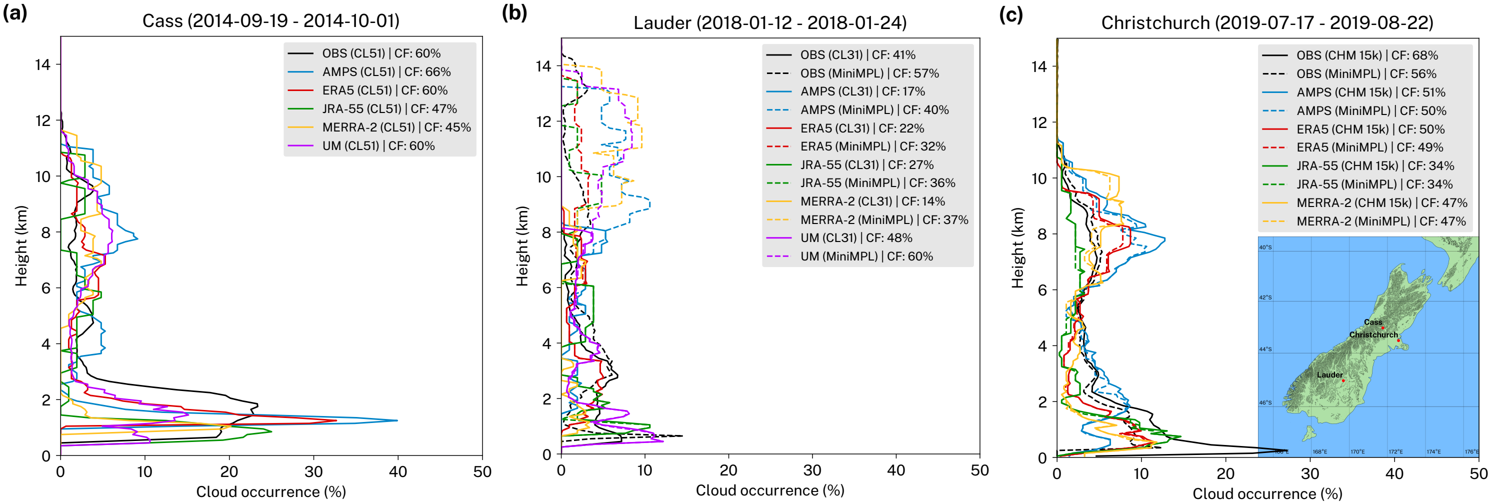

(a) Size distribution


(b) Lidar ratio


Ice cloud optical parameters

Case studies

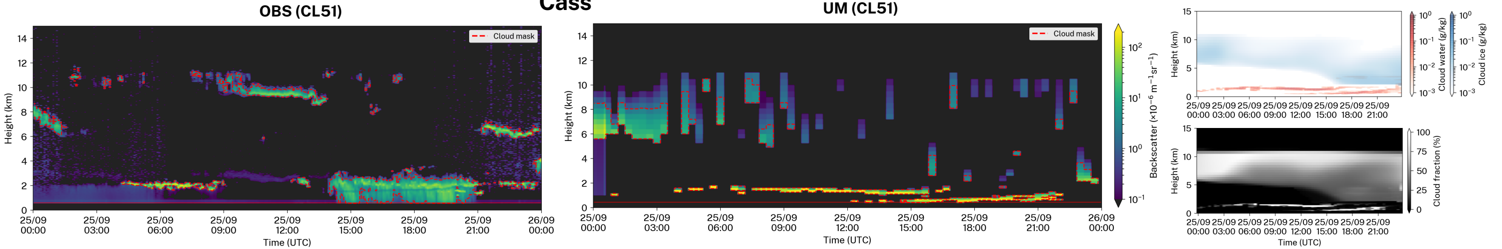
- To demonstrate how the ALCF can be used, we analysed ALC data from three stations in New Zealand (Cass, Lauder and Christchurch) and compared them with five models (AMPS, ERA5, JRA-55, MERRA-2, UM).
- The time-limited cloud mask statistics comparison shows that models tend to underestimate cloud occurrence.



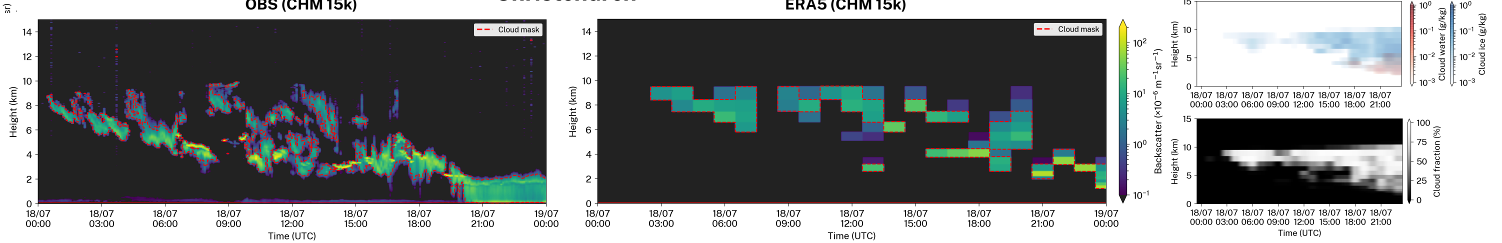
Case studies (cont.)

- Model cloud water liquid, ice content and cloud fraction interact through the SCOPS subcolumn generator, liquid and ice optical properties parametrisation and the lidar equation to produce attenuated volume backscattering coefficient.
- Comparison of 2-dimensional backscatter profiles can be very useful for identifying model deficiencies if resolution is high enough.

Cass



Christchurch

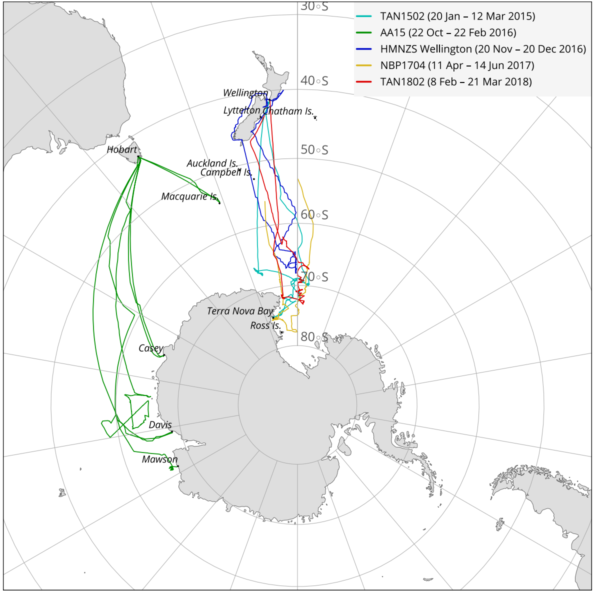


Part 3

Evaluation of Southern Ocean cloud in the HadGEM3 general circulation model and MERRA-2 reanalysis using ship-based observations

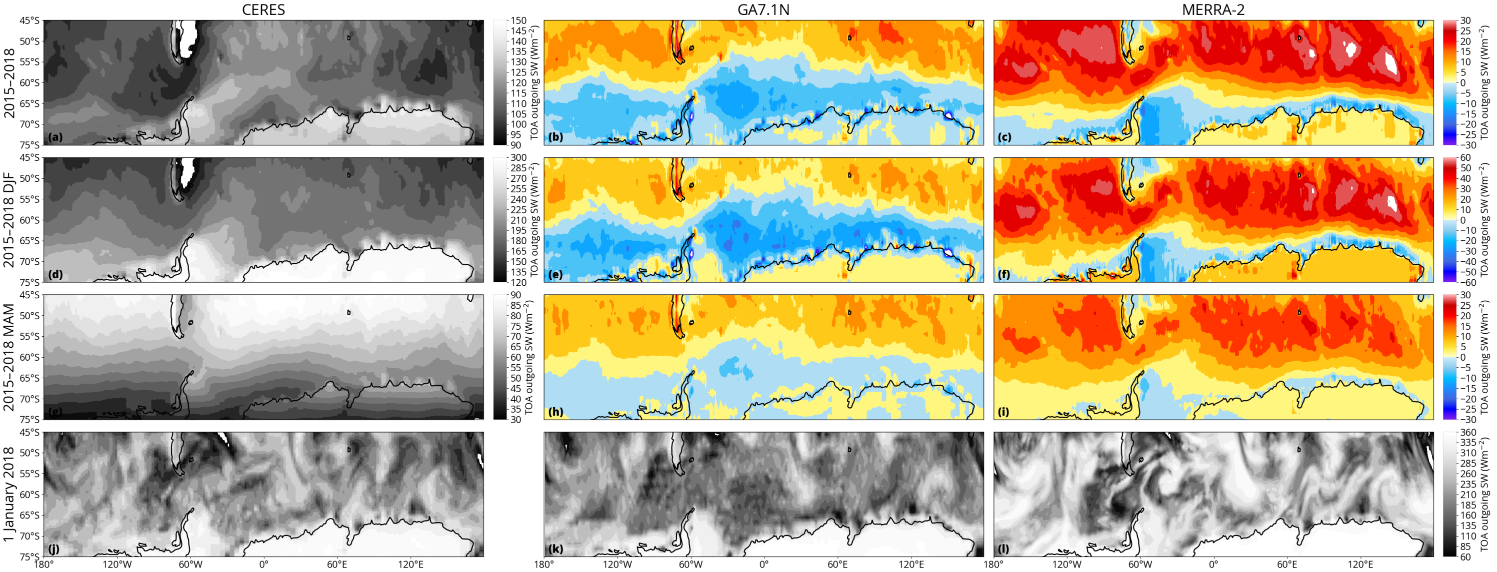
Voyages

- We evaluated GA7.1N (nudged GCM) and MERRA-2 (reanalysis) in comparison with ceilometer and radiosonde observations on five SO voyages between 2015 and 2018, a total of 298 days.
- The data were subsetted by 5° from 55°S to 70°S.



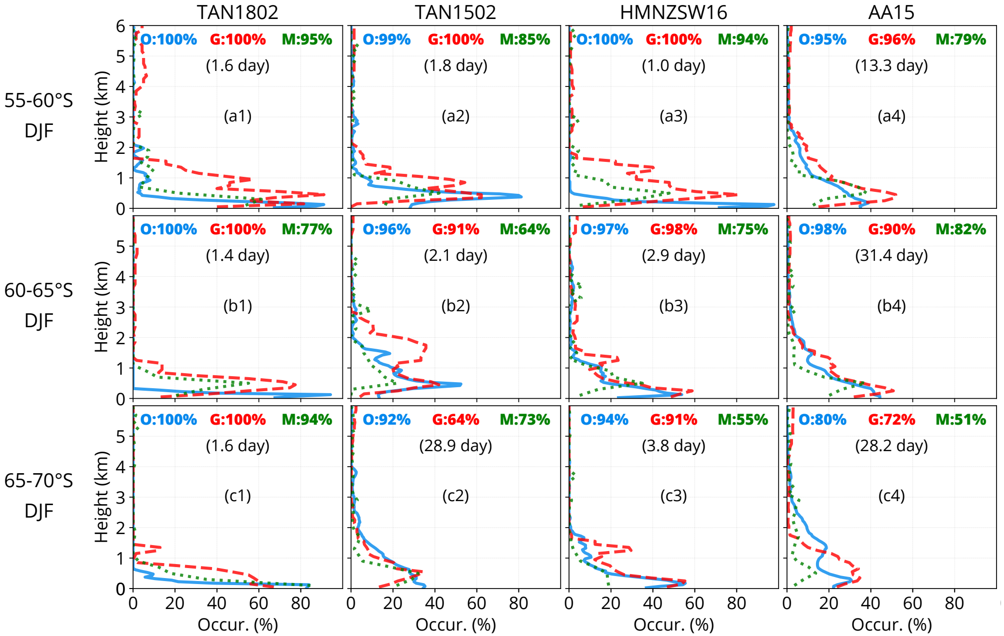
SW biases in GA7.1N and MERRA-2

- GA7.1N and MERRA-2 shows a bipolar reflected SW bias at TOA in the SO, too much radiation reflected in the low-latitude SO and too little reflected in the high-latitude SO.
- Bias visible even on daily means in summer.



Cloud occurrence in observations in models

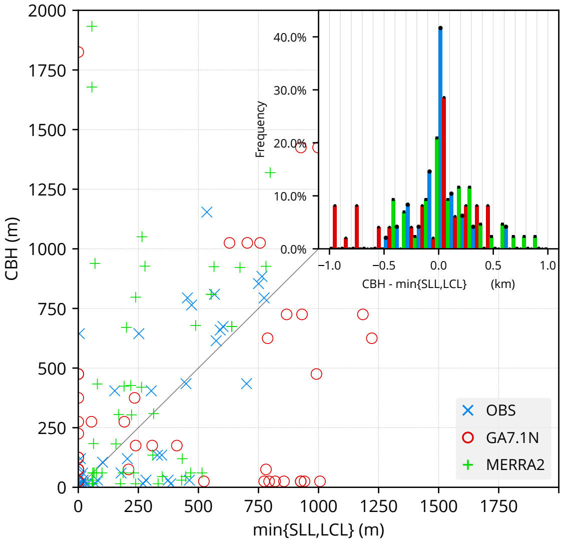
- Based on cloud mask calculated from observed and simulated ceilometer backscatter, we determined that low clouds below 1 km and fog dominate the observations, which is almost consistently underestimated by the GA7.1N (about 8%) and MERRA-2 (about 18%).



Relationship between boundary layer thermodynamics and cloud base height

- By analysing co-located radiosonde and ceilometer data we found a strong relationship between cloud base height (CBH) and two thermodynamic lifting levels, SST lifting level (SLL) and lifting condensation level (LCL).
- Over 40% of time is CBH within 200 m of the minimum of SLL and LCL. Models don’t represent this relationship well.

TAN1802, NBP1704; Feb–May, 60–70°S

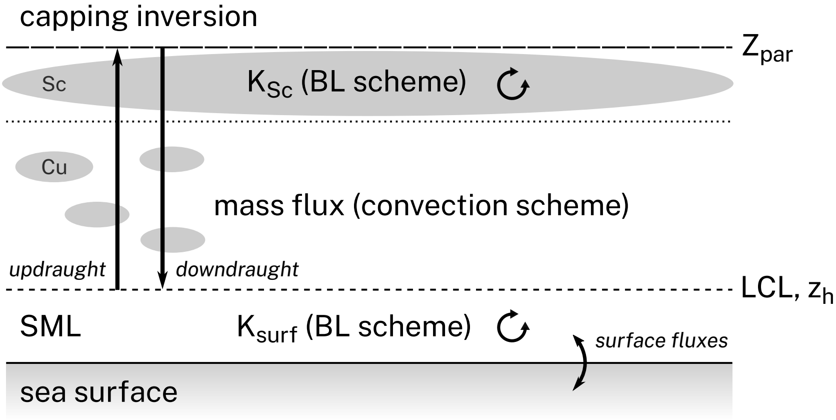


Part 4

Improving Southern Ocean boundary layer cloud parametrisation in the HadGEM3-GA7.1/UM11.4 general circulation model

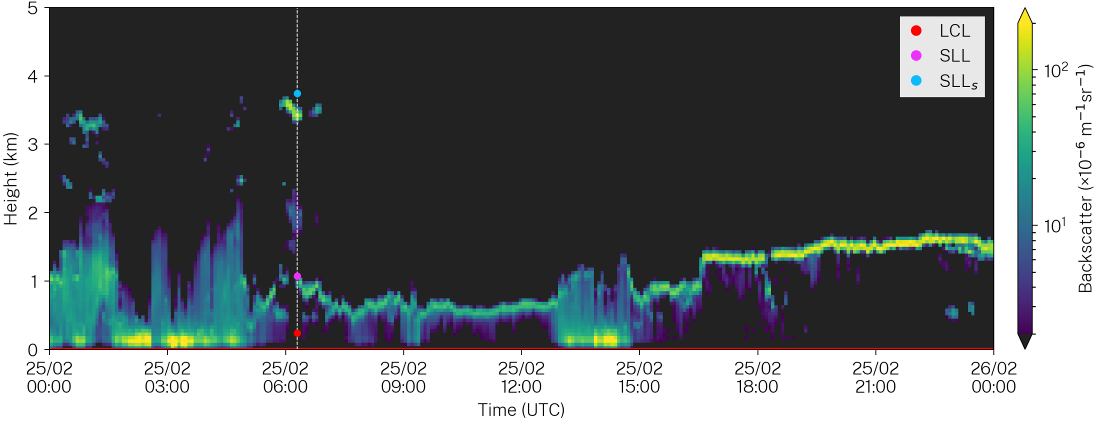
Boundary layer parametrisation in the Unified Model

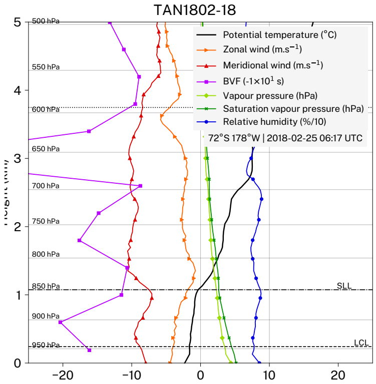
- SO boundary layer clouds were previously identified as a key deficiency in the HadGEM3 GCM (Part I).
- Our aim was to analyse and experimentally improve SO boundary layer cloud simulation in the HadGEM3/Unified Model (UM).
- The boundary layer in the UM is parametrised by the boundary layer (BL) and convection schemes. BL scheme parametrises turbulence and convection scheme parametrises mass flux.



Boundary layer clouds in the Southern Ocean

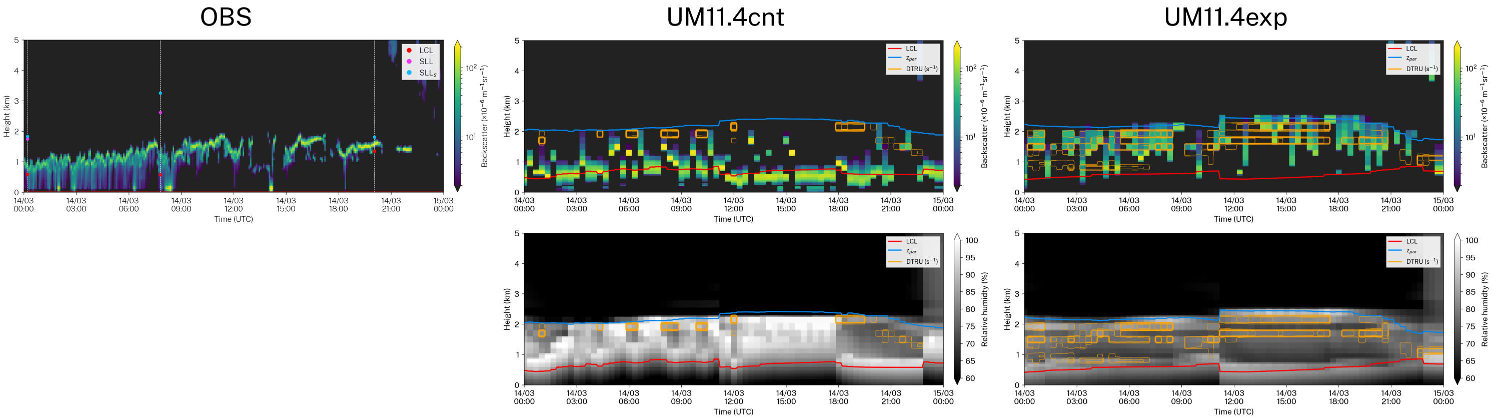
- Three-layer clouds were common on the TAN1802 voyage (Ross Sea), with layers of clouds forming on three lifting levels: lifting condensation level (LCL), SST lifting level (SLL) and saturated SST lifting level (SLL_S), corresponding to Cumulus (Cu; LCL), Stratocumulus (Sc; SLL) and Altocumulus (Ac, SLL_S). cloud types.
- Is this relationship and cloud types well-represented in the model?





Experimental run of the Unified Model

- Using the ALCF, we identified that in the period of TAN1802 observations (OBS), the UM tends to overestimate Cu clouds forming at LCL and underestimate Sc clouds forming at SLL (corresponding to z_{par} in the model).
- Using an experimental run, we could improve the fidelity of Sc clouds and reduce the amount of Cu clouds.
- The changes in the experimental (exp) relative to the control run (cnt) were increased sea surface roughness length and increased c_{mass} coefficient relating sub-cloud convective velocity to initial mass flux, increasing fluxes from the surface to the z_{par} level.

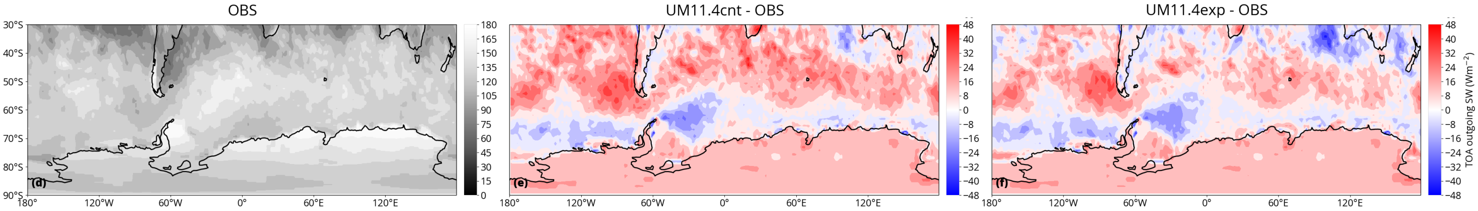

OBS

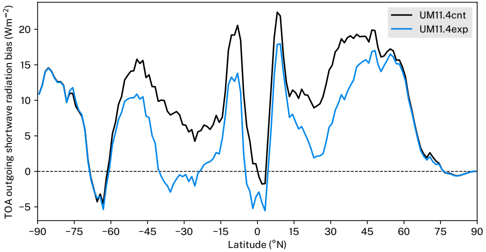
UM11.4cnt

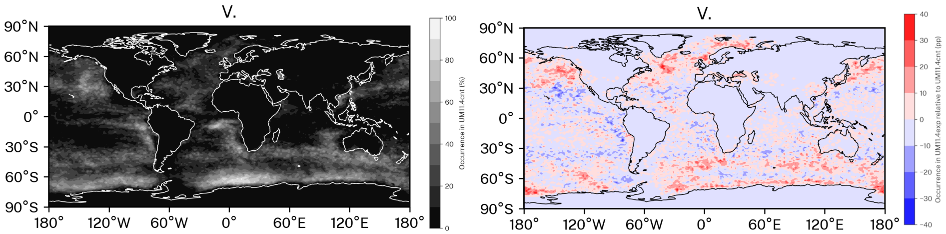
UM11.4exp

Effect on SW radiation

- The proposed changes improve the summertime SW radiation biases in the SO, but more research is needed.
- The global effect of SW biases in the limited time period appears to be consistently positive.
- The underestimated boundary layer type ”Cu below Sc” (Type V) is increased, but the global effect of this change would have to be evaluated before recommending production changes.







Part 5

Conclusions

Evaluation of Southern Ocean cloud in the HadGEM3 general circulation model and MERRA-2 reanalysis using ship-based observations

- We used 4 years of satellite observation from CERES, ceilometer and radiosonde observations from five SO voyages to analyse cloud representation in GA7.1 and MERRA-2.
- We found regional summertime TOA reflected SW radiation bias of up to 60 $\mathrm{W m^{-2}}$ in the models, which is positive in the low-latitude SO and negative in the high-latitude SO.
- We found that GA7.1 underestimates the predominantly low clouds by 4–9% and MERRA-2 by 18%.
- We found that low level clouds are strongly linked to boundary layer lifting levels and this relationship is poorly represented in the models.
- GA7.1 and MERRA-2 simulate very different cloud phase in the SO, with GA7.1 having both liquid water and ice and MERRA-2 almost exclusively liquid water.
- MERRA-2 has a strong ”too few too bright” bias, i.e. cloud occurrence is underestimated, while cloud albedo is overestimated, leading to overestimated SW radiation reflection at the TOA.

Ground-based lidar processing and simulator framework for comparing models and observations (ALCF 1.0)

- We developed an open source framework for processing of automatic lidar and ceilometer (ALC) data and a ground-based forward ALC simulator derived from COSP, supporting 4 off-the-shelf instruments and 5 reanalyses and models.
- Parametrisation of scattering from liquid cloud droplets is based on Mie theory and scattering from ice is empirically based on global CALIPSO data.
- Cloud occurrence can be compared between observations and models statistically or based on 2-dimensional attenuated volume backscattering coefficient profiles.
- Current focus of the ALCF is on clouds, but precipitation and aerosol can be added in the future.
- We demonstrated on three case studies in New Zealand how the ALCF can be used for model evaluation.

Improving Southern Ocean boundary layer cloud parametrisation in the HadGEM3-GA7.1/UM11.4 general circulation model

- A strong link between three lifting levels (LCL, SLL, SLL_s) and cloud layers was identified on TAN1802 ceilometer and radiosonde observations.
- The Unified Model appears to be underestimated Sc clouds due to lack of flux across LCL.
- Separation of the boundary layer parametrisations into boundary layer and convection schemes and a lack of coupling between the two appears to be the problem.
- Increasing sea surface roughness and initial mass flux increases moisture flux to the level of capping inversion, leading to improved Sc cloud formation in the model.
- This change improves SW radiation biases in the SO and globally in the time period studies, but more research is needed before it can be recommended.
- This study demonstrates the usefulness of the ALCF for studying boundary layer clouds using ground-based lidar observations.

Author’s contributions

- Participation on the TAN1702 and TAN1802 voyages, deployments on NBP1704, HMNZS *Wellington*.
- We identified large deficiencies in low level clouds in the SO based on a five voyage datasets and their links to boundary layer thermodynamics (Kuma et al., 2020a, published in ACP).
- The Automatic Lidar and Ceilometer Framework implements a ground-based lidar simulator, supports 4 instruments and 5 models and is made available under an open source license (Kuma et al., 2020b, in review in GMD).
- Post-processing of atmospheric measurements for the public TAN1802 voyage dataset (Kremser et al., 2020, manuscript in preparation).
- Analysis of clouds over the Ross Sea and Ross Ice Shelf using a CloudSat–CALIPSO dataset (Jolly et al., 2018).
- Collaboration on SO atmospheric studies (Hartery et al., 2020b,a; Klekociuk et al., 2019).
- Ceilometer and lidar measurements at the ER building (University of Canterbury) contributed to a 2019 Christchurch air pollution measurement campaign (Dale et al., 2020, submitted to ESSD).
- International collaboration on improved range-dependent calibration of the MiniMPL.
- Open source tools for post-processing of lidar, micro rain radar, radiosonde data already in use by the community: cl2nc, mpl2nc, mrr2c, rstool[1].
- Results presented internationally at the POLAR 2018 (Davos, Switzerland), AMS 15th Conference on Cloud Physics (Vancouver, Canada, 2018), CFMIP 2019 Meeting (Mykonos, Greece), and domestically at the New Zealand Antarctic Science Conference (Dunedin, 2017), 2017 MetSoc Conference (Dunedin), Deep South Challenge Symposium (Wellington, 2017), 2018 MetSoc Conference (Christchurch), Deep South Challenge Conference (Auckland, 2019), New Zealand Antarctic Science Conference (Christchurch, 2019) and Gateway Antarctica Conference (Christchurch, 2019).

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[1] `https://github.com/peterkuma/cl2nc`; `https://github.com/peterkuma/mpl2nc`; `https://github.com/peterkuma/mrr2c`; `https://github.com/peterkuma/rstool`

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