Doctoral Confirmation Presentation

Assessment of Southern Ocean Clouds and Aerosol in General Circulation Models

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Peter Kuma[1]

Supervisor: Associate Prof. Adrian McDonald[1]

Co-supervisor: Dr Olaf Morgenstern[2]

[1]University of Canterbury, Christchurch, New Zealand

[2]NIWA, Wellington, New Zealand

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Part 1

The Problem

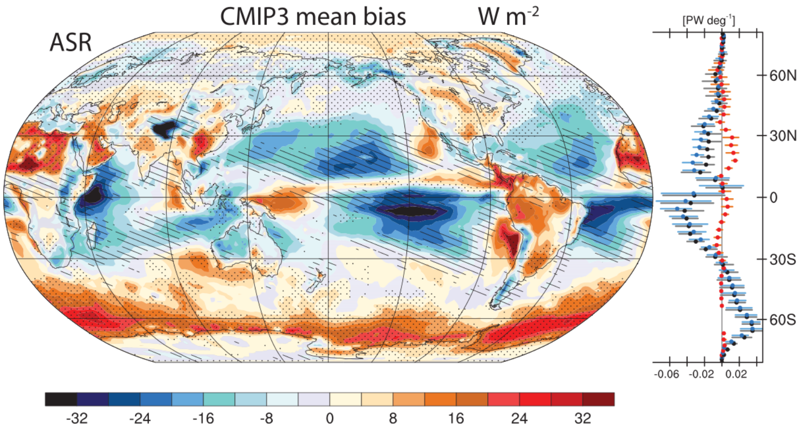
Absorbed shortwave radiation over the Southern Ocean in CMIP models is substantially overestimated compared to satellite observations (CERES).

Well-documented problem affecting multiple GCMs:

- **30 Wm^{-2} in CMIP3 models.** *"In modern-day climates, mainly because of systematic deficiencies in cloud and albedo at mid- and high latitudes, too much solar radiation enters the ocean."* (Trenberth and Fassulo (2010)[1]
- **Persistent in CMIP5 models.** *"Substantial biases in shortwave cloud forcing of up to 30 Wm^{-2} are found in the midlatitudes of the Southern Hemisphere in the historical simulations of 34 CMIP5 coupled general circulation models."* (Ceppi et al. 2012)[2]
- **Affecting HadGEM/UKESM.** 10–30 Wm^{-2} in GA7 (next slide).

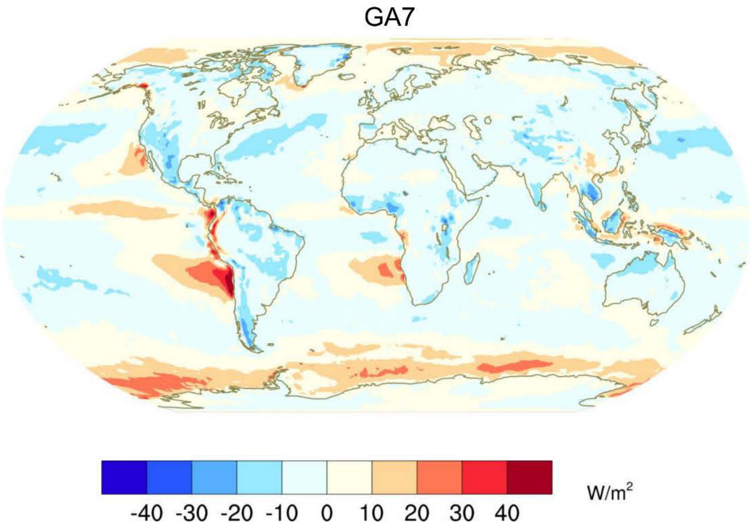
[1] Trenberth and Fasullo (2010), Simulation of Present-Day and Twenty-First-Century Energy Budgets of the Southern Oceans.
[2] Ceppi et al. (2012), Southern Hemisphere jet latitude biases in CMIP5 models linked to shortwave cloud forcing.

1.1 CMIP3 Shortwave Bias



Biases in absorbed solar radiation relative to observations regionally for 1990–99. At right the zonal mean is given over land (red), ocean (blue), and all (black). Adopted from Trenberth and Fassulo (2010).

1.2 HadGEM Shortwave Bias



Shortwave radiative bias in GA7. Adopted from presentation by Varma et al. (2017).

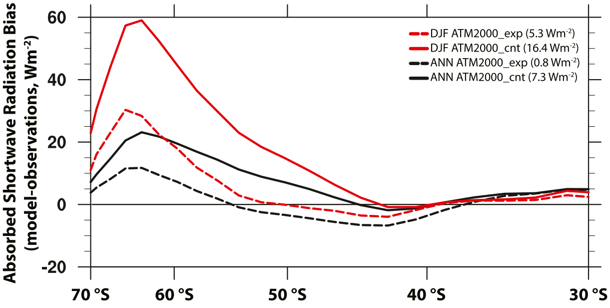
1.3 Potential Culprits

- Supercooled liquid occurrence
- Cloud homogeneity
- Cloud occurrence (vertical and horizontal)
- Cloud optical thickness
- Cloud-aerosol interaction
- Cloud in extratropical/polar cyclones
- Misrepresentation of cloud types
- Convective processes
- Sea ice-atmosphere interaction
- Radiative transfer parametrisation

1.4 Attempted Solutions

Supercooled liquid:

- Increasing supercooled liquid content by decreasing freezing temperature (Kay et al. 2016)[3]
- Switching off supercooled liquid formation in GA7 (presentation by Varma et al. 2017)



Absorbed shortwave radiation in CAM5 relative to CERES (Kay et al. 2016).

[3] Kay et al. (2016), Global Climate Impacts of Fixing the Southern Ocean Shortwave Radiation Bias in the Community Earth System Model (CESM).

1.5 Motivation

> *”You see, Momo... it’s like this. Sometimes, when you’ve a very long street ahead of you, you think how terribly long it is and feel sure you’ll never get it swept... And then you hurry. You work faster and faster, and everytime you look up there seems to be just as much to sweep as before, and you try even harder…, and you panic, and in the end you’re out of breath and have to stop—and still the street stretches away in front of you.”*
>
> — Michael Ende, Momo

We are working hard yet doing poorly, unspoilt nature might be gone as we know it less than 100 years.

Through greater understanding of nature we learn how to value and protect it.

Part 2

Methods

Comparison of modelled cloud and observed cloud from surface-based and satellite measurements, correlation with synoptic and thermodynamic conditions and aerosol.

Datasets:

- Surface-based – voyages (ships of opportunity) and subantarctic ground stations
- Satellite – *CERES, CloudSat, CALIPSO, AMSR-E (sea ice), MODIS, ISCCP*
- New Zealand-based (validation) – NWP and ground-based observations

Tools:

- NZESM
- COSP/ACTSIM

Fieldwork – participation on Southern Ocean voyages

2.1 Fieldwork

Participation on:

- **TAN1702 R/V Tangaroa voyage on the Campbell Plateau** (*2 weeks; March 2017*)
  2-daily radiosondes, ceilometer, micro rain radar, sky camera
- **TAN1802 R/V Tangaroa voyage in the Ross Sea** (*6 weeks; February–March 2018*)
  3-daily radiosondes, ceilometer, micro-pulse lidar, micro rain radar, optical particle counters, UAV, helikite, sky cameras, manned observations

2.2 NZESM[4]

New Zealand Earth System Model (NZESM):

- developed by The Deep South National Science Challenge and NIWA
- based on UKESM/GA7

"efforts on a few selected model development topics, which are well-known and longstanding biases of particular relevance in the Southern Hemisphere":

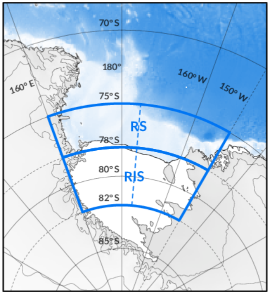
- aerosol-cloud-radiation linkages over the Southern Ocean
- sea ice physics
- Antarctic Bottom Water (ABW) formation

[4] J. Williams et al. (2016), Development of the New Zealand Earth System Model: NZESM.

Part 3

The Ross Sea and Ross Ice Shelf Cloud Study

We conducted as study of cloud over the Ross Sea (RS) and Ross Ice Shelf (RIS) based on 4 years of CloudSat/CALIPSO satellite observations.

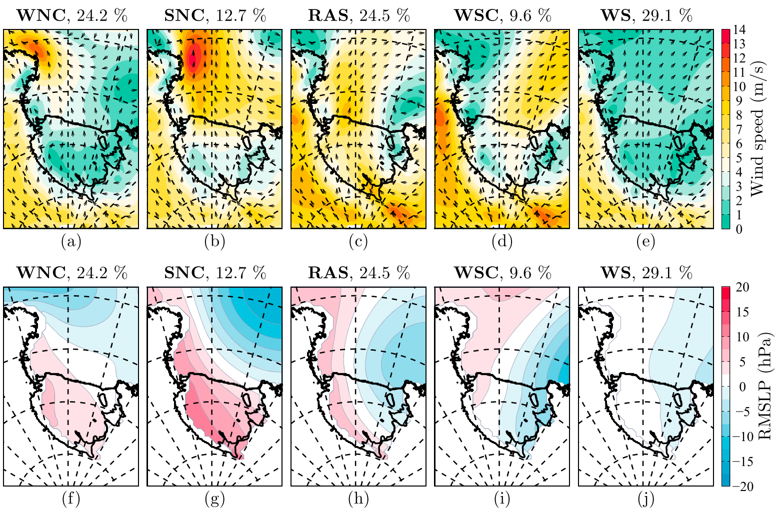


Follow-up on Coggins et al. (2014)[5] who produced synoptic classification for the region. How does cloud vertical distribution, cloud phase and cloud types vary with seasons and regimes over RS and RIS?

Jolly, B., Kuma, P., McDonald, A., and Parsons, S.: **An analysis of the cloud environment over the Ross Sea and Ross Ice Shelf using CloudSat/CALIPSO satellite observations: The importance of synoptic forcing**, Atmos. Chem. Phys. Discuss., in review, 2017.

[5]Coggins, McDonald, Jolly (2014), Synoptic climatology of the Ross Ice Shelf and Ross Sea region of Antarctica: k-means clustering and validation

3.1 Coggins Regimes

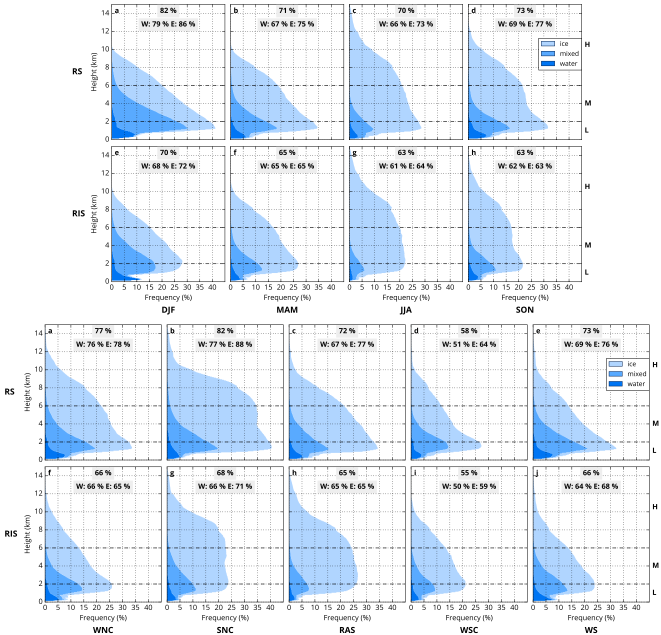


WNC – Weak Northern Cyclonic, **SNC** – Strong Northern Cyclonic, **RAS** – Ross Ice Shelf airstrem, **WSC** – Weak Southern Cyclonic, **WS** – Weak Synoptic

3.2 Key Findings

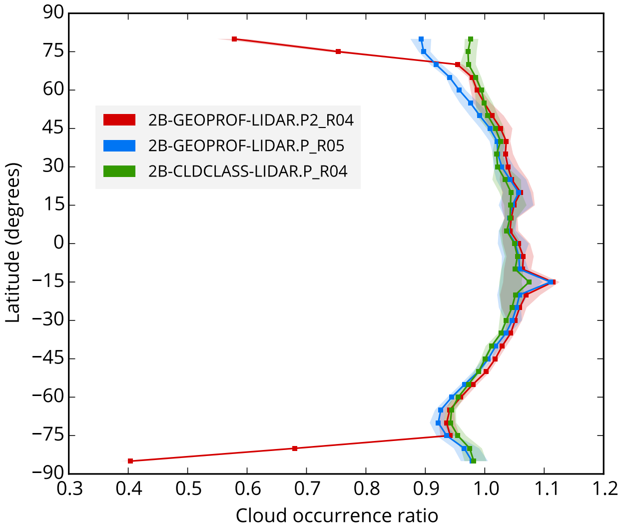
1. Low level cloud (< 3 km) is dominating in both RS and RIS. Mixed-phase cloud is abundant in RS and RIS regions in all seasons. Low level liquid and mixed-phase cloud is associated with weak synoptic conditions, summer and RS, while high-level ice cloud is associated with strong synoptic conditions, winter and RIS.

2. Synoptic regimes are a better predictor for cloud vertical occurrence than seasons.



Cloud vertical occurrence by season (top) and regime (bottom).

3. We compared 3 datasets 2B-GEOPROF-LIDAR.P2_R04, B-GEOPROF-LIDAR.P_R05 and 2B-CLDCLASS-LIDAR.P_R04 and identified a flaw in 2B-GEOPROF-LIDAR.P2_R04, in which cloud occurrence above 8 km AGL is markedly underestimated in polar latitudes, affecting previously published studies.



Part 4

Southern Ocean Datasets

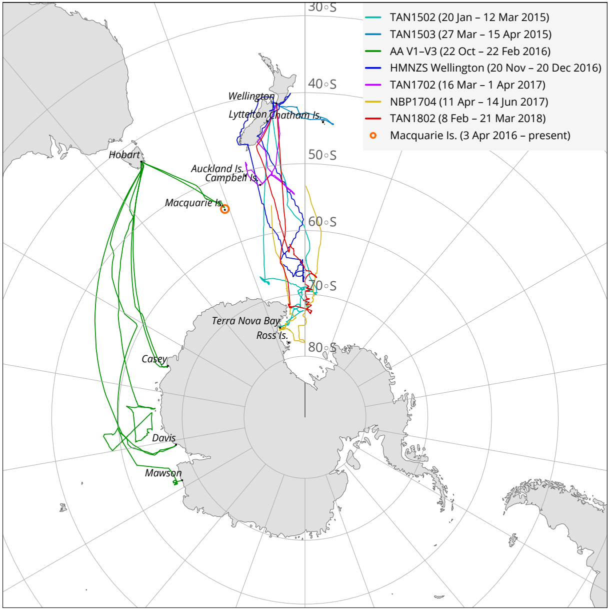
We are building a Southern Ocean dataset of cloud and aerosol observations. This involves processing of old data and collection of new data.

Data available from 6 observational campaigns (2015–2018): 7 Southern Ocean voyages and 1 sub-antarctic station.

Observation types:

- **cloud:** ceilometer, lidar, sky cameras
- **aerosol:** optical particle counters
- **precipitaion:** micro rain radar
- **(thermo)dynamics:** radiosonde, AWS
- **weather:** manned observations

4.1 Observation Campaigns



4 years of data

7 voyages

1 ground-based station

344 days of Antarctic voyage observations

736 days of subantarctic land observations

Voyage data spanning months of October–June

4.2 Instruments

Ceilometer
Lufft CHM15k – 1064-nm near-infrared lidar
Vaisala CL51 – 910-nm near-infrared lidar

Weather radar
Metek MRR-2 – 24-GHz radar

Micro pulse lidar
SigmaSpace MiniMPL – 532-nm visible light polarisation lidar

Sky cameras
5-min time lapse of the sky

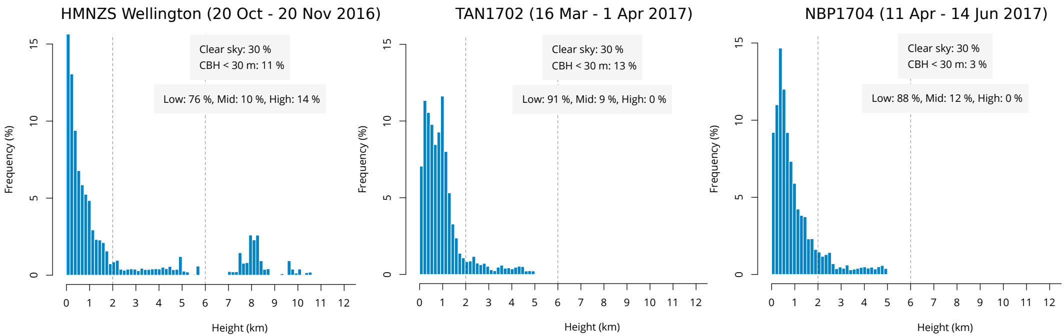
Optical particle counters
Alphasense OPC-N2 – particle counter 0.38–17 µm
(16 bins, PM2.5, PM5, PM10)

Radiosondes
iMet-1 ABx – pressure, temperature, humidity, GPS
(wind speed and direction) up to 20 km

AWS
pressure, temperature, dewpoint temperature, SST,
true wind speed and direction, radiometer

UAV and helikite
radiosonde + optical particle counter up to 200 m

4.3 Cloud Base Height



Cloud base height distribution from 3 Southern Ocean voyages derived from ceilometer measurements.

Cloud observed from the ground is dominated by low level cloud (76–91% of total cloud).

Cloud cover as abundant over the Southern Ocean (70%).

Fog and precipitation is very frequent (3–11%).

4.4 Acknowledgments

The work was funded by the New Zealand Deep South National Science Challenge.

The following people have contributed to formation of the dataset (noninclusive list in alphabetical order):

Adrian McDonald
Graeme Plank
Jamie Halla
Kelly Schick
Peter Guest
Mike Harvey
Sally Garett
Sean Hartery
Simon Alexander
Simon Parsons
R/V Tangaroa crew

Part 5

Lidar

Lidar works by sending pulses of laser EM radiation (usually in the visible or near-infrared range) and measuring backscattered radiation.

Products:

- 2-dimensional attenuated backscatter profile (time $\times$ range)
- cloud base
- cloud layers
- cloud occurrence
- boundary layer height
- cloud types, cloud phase, aerosol layers (if multiple polarisations or wavelengths are available)

Wavelengths:

- 532 nm
- 910 nm

- 1064 nm

5.1 Sources of Noise and Error[6]

Primary:

- Electronic noise
- Photon counting
- Sunlight
- Multiple scattering
- Molecular backscatter

Secondary:

- Inconsistent scaling
- Miscalibration
- Transceiver-receiver overlap

[6] Kotthaus et al. (2016), Recommendations for processing atmospheric attenuated backscatter profiles from Vaisala CL31 ceilometers.

5.2 Lidar Backscatter Processing

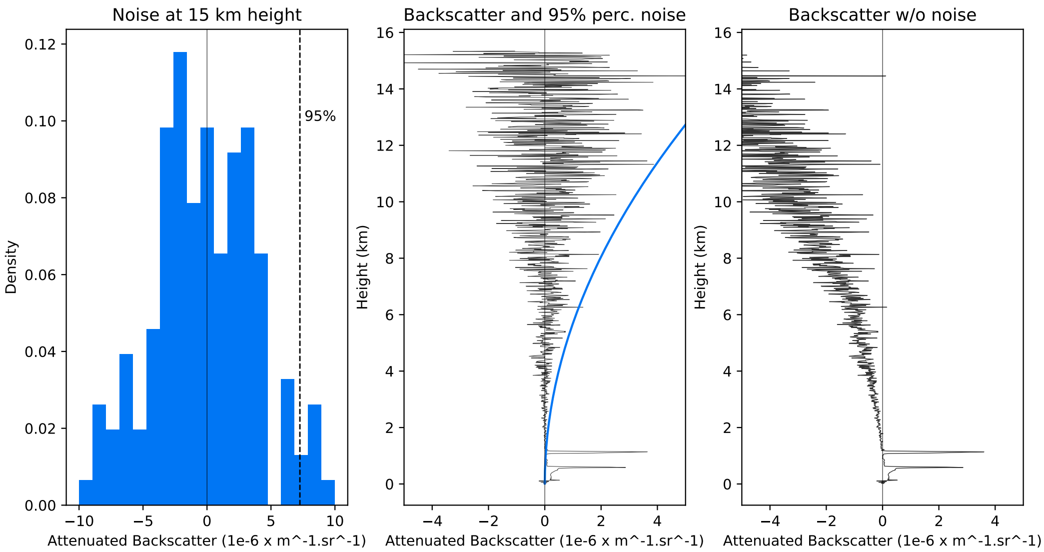
Processing of backscatter measurements involves:

1. Noise removal and averaging
2. Backscatter calibration[7]
3. Cloud base detection
4. Cloud layer detection
5. Cloud phase and type classification
6. Boundary layer height determination
7. Aerosol layer detection
8. Precipitation detection

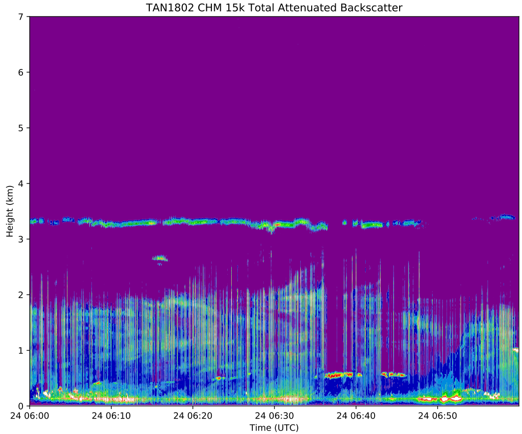
[7] O'Connor et al. (2004), A Technique for Autocalibration of Cloud Lidar.

5.3 Noise Removal

Noise distribution can be determined from the topmost levels (15 km) – unlikely to be affected by cloud or aerosol. Electronic + sunlight noise.



5.4 Effect of Ship Movement



1-h sample of ceilometer total attenuated backscatter from the TAN1802 voyage. 2-s profile averaging has been applied in firmware. Visible is stratus (1–2 km) and stratocumulus cloud (3 km).

Different parts of cloud are scanned depending on ship's pitch and roll.

Pitch and roll data available, but correction is not readily achievable.

Part 6

COSP[8]

CFMIP Observation Simulator Package (COSP) is a suite of simulators which convert model clouds, aerosols, precipitation and thermodynamic fields to virtual satellite and ground-based remote sensing measurements:

- ISCCP, MODIS, MISR, CloudSat, CALIPSO
- ARM ground-based radars[9]

COSP:

- works by solving the radiative transfer equation.
- is Fortran code which can be run online (inside of model) or offline (outside of model).
- contains its own subcolumn cloud generator (SCOPS).
- has been used extensively for climate model validation.
- version 2 was recently released.[10]

[8] Bodas-Salcedo et al. (2011), COSP: Satellite Simulation Software for Model Assessment.
[9] Zhang, Xie, Klein (2018), The ARM Cloud Radar Simulator for Global Climate Models: Bridging Field Data and Climate Models.
[10] Swales et al. (2018), The Cloud Feedback Model Intercomparison Project Observational Simulator Package: Version 2.

6.1 ACTSIM

The spaceborne lidar simulator in COSP is called ACTSIM.[11]

Laser radiation is scattered by cloud droplets, ice crystals, aerosol, precipitation (rain and snow) and air molecules. Fraction of the scattered radiation is backscattered at approx. 180° and measured by the receiver. Laser radiation is attenuated on the way to the target and back.

Received power P_k (relative to transmitted power) from layer k calculated by integrating backscatter attenuated by optical depth τ over the layer:

$$P_k = \int_{z_k}^{z_{k+1}} \beta e^{-2\tau(z_0,z)} dz$$

$$\beta'_k = \frac{P_k}{\Delta z_k} = \frac{\beta_k}{2\tau_k} e^{-2\tau(z_0,z_k)} \left(1 - e^{-2\tau_k}\right)$$

If we know volume absorption coefficient and backscatter coefficient we can calculate attenuated backscatter β'_k observed by a ceilometer.

[11] Chiriaco et al. (2005), The Ability of MM5 to Simulate Ice Clouds: Systematic Comparison between Simulated and Measured Fluxes and Lidar-Radar Profiles at Site Instrumental de Recherche par Teled'etrection Armospherique Atmospheric Observatory.

Surface Lidar Simulator

Surface lidar can be simulated using ACTSIM (previously spaceborne 532 nm only), but modifications needed:

- reversal of layers
- change of wavelength (532 nm →1064 nm & 910 nm)
- running offline on existing NZESM model output

Lidar Ratio

Supporting new wavelength requires new lidar ratio parametrisation.

Lidar ratio is the reciprocal of phase function at 180°:

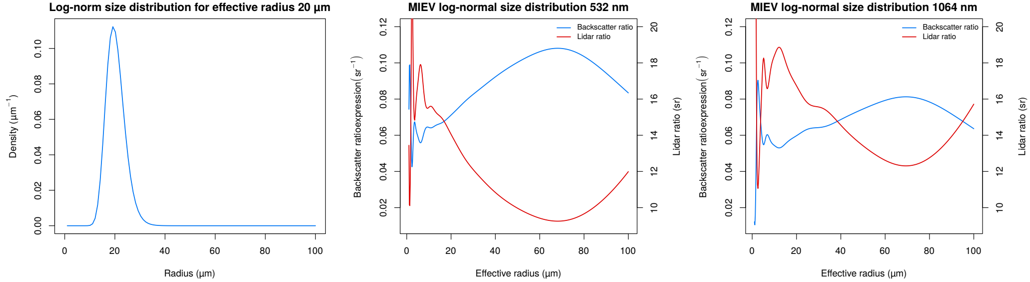
$$p(\pi) = \beta/\alpha$$
$$S = 1/p(\pi)$$

where α is volume absorption coefficient and β is backscatter. Typical value reported in literature S $=$ 18 sr.[12]

[12] O'Connor et al. (2014), Technique for Autocalibration of Cloud Lidar.

New Backscatter Ratio

Backscatter ratio polynomial for 532 nm laser present in ACTSIM but needs to be recalculated for 1064 nm and 910 nm using Mie scattering code. We used MIEV (Wishcombe 1980)[13], MIESPHR (Bohren, Huffman 1983)[14], MieScatter.jl and libradtran codes to calculate new backscatter ratio.



Backscatter ratio and lidar ratio for a 532-nm and 1064-nm lidar and assumed radius distribution for an example effective radius value of 20 μm. The function has been calculated using MIEV Mie scattering code based on log-normal radius size distribution (Chiriaco et al. 2006).[15]

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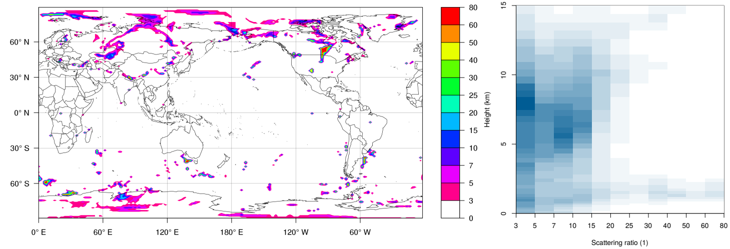
[13] Wishcombe (1980), Improved Mie scattering algorithms.

[14] Bohren, Huffman (1983), Absorption and scattering by a sphere.

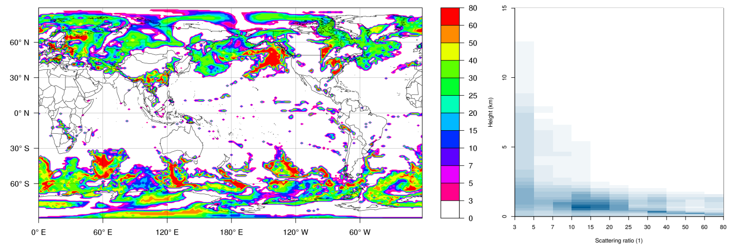
[15] Chiriaco et al. (2006), The Ability of MM5 to Simulate Ice Clouds: Systematic Comparison between Simulated and Measured Fluxes and Lidar-Radar Profiles at the SIRTA Atmospheric Observatory.

6.2 Space vs Ground-based Lidar

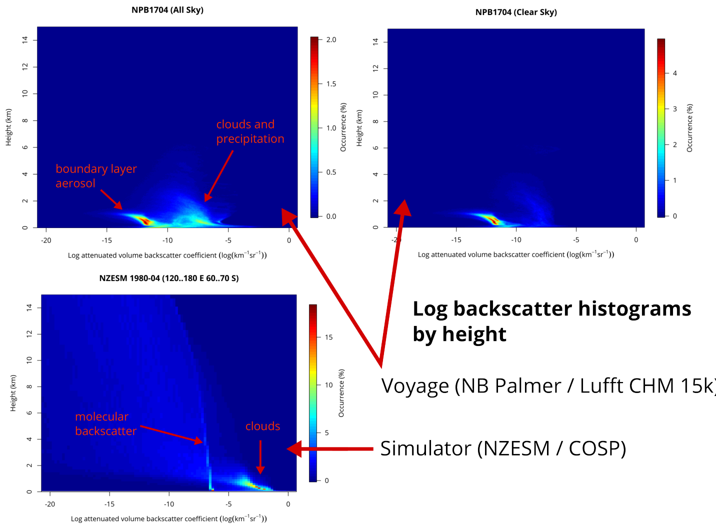
Simulated spaceborne lidar, 532 nm wavelength



Simulated ground-based lidar (ceilometer), 532 nm wavelength



6.3 Direct Comparison



6.4 Inverted Comparison

Instead of comparing modelled and observed backscatter we can estimate cloud liquid content from backscatter by inversion.

Maximum likelihood estimation (MLE) – fast but does not provide uncertainty range

Metropolis algorithm – provides uncertainty range but slow:

$$P(\text{transition}) = max\{1, P(\text{new})/P(\text{old})\}$$

results in unbiased posterior distribution

PyMC3[16]:

1. Suggest cloud liquid content profile
2. Calculate backscatter (ACTSIM)
3. Compare with observed backscatter
4. Repeat until likelihood is maximised

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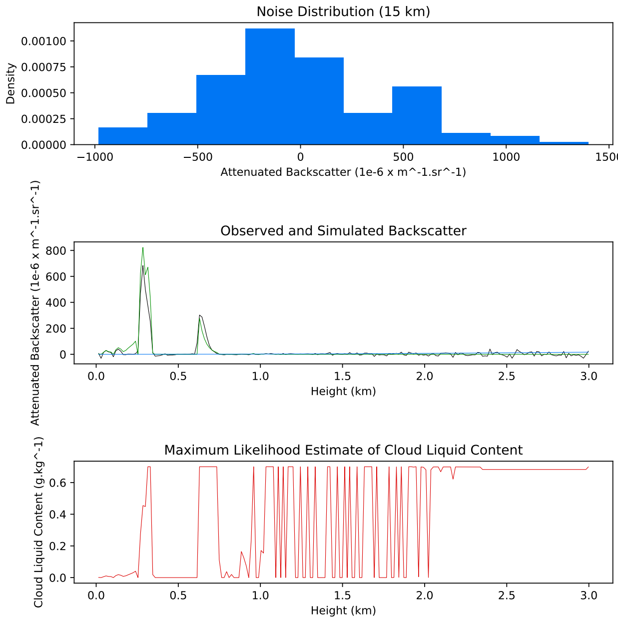
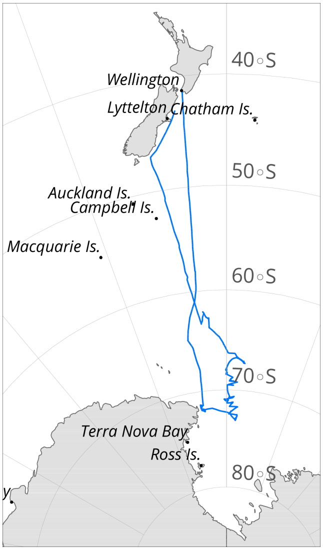
[16] Salvatier, Wiecki, Fonnesbeck (2016), Probabilistic programming in Python using PyMC3.



Maximum likelihood estimation of cloud liquid content from a single ceilometer backscatter profile using PyMC3 and ACTSIM.

Part 7

TAN1802



Ross Sea Environment and Ecosystem Voyage 2018

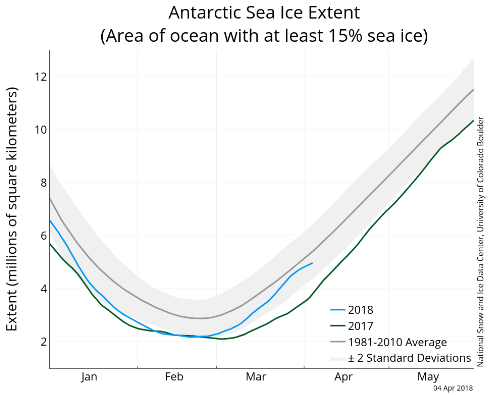
8–21 March 2018, Wellington – Ross Sea – Wellington

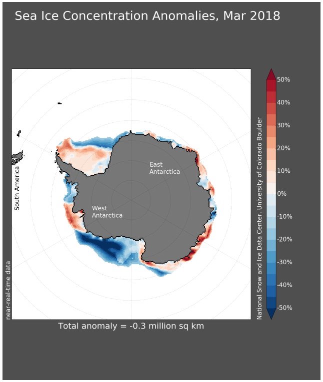
6 weeks in the Southern Ocean, 4 weeks in the Antarctic on R/V Tangaroa

- 3 daily weather balloons (iMet-1 ABx)
- Ceilometer (Lufft CHM 15k), lidar (SigmaSpace MiniMPL), weather radar (Metek MRR-2)
- Optical particle counters (Alphasense OPC-N2), sky cameras
- UAV, Helikite
- AWS, 2–4 daily manned observations


SAFETY FIRST
NIWA

7.1 Sea Ice Extent



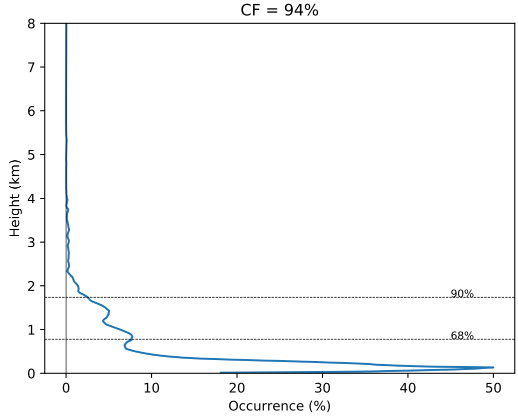


Antarctic sea ice extent in 2017, 2018 and sea ice concentration anomaly in 2018. Source: NSIDC[17].

Antarctic summer sea ice very low in the last 2 summers (minimum below 2σ).
We are in a unique position to describe the effect of the sea ice anomomaly compared to previous years.

[17] https://nsidc.org/data/seaice_index

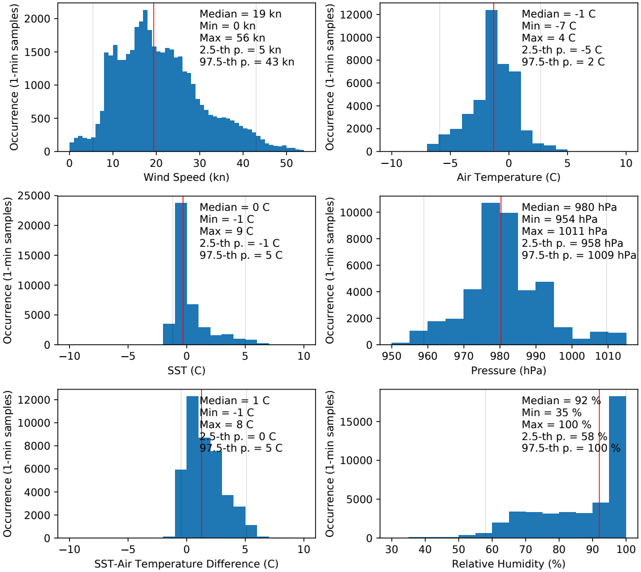
7.2 Cloud Occurrence



Ceilometer vertical cloud occurrence from TAN1802 voyage (60–72° S).

Most cloud located below 2 km (higher cloud may be present but overcast).
Very high total cloud fraction of 94%.

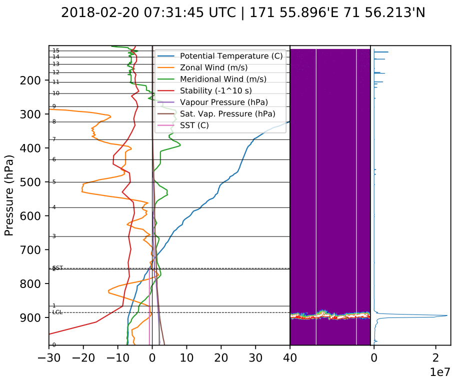
7.3 Synoptic Climatology (AWS)

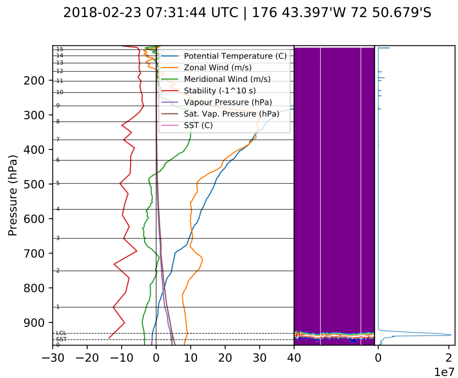


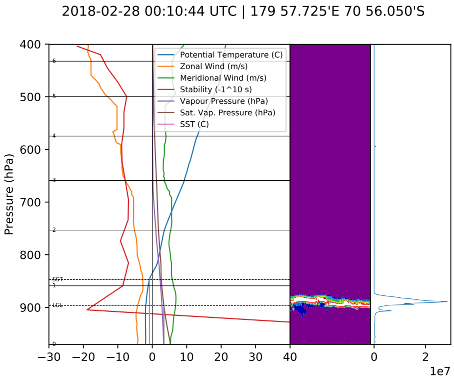
7.4 Thermodynamic Profile and Cloud Base

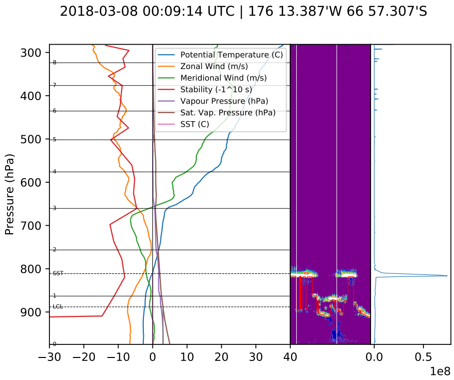
LCL – lifting condensation level defined as level where air parcel lifted from the ground reaches water vapour saturation.

SCL – “SST condensation level”, here defined as level to which air parcel having the same temperature as the sea surface can rise from the water level by buoyancy (i.e. where potential temperature is equal to SST).

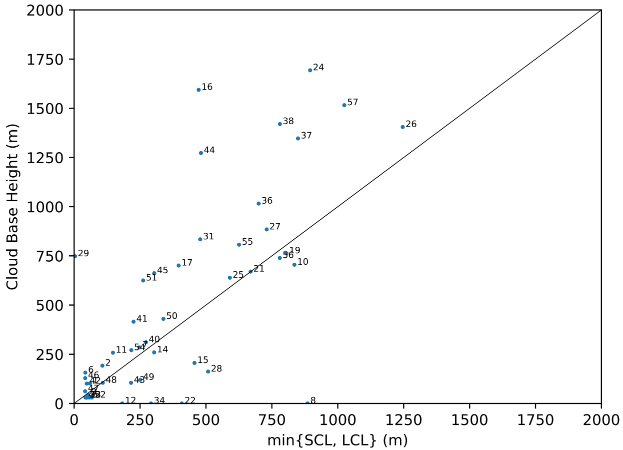





2018-02-28 00:10:44 UTC | 179 57.725'E 70 56.050'S
Pressure (hPa)
Potential Temperature (C)
Zonal Wind (m/s)
Meridional Wind (m/s)
Stability (-1^10 s)
Vapour Pressure (hPa)
Sat. Vap. Pressure (hPa)
SST (C)
SST
LCL
1e7


2018-03-08 00:09:14 UTC | 176 13.387'W 66 57.307'S
Pressure (hPa)
Potential Temperature (C)
Zonal Wind (m/s)
Meridional Wind (m/s)
Stability (-1^10 s)
Vapour Pressure (hPa)
Sat. Vap. Pressure (hPa)
SST (C)
SST
LCL
1e8

SCL/LCL as a Predictor for Cloud Base



SST Condensation Level (SCL)/Lifting Condensation Level (LCL) compared to Cloud Base Height (lidar) for 58 radiosonde launches.

SCL/LCL appears to be a good predictor for cloud base.

7.5 UAV & Helikite

2 experimental UAV flights to sample aerosol – first time on R/V Tangaroa

2 helikite flights

UAV flights very challenging in the environment but not impossible. Better systems and procedures needed.

Part 8

Conclusion

Directions of research

- Southern Ocean dataset
- COSP/ACTSIM direct (backscatter) and inverted (cloud liquid content) comparison
- Identification of deficiencies in cloud parametrisation in NZESM
- Thermodynamic profile as a predictor for cloud base in the Southern Ocean
- Use of spaceborne lidar and radar for Southern Ocean cloud assessment in contrast with ground-based observations
- Effect of 2016–2018 anomalous summer sea ice extent on atmospheric conditions compared to previous years

8.1 Presentations, Papers and Software

Presentations:

- Antarctica New Zealand Conference 2017, Dunedin (*poster*)
- Deep South Challenge Symposium 2017, Wellington (*poster*)
- Met Soc NZ Meeting 2017, Dunedin (*oral presentation*)
- Polar 2018, Davos (*accepted for poster presentation*)
- AMS 15th Conference on Cloud Physics, Vancouver (*abstract submitted*)

Papers:

Jolly, B., Kuma, P., McDonald, A., and Parsons, S.: **An analysis of the cloud environment over the Ross Sea and Ross Ice Shelf using CloudSat/CALIPSO satellite observations: The importance of synoptic forcing**, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-547, in review, 2017.

In review: minor comments from reviewers have been address and we expect that it will be accepted.

Open source software published on GitHub:

- **mrr2c**[18] – Convert Metek MRR-2 micro rain radar data files to HDF
- **cl2nc**[19] – Convert Vaisala CL51 and CL31 ceilometer dat files to NetCDF

Already being used by other researchers (personal correspondence).

[18] https://github.com/peterkuma/mrr2c
[19] https://github.com/peterkuma/cl2nc

8.2 Summary

- Southern Ocean shortwave radiative bias present in multiple climate models including HadGEM/UKESM, and not resolved yet.
- Low cloud dominating in the region, and ground-based observations essential for complementing satellite observations.
- Southern Ocean dataset of cloud and aerosol observations is being collected.
- COSP has been modified to simulate ground-based lidars and run offline on NZESM model output.
- COSP will allow for direct backscatter comparison with observations. Inverted (cloud liquid content) comparison may be possible.
- Fieldwork results suggest thermodynamics is a strong driver of cloud formation in the absence of sea ice.

Thank you

Questions?

ResearchGate: https://www.researchgate.net/profile/Peter_Kuma

GitHub: https://github.com/peterkuma

ORCID: https://orcid.org/0000-0002-0910-8646