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

Corresponding author:
Peter Kuma
pku33@uclive.ac.nz
peterkuma.net/science

Atmospheric Chemistry and Physics Discussion Paper

Peter Kuma[1], Adrian J. McDonald[1], Olaf Morgenstern[2], Simon Parsons[1], Sean Hartery[1], Simon P. Alexander[3], John J. Cassano[4], Jamie Halla[5], Sally Garrett[5], Mike J. Harvey[2], Graeme Plank[1], Jonny Williams[2]

[1]School of Physical and Chemical Sciences, University of Canterbury, Christchurch, [2]NIWA, Wellington, [3]Australian Antarctic Division, Kingston, Australia, [4]Cooperative Institute for Research in Environmental Sciences and Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, CO, USA, [5]Defence Technology Agency, New Zealand Defence Force, Wellington

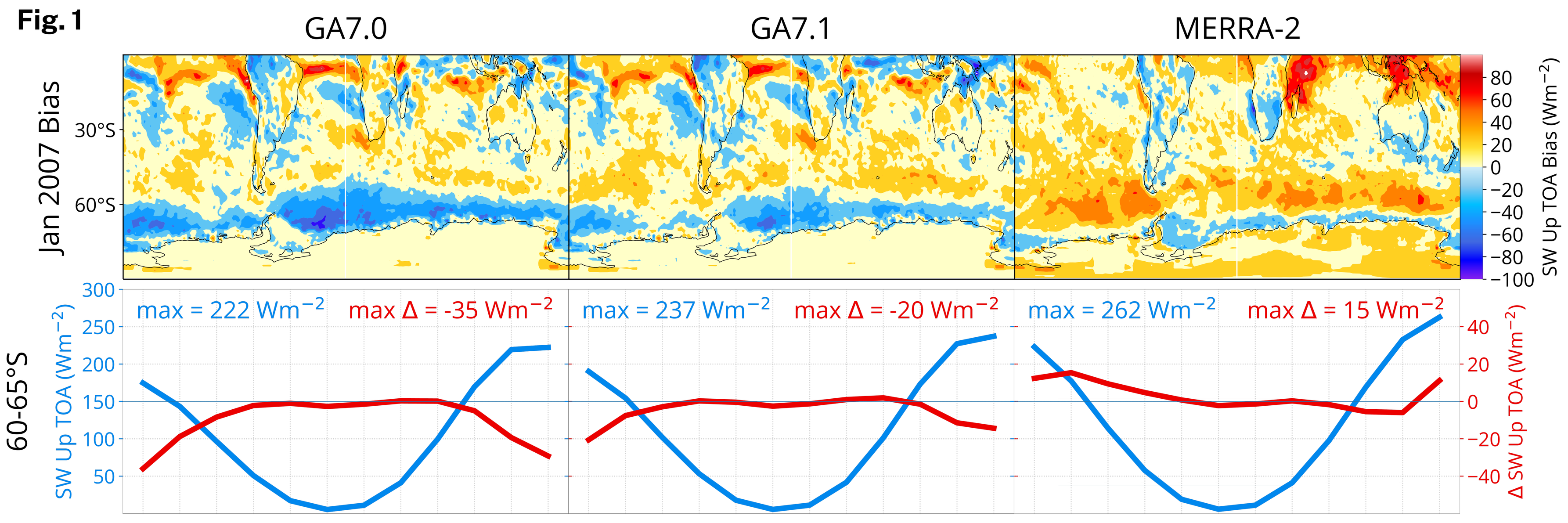
Introduction

We evaluated Southern Ocean clouds in two models, a general circulation model (GCM) HadGEM3/GA7.0 and GA7.1 and a reanalysis MERRA-2, with the aim of identifying the causes of the large shortwave radiation biases present in many contemporary climate models. These biases are considered to be a limiting factor of the accuracy of future climate projections in the Southern Hemisphere.

Models

We used a 10-year free-running and "nudged" global model simulations by the HadGEM3 GCM with GA7.0 and GA7.1 atmospheric components with resolution of about 100×140 km, and the MERRA-2 global reanalysis with resolution of about 50×50 km. We used the COSP lidar simulator to simulate backscatter measurements from the model output. This allowed us to perform a one-to-one comparison between the model and ceilometer cloud observations, which are strongly affected by attenuation in thick clouds.

Fig. 1



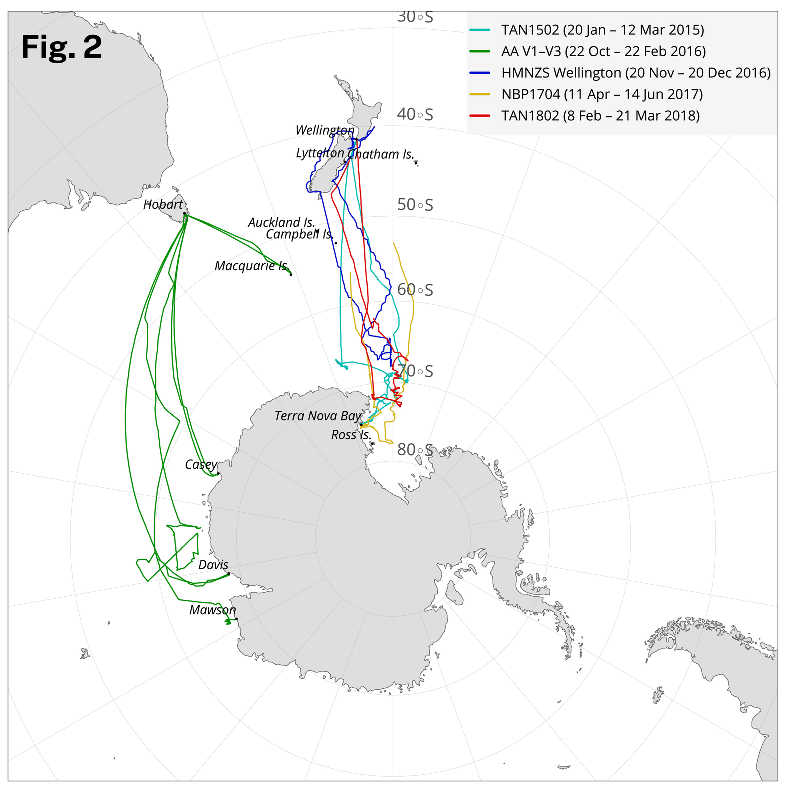
Shortwave radiation

Southern Ocean shortwave radiation bias in HadGEM3 and MERRA-2, compared to satellite measurements by CERES, is the most pronounced in January, at the peak of solar irradiance (Fig. 1). Cloud simulation is thought to be the dominant factor causing the bias. This can be due to misrepresentation of cloud fraction or cloud opacity. In HadGEM3, the bias over the Southern Ocean is negative (too little radiation is reflected back to space), while in MERRA-2 it is positive, but the magnitude and sign is dependent on latitude. The monthly mean bias peaks at -35 Wm^{-2} in GA7.0, -20 Wm^{-2} in GA7.1 and +15 Wm^{-2} in MERRA-2.

Southern Ocean voyages

We have analysed measurements from 5 Southern Ocean voyages on *R/V Tangaroa* (NIWA), *Aurora Australis* (Australian Antarctic Division), *HMNZS Wellington* (Royal New Zealand Navy) and *Nathaniel B. Palmer* (National Science Foundation) between 2015 and 2018 (Fig. 2). The measurements included ceilometers (Vaisala CL51, Lufft CHM 15k), radiosonde profiling of atmospheric temperature, pressure, humidity and wind, and ship automatic weather station data.

Fig. 2



Cloud phase

HadGEM3/GA7.0 generates much less liquid cloud and much more ice cloud than MERRA-2 at 60°S (Fig. 3). Liquid clouds are more reflective than ice clouds, which explains why MERRA-2 shows positive shortwave bias in the Southern Ocean and HadGEM3 shows negative bias, even though they both underestimate the total cloud cover. The difference does not appear to be related to the potential temperature or the relative humidity fields. Differences in the subgrid-scale parametrisation of cloud are likely responsible for this difference.

Fig. 3

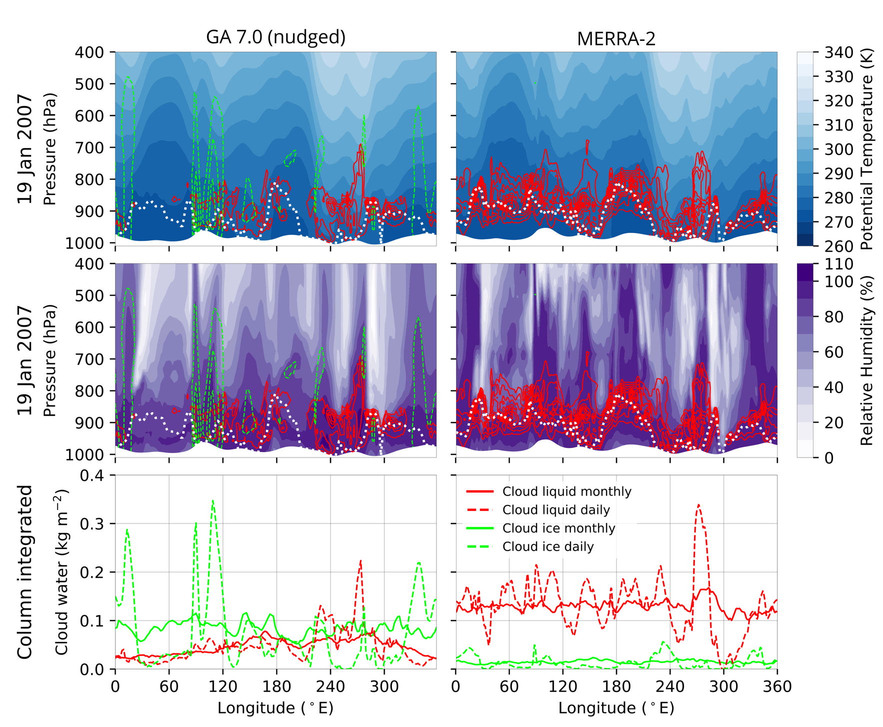
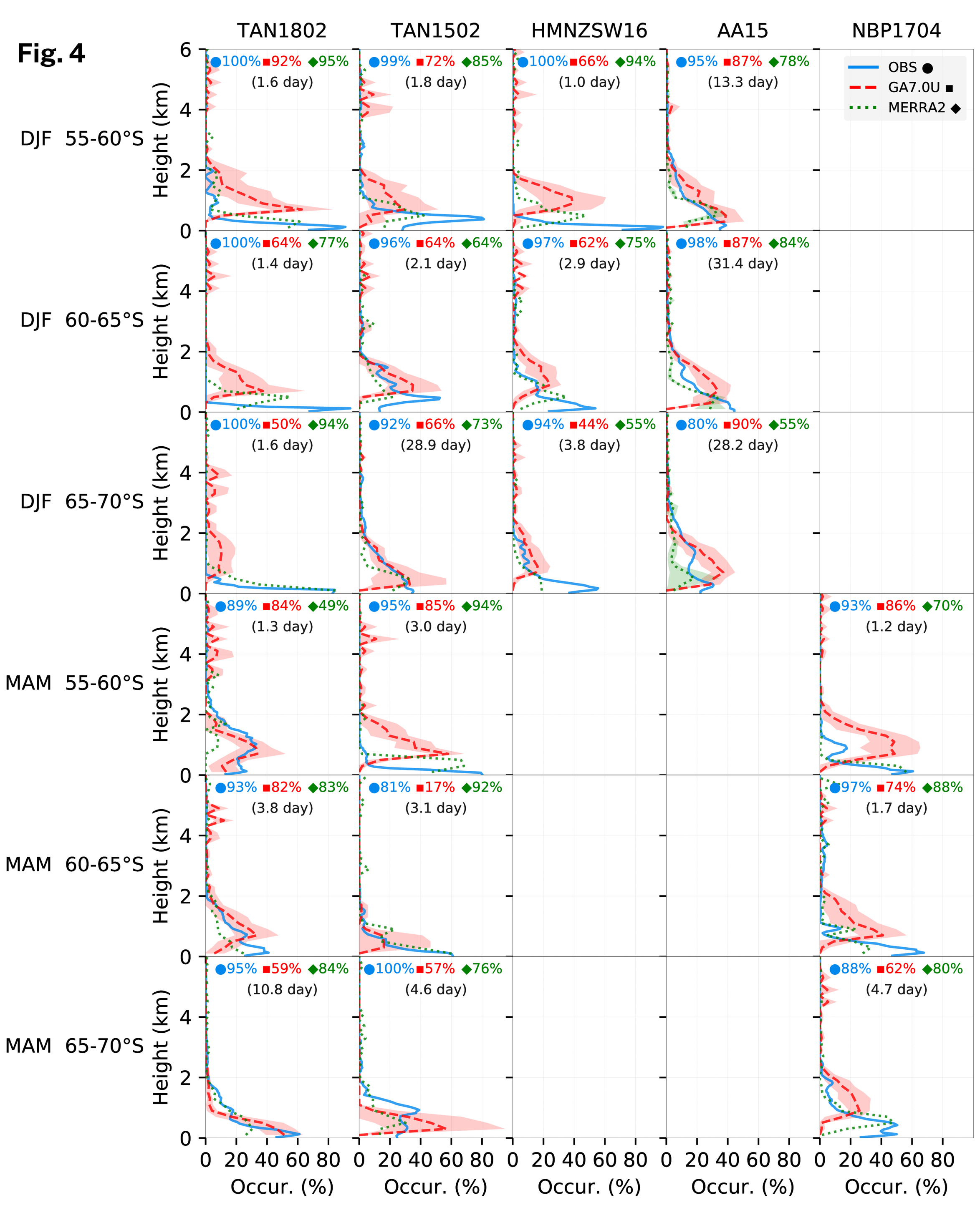


Fig. 4



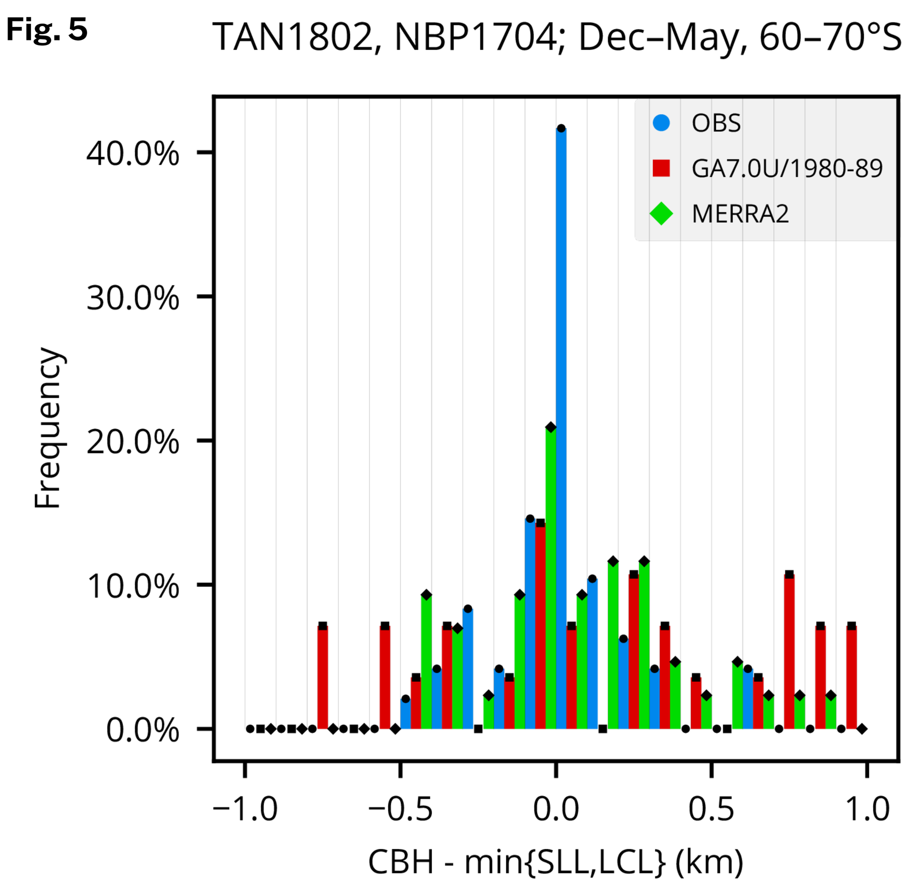
Cloud occurrence

We calculated cloud occurence based on cloud masking of the ceilometer backscatter data and corresponding model simulated backscatter, subsetted by month and latitude band (Fig. 4). In observations the Southern Ocean austral summer cloud fraction commonly peaked at 100%. Models tended to underestimate the cloud fraction by about 20%.

Cloud base height and stability

Cloud base height (CBH) and metrics based on boundary layer stability show strong correspondence in radiosonde/ceilometer observations but not in the models (Fig. 5). Lifting condensation level (LCL) and sea surface temperature (SST) lifting level (SLL), defined as level to which an air parcel at SST would rise by buoyancy, are shown to be a very good predictor for CBH. Misrepresentation of the boundary layer cloud formation process dependent on stability conditions is likely the key contributor to the model cloud fraction bias.

Fig. 5



We found that HadGEM3 and MERRA-2 underestimate austral summer Southern Ocean cloud occurrence by 18–25% compared to ship observations, with predominanly low cloud (< 2 km) present in observations but not in the models. Lack of cloud fraction appears to be the main cause of the shortwave radiation bias, which reaches 20 Wm^{-2} in HadGEM3/GA7.1 and 15 Wm^{-2} in MERRA-2 in January between 60 and 65°S. The models differ substantially in their representation of cloud phase. Boundary layer thermodynamics is highly correlated with cloud base in observations, but not in either of the models, suggesting that subgrid-scale parametrisation in relatively calm conditions rather than large scale dynamics is responsible for the lack of cloud cover in the models. Situations when sea surface temperature is higher than surface air temperature show the greatest bias, which should be the focus of futher studies.

Acknowledgements We would like to thank everyone who participated on obtaining the Southern Ocean voyage observations, especially Kelly Schick and Peter Guest for performing ceilometer and radiosonde measurements on RV Nathaniel B. Palmer; the Royal New Zealand Navy for ceilometer and radar measurements on HMNZS Wellington; Alex Schuddeboom for deployment of instruments on RV Nathaniel B. Palmer, the crew of the TAN1502, Aurora Australis V1–V3 2015/16, HMNZS Wellington, NBP1704 and TAN1802 voyages. Logistical and technical support for the ceilometer observations made aboard Aurora Australis during the summer of 2015/16 were provided as part of the Australian Antarctic Science project 4292. We acknowledge the Met Office for use of the MetUM, and for providing the HadGEM3 model. We acknowledge NASA-GMAO and ECMWF for the MERRA-2 and ERA-Interim reanalyses, respectively. In this analysis we used publicly available satellite datasets provided by NASA and NSIDC. The CERES data were obtained from the NASA Langley Research Center CERES ordering tool (https://ceres.larc.nasa.gov). We wish to acknowledge the contribution of the NeSI high-performance computing facilities to the results of this research. New Zealand's national facilities are provided by the NZ eScience Infrastructure and funded jointly by NeSI's collaborator institutions and through the Ministry of Business, Innovation & Employment's Research Infrastructure programme 5 (https://www.nesi.org.nz). We would like to acknowledge the financial support that made this work possible provided by the Deep South National Science Challenge via the "Clouds and Aerosols" project. We acknowledge the software tools Python, R (R Core Team, 2018), numpy (Oliphant, 2006), scipy (Jones et al., 2001–), matplotlib (Hunter, 2007), Climate Data Operators (CDO) (Schulzweida, 2018) and parallel (Tange et al., 2011), which we used in our data analysis.

UC University of Canterbury — Te Whare Wānanga o Waitaha — Christchurch New Zealand
NIWA Taihoro Nukurangi
National Science Challenges — The Deep South — Te Kōmata o Te Tonga
Australian Government — Department of the Environment and Energy — Australian Antarctic Division
ATOC
dta Defence Technology Agency