THE AMPS WINTER YOPP-SH DATA IMPACT STUDY

Jordan G. Powers[1], Kevin W. Manning[1], and David H. Bromwich[2]

[1]Mesoscale and Microscale Meteorology Laboratory
National Center for Atmospheric Research
Boulder, Colorado, USA

[2]Polar Meteorology Group, Byrd Polar and Climate Research Center
The Ohio State University
Columbus, Ohio, USA

1. INTRODUCTION

Since 2013 the World Meteorological Organization (WMO) has led the Polar Prediction Project (PPP) (www.polarprediction.net) to promote international research toward improved weather prediction services for the polar regions. One focus of the PPP has been the Year of Polar Prediction (YOPP) program, which has both Arctic and Antarctic southern components. The YOPP-Southern Hemisphere (YOPP-SH) effort is focused on the high southern latitudes (Jung et al. 2016), it and has now conducted special observing campaigns with increased atmospheric measurement in both summer and winter over the high southern latitudes. Bromwich et al. (2020) describe the activities of YOPP-SH, and a goal of these campaigns is to generate enhanced observational datasets for use in efforts to improve polar numerical weather prediction (NWP) capabilities.

This paper summarizes a new a study using the Antarctic Mesoscale Prediction System (AMPS) (Powers et al. 2012) to investigate the impact of the recently-gathered YOPP-SH data on forecasts of winter weather over Antarctica. AMPS is a real-time atmospheric modeling capability covering Antarctica and the high southern latitudes. While its primary mission is to provide guidance for the weather forecasters of the U.S. Antarctic Program, it also supports research and field campaigns and assists international program efforts. The current study is a progression of previous research that used AMPS to determine the impact of the YOPP-SH summer dataset on forecasts of summer Antarctic weather (Bromwich et al 2022). The new YOPP-SH winter dataset collected is primarily composed of radiosonde data from a host of participating Antarctic programs and their stations across the high southern latitudes.

The YOPP-SH winter observing effort ran from April–August 2022. In contrast to the YOPP-SH summer campaign of November 1018–February 2019 in which extra observations were made every day, the winter campaign launched extra radiosondes in selected Targeted Observing Periods (TOPs) of approximately 1–2 weeks each. The TOPs were determined based on the predicted occurrence of weather phenomena of interest, such as atmospheric rivers and deep cyclones. Some TOPs called for sonde launches over all of Antarctica ("pan-Antarctic" TOPs), while others involved launches only over selected areas where the target events were expected ("regional" TOPs). Table 1 (at the end of the paper) presents the TOPs.

Approximately 1120 extra sondes were launched over the winter YOPP-SH period. Figure 1 shows the TOP extra radiosonde sites, with the numbers of regular and extra sondes per day indicated next to the site name.

This study is a collaboration between the National Center for Atmospheric Research (NCAR) and The Ohio State University to apply the YOPP-SH TOP data in modeling experiments using the AMPS framework, in line with the goals of the PPP.

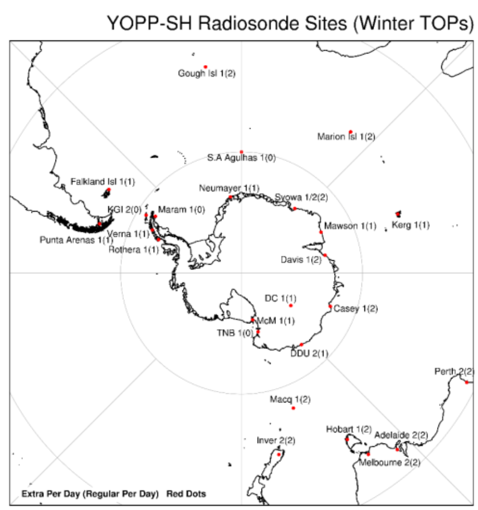


Fig.

Fig. 1: YOPP-SH extra radiosonde sites for winter campaign. Numbers: X(Y): First value is the number of extra sondes/day, while the second is that of the regular sondes/day.

Specifically, the framework is being used in modeling experiments exploring the impact of, and approaches to, assimilating the TOP sounding data. The core experiments consist of simulations that add the enhanced datasets to a base set of the routine meteorological observations. This experimentation has two core aims: (i) to determine the effects of the YOPP-SH TOP sonde data on Antarctic *winter* forecasts and (ii) to examine a new DA approach for AMPS for improved Antarctic prediction. For this study, AMPS's main forecast model, the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008; Powers et al. 2017) with polar physics enhancements (Bromwich et al. 2013) is used.

2. MODEL EXPERIMENTS

a. WRF Setups in AMPS

The grid configuration for the experiments is a modification of the AMPS configuration and applies two of the five regular WRF forecast domains. These are the outer forecast domains of 24-km and 8-km horizontal grid spacing (Fig. 2), with the 8-km nest covering the Antarctic continent. These grids are used for the observation impact and the DA method experiments (described below). The finer WRF grids in AMPS of 2.67 km over the Ross Ice Shelf, 2.76 km over the Antarctic Peninsula, and .89 km over the Ross Island region are not employed.

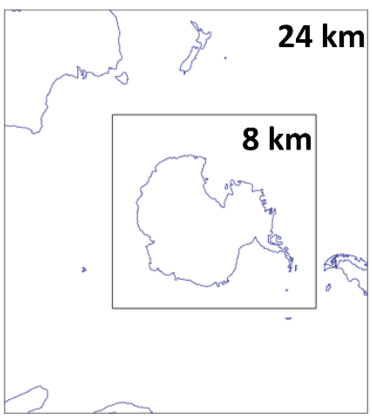


Fig. 2: Experiment WRF forecast grids. Horizontal grid spacings are 24 km and 8 km. Outer domain expanded from original AMPS size to capture sonde sites active in the YOPP-SH TOPs.

b. Experiment Configurations

The primary basic experiment layout consists of parallel WRF simulations applying different observation sets and DA approaches. There are two experiment methodologies. The first is defined by the datasets used in WRF initialization, and the second is defined by the DA procedures employed. Table 1 lists the experiments.

For the first experiment type, one set of runs assimilates in WRF the standard set of observations that is regularly ingested for AMPS forecasts: surface data (e.g., AWS, SYNOP, METAR); upper-air soundings; aircraft observations; ship and buoy observations; geostationary and polar-orbiting satellite AMVs (atmospheric motion vectors); GPS radio occultations; and AMSU (Advanced Microwave Sounding Unit) radiances. While this contains a range of observation types, the sounding data in it is that of the routine radiosondes from sites within the experiment domains during the austral winter. The experiment using these observations is labeled “STD”.

The other set of runs in this experiment pair adds, in the WRF DA step, to the STD array of observations the soundings that were specially launched under YOPP-SH. This experiment is labelled “TOP”. For each setup, five-day WRF forecasts are produced from initialization times of 2100 UTC and 0900 UTC for each day of each TOP, with all of the seven winter TOPs being simulated. The reason for starting at these times is to maximize the use of the observations collected around 0000 and 1200 UTC each day, with the 6-hr 4DVAR assimilation window capturing those primary synoptic times.

The second experiment methodology varies the data assimilation (DA) procedure. The main technique of interest is a relatively new DA option in WRF, and it has not previously been used over Antarctica for AMPS. This is Multi-Resolution Incremental 4DVAR (4-Dimensional Variational) (MRI-4DVAR) (Liu et al. 2020), which has been added as an option in the WRFDA data assimilation system (Barker et al. 2012).

The MRI approach to 4DVAR (Courtier et al. 1994) has two phases in the assimilation process— one in model space for updating the model trajectory and calculating its difference from observations, and one in control-variable space for cost function minimization for the analysis increments determined from the new trajectory. By applying different model grid resolutions in the different phases (Veersé and Thépaut 1998), MRI-4DVAR reduces computational cost compared to traditional 4DVAR.

The second DA approach applied, with forecast sets using both the STD and TOP input data configurations, is 3DEnVar, the hybrid 3-dimensional ensemble/variational approach (Wang et al. 2008) that is used operationally for WRF in AMPS. The hybrid 3DEnVar approach blends static background error (BE) covariances calculated from previous WRF forecasts with flow-dependent covariances derived from a current ensemble of forecasts. Here the ensemble is a 20-member set of produced during each TOP over the domains shown in Fig. 2 and initialized from NCEP's Global Ensemble Forecasting System (GEFS; Zhou et al. 2017). The hybrid system thus incorporates a measure of flow-dependent information into the assimilation process.

In all of the experiments here, the WRF first-guess fields are coming from WRF forecasts, i.e., model cycling is performed. This is to avoid using the GFS analyses for initialization, as these analyses had assimilated the global observations distributed during the TOPs, which included the special YOPP-SH soundings. For the cycling, a new analysis is prepared every 6 h using the previous 6-h WRF forecast as the background. For the experiment sets described above, both MRI-4DVAR and En3DVar are used for data assimilation during the cycling period, and either the STD or TOP observation sets are assimilated. These experiments aim to test how the enhanced soundings and a new DA method may improve AMPS WRF forecasts for winter weather in Antarctica. Verifications of the forecasts from the experiments will be done using ERA5 analyses and observations.

For both types of experiments, the target WRF forecasts to be analyzed are those initialized at 2100 and 0900 UTC for each day of the TOPs. As explained above, these initialization times are done to best configure the 4DVAR assimilation window. The model forecasts go out 120 hours to reveal the SOP data's influences over the usual AMPS forecast period of 5 days. Table 1 shows the experiments and their datasets used.

3. Microphysics Investigations

The examination of high-latitude cloud phase and precipitation, especially in conjunction with atmospheric rivers, was a focus of the YOPP-SH winter campaign. Another facet of this study seeks to exploit that interest to improve the prediction of polar clouds by WRF that to date has been challenging (e.g., Silber et al., 2019; Hines et al., 2019). Sketched here, and led by Ohio State, this work will focus on the warmer cloud conditions typical of atmospheric rivers and warm air advection events occurring in coastal Antarctica during winter.

Relatively warm precipitation events over Antarctica are likely to fall within the temperature range of secondary ice production (SIP) being active in cloud particle processes. That breakup of frozen cloud particles has gained attention in the past decade, and several papers have discussed the importance of SIP within polar cloud microphysics. (e.g., Field et al. 2017; Young et al. 2019, Sotiropoulou et al. 2020, 2021). The best-known mechanism for SIP is the rime-splintering process between -3° and -8°C known as the Hallett–Mossop (H-M) process (Hallett and Mossop, 1974). And, Sotiropoulou et al. (2020, 2021) show that WRF can be updated and adjusted to better simulate SIP processes in the polar regions.

Inadequate cloud and aerosol observations have been a reason why the spatial and temporal variability of cloud-producing aerosols historically has not been addressed in mesoscale cloud modeling (e.g., Wang et al. 2016). Thus, the work here will explore the approach of prognostic aerosol treatments (Xie et al. 2017) to improve the model representation of polar clouds. In this, we will look at the impact of two SIP processes and of storm-related aerosol variability on Antarctic clouds during the TOPs, conducting WRF runs apart from the DA simulations and with a higher-resolution grid configuration.

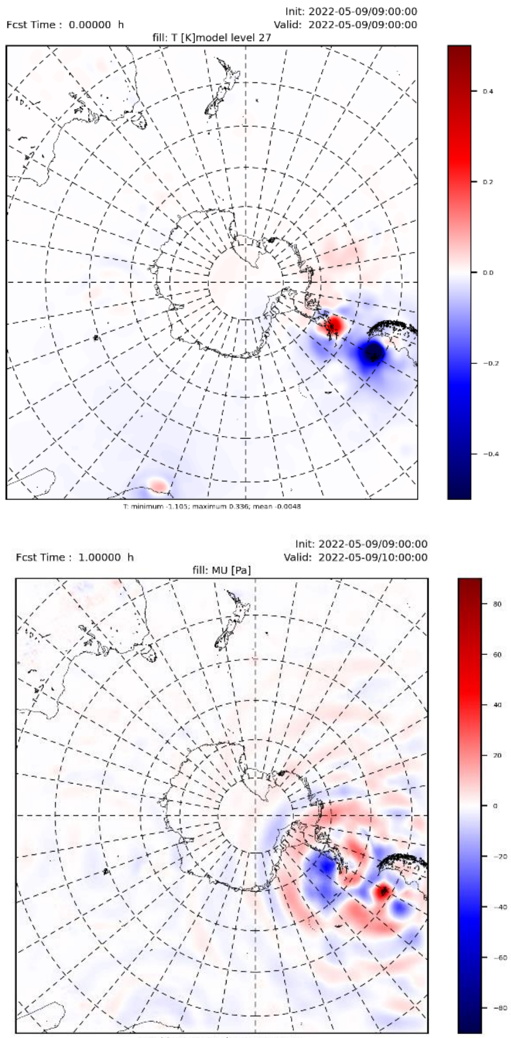
For this investigation WRF will primarily be run with the two-moment Morrison et al. (2005) microphysics scheme, widely used in polar applications. We note, however, that Young et al. (2019) and Sotiropoulou et al. (2020, 2021) found that the representation of the HM scheme could be enhanced in WRF and also that Sotiropoulou et al. (2021) found that including a representation of SIP from breakup from ice particle collisions better simulated ice in mixed-phase clouds over Antarctica. Thus, we will test the modified Morrison microphysics scheme approaches described in Young et al. (2019) and Sotiropoulou et al. (2021). Performing modified code simulations, cloud ice and cloud liquid water forecasts will be assessed with in-situ and remotely-sensed observations of these variables at Davis Station, Vernadsky Station, and possibly others.

To evaluate the local synoptic and mesoscale influence on liquid and ice-forming aerosols (i.e., "water-friendly" and "ice-friendly" aerosols) we will also enlist the Thompson-Eidhammer (2014) aerosol-aware microphysics scheme. This scheme specifies background aerosol levels globally using previous climatological simulations from a global atmospheric chemistry model. We will, however, replace the background ice-friendly aerosol representation with one from the Southern Ocean parameterization of Vignon et al. (2021). The hypothesis to be tested is that more-realistic model treatments of ice multiplication effects and cloud-forming aerosols lead to better forecasts of Antarctic coastal clouds and precipitation.

4. Developments to Date

Here we summarize the data impact component of this study and not the cloud simulation component. Work to date has focused on three areas: (i) data acquisition, (ii) DA system preparation, and (iii) model tuning.

First, Ohio State and NCAR have collected all of the special TOP sounding data. While many stations' observations were available through the GTS, others were obtained from direct contact with the programs. All of the special data, as well as the routine observations, have been acquired. The sounding data have been processed for use in WRFDA, including QC and reformatting, and have been segregated to make their addition into the TOP experiments straightforward.



a)

(b)

Fig. 3: Differences of T and μ (p_$_{surface}$ –p_$_{top}$) fields. Shown are TOP–STD differences (MRI-4DVAR applied) for hours 0 and 1 of simulations initialized 0900 UTC 9 May 2022. (a) T at model level 27 (approx. 500 mb). Difference field (K) shaded, scale to right. (b) μ. Difference field (Pa) shaded, scale to right.

Second, we have implemented MRI-4DVAR for the modified AMPS WRF domain setup. MRI-4DVAR is a complex system with numerous components to configure and check. In this work issues were encountered in computational requirements (e.g., memory and CPU allocations), as MRI-4DVAR is much more computationally demanding and expensive than the 3DVAR-based DA used in real-time in AMPS. Second, the ingest of radiance observations required troubleshooting. Due to their density, the radiance observations need to be thinned, but this must be done consistently within the MRI-4DVAR iterations. Initial failures in the running of 4DVAR with radiance data were encountered, but restricting observation thinning to the initial 4DVAR minimization pass has resolved this.

Third, we have done a bit of WRF tuning. In initial review, one discovery was that use of WRF's adaptive timestep option was leading to some noise in forecast fields. In switching to a fixed timestep for the runs, this issue has been has eliminated. More notably, after suspicious forecast errors were seen in test runs (e.g., substantial cold biases at model upper levels), it was decided to apply spectral nudging in the WRF preparation. Thus, using UFS analyses, limited nudging is performed for model vertical levels 51 and above (with the model top at level 61) to the fields of *u*, *v*, *T*, and geopotential height. We do this in the WRF 6-hr cycling periods that are involved in preparing new forecast analyses. Nudging is applied up to wave number 8 in the coarse domain and wave number 4 in the fine domain.

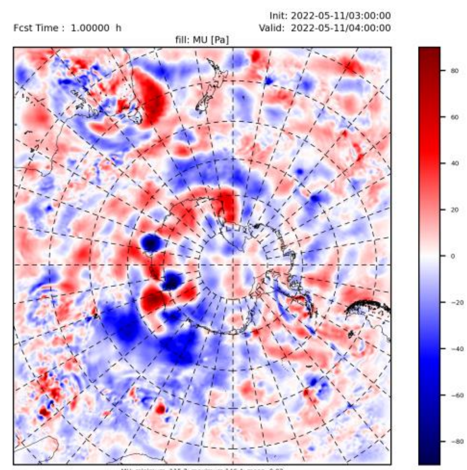


Fig. 4: Differences of μ (p_$_{surface}$–p_$_{top}$) field. Shown is TOP–STD difference (MRI-4DVAR applied) for hour 1 of simulations initialized 0300 UTC 11 May 2022. Difference field (Pa) shaded, scale to right.

Preliminary results of forecasts with and without the TOP soundings in MRI-4DVAR runs are shown in Figs. 3 and 4. Fig. 3(a) shows the difference in mid-tropospheric (approx. 500 mb) temperatures in the two analyses (TOP and STD) at 0900 UTC 9 May 2022. The temperature difference scale (K, shaded) is shown to the right, and the field is the TOP-STD T difference. It is obvious that differences occur where the extra soundings were for this 4DVAR assimilation (temporal) window: Mt. Pleasant (Falkland Islands) and over the Antarctic Peninsula (Vernadsky, Marambio, and Rothera). Figure 3(b) shows the differences in the WRF μ (mu) field at one hour into this forecast. μ represents the model top pressure minus the model surface pressure, and the pressure difference scale (Pa, shaded) is shown to the right.

We find areas of μ difference that radiate from the initial areas of difference in the two models, originating at the sounding locations. Furthermore, the zones of difference take on an arc shape and propagate from the source points (see., e.g., arc of red shading over the Ronne Ice Shelf).

Figure 4 shows another μ difference field at one hour into a forecast initialized at 0300 UTC on 11 May 2022. This shows prominent differences that have emanated from a number of sites across East Antarctic that launched TOP soundings in the 4DVAR assimilation window for this day: Syowa, Mawson, Davis, Zhongshan, Casey and Dumont d'Urville. This behavior is currently being analyzed.

SUMMARY

To address the aims of the Polar Prediction Project and the YOPP, the AMPS framework is being used to examine the value to Antarctic forecasting of (i) enhanced Southern Hemisphere radiosonde observations and (ii) new data assimilation (DA) techniques. The bulk of this study focuses on data impact experiments in which the extra soundings launched for the Winter 2022 YOPP-SH observation campaign are assimilated in WRF forecasts, with the targets being the seven Targeted Observing Periods TOPs. This study is also comparing the current 3DVAR-based AMPS DA approach with a newer 4DVAR-based approach for possible future implementation. A second area of investigation is WRF's simulation of polar clouds and microphysical scheme developments to improve it. This component of the project is exploiting other special data from Antarctic sites collected during the YOPP-SH winter period, but no results are reported here.

The forecast experiment effort to date has acquired and prepared the special sounding data from the YOPP-SH participants. The MRI-4DVAR system has been built and tested for the AMPS WRF domain configuration and cycling strategy. Numerous issues were uncovered and resolved with this first-ever application of 4DVAR for WRF in AMPS. Similarly, WRF itself has been tuned for these forecasts. In particular, we have applied spectral nudging via UFS analyses in the 6-hourly pre-forecast cycling periods used in preparation of the WRF analyses. This is done to reduce errors in various fields (e.g., temperature) seen in initial testing.

The simulations for the first TOP (9–16 May 2022) are in progress. Results to date reveal prominent local impacts of the extra sonde data. They also show that differences in state variables propagate from the initial regions of data additions. Detailed verifications will be done next. Results will be presented at future workshops, but the community is welcome to contact the authors for updates.

ACKNOWLEDGMENTS

The authors thank the NSF Division of Polar Programs for its support of AMPS. This YOPP-SH project is supported by NSF Award 2205398 to The Ohio State University.

REFERENCES

Barker, D.M., and Co-Authors, 2012: The Weather Research and Forecasting Model's community variational/ensemble data assimilation system: WRFDA. *Bull Amer. Meteor. Soc.*, **93**, 831–843.

Bromwich, D.H., and Co-Authors, 2020: The Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bull. Amer. Meteor. Soc.*, **101**, 1653-1676, https://doi.org/10.1175/BAMS-D-19-0255.1

Bromwich, D. H., J. G. Powers, K. W. Manning, and X. Zou, 2022: Antarctic data impact experiments with polar WRF during the YOPP-SH summer Special Observing Period. *Quart. J. Roy. Meteor. Soc.*, **148 (176)**, 2194–2218, http://doi.org/10.1002/qj.4298.

Bromwich, D. H., F. O. Otieno, K. M. Hines, K. W. Manning, and E. Shilo, 2013: Comprehensive evaluation of polar weather research and forecasting performance in the Antarctic. *J. Geophys. Res.*, **118**, 274-292, doi: 10.1029/2012JD018139.

Courtier, P., J.-N. Thépaut, and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var using an incremental approach. *Quart. J. Roy. Meteor. Soc.*, **120**, 1329–1347.

Field, P., and coauthors, 2017: Chapter 7: Secondary ice production – current state of the science and recommendations for the future. Meteor. Monogr., **58**, 7.1–7.20, doi:10.1175/AMSMONOGRAPHS-D16-0014.1.

Hallett, J., and S. C. Mossop, 1974: Production of secondary ice particles during the riming process. *Nature*, **249**, 26–28, doi:10.1038/249026a0.

Liu, Z., J. Ban J, J.-S. Hong, and Y.-H. Kuo, 2020: Multi-resolution incremental 4D-Var for WRF: Implementation and application at convective scale. *Quart. J. Roy. Meteor. Soc.*, **146**, 3661–3674, https://doi.org/10.1002/qj.3865.

Hines, K.M., D.H. Bromwich, S.-H. Wang, I. Silber, J. Verlinde, and D. Lubin, 2019: Microphysics of summer clouds in central West Antarctica simulated by Polar Weather Research and Forecasting Model (WRF) and the Antarctic Mesoscale Prediction System (AMPS). *Atmos. Chem. Phys.*, **19**, 12,431-12,452, doi:10.5194/acp-19-124310-2019.

Houtekamer, P. L., and F. Zhang, 2016: Review of the ensemble Kalman filter for atmospheric data assimilation. *Mon. Wea. Rev.*, **144**, 4489–4532.

Jung, T., and Coauthors, 2016: Advancing polar prediction capabilities on daily to seasonal time scales. *Bull. Amer. Meteor. Soc.*, **97**, 1631–1647. doi:10.1175/BAMS-D-14-00246.1.

Morrison, H., J.A. Curry, and V.I. Khvorostyanov, 2005: A new double-moment microphysics parameterization for applications in clouds and climate models. Part I: Description. *J. Atmos. Sci.*, **16**, 1665-1677.

NOAA Environmental Modeling Center, 2003: The GFS Atmospheric Model. NCEP Office Note 442. 14 pp. [Available from U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction, 4700 Silver Hill Rd., Mail Stop 9910, Washington, DC, 20233.]

Powers, J.G., K.W. Manning, D.H. Bromwich, J.J. Cassano, and A.M. Cayette, 2012: A decade of Antarctic science support through AMPS. *Bull. Amer. Meteor. Soc.*, **93**, 1699–1712. (PR-AMPS)

Powers, J. G., and Coauthors, 2017: The Weather Research and Forecasting Model: Overview, system efforts, and future directions. *Bull. Amer. Meteor. Soc.*, **98**, 1717–1737. doi:10.1175/BAMS–D–15–00308.1.

Silber, I., J. Verlinde, S.-H. Wang, D. H. Bromwich, A. M. Fridlind, M. Cadeddu, E. W. Eloranta, and C. J. Flynn, 2019: Cloud influence on ERA5 and AMPS surface downwelling longwave radiation biases in West Antarctica. J. Climate, 32, 7935-7949, doi: 10.1175/JCLI-D-19-0149.1.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, and J. G. Powers, 2008: A description of the Advanced Research WRF Version 3. NCAR Tech. Note, NCAR/TN-475+STR, 113 pp.

Sotiropoulou, G., S. Sullivan, J. Savre, G. Lloyd, T. Lachlan-Cope, A.M.L. Ekman, and A. Nenes, 2020: The impact of secondary ice production on Arctic stratocumulus. *Atmos. Chem. Phys.*, **20**, 1301–1316, doi:10.5194/acp-20-1301-2020.

Sotiropoulou, G., É. Vignon, G. Young, H. Morrison, S. O'Shea, T. Lachlan-Cope, A. Berne, and A. Nenes, 2021: Secondary ice production in summer clouds over the Antarctic coast: An underappreciated process in atmospheric models. *Atmos. Chem. Phys.*, **21**, 755–771, doi:10.5194/acp-21-755-2021.

Thompson, G. and T. Eidhammer, 2014: A study of aerosol impacts on clouds and precipitation development in a large winter cyclone. *J. Atmos. Sci.*, **71**, 3636–3658, doi:10.1175/JAS-D-13-0305.1.

Veersé, F. and J.-N. Thépaut, 1998: Multi-truncation incremental approach for four-dimensional variational data assimilation. *Quart. J. Roy. Meteor. Soc.*, **124**, 1889–1908.

Vignon, E., and coauthors, 2021: Measured ice nucleating particle concentrations improve the simulation of mid-level mixed-phase clouds over the high-latitude Southern Ocean. *J. Geophys. Res.*, **126**, doi:10.1029/2020jd033490.

Wang, J., X. Dong, and R. Wood, 2016: Aerosol and Cloud Experiments in Eastern North Atlantic (ACE-ENA) Science Plan. U.S. Department of Energy, DOE/SC-ARM-16-006, 38 pp.

Wang, X., D. M. Barker, C. Snyder, and T. M. Hamill, 2008: A hybrid ETKF–3DVAR data assimilation scheme for the WRF model. Part I: Observing system simulation experiment. *Mon. Wea. Rev.*, **136**, 5116–5131.

Xie, X., H. Zhang, X. Liu, Y. Peng, and Y. Liu, 2017: Sensitivity study of cloud parameterizations with relative dispersion in CAM5.1: Impacts on aerosol indirect effects. Atmos. Chem. Phys., 17, 5877–5892, doi:10.5194/acp-17-5877-2017.

Young, G., T. Lachlan-Cope, S.J. O'Shea, C. Dearden, C. Listowski, K.N. Bower, T.W. Choularton, and M.W. Gallagher, 2019: Radiative effects of secondary ice enhancement in coastal Antarctic clouds. *Geophys. Res. Lett.*, **46**, 23122321, doi:10.1029/2018GL080551.

Zhou, X., Y. Zhu, D. Hou, Y. Luo, J. Peng, and R. Wobus, 2017: Performance of the new NCEP Global Ensemble Forecast System in a parallel experiment. *Wea. Forecasting*, **32**, 1989–2004.

Table 1: YOPP-SH Targeted Observing Periods

Period	Region of Extra Sondes
9–16 May	pan-Antarctic
2–8 June	pan-Antarctic
1–9 July	East Antarctica–Ross Sea
14–19 July	pan-Antarctic
23–29 July	Antarctic Peninsula
29 July–3 August	East Antarctica
20–30 August	pan-Antarctic

Table 2: YOPP-SH SOP Data Assimilation Experiments

STD= Current operational standard observations
TOP= YOPP-SH Targeted Observing Period extra soundings

Experiment	Obs Assimilated	DA Procedure
STD	STD	MRI-4DVAR
TOP	STD + TOP	MRI-4DVAR
STD3DV	STD	3DEnVar
TOP3DV	STD + TOP	3DEnVar