An evaluation of surface climatology in state-of-the-art reanalyses over the Antarctic Ice Sheet

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ABSTRACT

18 In this study, we evaluate output of near-surface atmospheric variables
19 over the Antarctic Ice Sheet from four reanalyses: European Centre for
20 Medium-Range Weather Forecasts's new ERA-5 and its predecessor ERA-
21 Interim, the Climate Forecast System Reanalysis (CFSR), and the Modern
22 ERA Retrospective-Analysis for Research and Applications 2 (MERRA-2).
23 The near-surface temperature, wind speed and relative humidity are compared
24 against datasets of in-situ observations. The reanalysis performance of simu-
25 lated surface mass balance (approximated by precipitation minus evaporation)
26 is also assessed. While no reanalysis clearly stands out as the best performing
27 for all areas, seasons and variables, each of the reanalyses display different
28 biases. CFSR agrees best with relative humidity observations, both regard-
29 ing the mean values and the seasonal cycle, whereas all other reanalyses are
30 unable to simulate adequate relative humidity at low temperatures, and in the
31 interior of the ice sheet. ERA-5 captures the seasonal cycle of near-surface
32 temperature best, and shows the smallest bias compared to the observations.
33 The other reanalyses show a general temperature underestimation during the
34 winter months in the Antarctic interior, and overestimation in the coastal ar-
35 eas. All reanalyses overestimate the mean near-surface winds in the interior
36 and underestimate winds along the coast during the entire year, except for
37 MERRA-2 during the Antarctic summer. Finally, all models are able to cap-
38 ture snowfall patterns related to atmospheric rivers, with varying accuracy.
39 Accumulation is best represented by ERA-5, although it underestimates ob-
40 served SMB, while all other reanalyses overestimate this parameter except
41 over coastal areas and in the interior.

42 1. Introduction

43 The Antarctic continent, which is almost fully covered by snow and ice, is not only the largest,
44 coldest, windiest, highest, and driest, but also the most remote land mass on Earth, entirely sur-
45 rounded by the Southern Ocean. Owing to the remote location and harsh climate conditions,
46 especially outside austral summer, we know relatively little about the Antarctic surface climate.

47 Currently, only about 100 Automatic Weather Stations (AWS) are installed on the Antarctic Ice
48 Sheet (AIS), the majority of which ($\approx 90\%$) on East Antarctica (Lazzara et al. 2012). Those AWSs
49 are unmanned and most of them irregularly serviced, which increases the likelihood of data loss
50 through instrument failure and/or power shortage.

51 There are around 100 manned stations, but less than half provide year-round observations, and
52 most are situated along the Antarctic coast. The lack of observations complicates the detection
53 of climate variability and change on Antarctica. In addition, near-surface climate affects surface
54 mass balance (SMB) processes (and vice-versa), such as precipitation, surface melt, and snow
55 redistribution. The scarcity of in-situ observations currently prevents us from accurately estimating
56 the Antarctic ice sheet (AIS) SMB, its spatial and temporal variability, and its impact on AIS
57 mass balance and consequent contribution to sea level rise, from observations alone. In recent
58 years, satellite remote sensing datasets are emerging, but the polar night or limitation to clear sky
59 conditions impede measurements, large uncertainties limit the retrieval algorithms, and while they
60 provide multi-year datasets, time series are still limited for long-term climate research.

61 Alternatively, we can use atmospheric reanalysis products, which now give us four decades
62 of continuous, gridded atmospheric data at high temporal resolution. Reanalyses are essentially
63 global climate models that are assimilated with atmospheric observations to obtain a reanalysis of
64 the global atmosphere, including that at the high latitudes.

65 Due to the scarcity of observational data over Antarctica, little atmospheric information is assim-
66 ilated in the global climate model that underlies the reanalysis. This leads to a stronger sensitivity
67 of the simulation to the actual global model physics, and biases therein. Global climate models are
68 optimized for mid-latitude atmospheric conditions, which enhances model biases in high-latitude
69 regions, including Antarctica. Recent studies have highlighted deficient performance of atmo-
70 spheric reanalyses in clouds and radiation (Lenaerts et al. 2017; Miller et al. 2018), precipitation
71 (Bromwich 2010; Bromwich et al. 2012; Chen et al. 2011; Medley et al. 2013, 2014; Nicolas and
72 Bromwich 2011), (near-) surface temperature (Fréville et al. 2014; Jones and Lister 2015; Nico-
73 las and Bromwich 2014; Bracegirdle and Marshall 2012), and turbulent heat exchange (Miller
74 et al. 2018) over ice sheets. Newly emerging reanalysis products will likely improve on many of
75 these issues. In particular, the European Centre for Medium-Range Weather Forecasts (ECMWF)
76 new reanalysis product ERA-5 combines unparalleled horizontal resolution (0.25°) with refined
77 atmospheric physics and a revised snow scheme (Dutra et al. 2010).

78 Existing studies comparing reanalysis products over Antarctica, have generally concluded that
79 ERA-Interim shows the smallest biases (Bracegirdle and Marshall 2012). However, these com-
80 parisons are mostly focused on one atmospheric parameter, such as surface mass balance or tem-
81 perature (Bromwich et al. 2011; Wang et al. 2016). Here, we present a comprehensive assessment
82 of the capacity of several reanalysis products, including the new ERA-5, to reproduce the (near-
83) surface climate conditions over the Antarctic Ice Sheet. To do so, we analyze several surface
84 atmosphere parameters, and compare several reanalysis products with available in-situ data from
85 weather stations.

86 Section 2 presents the dataset compiled to evaluate the reanalyses, and the comparison method.
87 Results are presented in Section 3, and finally, Section 4 concludes on the strengths and weak-
88 nesses of each of the reanalyses.

89 2. Material and methods

90 *a. Reanalyses overview*

91 In an atmospheric reanalysis, observations of the Earth's atmosphere, land and ocean surface are
92 assimilated in global climate model simulations in order to produce a spatially complete, multi-
93 variate, 3-dimensional dataset of the Earth's atmosphere that is as close to reality as possible. To
94 minimize the bias of the modeled atmosphere compared to observations, a wide variety of ob-
95 servational products is used, including satellite data, ground stations, sea buoys, radiosondes and
96 airplane observations. Reanalysis products have been developed and improved since the start of
97 the satellite era, circa 1979, and have proven invaluable tools for understanding our climate system.
98 In this paper, we evaluate four reanalysis products: European Center for Medium-Range Weather
99 Forecasts's (ECMWF) ERA-5 and ERA-Interim, National Centers for Environmental Prediction
100 (NCEP) Climate Forecast System Reanalysis (CFSR) and National Aeronautics and Space Ad-
101 ministration (NASA) Modern-Era Retrospective analysis for Research and Applications, Version
102 2 (MERRA-2). Since ERA-5 is only available for 2000 to 2017 up to now, we limit our analysis
103 to this time period. We investigate the near-surface temperature, wind speed, and relative humid-
104 ity for the four reanalyses. We use the reanalysis output at timesteps 0 and 12 UTC. For SMB
105 evaluation, 6-hourly precipitation and evaporation output is used.

106 ERA-5

107 ERA-5 is the most recent reanalysis product produced at ECMWF. In the near future, it will
108 fully replace its predecessor ERA-Interim as ECMWF's most state-of-the-art reanalysis product,
109 covering the time period of 1979 up to the present day. Currently, production is still incomplete,
110 and model output is available only for the time period 2000-2017. One of the main improvements

over ERA-Interim is a higher horizontal and vertical resolution, as ERA-5 uses a horizontal resolution of 31 km (0.28 degrees) and 139 vertical levels, covering the atmosphere from the surface up to 0.01 hPa (≈ 80 km). In addition, ERA-5 uses a more recent and improved version of the Integrated Forecast System (IFS) Earth System Model and associated observational assimilation system (Cycle 41r2, Hersbach and Dick (2016)). Improvements have been made not only to the assimilation of satellite observations, but also to the assimilation of ozone, and aircraft and surface pressure data (Albergel et al. 2018). Compared to ERA-Interim, additional observational products are assimilated, that were not available before (Hersbach and Dick 2016). Moreover, the updated snow scheme enables a reduction of the snow albedo bias and an improved hydrological cycle (Dutra et al. 2010). Finally, model forcings were also improved, and now include CMIP5 greenhouse gases, volcanic eruptions as well as improved sea-surface temperature and sea-ice cover. ERA-5 data products are available on an hourly timescale, compared to 6-hourly for ERA-Interim. In addition, uncertainty estimates are available, calculated by means of a 10-member ensemble at reduced resolution (horizontal resolution of 62km, 0.5625 degrees).

ERA-Interim

ERA-Interim is the predecessor of ERA-5. This reanalysis product covers the time period of 1979 up to the present day. The production of ERA-Interim started in 2006, as the successor to ECMWFs previous reanalysis product ERA-40. It uses the spectral model IFS Cycle 31r2 assimilation system, a 4D-var data assimilation and 12 hour analysis window. The prognostic equations that determine atmospheric flow are solved using the semi-Lagrangian method with a finite element method in the vertical (Hodges et al. 2011). ERA-Interim uses a horizontal spatial resolution of 80 km and a vertical resolution of 60 levels, covering the surface up to 0.1 hPa.

133 Reanalysis output is available on a 6-hourly timescale (0, 6, 12 and 18 UTC). For further details
134 on ERA-Interim, we refer to Dee et al. (2011).

135 NCEP CFSR

136 The Climate Forecast System Reanalysis is produced by NCEP, the National Center for Envi-
137 ronmental Prediction and NCAR, National Center for Atmospheric Research. CFSR is a third
138 generation reanalysis product, and uses the NCEP Coupled Forecast System model, which is a
139 spectral atmospheric model (Saha et al. 2010). It has a horizontal resolution of 38 km, and a
140 vertical resolution of 64 levels. Atmospheric, oceanic and land surface output products are avail-
141 able at an hourly time resolution. Compared to previous versions of CFSR, climate is now forced
142 with observed estimates of evolving green house gas (GHG) concentrations, aerosols, and solar
143 variations (Wang et al. 2011).

144 NASA MERRA-2

145 The Modern ERA Retrospective Analysis for Research and Applications version 2 is a reanalysis
146 product provided by NASA. It uses the GEOS-5 model physics and a grid point statistical interpo-
147 lation data assimilation system, and has a 6-hourly observational assimilation cycle (Hodges et al.
148 2011). The horizontal resolution employed is 0.5 degrees in the latitudinal and 0.66 degrees in the
149 longitudinal direction. In the vertical, 72 layers are used. Output variables are available on differ-
150 ent time resolutions depending on the variable: hourly for the 2-D diagnostic fields, 3-hourly for
151 the 3-D diagnostic fields and 6-hourly for the prognostic fields. Among others, MERRA-2 con-
152 tains several improvements to hydrology, as this aspect was found lacking in previous reanalysis
153 produced by NASA (Rienecker et al. 2011).

b. Observations and methodology

In order to evaluate the performance of the different reanalysis products, an observational database was compiled. Basic ground-based meteorological observations over the AIS were gathered from several sources: the SCAR database (Turner et al. 2004), the AMRC program (<http://amrc.ssec.wisc.edu/>), the Australian Antarctic AWS dataset (<http://aws.acecrc.org.au/>) and the Italian Antarctic Research Program (<http://www.climantartide.it>). In total, monthly near-surface temperature and wind speed observations are available for more than 10 years for 79 individual sites over the AIS since the year 2000 (Figure 1). A detailed overview of the stations, including their height and temporal coverage is given in Table A1 in the appendix. Generally, temperature observations are available at 2 meter above ground level (a.g.l.), but wind speed observations vary with height. Therefore, all wind speed observations are extrapolated to 10 m a.g.l. assuming a Monin-Obukov logarithmic vertical profile at neutral conditions (Sanz Rodrigo 2011). Near-surface relative humidity observations are obtained by AWS measurements of the IMAU Antarctic AWS Project (<https://www.projects.science.uu.nl/iceclimate/aws/antarctica.php>). Long-term observations are available for 11 sites, which are mainly located in the Dronning Maud Land region and the Antarctic Peninsula (Pink dots in Figure 1). Detailed information about these AWSs is given in Table A2 in the appendix. These wind speed, near-surface relative humidity and temperature observations are not assimilated in the reanalysis and therefore constitute independent measurements to perform the evaluation.

For each of the stations, observations of temperature, wind speed and relative humidity are compared to the value at the corresponding location in the different reanalyses. The reanalysis pixels that are in the vicinity of 50 km from the station are equally considered. We compare the average annual values, and the mean absolute error (MAE) and the Pearson correlation coefficient

are calculated by comparing the individual monthly registered values of each observation to the corresponding month in the reanalyses. Furthermore, the annual cycle of the variables is also evaluated. As such, in addition to getting an overview of the average performance of the reanalysis, information about the temporal variability is obtained. For all near-surface atmospheric variables, we distinguish between three zones: the coastal Antarctica (< 1500 m a.s.l.), the interior (> 1500 m a.s.l.) of the continent, and the Antarctic Peninsula.

Surface mass balance over Antarctica is defined as precipitation minus melt water runoff, surface sublimation, and redistribution and sublimation of blowing snow particles (van den Broeke et al. 2004). Precipitation is the dominant source of AIS SMB. Meltwater runoff is only important for areas below 1000m a.s.l, and a small component of the AIS-integrated SMB. Blowing snow processes are not represented by the reanalyses. We therefore use accumulation, i.e. precipitation minus evaporation/sublimation in the reanalysis output as proxy for SMB. To evaluate the performance of the reanalyses, we use the surface mass balance dataset compiled by Favier et al. (2013). This quality-controlled observational dataset contains single-year measurements from various sources, such as ice cores, ground penetrating radar and stake measurements. In addition to the quality check performed by Favier et al. (2013) (using only the A-rated observations), we discard data with more than 150 m mismatch between the elevation given in the dataset and the elevation of the reanalysis pixel. We compare each of the observation to the accumulation value of the corresponding model grid cell of the same year. If more than one observation is located within the same pixel or if an observation covers several years, each of the single year observations is treated individually and compared to the model value. We then bin the resulting 203 SMB observations in four classes, according to elevation and roughly corresponding to different zones of the AIS. < 500 meters above sea level (a.s.l.) represent the coastal zones, including the ice shelves. From 500 to 1000 meters a.s.l. to represent the higher-elevation peripheral zones, 1000 to 2000

201 meters a.s.l., corresponding roughly to the escarpment zone, and lastly the interior of Antarctica:
202 2000 to 3000 meters a.s.l. and higher than 3000 meters a.s.l.

203 The satellite gravimetry mission GRACE (Gravity Recovery and Climate Experiment (Tapley
204 et al. 2004)) enables to measure AIS surface mass changes:

$$\frac{dm}{dt} = sources - sinks \quad (1)$$

205 Where the net source is the SMB and the remaining sink of mass is the ice discharge from the
206 edges of the ice sheet. A direct comparison of mass anomaly from GRACE with the reanalyses is
207 impossible, since the latter sink term is not available from the reanalyses. However, in Dronning
208 Maud Land two large snowfall events (atmospheric rivers in 2009 and 2011 (Gorodetskaya et al.
209 2013, 2014)) explain the anomalies in mass change (Shepherd et al. 2012; Boening et al. 2012),
210 since the other components of SMB exhibited little changes during this period (Rignot et al. 2011;
211 Lenaerts et al. 2012). Therefore we use the gridded Gravimetric Mass Balance product by TU
212 Dresden (Groh and Horwath 2016), sub-sampled to drainage basins (Zwally et al. 2012) from the
213 entire ice sheet and extract the Dronning Maud Land region (basins 5,6,7 and 8).

214 To calculate the reanalysis mass change ($\frac{dm}{dt}|_{RA}$) for each month, we attribute the sources of mass
215 to snowfall minus sublimation for each reanalysis, and compute the anomaly by subtracting the
216 monthly mean amount of SMB (snowfall minus sublimation, calculated on a base period of 22
217 years prior to the launch of GRACE) to the snowfall amount. In that way, since the anomalies are
218 mostly explained by the large snowfall events and the sink term can be neglected. Due to the fact
219 that the ERA-5 reanalysis product is only available from 2000 onward, we use the ERA-Interim
220 1980-2000 monthly means of the source. This has to be kept in mind when evaluating ERA-5's
221 performance, as a small shift is observed between Era-Interim 1980-2000 and Era-5 2000-2017
222 snowfall amounts.

3. Results and discussion

a. Near-surface temperature

A comparison between the annual average near-surface temperature in the four reanalysis and the observations is presented in Figures 2 and 3. Overall, all reanalyses are able to cover, to some extent, the observed temperature range on the Antarctic Ice Sheet. However, lowest temperatures (< -40 degrees) are overestimated by ERA-Interim and CFSR (up to 5 to 10 degrees), while ERA-5 and MERRA-2 better represent these low temperatures. ERA-5 performs best in simulating the near-surface temperature with a mean absolute error (MAE) of 2.0, followed by ERA-Interim, with a MAE of 2.5 (Figure 2). CFSR and MERRA-2 perform less good, showing a MAE of 2.8 and 3.1 respectively. These reanalyses also show the largest spread of annual average temperature values around the 1:1 line.

Next, we compare the seasonal variability of the four reanalyses temperature to the observations, over the three Antarctic climate zones (Figure 3). Note, however, that due to the different seasonal temperature range for the different Antarctic regions, the ranges of the y-axes differ between the three panels of Figure 3. There are large differences in performance for the reanalyses, both for the winter (JJA) and summer (DJF) seasons and between the different Antarctic regions. In the interior, MERRA-2 shows a very good correspondence to the observations during the Antarctic fall, winter, and spring. The other reanalyses strongly overestimate surface temperature during these seasons. During the winter season, the differences in temperature between these reanalyses and the observations reach values up to 5 degrees or more. Highest bias is found especially for CFSR, which overestimates the interior winter temperatures by almost 10 degrees. In the summer season, the spread in performance is much smaller for the Antarctic interior (differences of maximally 2 degrees) and ERA-5 clearly shows the best performance of all reanalyses. Also over

246 coastal Antarctica, ERA-5 performs best over all seasons. CFSR also performs quite well, es-
247 pecially in the winter season, while ERA-Interim and MERRA-2 underestimate the temperature
248 during winter (up to 5 degrees). Similar as over coastal Antarctica, ERA-5 captures the seasonal
249 cycle of surface temperature rather well over the Antarctic Peninsula. The other reanalyses show
250 a bias during winter and summer over this region. For example, CFSR and MERRA-2 are quite in
251 line with the observations during the winter season, but underestimate the temperature with 1 to
252 2 degrees during summer. ERA-Interim, on the contrary, performs very well during summer, but
253 shows a 2-degree overestimation of temperature during winter.

254 The reanalysis performance in representing the seasonal cycle of near-surface temperature de-
255 pends on the season as well as on the region, as was already mentioned by Bracegirdle and Mar-
256 shall (2012). ERA-5 performs very well over coastal Antarctica and the Antarctic Peninsula, while
257 MERRA-2 comes out as the best performing reanalysis product over the interior.

258 *b. Near-surface wind speed*

259 The near-surface wind speed performance is relatively similar for the different reanalyses, with
260 a good representation of the spatial variability: wind speeds range from 2 m s^{-1} to about 15 m
261 s^{-1} , with a slight underestimation of the strongest winds (especially in CFSR and ERA-Interim),
262 which might be at least partly related to the comparison between point observations with grid-box
263 averages (Figure 4). RMSE values range from 1.8 to 2.1 m s^{-1} , reflecting the large scatter in
264 Figure 4. Part of this is likely explained by the effect of local conditions (especially in regions of
265 complex orography) on the measured wind speed.

266 Highest wind speeds are observed during the winter season, when the katabatic forcing is
267 strongest (Figure 5). During the summer season, the large-scale pressure gradient force (PGF)
268 becomes the dominating driver of the wind (van den Broeke and van Lipzig 2003). The seasonal

cycle on the Antarctic Peninsula is controlled by the large-scale PGF, more specifically by the climatological low pressure system (the Amundsen Sea Low) that moves from the Ross Sea in winter (generating strong winds over the Peninsula) towards the Bellingshausen sea (generating weak winds over the Peninsula) (van den Broeke and van Lipzig 2003).

All reanalyses capture this typical annual cycle in the different Antarctic regions. However, in the interior during winter, MERRA-2 strongly overestimates the winds by $\approx 2 \text{ m s}^{-1}$. In coastal regions, ERA-5, CFSR and MERRA-2 underestimate summer winds while in winter ERA-5 and CSFR strongly underestimate winds. It is clear that both for the interior and the coast, the performance of the reanalyses decreases during the winter when the katabatic forcing becomes more important. The winter katabatic forcing is strongest in coastal regions, inducing stronger winds near the coast compared to the interior and only ERA-Interim is able to represent this behavior. In the Peninsula, where the large-scale PGF dominates, the accuracy generally improves, but ERA-Interim and MERRA-2 overestimate the winds here. Overall, the performance of the reanalyses for wind strongly depends on the region and season considered and there is no clear-cut best performing reanalysis for wind.

c. Near-surface relative humidity

ERA-Interim, ERA-5 and MERRA-2 all underestimate relative humidity with respect to ice (Figure 6). The underestimation is most prominent for the inland and coastal stations, and smaller for the Peninsula. In contrast, simulated relative humidity in CFSR is close to the observations for all locations, and its MAE is low (5.0) compared to the other three reanalyses (15.9, 13.3 and 16.0 for ERA-5, ERA-Interim and MERRA-2, respectively).

ERA-Interim, ERA-5 and MERRA-2 strongly overestimate the amplitude of the annual cycle, with substantial low relative humidity values during winter, which is not supported by the ob-

served data. CFSR is relatively close to observations the entire year. Thus, the underestimation of relative humidity is largest for low temperatures, as it is larger in winter and larger closer to the pole. Or phrased differently, ERA-Interim, ERA-5 and MERRA-2 appear to be unable to accurately simulate relative humidity at very low temperatures. Finally, note that for relative humidity, measurement accuracy is relatively high: the measurement accuracy for the Vaisala HMP35AC instrument used is 2% for $RH < 90\%$ and 3% for $RH > 90\%$ (van den Broeke et al. 2004; Lazzara et al. 2012). Therefore, it is very likely the underestimations seen in ERA-Interim, ERA-5 and MERRA-2 represent genuine model biases.

d. Surface mass balance

Figure 8 shows the performance of the SMB (approximated by accumulation) of the reanalyses in comparison to the observations. In general, all reanalyses display the same pattern, with varying biases. ERA-5 shows the closest agreement to the observations (MAE of 106 mm year^{-1} , in water equivalent (w.e.)) but underestimates the SMB, while the other reanalyses overall overestimate the accumulation. ERA-Interim (MAE of $111 \text{ mm w.e. year}^{-1}$) tends to overestimate areas between 500 and 2000 m a.s.l., which is also the case for and MERRA-2 and CFSR (MAE of 142 and 192, respectively). The coastal areas and ice shelves are underestimated by all reanalyses except MERRA-2. The peripheral zones are all overestimated, especially by ERA-Interim and MERRA-2. ERA-5 underestimates the accumulation in the escarpment zone, while all other reanalyses overestimate it. ECMWF's reanalyses lie closest to the observations for this elevation class. Finally, only MERRA-2 simulates the SMB in the interior with the least bias, and ERA-Interim, ERA-5 and CFSR underestimate the accumulation on the plateau, with a slightly larger bias for ERA-5. The relative biases are higher for the elevation classes above 2000 m a.s.l., as

314 they receive a limited amount of precipitation compared to the other areas, where the relative bias
315 is limited below 50%.

316 In general, the spread of the modelled SMB is narrower for all reanalyses, in comparison to
317 the SMB dataset. This can be explained by the smoothening of SMB variability in the reanalyses
318 due to their relatively coarse horizontal resolution. As a result, SMB variations smaller than the
319 reanalysis grid size are not resolved. In addition, since the modelled SMB only represents pre-
320 cipitation minus sublimation, melt and blowing snow processes are not taken into account. This
321 leads to under- and over-estimations of local SMB, mainly over the ice shelves and at the coastal
322 locations, where these processes are most effective. The interior of the continent, less prone to
323 melt and blowing snow, receives very limited amount of precipitation.

324 The comparison of the mass change derived from the reanalyses to the mass anomaly retrieved
325 from GRACE for the Dronning Maud Land area (Figure 9) show that sharp increase due to the
326 surface mass anomalies of 2009 and 2011 are present in all reanalyses. ERA-5 and ERA-Interim
327 show the smallest MAE (30 and 24 Gt year⁻¹, respectively) and closely follow the cumulative
328 mass change derived from Grace gravimetry. The signature of the atmospheric rivers, although
329 present in CFSR and MERRA-2, are less pronounced and lead to a larger bias to the observed
330 mass anomalies (MAE of 91 and 68 Gt year⁻¹, respectively). Since the comparison is only valid
331 for the years 2009 and 2011, no conclusion can be drawn from the rest of the time series.

332 The difference in performance between SMB compared to the dataset of Favier et al. (2013)
333 and the mass anomaly derived from Grace gravimetry are due to different time resolutions, and
334 different localizations.

335 4. Conclusions

336 We present here an evaluation of near-surface atmospheric variables and SMB over the Antarctic
337 Ice Sheet in four reanalysis products, namely ECMWF's ERA-5 and its predecessor ERA-Interim,
338 NCEP CFSR and NASA MERRA-2 against a set of in-situ observations over the 2000-2017 time
339 period. The mean near-surface temperature, wind speed and relative humidity are investigated, as
340 well as their annual cycle.

341 The results regarding near-surface temperature show that all reanalyses are able to some extent
342 to cover the temperature range of the AIS, and highlight that the latest state-of-the-art reanalysis
343 product, ERA-5, overall captures the mean temperature climatology best compared to the other
344 reanalyses.

345 The typical annual cycle of wind speed, with a strong influence of the katabatics in winter and
346 the pressure gradient force in summer, is captured by all reanalyses. However, performance of
347 the reanalyses decreases during winter when the katabatic forcing is prevailing: the strongest wind
348 speeds are strongly underestimated by ERA-5 and CFSR in the coastal regions during winter while
349 MERRA-2 substantially overestimates the wind in the interior during winter.

350 Regarding the relative humidity, CFSR clearly performs best, both regarding the mean values
351 and the annual cycle. There is an overall under estimation of ERA-5, ERA-Interim and MERRA-
352 2 relative humidity, especially during the Antarctic winter and in the interior. It seems that these
353 reanalyses are unable to simulate the relative humidity accurately at low temperatures.

354 For SMB, the performance of the individual models vary according to the zones investigated.
355 Despite a general similar pattern for all reanalyses, ERA-5 shows the smallest bias to the obser-
356 vations, but tends to underestimate SMB, while all other reanalyses overall overestimate accumu-
357 lation over the AIS. In addition, all are able to represent the atmospheric rivers, but ECMWF's

358 reanalyses show the smallest bias in accumulation in Dronning Maud Land. SMB is very chal-
359 lenging to model accurately, and includes processes not accounted for in the reanalyses. Therefore,
360 inclusion of blowing snow and melt processes, as well as a better representation of snowfall over
361 the AIS are crucial to represent the observed SMB in an accurate way.

362 Finally, even though the different reanalyses perform very differently and there is no best model
363 for all variables, the analysis performed in this paper enables the users to choose the best perform-
364 ing reanalysis, depending on the area of investigation, the season and the variable to represent (see
365 Table 10).

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378 APPENDIX

379 Table A1/A2 here

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522 Antarctic Survey (Turner et al. 2004).

#	Name	Lat (°)	Lon (°)	Height (m)	T (# years)	WS (# years)	Source	Notes
1	Allesandra	-73.6	166.6	160	2000-2016 (17)	2000-2016 (17)	ITA	
2	Amery	-70.9	69.9	4	2000-2016 (17)	2000-2011 (12)	AUS	
3	Amundsen Scott	-90	0	2835	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
4	Arelis	-76.7	163	150	2000-2016 (17)	2000-2016 (17)	ITA	
5	Arturo Prat	-62.5	-59.7	5	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
6	Belgrano II	-77.9	-34.6	256	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
7	Bellinghausen	-62.2	-58.9	16	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
8	Bonaparte Point	-64.8	-64.1	8	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
9	Butler Island	-72.2	-60.2	91	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
10	Byrd	-80	-119.4	1530	2000-2016 (17)	2002-2016 (15)	USAP/SCAR	WS only in DJF
11	Cape Philips	-73.1	169.6	310	2000-2016 (17)	2000-2005 (6)	USAP/SCAR	WS no data in SON
12	Cape Ross	-76.7	163	201	2000-2016 (17)	2000-2005 (6)	USAP/SCAR	
13	Casey	-66.3	110.5	42	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
14	D10	-66.7	139.8	240	2000-2014 (9)	2000-2016 (11)	USAP/SCAR	
15	D47	-67.4	138.7	1560	2008-2016 (9)	2000-2016 (14)	USAP/SCAR	No data in July
16	Davis	-68.6	78	13	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
17	Dome A	-80.4	77.4	4084	2005-2016 (12)	2005-2016 (12)	AUS	WS only in DJF/MAM
18	Dome C	-75.1	123.4	3280	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
19	Dumont D'Urville	-66.7	140	43	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
20	Eagle	-76.4	77	2824	2005-2016 (12)	2005-2016 (12)	AUS	WS only in DJF/MAM
21	Elaine	-83.1	174.2	60	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
22	Elizabeth	-82.6	-137.1	549	2000-2016 (12)	2000-2016 (12)	USAP/SCAR	No data in JJA/SON
23	Eneide	-74.7	164.1	92	2000-2016 (17)	2000-2016 (17)	ITA	
24	Erin	-84.9	-128.8	990	2000-2016 (12)	2000-2016 (12)	USAP/SCAR	No data in JJA
25	EspERAnza	-63.4	-57	13	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	

26	Ferrell	-77.9	170.8	45	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
27	Gill	-80	-178.6	30	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
28	Giulia	-75.6	145.8	2200	2000-2016 (16)	2000-2016 (15)	ITA	
29	Great Wall	-62.2	-59	10	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
30	Grytviken	-54.3	-36.5	3	2000-2016 (17)	2001-2016 (13)	USAP/SCAR	
31	Halley	-75.5	-26.4	30	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
32	Harry	-83	-121.4	954	2000-2016 (16)	2000-2016 (16)	USAP/SCAR	WS only in DJF/MAM
33	Henry	-89	-1	2754	2000-2016 (14)	2000-2016 (12)	USAP/SCAR	
34	Irene	-71.6	148.7	2000	2001-2015 (13)	2001-2015 (13)	ITA	Only in DJF/MAM
35	Jubany	-62.2	-58.6	4	2000-2016 (17)	2000-2016 (16)	USAP/SCAR	
36	King Sejong	-62.2	-58.7	11	2000-2014 (11)	2000-2014 (11)	USAP/SCAR	
37	Larsen Ice Shelf	-66.9	-60.9	17	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
38	Lettau	-82.5	-174.4	55	2000-2016 (17)	2000-2016 (10)	USAP/SCAR	
39	Limbert	-75.4	-59.9	40	2000-2016 (15)	2000-2016 (11)	USAP/SCAR	WS only in DJF/MAM
40	Linda	-78.5	168.4	50	2000-2012 (13)	2000-2012 (13)	USAP/SCAR	WS only in DJF/MAM
41	Lola	-74.1	163.4	1621	2000-2016 (17)	2000-2016 (17)	ITA	
42	Macquarie	-54.5	158.9	8	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
43	Manuela	-74.9	163.7	80	2000-2016 (15)	2000-2016 (9)	USAP/SCAR	
44	Marambio	-64.2	-56.7	198	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
45	Marble Point	-77.4	163.7	120	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
46	Maria	-74.6	164	355	2006-2016 (10)	2006-2016 (10)	ITA	No data in JJA
47	Marilyn	-80	165.1	75	2000-2016 (17)	2000-2016 (15)	USAP/SCAR	
48	Mario Zucchelli	-74.7	164.1	92	2000-2015 (14)	2000-2015 (14)	USAP/SCAR	
49	Marsh	-62.2	-58.9	10	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
50	Mawson	-67.6	62.9	16	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
51	McMurdo	-77.9	166.7	24	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
52	Minna Bluff	-78.6	166.7	50	2000-2016 (13)	2000-2010 (10)	USAP/SCAR	WS only in DJF

53	Mirny	-66.5	93	30	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
54	Modesta	-73.6	160.7	1924	2000-2016 (17)	2000-2016 (17)	ITA	
55	Mount Siple	-73.2	-127.1	30	2000-2011 (11)		USAP/SCAR	
56	Neumayer	-70.7	-8.4	50	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
57	Nico	-89	89.7	3065	2000-2016 (13)	2000-2014 (10)	USAP/SCAR	
58	Novolazarevskaya	-70.8	11.8	119	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
59	O'Higgins	-63.3	-57.9	10	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
60	Orcadas	-60.7	-44.7	6	2000-2016 (17)	2000-2016 (16)	USAP/SCAR	
61	Palmer	-64.3	-64	8	2002-2016 (14)	2002-2016 (14)	USAP/SCAR	
62	Paola	-72.8	159	0	2003-2016 (13)	2003-2016 (12)	ITA	Only in DJF/MAM
63	Pegasus North	-77.9	166.5	20	2000-2013 (13)	2000-2013 (12)	USAP/SCAR	
64	Possession Island	-71.9	171.2	30	2000-2016 (17)		USAP/SCAR	
65	Relay Station	-74	43.1	3353	2000-2016 (13)	2000-2016 (12)	USAP/SCAR	
66	Rita	-74.7	164.	268	2000-2016 (17)	2000-2016 (17)	ITA	
67	RothERA	-67.5	-68.1	32	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
68	San Martin	-68.1	-67.1	4	2000-2016 (15)	2000-2016 (15)	USAP/SCAR	
69	Schwerdtfeger	-79.9	170	60	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
70	Scott Base	-77.9	166.7	16	2000-2009 (10)	2000-2009 (8)	USAP/SCAR	WS only in DJF
71	Silvia	-73.5	169.7	536	2000-2016 (17)	2000-2016 (17)	ITA	
72	Sofia	-74.8	163.3	40	2000-2016 (17)	2000-2016 (17)	ITA	
73	Syowa	-69	39.6	21	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
74	Terra Nova Bay	-74.7	164.1	92	2000-2016 (14)	2000-2005 (5)	USAP/SCAR	
75	Theresa	-84.6	-115.8	1463	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
76	Vostok	-78.5	106.9	3490	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
77	Willie Field	-77.9	167.0	14	2000-2007 (8)	2000-2007 (8)	USAP/SCAR	
78	Zhongshan	-69.4	76.4	18	2000-2016 (17)	2000-2016 (17)	USAP/SCAR	
79	Zoraida	-74.2	162.9	644	2000-2016 (17)	2000-2016 (17)	ITA	

523 Table A2. Overview of the ground-based radiative flux and relative humidity observational data
524 availability (Rad). All data is retrieved from the IMAU Antarctic AWS Project accessible via
525 <https://www.projects.science.uu.nl/iceclimate/aws/antarctica.php>.

#	Name	Lat (°)	Lon (°)	Height (m)	Rad (# years)
1	AWS04	-72.8	-15.5	35	2000-2002 (3)
2	AWS05	-73.1	-13.2	360	2000-2013 (14)
3	AWS06	-74.5	-11.5	1160	2000-2009 (10)
4	AWS08	-76	-8.1	2400	2000-2003 (4)
5	AWS09	-75	0	2900	2000-2016 (17)
6	AWS11	-71.2	-6.8	690	2007-2016 (10)
7	AWS14	-67	-61.5	50	2009-2016 (8)
8	AWS15	-67.6	-62.2	50	2009-2014 (6)
9	AWS16	-72	23.3	1300	2009-2016 (8)
10	AWS17	-65.9	-61.9	50	2011-2016 (6)
11	AWS18	-66.4	-63.4	70	2014-2016 (3)

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541	Fig. 6.	Annually averaged 2-meter relative humidity observations compared to the different reanal-	
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543		on individual monthly values for each station to take temporal variability into account.	38
544	Fig. 7.	Averaged annual cycles of 2-meter relative humidity for all reanalyses compared to the ob-	
545		servations.	39
546	Fig. 8.	Accumulation of each reanalysis against the stratified mean observed accumulation from the	
547		dataset of Favier et al. (2013) (circles). The error bars indicate the 10 and 90th percentile of	
548		the measurements (horizontal) and reanalysis (vertical) accumulation values.	40
549	Fig. 9.	Comparison of mass anomaly derived from Grace, and the mass anomaly computed using	
550		the accumulation (precipitation minus sublimation) from each reanalysis minus the clima-	
551		tological mean accumulation from a 22 years time period previous to the launch of Grace.	
552		Since the ERA5 timeseries is not available prior to 2000, we used the climatological mean	
553		of ERA-Interim.	41
554	Fig. 10.	Mean absolute error for each reanalysis for each of the studied variables: temperature (T, in	
555		degrees), wind speed (WS, in m s^{-1}), relative humidity (RH, in %) and surface mass balance	
556		(SMB) from both methods (validation against Favier et al. (2013) and Grace mass anomaly	
557		derived from altimetry. The color denotes the relative performance compared to the other	
558		reanalysis.	42

559 FIG. 1. Ground-based meteorological observation network. Only stations with data availability of more than
 560 10 years are included. Pink dots denote stations which have relative humidity measurements available.

FIG. 2. Annually averaged 2-meter temperature observations compared to the different reanalyses. Mean absolute error (MAE) and Pearson correlation coefficient (r) are calculated based on individual monthly values for each station to take temporal variability into account.

FIG. 3. Averaged annual cycles of 2-meter temperature for all reanalyses compared to the observations.

FIG. 4. Annually averaged 10-meter wind speed observations compared to the different reanalyses. Mean absolute error (MAE) and Pearson correlation coefficient (r) are calculated based on individual monthly values for each station to take temporal variability into account.

FIG. 5. Averaged annual cycles of 10-meter wind speed for all reanalyses compared to the observations.

FIG. 6. Annually averaged 2-meter relative humidity observations compared to the different reanalyses. Mean absolute error (MAE) and Pearson correlation coefficient (r) are calculated based on individual monthly values for each station to take temporal variability into account.

FIG. 7. Averaged annual cycles of 2-meter relative humidity for all reanalyses compared to the observations.

FIG. 8. Accumulation of each reanalysis against the stratified mean observed accumulation from the dataset of Favier et al. (2013) (circles). The error bars indicate the 10 and 90th percentile of the measurements (horizontal) and reanalysis (vertical) accumulation values.

FIG. 9. Comparison of mass anomaly derived from Grace, and the mass anomaly computed using the accumulation (precipitation minus sublimation) from each reanalysis minus the climatological mean accumulation from a 22 years time period previous to the launch of Grace. Since the ERA5 timeseries is not available prior to 2000, we used the climatological mean of ERA-Interim.

	T	WS	RH	SMB
ERA5	2.0	2.1	15.9	
ERA-Interim	2.5	2.1	13.3	
CFSR	2.8	2.0	5.0	
MERRA-2	3.1	1.8	16.0	

577 FIG. 10. Mean absolute error for each reanalysis for each of the studied variables: temperature (T, in degrees),
 578 wind speed (WS, in m s^{-1}), relative humidity (RH, in %) and surface mass balance (SMB) from both methods
 579 (validation against Favier et al. (2013) and Grace mass anomaly derived from altimetry. The color denotes the
 580 relative performance compared to the other reanalysis.