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Reply to Comment by Genthon et al. on “Surface Air Relative Humidities Spuriously Exceeding 100% in CMIP5 Model Output and Their Impact on Future Projections”

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Abstract The commentators regard a categorical truncation of supersaturations with respect to ice in climate model output as an inappropriate solution to the supersaturation issue. This view is supported by observational evidence from the East Antarctic Plateau. We accept this criticism to a certain degree. Even so, it is necessary to make a clear distinction between the true supersaturations measured in the atmosphere and the spurious supersaturations existing in archived model output datasets: the latter result, for example, from inconsistencies in the interpolation of temperature and specific humidity to the near-surface level. In the CMIP5 model output datasets, the largest relative humidities in near-surface air are far above those observed. Moreover, supersaturations given at the 2-m height are generally much larger than those at the lowermost tropospheric isobaric levels. Projections of relative humidity for the future may be considerably distorted if founded on unmodified output data sets.

1. Introduction

In their comment paper, Genthon et al. (2018; hereafter G18) stress that in the atmosphere physical processes commonly produce supersaturations with respect to ice. They also reference substantial observational supersaturations over the Antarctic Plateau where the air is extremely cold and clean; according to measurement data from the Dome C station, under meteorological conditions in which the measurement system can be regarded as reliable (water vapor pressure higher than 2 Pa), relative humidity with respect to ice (RH) may occasionally reach \( \sim 150\% \) (Genthon et al., 2017). G18 likewise give several examples of weather models (e.g., Tompkins et al., 2007) and global climate models (GCMs; e.g., Gettelman et al., 2010; Liu et al., 2007) participating in phase 5 of Coupled Model Intercomparison Project (CMIP5) in which the occurrence of supersaturation is allowed inherently. Accordingly, G18 argue that it is not justifiable to categorically eliminate supersaturations with respect to ice in climate model output. Rather, reasonable supersaturations should be considered appropriate.

In section 5.1 of our original paper (Ruosteenoja et al., 2017, hereupon R17), we likewise referred to literature in which supersaturations with respect to ice were reported, particularly in the free atmosphere (Andreas et al., 2002; Genthon et al., 2010; Gettelman et al., 2006). However, in light of the new measurement data of Genthon et al. (2017), it is likely that the actual supersaturations are more frequent and intense than assessed in R17, in the extreme conditions prevailing over the East Antarctic Plateau even in near-surface air. Nevertheless, it is essential to make a distinct separation between the true supersaturations indeed occurring in the atmosphere and the spurious extremely high (up to \( >1,000\% \)) near-surface RHs in the model output files.

In climate models, temperature and specific humidity are typically calculated as prognostic variables at the model levels and thereafter interpolated diagnostically onto the 2-m height to calculate near-surface RH (R17). In this paper, model-produced 2-m RH refers to this interpolated quantity that is provided at the daily or monthly level in the archived model output files; for example, in the CMIP5 archive from which the data utilized in the present work have been downloaded. We first show that the maximum near-surface air supersaturations in the model output are typically far larger than the measurement-based ones displayed in Figure 1 of G18 (section 2). Moreover, in the model output supersaturations tend to be much higher in the near-surface air than at tropospheric isobaric levels. Thereafter, in section 3, we examine two CMIP5 GCMs to compare climate change projections derived from the near-surface and lower troposphere RH data. In one model, high
Projected change in temporally averaged RH (in percentage points) by INMCM4 in June–August from 1981–2010 to 2070–2099 under RCP8.5, derived from (a) RH data represented at the lowermost atmospheric pressure level and at the 2-m height (b) without truncations and (c) with RH > 100% truncated in the daily mean output. RH = relative humidity.

RHS at the 2-m height appear to be predominantly spurious, while in the other GCM they may be partly reasonable. Finally, the main inferences of the work are presented in section 4.

2. Model-Produced Near-Surface Supersaturations Over Central Antarctica

The statistical distribution of model-produced daily mean 2-m RH, at an example grid point located in the East Antarctic Plateau is shown in Table 1. The data have been binned into five classes, the first of which represents subsaturation (note the upper limit of 100.1% that was used to prevent 100% RHs from being classified as supersaturation) and the remaining four classes supersaturations of different degree. In addition, we give the absolute maxima of RH, at that point. All seasons have been included. The distributions have been compiled for those 10 GCMs that fulfil two criteria: Surface air RH needs to be available at daily level, and the data has to contain higher than 100% RHs (Table 1 of R17).

At this grid point, substantial exceedances over 100% RH occur in the output of all 10 GCMs (Table 1). As expected, the pointwise daily mean supersaturations are considerably larger than those in Table 1 of R17, which displayed the long-term mean spatial averages of the exceedance over the entire polar area. In the individual GCMs, even larger RHs than those given in Table 1 existed at nearby points.
Table 1

Statistical Distribution of Model-Produced Interpolated Daily Mean Surface Air RH at the Model Grid Point Closest to 81° S, 75° E in Selected Models

<table>
<thead>
<tr>
<th>Model</th>
<th>φ</th>
<th>λ</th>
<th>0–100.1%</th>
<th>100.1–140%</th>
<th>140–200%</th>
<th>200–1,000%</th>
<th>&gt;1,000%</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIROC5</td>
<td>80.54° S</td>
<td>74.53° E</td>
<td>24.82</td>
<td>61.36</td>
<td>13.46</td>
<td>0.36</td>
<td>—</td>
<td>281</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>82.31° S</td>
<td>75.94° E</td>
<td>26.16</td>
<td>47.13</td>
<td>24.97</td>
<td>1.74</td>
<td>—</td>
<td>256</td>
</tr>
<tr>
<td>FGOALS-s2</td>
<td>80.46° S</td>
<td>75.94° E</td>
<td>6.77</td>
<td>21.81</td>
<td>61.73</td>
<td>9.69</td>
<td>—</td>
<td>512</td>
</tr>
<tr>
<td>INMCM4</td>
<td>80.25° S</td>
<td>75.00° E</td>
<td>25.95</td>
<td>43.66</td>
<td>1.14</td>
<td>0.05</td>
<td>—</td>
<td>264</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>81.25° S</td>
<td>75.00° E</td>
<td>29.16</td>
<td>30.00</td>
<td>40.84</td>
<td>—</td>
<td>—</td>
<td>197</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>81.25° S</td>
<td>75.00° E</td>
<td>29.09</td>
<td>29.23</td>
<td>41.68</td>
<td>—</td>
<td>—</td>
<td>197</td>
</tr>
<tr>
<td>GFDL-CM3</td>
<td>81.00° S</td>
<td>76.25° E</td>
<td>10.00</td>
<td>30.20</td>
<td>16.89</td>
<td>42.87</td>
<td>0.03</td>
<td>1315</td>
</tr>
<tr>
<td>GISS-E2-R</td>
<td>81.00° S</td>
<td>76.25° E</td>
<td>78.49</td>
<td>4.71</td>
<td>0.61</td>
<td>—</td>
<td>—</td>
<td>333</td>
</tr>
<tr>
<td>NCAR-CCSM4</td>
<td>80.58° S</td>
<td>75.00° E</td>
<td>40.66</td>
<td>49.58</td>
<td>8.94</td>
<td>0.83</td>
<td>—</td>
<td>280</td>
</tr>
</tbody>
</table>

Note. Columns 4–8 show the percent frequencies of RH falling in the given five histogram classes in historical runs. The last column shows the corresponding absoltemaximaof RHduring the period 1950–2005 (for NCAR-CCSM4, 1960–2005); (φ, λ) give the exact position of the point. RH = relative humidity.

In Table 1, the highest near-surface air supersaturations derived from the model output are far larger than those measured by Genton et al. (2017) in comparable climatological conditions. In their measurements, the largest plausible RH lone were close to 150% and the proportion of RH > 140% was about 1% (Figure 1 of G18). In the model output, by contrast, the maximum values are slightly smaller than 200% only in the two versions of HadGEM2. In the other GCMs, the maxima substantially exceed 200% and in two GCMs, even 1,000%. In these two models, INMCM4 and GFDL-CM3, the proportion of humitudes >200% is more than 40% of all occasions. The output of FGOALS-s2 likewise appears rather unsatisfactory, with the maximum RH larger than 500% and the portion of RH ≤ 100% being only 7%. In seven GCMs out of 10, more than 10% of all events fall in the 140–200% category; in the observational histogram of G18, only 1%. NorESM1-M is the only model with the statistical distribution of RH somewhat similar to the observational one. In that model as well, however, the maximum RH = 264%. The share of supersaturations is smallest in GISS-E2-R, but even for that GCM, the absolute maximum value appears unrealistic.

In addition to the 2-m height, the temporal maxima of RH were sought from the lowest atmospheric level having no missing daily output. Usable data were available only from 5 of the 10 GCMs represented in Table 1, and owing to the large size of the files, we were obliged to examine fairly short time slices consisting of 4 to 20 years. Considering the Antarctic Plateau grid point explored in Table 1, MIROC5 was the only of these five GCMs that showed significant supersaturation, with a maximum RH of 161%. In the other GCMs examined (MIROC-ESM, NorESM1-M, HadGEM2-ES, and NCAR-CCSM4), even the largest values of RH at the lowest isobaric level ranged from ~100 to ~102%. Even so, in some GCMs larger RH did exist elsewhere in the world.

In many GCMs, the area over which supersaturations at the 2-m height occur tends to be overly extensive, even covering the entire Antarctic continent (Figures 1 and 2 of R17). In the periphery of Antarctica that is under the influence of katabatic winds, the measured relative humidities actually tend to be quite low. For example, in the Lake Untersee area in East Antarctica, the observed mean humidities (expressed with respect to liquid water in above-zero and with respect to ice in subzero temperatures) are smaller than 40% (Andersen et al., 2015). In areas covered by blue ice, annual net evaporation from the ice surface exceeds the accumulation due to precipitation and snow drift convergence (van den Broeke et al., 2006); this is an indication of significant time mean subsaturation with respect to ice. Accordingly, the model-produced supersaturations should be restricted onto the inner Plateau.

3. Impact of Large Supersaturations on Future Projections of RH

In this section, future projections of RH are calculated for two GCMs (INMCM4 and MIROC5) by using three data sources: (a) RH data from the lowermost atmospheric pressure level, (b) RH interpolated onto the 2-m height in an unmodified form (i.e., identical to that in the model output files), and (c) 2-m RH data from which humidities above 100% have been truncated before calculating the response. The projections are calculated for the period 2070–2099 (relative to 1981–2010) in response to the RCP8.5 forcing.
INMCM4 (Volodin et al., 2010) constitutes an example of a GCM in which supersaturations in the 2-m level output are very strong (Table 1; Figure 2 of R17). RH projections of that model for southern polar areas, using the above-mentioned three alternatives, are shown in Figure 1.

Where the 1,000-hPa level resides below the Earth surface, the 1,000-hPa RH in the output of the INMCM models contains RH extracted from the lowest sigma level of the model (Evgeny Volodin, personal communication, 2012). Accordingly, in all the elevated areas, including virtually the entire Antarctic continent, Figure 1a displays the RH projection for that model level. In this case the resulting climate change response is fairly moderate, approximately ranging from a reduction of 10% to an increase of 16%. This is in agreement with the fact that at this level, unlike in the 2-m height data, exceedances above 100% RH in the time mean fields only occur in quite small areas (not shown).

The RH response calculated from the INMCM4 output for the 2-m height (Figure 1b) is entirely different from that derived from the lowest model level data (Figure 1a). The direct use of the 2-m height data results in a large projected decrease of RH over nearly the entire Antarctic continent, over the eastern inland areas even by up to 50–100%. On the other hand, if the corresponding projection is calculated after truncating all the exceedances above \( RH = 100\% \) in the daily mean data (Figure 1c), the resulting projected change is much
more reasonable, within the range of −5 to +11%. Even more importantly, the geographical distributions of the change in Figures 1a and 1c bear many similarities, particularly near the East Antarctic coast.

These findings suggest that the simulation of RH at the INMCM4 sigma levels is physically consistent, and the extremely large values of RH have only arisen when interpolating RH onto the 2-m height. In this case it appears evident that the RH response calculated from the truncated 2-m RH data is, compared to the response derived from the unmodified data, closer to what this model actually wants to tell about the future changes of RH.

In the output of the other GCM scrutinized, MIROC5 (Watanabe et al., 2010), pressure level data for subterranean areas have been left empty. Therefore, for this GCM the RH fields representing the lower tropospheric conditions were here conglomerated by using, for every grid point, long-term mean RH at the lowest isobaric level available (1,000, 925, 850, 700 hPa, etc.). Consequently, in elevated areas this field does not generally correspond very closely to the first hybrid level, and the resulting spatial pattern is somewhat noisy. Even so, in MIROC5 the largest 2-m supersaturations occur in northern polar areas (R17, Table 1) that largely consist of ocean. In this area RH data exist down to the 1,000-hPa level.

The RH responses derived from the MIROC5 output for northern polar areas, calculated by using the three methods, are depicted in Figure 2. Now all three fields are qualitatively fairly similar. In many areas, the RH projection derived from the lower troposphere data is an intermediate of the 2-m height RH responses calculated with and without the truncation of supersaturations. For example, in central Arctic Ocean, the lower troposphere response resembles most closely the 2-m response obtained after truncation, but over the Barents Sea the state is opposite. For northern continental areas where this GCM produces only very minor supersaturations (Figure 3 of R17), the 2-m RH projections obtained with and without truncation are nearly identical (Figures 2b and 2c), but both of them exhibit qualitative differences in comparison with the lower troposphere response; for example, in Alaska and Eastern Siberia. In these areas, the 1,000-hPa level mainly lies below the ground, and the lower troposphere data is taken from a higher isobaric level that does not necessarily properly represent conditions near the surface.

To conclude, in the MIROC5 output, supersaturations occurring at the 2-m height appear to be partly reasonable. Even so, it is evident that they likewise include an artificial component originating from vertical interpolation; this is also indicated by the substantial proportion of occasions with RH\textsubscript{i}, manifesting overly large supersaturation in East Antarctica (Table 1). It should be noted that MIROC5 belongs to those GCMs in which parameterizations allow the occurrence of higher than 100% humidities with respect to ice at the model levels (Masahiro Watanabe, personal communication, 2017). Accordingly, in analyzing the output of MIROC5, the plain truncation of humidities above 100% is not a satisfactory approach to resolve the issue of excessive near-surface layer supersaturations.

4. Conclusions

In the output files of the 10 GCMs examined in this response paper, the largest near-surface air supersaturations in the East Antarctic Plateau are much larger than those in the observational statistics presented in Figure 1 of G18. Furthermore, with the exception of the MIROC5 model, supersaturations simulated for the lower troposphere are negligible compared to those for the 2-m height at the same location. This indicates that the very high RH\textsubscript{i}’s diagnosed for the 2-m height are to a large degree unphysical. As discussed in section 5.2 of R17, there are two main explanations for the unrealistically high near-surface air humidities. First, in many models air temperature and specific humidity are interpolated independently onto the 2-m level, for example, by using the Monin-Obukhov similarity theory. If the resulting near-surface air specific humidity and temperature are mutually inconsistent, specific humidity may substantially exceed the saturated value, leading to spurious supersaturation. Second, saturation specific humidity is a nonlinear function of temperature. Accordingly, if RH at the lowermost model level is close to saturation, even a plain linear vertical interpolation of temperature and specific humidity is able to engender supersaturation. In many models, both of these processes may operate simultaneously.

In Genthon et al. (2017) and G18, the measured relative humidities were considered plausible up to 150%. In temperatures typical of the East Antarctic Plateau, homogeneous nucleation of ice crystals initiates at RH ≈ 160% (Gettelman et al., 2006; Tompkins et al., 2007), thus precluding the generation of even higher supersaturations. When fine ice crystals (e.g., diamond dust) have been formed as a result of nucleation, they correspondingly act as condensation nuclei, thus eradicating any significant supersaturation fairly rapidly.
In the air in an immediate contact with the surface, RHs > 100% should likewise be reduced by condensation at the snow surface. In recent experimental studies (e.g., Genthon et al., 2017; Makkonen & Laakso, 2005), heated instruments have been utilized to measure supersaturations with respect to ice in order to elude potential biases caused by condensation of extra water vapor onto the device. For the authors of the present response paper, it is unclear how to avoid diamond dust to be spuriously measured as extra air humidity when using such heated measurement systems. In any case, we expect that the findings of the pioneering work of Genthon et al. (2017) will be confirmed or refined by forthcoming measurement campaigns. This will clarify the magnitude of supersaturations actually occurring in the near-surface air layer in the extreme conditions prevailing in the East Antarctic Plateau.

Notwithstanding the potential measurement uncertainties, it is evident that in some polar areas a certain degree of supersaturation with respect to ice frequently occurs in the near-surface air. Moreover, in several GCMs parameterizations have been designed to allow supersaturation (G18). Accordingly, the conclusion of R17 needs to be amended: It is not appropriate to aim at disposing the model-produced near-surface air supersaturations with respect to ice altogether, but only the spurious component caused by vertical interpolations and so forth should be eliminated.

In particular, a formulaic truncation of RHs above 100%, either during the model run or afterward when processing the model output files, is an oversimplified way to resolve the supersaturation issue (as already mentioned in the conclusions section of R17). For those GCMs in which significant supersaturations are allowed in prognostic calculations at the model levels, RH projections obtained after the truncation of RHs > 100% in R17 should be interpreted as sensitivity assessments of the methodology rather than actual predictions of the RH response.

Nevertheless, it is either not a good choice to base the future RH projections directly on unmodified near-surface humidities. The unphysical component of supersaturation tends to be attenuated as a consequence of global warming, resulting in a spurious negative trend in the RH projection; an illustrative example of this was given in Figure 1b. Accordingly, we do not fully agree with the suggestion of G18 that, when elaborating future projections, one should particularly favor those GCMs that produce supersaturations; conversely, we recommend that the models manifesting overly high near-surface air supersaturations should rather be excluded.

Ideally, the issue will be solved by a continuing improvement in modeling. First, it should be ensured that prognostic calculations in the GCMs produce a reasonable simulation of atmospheric humidity at the model levels, inclusive of the occurrence of supersaturations with respect to ice to a realistic degree. Second, in particular, the diagnostic algorithms used to calculate the 2-m RH have to be developed so that the resulting interpolated humidities would no longer contain any unphysical component induced by ill-behaving vertical interpolation. If these conditions are fulfilled, no spurious trends in future RH projections will arise.

In the coming years, provided that the model output archives will contain data from numerous GCMs with near-surface air RH fulfilling both the above-mentioned conditions (humidity is simulated correctly at the model levels and interpolated realistically onto the 2-m height), it might be possible to found RH projections on these GCMs alone. However, the number of the GCMs providing usable data should be adequate to yield reliable uncertainty estimates.

In compiling model output repositories (e.g., the CMIP6 data bank and COPERNICUS Climate Data Store), the near-surface RH data produced by the various GCMs should be controlled carefully and the users of the data should be informed which GCMs are plausible in this respect. RH data from GCMs providing very unphysical humidities might be excluded altogether from the repositories.

Regarding those GCMs in which the simulation of RH at the model levels works reasonably but interpolation onto the 2-m height does not, an attracting alternative is that the repository would provide RH at the lowermost model level rather than (or, at least, besides) at the 2-m height.

Finally, we emphasize that the overly high RHs in high-latitude areas may be a symptom of fundamental deficiencies in the algorithms used to produce the near-surface air RH, even if higher than 100% time mean humidities are not apparent elsewhere in the world. Accordingly, one should be cautious in using such GCMs for creating the RH projections, even outside of polar areas.
Acknowledgments

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References


