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**Comment on "Surface Air Relative Humidities
Spuriously Exceeding 100% in CMIP5 Model Output
and Their Impact on Future Projections" by K.
Ruosteenoja et al. (2017)**

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COMMENT

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This article is a comment on Ruosteenoja et al. (2017) <https://doi.org/10.1002/2017JD026909>.

Key Points:

- Ruosteenoja et al.'s (2017) claim that supersaturation in the surface atmosphere is unrealistic and necessarily spurious and incorrect
- Supersaturations are a reality that an increasing number of atmospheric models can reproduce even in the surface atmosphere
- Modelers should not artificially cap relative humidity at 100% when feeding climate model archives

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Comment on "Surface Air Relative Humidities Spuriously Exceeding 100% in CMIP5 Model Output and Their Impact on Future Projections" by K. Ruosteenoja et al. (2017)

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1. Introduction

Ruosteenoja et al. (2017; R17 hereafter) analyzes the near-surface atmospheric relative humidity (RH) for current and future climate in 29 different climate models or versions of a given model in the Climate Model Intercomparison Project 5 (CMIP5) archive. They find that the near-surface RH with respect to ice (RHi) frequently exceeds 100% in polar areas in winter. They consider that supersaturation results from inadequate interpolation of atmospheric temperature and moisture to the so-called *surface* level required in the CMIP archives (in principle, the meteorological standard 2-m level). In the abstract, R17 states that "The algorithms used to produce near surface RH should be developed to eliminate the problem" (of RHi > 100%).

Although we fully agree that inappropriate interpolation of prognostic specific humidity and temperature from model levels to a standard surface diagnostic level can result in RH spuriously above 100%, we disagree with the recommendations stating that "the procedure applied to producing near-surface RH data should be revised to avoid the occurrence of significant supersaturations" and "the algorithms used to calculating near-surface RH data should be formulated to eliminate the fundamental causes of supersaturation," in the conclusions of R17. "Eliminate the fundamental causes" is a particularly unfortunate wording. Fundamental physics does allow significant supersaturations with respect to ice to occur in the atmosphere, even near the surface. Considering heterogeneous ice nucleation processes, three of them—immersion freezing, condensation freezing, and contact freezing of water droplets—occur at an RH with respect to liquid water close to saturation, which corresponds to significant values of supersaturation with respect to ice (e.g., ~140% at $T = 240$ K, see Lohmann et al., 2016, Chap. 8).

Significant supersaturations with respect to ice do occur in the surface atmosphere in regions where the atmosphere is cold and clean. An increasing number of climate models have cold microphysics parameterizations, which let RHi exceed 100%. R17 states that "In the real world, near-surface air supersaturations comparable to those occurring in the output files of several GCMs do not appear plausible" (their section 5). They also mention that "supersaturation (in the CMIP models) is largest over central east Antarctica in winter" (their section 3). This is precisely where it is most likely to occur in the real world and where one would like realistic models to reproduce supersaturations with respect to the ice phase. The authors cite the observations of near and slightly over saturation in Genthon et al. (2010) on the high Antarctic Plateau and mention measurement uncertainties but fail to report Genthon et al.'s (2010) comment that supersaturation is not unlikely considering the observed amount of frost deposition in the area, while the hygrometers used cannot measure humidity that exceeds saturation. From carefully calibrated radiosondes, Gettelman et al. (2006) show significant supersaturation over ice in the lower troposphere from Dome C. Reporting further measurements at Dome C, Genthon et al. (2013) explicitly states in the abstract that "Supersaturations are very likely but are not revealed by the observations. This is possibly an instrumental artifact that would affect other moisture measurements made in similar conditions". Genthon et al. (2017) provides a short review of atmospheric moisture measurement techniques and reasons why standard instruments generally fail with supersaturation. They present a new instrumental design that allows the measurement of supersaturation to demonstrate that

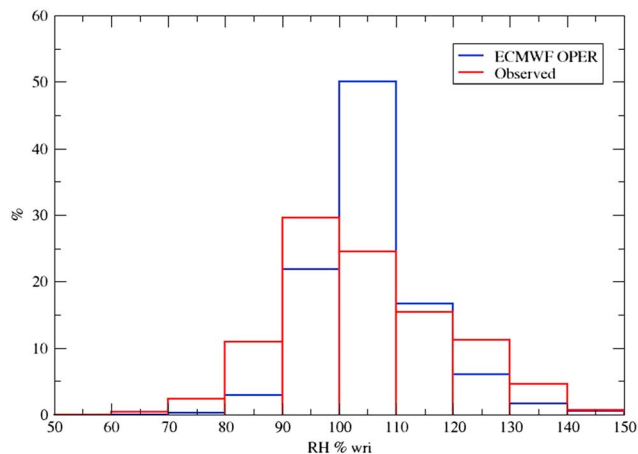


Figure 1. The observation and ECMWF operational analysis of the distribution of RH_i in the surface atmosphere of Dome C, East Antarctica, in 2015. Adapted from Genthon et al. (2017). ECMWF = European Centre for Medium-Range Weather Forecasts; RH = relative humidity.

“in the surface atmosphere of Dome C, East Antarctic Plateau, supersaturation is the norm rather than an exception” (Figure 1). RH_i occasionally reaching above 150% is reported and thus should not necessarily be considered as an artifact in all models. Similar observations were made at Halley station in Antarctica (King & Anderson, 1999) using a frost-point hygrometer. Finally, Gettelman et al. (2006) looked at satellite observations from AIRS (which were validated with Radiosondes at Dome C) and found significant ice supersaturations in the lower troposphere extending over the entire Antarctic plateau.

A common approach in the earlier development of general circulation models (GCMs) has been to apply saturation adjustment when RH_i reaches 100%, assuming rapid removal (within one time step) of any ice supersaturation to form ice cloud. However, this was contrary to observations of supersaturations in the upper troposphere from aircraft and remote sensing (e.g., Heymsfield & Miloshevich, 1995; Heymsfield et al., 1998; Gierens et al., 1999; Spichtinger et al., 2003) and motivated an explicit representation of ice supersaturation in a number of global atmospheric models with varying degrees of complexity of ice nucleation and deposition processes. Ice nucleation processes in particular are complex and

highly uncertain in the atmosphere, yet simple parametrization schemes have shown significant success in capturing both the spatial/temporal occurrence and magnitude of ice supersaturation. A simple parametrization scheme for homogeneous ice nucleation described by Kärcher and Lohmann (2002) is based on observations by Koop et al. (2000) that homogeneous freezing is independent of the chemical nature of the solution and only depends on the water activity of the solution droplets. This scheme, which allows ice supersaturation up to a defined threshold between water and ice saturation before cloud formation, was implemented in the European Centre for Medium-Range Weather Forecasts global operational model and ERA-Interim re-analysis (Tompkins et al., 2007) and is also used in the GISS-E2 models (Schmidt et al., 2014) included in R17. Tompkins et al. (2007) show that the ice supersaturation scheme, while simple, reproduces well the climatological probability density function of upper tropospheric supersaturations derived from MOZAIC aircraft observations (Gierens et al., 1999) as well as the geographical distribution of ice supersaturation given by the MLS satellite retrievals (Spichtinger et al., 2003). The CMIP5 simulations in R17 based on the Met Office Unified Model (HadGEM2 and ACCESS1 models) also allow supersaturation (Franklin et al., 2012; Wilson & Ballard, 1999) by assuming homogeneous nucleation at a critical RH threshold relative to water saturation at subfreezing temperatures, and heterogeneous nucleation at cold temperatures once water cloud is present. Supersaturation within cloud is then depleted by the parametrized ice deposition. MIROC5 also uses the Wilson and Ballard (1999) microphysics parametrization (Watanabe et al., 2010) allowing ice supersaturation. The NCAR-CESM1-CAM5 model (Gettelman et al., 2010; Liu et al., 2007) used for CMIP5 features the Liu and Penner (2005) parameterization of ice nucleation processes, with homogeneous nucleation at a supersaturated RH_i threshold similar to Kärcher and Lohmann (2002) and a more complex representation of heterogeneous nucleation processes determining the formation of ice particles, which permits significant ice supersaturation (Gettelman et al., 2010). In all these models the various levels of representation of heterogeneous ice nucleation processes all act to nucleate small amounts of ice that then lead to the in-cloud supersaturation being controlled by the ice deposition process.

Despite the general lack of complexity in these GCM parametrization schemes, particularly regarding ice nucleation process, evaluation with observations has shown it is possible to represent the first-order ice supersaturation occurrence and magnitude in the free troposphere, albeit with varying degrees of success. The applicability of such nucleation schemes to near-surface air is perhaps more questionable, but recently available near-surface data over Antarctica suggests that these same physically based parametrizations also have applicability in cold temperatures in the boundary layer. Genthon et al. (2017) shows that the operational European Centre for Medium-Range Weather Forecasts model with the Kärcher and Lohmann (2002) homogeneous ice nucleation parametrization (Figure 1) and the Modèle Atmosphérique Régional (e.g., Gallée & Gorodetskaya, 2010) do simulate frequent near-surface supersaturation at Dome C, although not quite with the same statistics as observed and thus may deserve further improvements in this respect.

In addition to improving the parametrization of clouds (e.g., Gettelman et al., 2010) and predicting the moisture distribution in polar regions, accounting for supersaturation is of first importance for assessing the snow accumulation over the central part of the ice sheets and for understanding the water isotopes dynamics (Berkelhammer et al., 2016; Casado et al., 2016). The parametrizations in GCMs continue to be developed, with increasingly complex representations of ice microphysics. The observed statistics of RH_i including frequent and often high ice supersaturations, in both the free troposphere and near the surface, should be considered as challenges and targets rather than artifacts in models that implement advanced cold microphysics parameterizations.

In conclusion, we fully agree with R17's point that poorly designed cointerpolation of temperature and moisture from prognostic model levels can result in spurious diagnostics of supersaturation at the surface level requested in the CMIP and possibly other widely distributed and used archives of climate model simulations and predictions. We fully appreciate the point made that inappropriate interpolations may result in biased near-surface RH values and spurious estimations of the amplitude of moisture change with climate change. On the other hand, we do not agree with R17 stating that supersaturations in the surface atmosphere are not realistic and should altogether be removed from model data sets feeding archives. This recommendation is misleading. One would not like for instance that on the basis of R17's recommendations, model analysts feeding the CMIP6 archive decide to cap all RH_i at the surface level to 100% even in models that purposely account for and produce supersaturations. This would be detrimental for simulations of high-latitude regions, particularly over ice sheets, and properly representing the snow accumulation onto the ice sheet. In addition, R17 makes the statement on GCMs that represent near-surface ice supersaturation, that climate projections of RH "should not be founded on any of these particular GCMs alone or on a limited ensemble of GCMs within which the weight of such ill-behaved models would be large." In fact, to the contrary, we suggest that those GCMs that have a physically based representation of ice supersaturation may be more representative in giving an indication of the impact of climate change on near-surface polar RH.

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