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How microphysical choices affect simulated infrared brightness temperatures

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ABSTRACT

Numerical weather prediction (NWP) today relies more and more on satellite data, both for assimilation and for evaluation. However, process-based analyses of the biases between observed and simulated satellite data, which go beyond a mere identification of the biases, are rare. The present study investigates a long-known bias (Böhme et al., 2011) between brightness temperatures (BTs) simulated from the regional NWP model COSMO-DE forecasts via RTTOV (Radiative Transfer for TOVS) and those observed by Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). The pivotal question is whether a novel two-moment cloud ice scheme, developed by Köhler (2013) primarily to improve the representation of ice nucleation processes, exhibits an improved performance with respect to this bias and, if that is so, to provide a process-based analysis which identifies the reasons for the improved behaviour.

It is shown that the new two-moment cloud ice scheme reduces the BT bias distinctly and can therefore be considered an improvement in comparison to two standard schemes, the two-category ice scheme and the three-category ice scheme. The improvement in simulated BTs is due to a vertical redistribution of cloud ice to lower model levels. Sensitivity studies identify two of the introduced changes in the two-moment cloud ice scheme to be hand-in-hand responsible for most of the improved performance: the choice of heterogeneous ice nucleation scheme and the consideration of cloud ice sedimentation. Including only cloud ice sedimentation without changing the heterogeneous ice nucleation scheme has no distinct effect on cloud ice. Further sensitivity studies with varying aerosol number densities reveal a comparably small sensitivity, indicating that the use of a physically reasonable heterogeneous ice nucleation scheme is far more important than the exact knowledge of the actual aerosol number densities.

1. Introduction

Numerical weather prediction (NWP) relies heavily on the use of satellite data. These are used primarily for assimilation but also as an observed truth for the evaluation of NWP models. Satellite remote sensing instruments measure different quantities (e. g. brightness temperatures, BTs) than NWP models predict (e. g. hydrometeor contents). As a consequence, evaluation takes place in either the observation (BTs) or the model (hydrometeor contents) space, requiring either the retrieval of model quantities from observations or the forward modelling of observed quantities from model data. Both approaches—retrieval and forward operator—require a series of assumptions. For the evaluation of cloud properties, a forward operator producing synthetic satellite observations is often preferred, since it is less ambiguous than a retrieval. For example, the impact of instrument effects can easily be tested.

Though the comparison of synthetic to real-world satellite observations is a frequently used approach in model

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evaluation, most studies have in common that they only identify biases in the different parameterization schemes and evaluate their relative performance (e. g. Cintineo et al., 2014; Otkin and Greenwald, 2008; Jankov et al., 2011). However, the reasons for these biases often remain unclear or speculative because a process-based analysis, that is the identification of the relevant processes causing these biases, is missing. Cintineo et al. (2014) evaluate the cloud cover of various boundary layer and cloud microphysical parameterization schemes in the Weather Research and Forecasting Model (WRF) ensemble using Geostationary Operational Environmental Satellite (GOES) infrared (IR) BTs. They identify the schemes which perform best in certain cloud situations, but only hypothesise on the reasons, namely a connection between the over- or underestimation of cloud ice water content (CIWC) and that of cloud cover. They do not explicitly look at the vertical distribution of cloud ice from the various schemes nor give reasons for why cloud ice is produced at a given altitude. A similar comparison is done by Otkin and Greenwald (2008) but with Moderate Resolution Imaging Spectroradiometer (MODIS) instead of GOES BTs. Jankov et al. (2011) also use GOES IR BTs to complement their evaluation of WRF and they emphasise the benefits of synthetic satellite data in comparison to traditional validation techniques such as surface precipitation. They demonstrate that only the simulated BTs reveal that WRF produces too many clouds, whilst all other metrics provide no indication of this. Still, though identifying the model deficiency, they do not aim to identify the processes actually responsible for it.

At Deutscher Wetterdienst (DWD), a long-term goal is to assimilate Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) BTs (Schmetz et al., 2002) in the operational short-range NWP model COSMO-DE (an application of the Consortium for Small-scale Modelling, COSMO; Baldauf et al., 2011). To this end, like other NWP centres, DWD coupled the fast radiative transfer model RTTOV (Radiative Transfer for Television Infrared Observation Satellite Operational Vertical Sounder; Saunders et al., 2010) to COSMO-DE via the diagnostic tool SynSat (Synthetic Satellite imagery; Keil et al., 2006). This enables the real-time operational simulation of MSG SEVIRI's BTs from COSMO-DE output.

Within their evaluation of COSMO-DE's forecasting performance during the General Observation Period (GOP; 2007–2008; Crewell et al., 2008) of the German Priority Programme on Quantitative Precipitation Forecasting (Praecipitationis Quantitativae Praedictio, PQP), Böhme et al. (2011) find a distinct bias between simulated COSMO-DE and observed MSG SEVIRI BTs in the frequently used window channel at 10.8 μm. In this channel, COSMO-DE distinctly overestimates the occurrence of low BTs resulting in a secondary peak at approximately 230 K in the frequency distribution, in addition to the main peak at 270 K. This secondary peak is non-existent in the MSG SEVIRI observations. Since cold BTs indicate high (cold) clouds, this secondary peak at low BTs suggests that COSMO-DE either overestimates the occurrence of high clouds in general (too frequent or horizontally too extended) as proposed by Pfeiffer et al. (2010), overestimates cloud top height when high clouds are present, overestimates cloud optical thickness, or a combination of all these.

The goal of the present study is to determine firstly, whether a more recent version of COSMO-DE still exhibits the same behaviour, secondly, whether a novel two-moment cloud ice microphysical parameterization developed by Köhler (2013) performs better than the standard three-category ice scheme with respect to this secondary peak, and thirdly, if yes, to provide a process-based analyses which identifies the reasons for the different behaviour.

The paper is structured as follows. Firstly, COSMO-DE and its modifications are introduced in Section 2.1, followed by a description of the MSG SEVIRI observations themselves, the forward operator RTTOV, and the diagnostic tool SynSat in Section 2.2. The results of the statistical approach and from the sensitivity studies are presented in Section 3. Finally, summary and conclusions are given in Section 4.

2. Data

2.1. COSMO-DE

2.1.1. General

The convection-resolving regional NWP model of Deutscher Wetterdienst (DWD), COSMO-DE (Baldauf et al., 2011), is a non-hydrostatic, fully compressible limited-area model of the atmosphere. Its domain covers Germany and some parts of the neighbouring countries (cf. Fig. 1). The thermo-hydrodynamical equations describing compressible flow in a moist atmosphere are solved using a finite-difference method on an Arakawa-C grid (Arakawa and Lamb, 1977). The COSMO-DE model uses rotated latitude/longitude coordinates in the horizontal and time-independent, generalised terrain-following coordinates in the vertical. COSMO-DE has a horizontal resolution of 2.8 km and 50 hybrid levels in the vertical. Level thickness ranges approximately from 20 m at the Earth's surface, 400 m in 5 km height, to 1000 m in 20 km height. Note that up to now, no BTs are assimilated in COSMO-DE.

2.1.2. Microphysics

For the present study, three different microphysical schemes are used for COSMO-DE. The first is the currently operational three-category ice scheme (Doms et al., 2011), which features five prognostic grid-scale hydrometeor classes in total: cloud water, cloud ice, rain, snow, and graupel. It is in the following referred to as 3I. The assumed particle size distributions are monodisperse for both cloud water and cloud ice, gamma for rain, and exponential for both snow and graupel.

The second microphysical scheme is the two-category ice scheme (Doms et al., 2011), which lacks graupel, but apart from that is very similar to the three-category ice scheme. This scheme is in the following referred to as 2I.

The third is the novel two-moment cloud ice scheme developed by Köhler (2013). Similar to the two-category ice scheme 2I, it features four hydrometeor classes, but for cloud ice two moments are predicted. That is, not only the specific hydrometeor content of cloud ice as in the one-moment schemes, but also the number concentration for cloud ice is predicted. In the following, this scheme is referred to as 2MI. Coupled to the two-moment treatment of cloud ice is a different treatment of diffusional growth: A relaxation approach following Morrison et al. (2005) replaces the original