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Uncertainties in synthetic Meteosat SEVIRI infrared brightness temperatures in the presence of cirrus clouds and implications for evaluation of cloud microphysics

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ABSTRACT

Synthetic brightness temperatures of five infrared Meteosat SEVIRI channels are investigated for their sensitivities on cirrus radiative properties. The operational SynSat scheme of the regional German weather prediction model COSMO-DE is contrasted to a revised scheme with a special emphasis on consistency between the model-internal ice-microphysics and infrared radiation in convective situations. In particular, the formulation of generalized effective diameters of ice, snow and graupel as well as subgrid-scale cloud cover has been improved. Based on the applied modifications, we first show that changed assumptions on the cirrus radiative properties can lead to 10 K warmer brightness temperatures. Second, we demonstrate that prescribed relative changes of 20% in cloud cover and particle size induce maximum changes of around 4 to 5 K. The maximum sensitivity appears for semi-transparent cirrus having brightness temperatures around 240 and 260 K and total frozen water path around 30 $\mathrm{gm^{-2}}$ for viewing geometries over Central Europe. We further consider the known COSMO-DE cold bias to discuss the problem of inconsistencies in model-internal and external formulations of cloud microphysical and radiative properties. We demonstrate that between 35% and 70% of the cold bias can be attributed to the radiative representation of cirrus clouds. We additionally discuss the use of window-channel brightness temperature differences for evaluation of model microphysics and hypothesize that the amount of COSMO-DE ice is overestimated in convective situations.

1. Introduction and motivation

Over the last decades, satellite observations have become indispensable data source for numerical weather prediction leading to substantial improvement in forecasting skill (Bauer et al., 2015). While the methods of using cloud-free hyperspectral infrared or microwave radiances from polar orbiting satellites together with variational data assimilation have reached a level of maturity in retrieving atmospheric profile information on global scales, the use of cloud-affected radiances of frequently observing, high resolution geostationary imagers remains one of the major challenges for data assimilation on the regional or convective scale (Bauer et al., 2011).

One major component of state-of-the-art data assimilation and model verification/evaluation strategies consists of the transfer of model data into observation space using computationally efficient radiative transfer models (e.g. (Saunders et al., 1999)), also called forward operators. Resulting synthetic satellite observations represent the simulated spatial distribution of the top-of-atmosphere outgoing radiation accounting for the spectral response of a chosen satellite sensor and can easily be compared to real observations. Synthetic satellite images derived for imaging radiometers have been used for model verification for more than twenty years. Morcrette (1991) used synthetic infrared Meteosat images to evaluate the diurnal cycles of surface temperature and cloudiness of the global ECMWF (European Centre for Medium-Range Weather Forecasts) model. He coined the term model-to-satellite approach. Roca et al. (1997) investigated the ability of a general circulation model to reproduce the observed relationship between tropical convection and subtropical moisture in the upper troposphere. The life-cycle of cloud systems and the diurnal cycle of cloud cover was further studied based on different model architectures with special emphasis on the representation of temporal and spatial variability in cloud forecasts (Chaboureau et al., 2000; Chevallier & Kelly, 2002; Slingo et al., 2004). For instance, Chaboureau et al. (2000) found an overestimation of the upper-level cloud cover in simulations of their Meso-NH model. Otkin et al. (2009) derived synthetic infrared MSG SEVIRI (Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager) brightness temperatures for high resolution model runs and showed that the simulated brightness temperatures realistically depict many of the observed features. Using a joint analysis of window-channel brightness temperature distributions and cross-channel differences, they could identify limitations in their current cloud-microphysical

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scheme. Sensitivities of derived model forecasts and correspondingly of synthetic brightness temperatures to variations in microphysics and boundary layer parameterizations have been investigated by e.g. Otkin & Greenwald (2008) and Cintineo et al. (2014). Based on the comparison with observed cloud features as well as brightness temperatures, they identified the typical range of variations and the best performing schemes for certain cloud types. As model resolution steadily improves synthetic satellite images become increasingly important for the validation of deep convective processes (see e.g. (Bikos et al., 2012)).

For the German numerical weather prediction model COSMO-DE (Consortium for Small-scale Modeling - DE), a systematic bias in cold cloud cover was identified in several earlier studies (Pfeifer et al., 2010; Böhme et al., 2011; Eikenberg et al., 2015) which were using synthetic satellite images derived with the operational SynSat algorithm (Keil et al., 2006). It was found that the occurrence frequencies of brightness temperatures in the MSG SEVIRI 10.8 μm channel (BT10.8) at around 230 K are significantly overestimated by the model-based synthetic satellite images. Recently, Eikenberg et al. (2015) could show that the cold bias can be partially reduced when improvements to the microphysical parameterization, especially concerning the representation of ice nucleation processes as described in Köhler & Seifert (2015), are included.

For current data assimilation systems, the incorporation and beneficial use of cloud-affected satellite radiance is still challenging. For instance, Stengel et al. (2013) discussed the positive impact of the assimilation of cloud-affected infrared radiances on the moisture and geopotential height fields. Okamoto et al. (2013) assessed the use of the average cloud effect defined as difference between cloudy and clear-sky radiation for data assimilation purposes. Furthermore, Schomburg et al. (2014) established a concept for the assimilation of satellite-derived cloud properties within a mesoscale model using an ensemble Kalman Filter approach. All these data assimilation activities can benefit from a good assessment of uncertainties of synthetic satellite images in cloudy conditions.

However, one current problematic aspect in the simulation of synthetic satellite images is that often differing and contradicting assumptions on the properties of hydrometeors are applied in the model microphysics and in the radiative transfer. Therefore, several variables that are derived from the prognostic model variables via diagnostic schemes, for instance subgrid-scale cloud cover and effective particle size, are to some degree unconstrained. This can introduce uncertainties in the synthetic radiances and partially complicates the interpretation of observed model biases and their sensitivity to model changes. To address that issue, a more strict reformulation of subgrid-scale parameterizations imposing self-consistency has been proposed (Baran, 2012; Baran et al., 2014a, b; van Diedenhoven et al., 2014) in which essentially the same assumptions about hydrometeor properties are applied to the model-internal microphysical and radiative calculations. For instance, Baran et al. (2014b) established a parameterization of microphysical ice crystal properties that preserves the physical consistency between the cloud physics and radiation schemes across a large range of wavelengths in climate model simulations. They pointed to the importance of the choice of the particle size distributions as well as the assumed shape mixtures. Moreover, we like to emphasize that self-consistency should also be extended to model-external calculations that deal with the simulation of synthetic observations using forward operators and with the derivation of cloud properties using observation-based retrieval algorithms. Within that line, Thompson et al. (2016) provided a recent study in which effective radii of cloud water, cloud ice, and snow were diagnosed based on assumptions in the model microphysics scheme. The authors could show that the subsequent use of consistently derived effective particle sizes in the model-internal radiation calculations and in the satellite forward operator can improve the agreement with observations.

Furthermore, the ice-microphysics parameterization faces the challenge that a distinction of frozen condensate in categories, e.g. ice, snow and graupel, with predefined characteristics is inherently artificial and often done without a strong theoretical or empirical basis [see e.g. (Morrison & Milbrandt, 2015) and discussion and references therein]. Due to their importance on the global scale, shortcoming in the representation of cirrus-micro physical and radiative properties can lead to significant errors in weather forecasts and climate predictions (see e.g. (Waliser et al., 2009)). In addition, Waliser et al. (2009) discussed that difficulties in the interpretation of simulated frozen hydrometeor variables can delay progress in model improvements, especially when suspended cloud ice is distinguished from precipitating particles and when observations or retrievals are highly sensitive to different parts of the hydrometeor size spectrum. This emphasizes the central point of our paper that a consistent description of hydrometeor radiative properties is needed across the full range of the electromagnetic spectrum, also in view of the synergistic utilization of future multi-sensor active and passive satellite observation (see e.g. (Illingworth et al., 2015)).

The primary goal of our study is to quantify and understand uncertainties in synthetic brightness temperature which arise from various assumptions about microphysical properties of frozen hydrometeors and subgrid-scale cloud cover in realistic cloud scenes. We therefore introduce the Meteosat and COSMO-DE data in Section 2. The simulation of cloud-affected radiances via the operational scheme as well as with the revised scheme is explained in Section 3. Systematic changes and sensitivities to perturbations of cloud properties are assessed in the results section 4. A discussion on the origin of emerging uncertainties and implication for the interpretation of model biases is examined in Section 5. Finally, conclusions are given in Section 6.

2. Data

2.1. Infrared MSG SEVIRI data

This study uses observational data and sensor characteristics of five infrared channels of the imaging radiometer Spinning Enhanced Visible and Infrared Imager (SEVIRI) aboard the geostationary Meteosat Second Generation (MSG) satellites operated by EUMETSAT (Schmetz et al., 2002). The studied channels are centered around 6.2, 7.3, 8.7, 10.8 and 12.0 μm and form a subset of all available SEVIRI channels comprising all together of 11 narrow-band and one broad-band high-resolution visible channel. We focus on data of the primary scan service, which has an orbital position at zero degree longitude and an image update cycle of 15 min. We concentrate on the domain covered by the forecast model COSMO-DE, which is further described in the next section. The SEVIRI narrow-band channels have approximately a resolution of $4 \times 6 \text{km}^2$ in this domain which is coarser than the COSMO-DE grid size of $2.8 \times 2.8 \text{km}^2$ (see next subsection). Before comparison with synthetic satellite images, SEVIRI observations are regridded onto COSMO-DE grid using nearest-neighbor interpolation.

The selected SEVIRI channels essentially fall into two categories: water vapor and window channels. In the 6.2 and 7.2 μm channels, water vapor absorption and emission is strongly influencing the outgoing radiation. The transmissivity of a cloud-free atmosphere is lower in the 6.2 μm channel leading to an increased effective emission altitude compared to the 7.3 μm channel. This altitude is around 9 and 7 km for the 6.2 and 7.3 μm channels, respectively, with a typical variation of 1 km in both channels due to variations in atmospheric temperature and moisture. Clouds affect the outgoing thermal radiation at 6.2 and 7.3 μm, if the cloud-top height is close to or higher than the effective emission altitude. The other three channels, centered around 8.7, 10.8 and 12.0 μm, fall into the window channel category. They are less affected by atmospheric gases and show the radiative signature of surface, clouds, aerosols or a combination of these. As the liquid and ice cloud emissivities are slightly different for all the three window channels, cross-channel brightness temperature differences (BTDs) carry information about in-cloud microphysical properties such as cloud phase and ice crystal size (see e.g. (Strabala et al., 1994; Pavolonis, 2010)).