Evaluating the ECMWF model's clouds and radiation with ARM observations

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1. Introduction

The Atmospheric Radiation Measurement program maintains five permanent and two mobile observational facilities around the world. These are heavily instrumented sites including active and passive sensors to measure cloud properties and radiation, similar to the European sites that form the CloudNet network (Illingworth et al, 2007). Some of the ARM sites have been maintained for over a decade and provide long-term observational records.

Radiation and precipitation are two prime reasons why we care about clouds in models. While clouds also impact dynamics via latent heating, this is a more indirect effect, and as such it is more challenging to try and link the impact on dynamics to cloud properties or specific parameterizations. Evaluation products for radiation, particularly for top-of-the-atmosphere (TOA) fluxes, and for precipitation are available from satellites, and are quite well established. It is inevitable that in comparison with these products the model will fall short in some area.

The challenge lies in establishing a link between the model errors and a specific aspect of the model that needs to be improved. As a first step towards this goal, it is helpful to identify conditions under which the error occurs, e.g. a region, cloud type or regime. A second step would be to establish a link between the model error and a particular model parameterization. Often, and particularly in the NWP environment, the model is tuned for best performance and may produce good results due to compensating errors. The goal must be to identify these compensating errors and maintain or improve the good performance, but for the “right reason”.

Ground based observations are particularly well-suited to establish this link between model error and parameterized process. They provide vertically resolved cloud micro- and macrophysical properties in conjunction with radiative observations. Often, parameterizations are built based on a small number of case studies tested with large eddy simulations, single column models or limited area cloud resolving models. The long time series available from the ARM sites allow an evaluation of model performance under less idealised, and more “messy” conditions. A limitation is the scarcity of sites, which poses the question of whether conclusions drawn from a handful of locations are representative of the globe. Here, a link with satellite observations to extrapolate from single locations to the globe is helpful to establish relevance.

2. Model bias in shortwave radiation, and link to cloud parameterization

The following example will illustrate this approach by establishing a link between a long standing model bias in TOA shortwave radiation and aspects of the boundary layer (BL) parameterization in the IFS. Figure 1 shows the model's TOA shortwave bias compared to the CERES EBAF data product for a climate run (recent cycle; ensemble of four year-long forecasts). The cloud forcing is underestimated in the stratocumulus regions, the Southern Ocean and over the North American continent. In large of parts of the subtropical oceans (trade wind regions), the cloud forcing is overestimated. It is unclear whether this model bias is related to errors in cloud fraction, cloud occurrence or cloud properties, or a mixture of all three. While the cause may not matter for the bottom line - the TOA radiative flux - it does matter to establish that link with parameterizations.

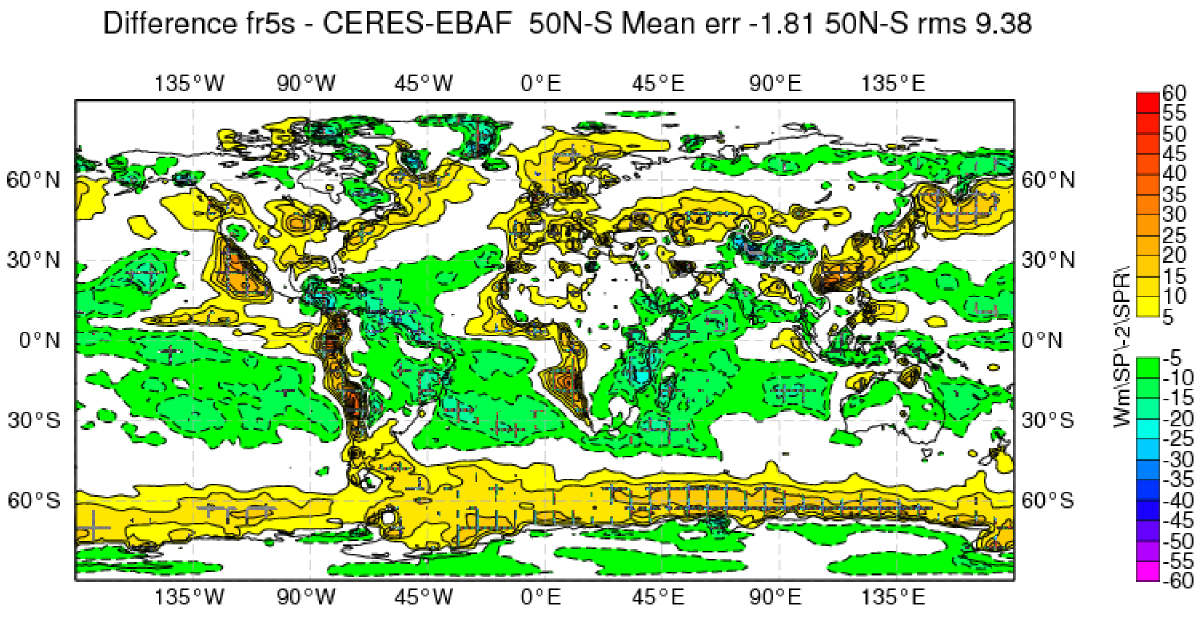

Figure 1: Shortwave bias of the IFS in compared to the CERES Energy Balanced and Filled data product for a climate run. Green shading indicates areas where too much SW is reflected back to space, while yellow/orange areas indicate regions where too much SW is absorbed.

A model error consistent with the TOA shortwave flux can be found in the surface irradiance record at the ARM SGP site in Oklahoma (Fig. 2, left panel). Based on previous, month-long study, fair weather cumulus clouds common during the summer months are suspected to contribute to the bias in surface irradiance (Cheinet et al, 2005). Yet, a composite of 146 select days with fair weather cumulus clouds shows that the model's cloud forcing in this regime is in good agreement with observations (Fig. 2, center and right panels). However, this agreement is achieved through compensation of errors. The model fails to produce clouds on some days, but compensates by producing too reflective clouds with higher liquid water paths than observed on other days. Hence, the fair weather cumulus regime does not contribute significantly to the multi-year mean bias in surface irradiance at the SGP site (Ahlgrimm and Forbes, 2012).

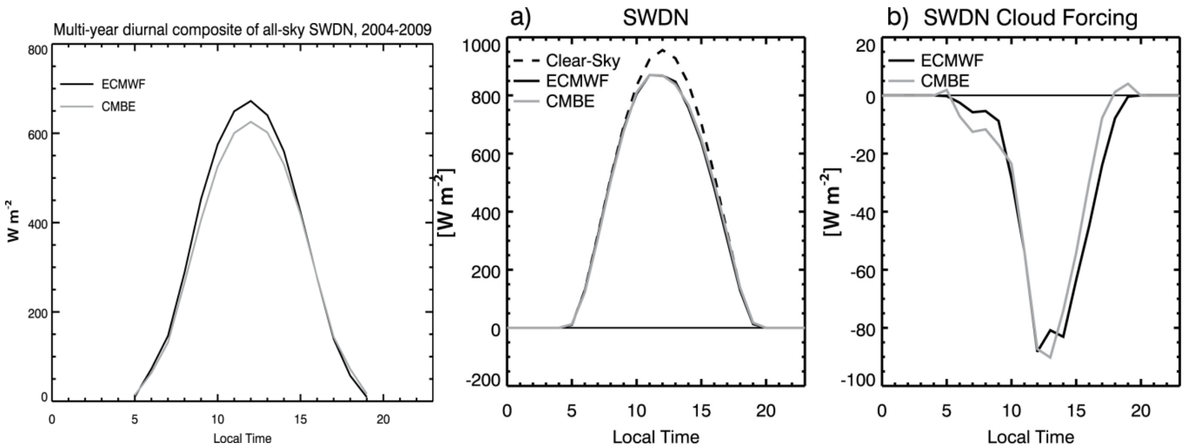

Figure 2: (Left) Multi-year diurnal composite of surface irradiance at the ARM SGP site from IFS and observations [ARM Cloud Modeling Best Estimate product, CMBE]. (Center) Diurnal composite of surface irradiance at SGP site for 146 select days with fair weather cumulus present. (Right) Shortwave cloud forcing (vs. model clear sky) for fair weather cumulus days at SGP.

In order to identify clouds that contribute to the bias, hourly samples from observations and model are classified into cloud types based on cloud base height and vertical extent. Each sample pair has an associated surface irradiance bias. Cloud type combinations are then ranked by how much they contribute to the shortwave bias, using the cumulative bias of each combination as a measure (for details, see Ahlgrimm and Forbes, 2012). Low clouds emerge as contributing significantly to the mean bias. This contribution stems primarily from overcast low cloud situations where the model underestimates cloud fraction and produces broken clouds instead. But even when the model correctly forecasts overcast conditions, liquid water path and cloud forcing are underestimated. Consistent with the results from the fair weather cumulus days, the opposite model error is found for broken clouds: liquid water path and cloud forcing are overestimated. Thus, errors from overcast and broken cloud types partially compensate, with the overcast cloud errors dominating.

While the radiation bias found at the ARM SGP site is consistent with the global picture, it is by no means certain that the conclusions drawn from the SGP site data also apply elsewhere. Another ARM facility, stationed for 19 months on the island of Graciosa in the Azores provides similar observations from a location dominated by marine boundary layer clouds.

Figure 3a shows a joint histogram of observed and modelled total cloud cover for hourly samples collected over the 19 months at Graciosa. While overcast conditions are often observed and modelled, there is also significant mis-match. Notably, the model produces few cases with cloud fractions between 50 and 90%, and also overall fewer overcast cases. The centre and right panels show the downward shortwave and longwave biases associated with each bin of the joint histogram. Along the diagonal lie samples where model and observations agree on cloud fraction. If the model reproduced the cloud properties perfectly, there should be no bias associated with these samples. However, surface irradiance is overestimated for overcast conditions and underestimated for broken cloud conditions (opposite for downward longwave). This is consistent with the conclusions drawn from the SGP site, and gives confidence that these results are robust for continental and maritime dominated low cloud regimes.

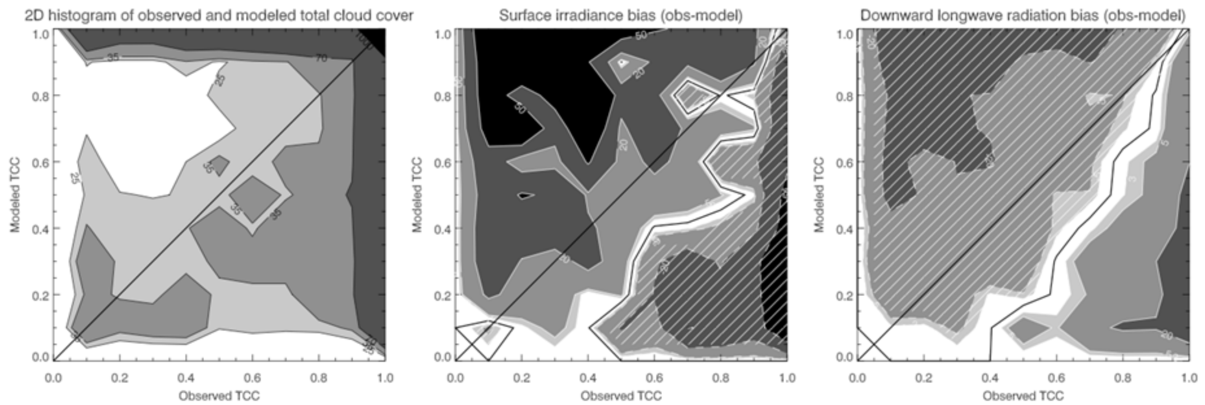

Figure 3(Left) Joint histogram of observed and modelled total cloud cover for hourly samples from 19 months of observations collected at the ARM mobile facility on Graciosa Island. The center and right panels show the mean shortwave and longwave downwelling surface radiation biases associated with each bin in the joint histogram.

After identifying these opposite and partially compensating biases for broken and overcast low cloud cover, it is possible to target the parameterizations involved in creating these clouds.

3. The EDMF scheme

The ECMWF model currently uses the Eddy Diffusivity/Mass Flux scheme (Köhler et al. 2011) to treat boundary layer (BL) transport. Four boundary layer types are distinguished: stable, dry convective, stratocumulus and decoupled. The sign of the surface buoyancy flux determines whether the BL is stable or convective. If convective, a test parcel ascent is calculated. Air properties from the lowest model layer are given a temperature and moisture excess based on the surface fluxes. Lateral entrainment mixes environmental air with the parcel during the ascent until the parcel's vertical motion ceases. If the parcel saturates during the ascent, the BL is considered to be cloudy. In case of high lower level stability (Klein and Hartmann 1993), the BL type is "stratocumulus", and the EDMF scheme treats the moist transport throughout the subcloud and cloud layer, producing a tendency for cloud fraction and condensate. If the stability criterion is not met, transport is only treated up to cloud base, and transport throughout the cloud layer is left to be treated by the convection scheme (the "decoupled" case).

The concept of separate BL types has advantages and disadvantages. One advantage is that the focus on a BL type reduces the number of processes that need to be represented to model that particular BL type well. A drawback is that the transition between BL types and situations that don't fall neatly into any particular category may not be treated well. To take full advantage of this approach's strengths (i.e. the accurate representation of well-defined BL types) it is crucial that the appropriate BL type is selected for a given situation.

A single column model experiment of a stratocumulus-to-trade cumulus transition case reveals that in the IFS, the "dry BL" type is commonly active in combination with shallow convection, even under conditions where the BL is well mixed and stratocumulus should be present. This indicates that the BL test parcel failed to reach the lifting condensation level, and as a result, the cloud produced by the shallow convection scheme underestimates cloud fraction.

As a sensitivity experiment, the lateral entrainment formulation of the test parcel is modified. The more the parcel entrains, the more rapidly the temperature and moisture excess is diluted, and buoyancy is lost. A more conservative (i.e. less entraining) parcel rises higher, finds cloud base and the BL type "stratocumulus" is switched on correctly, leading to higher cloud fraction.

When applied globally, the improved triggering of the stratocumulus scheme leads to an improvement of the systematic TOA shortwave error, though it does not fully resolve it.

4. Cloud microphysics

Figure 4 shows liquid water path (LWP) distributions observed and modelled at the ARM SGP site for broken and overcast low cloud. Under broken cloud conditions, the model overestimates the number of high-LWP samples, but underestimates the number of low-LWP samples. This is consistent with the shortwave cloud forcing discussed previously for fair weather cumulus clouds. The LWP distribution for overcast low clouds is shifted in the opposite direction, i.e. the model underestimates the occurrence of high-LWP samples. Again, this is consistent with the radiation bias for this cloud type. In addition, the model's effective radius in low clouds is larger than observed for all low clouds, lowering the clouds' reflectance in the shortwave. However, this effect appears to be secondary to the LWP error.

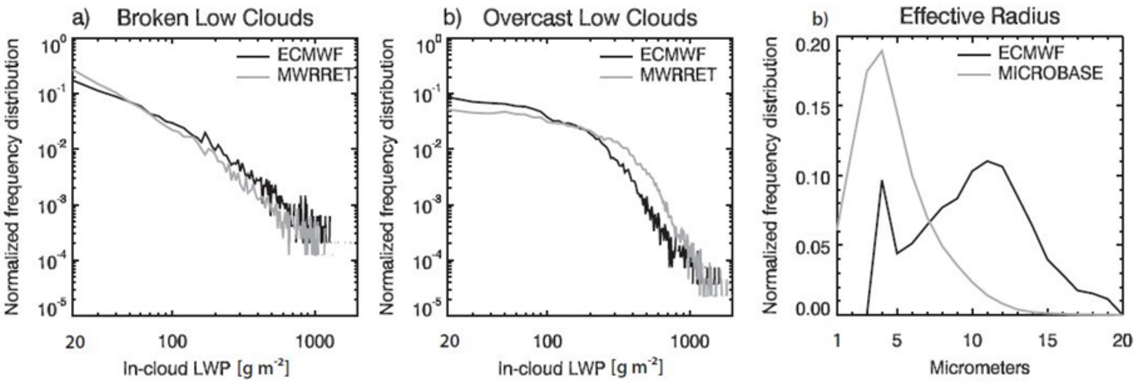

Figure 4: Normalized frequency distributions of (grey) observed and (black) modelled in-cloud LWP at ARM SGP. (Left) For samples with broken (< 90%) low clouds in model and observations. (Centre) For samples with overcast (≥90%) low clouds in model and observations. (Right) Observed (ARM Microbase product) and modelled effective radius for low clouds observed at ARM SGP.

5. Summary

This example of the shortwave error in the IFS model illustrates how ground-based observations used in conjunction with satellite products can help to identify shortcomings in the model's parameterizations, and guide efforts for model improvement. In this particular case, several aspects of the boundary layer/shallow convection complex were identified as contributing to the bias. In order to improve the representation of BL clouds, triggering of the BL scheme needs to be improved. Future parameterization changes should also aim to increase LWP in overcast low clouds, while reducing LWP in broken low clouds. Since the errors identified are compensating to a degree, a holistic approach is needed that addresses all aspects of the parameterization together, else lack of compensation will lead to a deterioration of the forecast.

More and more observational products are becoming available that are potentially useful to constrain model parameterizations, such as estimates of vertical velocity below and within the cloud, as well as derived quantities such as mass flux and plume dimensions (Chandra et al., 2010; Ghate et al., 2010; Ghate et al. 2011). Accurate drizzle retrievals are promising to better constrain assumptions on autoconversion and accretion rates (O'Connor et al., 2005, Kollias et al. 2011).

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