Clouds in the trade wind regime – the “too few, too bright” problem

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1. Introduction

Many global models have long-standing biases in top-of-the-atmosphere shortwave radiation over the subtropical oceans. The cloud albedo is typically too low over the maritime stratocumulus decks and too high over the regions of trade cumulus, with consequences for the model’s radiation budget and response of the ocean in coupled models. The cause of radiation biases in the stratocumulus areas is generally consistent with a lack of cloud cover and liquid water path and is reasonably straight-forward to interpret (though by no means easy to remedy). However, in the trade cumulus regime the clouds in many models are still too reflective, yet comparison against satellite observations indicates that cloud fraction and/or liquid water path (LWP) are underestimated.

Here, we draw on ground-based observations from the MAGIC campaign to complement the view from satellite, and gain a better understanding of the underlying causes for trade cumulus clouds to be “too bright”, despite the apparent lack of cloud cover and water compared to satellite observations.

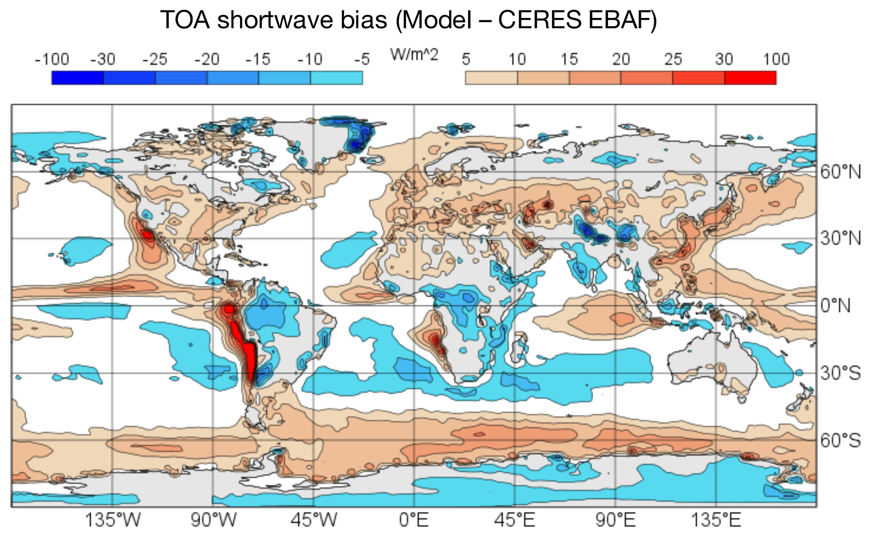

Figure 1 Model bias in TOA shortwave radiation compared to CERES EBAF observations for an ensemble of long-range runs covering 30 years. Blue shades indicate areas where too much sunlight is reflected back to space.

The map above illustrates the global scale of the problem, and that apart from MAGIC, few permanent observational sites are ideally located to tackle it.

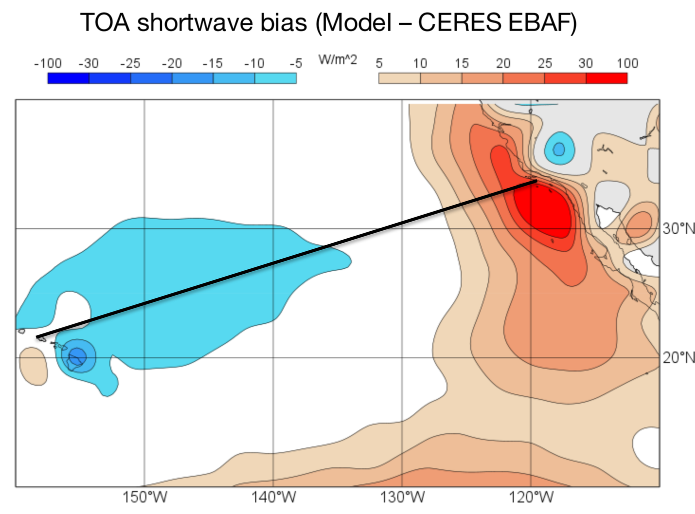

Figure 2 Highlighting the area of interest in the North East Pacific. The approximate MAGIC ship track between LA and Hawaii is marked.

References:

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Painemal, D., Greenwald, T., Cadeddu, M. and Minnis, P., 2016. First extended validation of satellite microwave liquid water path with ship-based observations of marine low clouds. GRL, 43(12), pp.6563-6570.

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2. What do the observations tell us?

Satellite observations

Gridded and averaged for JJA 2013, shown along average MAGIC ship track, and corresponding JJA 2013 average model data

MAGIC ship-based observations

Averaged over legs 10-17 (mid-May through August 2013), model data matched in time and space to each ship track, then averaged over legs 10-17

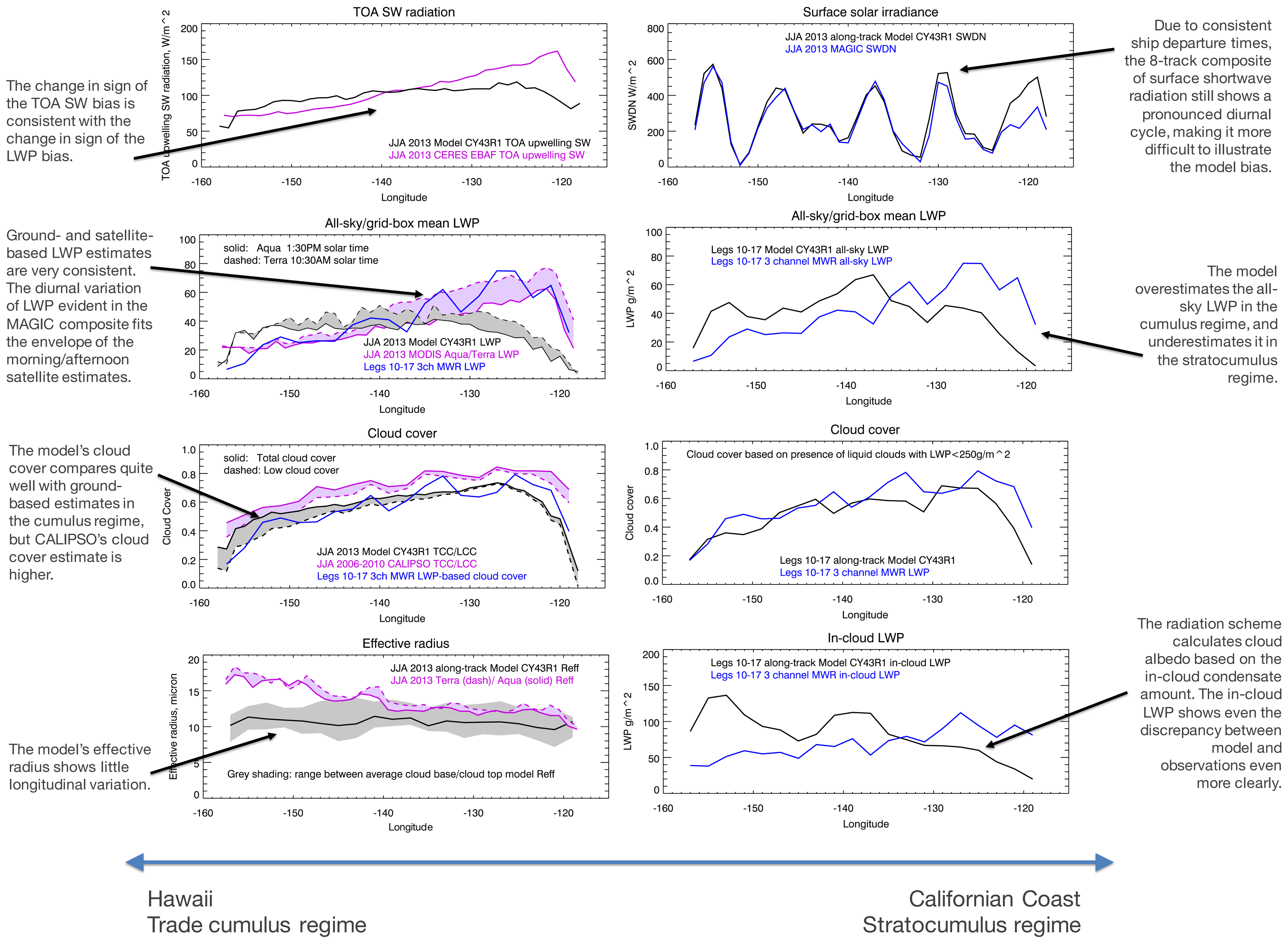

Figure 3: (Left) JJA 2013 mean satellite observations compared to the model along the average MAGIC ship track. (Right) Ship-based observations for MAGIC Legs 10-17 compared to model output matched in time and space.

3. Key insights

- The all-sky LWP retrieved from ARM’s 3-channel microwave radiometer agrees well with LWP estimates retrieved from MODIS (using the 3.7μm channel) in combination with CERES. Compared with these observations, **the model overestimates LWP in the trade cumulus regime**, consistent with the sign of the shortwave radiation bias. Previous model evaluations relied on LWP retrieved from SSMI. However, the SSMI estimates are biased high in the cumulus regime (Painemal et al. 2016) due to ambiguities in radiance attribution to clouds vs. water vapour vs. the ocean surface. This likely explains the apparent inconsistency between radiation and LWP biases.
- Cloud cover derived from CALIPSO is around 5-10% greater than cloud cover estimates from ground-based instruments (ceilometer and MWR). The **model’s cloud cover is in reasonable agreement** with the MAGIC observations in the transition and cumulus regimes, but underestimated near the Californian coast. The model’s apparent underestimate of cloud cover compared to CALIPSO is of the same order as the disagreement between ground- and satellite based observations.
- To **improve the model’s cloud albedo, LWP must be reduced in the cumulus regime while maintaining cloud cover.**
- A more realistic representation of **cloud effective radius could enhance** the contrast in cloud albedo between the two cloud regimes.

4. SCM experiments – tackling the problem

The LES forcing dataset developed by McGibbon and Bretherton (2017) for MAGIC Leg 15a has been adapted to drive the ECMWF single column model, and provides the opportunity to test model changes that address the challenges identified to the left.

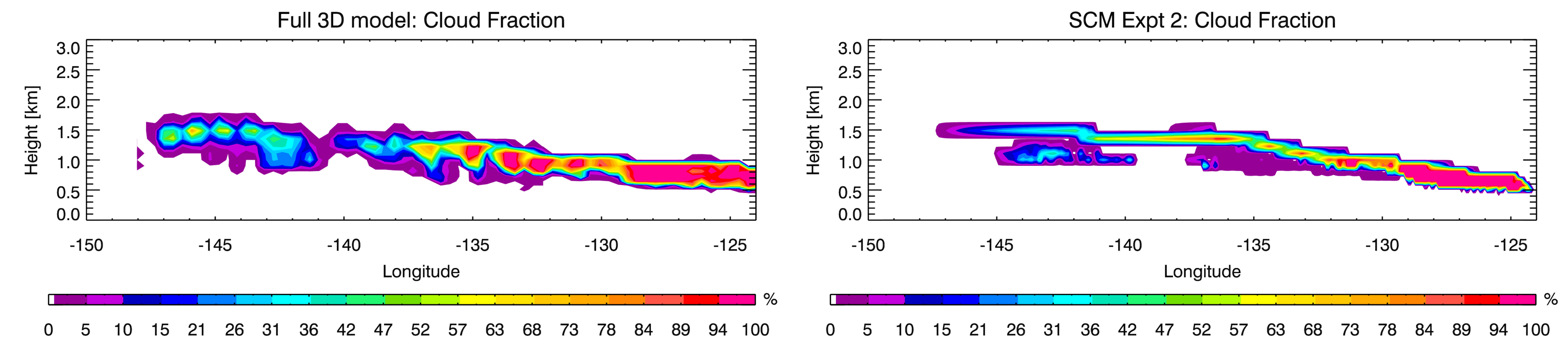

Figure 4: Model cloud fraction along MAGIC Leg 15a from (left) the full forecast model, and (right) the single column model.

1) Warm rain processes and cloud erosion

The amount of liquid retained in the cloud is the result of a delicate balance between processes that act as sources of liquid water, and those that deplete the cloud. We test a package of changes that impacts this balance by introducing a more realistic rain fall speed (depending on DSD) to replace a constant value. Together with some numerical changes, this alters the residence time of precipitation in a given model layer, and the rate of rain evaporation. We also test a new parameterization for cloud erosion (Morcrette 2012) which takes into account an estimate of how much cloud edge is exposed to the environment.

2) Cloud microphysical properties

The model’s droplet number concentration over ocean is solely dependent on wind speed. This accounts for variation in N_d from sea spray, but does not account for variation in other aerosol species due to e.g. pollution near the coast. The CAMS climatology offers an alternative way to parameterise N_d based on climatological sea salt, organic matter and sulfate concentrations (following Menon et al. 2002), which may better capture the observed longitudinal dependence of the effective radius.

3) Cloud heterogeneity

The model does not resolve how cloud condensate varies at subgrid scales. Instead, this subgrid-scale heterogeneity is parameterized. Observations from ARM sites around the world show that overcast boundary layer clouds, such as stratocumulus, tend to be more homogeneous than cumulus clouds (Ahlgrimm and Forbes 2016). A new regime-dependent heterogeneity parameterization replaces a constant value, and impacts the in-cloud condensate amount used in the radiation scheme.

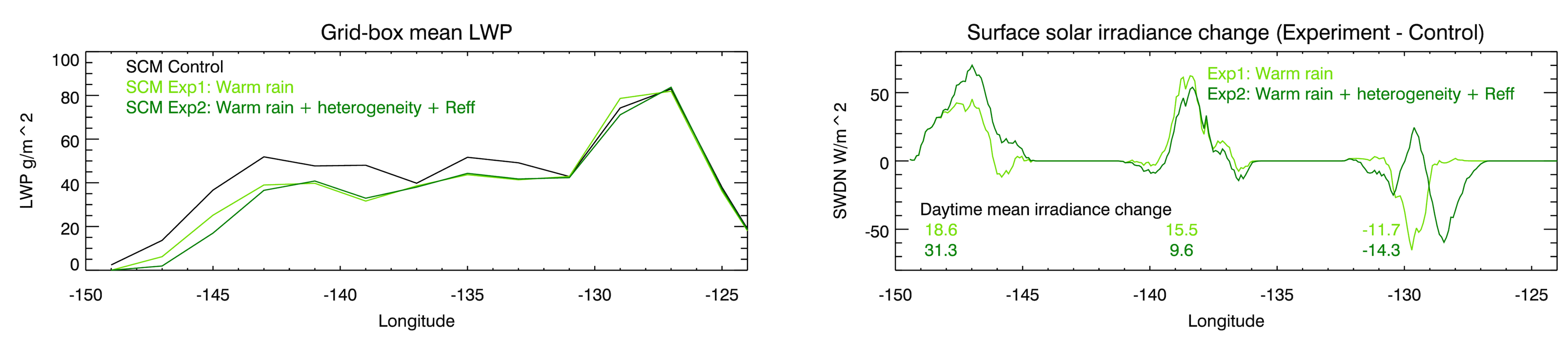

Figure 5: (Left) Grid-box mean LWP for three SCM experiments. (Right) Difference in surface solar irradiance between two SCM experiments and control. A positive difference indicates that more shortwave radiation is reaching the surface.

5. Results

The new fall speed, evaporation and cloud erosion changes **reduce LWP in the cumulus regime**, while maintaining it in the stratocumulus regime. The decreased LWP in the cumulus regime allows more solar radiation to reach the surface.

Adding the regime-dependent heterogeneity parameterization and climatology-based droplet number concentration **enhances the contrast in cloud albedo** between the stratocumulus and cumulus regimes further.