Response to J.-F. Müller's interactive comment concerning the calculation of cloud and ice particle radii

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We thank Dr. J.-F. Müller for his new comments related to our manuscript and his effort in trying to reconstruct effective cloud and ice radii using details provided in out manuscript. Indeed, Fouquart et al., (1990) give a parameterization for calculating the effective radius of cloud droplets (r_{eff}), which is dependent on liquid water content (LWC, g/m^3), rather than liquid water path (LWP, g/m^2). In C-IFS, the r_{eff} values are subsequently nested into the parameterization of Slingo (1989) for the calculation of cloud optical properties so as to provide a more realistic variability in the scattering component rather than adopting a fixed global mean r_{eff} of 8μm. Typically the physical r_{eff} is smaller than the optical r_{eff} by 1-2 μm (e.g., http://www-das.uwyo.edu/~geerts/cwx/notes/chap08/moist_cloud.html). To account for this effect, a down-scaling has been applied in C-IFS, in line with the original implementation in the TM5 CTM (Williams et al, 2012).

Upon testing the direct implementation of the parameterization of Fouquart et al., (1990) using the LWC values in the C-IFS results in a global r_{eff} value that is too low, as was also pointed out by Martin et al. (1994). This is undesirable for our modeling purposes as low r_{eff} results in too high optical depths as well as Surface Area Density (SAD) values. This is why, in the original implementation, we erroneously used the LWP instead, in order to achieve realistic r_{eff} values. For instance, r_{eff} associated with stratocumulus clouds over the oceans exhibit typical annual averages of ~11-12μm depending on the global region (Han et al., 1994).

To address this issue, and further homogenize with the IFS approach (see IFS manual, http://ecmwf.int/research/ifsdocs/CY38r1/), we choose to update our r_{eff} parameterization to that of Martin et al. (1994), which differentiates between continental and maritime air masses. For our purpose, we assume an aerosol number concentration of 40 particles/cm^3 over sea and 900 particles/cm^3 over land in order to compute cloud condensation nuclei. We place constraints on the range of r_{eff} between 4 and 14 μm. Compared to the previous implementation used in our manuscript, the r_{eff} effectively increases in the tropics, while it decreases towards high latitudes, hence leading to some changes in the photolysis rates and SAD values. Figure 1 gives an updated zonal mean r_{eff} for 1 April 2008, using the Martin et al. (1994) parameterization.

With respect to the parameterization of ice clouds, we agree that this was written too cryptically in our original version of the manuscript. In fact, we make use of the relationship of the cross sectional area A_c of the ice particle with respect to ice water content (IWC), as derived from observations (Heymsfield and McFarquhar, 1996):

$$A_c = 10^{-4} IWC^{0.9} \qquad (1)$$

In this equation IWC is given in units [g/m^3] and scaled with cloud fraction, to be representative to the cloudy part of the grid cell. Note that A_c refers to the cross sectional area of the ice particle, with units [cm^2/cm^3], rather than the SAD. To arrive at the SAD for ice particles, the A_c needs to be enhanced to account for irregularities introduced by the non-spherical shape of ice particles. This has been used in previous studies related to the extent of denitrification in the upper troposphere, due to the scavenging of HNO_3 on ice particles (von Kuhlmann and Lawrence, 2006), where they scale up A_c by a factor of two. Previous studies used scaling values between 2 and 4 (Lawrence and Crutzen, 1998). Therefore, we are confident that this approach is justified. We assume a factor 10 according to Schmitt and Heymsfield (2005).

The parameterization of ice cloud effective radius $r_{eff,ice}$ is based on Fu (1996), using A_c as computed from Eq. 1:

$$r_{eff,ice} = \frac{3}{4\varrho_i}\frac{IWC}{A_C} \qquad (2)$$

In this equation we use IWC with units [g/m^3] scaled with the cloud fraction, and ρ_i the ice water density in [g/m^3], while keeping A_c and $r_{eff,ice}$ in units [cm^2/cm^3] and [cm], respectively. We noted that also a small error appeared when taking over eq. 2 from Fu (1996) in our original manuscript. This leads to a ~20% increase in ice cloud radius $r_{eff,ice}$ compared to our original implementation, although $r_{eff,ice}$ was still in the observed range. In Fig. 1 the updated zonal mean $r_{eff,ice}$ is given. This increase in the effective radius leads to only negligible changes to concentration fields, as the evaluation of ice SAD is not affected. Nevertheless, in our improved version of our manuscript we will use the correct parameterization.

In the revised version of our manuscript we will use the updated parameterizations, and provide more clear explanations accordingly.

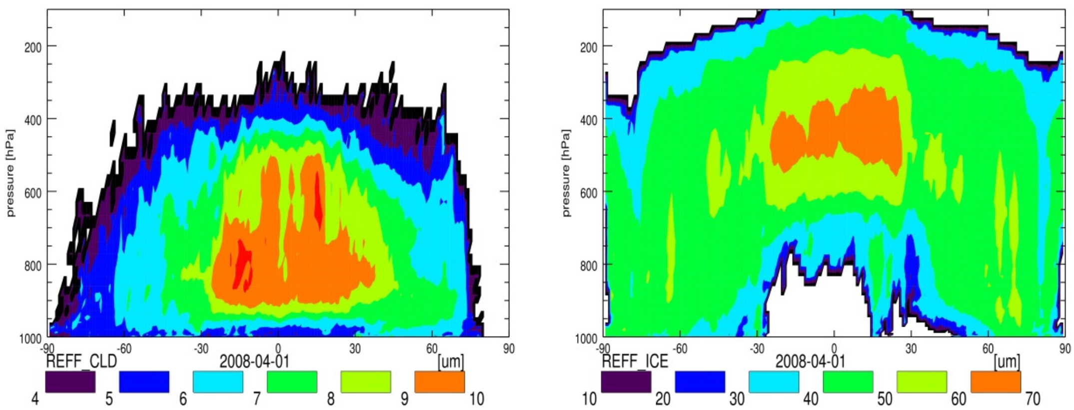

Figure 1. The zonal mean physical effective radius of liquid (left) and ice (right) cloud particles on April 1st 2008, given in μm.

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