6.4

PARAMETERIZATION OF IN-CLOUD VERTICAL VELOCITIES FOR CLOUD DROPLET ACTIVATION IN COARSE-GRID MODELS: ANALYSIS OF OBSERVATIONS AND CLOUD RESOLVING MODEL RESULTS

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1. INTRODUCTION

The activation of aerosol particles to cloud droplets depends on the degree of supersaturation, which in turn is related to the in-cloud vertical updraft velocity. Vertical velocity varies significantly in space, typically on scales of tens to hundreds of meters. As such, the relevant in-cloud updrafts are unresolved in global climate models (GCMs) with grid spacings of 100-200km. The prognostic calculation of cloud droplet activation in these models, required for the assessment of global aerosol indirect effects, relies therefore on parameterizations: Either updraft values are prescribed, or the updraft velocity is diagnosed from other simulated parameters, typically the eddy diffusion coefficient or the turbulent kinetic energy. GCMs formulate either a gaussian distribution of w, with a standard deviation σ_w, around the grid-mean value, or a single 'characteristic' updraft value w_{char}. As shown by Peng et al. (2005) and Fountoukis et al. (2007), these formulations are approximately equivalent, with $w_{\text{char}} \approx 0.8\sigma_w$.

Table 1 summarizes some global model formulations for σ_w and w_{char}. Often, the prescribed cloud-base updraft values (or the lower bounds applied to the formulations) are used as tuning parameters which are adjusted in order to simulate realistic droplet concentrations and/or cloud optical properties. The updraft velocities themselves have so far not been validated against observations.

We have analyzed different parameterizations for subgrid vertical velocities in the CAM-Oslo global aerosol-climate model and compared to observations and LES simulations from different campaigns.

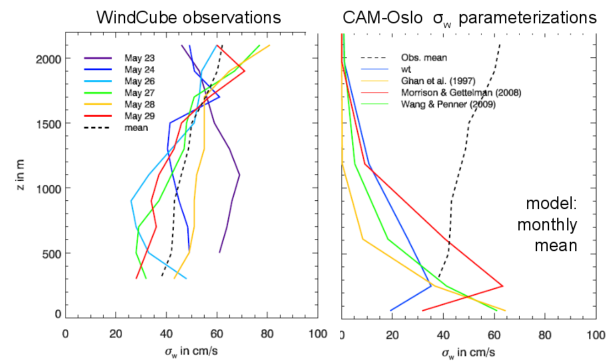

FIGURE 1: Vertical profiles of σ_w at Cabauw, the Netherlands. w_t is the 'turbulent velocity scale' of the Holtslag and Boville (1993) boundary layer scheme.

2. COMPARISON TO CABAUW IMPACT DATA

Figure 1 shows lidar-observed vertical profiles of σ_w (calculated from 24 hour time spans of measurements, lasting 20 s, at 6 minute intervalls) for 6 days during the IMPACT campaign, compared to simulated σ_w at the nearest model gridpoint. The model data are from a climatological month of May.

It is found that the model σ_w decreases rapidly with height, mispredicting the shape of the average observed σ_w profile at this location. A more detailled analysis shows that the tested GCM parameterizations for subgrid vertical velocity compare favourably to the observations in cloud-free conditions, but predict significantly too low updrafts inside clouds, which were located in the upper portion of the boundary layer at 1000-2000m. This is because these parameterizations, all based on the boundary layer scheme in CAM-Oslo (Holtslag and Boville, 1993), have the common weakness not to account for turbulence generated by the clouds themselves (e. g. by latent heat release, cloud-top cooling) and for the fact that (cumulus) clouds are co-located with the strongest updrafts.

3. ANALYSIS OF IN-CLOUD DATA

As a first-order relationship, textbook knowledge suggests that typical updraft velocities in different cloud regimes may increase simultanuously with the liquid water content (*LWC*, see Figure 2). In the following, we investigate whether such a correlation is confirmed from

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Table 1: Parameterizations of subgrid updrafts in recent GCM studies of the aerosol indirect effect. K is the eddy diffusion coefficient for heat, Δz the vertical layer thickness, l_c = 30 m a constant mixing length, $m_l(z)$ a height-dependent mixing length, and *TKE* the turbulent kinetic energy.

GCM	Parameterization	lower bound
NCAR CAM3 (Morrison and Gettelman, 2008)	$w_{char} = K/l_c$	0.1 m/s
CAM-Oslo (Storelvmo et al., 2006), based on Ghan et al. (1997)	$\sigma_w = \sqrt{2\pi}K/\Delta z$	0.3 m/s
CAM-UMich (Wang and Penner, 2009)	$\sigma_w = K/m_l(z)$	-
GFDL AM3 (Salzmann et al., 2010), BASE simulation	$\sigma_w = \sqrt{2/3} \cdot 1.83K/\Delta z$	0.7 m/s
GFDL AM3 (Salzmann et al., 2010), NEW simulation	$\sigma_w = \sqrt{2/3} \cdot 1.83K/\Delta z$	0.3 m/s
ECHAM5 (Lohmann et al., 2007)	$w_{char} = 1.33\sqrt{TKE}$	-
SPRINTARS (Takemura et al., 2005)	$w_{char} = 0.7\sqrt{TKE}$	-
GLOMAP (Pringle et al., 2009) (sensitivity experiments)	w_{char} = 0.15 or 0.3 m/s	-
GLOMAP (Korhonen et al., 2010)	σ_w = 0.25 m/s	-
NASA GMI (Meskhidze et al., 2007)	w_{char} = 0.35 m/s over ocean, w_{char} = 1 m/s over land	-
NASA GMI (Sotiropoulou et al., 2007)	w_{char} = 0.5 m/s over ocean, w_{char} = 1 m/s over land	-

in-cloud observations.

3.1 *ACTOS continental shallow cumulus*

The helicopter payload ACTOS, designed to measure fine-scale turbulence and microphysical parameters (Siebert et al., 2006), was deployed to measure continental cumulus humilis in Winningen, Germany, in spring 2005 and fall 2006. An exemplary horizontal flight leg is shown in Figure 3. The data are recorded at 100 Hz, which corresponds to a spatial resolution of $\approx$ 0.2 m. Running averages (for *LWC*) and standard deviations (for w) are calculated for segments of 1000 points (approximately 200m). The fluctuations of the vertical velocity correlate strongly with the *LWC*, and can be described well by a linear function: $\sigma_w = a + b \cdot LWC$.

In Figure 4, the data pairs of (σ_w, in-cloud *LWC*) for flights during five different days are summarized in 2-dimensional histograms. 'In-cloud' is defined here as $LWC > 0.01$g/m^3. While on all days a positive correlation between σ_w and the in-cloud *LWC* is found, the slopes (b) and offsets (a) vary from case to case and the correlation coefficients are low (0.3 for all data together).

3.2 *RICO marine shallow cumulus*

The second data set investigated here is from aircraft measurements during the RICO campaign (Rauber et al., 2007) in December 2004/January 2005 in the Caribbean. With a sampling frequency of 25Hz interpolated to 10Hz, the horizontal resolution is approximately 10 m. Points with a droplet concentration larger than 10 cm^{-3} are defined to be 'in-cloud', and the correlation analysis is performed for 8 s ($\approx$ 800 m) segments which are required to be at least 50% in-cloud. As seen from the histograms in Figure 5, higher correlation coefficients are found for RICO than for the ACTOS measurements, and also higher values of the slope b. This is at least partly due to the sampling method: While ACTOS data are only from the upper portions of clouds, the RICO aircraft probed different levels within the clouds. The *LWC* as well as σ_w increased with height, resulting in a relatively strong correlation if all data are plotted together.

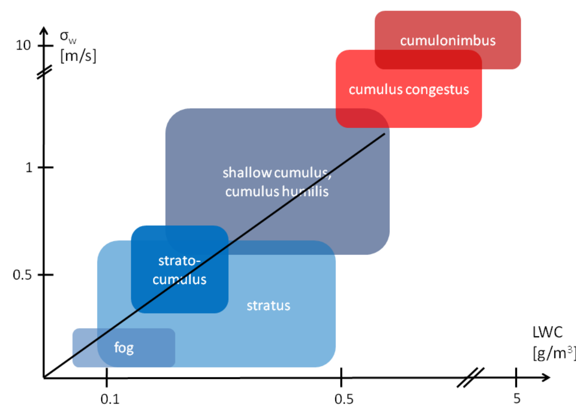

FIGURE 2: Typical values of σ_w and *LWC* for different cloud types (after Cotton and Anthes, 1989), and the proposed empirical relationship (black line).

Additionally, we have analysed cloud resolving model simulations of stratocumulus clouds over the North Sea. For this case, $\sigma_w = b \cdot LWC$ (for the cloud-average *LWC*) with $b = 2\frac{\text{m kg}}{\text{s g}}$ described the simulated σ_w reasonably well.

4. CONCLUSIONS

Based on the observed general increase of σ_w with the in-cloud *LWC*, we propose the following heuristic parameterization (see also Figure 2):

$$\sigma_w = w_t + 2\frac{\text{m kg}}{\text{s g}} \cdot LWC \qquad (1)$$

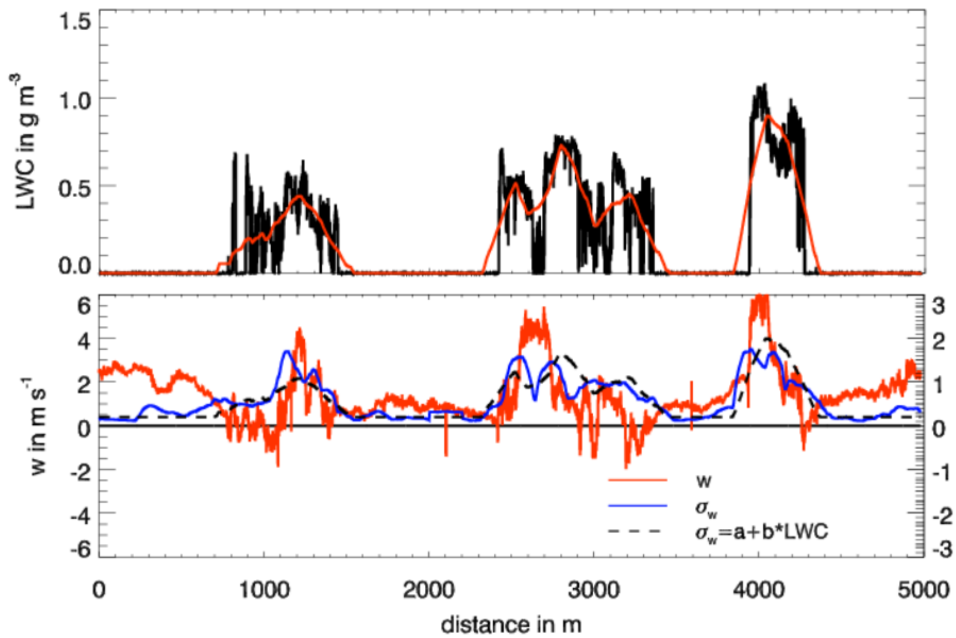

FIGURE 3: *LWC* and vertical velocity during an ACTOS flight.

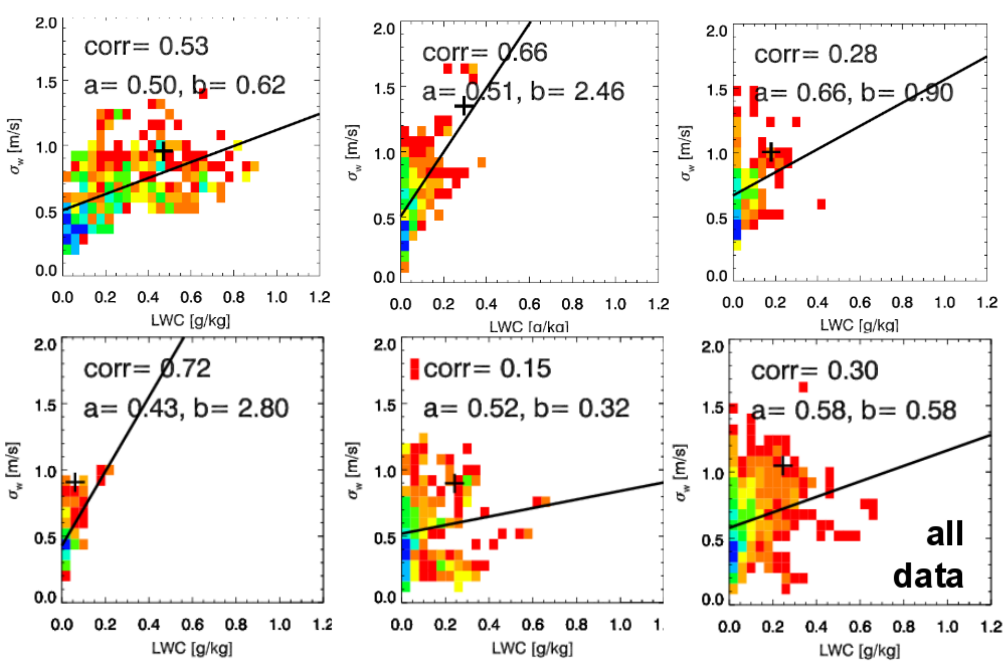

FIGURE 4: 2-dimensional histograms of (σ_w,*LWC*) values from five different days of ACTOS flights, and all data together in the last plot. Each color of the 10-level color scale (red to blue) covers 10% of the datapoints, ordered by their frequency of occurrence. *a* and *b* are the coefficients for a linear regression fit of the form $\sigma_w = a + b \cdot LWC$.

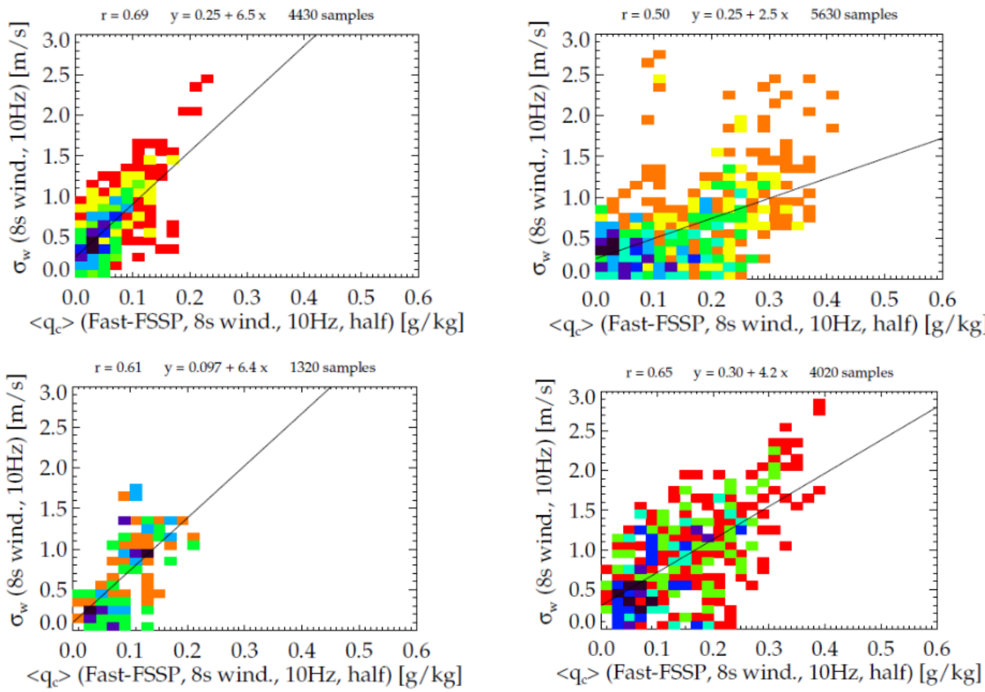

FIGURE 5: As Figure 4, for four flights during RICO.

for (in-cloud) *LWC* in g/kg. w_t is the 'turbulent velocity scale' in the Holtslag and Boville (1993) scheme and is assumed to represent the boundary layer turbulence without consideration of cloud presence. As seen from the analyzed observations, this relationship is not generally valid for individual cases. Neither is it intended to represent necessarily a causal relationship. As GCMs predict the *LWC* from condensation adjustment (independent of vertical velocity), this empirical relationship can be used to obtain a better estimate of the in-cloud σ_w than from the currently used turbulence parameterization. It ensures that the in-cloud updraft velocity is never close to 0, thereby eliminating the need for arbitrary lower bounds or prescribed values (as used together with other parameterizations, see Table 1).

When implementing the new and three different commonly used parameterizations of σ_w into the CAM-Oslo GCM (Storelvmo et al., 2006; Hoose et al., 2009), large differences are found. Compared to the Ghan et al. (1997) and Wang and Penner (2009) parameterizations, equation 1 gives comparable values in the boundary layer over land, but higher values over ocean (Figure 6). This results in an increase in the cloud droplet burden of 36%. The Morrison and Gettelman (2008) parameterization results in very high values of σ_w over continents, which are only realistic in strongly convective conditions.

With the next generation of GCM boundary layer schemes (e. g., Neggers, 2009; Bretherton and Park, 2009), our empirical approach is expected to become redundant. However, the current schemes will likely continue to be used for the next few years. We suggest that the simulated σ_w values in GCMs should be evaluated with observations more extensively, and that lower bounds for in-cloud updrafts are used consciously and with caution.

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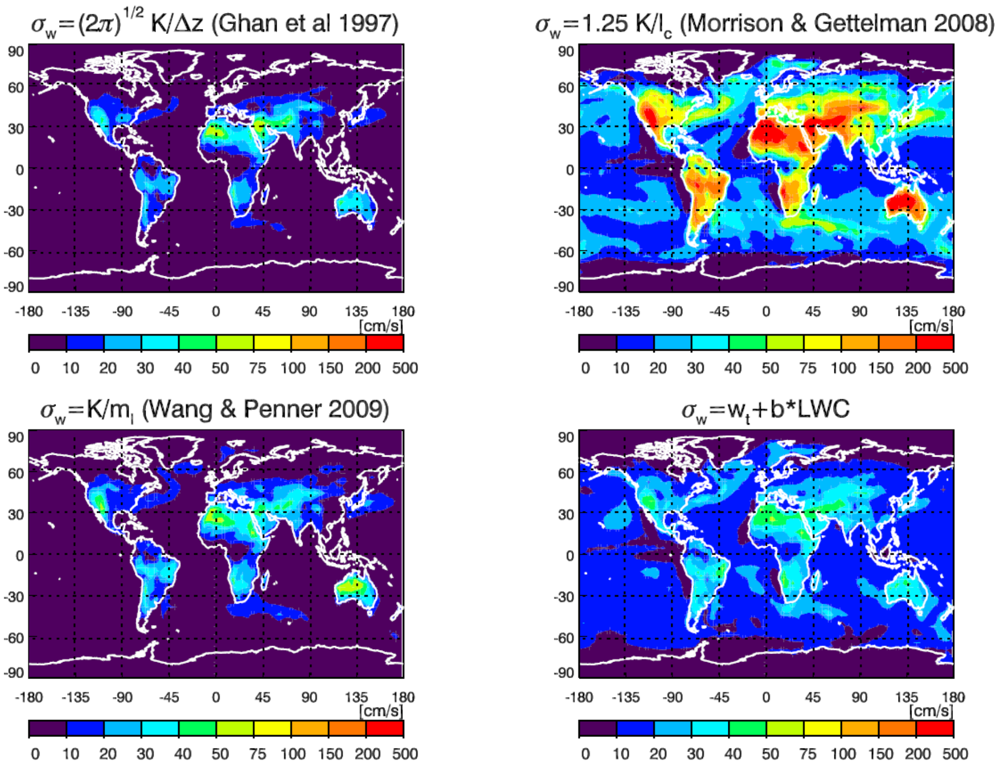

FIGURE 6: Annual averages of the grid-mean σ_w for the lowest five model levels (≈2km), calculated with four different parameterizations implemented in CAM-Oslo.

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