Evaluating the Impact of Different Autoconversion Schemes in an Isentropic Model with Three Hills

Maurice Huguenin-Virchaux

Supervisors:
Prof. Dr. Ulrike Lohmann, Dr. Linda Schlemmer
Roman Brogli, Laureline Hentgen and Davide Panosetti

ETH Zurich - Institute for Atmospheric and Climate Science

June 30, 2017

Contents

1 Introduction to Warm Cloud Bulk Microphysics

Parameterized cloud microphysics schemes allow to simulate important physical processes within a cloud on the subgrid scale. A commonly used warm cloud scheme is the one by **Kessler** (1969) and among others described in Houze (2014). This cloud microphysics scheme is implemented in the isentropic model used in this study. The model this study is using is called *isentrop_2017* and available for download on the webpage for the lecture Numerical Modelling of Weather and Climate at ETH Zrich given the reader has an nethz authentication key [1].

The Kessler scheme includes three mass continuity equations for the mixing ratios of water vapor q_v, cloud water q_c and rain droplets q_r

$$\frac{Dq_v}{Dt} = -C_{v,1} + E_{c,1} + E_{r,1} \tag{1}$$

$$\frac{Dq_c}{Dt} = C_{v,1} - E_{c,1} - A_{c,1} - K_{c,1} \tag{2}$$

$$\frac{Dq_r}{Dt} = A_{c,1} + K_{c,1} - E_{r,1} - F_{r,1} \tag{3}$$

where the subscript 1 denotes the tendency for the first moment, C_c is the rate of condensation of water vapour, E_c is the rate of evaporation of water vapour, E_r is the rate of evaporation of rainwater, A_c is the rate of autoconversion, K_c is the accretion rate (i.e. the collection of cloud droplets by rain drops) and F_r is the sedimentation rate of raindrops in the air parcel.

The following Figure 1 illustrates relationship of the three mixing ratios within the Kessler microphysics scheme and the particular processes which change them over time.

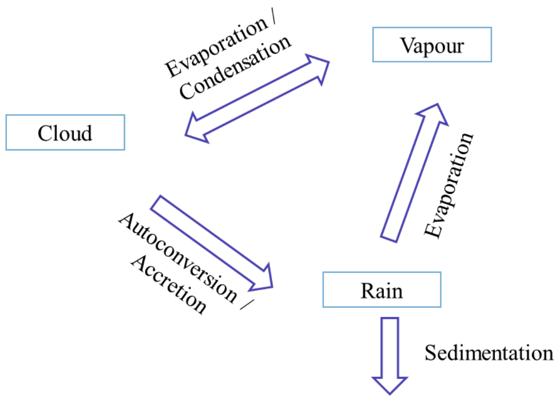

Figure 1: Schematic of microphysical processes in the warm cloud Kessler scheme (Equations 1–3). Figure adaptated from a presentation given by Morrison (2010) at NCAR.

This study will also make use of the **Two Moment** warm cloud scheme stated in Seifert and Beheng (2006) by comparing the impact of different autoconversion

[1] https://www.ethz.ch/content/dam/ethz/special-interest/usys/iac/iac-dam/documents/edu/courses/numerical_modelling_of_weather_and_climate/Tutorial2017/isentrop_2017.zip

rates with the Kessler microphysics scheme. The two moment scheme in addition to Equations 1–3 includes the following two equations on the droplet size distribution

$$\frac{Dn_c}{Dt} = K_{c,2} - A_{c,2} + C_{c,2} \tag{4}$$

$$\frac{Dn_r}{Dt} = A_{c,2} + SC_{r,2} - E_{c,2} \tag{5}$$

where n_c and n_r are the number densities of cloud droplets and rain droplets respectively, the subscript 2 denotes the tendency for the second moment and SC_r is the rate of self-collection and breakup of rain droplets as stated in Lin et al. (1983).

This study will mainly focus on the autoconversion rate A_c by implementing new ones in the model. The process of autoconversion describes the conversion of cloud water to precipitation particles by collision and coalescence. If not noted otherwise, the word scheme from here on will refer to the autoconversion scheme rather than the full cloud microphysics scheme in the model.

2 New Integrations

2.1 Integration of the Berry (1968) Autoconversion Scheme

Two different autoconversion schemes are widely used in numerical models (Simpson and Wiggert, 1969) and given in the following two equations. Equation 6 describes the autoconversion according to the **Kessler** scheme (Beard, 1976) and Equation 7 the **Berry** scheme as stated in (Berry and Reinhardt, 1974).

$$\frac{dM}{dt} = k_1 \cdot (m - a) \tag{6}$$

$$\frac{dM}{dt} = \frac{m^2}{60 \cdot (5 + \frac{0.0366 \cdot N_b}{m \cdot D_b})} \tag{7}$$

where $\frac{dM}{dt}$ is the change of precipitation water content with time [$\mathrm{g\,m^{-3}\,s^{-1}}$], k_1 is the autoconversion rate (in this study $7 \cdot 10^{-4}$ $\mathrm{s^{-1}}$), m is the cloud water content [$\mathrm{g\,m^{-3}}$], a is the autoconversion threshold (in this study 0.0001 $\mathrm{g\,m^{-3}}$), N_b is the droplet number density [$\mathrm{cm^{-3}}$] and D_b is the unitless droplet relative dispersion at cloud base.

The Kessler scheme given in Equation 6 is fully implemented in the isentropic model. This study here implements the **Berry** scheme and evaluates its impacts on the diabatic flow in the model.

2.1.1 Matlab code

The following matlab code shows the implementation of the Berry scheme (Equation 7. This section shown here is implemented in the *kessler.m* file of the isentropic model and replaces lines 134–137. In order to run this code successfully with only one autoconversion scheme active, the other schemes have to be commented out so the model does not receive conflicting information.

```
    % *** Kessler scheme (default) ***
qrprod = qc .* (1-factorn) + c1*dt_in*factorn.*max(zeros(nxb,nz),qc-c2);

    % *** Kessler scheme without accretion ***
qrprod = c1*dt_in*max(zeros(nxb,nz),qc-c2);


    % *** Berry scheme implementation starts here ***
    % constants for the scheme
Nb = 50;            % maritime cloud number density [cm^-3]
Db = 0.366;         % maritime cloud relative dispersion [...]
Nb = 2000;          % continental cloud [cm^-3]
Db = 0.146;         % continental cloud [...]

    % converting q_c from [kg kg^-1] to [g kg^-1]
m = max(zeros(nxb,nz),qc.*1000);
const = (Nb/Db);
mconst = 0.0366 ./ m;
m2 = m.^2;

qrprodb=dt_in*(m2./(60*(5+const*mconst)));

    % converting production of q_r back to [kg kg^-1]
qrprod=qrprodb ./ 1.0e3;
    % *** Berry scheme implementation ends here ***
```

An important feature of Berry's equation is that it allows to simulate different autoconversion rates for maritime and continental clouds. Typical values are given in Ghosh and Jonas (1998) with $N_b \sim 50$ cm^{-3}, $D_b \sim 0.366$ for maritime clouds and $N_b \sim 2000$ cm^{-3}, $D_b \sim 0.146$ for continental clouds based on the study by Simpson and Wiggert (1969).

2.2 Integration of new Topography

To evaluate the impact of the new autoconversion scheme on a more complex terrain, new topographic values are additionally added into the model to simulate three hills instead of the single hill. The new topography is illustrated in the following Figure 2.

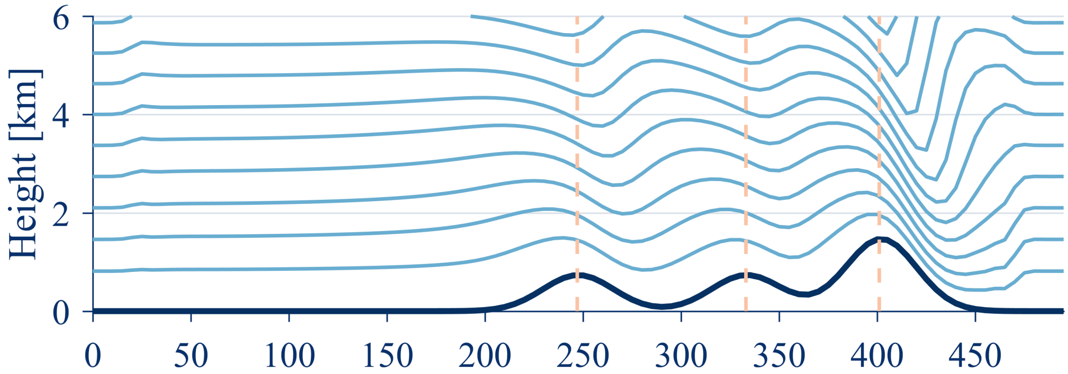

Figure 2: New topographic profile in dark blue showing three hills in consecutive order with their peaks at 247, 333 and 401 km distance to the model's coordinate point of origin. In bright blue are the isolines of density after the model has been run for seven hours. Dashed vertical lines in orange denote the location of the three peaks.

2.2.1 Matlab Code

The following matlab code shows the implementation of new topographic values. This section shown here is implemented in the *maketopo.m* file of the isentropic model and replaces lines 11–20.

```
    % *** First hill (default) ***
x0 = (nxb-1)/2 + 1 ;          % peak at 247 km distance
toponf = topo;
i=1:nxb;
x(i,1) = (i-x0).*dx;
toponf(i,1) = topomx.*exp(-(x(i,1)./topowd).^2);

    % *** Second hill ***
x0 = (nxb-1)/1.5 + 1 ;        % peak at 333 km distance
topona = topo;
i=1:nxb;
x(i,1) = (i-x0).*dx;
topona(i,1) = topomx.*exp(-(x(i,1)./topowd).^2);

    % *** Third hill ***
x0 = (nxb-1)/1.25 + 1 ;       % peak at 401 km distance
toponb = topo;
i=1:nxb;
x(i,1) = (i-x0).*dx;
toponb(i,1) = topomx.*exp(-(x(i,1)./topowd).^2);

    % *** Fourth hill  ***
    % same specifics as Mountain III but stacked on top
    % so only one hill results
x0 = (nxb-1)/1.25 + 1 ;       % peak at 401 km distance
toponc = topo;
i=1:nxb;
x(i,1) = (i-x0).*dx;
toponc(i,1) = topomx.*exp(-(x(i,1)./topowd).^2);

```

```
    % *** Calculating final topographic values  ***
i=2:nxb-1; % filter
topo(i) = toponf(i)+0.25.*(toponf(i-1)-2.*toponf(i)+toponf(i+1))+...
          topona(i)+0.25.*(topona(i-1)-2.*topona(i)+topona(i+1))+...
          toponb(i)+0.25.*(toponb(i-1)-2.*toponb(i)+toponb(i+1))+...
          toponc(i)+0.25.*(toponc(i-1)-2.*toponc(i)+toponc(i+1));
```

3 Results and Discussion

3.1 Comparing the Schemes: Total Accumulated Rain

To evaluate the impact of the three different autoconversion schemes, independent simulations, each varying only in the autoconversion schemes, are run for seven hours. Shown in Figure 3 is the total accumulated precipitation after the simulation ended. The Kessler and Barry Maritime schemes have nearly identical impacts on the overall accumulated rain rate while the Barry Continental scheme leads to accumulated rain of orders of magnitude lower.

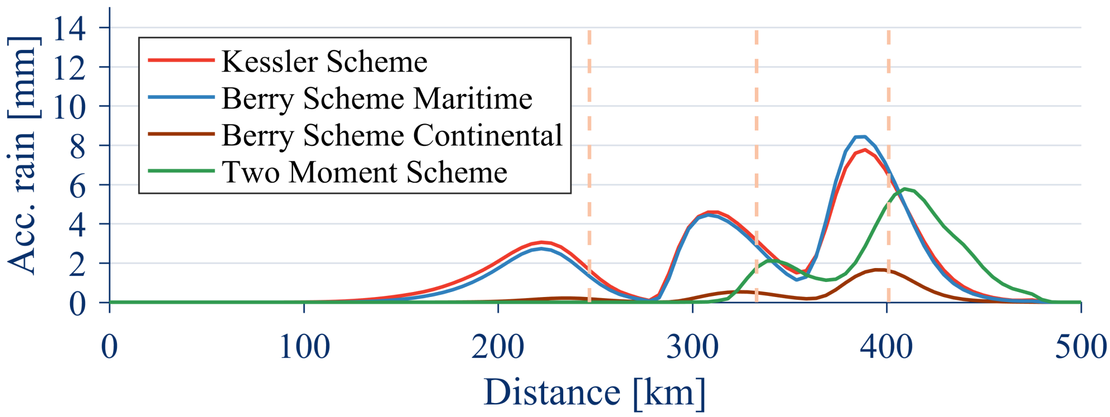

Figure 3: Comparison of accumulated rain for the four different autoconversion schemes used in this study. The orange dashed vertical lines indicate the region of maximum altitude of the three hills in the adjusted topography at 247, 333 and 401 km.

A total of 159.75 mm accumulates in the simulation with the Kessler scheme while values for the Berry scheme show 150.91 mm (21.17 mm) for the maritime (continental) simulation. The simulated continental clouds according to the Berry scheme therefore show vastly different accumulated total rain (85% less). This finding is consistent with the study by Ghosh and Jonas (1998). The effect is mainly due to decreased aerosol concentrations over the oceans as indicated by the different N_b and D_b values. This leads to equal cloud water content being distributed to fewer cloud droplets and therefore maritime clouds tend to exhibit bigger droplets. They fall out of the cloud more readily as precipitation than their smaller continental counterparts.

A comparison of the Kessler microphysics scheme with the Two Moment microphysics scheme shows that the latter simulates lower accumulated rain values.

Most of the precipitation is, according to the Kessler microphysics scheme located to the east of the hill peaks. The Two Moment scheme simulates a total of 76.59 mm over the full spatial domain which is $\sim$ 50% less than the Kessler and Berry Maritime schemes. However, one has to be careful when comparing the Kessler and Berry autoconversion schemes with the Two Moment scheme since the former only differs in the parameterization of the autoconversion and the latter includes a different cloud microphysics scheme altogether.

3.2 Comparing the Schemes: Cloud Water Mixing Ratio

The considerable differences in simulated total rain values between the different schemes also suggests diverging cloud water content after the seven hour simulation. The following Figure 4 shows the distribution of liquid water mixing ratios as well as the differences of the autoconversion schemes relative to the default Kessler scheme.

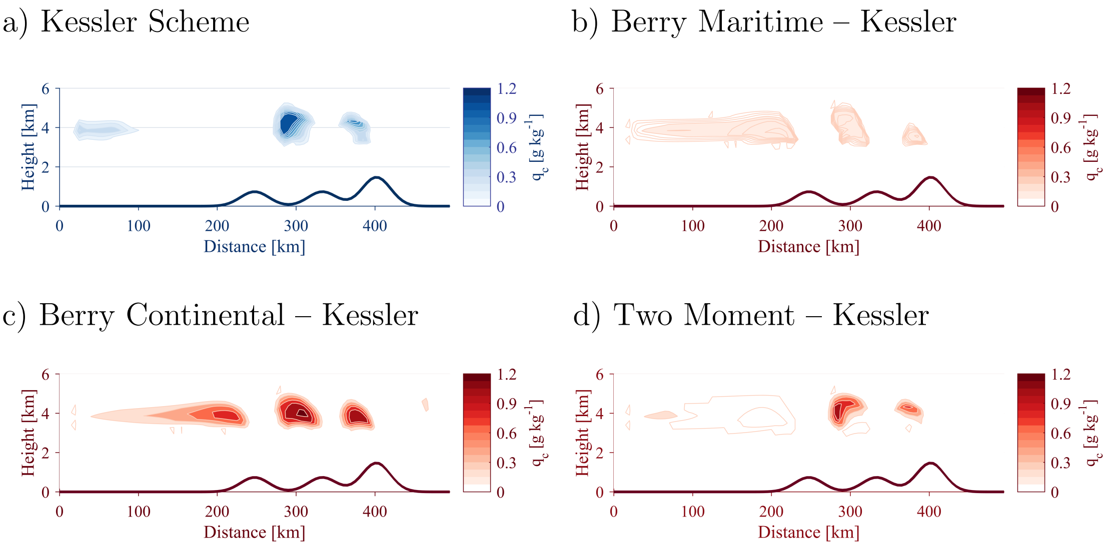

Figure 4: In a) the spatial distribution of the liquid water mixing ratio q_c after the seven hour simulation with the Kessler autoconversion scheme. In b) - d) the difference in q_c relative to the Kessler scheme when using the Berry Maritime, Continental and Two Moment schemes.

In Figure 4a) the remaining liquid water content within the model when run with the Kessler scheme is shown. Most of the liquid water content is situated in three clouds at about four kilometers height west of the three hill peaks. A lot of initial moisture after this seven hour simulation with the Kessler scheme has already left the system as precipitation. Therefore, the clouds do not contain as much liquid water as before.

The three red coloured plots in Figure 4b)–d) all show the differences in liquid water content relative to the Kessler scheme. The liquid water content simulated with the Berry Maritime autoconversion scheme shows the smallest difference to the default Kessler scheme, which is expected due to the Kessler scheme with a given k_1 of 10^{-3} being representative of a maritime cloud (Ghosh and Jonas, 1998).

Greater differences in the spatial distribution as well as in the total amount of liquid water content left in the clouds can be found when comparing the Kessler with the Berry Maritime scheme. As can be seen in Figure 4c), the Berry Continental scheme exhibits higher q_c. A total of 167.40 g water is left within the system compared to the 31.77 g in the Kessler scheme simulation. The Berry Continental scheme models about a five times higher q_c after the seven hours and is consistent with the lower accumulated rain values in Figure 3.

The differences between the Kessler and the Two Moment scheme in Figure 4 are not as high as for the Kessler–Continental case but nonetheless there are considerable contrasts. Especially the second cloud situated to the left above the centered hill shows the highest q_c values, contains a total of 32.17 g liquid water and about four times more than the same cloud in the Kessler scheme.

4 Topographic Limitations to the Model

Custom topography settings in the model need to be simple in order not to overload it. More complex topography such as the one illustrated in Figure 5 require very small time steps in order to still meet the CFL criteria. This is due to velocities increasing quickly to values over 100 m s^{-1} on the lee side. The overall computation time for complex topography increases faster than anticipated which raised the need to simulate flat hills.

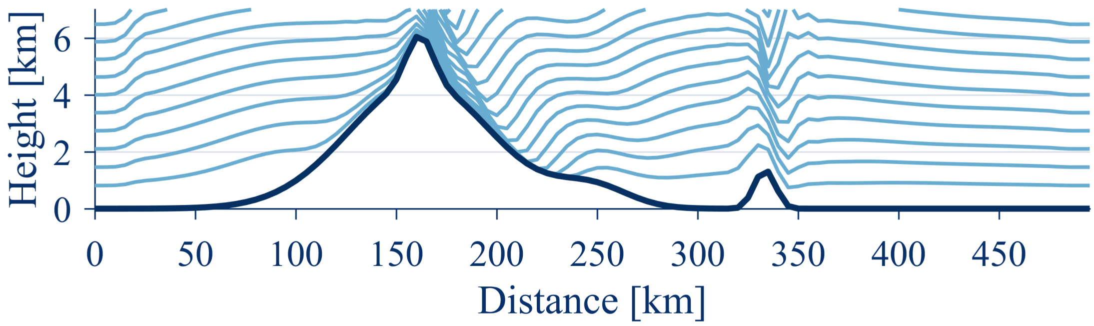

Figure 5: Custom topography of a shield volcano too complex for the model to be resolved.

References

Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft. *Journal of the Atmospheric Sciences*, **33**, 851–864.

Berry, E. X. and R. L. Reinhardt, 1974: An analysis of cloud drop growth by collection: Part I. Double distributions. *Journal of the Atmospheric Sciences*, **31**, 1814–1824.

Ghosh, S. and P. Jonas, 1998: On the application of the classic Kessler and Berry schemes in Large Eddy Simulation models with a particular emphasis on cloud autoconversion, the onset time of precipitation and droplet evaporation. *Annales Geophysicae*, Springer, volume 16, 628–637.

Houze, R. A., 2014: *Cloud Dynamics*, volume 104. Academic press.

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *Journal of Climate and Applied Meteorology*, **22**, 1065–1092.

Morrison, H., 2010: An overview of cloud and precipitation microphysics and its parameterization in models. Online Presentation.

Seifert, A. and K. Beheng, 2006: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 1: Model description. *Meteorology and Atmospheric Physics*, **92**, 45–66.

Simpson, J. and V. Wiggert, 1969: Models of precipitating cumulus towers. *Monthly Weather Review*, **97**, 471–489.