- Supporting Information -

The role of ascent timescale for WCB moisture transport into the UTLS

Cornelis Schwenk[1] and Annette Miltenberger[1]

[1]Institute for Atmospheric Physics, Johannes Gutenberg University Mainz

1 ICON calculations and the two-moment microphysics scheme

In this section we describe which calculations are performed by the two-moment microphysics scheme (Seifert, 2008) in ICON. The operations/calculations are preformed in the order in which they are listed. Variables in bold are of particular interest for us.

- Update of tracer fields and slow-physics tendencies
  At each fast-physics time step, ICON first updates the tracer fields and then fetches the slow-physics tendencies from the previous time step. The turbulent transfer coefficients for the atmosphere-surface interface are then computed.

- First saturation adjustment (**satad_I**)
  In this step all all sub- or supersaturation generated in the current time step is removed by evaporating or condensing cloud droplets. This establishes thermodynamic equilibrium between water vapour and liquid water in a process that is technically instantaneous, i.e. it is assumed to takes place on a time scale much smaller than the fast-physics time step. The latent heating resulting from satad_I is used to update the temperature and exner pressure.

- Turbulent diffusion (**qxturb** for x = v, c, i)
  The turbulence scheme Doms et al. (2021) (Chapter 3) developed by Matthias Raschendorfer calculates the turbulent diffusion in the atmospheric column for vapour, cloud droplets and ice.

ICON then continues with the two-moment cloud microphysics scheme that does the following calculations (in order):

- CCN activation (**qcnuc**)
  The activation of cloud condensating nuclei (CCN) is computed through a parameterisation adapted and modified from Hande et al. (2016).

- Homogeneous and heterogeneous ice nucleation (**qihh**)
  The parameterisation for homogeneous freezing is based on Kärcher et al. (2006) and Kärcher and Lohmann (2002) and the parameterisation for heterogeneous freezing is modified from Hande et al. (2015) to also include immersion and deposition freezing.

- Homogeneous freezing of cloud droplets (**qihom**)
  The parameterisation for the homogeneous freezing of cloud droplets is taken from Jeffery and Austin (1997). This scheme exponentially increases the freezing rate with decreasing temperature and freezes all droplets immediately if the temperature drops below -50° C.

- Depositional growth of all ice particles (**qxdep**)
  In this step, both vapour deposition and ice sublimation are calculated individually for each frozen hydrometeor species using a relaxation timescale approach based on Morrison et al. (2005).

- Collisional growth of frozen hydrometeors (not written to file)
  ICON then calculates the particle-particle and self-collections of all frozen hydrometeor species as well as the wet growth and conversion of graupel to hail.

- Riming of frozen hydrometeors with cloud droplets and rain drops (**qxrim**)
  For ice and snow there are two separate schemes for calculating riming with both cloud and rain drops. Hail and graupel are treated together, with two schemes for cloud-drop and rain-drop riming. The sum of these processes is taken. These calculations are based on Seifert and Beheng (2005).

- Freezing of rain and conversion to ice/graupel/hail (**rfrez**)
  The calculated heterogeneous freezing rates of rain drops, based on Bigg (1953), increase with raindrop radius and decreasing temperature, with all raindrops instantly freezing below -40° C.

- Melting of frozen hydrometeors to cloud droplets (**qcmelt**)
  If the temperature rises above 0° C, all ice particles are immediately melted to form cloud drops.

- Melting of fzozen hydrometeors to rain (**qrmelt**)
  Snow, graupel and hail melting are treated separately and the melting rate is explicitly calculated. If the temperature rises above 10° C, all snow particles immediately melt into rain.

- Evaporation of snow, graupel and hail (**fevap**)
  The liquid forming on the surface of melting hydrometeors can evaporate. This calculation is similar to rain evaporation at 0° C and is based on Seifert and Beheng (2005).

- Raindrop growth (not written to file)
  Here the auto-conversion and accretion (Beheng, 1994), the self-collection (Seifert and Beheng, 2001) and the break-up of rain (Seifert, 2008) are calculated.

- Evaporation of rain (**revap**)
  If the air is sub-saturated, this final computation calculates the evaporation of raindrops according to Seifert (2008).

- Size limits for all hydrometeors are enforced.

End of two-moment cloud microphysics scheme. ICON then resumes with:

- Sedimentation (**qxin** and **qxout** for x = r,i,s,g,h)
  Different computations are implemented to calculate the sedimentation of (i) rain, (ii) snow and ice, and (iii) graupel and hail according to Blahak (2020).

- Second saturation adjustment (**satad_II**)
  Any sub- or supersaturation resulting from the microphysical calculations is dealt with by a second saturation adjustment using the same procedure as the first.

- Slow physics: convective tendencies (**qxconv** for x = v, c, r, i, s)
  While the previous steps are completed at each fast-physics time step, the subsequent slow-physics processes are completed at reduced time intervals. We are interested in the Tiedke-Bechthold convection scheme, which is switched on for the global domain and produces mass-flux tendencies for vapour, cloud droplets, rain drops, ice particles and snow (Tiedtke, 1989; Bechtold et al., 2008). Other slow-physics processes not relevant to the scope of this work include radiation (calculated on a coarser resolution grid) and non-orographic and orographic gravity wave drag.

2 Diagnostics and corrections

Note all diagnostics are computed on the instantaneous rates interpolated to the trajectory position at each model physics timestep.

2.1 Computation of evaporation and condensation rates from first call to saturation adjustment

Condensation and evaporation rates are diagnosed from the tendency from the first call to the saturation adjustment scheme according to its sign:

```
if satad_I > 0:
    cond = cond + satad_I
elseif satad_I < 0:
    evap = evap + satad_I
```

2.2 Computation of deposition rate, mass transfer rate by the Wegener-Bergeron-Findeisen processes, and "corrected" turbulence tendencies

In the ICON model deposition onto and sublimation of frozen particles, saturation adjustment, and the turbulence parameterisation determine the partitioning of water vapor and condensate. Saturation adjustment is called at the beginning of the microphysics timestep, then tendencies due to the deposition and turbulence parameterisations are computed followed by a second call to saturation adjustment. Hence, the redistribution of water mass from liquid to frozen hydrometeors by the Wegner-Bergeron-Findeisen (WBF) process effectively manifests as depositional growth of hydrometeors followed by evaporation in the second call of the saturation adjustment scheme. While having implications for latent heating, the WBF process does not result in condensate loss or gain and therefore its contributions to evaporation and deposition should be excluded from the moisture budget diagnostics. How this is done is documented below.
A second correction to the raw model tendencies was deemed necessary for a meaningful analysis of the moisture budget: In the ICON there is a strong compensation between tendencies to water vapor and cloud mass mixing ratio from the turbulence scheme and the second call to the saturation adjustment. Despite the root cause of this feature not clear yet, this compensation happens within the same timestep and therefore is thought to have no or limited physical meaning. We used a "correction" of the turbulence tendencies removing instantaneous compensation between turbulence and saturation adjustment tendencies as outlined below.

```
if |qxdep| < 1e-15 (i.e equal to zero):
    % There is no depostional growth and hence no WBF. We just need to account for the compensation between tencencies
    % from turbulence and second saturation adjustment.
    qvturc = qvturb - satad_II
    qcturc = qcturb + satad_II

elseif qxdep > 1e-15:
    % There is depositional growth. WBF, deposition, and "corrected" turbulencetendencies need to be computed.

    if qcturb + satad_II > 0:
        % There is net condensation. This should not happen based on microphysics only (deposition should push relative
        % humdity to below water saturation). Therefore all depsoition is counted as mass transfer from water vapor
        % to condensate and the net cloud condensate rate (sum of original turbulence and second saturation adjustment
        % rate) is attributed to the turbulence scheme. Note this may overestimate the turbulence contribution, if the
        % tendencies are partially down to WBF.
        qvturc = qvturb - satad_II
        qcturc = qcturb + satad_II
        depo = qxdep

    elseif qcturb + satad_II <= 0:
        % There is net evaporation, WBF is redistributing condensate mass. Note this may overestimate the role of WBF,
        % if net evaporation is down to turbulent mixing only.
        if qcturb - satad_II > qxdep:
            % There is more evaporation of cloud condensate than deposition on ice, i.e. turbulent processes and WBF
            % influence the gas-condensate partitioning. We assign the full deposition tendency to WBF mass transfer
            % and the rest of the net cloud condensate tendency to turbulence.
            qvturc = qvturb - satad_II - qxdep
            qcturc = qcturb + satad_II + qxdep
            wbf = qxdep
        elseif qcturb - satad_II <= qxdep:
            % There is less evaporation of cloud condensate than deposition on ice, i.e. there is more depositional growth
            % than can be explained by WBF. We assign all evaporation of cloud condensate to the WBF mass transfer
            % and the rest of the deposition tendency to actual mass transfer between the gas phase and condensate.
            % There is no tendency from turbulence of cloud condensate, only for water vapor.
            qvturc = qvturb + qcturb
            depo = qxdep + satad_II + qcturb
            wbf = -satad_II - qcturb
```

```
elseif qxdep < -1e-15:
    % Frozen hydrometeors are sublimating, hence WBF is not active. There is no physical reason for the cloud microphysics
    % to produce super-saturated conditions. The tendency from deposition parameterisation is assigned to the sublimation
    % rate. The net rate from turbulence and second saturation adjustment is assigned to the "corrected" turbulence
    % tendency.
    qvturc = qvturb - satad_II
    qcturc = qcturb + satad_II
    subl = qxdep
```

Note that the re-assignment of rates leaves the net tendency of condensate and water vapor at the end of the physics timestep unchanged.

REFERENCES

Bechtold, P., Köhler, M., Jung, T., Doblas-Reyes, F., Leutbecher, M., Rodwell, M. J., Vitart, F., and Balsamo, G. (2008). Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales. *Quarterly Journal of the Royal Meteorological Society*, 134(634):1337–1351.

Beheng, K. (1994). A parameterization of warm cloud microphysical conversion processes. *Atmospheric Research*, 33(1-4):193–206.

Bigg, E. K. (1953). The formation of atmospheric ice crystals by the freezing of droplets. *Quarterly Journal of the Royal Meteorological Society*, 79(342):510–519.

Blahak, U. (2020). New implementation of explicit hydrometeor sedimentation in the seifert-beheng 2-moment bulk microphysical scheme.

Doms, G., Förstner, J., Heise, E., Herzog, H.-J., Mironov, D., Raschendorfer, M., Reinhardt, T., Ritter, B., Schrodin, R., Schulz, J.-P., and Vogel, G. (2021). Cosmo-model version 6.00: A description of the nonhydrostatic regional cosmo-model - part ii: Physical parametrizations.

Hande, L. B., Engler, C., Hoose, C., and Tegen, I. (2015). Seasonal variability of saharan desert dust and ice nucleating particles over europe. *Atmospheric Chemistry and Physics*, 15(8):4389–4397.

Hande, L. B., Engler, C., Hoose, C., and Tegen, I. (2016). Parameterizing cloud condensation nuclei concentrations during HOPE. *Atmospheric Chemistry and Physics*, 16(18):12059–12079.

Jeffery, C. A. and Austin, P. H. (1997). Homogeneous nucleation of supercooled water: Results from a new equation of state. *Journal of Geophysical Research: Atmospheres*, 102(D21):25269–25279.

Kärcher, B., Hendricks, J., and Lohmann, U. (2006). Physically based parameterization of cirrus cloud formation for use in global atmospheric models. *Journal of Geophysical Research*, 111(D1).

Kärcher, B. and Lohmann, U. (2002). A parameterization of cirrus cloud formation: Homogeneous freezing of supercooled aerosols. *Journal of Geophysical Research*, 107(D2).

Morrison, H., Curry, J. A., and Khvorostyanov, V. I. (2005). A new double-moment microphysics parameterization for application in cloud and climate models. part i: Description. *Journal of the Atmospheric Sciences*, 62(6):1665–1677.

Seifert, A. (2008). On the parameterization of evaporation of raindrops as simulated by a one-dimensional rainshaft model. *Journal of the Atmospheric Sciences*, 65(11):3608–3619.

Seifert, A. and Beheng, K. D. (2001). A double-moment parameterization for simulating autoconversion, accretion and selfcollection. *Atmospheric Research*, 59-60:265–281.

Seifert, A. and Beheng, K. D. (2005). A two-moment cloud microphysics parameterization for mixed-phase clouds. part 1: Model description. *Meteorology and Atmospheric Physics*, 92(1-2):45–66.

Tiedtke, M. (1989). A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Monthly Weather Review*, 117(8):1779–1800.