Implementation of the hybrid cumulus convection parametrization scheme HYMACS in ICON

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1) Introduction

Cumulus convection can redistribute significant amounts of mass, heat and moisture in the atmosphere and it is one of the major drivers of atmospheric circulation systems. Additionally, cumulus convection can be accompanied by severe weather events such as torrential rain events or destructive wind gusts. Hence, its proper representation in numerical weather prediction (NWP) models is of great interest.

Even though global and regional NWP models make use of quite fine horizontal grid spacings with $\Delta x \sim 1-10$ km today, deep convection is not resolved explicitly by grid scale (thermo-) dynamics and henceforth, has to be parametrized (see Fig. 1). Since classical convection parametrization schemes, which are still used in contemporary NWP models, have been designed for rather coarse grids with $\Delta x \sim 50$ km, some incorporated assumptions have become more and more questionable.

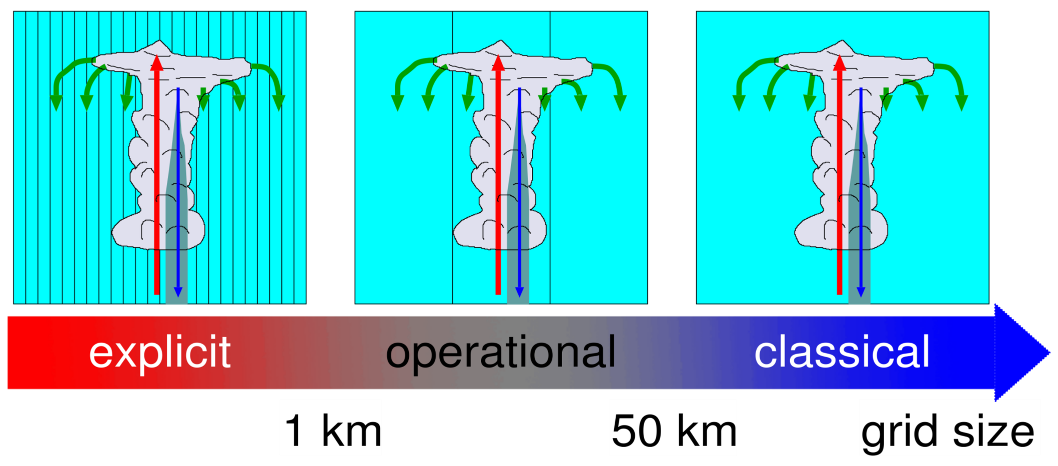

Fig. 1: Treatment of deep convection for different grid spacings in a numerical model.

The hybrid mass flux convection scheme HYMACS developed by *Kuell et al. (2007)* overcomes the conceptual problem of subgrid scale compensating subsidence by including a convective net mass transport. While up- and down-draft are still parametrized, the environmental subsidence is treated explicitly by the grid scale (thermo-)dynamics and the convective circulation becomes partially resolved.

HYMACS has already been tested successfully in the regional NWP model COSMO.

Our project aims to implement HYMACS in the new NWP model ICOsahedral Non-hydrostatic in order to improve the representation of convection and the grid scale dynamical response to convection. Besides, HYMACS proofed to be a convection parametrization scheme for a broad range of grid spacings including the *convective grey zone*. Therefore, we believe that HYMACS is particularly suitable for ICON which is supposed to operate on many different scales.

2) Theoretical Background

a) Convective mass transport

- consider an arbitrary fluid volume consisting of a convective part V_c and a non-convective environment V_e with partial densities ρ_c and ρ_e (see Fig. 2)
- barycentric velocity of this fluid volume:

$$\begin{aligned}\rho\mathbf{v} &= \rho_e\mathbf{v_e} + \rho_c\tilde{\mathbf{v}}_c \\ &= \rho_e\mathbf{v_e} + \rho_c\mathbf{v_e} + \rho_c\mathbf{v}_c \\ &= \rho\mathbf{v_e} + \rho_c\mathbf{v}_c\end{aligned}$$

- continuity equation:

$$\begin{aligned}\frac{\mathrm{D}\rho}{\mathrm{D}t} &= \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) \\ &= \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}_e) + \nabla\cdot\mathbf{J}_c\end{aligned}$$

with $\mathbf{J}_c = \rho_c\mathbf{v}_c$ for the convective mass flux

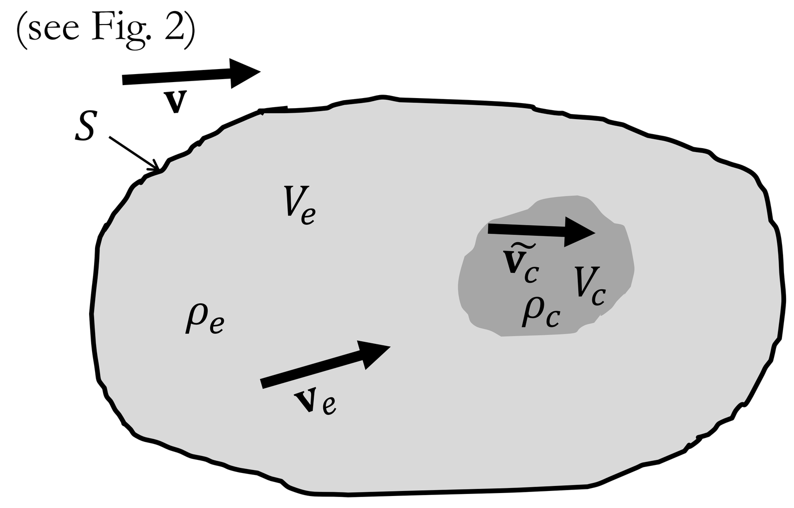

Fig. 2: Illustration of a fluid volume surrounded by the surface S and moving with the barycentric velocity **v**. The barycentric velocity is determined by the momentum of the environmental part (light grey) and the convective part (dark grey).

> The **local change in density**, i.e. the density of a grid box, can be split into an **environmental mass flux divergence** (given by grid scale advection) and into a **convective mass flux divergence** (to be parametrized by HYMACS).

- convective drafts are primary vertical: change in updraft and downdraft mass flux $M_{u,d}$ by entrainment ε or detrainment δ yields convective change in density $\left.\frac{\partial\rho}{\partial t}\right|_{conv}$

$$-\nabla\cdot\mathbf{J}_c = \left.\frac{\partial\rho}{\partial t}\right|_{conv} = \frac{\rho^* - \rho(t^n)}{\Delta t} = -\frac{1}{A}\frac{\partial M_{u,d}}{\partial z} = -\frac{1}{A\,\Delta z}(\varepsilon_{u,d} - \delta_{u,d})$$

b) Convective transport of heat, moisture and momentum

- in analogy to the approach above, the budget of any specific quantity ψ (i.e. enthalpy h, specific moisture content q^x, momentum) can be decomposed
- local change of ψ due to grid scale advection, divergence of convective flux $(\nabla\cdot\mathbf{J}_c^{\psi})$ and due to convective mass flux divergence $(\nabla\cdot\mathbf{J}_c)$:

$$\rho\frac{\partial\psi}{\partial t} = -\rho\mathbf{v}_e\cdot\nabla\psi - \nabla\cdot\mathbf{J}_c^{\psi} + \psi\nabla\cdot\mathbf{J}_c$$

- the last two terms can be discretized by

$$-\nabla\cdot\mathbf{J}_c^{\psi} + \psi\nabla\cdot\mathbf{J}_c = \rho\left.\frac{\partial\psi}{\partial t}\right|_{conv}$$

with $$\left.\frac{\partial\psi}{\partial t}\right|_{conv} = \left(\frac{\rho(t^n)}{\rho^*} - 1\right)\frac{\psi(t^n)}{\Delta t} - \frac{1}{A\Delta z\rho^*}(\varepsilon_{u,d} - \delta_{u,d})$$

Literature:

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3) HYMACS Core

- in general, every convection scheme consists of three parts: **cloud model, trigger function** and **closure assumption**

a) Cloud model

- describe the thermodynamics of the parametrized cloud, i.e updraft and downdraft for HYMACS
- diagnose ice/liquid water static energy h_{il} for thermodynamic cloud properties (as proposed by *Bechthold et al. (2001)*)

$$h_{il} = c_pT + gz - l_{lv}q^l - l_{iv}q^i$$ with $l_{lv,iv}$: latent heat of vaporization and sublimation

Updraft	Downdraft
source layer with Δp=60 hPa with buoyancy of test parcel	origin of downdraft source layer determined by buoyancy of test parcel
gradual glaciation (for $-5°C < T < -25°C$) above LCL (lifting condensation level)	supply by precipitation transfer from updraft
simple parametrization for formation of precipitation (see *Ogura and Cho (1973)*)	cooling by melting and evaporation of precipitation drives kinetics
LNB and CTL (level of neutral buoyancy and cloud top level) diagnosed by updraft velocity	downdraft spreading in downdraft detrainment layer (DDL) with $\Delta p_{max} = 50$ hPa below LCL

b) Trigger function

Check if lifted test parcel can overcome convective inhibition (CIN).

HYMACS incorporates one grid scale process and two subgrid scale processes for the initialization:

1) grid scale vertical wind at LCL following *Fritsch and Chappel (1980)*)
2) near-surface turbulence, i.e. mean TKE in lowermost 50 hPa
3) subgrid scale gust front from neighboring convective cells (gust front trigger)

c) Closure assumption

- constrain updraft mass flux M_u^{LCL} at LCL by grid scale horizontal mass flux convergence

$$M_u^{LCL} = \int_{surface}^{LCL} \nabla_h\cdot(\rho\mathbf{v}_h)A\,dz$$

4) HYMACS in ICON

HYMACS has already been successfully implemented into the regional non-hydrostatic NWP model COSMO. Now, we aim to implement the presented convection scheme into the ICON model.

In the following, the basic differences for the implementation of HYMACS in both models are pointed out. HYMACS returns convective tendencies of enthalpy, density, momentum and of the moisture components. Now, we focus on the transformation of these convective tendencies to the prognostic variables of the respective hosting model.

COSMO

- prognostic equations for temperature and pressure
- transformation relations:

$$\left.\frac{\partial T}{\partial t}\right|_{conv} = \frac{1}{c_{vd}}\frac{p}{\rho^2}\left.\frac{\partial\rho}{\partial t}\right|_{conv} + \frac{1}{c_{vd}}\left.\frac{\partial h}{\partial t}\right|_{conv}$$

$$\left.\frac{\partial p}{\partial t}\right|_{conv} = \frac{c_{pd}}{c_{vd}}\frac{p}{\rho}\left.\frac{\partial\rho}{\partial t}\right|_{conv} + \left(\frac{c_{pd}}{c_{vd}} - 1\right)\left.\frac{\partial h}{\partial t}\right|_{conv} + \cancel{\frac{c_{pd}}{c_{vd}}Q_{m,conv}}$$

- (convective) moisture source term $Q_{m,conv}$ is neglected in pressure tendency equation

ICON

- prognostic equations for density and Exner function π (*Zaengl et al. (2015)*)→ convective density tendency can be used directly
- transformation relation:

$$\left.\frac{\partial\pi}{\partial t}\right|_{conv} = \frac{R_d}{c_{vd}}\frac{\pi}{\rho}\left.\frac{\partial\rho}{\partial t}\right|_{conv} + \frac{1}{\theta_v}\frac{R_d(1+\alpha)}{c_{vd}c_{pd}}\left.\frac{\partial h}{\partial t}\right|_{conv} + \frac{1}{\rho\theta_v}\frac{1}{c_{vd}}Q_{m,conv}$$

with

$$Q_{m,conv} = \rho R_d T\left.\frac{\partial\alpha}{\partial t}\right|_{conv}, \alpha = \left(\frac{R_v}{R_d} - 1\right)q^v - q^{l,f}$$

- (convective) moisture source term $Q_{m,conv}$ is retained in Exner tendency equation

- the convective tendencies for the specific moisture constituents q^x and for the momentum can be passed directly to the hosting model
- the gust front trigger of HYMACS needs to be reformulated since ICON makes use of a triangular grid instead of a (rotated) regular lat-/lon-grid as in COSMO (see *Kuell and Bott (2011)*)

5) Outlook

- perform idealized dry mass lift experiments (i.e no enthalpy and moisture transport) with HYMACS in ICON and analyze the grid scale (thermo-)dynamic response with special regard to the generation of gravity waves and secondary circulations
- further moist convection experiments (i.e. full physics)
  - idealized single convective cell in a conditionally unstable background atmosphere
  - idealized diurnal cycle of convection in a sea breeze simulation
- compare ICON convection experiments with the respective convection experiments in COSMO (see *Kuell et al. (2007)* and *Kuell and Bott (2008)*)
- perform real case studies with HYMACS in ICON including validation and verification against observations
- further tuning of HYMACS (CAPE-based closure assumption, entrainment and detrainment rates imitating behavior of convective cloud ensemble…)

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