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Wetter und Klima aus einer Hand

Where are the uncertainties in scientific understanding of cloud and precipitation processes

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An NWP perspective:

scientific understanding ← → capability to model

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Uncertainties in scientific understanding

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Different types of: scientific understanding ←→ uncertainties

- Uncertainties in our understanding of
  - elementary processes
    - we can not write down the mathematical equations
      - ➢ e.g. what is the chemistry of certain ice nuclei
    - we are unsure about some parameters in these equations
  - collective processes
    - too complex
    - too nonlinear (chaotic, not predictable)
  - atmospheric conditions / atmospheric composition
    - e.g. number and distribution of ice nuclei

scientific understanding ← → capability to model

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Where are the uncertainties? Everywhere – a few examples:

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- **Micro-physics**
  - **ice processes**
  - **micro-physics ←→ turbulence** interaction
  - **aerosol ←→ cloud** interactions
- **Subgrid variability**
  - **cloud geometry**
  - **dependence on history** of clouds and subgrid processes
- **Convective clouds**

  What determines the
  - **triggering** of convection
  - **mixing** of updraft/downdraft with ambient air
  - **microphysics** of convective clouds
- **Impact on dynamics**
  - **storm dynamics**
  - **organized convection**
  - **upscaling of errors**

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Why does it matter to data assimilation?

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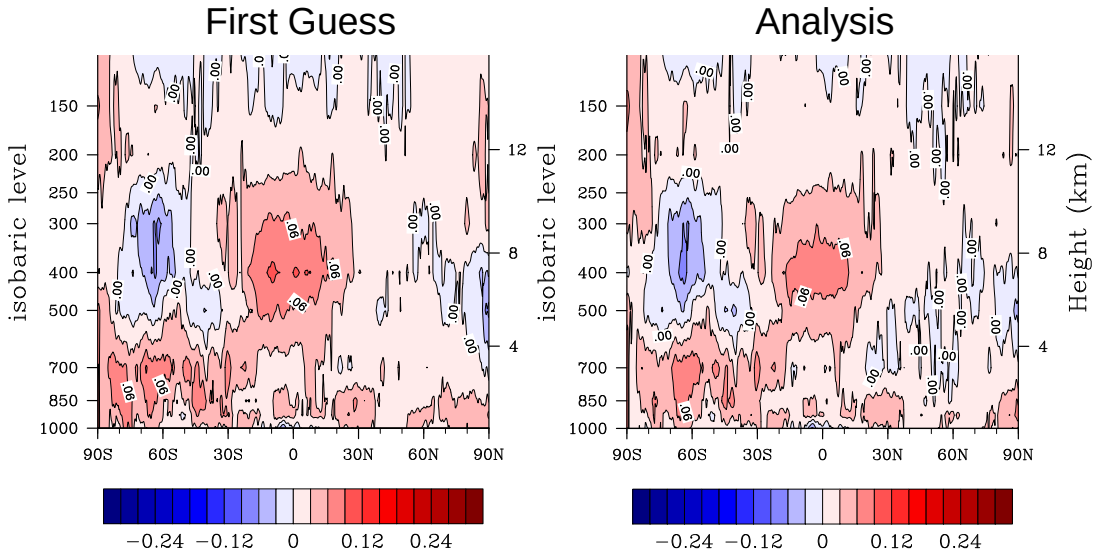
- Inaccuracies of **forward operators**

- Wrong **model balances** (DA can not change these but should be aware)
  - e.g., wrong tropospheric stability
  - may get disturbed when confronted with reality (observed data)
    - spin up/spin down problems

Example: HIRS assimilation

Temperature increm.: Exp. - Control
zonal and temporal mean



First HIRS exp. with our old model (GME)

- HIRS assimilation increased warm bias (both FG + Ana)
- But: analysis incr. reduced this increase

- Where did the heating come from???
  - ***Latent heat!!!***
  - Tropical precip 6% increased
  - **Assimilation disturbed model balance**

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- Which variables (**cloud properties**) should be **assimilated** to improve clouds in the model?
  - we should correct the **cause** and **not just** the **symptom**

- Many model improvements will (probably) largely depend on data assimilation

model improvements ←→ **data assimilation**

analysis closer to reality → better chance to detect **model deficiencies**
model closer to reality → better chance to improve/correct **data assimilation**

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Micro-Physics Matter! (1)

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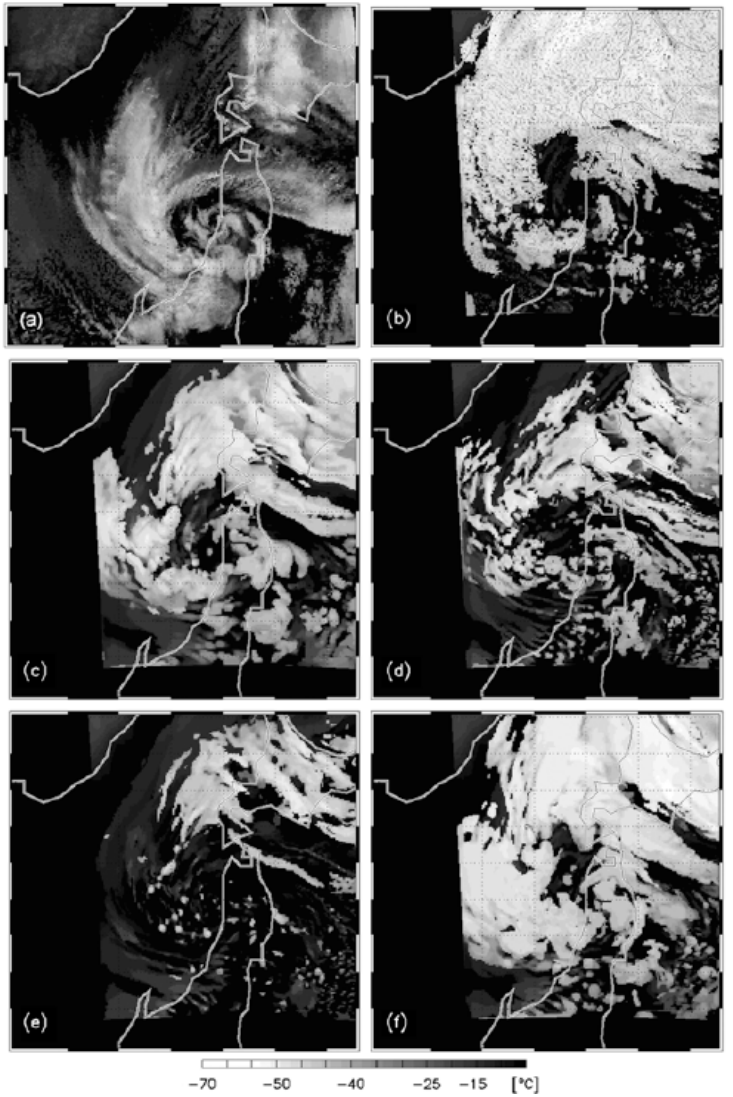
Different microphysics schemes can give very different results

→ For example, Wu and Petty (2011) „*Intercomparison of Bulk Microphysics Schemes in Model Simulations of Polar Lows*“, Mon. Wea. Rev.



Cloud top temperature in K, (a) observations, and (b-f) different microphysics schemes in WRF (Wu and Petty 2011, MWR)

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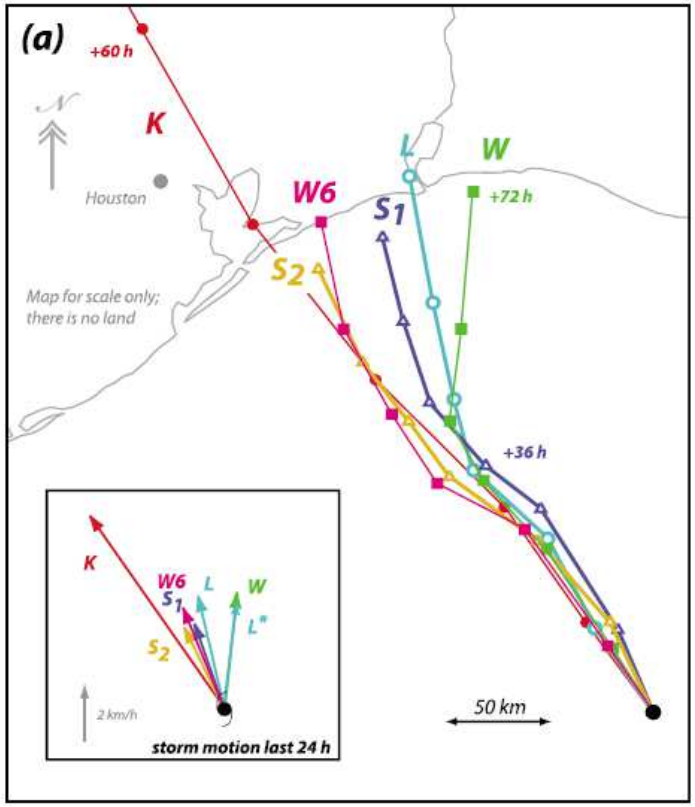
Micro-Physics Matter! (2)

Different microphysics schemes can give very different results

→ Example, Fovell et al. (2010) found a pronounced effect of **ice microphysical assumptions** on hurricane tracks.



Twelve hourly cyclone positions over 72 h for different microphysics schemes in WRF (Fovell et al. 2010)

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- **Micro-physics**
  - **ice processes**
    - nucleation: homogeneous ←→heterogeneous
    - accommodation coefficient
    - ice habit
    - ice fragmentation/multiplication/secondary ice production
    - hail growth
  - **micro-physics ←→ turbulence** interaction
  - **aerosol ←→ cloud** interactions

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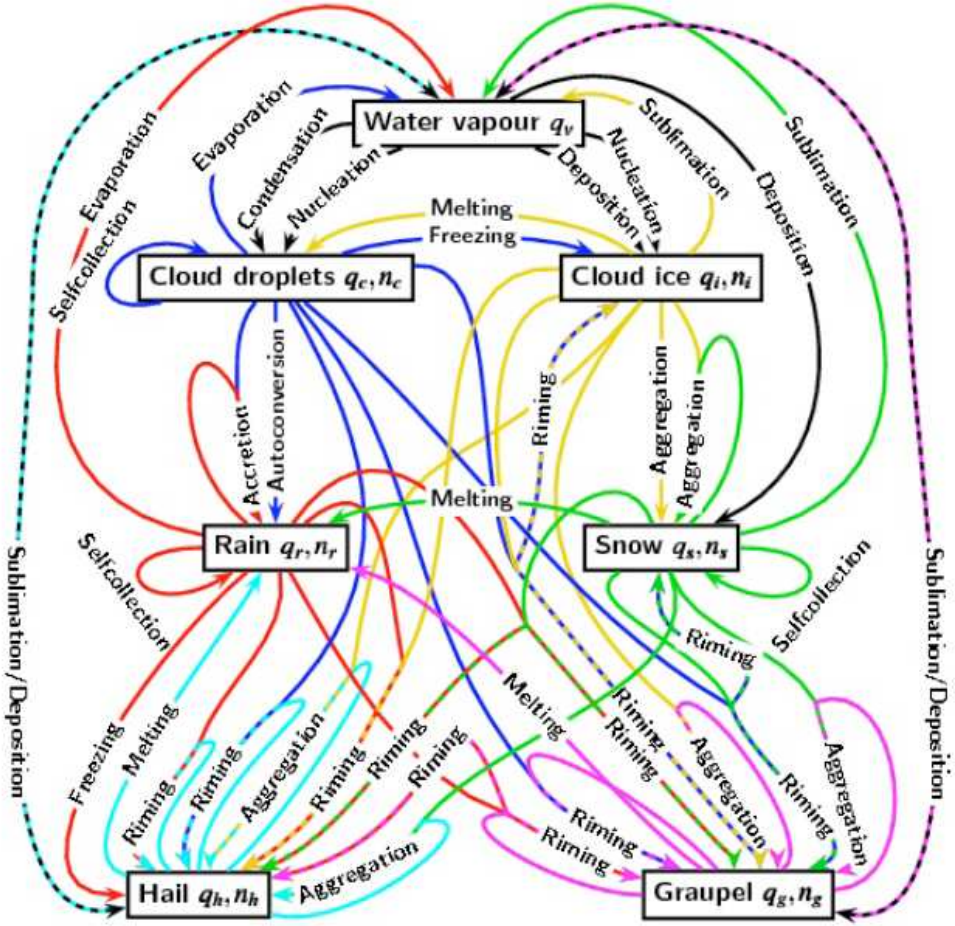
The Seifert and Beheng two-moment scheme:

Extended version by Blahak, Noppel, Beheng and Seifert



Number and mass concentrations of 6 different species

- cloud droplets
- rain drops
- cloud ice
- snow
- graupel
- hail (including wet growth)

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Uncertainty of particle properties

- Ice particles have many different shapes or habits.
- Preferred growth regimes depend on temperature and supersaturation.
- But due to sedimentation and advection there is no unique diagnostic relation between state variables and particle habits.

Hexagonal plate

Pictures from SnowCrystals.com

Needles

Bullet rosettes

Stellar dendrites

Rimed crystals

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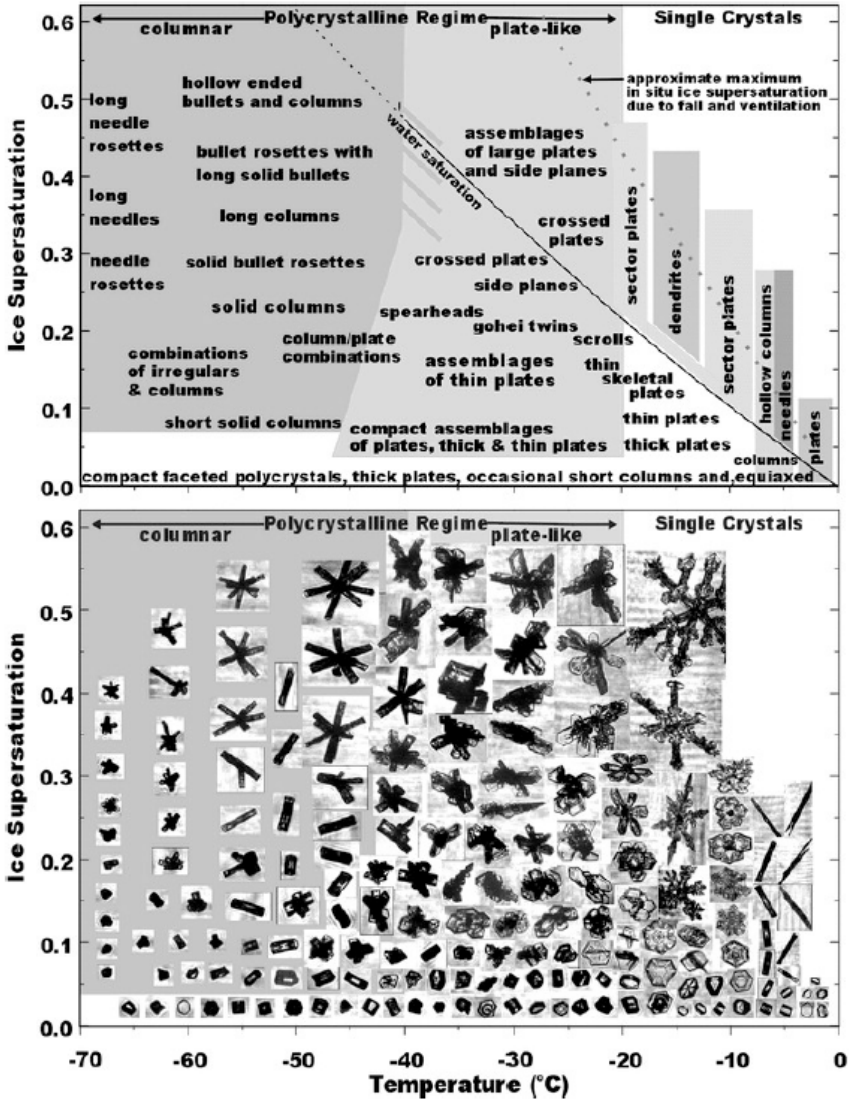

Habit diagram of Bailey and Hallet (2009)

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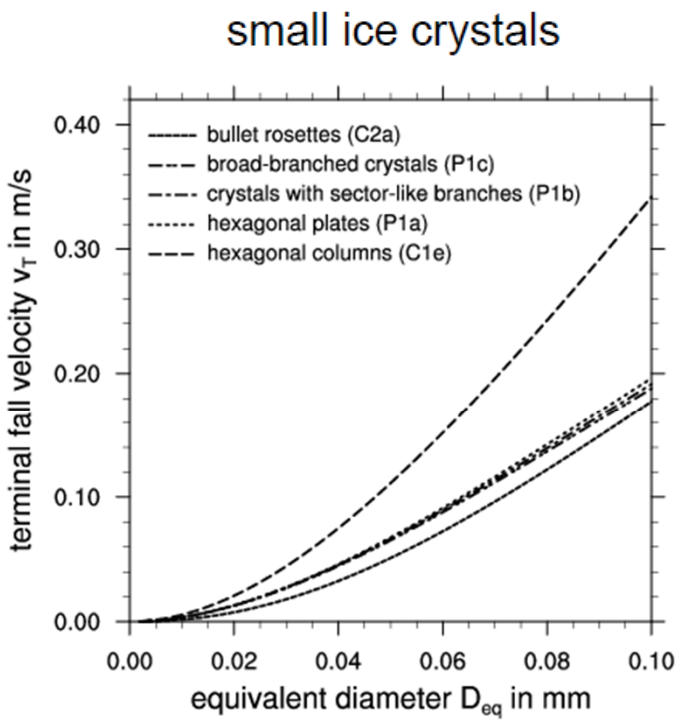
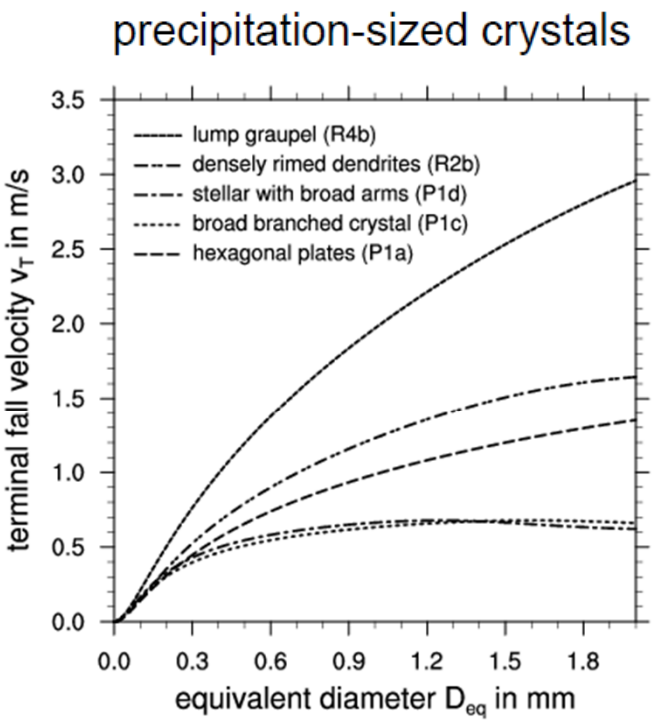
Uncertainty of particle properties → fall speeds

- **sedimentation** and **growth rates** strongly depend on the **terminal fall velocity**





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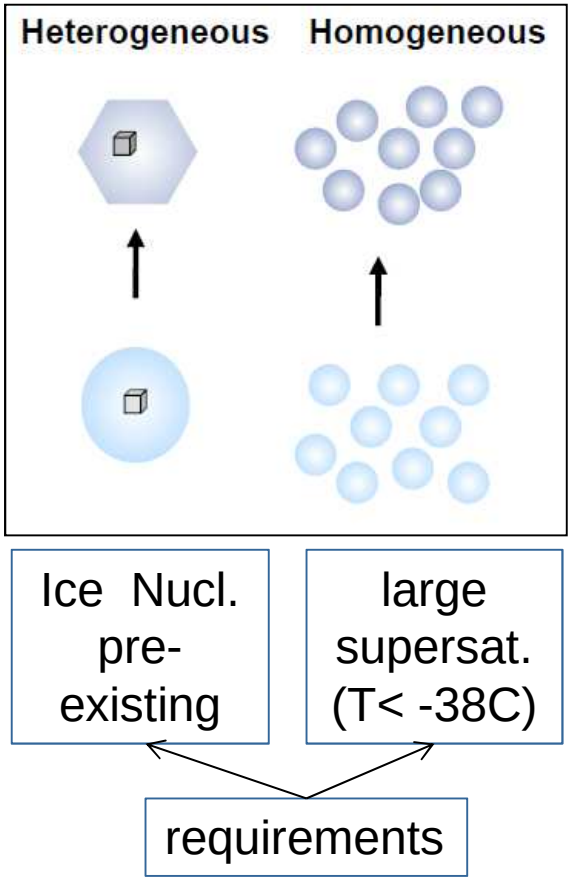
Multiple modes: Competing ice processes

- homogeneous nucleation
  - large number of cloud nuclei
  - high optical thickness
- heterogeneous nucleation
  - starts at higher temperatures
  - properties of ice nuclei
    → glaciation dynamics

Major uncertainties

- availability of ice nuclei (IN)
- properties of IN



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COSMO Model: second peak **Are there too many very cold clouds?**

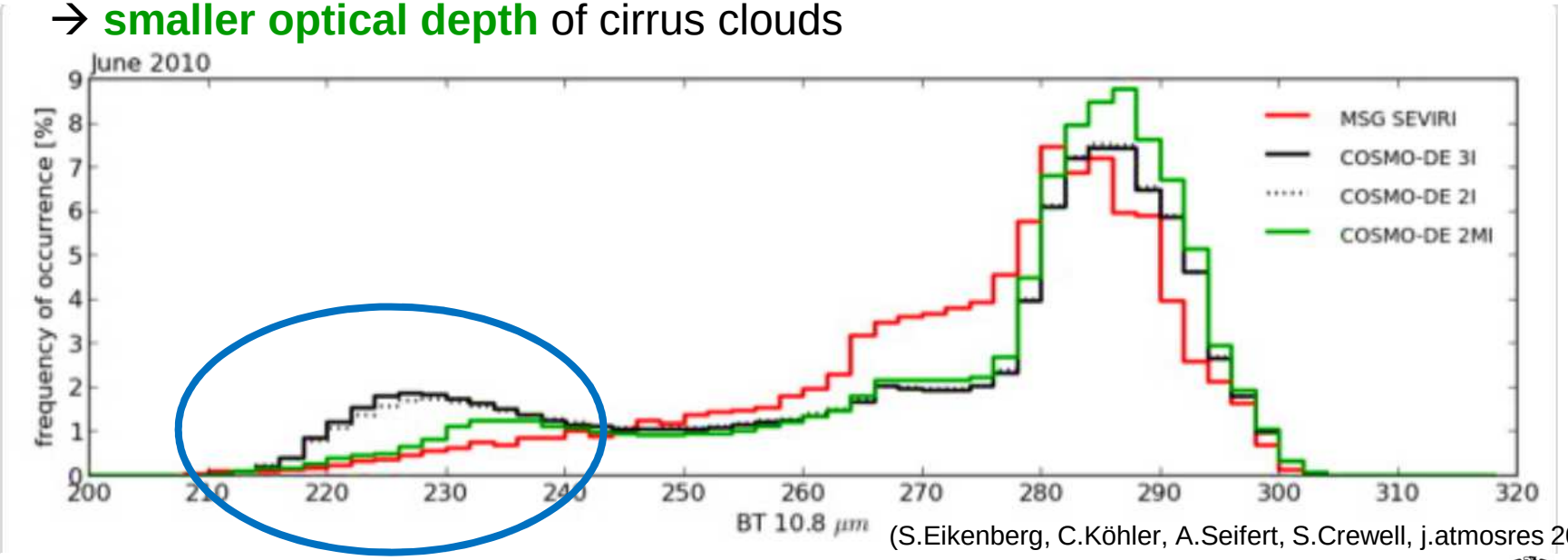
- Use more realistic micro-physics:
  - prognostic Ice Nuclei (IN) [can be trapped in snow]
  - sedimentation of ice not neglected

  → **heterogeneous nucleation** produces less but **larger ice particles**

  → sedimentation

  → **less** water available for **homogeneous nucleation**

  → **smaller optical depth** of cirrus clouds



(S.Eikenberg, C.Köhler, A.Seifert, S.Crewell, j.atmosres 2015)

Where are the uncertainties? Everywhere – a few examples:

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- **Micro-physics**
  - **ice processes**
  - **micro-physics ←→ turbulence** interaction
  - **aerosol ←→ cloud** interactions

- **Subgrid variability**
  - **cloud geometry**
    - cloud fraction
    - cloud overlap
    - in-cloud variability
  - **dependence on history** of clouds and subgrid processes
    - evolution of cloud patterns, spatial organization
    - cold pools, precip falling in moist/dry air

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Subgrid distribution of clouds

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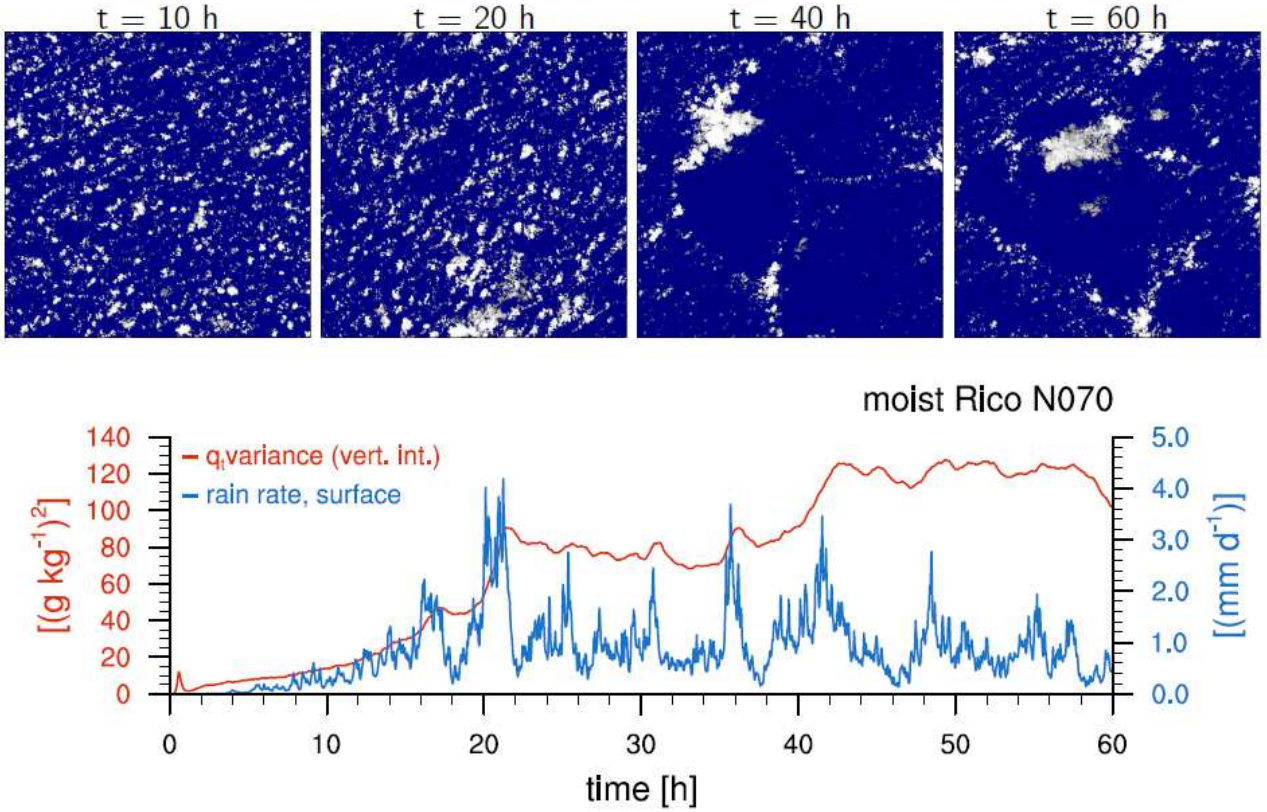
- **generally depends on the history of the clouds**

rain formation ←→ organization of clouds



(Schemann and Seifert 2015, in preparation)

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Subgrid distribution of clouds

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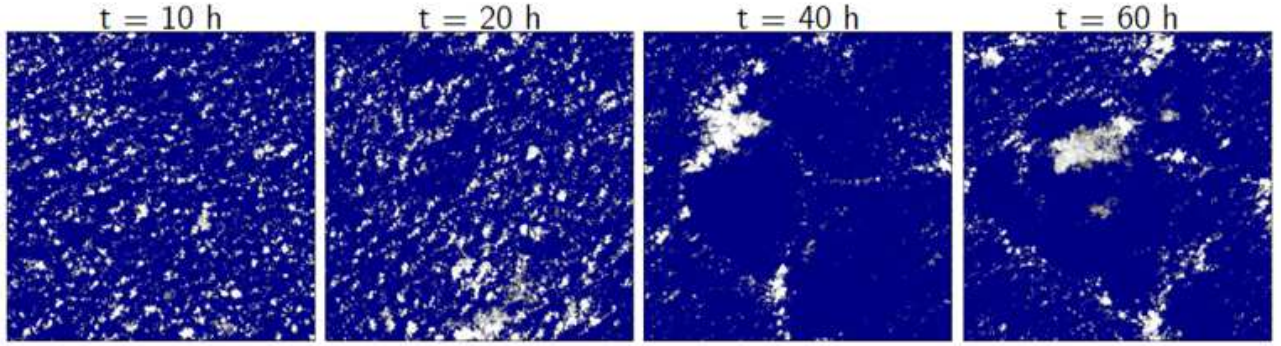

Computing **micro-physics ←→ dynamics** interactions require

- not only the PDFs of cloud water and rain water, e.g.,

$$P(x) = \frac{1}{\sqrt{2\pi}x\sigma_{\ln}} \exp\left(\frac{(\ln(x)-\mu)^2}{2\sigma_{\ln}^2}\right)$$

- but also joint probabilities (e.g., $x_1 = qc$, $x_2 = qr$):

$$P(x_1,x_2) = \frac{1}{\sqrt{2\pi}\sigma_{\ln,1}\sigma_{\ln,2}x_1x_2\sqrt{1-\rho^2}} \exp\left(\frac{(\ln(x_1)-\mu_1)^2}{2(1-\rho^2)\sigma_{\ln,1}^2}\right) \exp\left(\frac{(\ln(x_2)-\mu_2)^2}{2(1-\rho^2)\sigma_{\ln,2}^2}\right) \exp\left(\frac{\rho(x_1-\mu_1)(x_2-\mu_2)}{(1-\rho^2)\sigma_{\ln,1}\sigma_{\ln,2}}\right)$$

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Where are the uncertainties? Everywhere – a few examples:

- **Micro-physics**
- **Subgrid variability**

- **Convective clouds**

  What determines the
  - **triggering** of convection
    - cold pools, evolution, role for triggering
    - gravity waves
    - convergence
  - **mixing** of updraft/downdraft with ambient air
    - homogeneous ←→ heterogeneous mixing
    - importance (existence?) of less diluted updraft cores
    - overshoots
  - **microphysics** of convective clouds
    - in the anvils
    - in the updrafts - production of graupel, hail
    - evaporative cooling → downdrafts

- **Impact on dynamics**

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Where are the uncertainties? Everywhere – a few examples:

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- **Convective clouds**:

  What determines the
  - **triggering** of convection
  - **mixing** of updraft/downdraft with ambient air
  - **microphysics** of convective clouds

- **Impact on dynamics**
  - **storm dynamics**
  - **organized convection**
    - diurnal cycle
    - Mesoscale Convective Systems (MCS)
    - Madden-Julian Oscillations (MJO)
  - **upscaling of errors**
    - forecast busts
    - How chaotic is the moist atmosphere? (predictability)

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Convective Clouds
Large scale

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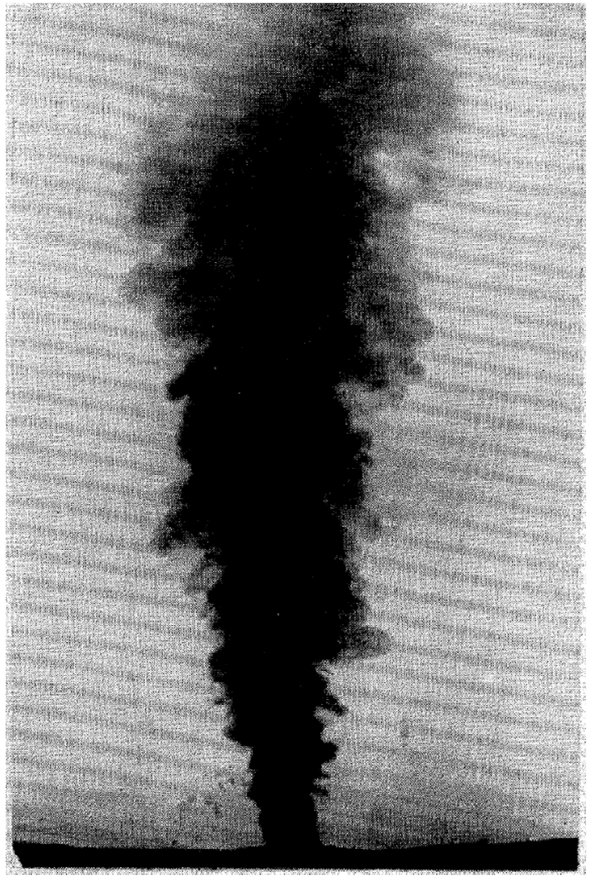
- Large scale model parametrizations:
  - based on entraining plumes studied in the 50s
    - steadily maintained point source (self similar)
    - No buoyancy reversal
  - problems to cover development/organization of convection on different scales, different regimes
    - diurnal cycle
    - Mesoscale Convective Systems (MCS)
    - Madden-Julian Oscillation (MJO)
  - However some progress, improvements
    - strong entrainment (more realistic) → **organization**
      - ➢ only in dry environment (RH dependent entrainment rates)
      - ➢ dryness prevents convection
    - splitting CAPE into tropospheric and BL part → **diurnal cycle**



(reproduced from Morton et al 1956: *Turbulent gravitational convection from maintained and instantaneous sources*)

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Convective Clouds diurnal cycle

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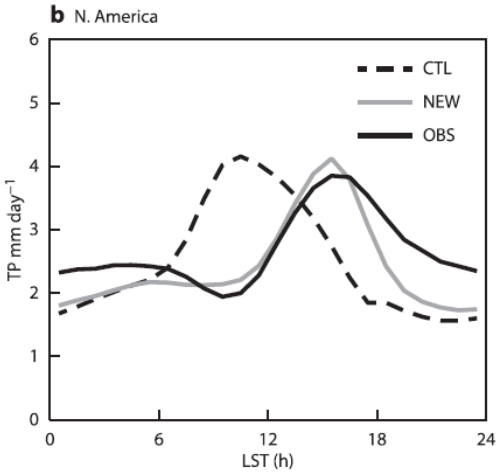
- Large scale model parametrizations:
  - Progress modelling diurnal cycle
    - splitting CAPE into tropospheric and BL part
      → **diurnal cycle**



From Bechtold et al (*JAS* 2013): *Representing Equilibrium and Nonequilibrium Convection in Large-Scale Models*

- Without (deep) convection scheme :
  - 3-10km grid spacing conv. "**grey zone**"
  - Diurnal cycle: convection typically too late
  - the coarser grid → later convection
    (*it takes longer to initiate larger clouds*)
    - **tuning** of subgrid (BL) **turbulence scheme** crucial
    - possible trade off:
      - ➢ convection early enough *but* T-profile too unstable
- Even smaller scales:
  - 500m-3km grid spacing "**cloud permitting models**"
  - < 500m grid spacing **Large Eddy Simulations**

➢ Diurnal cycle well resolved **depending on type of forcing** of the day

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Upscaling of Errors, Predictability

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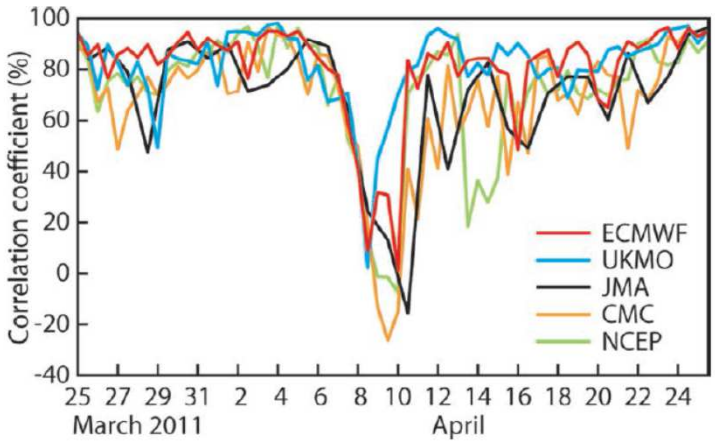
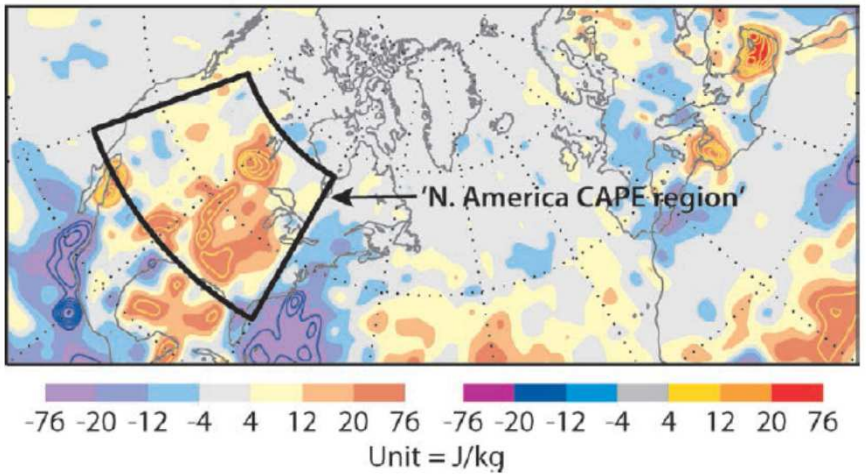
Rodwell et al 2013:
occasional poor forecasts

Busts 8-10 Apr 2011

Day 6 forecast skill over Europe



584 Busts in ERA Interim - Composite



Mean initial (6h) CAPE anomaly for Day 6 busts over Europe
5% level significance: bold color

- Increased initial CAPE over USA correlates with EU busts
- Best and worst ensemble member have same initial perturbation with opposite sign
- MCS slow synoptic evolution
- MCS requires parameterisation

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Upscaling of Errors, Predictability

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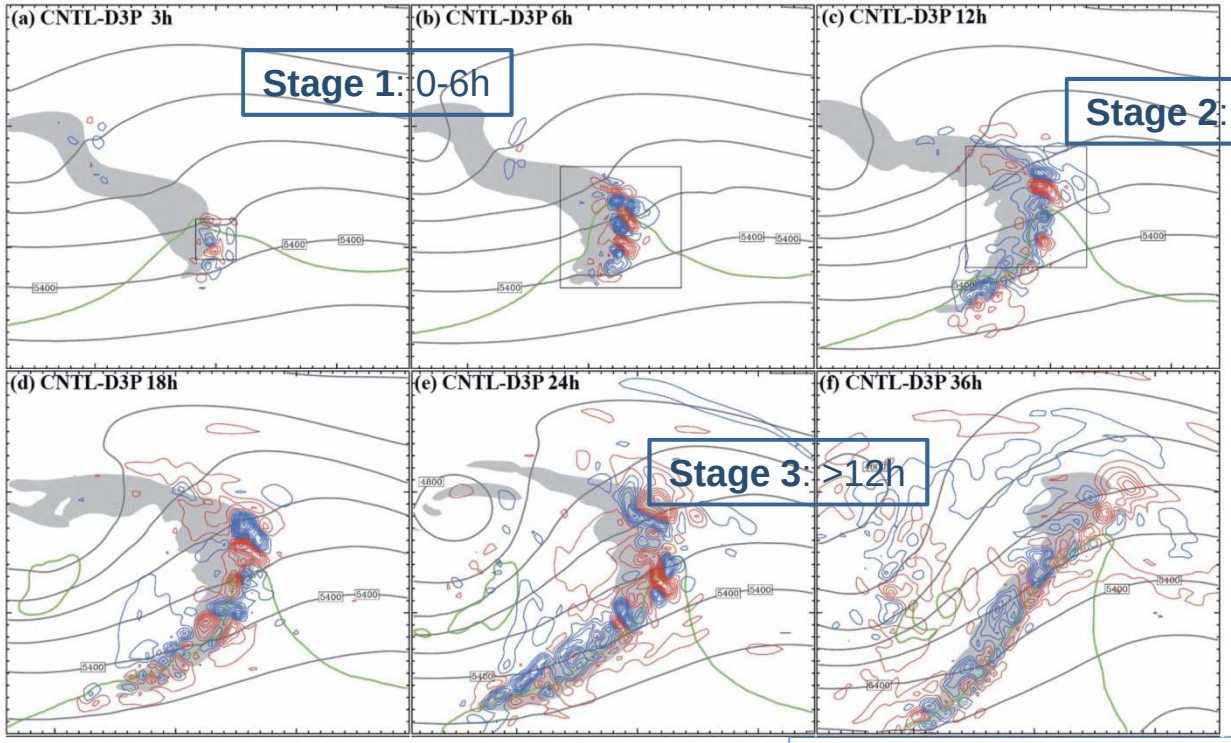
Idealized MM5 simulation, nested domain at 10km resolution



2700km

3400km

Perturbation: 0.2K

V 500hPa difference (red/blue)

Precipitation (grey shaded)
Z 500hPa (black)
CAPE (green)

Zhang et al 2007:
3 stages of error growth

- **Stage 1:** errors growth fast on small scales due to convective instability and latent heat release, but saturate quickly
- **Stage 2:** perturbations expand in spatial scale and come into geostrophic balance
- **Stage 3:** balanced perturbations grow on synoptic scales in presence of baroclinic instability

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Conclusions

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- **Moist processes involve uncertainties at all scales**
  - **micro-physics – subgrid – convective scale – large scale**
- **The perfect model assumption (in DA) is wrong**
- **Assimilating cloud and precipitation processes is important**
- **I wish us a good and interesting work shop**

Thank you for listening

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