Advanced precipitation scheme in ICOLMDZ with improved microphysics and subgrid cloud-hydrometeor interactions to better simulate polar precipitation

Étienne Vignon, Lea Raillard, Audran Borella, Gwendal Rivière,
Meryl Wimmer and Niels Dutrievoz

WAMC, 2025

ICOLMDZ presentation

ICOLMDZ = LMDZ GCM physics + Dynamico dynamical core

LMDZ:

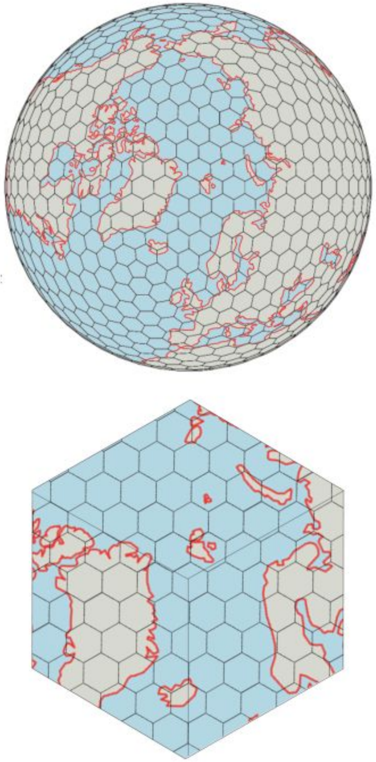
- **Atmospheric component of the IPSL Earth System Model**
- Actively involved in high latitude regional studies (e.g. AWACA project on atmospheric water cycle in Antarctica)

Improved Representation of Clouds in the Atmospheric Component LMDZ6A of the IPSL-CM6A Earth System Model

Jean-Baptiste Madeleine[1], Frédéric Hourdin[1], Jean-Yves Grandpeix[1], Catherine Rio[2],

Development priorities for the LMDZ cloud scheme for CMIP7:

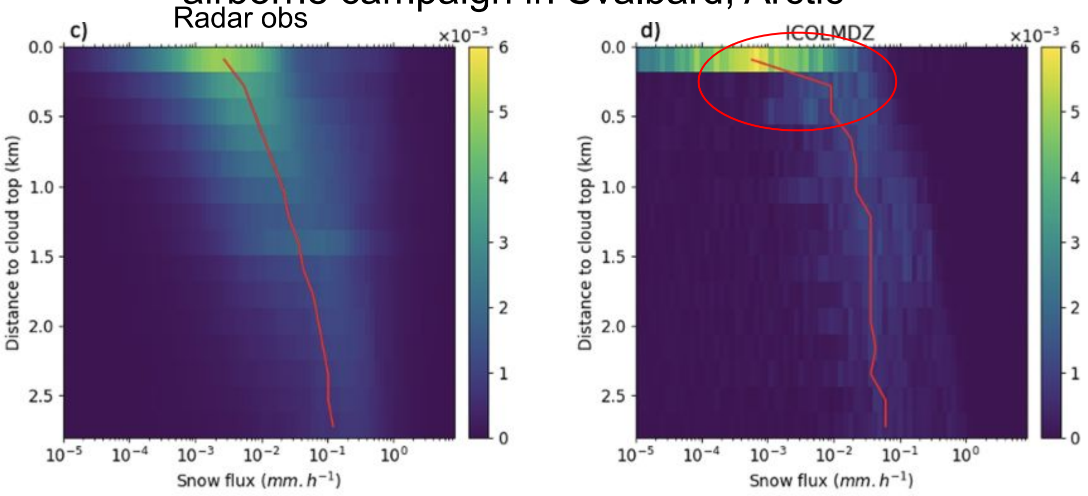
- Mixed Phase Clouds (Raillard et al, under review for JAMES)
- Cirrus clouds and supersaturation (Borella et al, in revision for JAMES)
- Blowing snow (Vignon et al, under review for GMD)
- Water isotopes in polar precipitation (Dutrievoz et al. 2025)
- **Precipitation treatment: this study**



Schematics of ICOLMDZ global (top) and regional configuration (bottom)

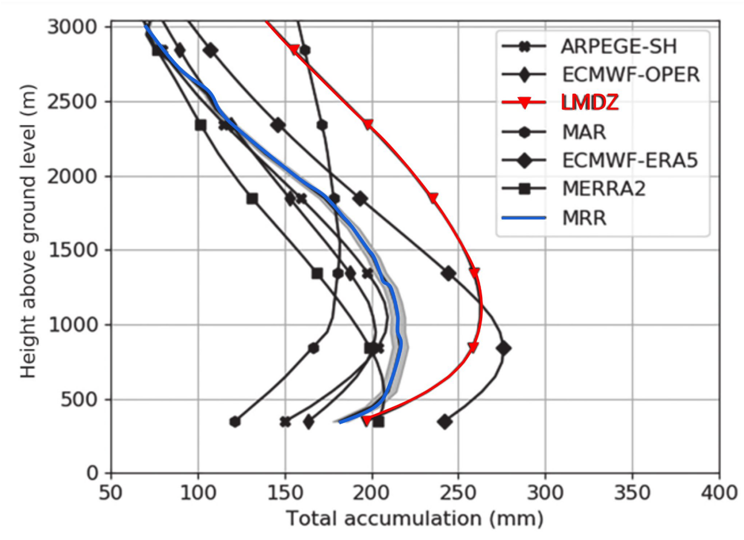
Current biases and shortcomings in LMDZ precipitation: focus on polar regions

Comparison with airborne radar obs during THINICE airborne campaign in Svalbard, Arctic



Raillard et al. 2024, Rivière et al. 2024

Comparison with ground-based radar, Dumont d'Urville station, Antarctica



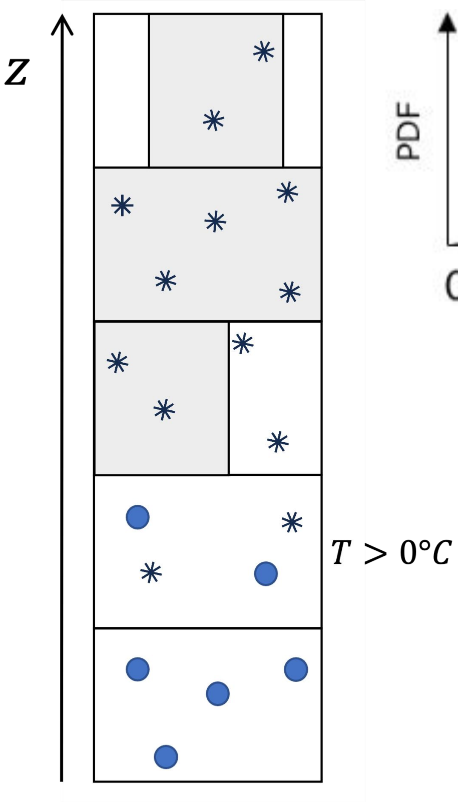
Roussel et al. 2023

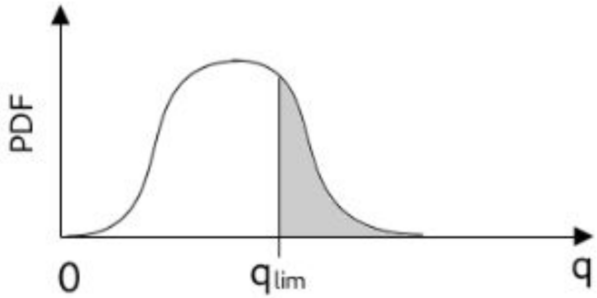
Shortcomings :

- gradual increase in snowfall below cloud not captured
- overly deep melting layer (not shown)
- strong excess in snowfall in altitude
- excess in low-level precip sublimation

Current cloud and precipitation scheme in LMDZ

→ **Based on a paradigm developed in the 1990s**

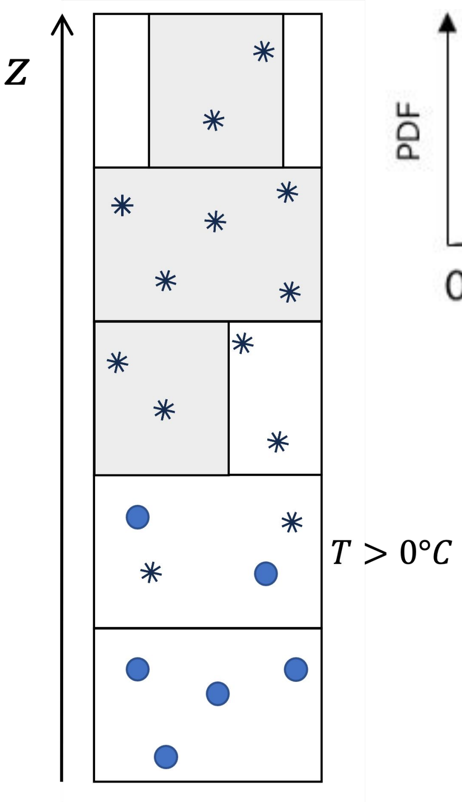


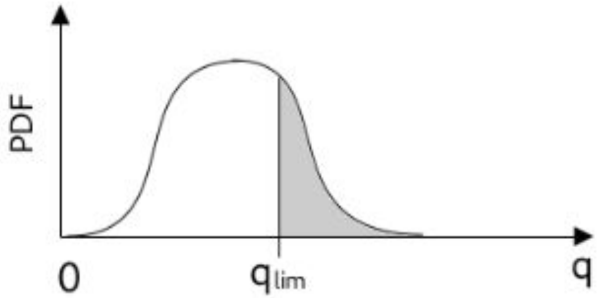


1. **Statistical cloud scheme** w/ **subgrid water distribution**
   Precipitation profile (in equilibrium with atmospheric column) is **diagnosed**
2. **Snowfall** formed by **instantaneous freezing** of rain or **autoconversion** following a **sedimentation-type** equation
3. **Snowfall sublimation** is calculated using **mean RH** in the mesh
4. Liquid fraction of snow flux during **melting** = **f(temperature)**

Current cloud and precipitation scheme in LMDZ

→ **Based on a paradigm developed in the 1990s**





No precipitation tracking and history

Main microphysical processes governing snowfall growth (vapor deposition, aggregation, riming) missing

No different treatment if snow falls in cloud or clear-sky

No dependency on layer depth ….

1. **Statistical cloud scheme** w/ **subgrid water distribution** **Precipitation** profile (in equilibrium with atmospheric column) is **diagnosed**
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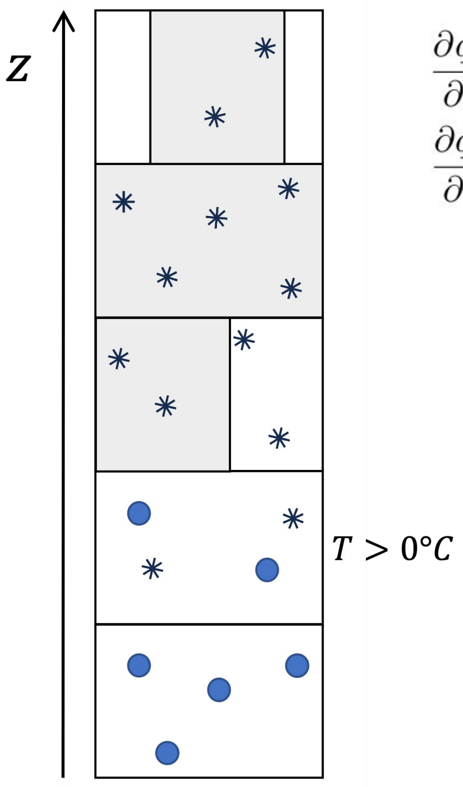
New Process-Oriented PRECIPitation (POPRECIP) scheme development

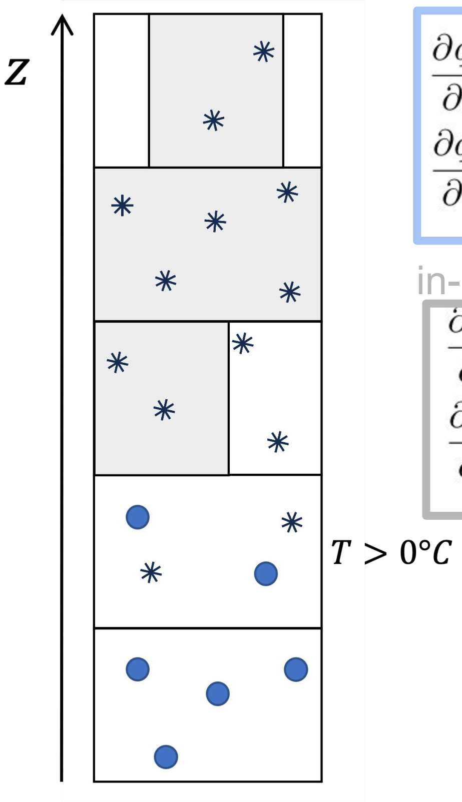
1-moment approach, evolution equation for rain and snow specific contents



$$\frac{\partial q_r}{\partial t} + \mathbf{u}\cdot\nabla q_r = \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{auto}} + \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{col}} + \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{melt}} + \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{freez}} + \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{eva}} + \left.\frac{\partial q_r}{\partial t}\right|_{\mathrm{sedim}}$$

$$\frac{\partial q_s}{\partial t} + \mathbf{u}\cdot\nabla q_s = \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{auto}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{agg}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{melt}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{freez}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{sub}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{rim}} + \left.\frac{\partial q_s}{\partial t}\right|_{\mathrm{sedim}}$$

New Process-Oriented PRECIPitation (POPRECIP) scheme development



1-moment approach, evolution equation for rain and snow specific contents

clear-sky

$$\frac{\partial q_r}{\partial t} + \mathbf{u} \cdot \nabla q_r = \left.\frac{\partial q_r}{\partial t}\right|_{melt} + \left.\frac{\partial q_r}{\partial t}\right|_{freez} + \left.\frac{\partial q_r}{\partial t}\right|_{eva} + \left.\frac{\partial q_r}{\partial t}\right|_{sedim}$$

$$\frac{\partial q_s}{\partial t} + \mathbf{u} \cdot \nabla q_s = \left.\frac{\partial q_s}{\partial t}\right|_{melt} + \left.\frac{\partial q_s}{\partial t}\right|_{freez} + \left.\frac{\partial q_s}{\partial t}\right|_{sub} + \left.\frac{\partial q_s}{\partial t}\right|_{sedim}$$

in-cloud

$$\frac{\partial q_r}{\partial t} + \mathbf{u} \cdot \nabla q_r = \left.\frac{\partial q_r}{\partial t}\right|_{auto} + \left.\frac{\partial q_r}{\partial t}\right|_{col} + \left.\frac{\partial q_r}{\partial t}\right|_{melt} + \left.\frac{\partial q_r}{\partial t}\right|_{freez} + \left.\frac{\partial q_r}{\partial t}\right|_{sedim}$$

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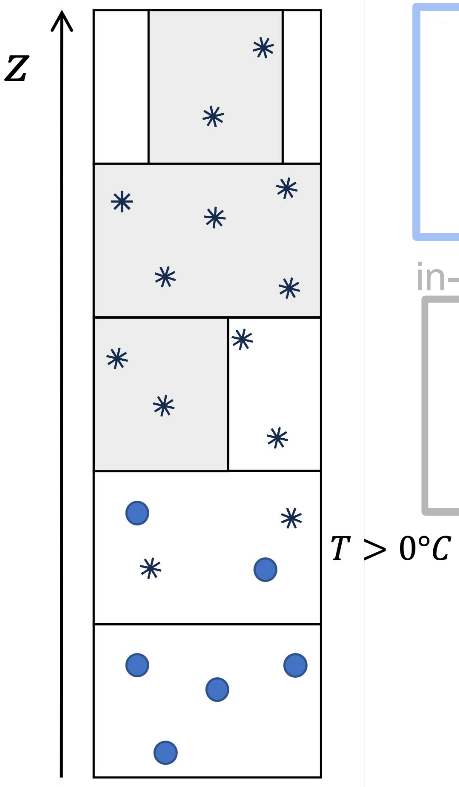
- Intermediate complexity parameterization of the different terms.
- Precipitation differently interacts with clouds and clear-sky (assuming maximum-random vertical overlap of clouds)
- Careful numerical treatment to ensure convergence and stability at typical GCM time-steps

New Process-Oriented PRECIPitation (POPRECIP) scheme development



1-moment approach, evolution equation for rain and snow specific contents

clear-sky

$$0 = \left.\frac{\partial q_r}{\partial t}\right|_{\text{melt}} + \left.\frac{\partial q_r}{\partial t}\right|_{\text{freez}} + \left.\frac{\partial q_r}{\partial t}\right|_{\text{eva}} + \left.\frac{\partial q_r}{\partial t}\right|_{\text{sedim}}$$

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in-cloud

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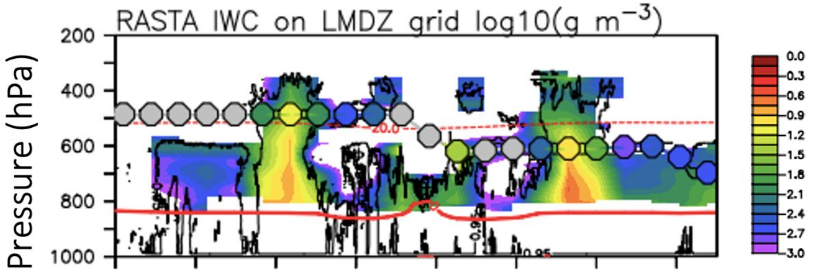
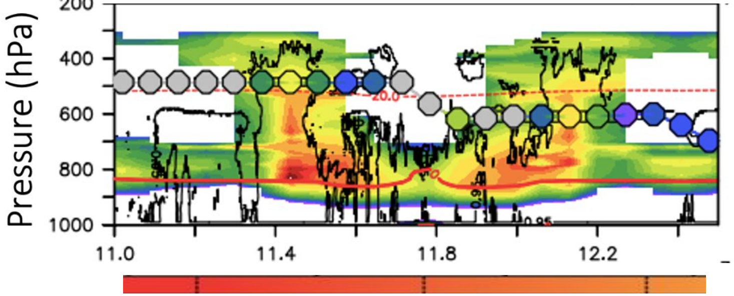
First developments and test on stationary version of the scheme (trade-off between sophistication and numerical cost)

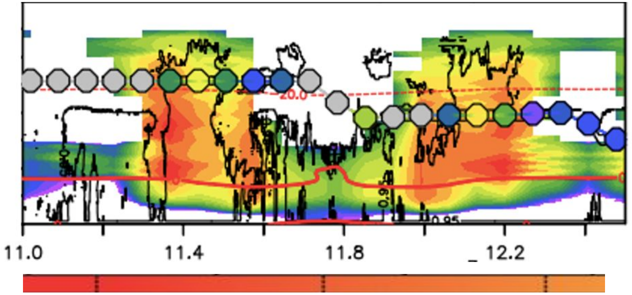
Preliminary evaluation over Svalbard: Ice water content

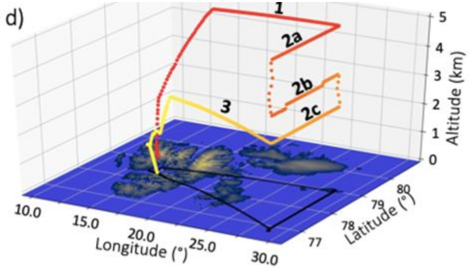


ICOLMDZ + POPRECIP



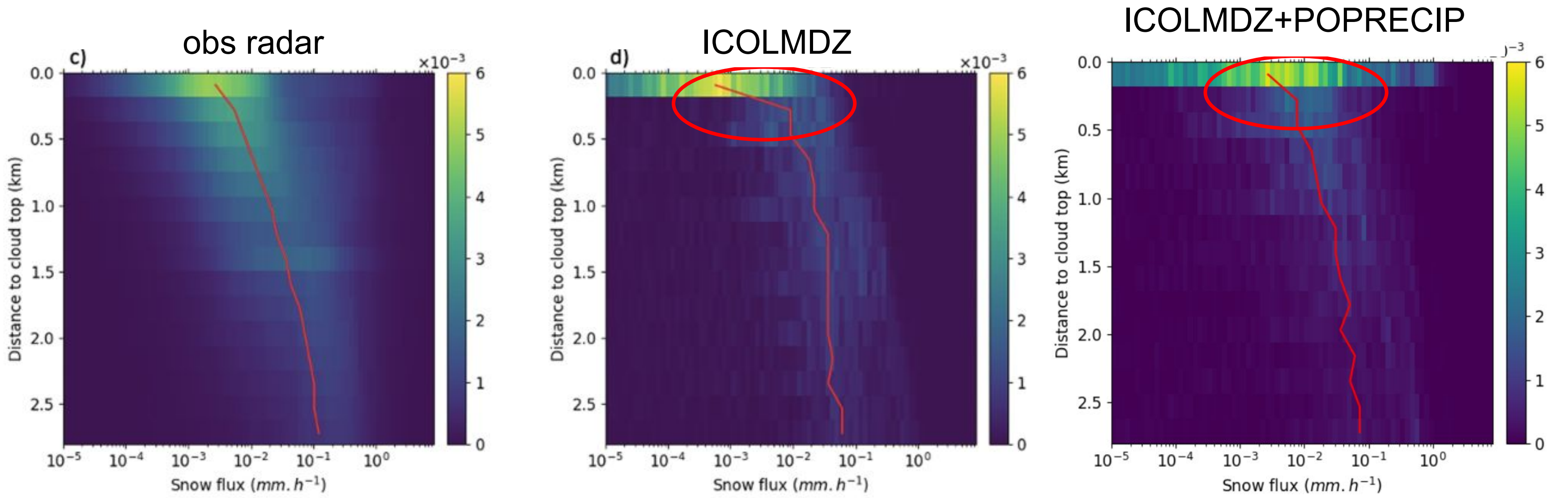
ICOLMDZ





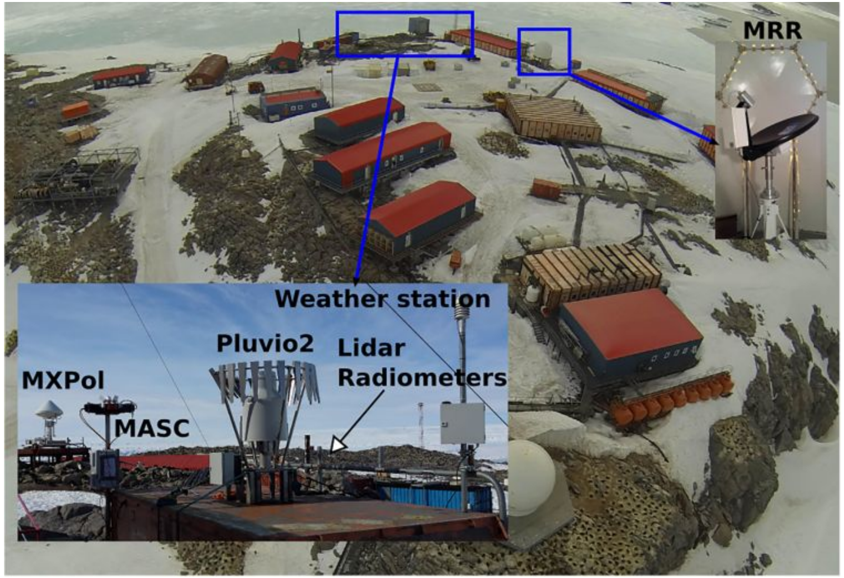
Preliminary evaluation over Svalbard: precipitation flux

2D distribution of snowfall over Svalbard

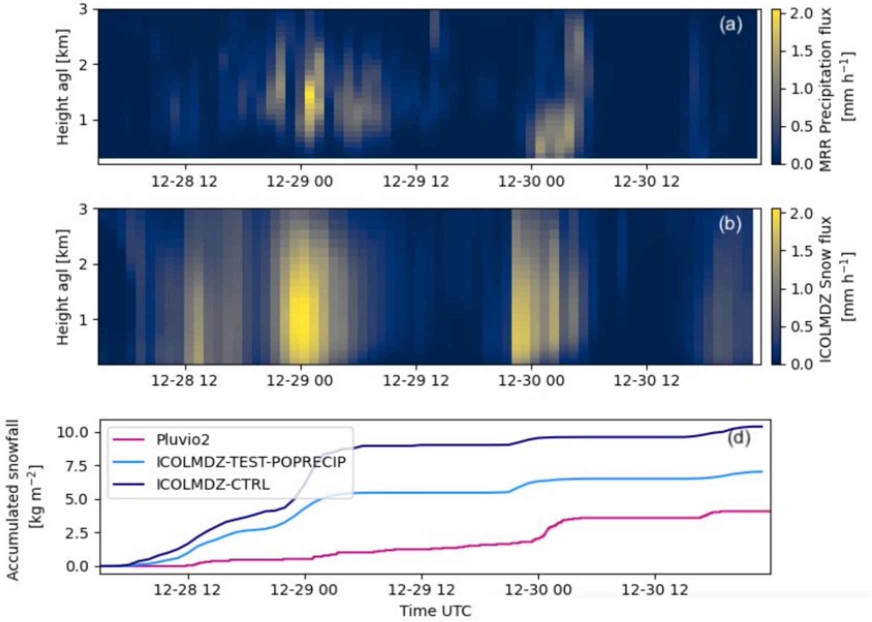


Preliminary evaluation at Dumont d’Urville station

Case study of a precipitation event in December 2015 (APRES3 campaign)



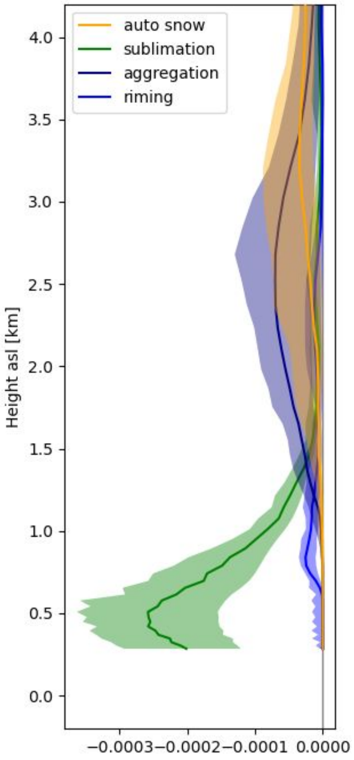
Grazioli et al . 2017



remaining biases:
structural deficiencies or free parameters’ calibration issues?

Constraints on free parameter ranges using polarimetric radar obs at DDU

Perturbed Parameter Ensemble experiments
6 free parameters in the new precipitation scheme
60 (6x10) simulations

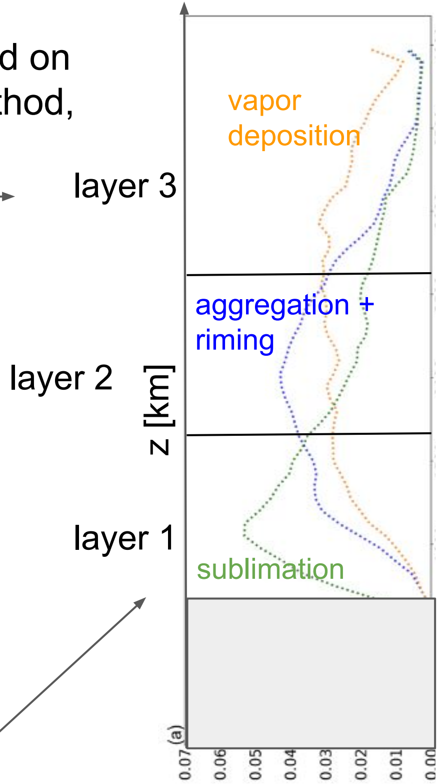


Snowfall growth tendency [kg/kg/s] in ICOLMDZ (minus for deposition, aggregation and riming)

Constraints on free parameter ranges using polarimetric radar obs at DDU

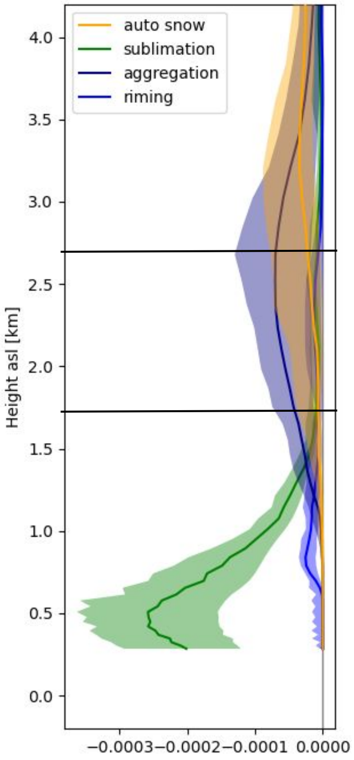
polarimetric X-band radar deployed at DDU, December 2015 - January 2016

“process identification based on vertical gradient signs” method, Planat et al. 2021



bias likely attributed to the representation of katabatic jump at the coast (Wiener et al. 2025)

probability that a process governs precipitation evolution



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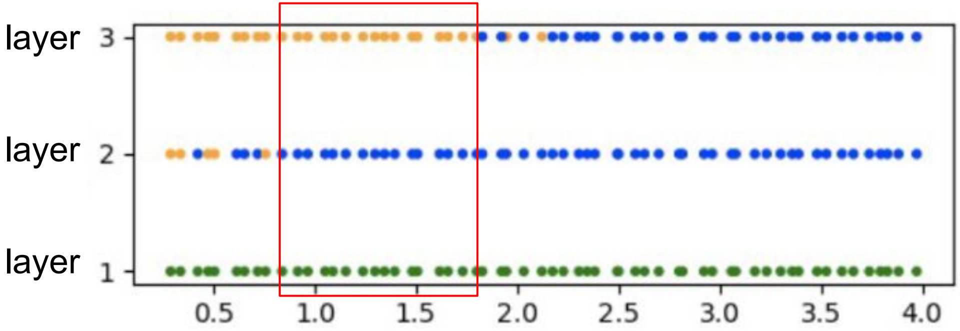
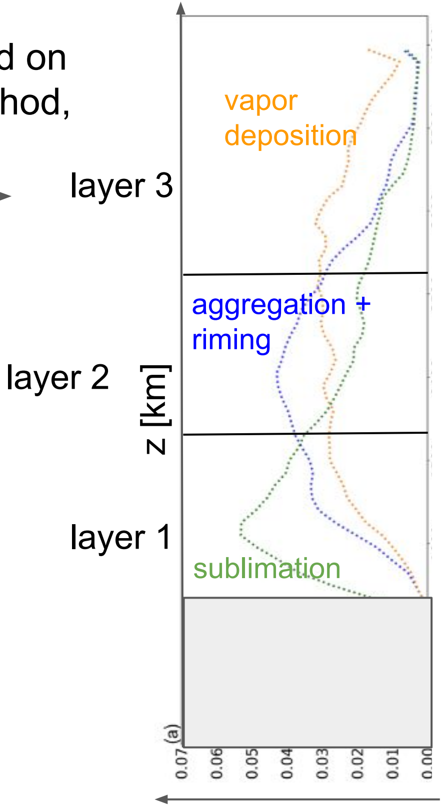
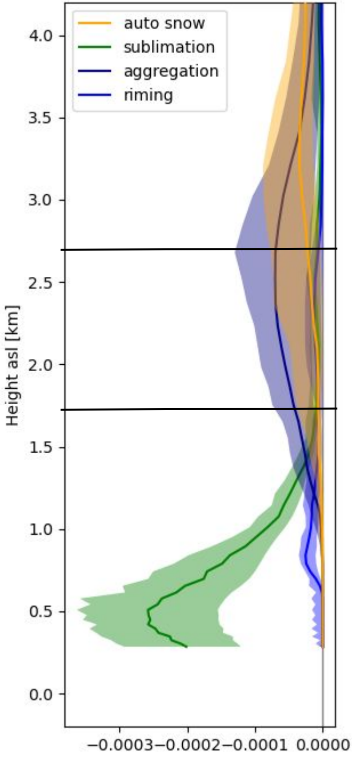


Snowflake aggregation efficiency in the 60 simulations of the PPE
(plausible range of values)



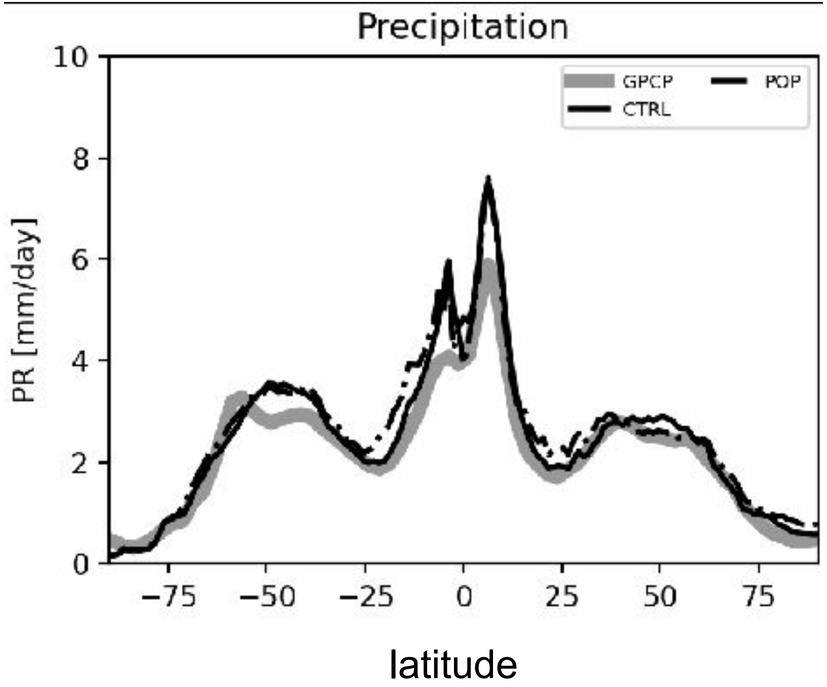
probability that a process governs precipitation evolution



Snowfall growth tendency [kg/kg/s] in ICOLMDZ (minus for deposition, aggregation and riming)

Outlook

- Full tuning on ‘warm’ and ‘cold’ reference simulations
- In-depth evaluation using the recent precipitation measurements along the Adélie Land transect (AWACA, https://awaca.ipsl.fr/en/)
- Application in global simulations (in progress)
- Development of a full prognostic version



Thank you for your attention

References:

Borella A, Étienne VIGNON, Olivier Boucher, et al. A New Prognostic Parameterization of Subgrid Ice Supersaturation and Cirrus Clouds in the ICOLMDZ AGCM. *ESS Open Archive* . December 28, 2024.

Dutrievoz, N., Agosta, C., Risi, C., Vignon, É., Nguyen, S., Landais, A., et al. (2025). Antarctic water stable isotopes in the global atmospheric model LMDZ6: From climatology to boundary layer processes. *Journal of Geophysical Research: Atmospheres*, 130, e2024JD042073.

Raillard L, Étienne VIGNON, Gwendal Rivière, et al. A turbulence-informed parameterization of phase partitioning in stratiform mixed-phase clouds for the ICOLMDZ model. *ESS Open Archive* . June 26, 2025.

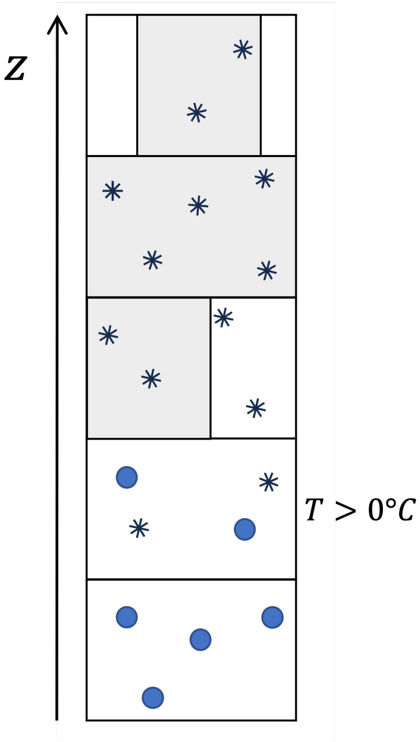
Raillard L, Borella A, Vignon É, Rivière G, Dutrievoz N, Wimmer M, Advanced precipitation scheme in ICOLMDZ with improved microphysics and subgrid cloud-hydrometeor interactions to better simulate polar precipitation, in prep for GMD

Roussel, M.-L., Wiener, V., Genthon, C., Vignon, E., Bazile, E., Agosta, C., et al. (2023) Assessing the simulation of snowfall at Dumont d'Urville, Antarctica, during the YOPP-SH special observing campaign. *Quarterly Journal of the Royal Meteorological Society*, 149(753), 1391–1406.

Vignon, É., Chiabrando, N., Agosta, C., Amory, C., Wiener, V., Charrel, J., Dubos, T., and Genthon, C.: Intermediate-complexity Parameterisation of Blowing Snow in the ICOLMDZ AGCM: development and first applications in Antarctica, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-2871, 2025.

Wiener, V., Vignon, É., Caton Harrison, T., Genthon, C., Toledo, F., Canut-Rocafort, G., Meurdesoif, Y., and Berne, A.: An extensive investigation of the ability of the ICOLMDZ model to simulate a katabatic wind event in Antarctica, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-2046, 2025

New Process-Oriented PRECIPitation (POPRECIP) scheme



- Accounts for **microphysical processes AND macrophysical (subgrid) interactions** between precip. and clouds
- Designed for GCMs (**intermediate complexity**) Δt~5-30min -> important work on **numerics**
- Stay diagnostics (for now, no full prognostic treatment) for numerical cost reasons

1. **Statistical cloud scheme** w/ **subgrid water distribution**
   Precipitation profile (in equilibrium with cloud field) is **diagnosed**

2. **Snowfall** is formed by vapor deposition, aggregation, riming
3. **Sublimation, growth by deposition, and collection processes** are calculated differently between cloud and clear sky fraction, assuming maximum-random overlap
4. **Melting** and **freezing** processes are physically consistent

+identification and minimization of tuning parameters -> full calibration possible

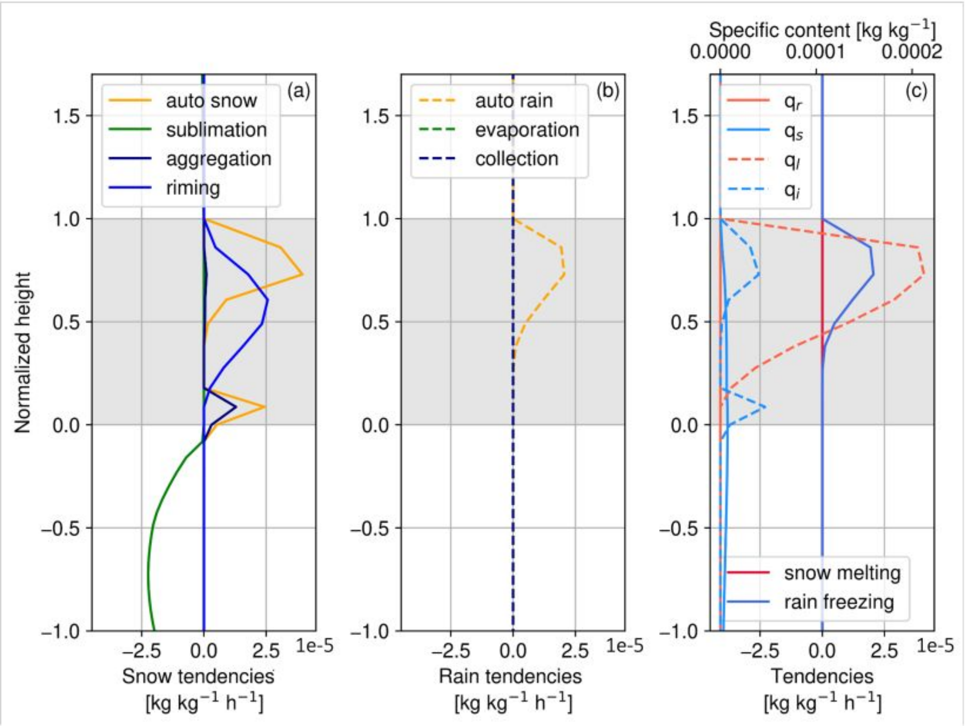
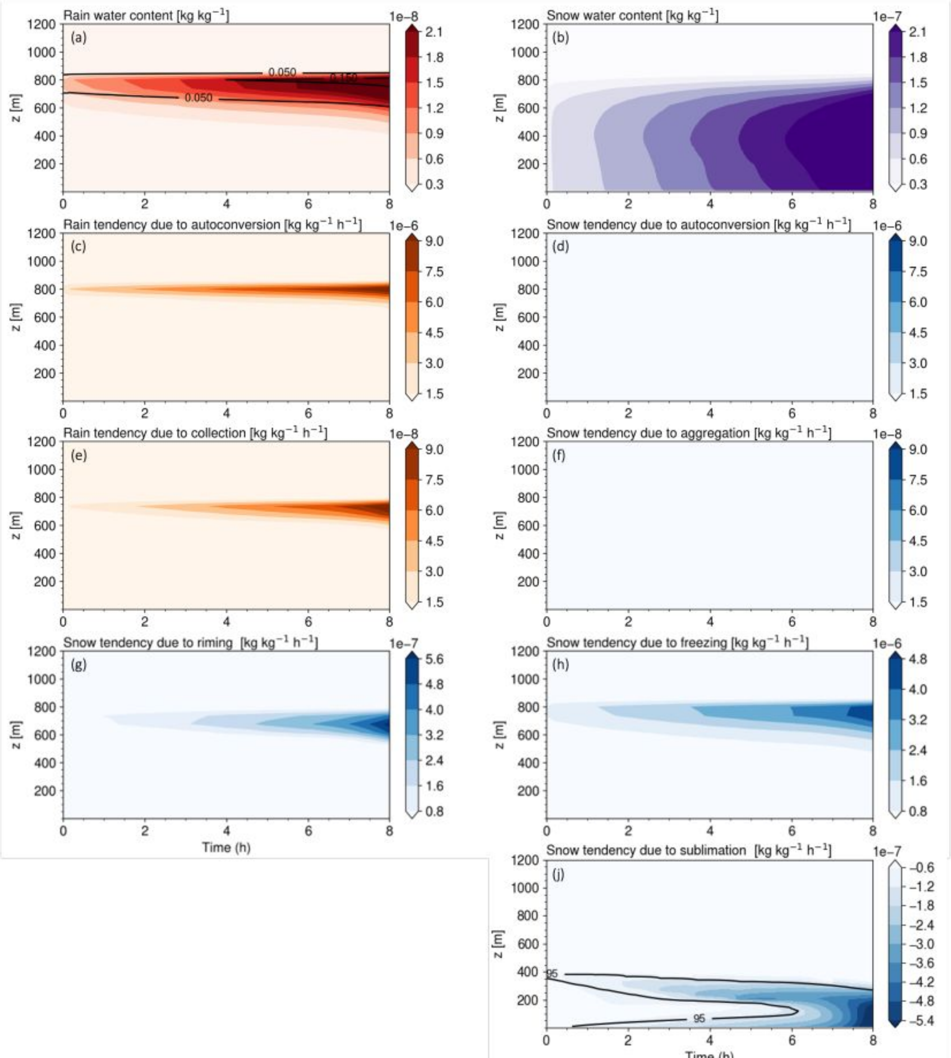
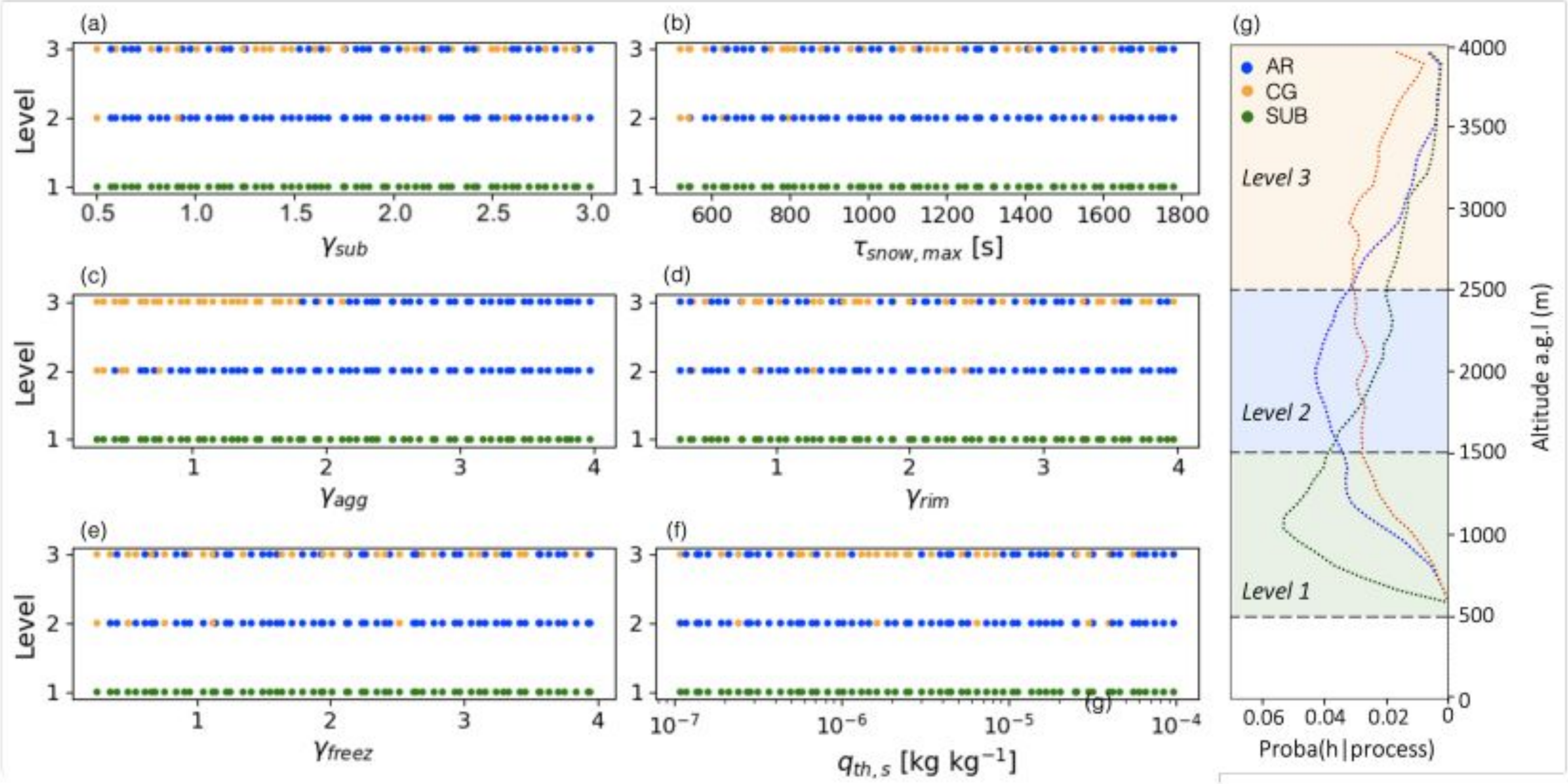
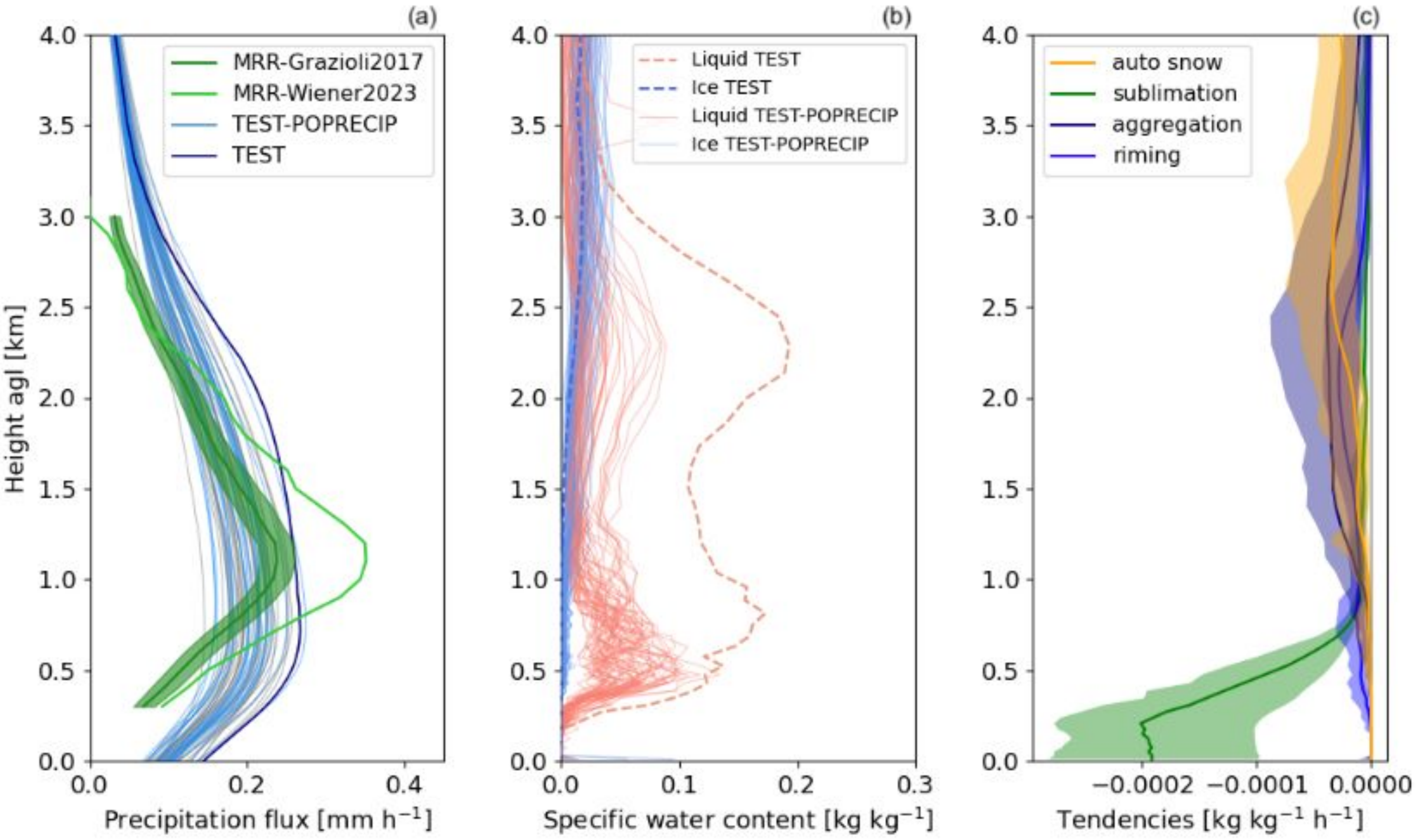
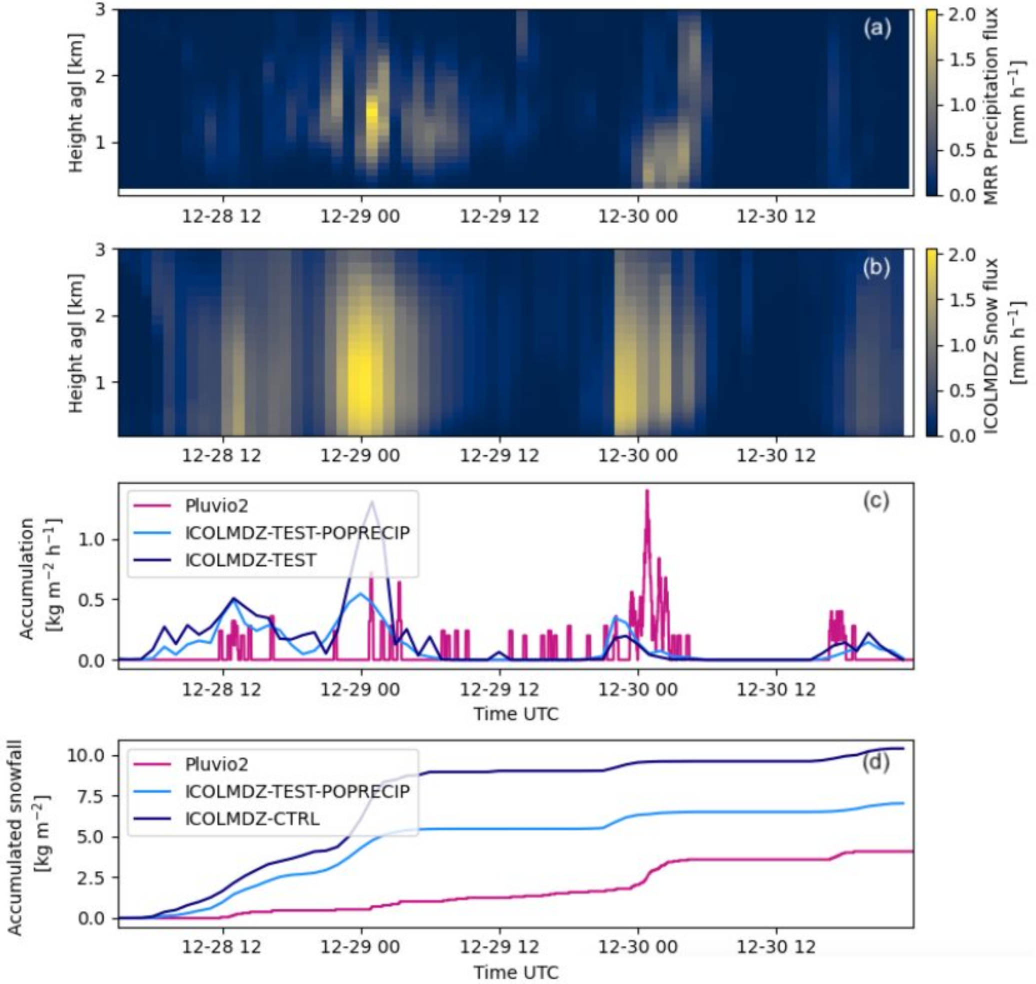


FIGURE 5.4 – Vertical profiles of the tendencies of the different precipitation processes in POPRECIP. (a) Tendencies affecting the snow flux, (b) Tendencies affecting the rain flux only, (c) Tendencies of transfer between the two precipitation fluxes. Snow melting and rain freezing are counted from the snow perspective (i.e. melting is a sink and freezing a source). Cloud ice and liquid contents (q_i and q_l, dashed lines) and diagnostic snow and rain contents (q_r and q_s, solid line) are shown. The diagnostic rain and snow contents are retrieved assuming a fall velocity of respectively 4 m s^{-1} and 1 m s^{-1}. The profiles represent the mean over the period from 00 :00 on 10 October to 05 :00 on 10 October 2004.


Rain water content [kg kg−1]
(a)
1e−8
Snow water content [kg kg−1]
(b)
1e−7
Rain tendency due to autoconversion [kg kg−1 h−1]
(c)
1e−6
Snow tendency due to autoconversion [kg kg−1 h−1]
(d)
1e−6
Rain tendency due to collection [kg kg−1 h−1]
(e)
1e−8
Snow tendency due to aggregation [kg kg−1 h−1]
(f)
1e−8
Snow tendency due to riming [kg kg−1 h−1]
(g)
1e−7
Snow tendency due to freezing [kg kg−1 h−1]
(h)
1e−6
Snow tendency due to sublimation [kg kg−1 h−1]
(j)
1e−7
z [m]
Time (h)


(a)
(b)
(c)
(d)
(e)
(f)
(g)
Level
γ_{sub}
$\tau_{snow,max}$ [s]
γ_{agg}
γ_{rim}
γ_{freez}
$q_{th,s}$ [kg kg^{-1}]
AR
CG
SUB
Level 3
Level 2
Level 1
Altitude a.g.l (m)
Proba(h|process)


(a)
(b)
(c)
MRR-Grazioli2017
MRR-Wiener2023
TEST-POPRECIP
TEST
Height agl [km]
Precipitation flux [mm h^{-1}]
Liquid TEST
Ice TEST
Liquid TEST-POPRECIP
Ice TEST-POPRECIP
Specific water content [kg kg^{-1}]
auto snow
sublimation
aggregation
riming
Tendencies [kg kg^{-1} h^{-1}]


(a)
Height agl [km]
MRR Precipitation flux [mm h⁻¹]
12-28 12
12-29 00
12-29 12
12-30 00
12-30 12
(b)
ICOLMDZ Snow flux [mm h⁻¹]
(c)
Pluvio2
ICOLMDZ-TEST-POPRECIP
ICOLMDZ-TEST
Accumulation [kg m⁻² h⁻¹]
Time UTC
(d)
ICOLMDZ-CTRL
Accumulated snowfall [kg m⁻²]