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Institut für Meteorologie
und Geophysik

Do we need more atmospheric data in mountainous terrain? Numerical modeling perspectives

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Annika Oertel, Karlsruhe Institute of Technology

Didier Ricard, Meteo France

Christoph Wittmann, Geosphere Austria

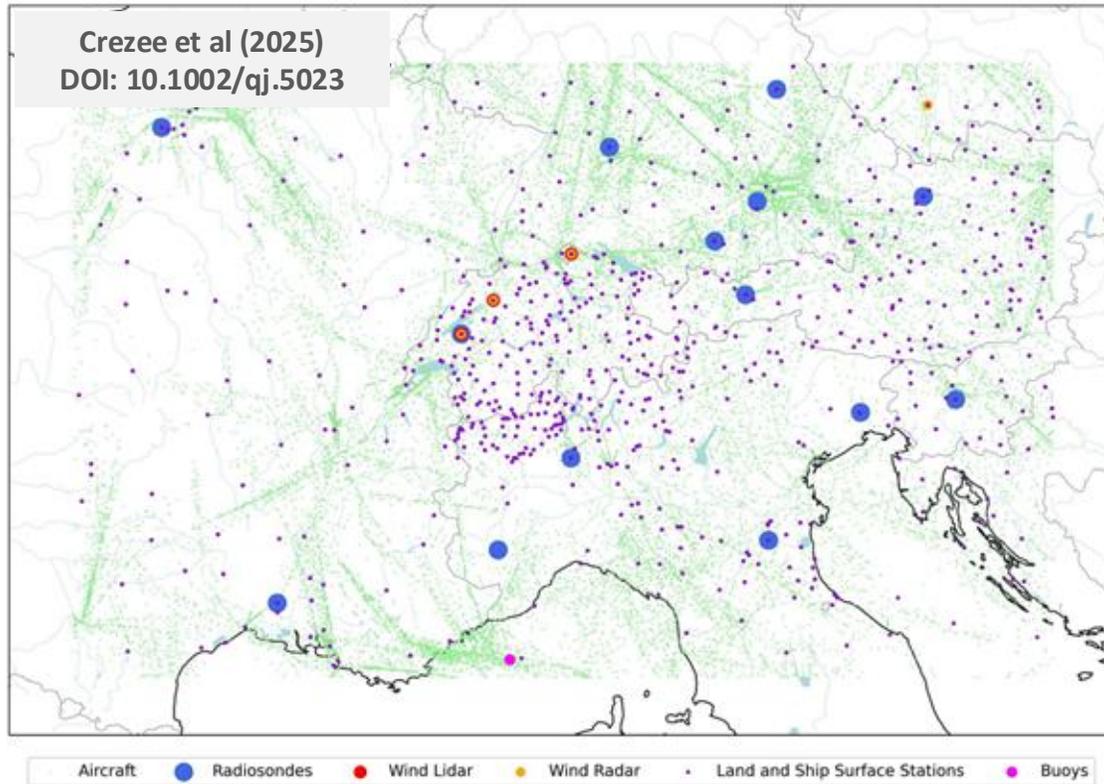
Günther Zängl, Deutscher Wetterdienst

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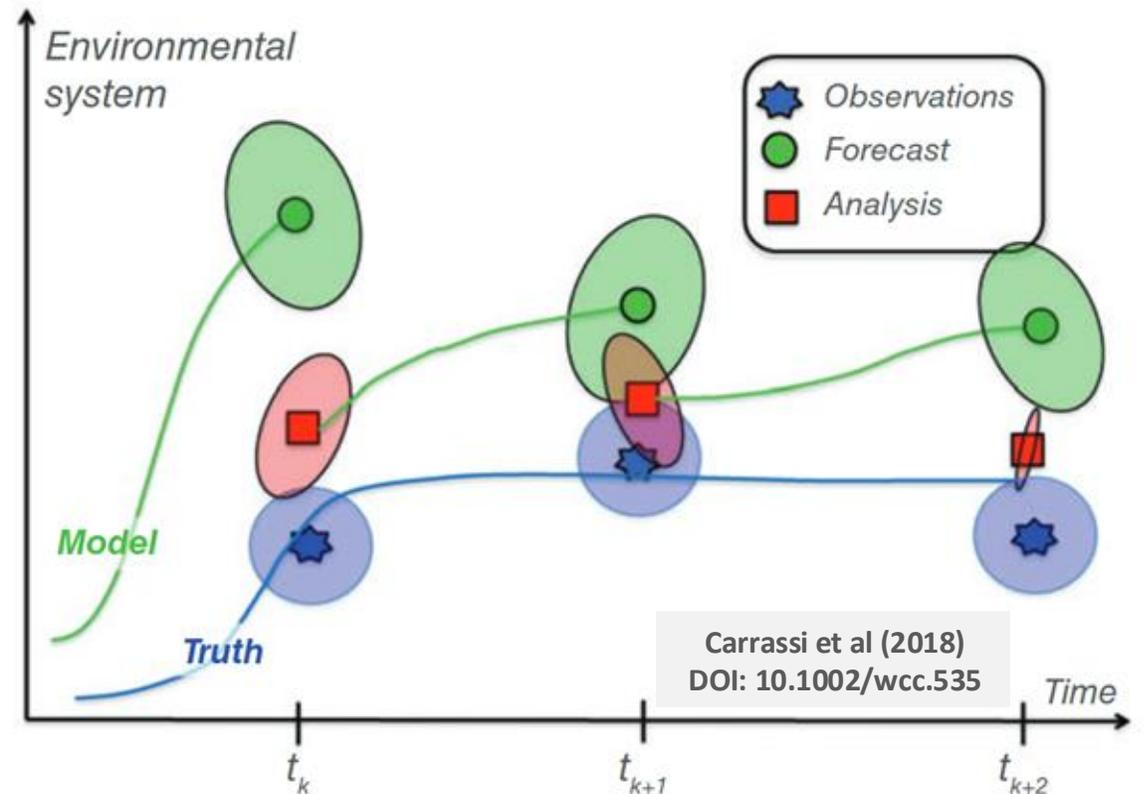
- Introduction: NWP and data assimilation
- What is special about NWP over mountains
- Does NWP need more atmospheric data in mountainous terrain? For what purpose?
- Thoughts on the integration of observations and NWP models

The NWP process: DA-forecast cycling

Available meteorological observations (example)

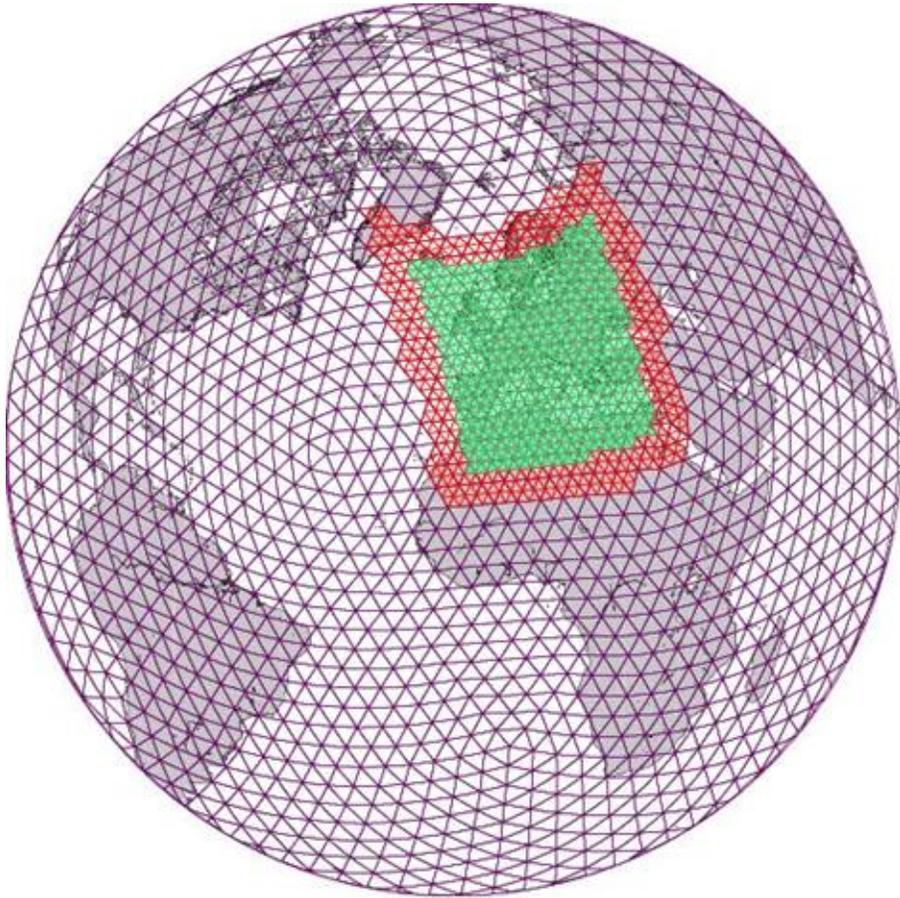


Data assimilation/forecast cycle

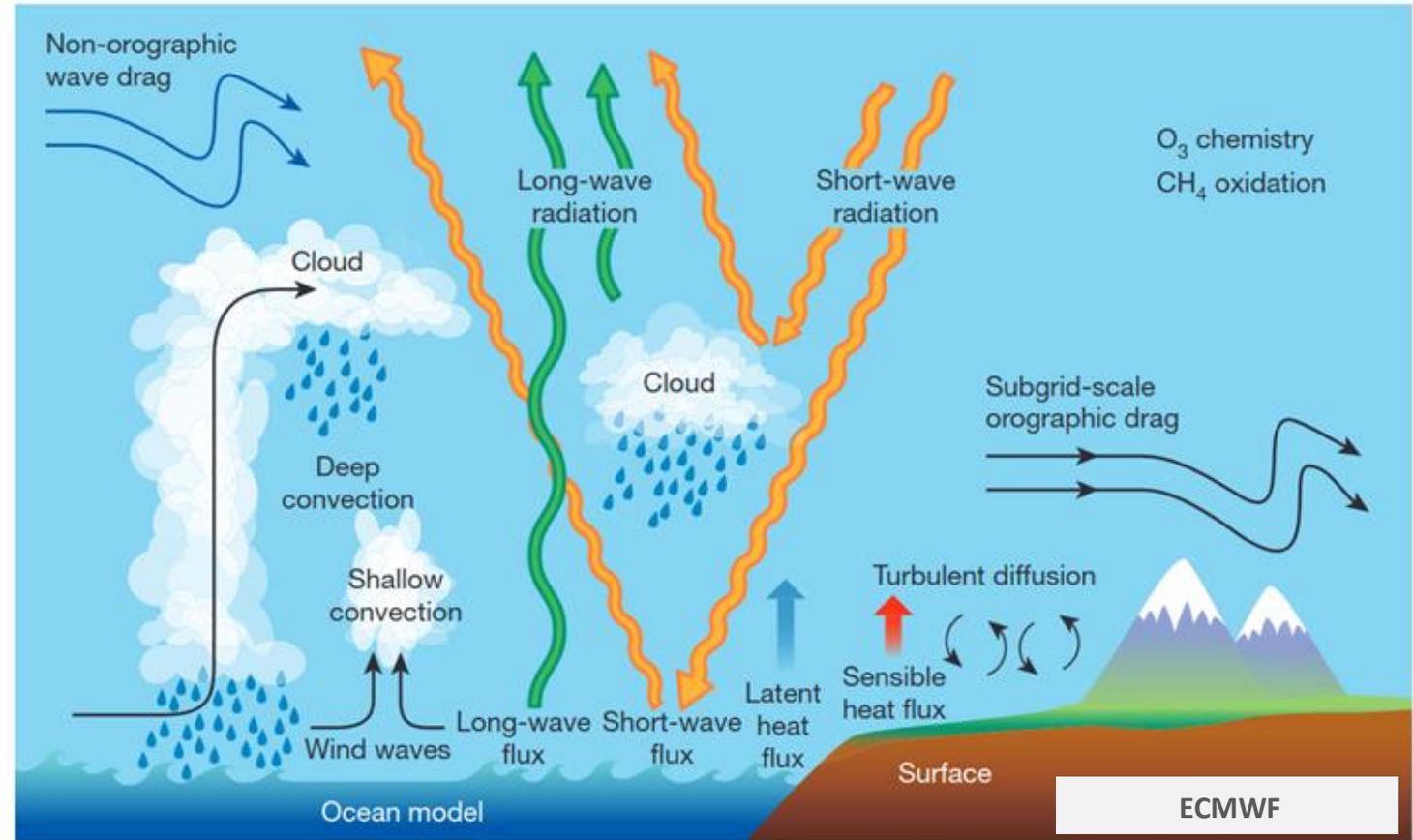


The NWP process: Parameterizations

NWP model grid

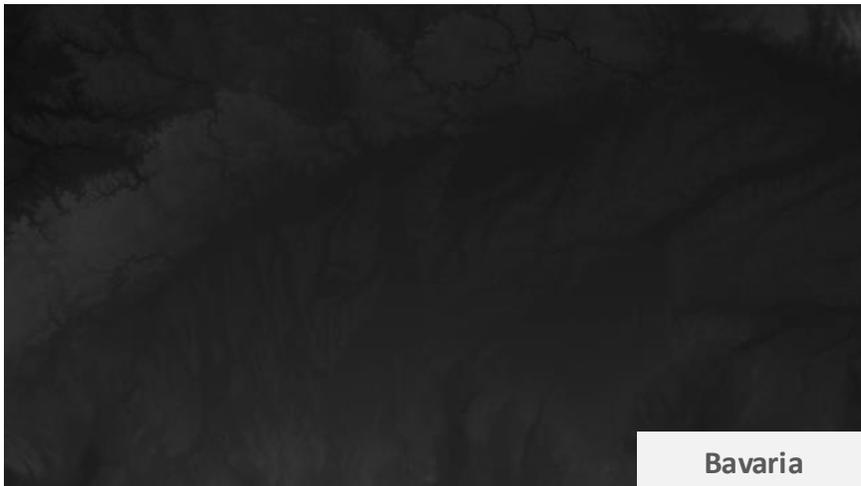
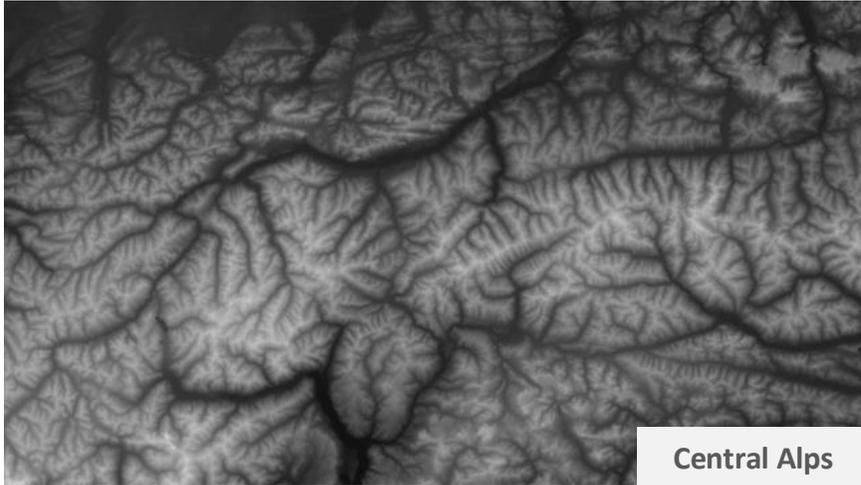


Parameterized processes

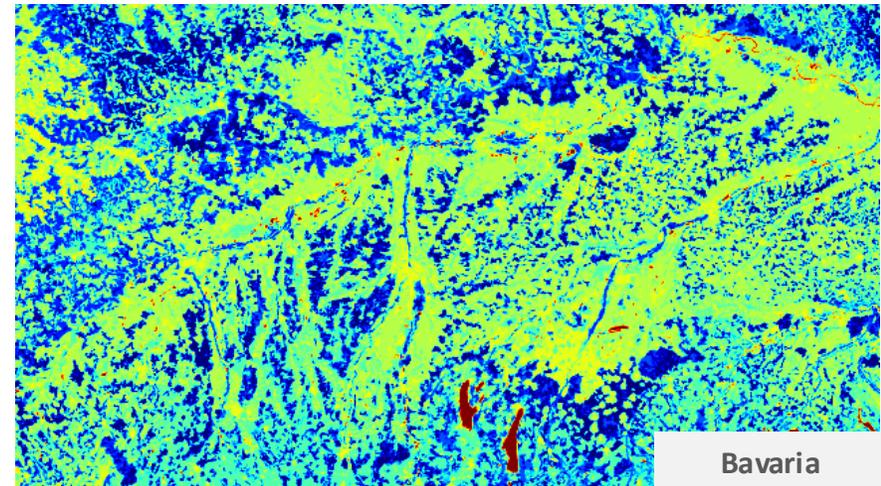
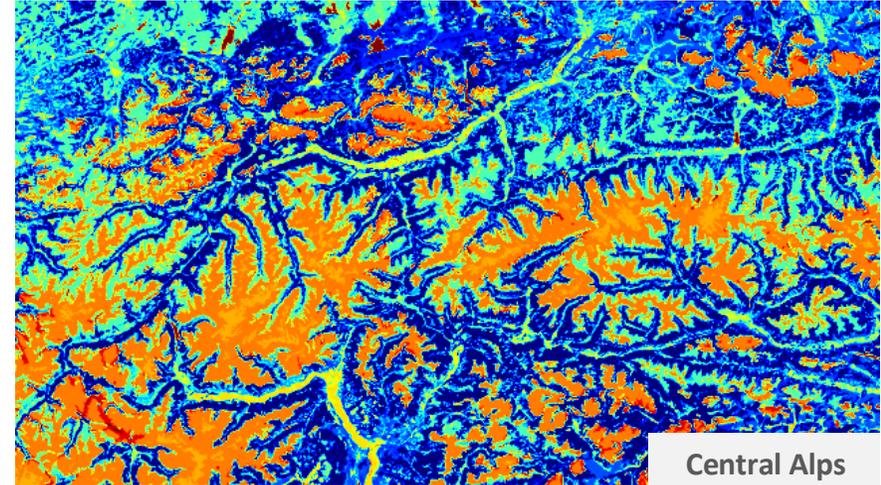


Why are mountains special? 1: Terrain heterogeneity

Terrain elevation

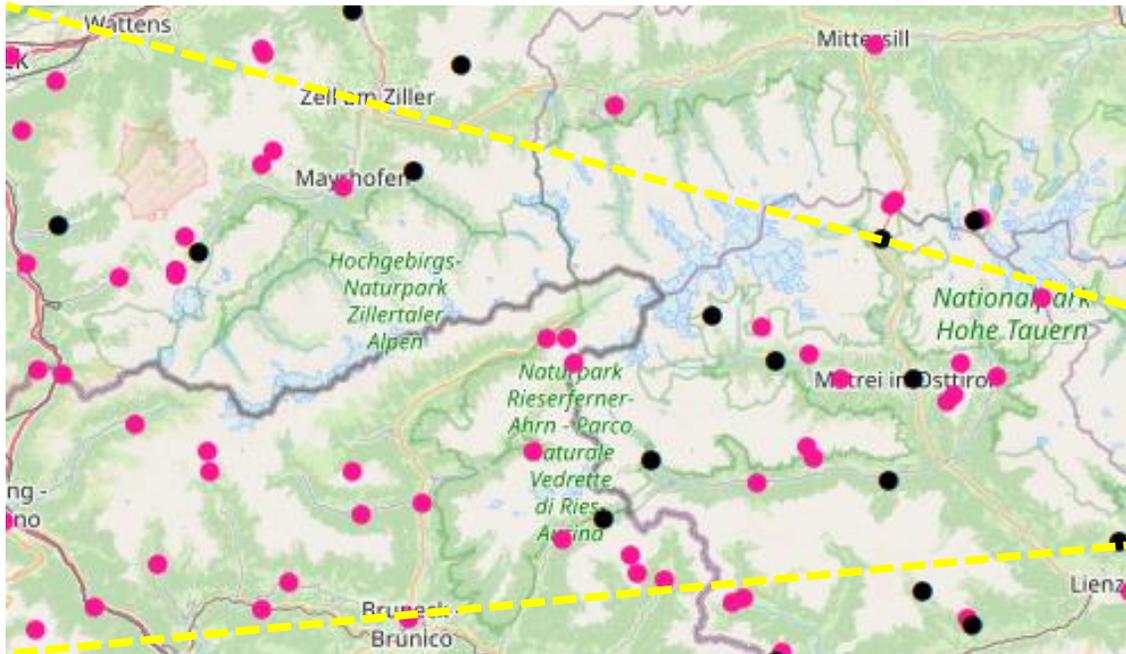


Land use

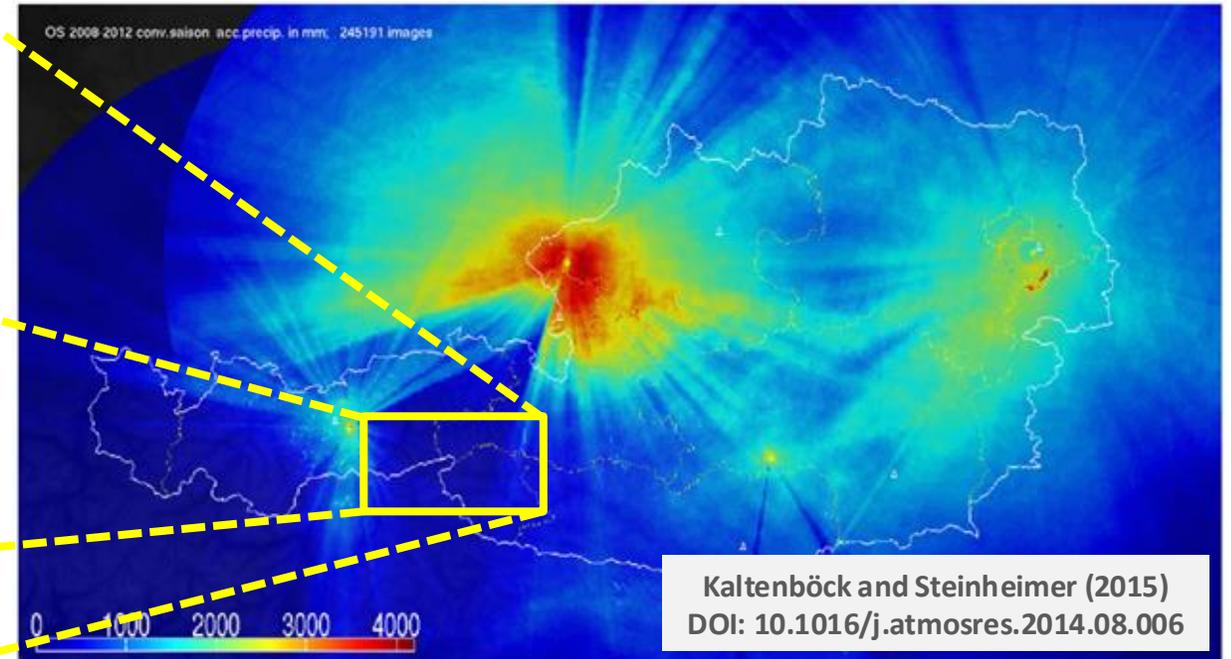


Why are mountains special? 2: Observation gaps

Surface observation network (AWS)

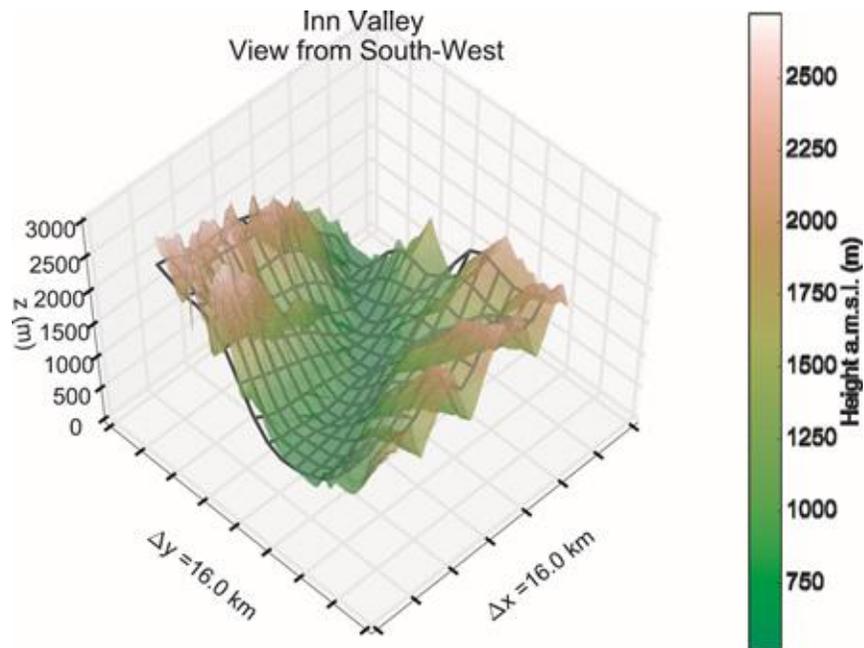


Accumulated rainfall over Austria (5 yrs), radar-based estimate



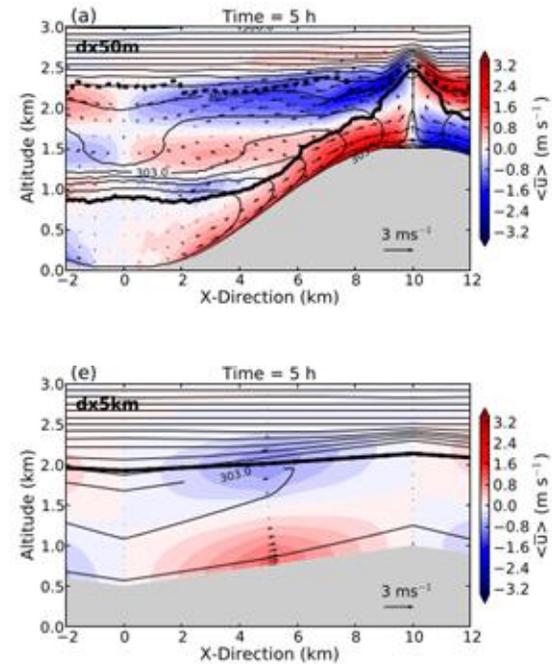
Why are mountains special? 3: Unresolved meteorological processes

Smoothed model orography

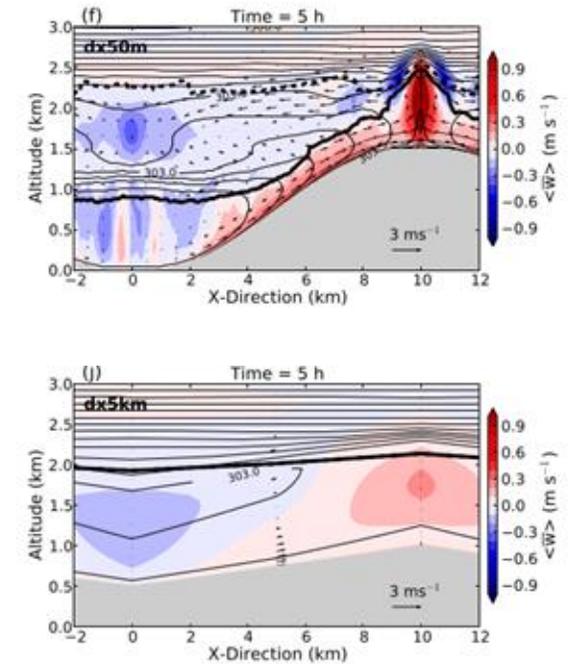


Rotach et al (2017)
DOI: 10.1175/BAMS-D-15-00246.1

Slope wind, u

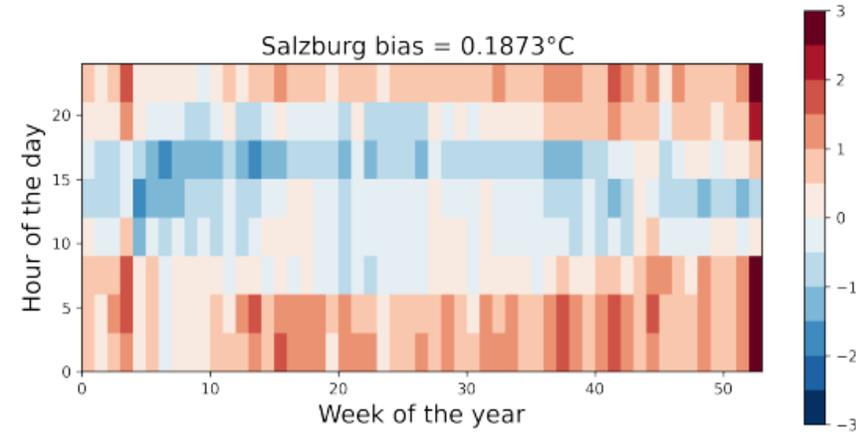
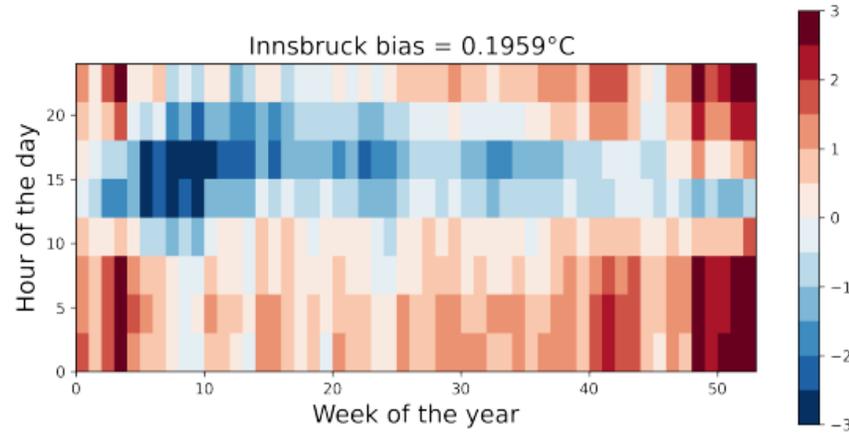


Slope wind, w



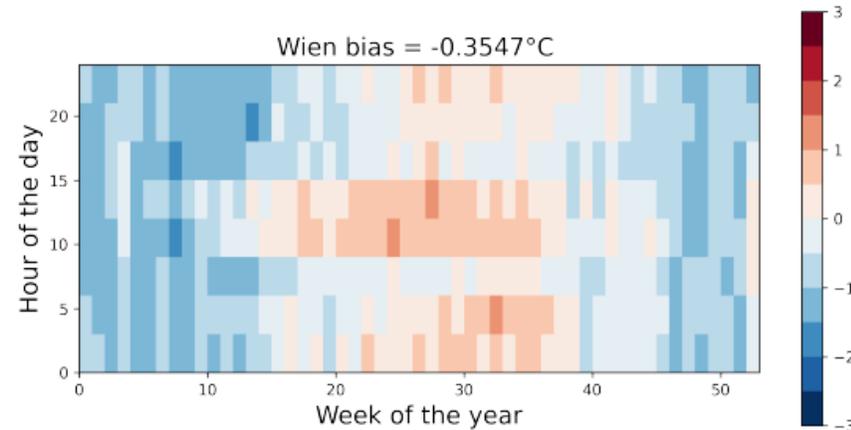
Wagner et al (2014)
DOI: 10.1175/MWR-D-14-00002.1

Why are mountains special? 4: Systematic forecast errors



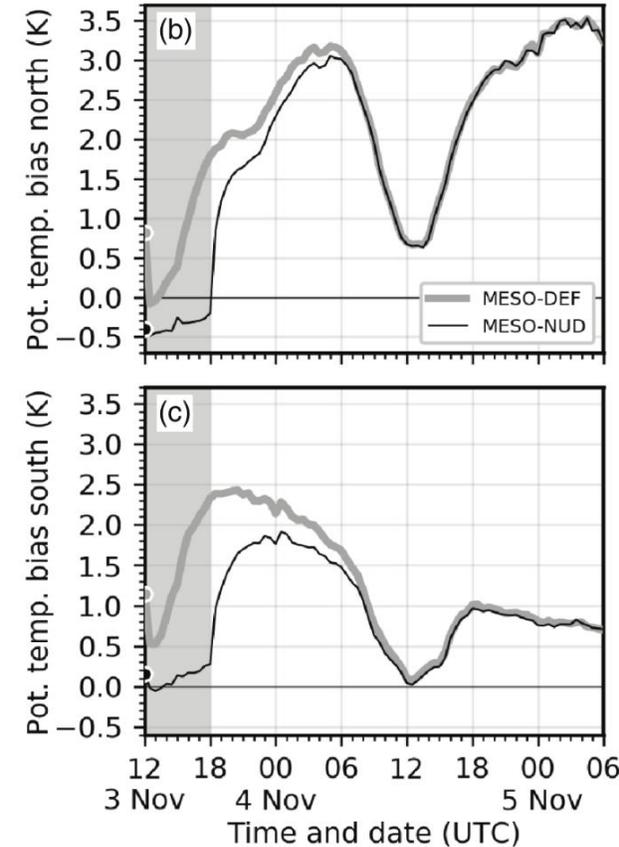
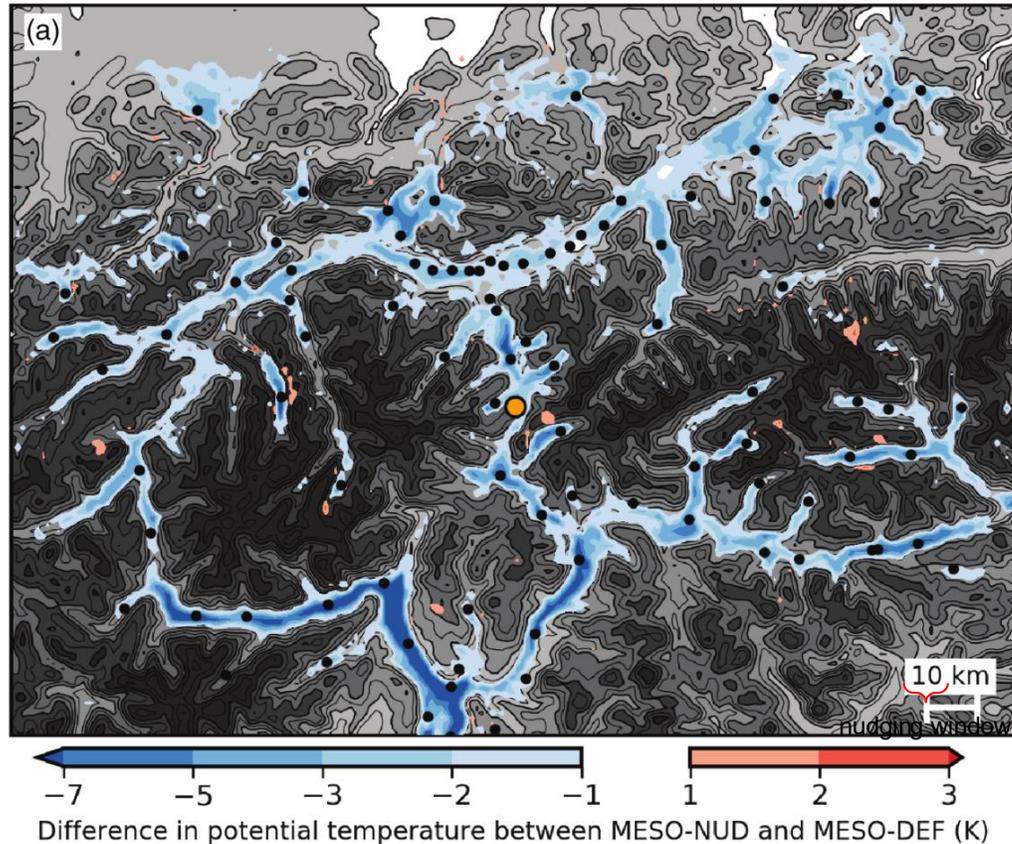
Mean error of T forecasts,
diurnal and seasonal cycle

Hutter (2022), MSc Thesis



Why are mountains special? 4: Systematic forecast errors

Domain covering large parts of North and South Tyrol



Stable boundary layers

WRF 1-km simulation with (MESO-NUD) and without nudging (MESO-DEF)

(a) Difference in θ at 2 m between MESO-NUD and MESO-DEF

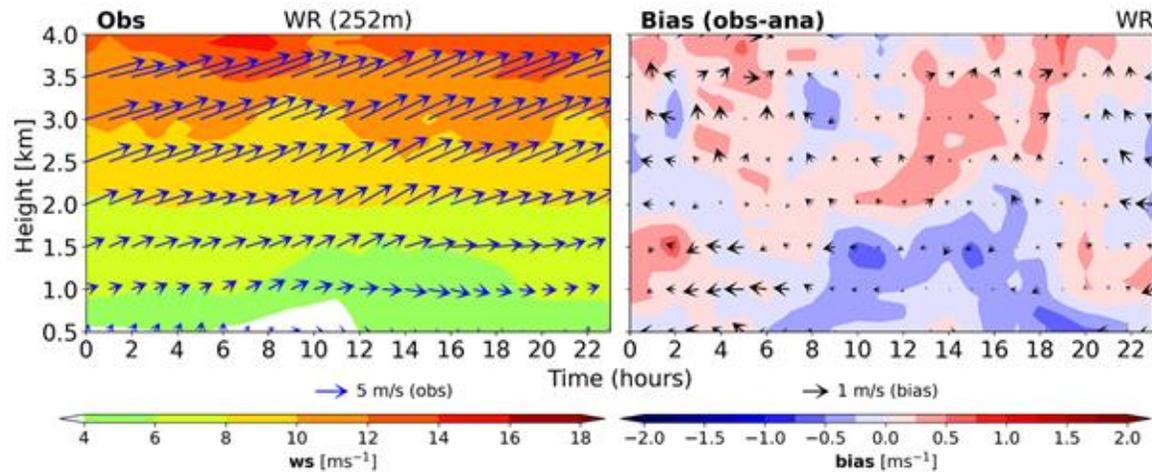
(b) Bias north of the Alps

(c) Bias south of the Alps

Umek et al. (2021)
DOI: 10.1002/qj.3954

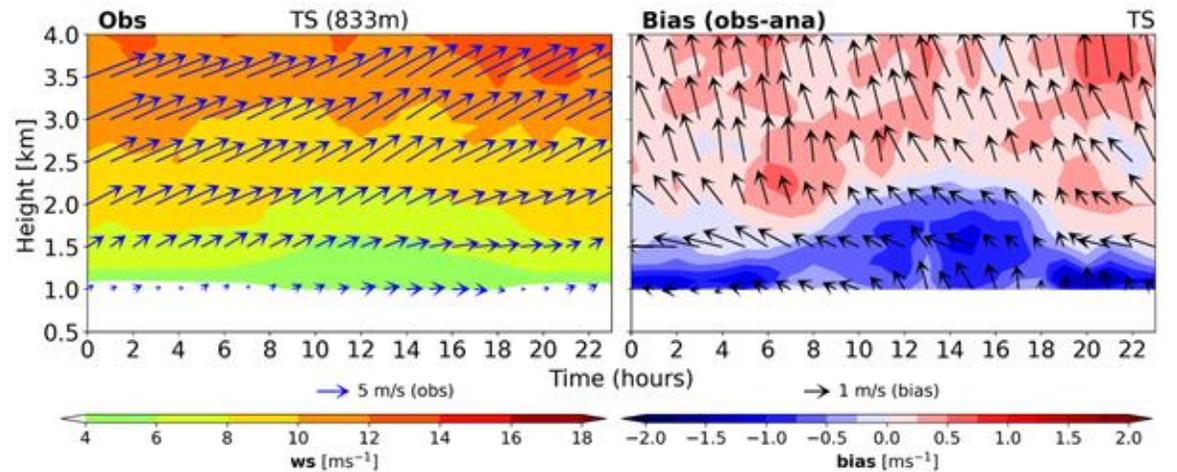
Why are mountains special? 4: Systematic forecast errors

Wind speed/direction bias
1-month average diurnal cycle
Flat terrain



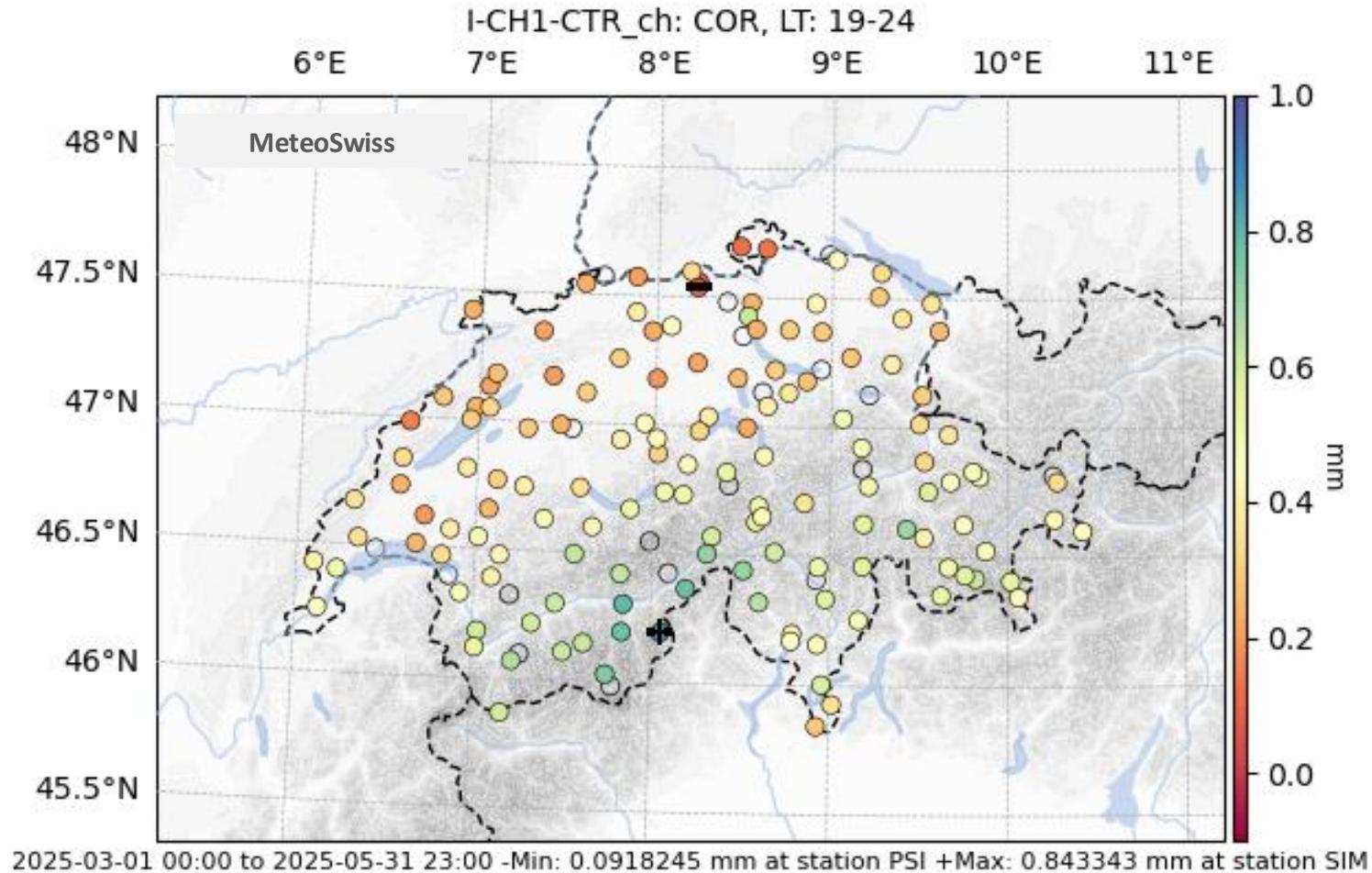
Nguyen (2025, PhD research)

Wind speed/direction bias
1-month average diurnal cycle
Hilly terrain



Nguyen (2025, PhD research)

Why are mountains special? 5: Source of predictability

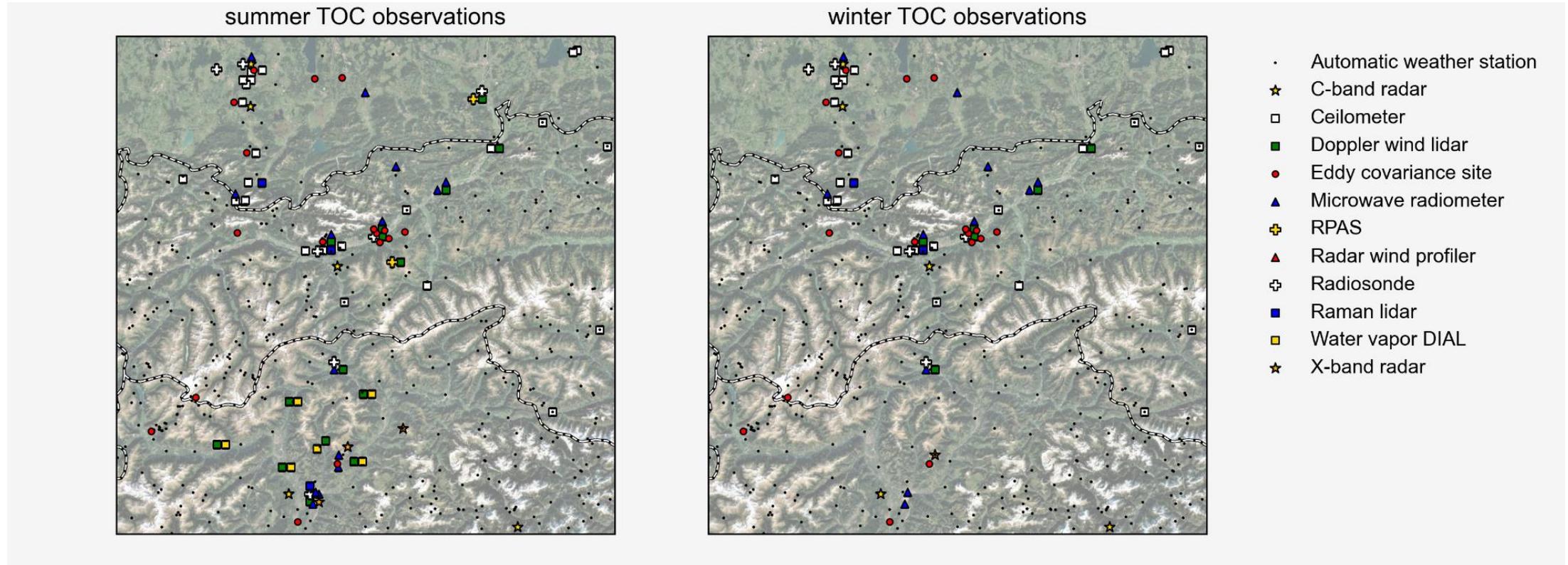


Precipitation in spring 2025,
correlation between observations and
1-day forecasts

Intermediate summary

- Reasons why NWP over mountains is challenging:
 - High spatial heterogeneity of atmospheric properties, induced by orography and land use
 - Observation gaps
 - Distinctive weather processes marginally resolved on NWP grids
 - Consequence: Systematic forecast errors
- Mountains enhance the predictability of some weather processes (e.g. precipitation)
- Most critical issues, probably: diurnal cycles near the surface, stable boundary layers
- Can field observations help us make progress?

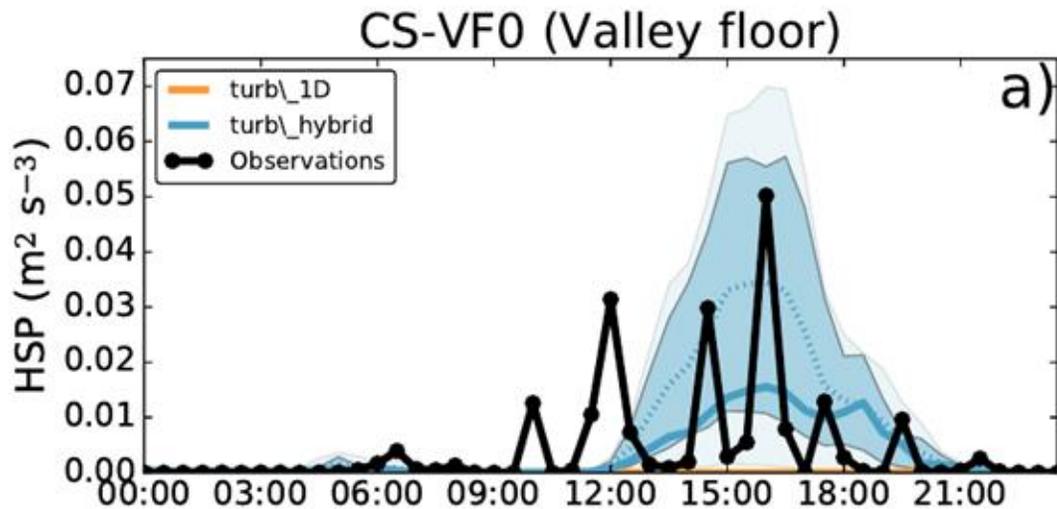
Field-campaign data and modelling: Enhanced pool of observations



- Routinely assimilated observations (AWS, RaSo, MWR, DOWL, radar): increased coverage.
- Special observations (Raman lidars, WV DIAL, UAS): evaluate potential benefit.

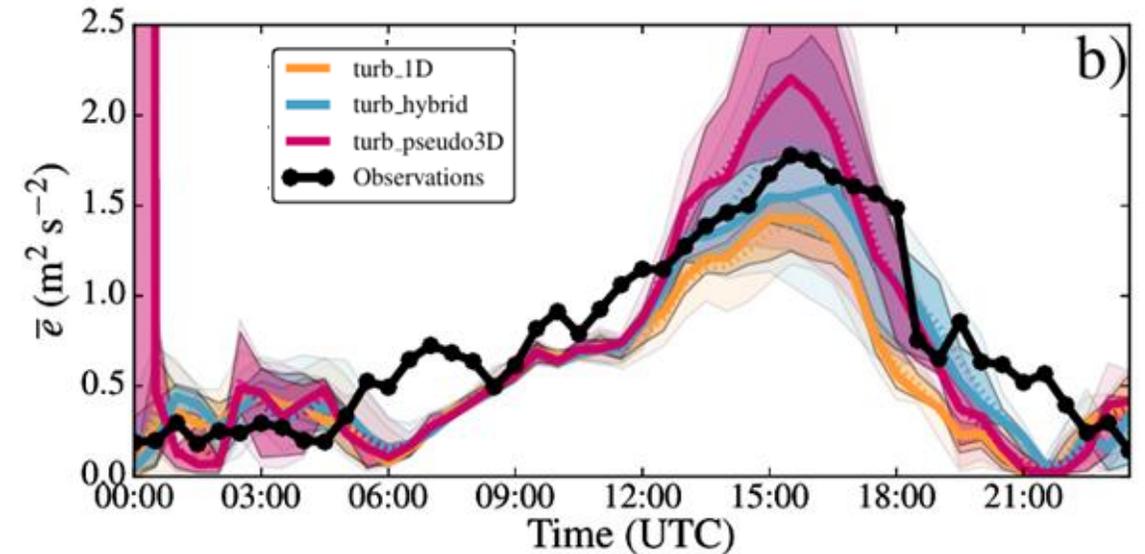
Field-campaign data and modelling: Improving models

- Observations: i-Box flux towers in the Inn Valley. Horizontal shear production (HSP) of turbulence during valley wind days.



Goger et al. (2018; DOI: 10.1007/s10546-018-0341-y)
Goger et al. (2019; DOI: 10.1175/JAMC-D-18-0328.1)

- Unrepresented HSP causes an underestimate of turbulent kinetic energy.



- Accounting for HSP solves (partially) the problem.

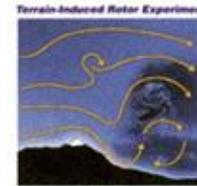
Optimal use of field campaign data

T-REX (Owens Valley, California, 2006):

- 43 published articles in 2007-2021.
- 38 different measurement platforms.
- More than 6 data sources used: 3 articles.
- Less than 4 data sources used: 30 articles.
- Most widely used: radiosoundings, surface AWS.
- Qualitative data integration (e.g. overlaid plots).

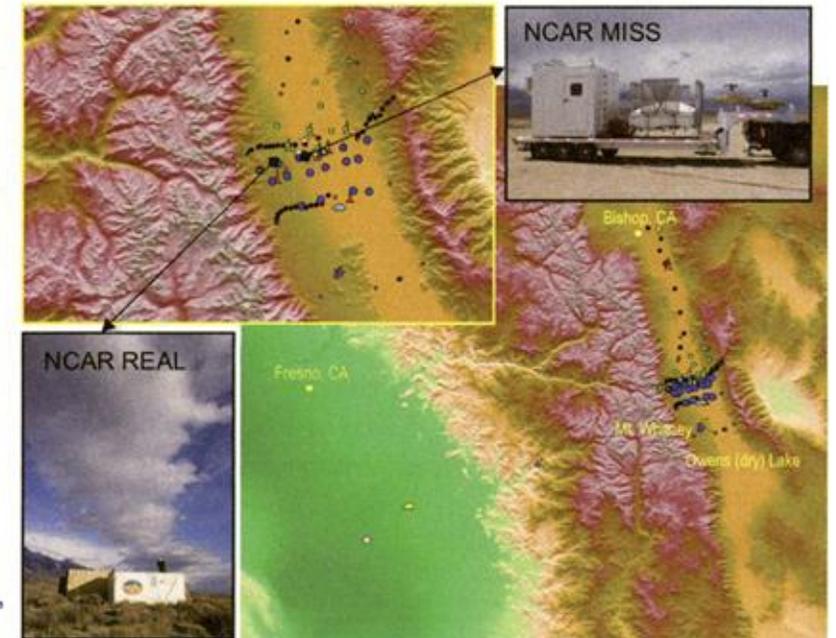
Can we use field observations more effectively?

Maybe yes, by integrating observations and background information from NWP models.



- Berkeley Soil Moisture
- Leeds IMS
- DRI IMS
- Weather Station on Wheels
- Utah Temperature (H000)
- DRI Stereo Cameras IOP-6
- Yale Fine Lapce Camera
- RSU Flux Tower
- U Houston Flux Tower
- Leeds Flux Tower
- NCAR OTHS
- NCAR ISFF
- NCAR MISS IOP-6
- NCAR ISS2
- NCAR ISS MRF
- U Houston Sodar
- RSU Sodar/WISS
- RSU Doppler Lidar
- DLK Doppler Lidar
- NCAR REAL
- Yale X-Band Radar
- WRL Therasonde/Radiosonde
- NRS Lemoore Radiosonde
- NCAR MGRUS IOP-6
- Leeds Independence Airport Radiosonde

T-REX Experiment Design Ground-based Instrumentation

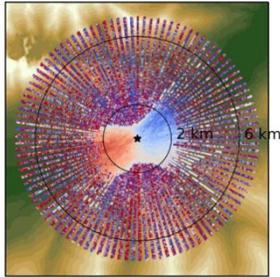


Grubisic et al. (2008; DOI: 10.1175/2008BAMS2487.1)

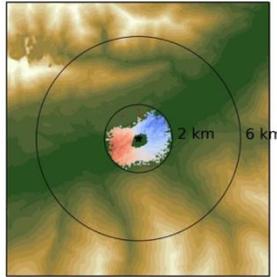
Optimal use of field campaign data: A campaign analysis

- Think of one remote-sensing platform (DOWL)

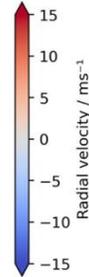
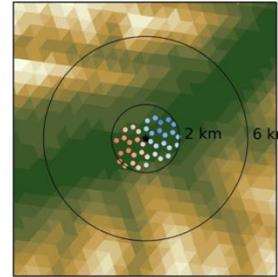
All Observations and Topography



QC Observations and Topography

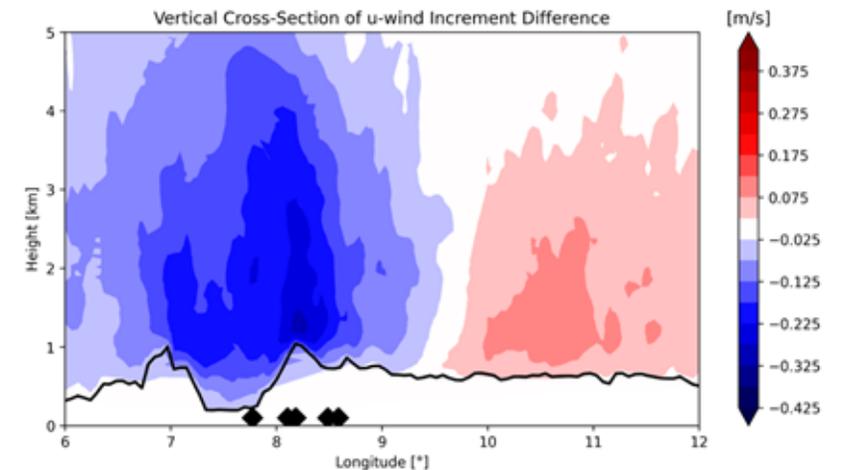
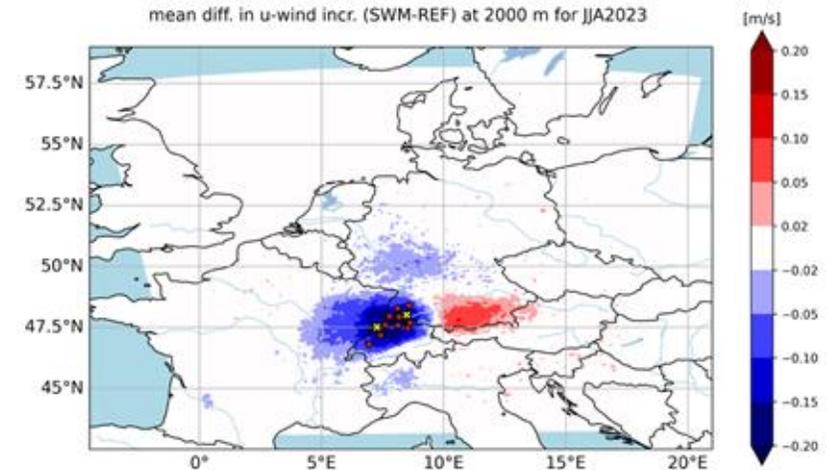


Superobservations and Model Topography



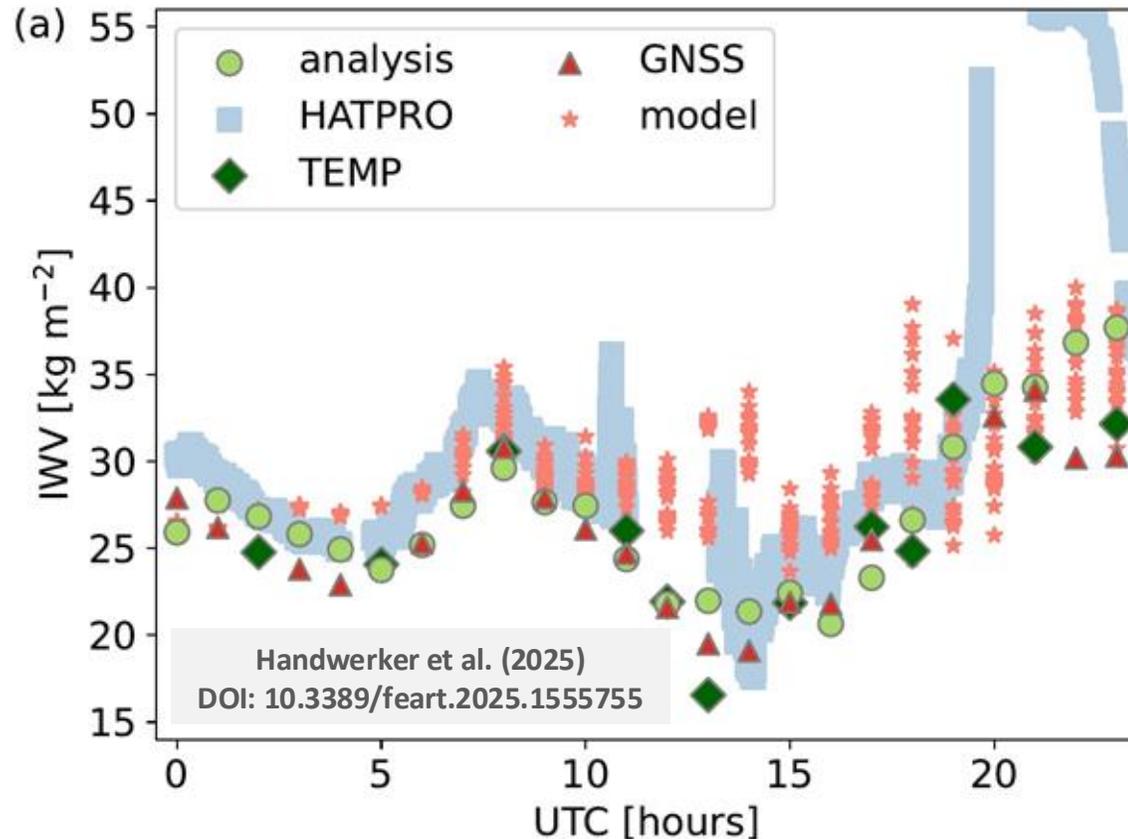
Wolfgruber (2024, MSc Thesis)

- Procedure
 - Eliminate flawed observations
 - Upscale observations (superobbing)
 - Repeat: all measurement platforms, whole campaign.
 - Assimilate into an O(100 m) NWP ensemble.
- Result: A 4D (xyzt) dataset that
 - Incorporates all observations
 - Has a unique data format
 - Fills observation gaps with background knowledge
 - Comes with an uncertainty estimate (ensemble)



Thomas (2025, PhD research)

Optimal use of field campaign data: Challenges



- Observations are not the truth.
- Representation issues: Co-located observations of the same quantity may differ substantially (here: Integrated Water Vapor, IWV over a day).
- Ensemble analysis: If observations disagree, the analysis does not correct the background field.

Summary and conclusions

Role of field campaign observations in advancing NWP over mountains

- Fill knowledge gaps: better process understanding, better parameterization schemes
- Evaluate potential benefit of novel measurement platforms

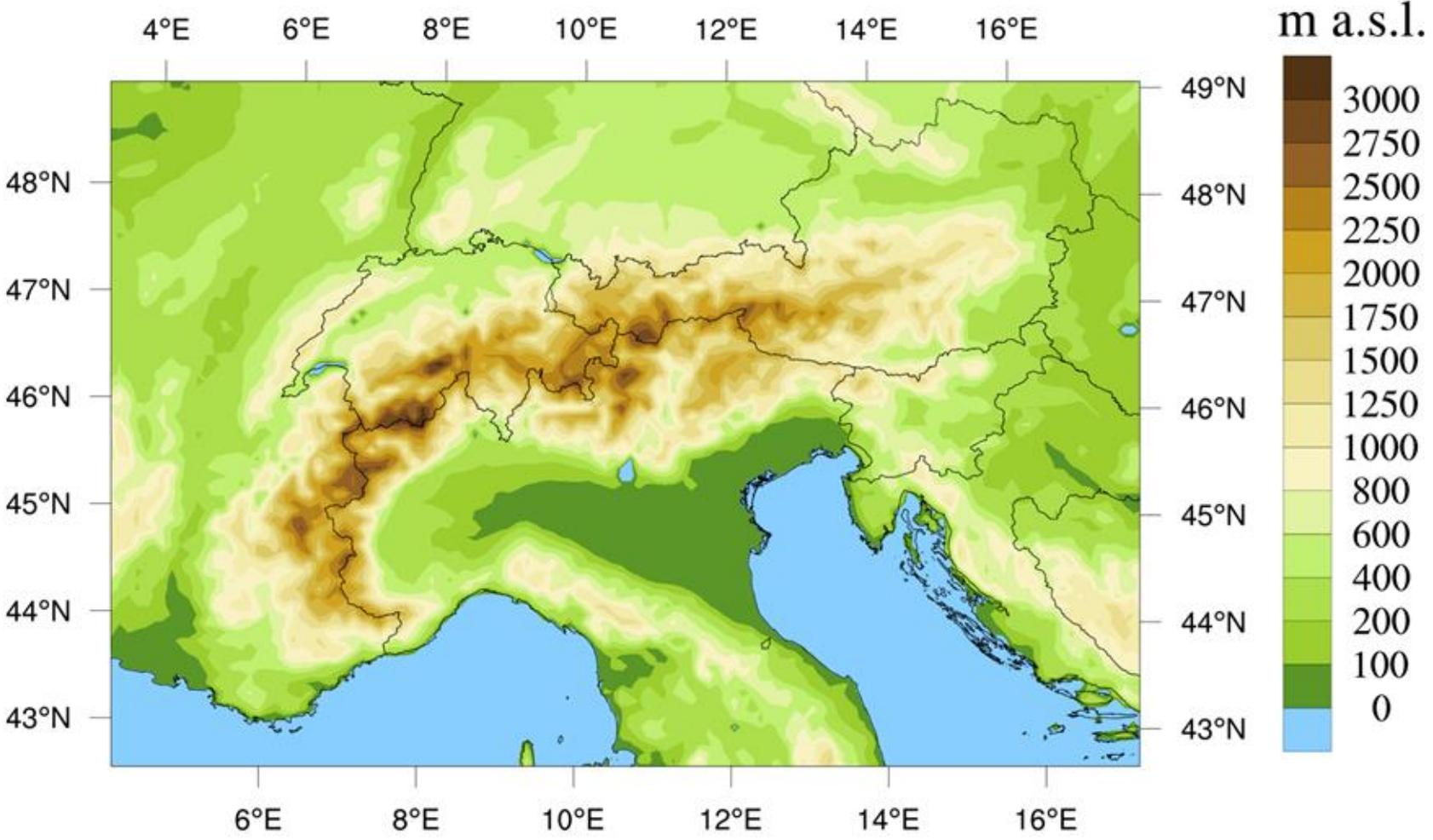
How do we best use field campaign observations?

- Optimally, with a campaign analysis
- But: considerable technical challenges

Field-campaign data collection is only the beginning of the work. NWP techniques have great potential for the production of an integrated data pool.

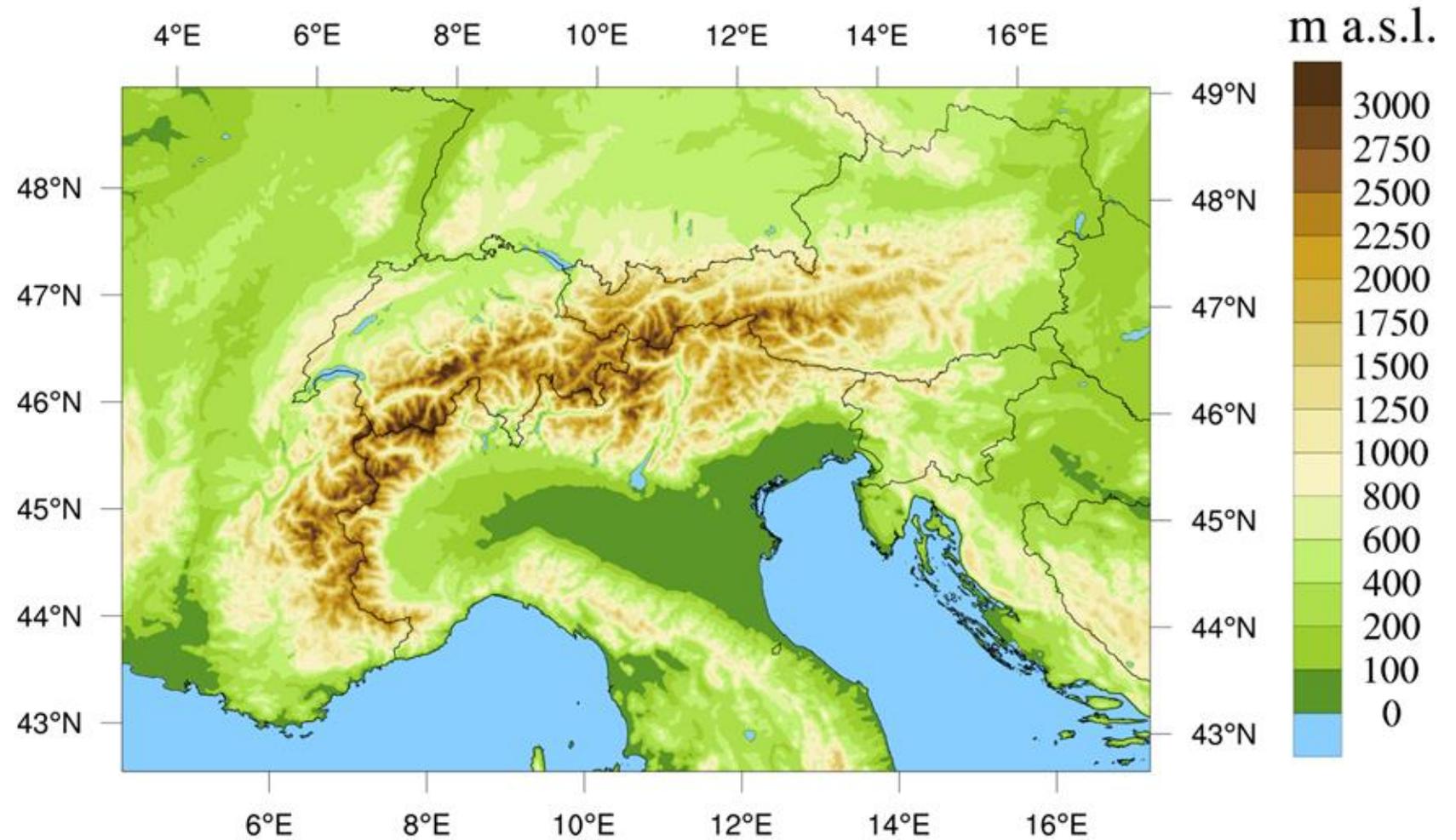
Why are mountains special? 1: Terrain heterogeneity

9-km grid spacing



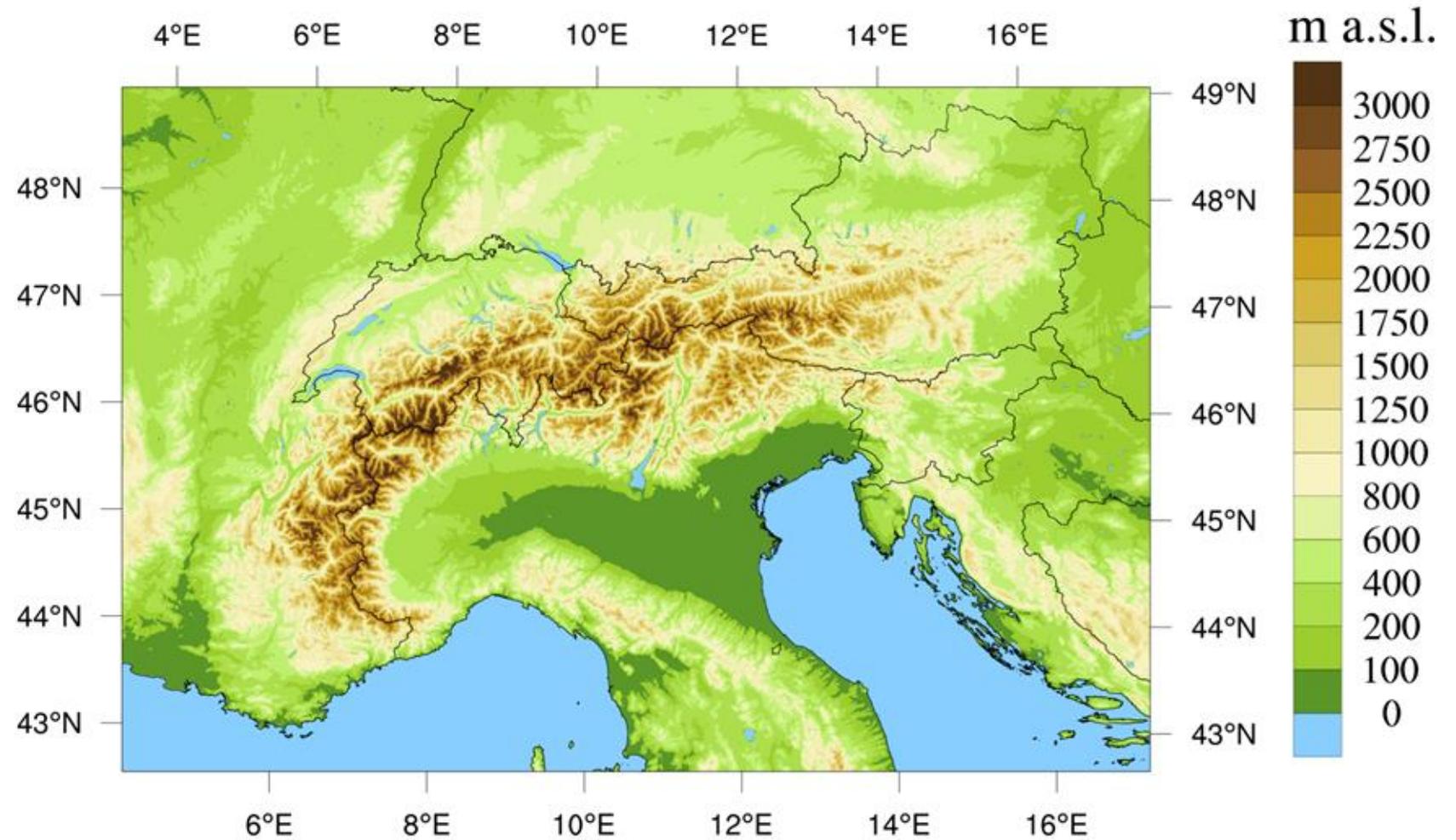
Why are mountains special? 1: Terrain heterogeneity

3-km grid spacing



Why are mountains special? 1: Terrain heterogeneity

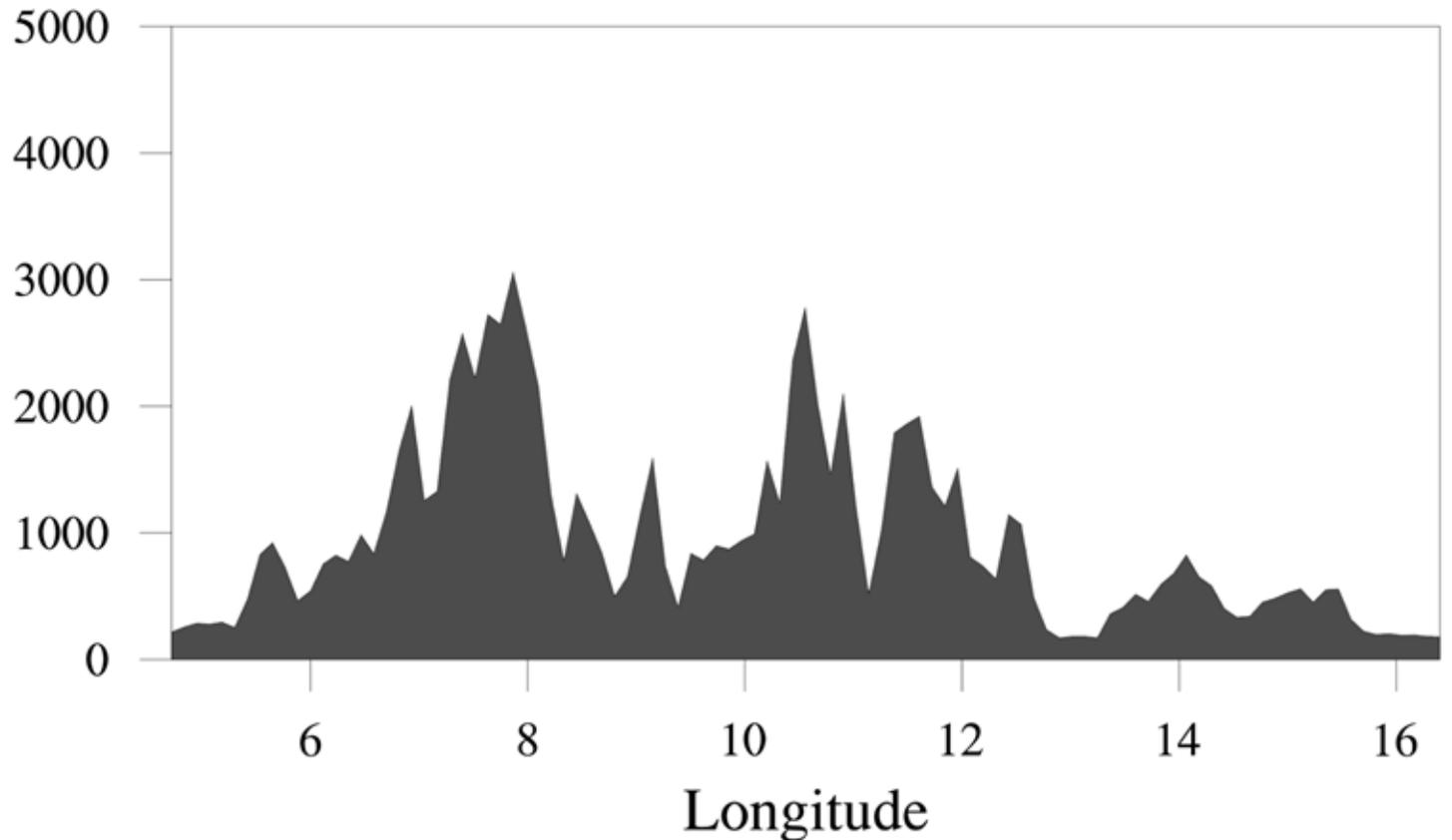
1-km grid spacing



Why are mountains special? 1: Terrain heterogeneity

West-east cross section of the Alps @ 46°N

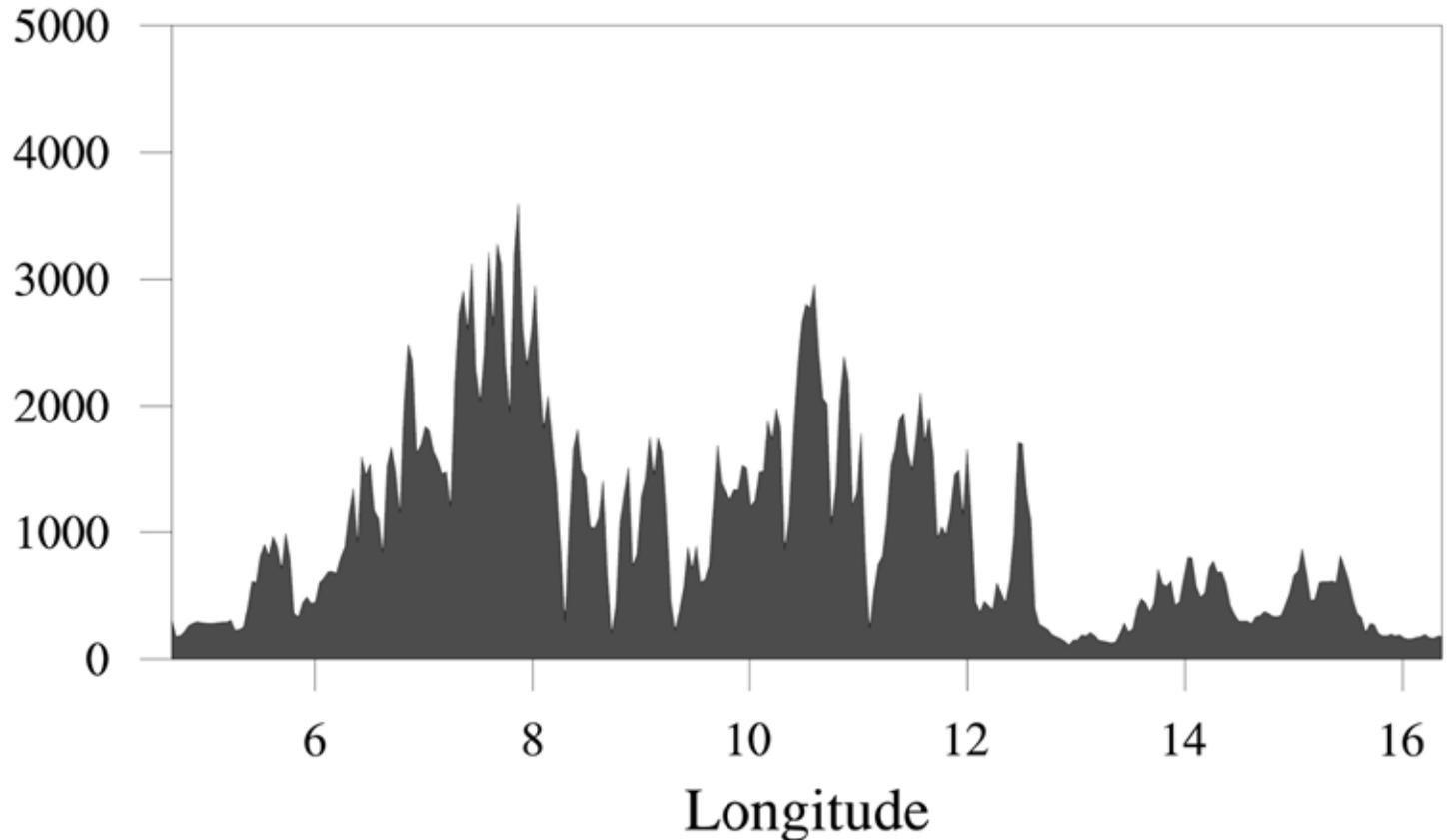
9-km grid spacing



Why are mountains special? 1: Terrain heterogeneity

West-east cross section of the Alps @ 46°N

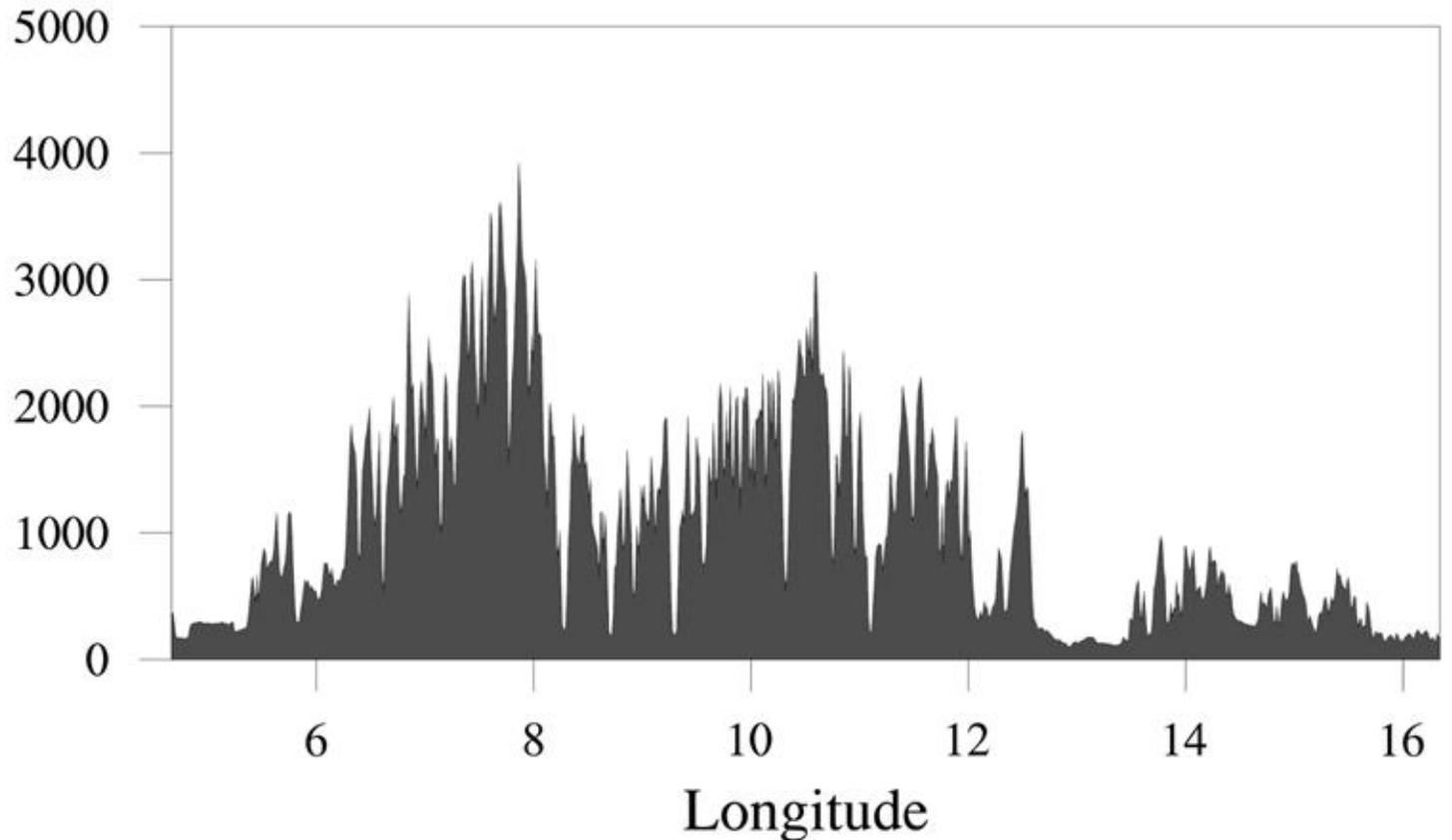
3-km grid spacing



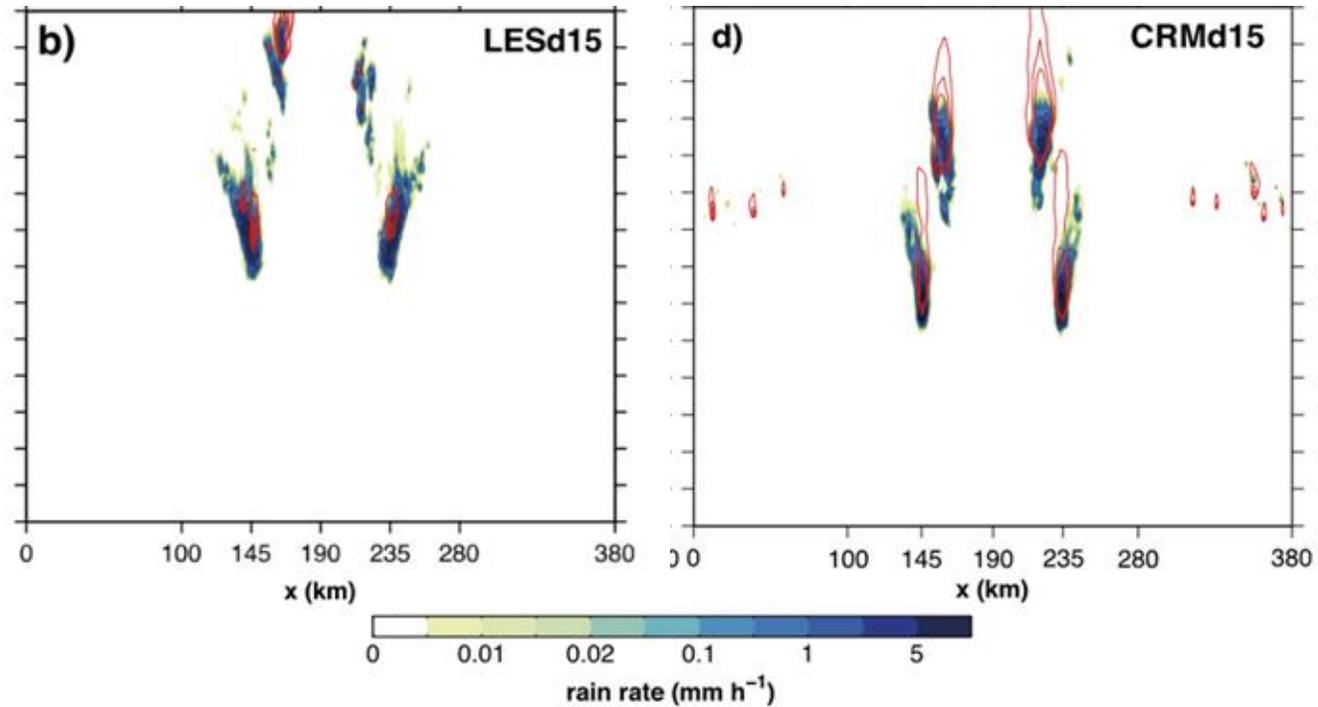
Why are mountains special? 1: Terrain heterogeneity

West-east cross section of the Alps @ 46°N

1-km grid spacing



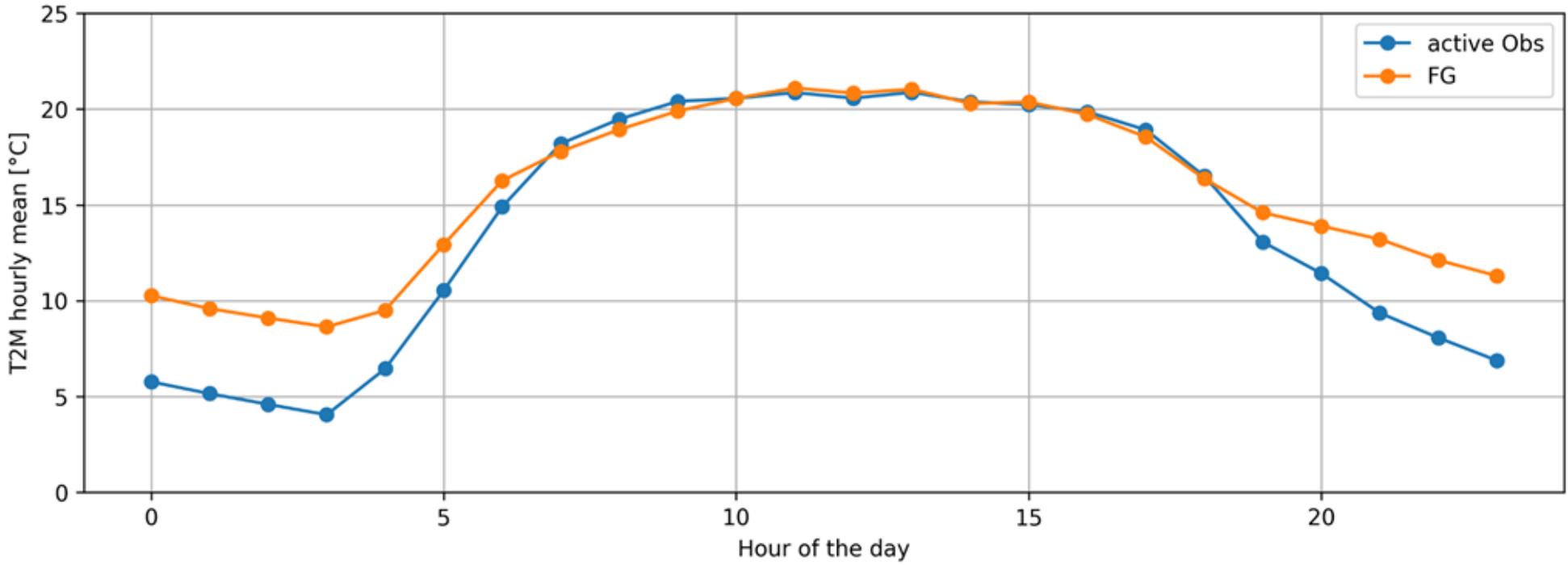
Why are mountains special? 3: Unresolved meteorological processes



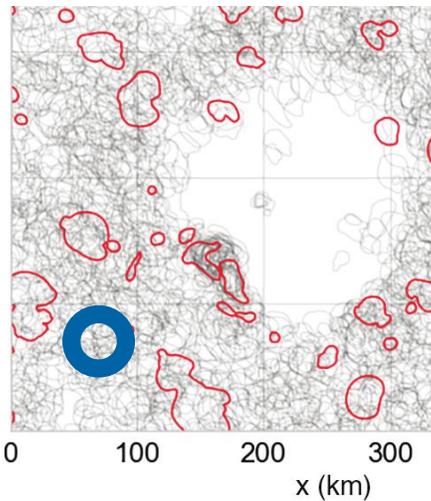
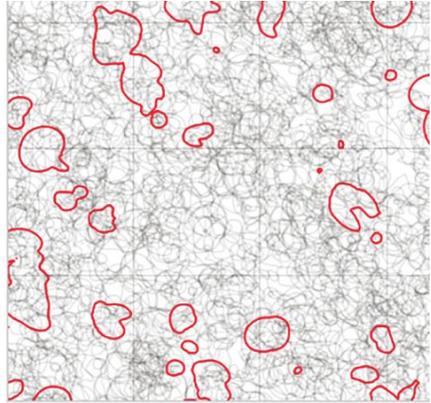
Panosetti et al (2016)
DOI: 10.1175/JAS-D-15-0341.1

Why are mountains special? 4: Systematic forecast errors

Mean diurnal cycle of FG and Obs for T2M in “complex” terrain in Black Forest; likely model misrepresentation of cold air at night at coarse resolution; PhD J. Thomas]



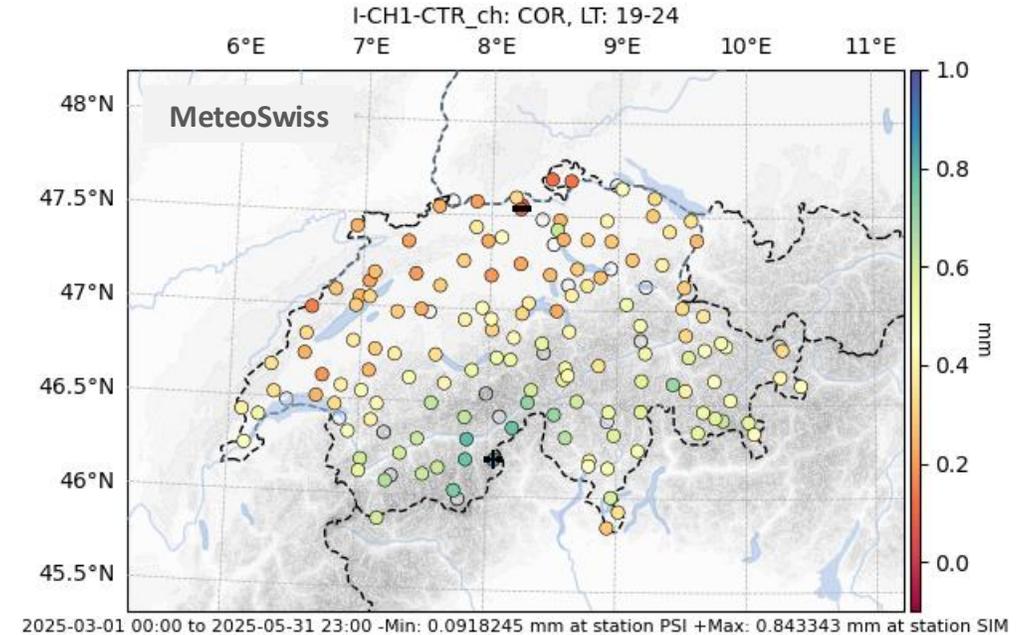
Why are mountains special? 5: Source of predictability



Radar reflectivity contours from two idealized simulations of atmospheric convection (above: flat; below: with a mountain). Red: reference simulation.

Grey: a large ensemble of simulations subject to minimal perturbations.

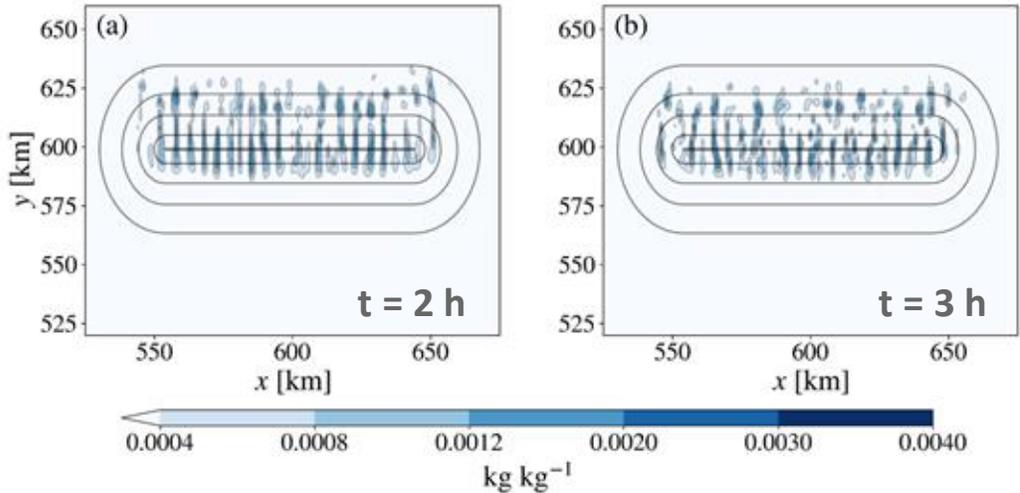
Bachmann et al. (2019)
DOI: 10.1002/qj.3412



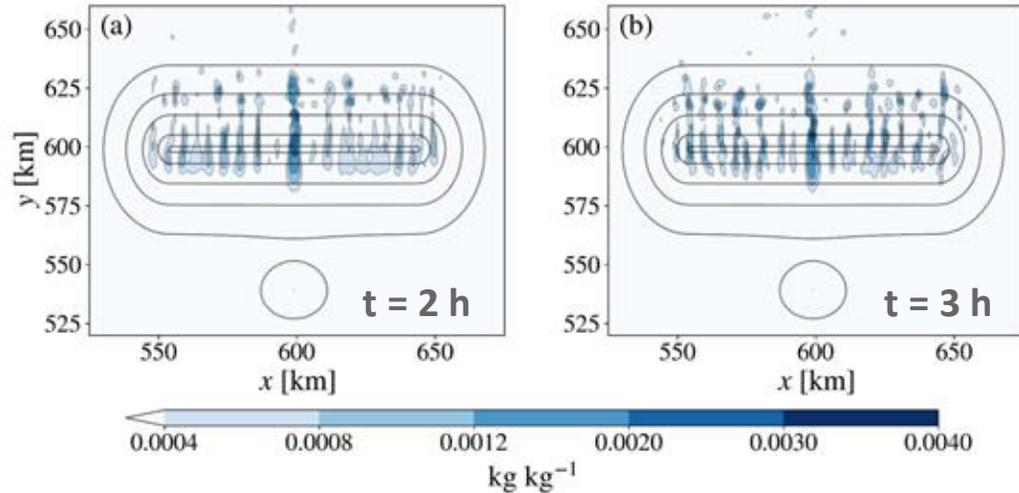
Precipitation in spring 2025,
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Why are mountains special? 5: Source of predictability

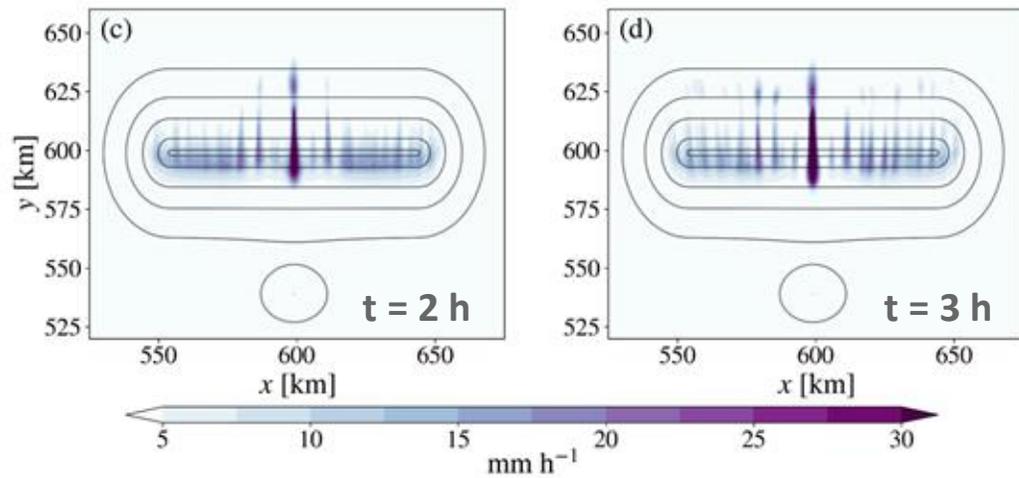
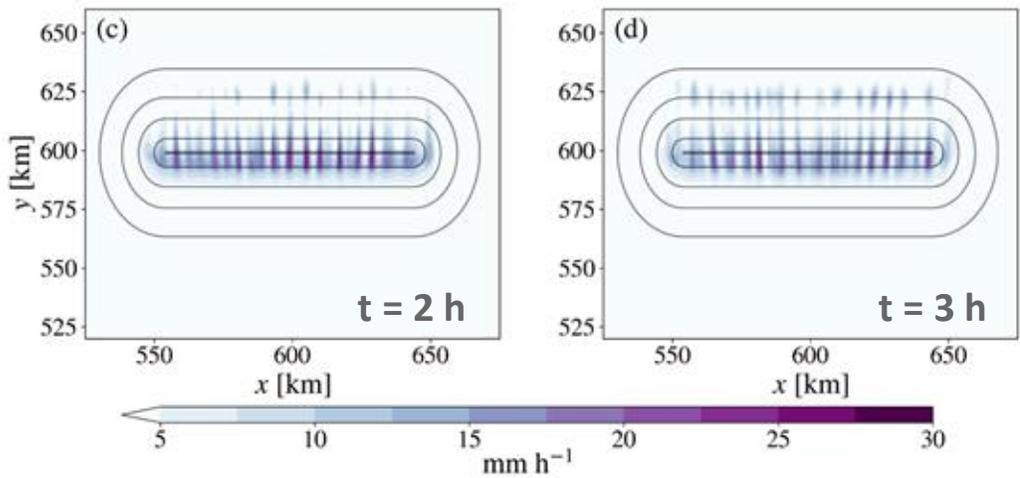
SMOOTH RIDGE



SMOOTH RIDGE WITH AN UPWIND ISOLATED HILL



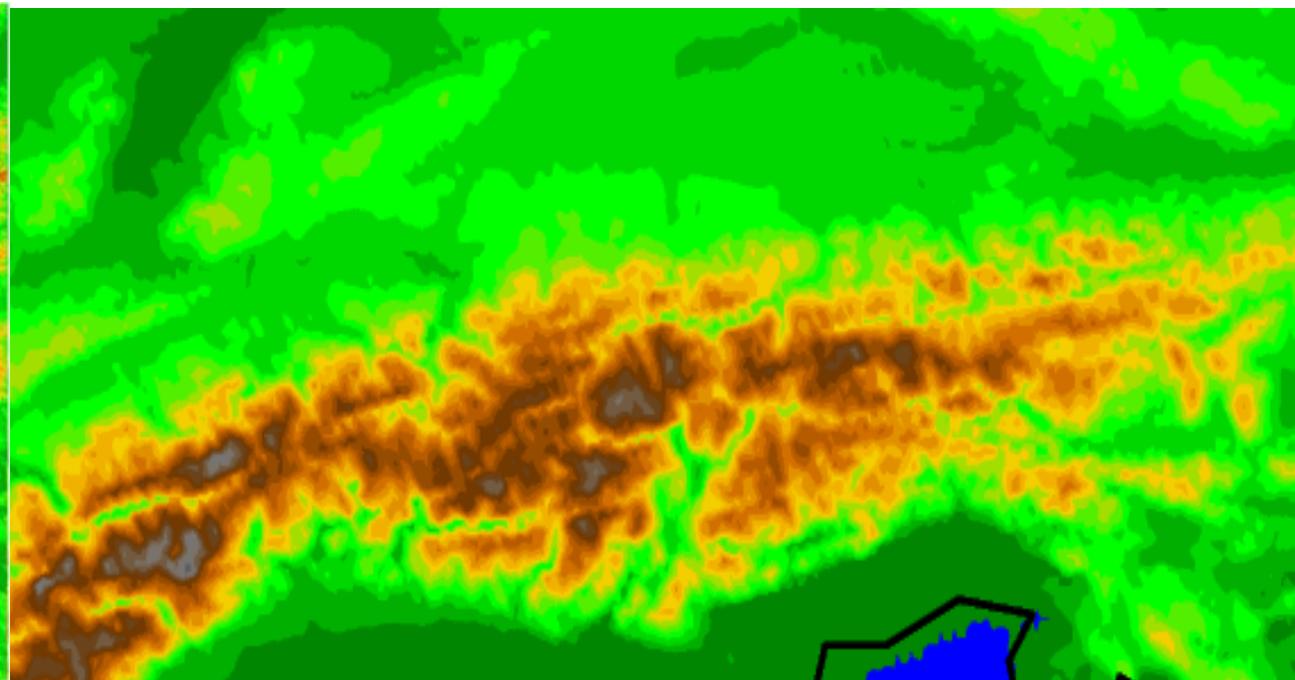
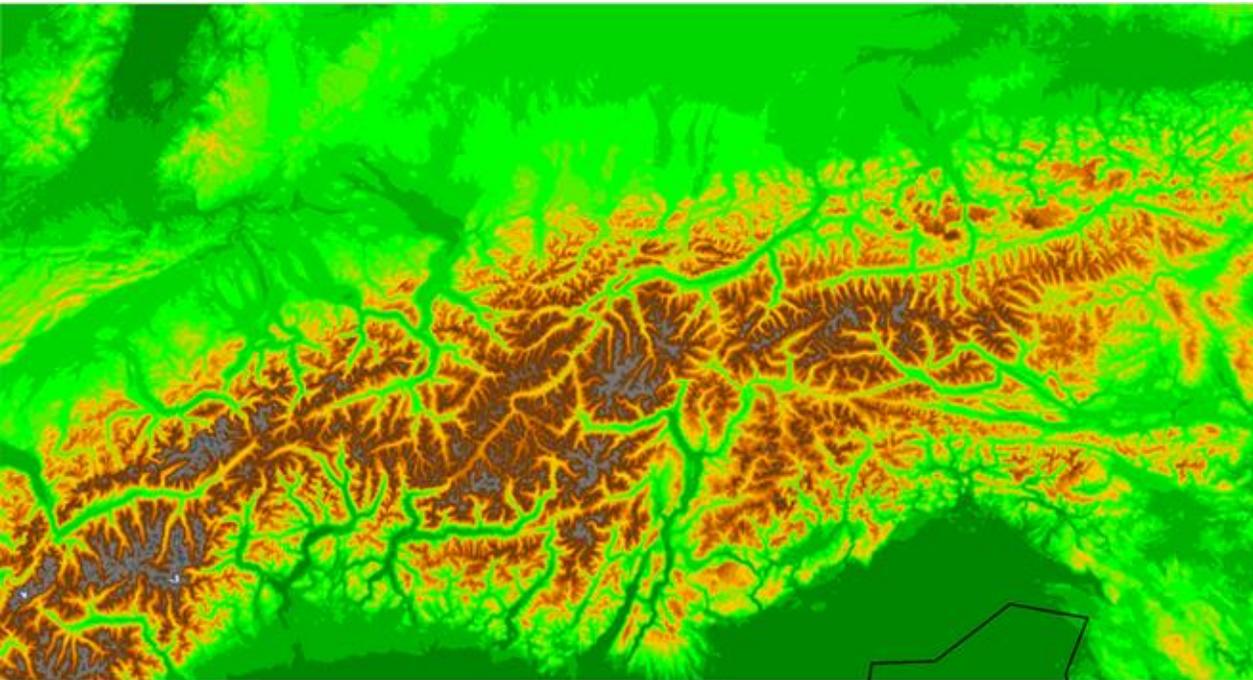
Rain liquid mixing ratio at 2000 m MSL



1-h accumulated rainfall

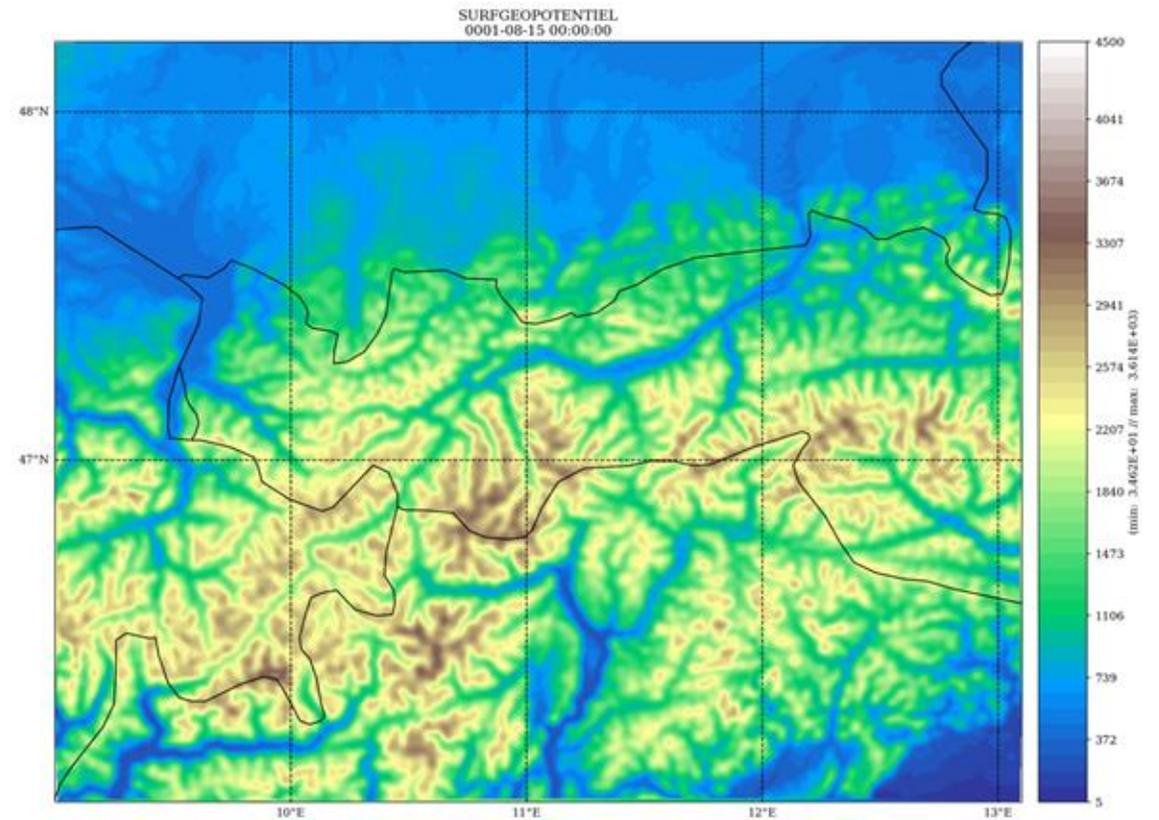
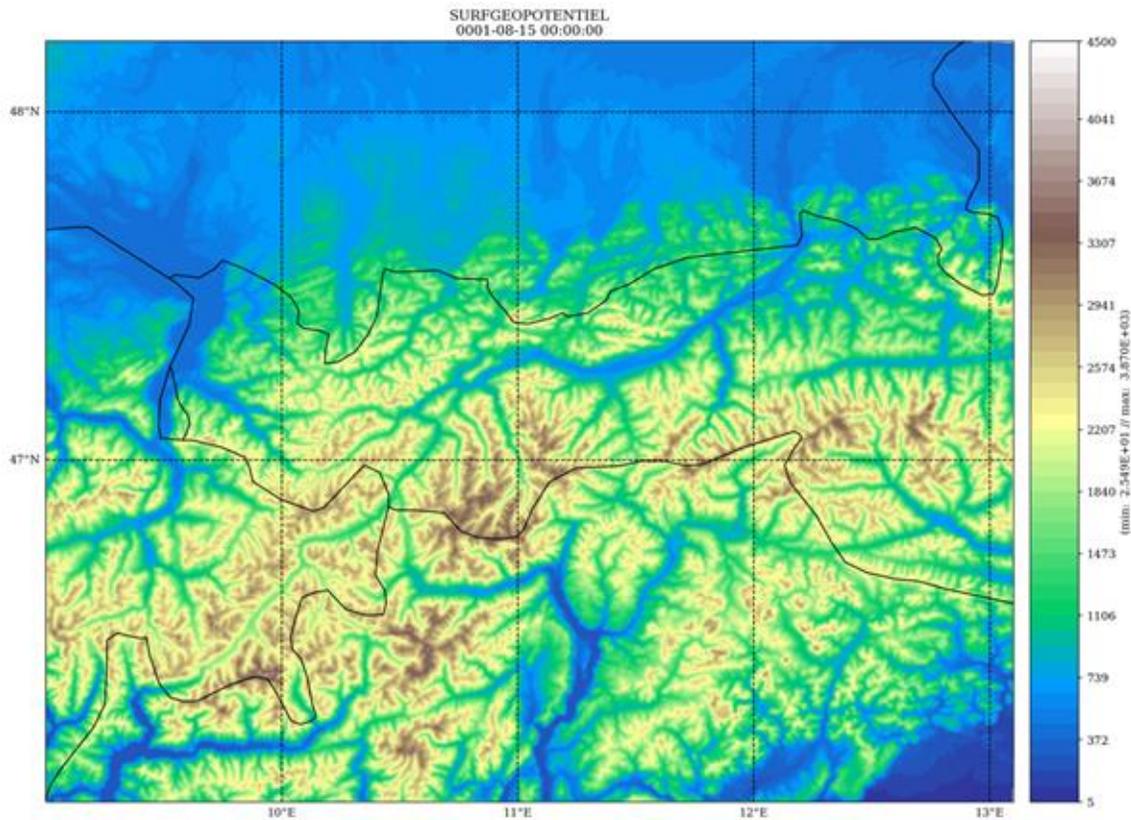
Importance of model resolution

ICON model orography for the Alpine region at 500 m and 5 km mesh size

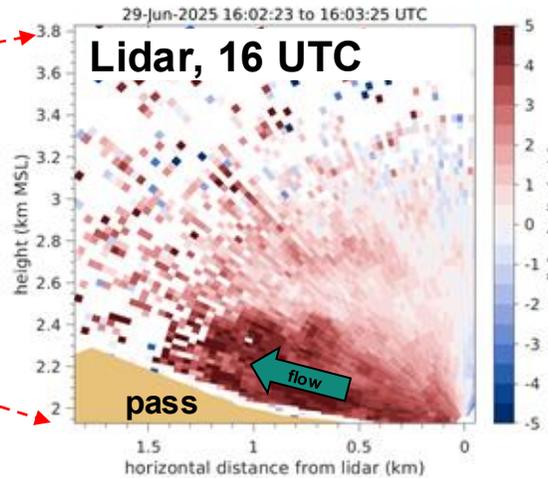
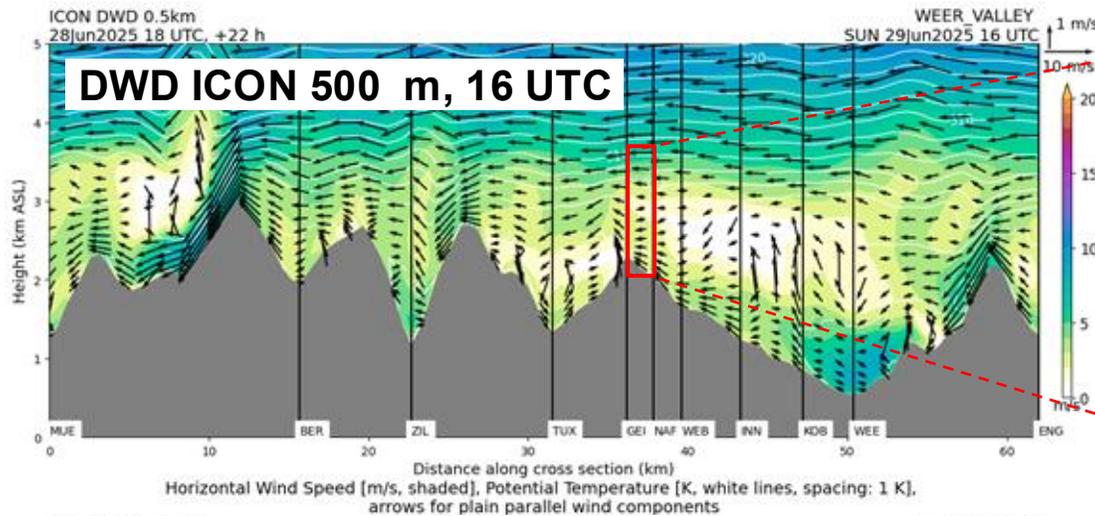


Importance of model resolution

AROME model orography for the Alpine region at 500 m and 1.3 km mesh size



Field-campaign data and modelling: Process-oriented verification

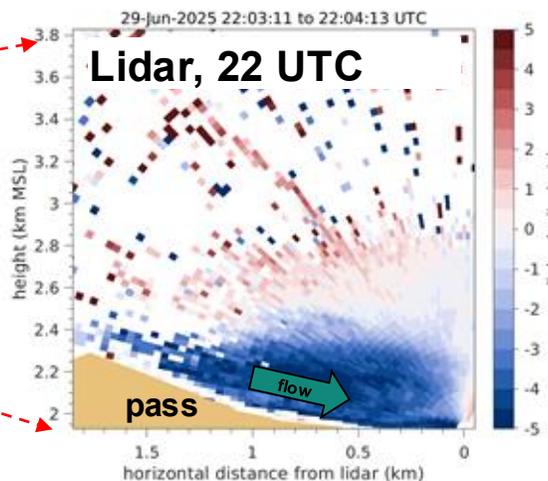
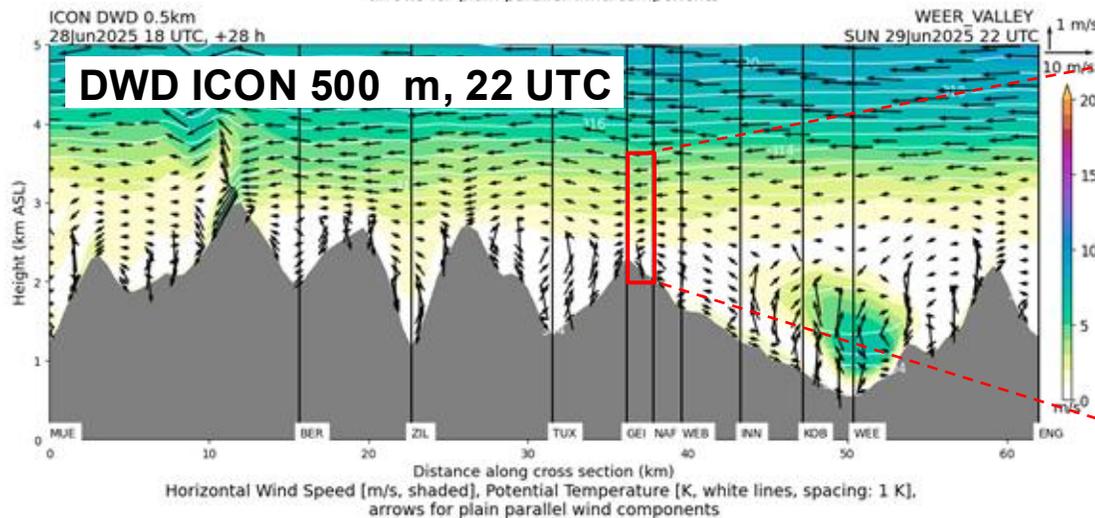


TEAMx, Nafingalm, Weer Valley

Left: wind field depicted by DWD ICON 500 m run

Right: radial velocity measured by Doppler wind lidar RHI scan

Top: Upvalley flow captured by the model during daytime



Bottom: Flow across pass and down the valley not properly captured by the model during early night

⇒ missing interaction between local and regional scale

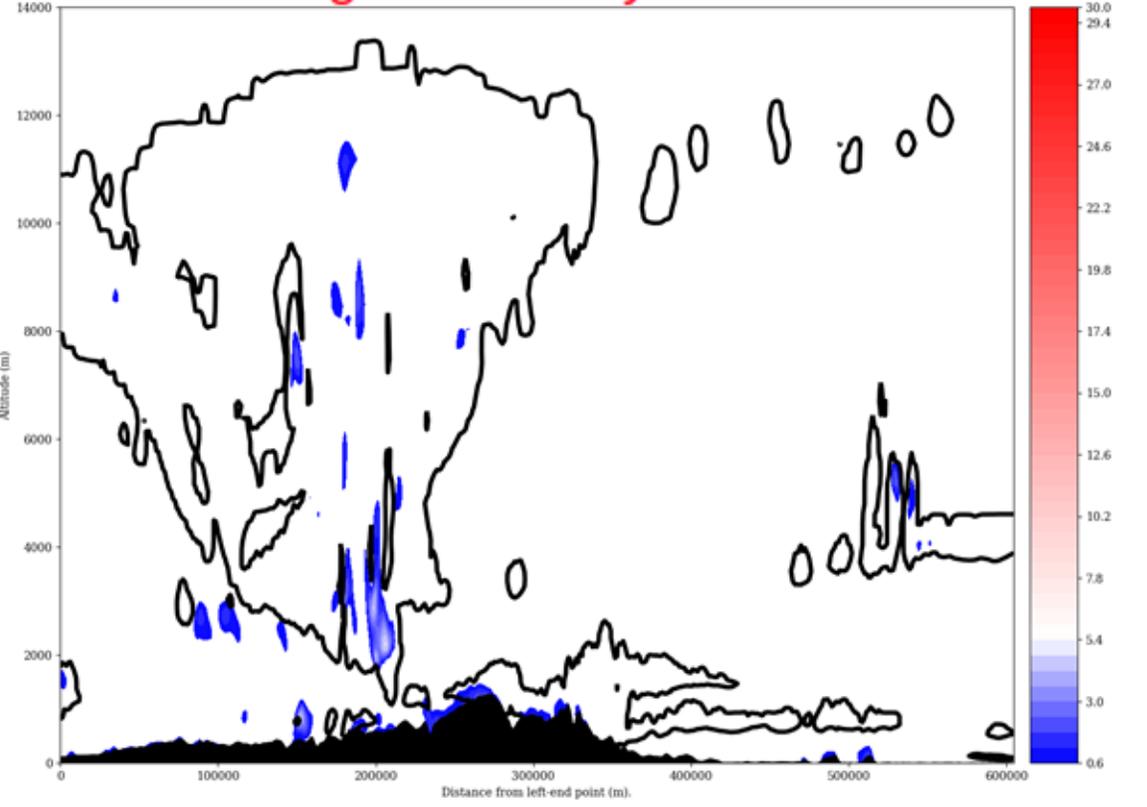
Evaluation of 3D effects in NWP models

- 3D Turbulence
 - Lack of turbulence in km-scale simulations
 - 3D vs 1D turbulence in mountainous areas, in particular in relation with development of convection
 - quasi-3D effect (Leonard terms) for vertical turbulent fluxes (AROME 1.3 km)
 - need of observations for validation (EDR, 3D wind...)
- 3D radiation effects of mountains
 - effects of mountain shadows in valleys
 - effects of clouds
 - observations (radiation sensors)

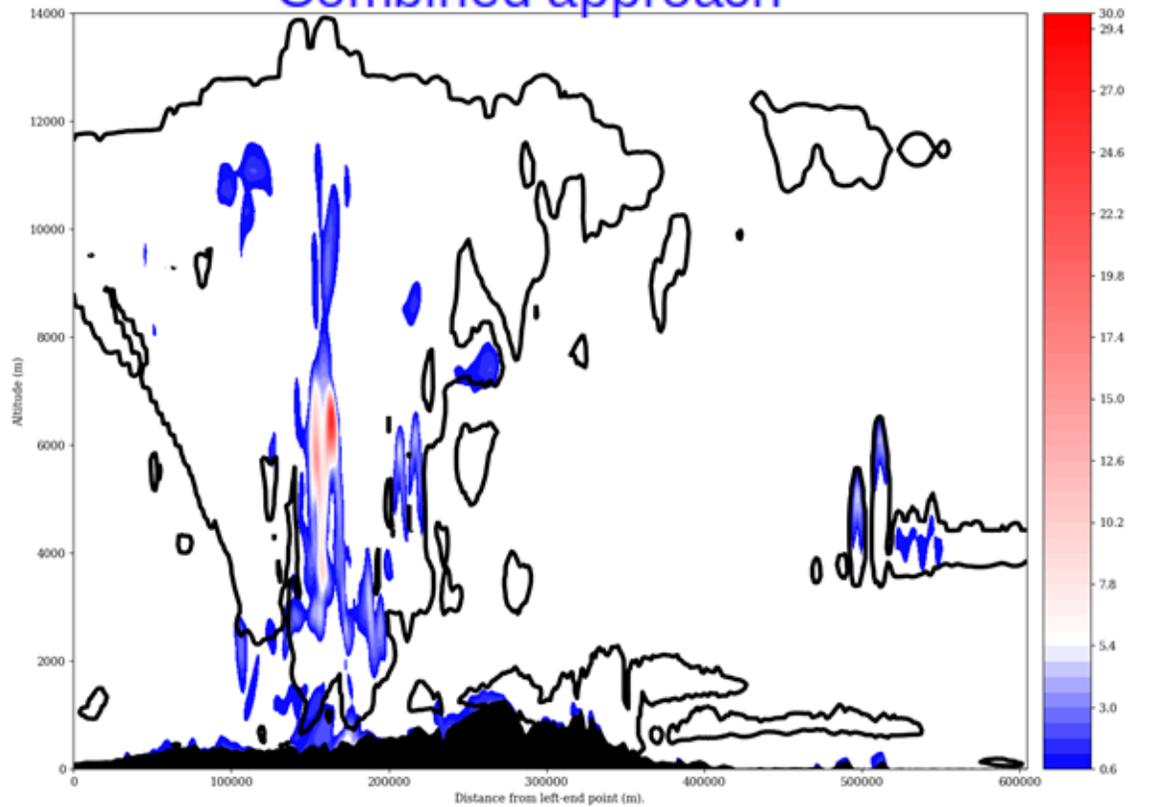
Importance of 3D effects

$$\frac{s^{n+1} - s^n}{\Delta t} = -\frac{\partial}{\partial z} \left(-K \frac{\partial s^{n+1}}{\partial z} \right) - \frac{K_L (\Delta x)^2}{12} \frac{\partial}{\partial z} \left(\frac{\partial w}{\partial x} \frac{\partial s^n}{\partial x} + \frac{\partial w}{\partial y} \frac{\partial s^n}{\partial y} \right)$$

K-gradient only



Combined approach



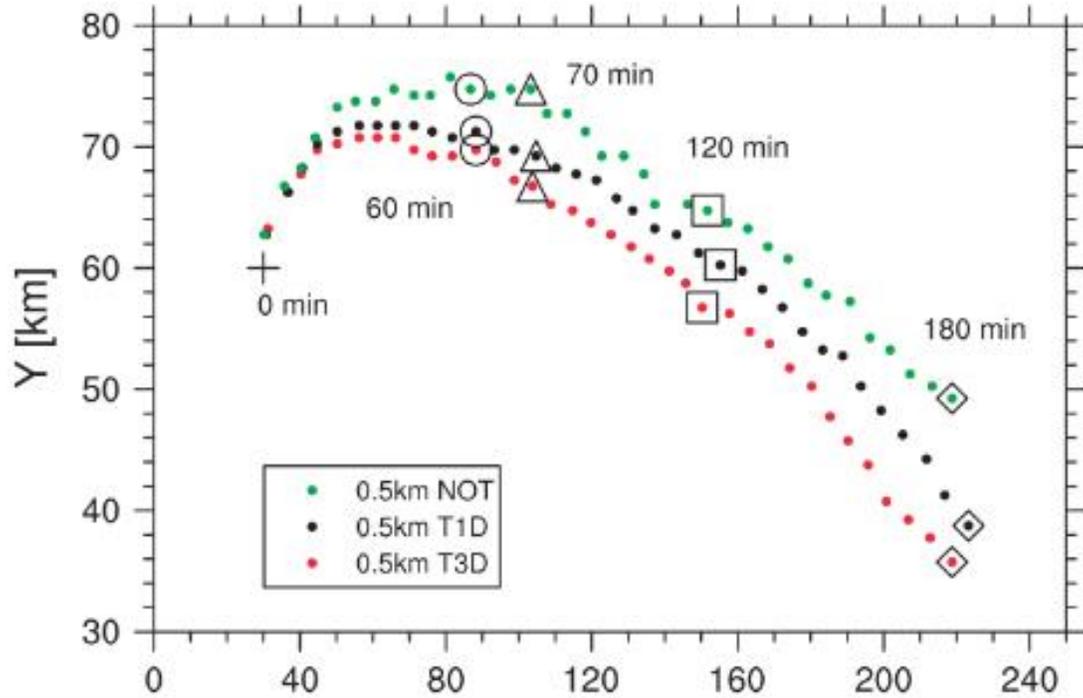
AROME 1.3km

Vertical cross section: subgrid TKE (shading) and cloud contours - 20 UTC (25 September 2021)

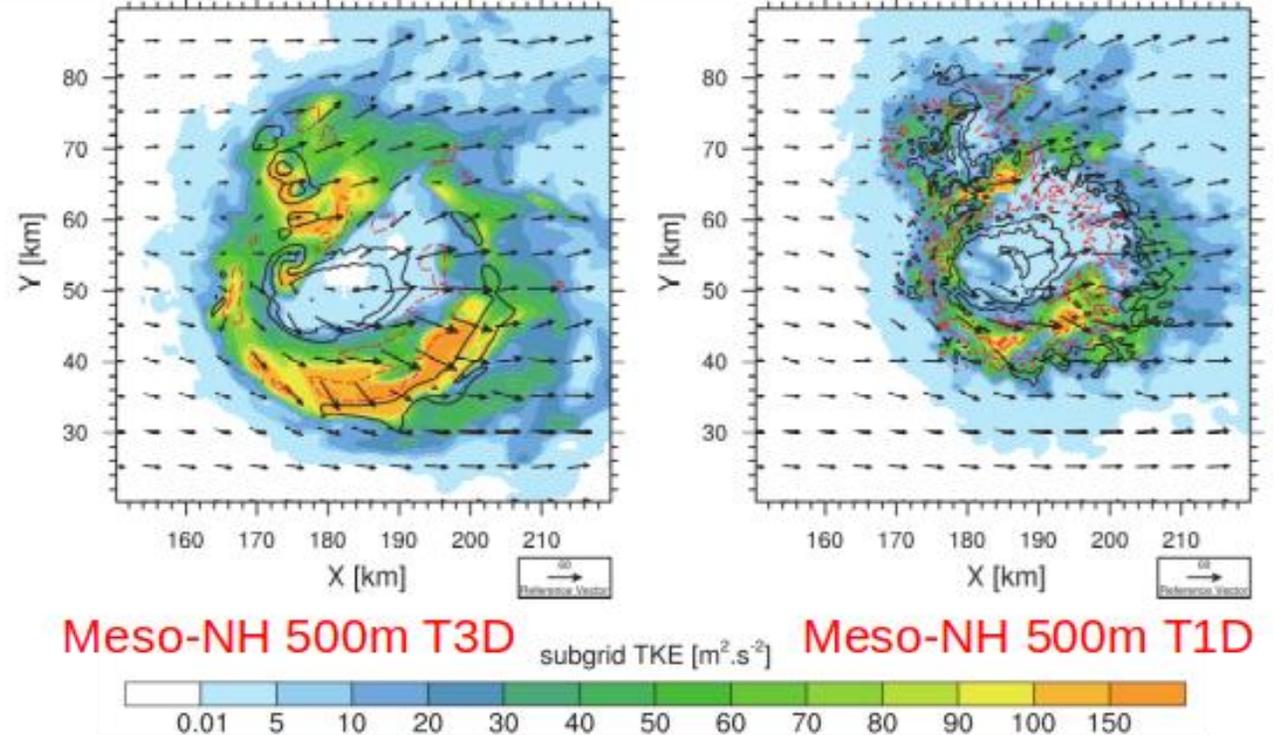
→ more subgrid TKE with the **Leonard terms** run (combined approach) compared to the **K-grad run**

Impact of 3D vs 1D turbulence scheme on a supercell (SC)

Time evolution of locations of vertical velocity maxima every 5 minutes (SC)



Horizontal cross sections:
Zoom over the SC at 150min of TKE (m^2s^{-2}) and positive (black) and negative (red) vertical velocities at 10km AGL



Meso-NH 500m no Turbulence, T1D, T3D

Verrelle et al, 2015, MWR

- impact on the supercell trajectory: more curved path with enhanced turbulent mixing
- with a T3D scheme: more subgrid TKE, with reduced intensity for updraughts and downdraughts