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The White Paper for TEAMx (Multi-Scale Transport and Exchange Processes in the Atmosphere over Mountains – Programme and Experiment)

Mathias W. Rotach, Marco Arpagaus, Joan Cuxart, Stephan De Wekker, Vanda Grubisic, Norbert Kalthoff, Dan Kirshbaum, Manuela Lehner, Stephen Mobbs, Alexandre Paci, Stefano Serafin, Dino Zardi

Outline

- TEAMx in a nutshell
- Process understanding
- Numerical modeling
- Observational issues
- Applications

An international programme for Mountain Weather and Climate

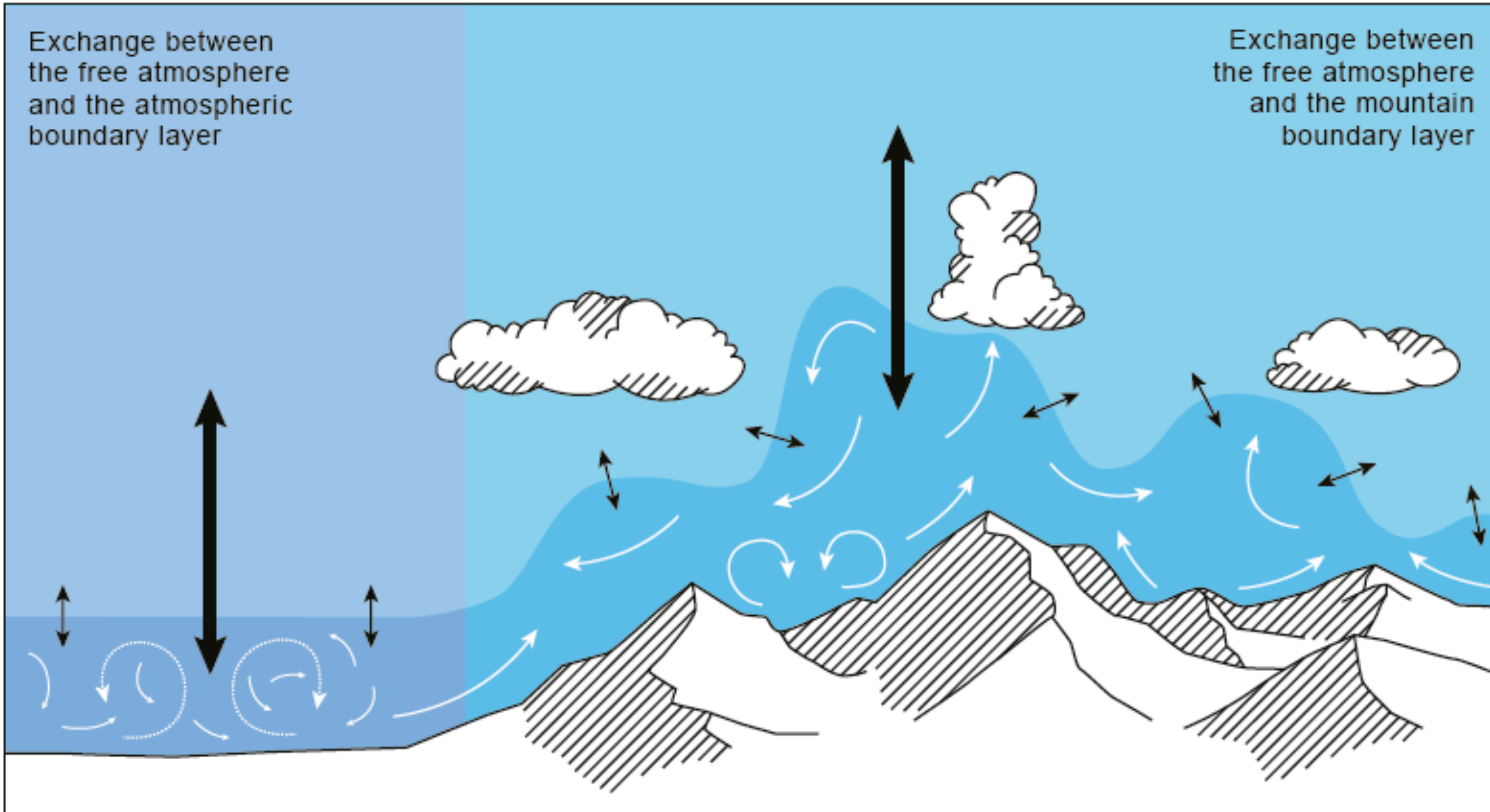
TEAMx

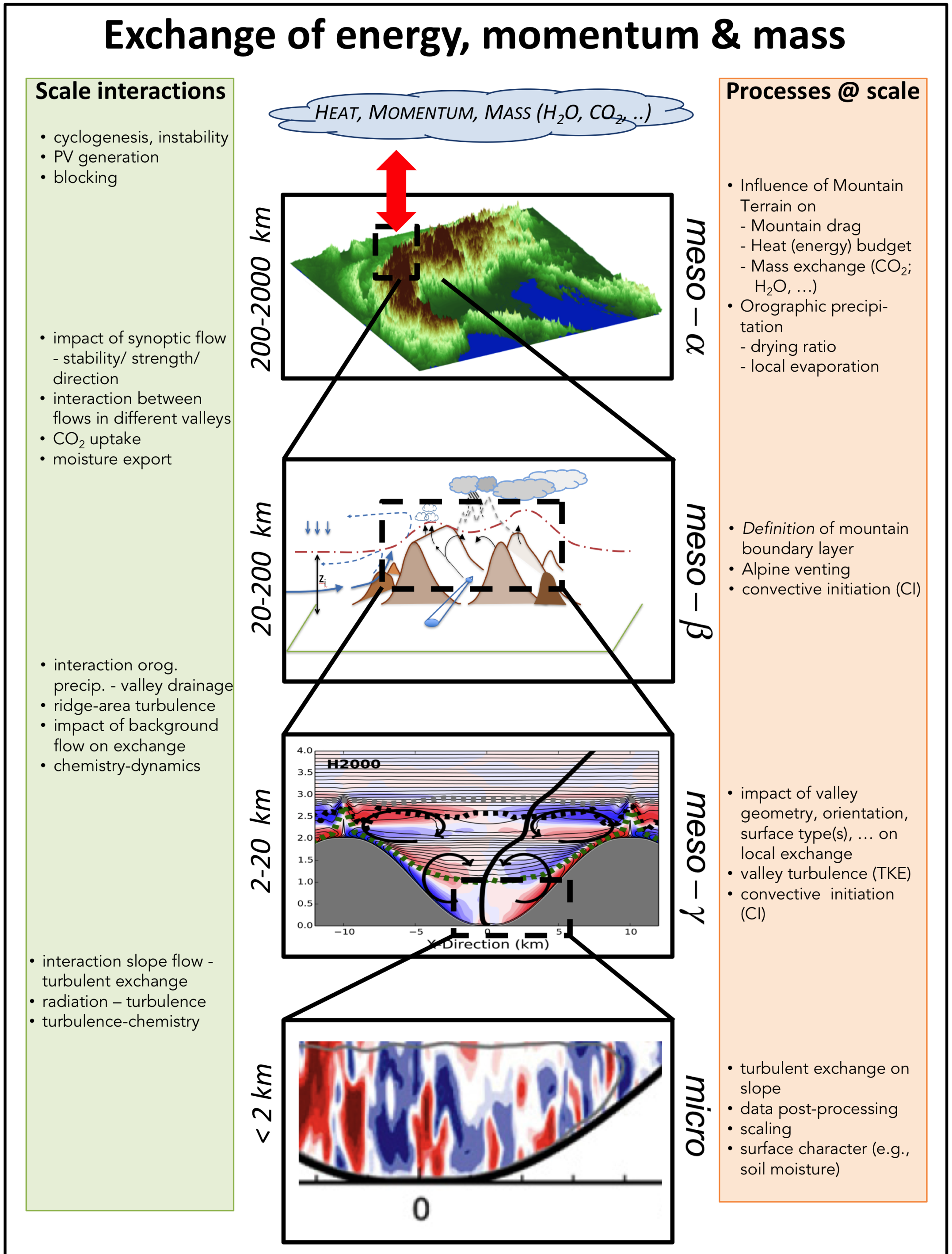
Multi-scale Transport and Exchange Processes in the Atmosphere over Mountains – Programme and Experiment

ALPEX $\longrightarrow$ *MAP* $\longrightarrow$ *TEAMx*

- discussion started: after ICAM-2015
- meetings aside conferences
- Coordination and Implementation Group established (9/2017)
- White Paper in preparation

Mountain Weather and Climate

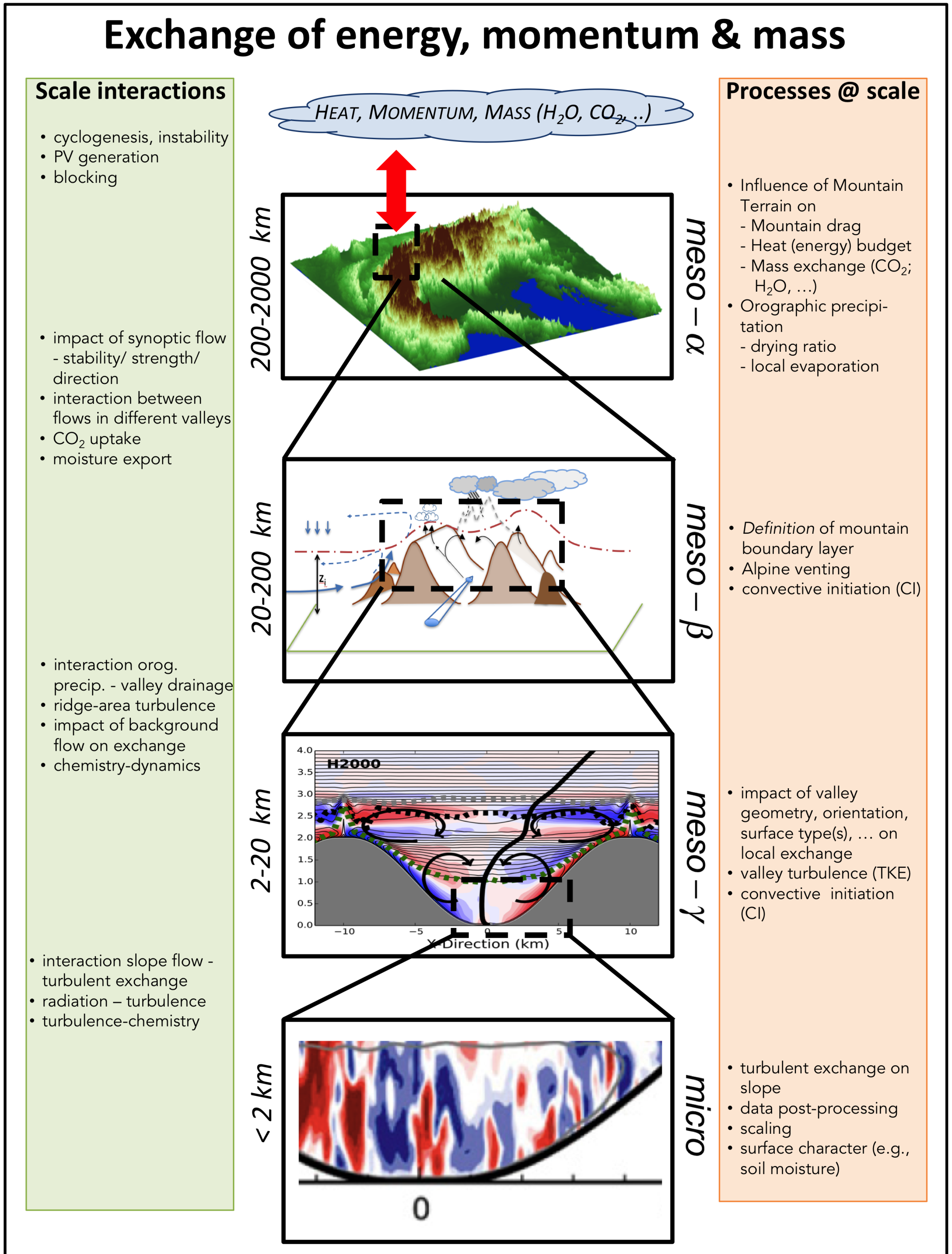




topics:

- BLs in complex terrain
- thermally driven flows
- dynamic transport (waves, breaking, …)
- convection & orography
- stable BLs
- pollutant transport and dispersion

→ ***and their interactions***



methods:

- numerical modeling
  → NWP (km-scale)
  → regional climate
  → processes and parameterizations
- observations
  → turbulent exchange
  → Lidar, scintillometer
  → obs strategies

goal:

→ coordinated *experiment (2022-23)*

TEAMx - Overarching research questions

- How does mountainous terrain impact exchange to the free atmosphere of energy, mass and momentum? (which processes, interaction, abundance, ...)
- Do we understand the relevant processes and their interactions *quantitatively*?
- Are current models (regional climate, NWP, pollutant dispersion) able to adequately reproduce these processes?
- Do we need a sgs-parameterization (*as for gravity wave drag*) for $\mathcal{O}$(10 km) grid spacing models?
- How does mountainous terrain affect air quality? (under which conditions is exchange suppressed?)

TEAMx - goals and targets

Goal	Specific description	Target
Understanding of exchange processes over mountains and their interactions	- micro-scale to meso-scale - interactions	- theoretical basis for regional water- and energy cycles - model parameterisations
Numerical modelling	- point forecast (weather) - point diagnostics (climate)	- models fit for application in complex terrain - comparable accuracy of point forecast / diagnose as over ‘flat terrain’
TEAMx joint experiment	- spatial inhomogeneity - coordination of instrumentation	- test scientific hypotheses - development/ verification of parameterisations
Weather / Climate Services	- input data to Atmosphere-influenced Process Models (AiPMs) - climate scenarios for mountainous areas feasible	- AiPMs can use (reliable) model output as input - accuracy not limited by atmospheric input

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TEAMx

partners (so far…)**:**

- University of Innsbruck
- Karlsruhe Institute of Technology (KIT)
- Mc Gill University
- University of Leeds (NCAS)
- University of Trento
- University of Virginia

- MeteoSwiss
- Meteo France (CNRS)
- NCAR
- ZAMG

TEAMx – organization

- TEAMx-Seed
  → coordination office (UIBK)
  → institutional crowd funding
  → Coordination and Implementation Group (CIG)
- Research is bottom-up financed
  → individual projects (e.g. CROSSINN, PI Bianca Adler, KIT)
  → bilateral (e.g., planned MF-ACINN)
  → multi-lateral: e.g., ASTER [Euregio], PI Manuela Lehner (ACINN), with U Trento and U Bolzano, e.g. planned ITN
  → similar to MAP
- Ressources for experiment
  → partners' (e.g., KIT cube, i-Box, MF, ...)
  → national obs programs (e.g., NCAS, NCAR, ...)
- Computing ressources: individual, PRACE, ...

TEAMx

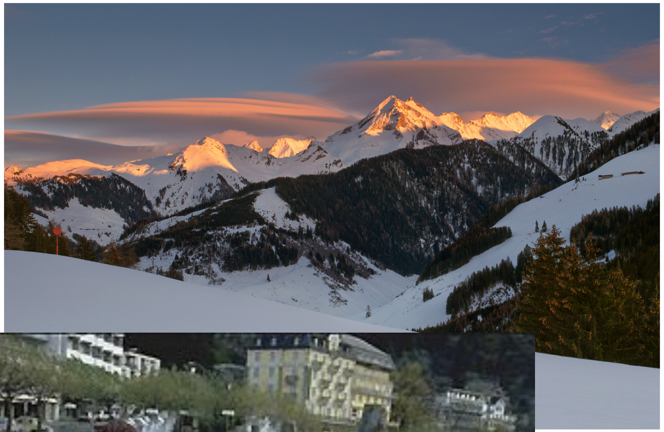
Forms of getting involved

PI's / institutions

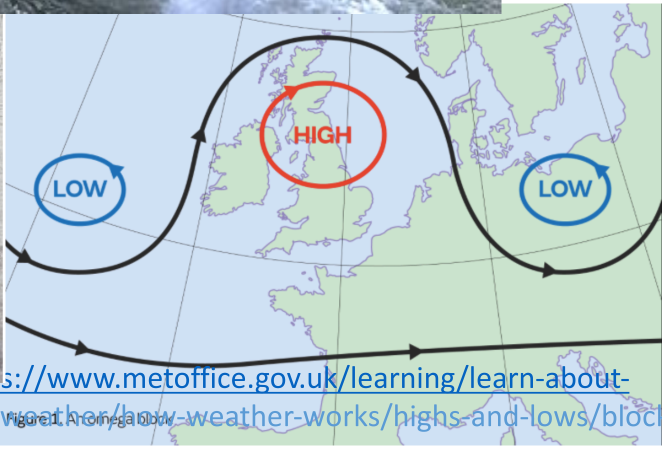
- sign TEAMx **MoU**
- participate in 1st TEAMx Workshop
  → August 28-30 2019, Rovereto (I)
  → refine / finalize *TEAMx-White Paper*
  → TEAMx working groups (join one...)
- write proposal (get it funded ....)
  → alone or join a team
  → get it approved by TEAMx
- 'observe from distance'

Status White Paper

- Understanding
- Modeling
- Observing
- Providing services for mountain weather and climate



p://blog.weatherflow.com/gravity-waves-over-new-hampshirevermont/



https://www.metoffice.gov.uk/learning/learn-about-the-weather/how-weather-works/highs-and-lows/bloc

Processes (understanding)

Understanding exchange processes in the MBL:

→ Three-dimensional structure

→ Land-atmosphre exchange

→ Heat and mass exchange with the free atmosphere

→ Boundary-layer control of convective pre-conditioning and initiation

→ Turbulent exchange due to low-level gravity-wave processes

→ Climate change and diagnostics

→ Air pollution in complex terrain

Mountain Boundary Layer

Where (what) is the MBL?

'The *Atmospheric Boundary Layer* is that part of the troposphere that is **directly influenced** by the presence of the **earth's surface**, and responds to surface forcing with a **timescale of about an hour or less**'.

Stull (1988)

diagnostics, ABL height:

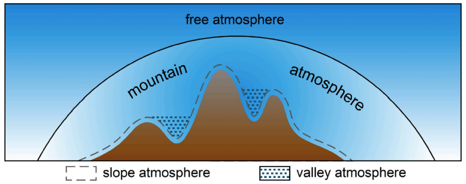
→ based on θ-profile (Zilitinkevich et al. 2012, Seibert et al. 2000, ...)

→ based on turbulence state of ABL (e.g., Ri / TKE criterion)

→ based on other influences (such as aerosol / water vapor mixing / concentrations)

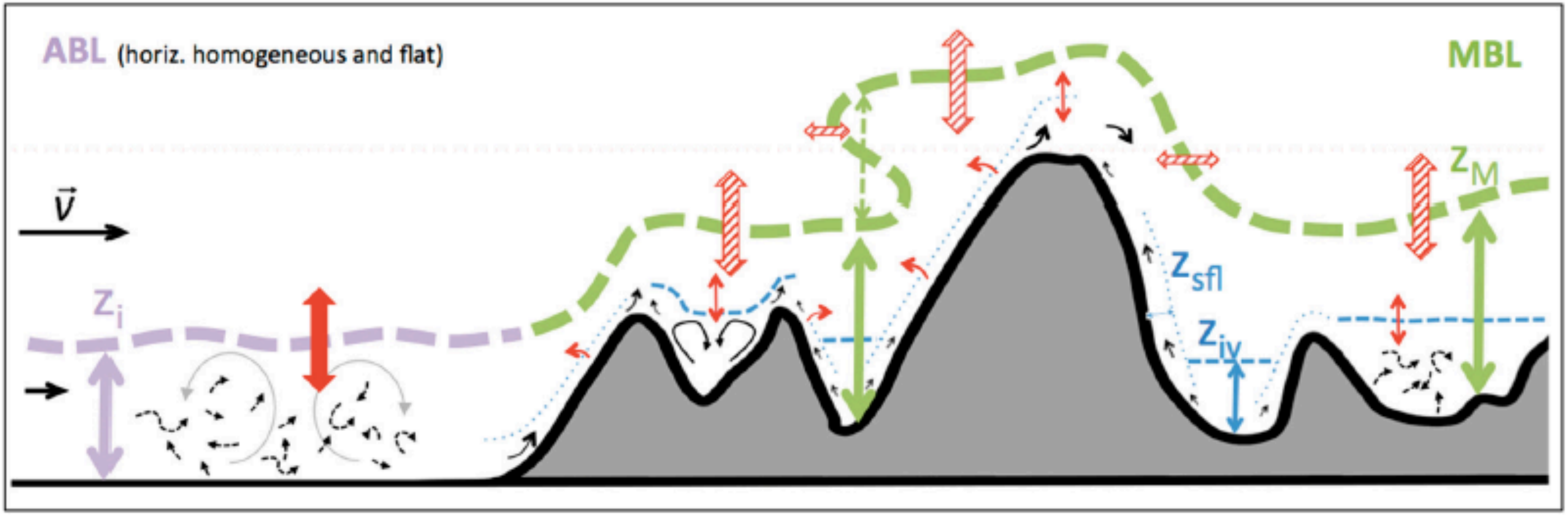
→ dependent on application (even in HHF terrain)

Mountain Boundary Layer (MBL)



- height of layer influenced by surface
  → not only surface character (turbulence)
  → interaction with meso-scale flow (valley / slope winds)
- traditional diagnostics do not yield z_{MBL}

unstable stratification (daytime)



Lehner and Rotach (2018)

Mountain Boundary Layer (MBL)

Suggested definition **Mountain Boundary Layer**

The Mountain Boundary Layer (MBL) is *the lowest part of the troposphere that is directly influenced by the mountainous terrain, responds to surface and terrain forcings with timescales of about one to a few hours , and is responsible for the exchange of energy, mass, and momentum between the mountainous terrain and the free troposphere.*

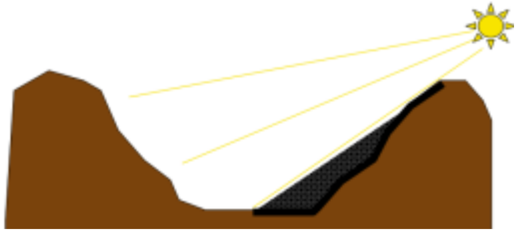
Lehner and Rotach (2018)

explicit research questions:

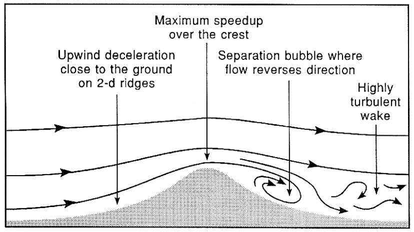
→ how (based on what) to define diagnostics for z_{MBL}?

→ 'general' structure feasible?

Mountain Boundary Layer



Inhomogeneous by definition:



Kaimal and Finnigan (1994)

- 'BL approximation' invalid
- diagnostics for MBL height
- three-dimensional structure
  - → related to thermally driven / dynamically modified meso-scale flow
  - → scale interactions

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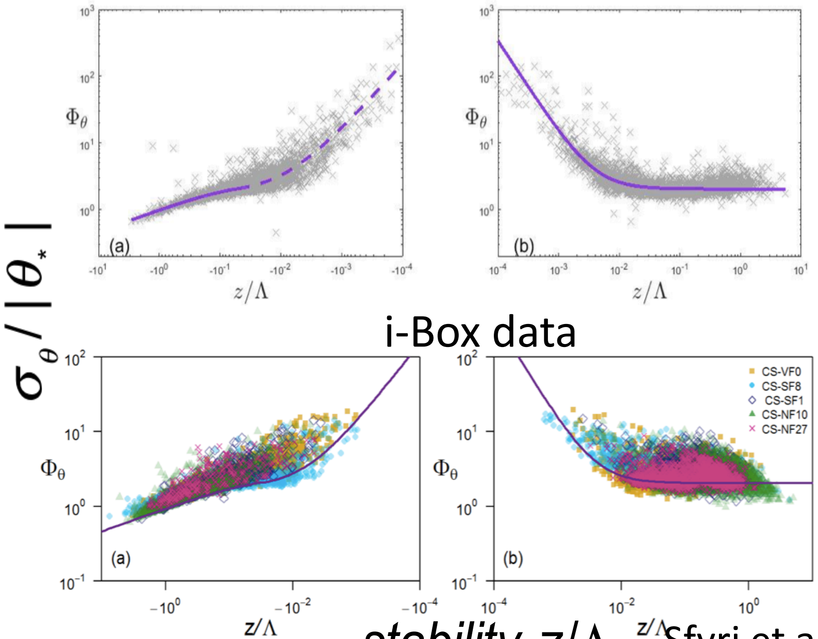
Land-atmosphre exchange

- Near-surface exchange (MOST or no-MOST)

ideal reference (Cabauw)

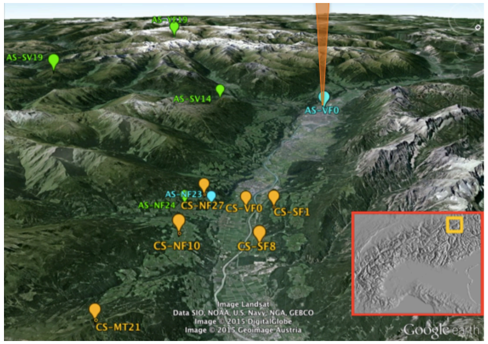


i-Box data

stability z/Λ

Sfyri et al. (2018)

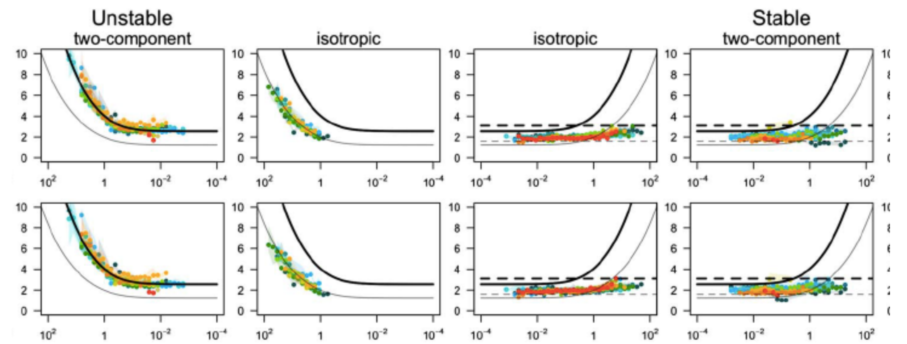
i-Box sites



- each site is different (all are higher than ref)
- not dependent on slope angle

→ scaling (*local* is not really satisfying)
→ data post-processing
→ differences to 'HHF terrain'?

Land-atmosphre exchange



- Scaling
  → value of local scaling?
  → how to address spatial inhomogeneity
  → isotropy scaling (Stiperski et al. 2019)

- Data treatment
  → 'slope normal' or vertical
  → data post-processing, DQ

← BL approximation!
(Oldroyd et al. 2015)

- Advection, EB closure

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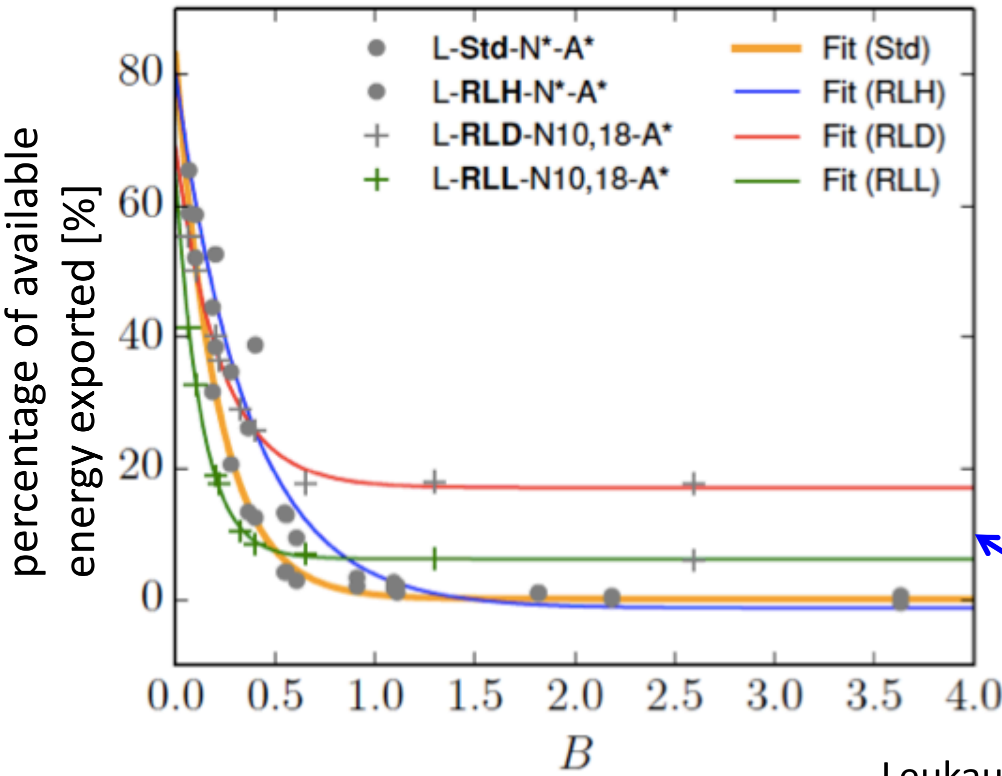
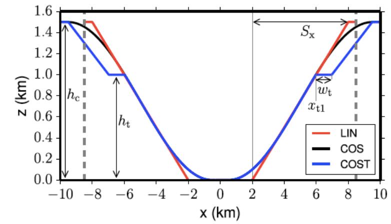
Heat export from idealized valley



B= Energy required to break up valley inversion / available energy

idealized WRF simulations:

→ dx = 200 m



→ different (solar) forcing, initital stratification, geometry

→ how much heat is exported?

Leukauf et al. (2017)

heat export even if 'not enough energy is available' [different initial stratification]

Heat and mass exchange with the free atmosphere

- Non-idealized topography
  → can overall behaviour be retained?

- Impact of background flow
  → synoptic wind
  → stratification

- Scale interactions (meso-, micro-scale flows)

- Experimental verification?

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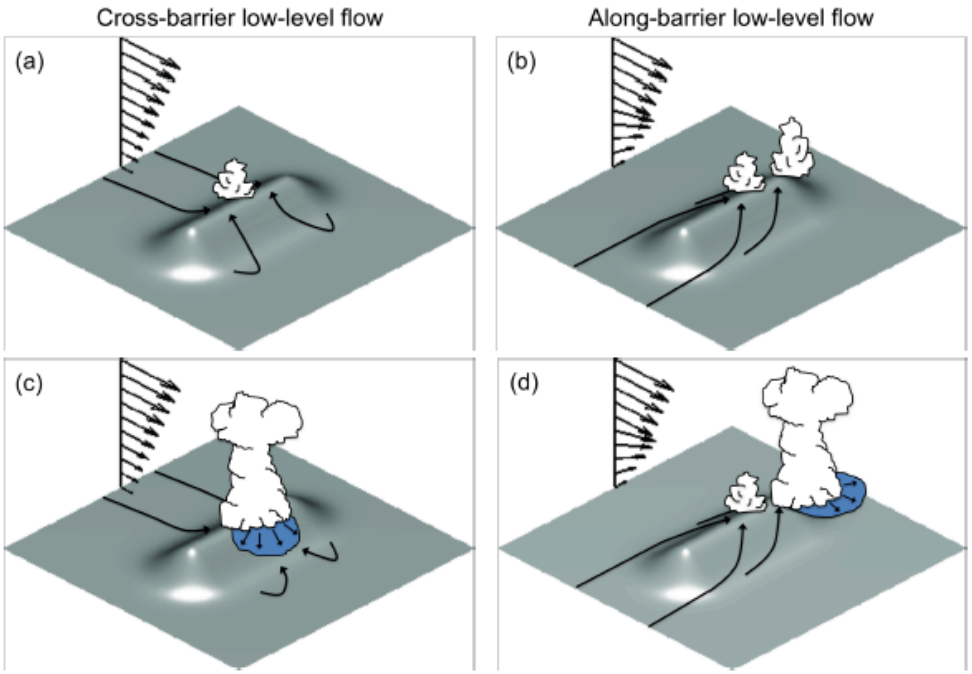
Convective pre-conditioning and initiation

- Role of orography for CI qualitatively understood
- Challenge: get it quantitatively right
- Challenge: interaction with BL flow
- Surface interaction (e.g. soil moisture)



Kirshbaum et al. 2018

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Turbulent exchange due to low-level gravity-wave processes

GW drag: the only parameterized exchange process (momentum) in numerical models (away from the surface…)

However:

- GW dynamics govern orographic flows such as föhn, gap flows rotors, ..
  → these contribute to exchange (but how?)
  → we only begin to learn
- Interaction to turbulence
  → not only wave breaking
- Add heat & mass (moisture) to GW parameterizations?
  → as ‘clear’ as for momentum?

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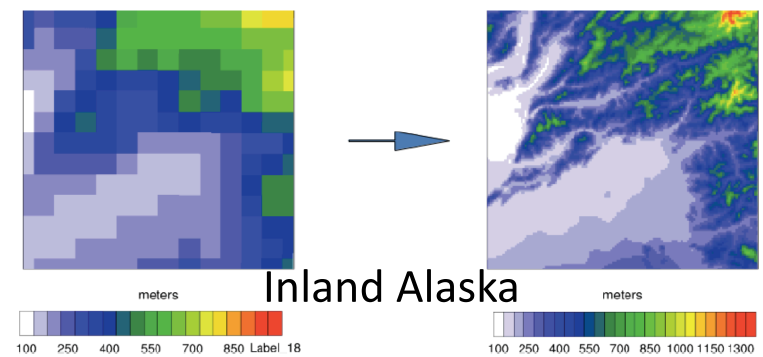
Mountain Climate change and diagnostics

- Mountainous regions more susceptible to climate change
  $\longrightarrow$ larger than average temperature change...
  $\longrightarrow$ elevation dependent warming (not generally consistent)
  $\longrightarrow$ other variables?

- Climate models not suffuciently resolved
  $\longrightarrow$ CORDEX: 12 km
  $\longrightarrow$ interpolation not a solution!
  $\longrightarrow$ $\mathcal{O}$(1 km) extremely expensive
  $\longrightarrow$ downscaling!

9 km grid spacing 1 km grid spacing



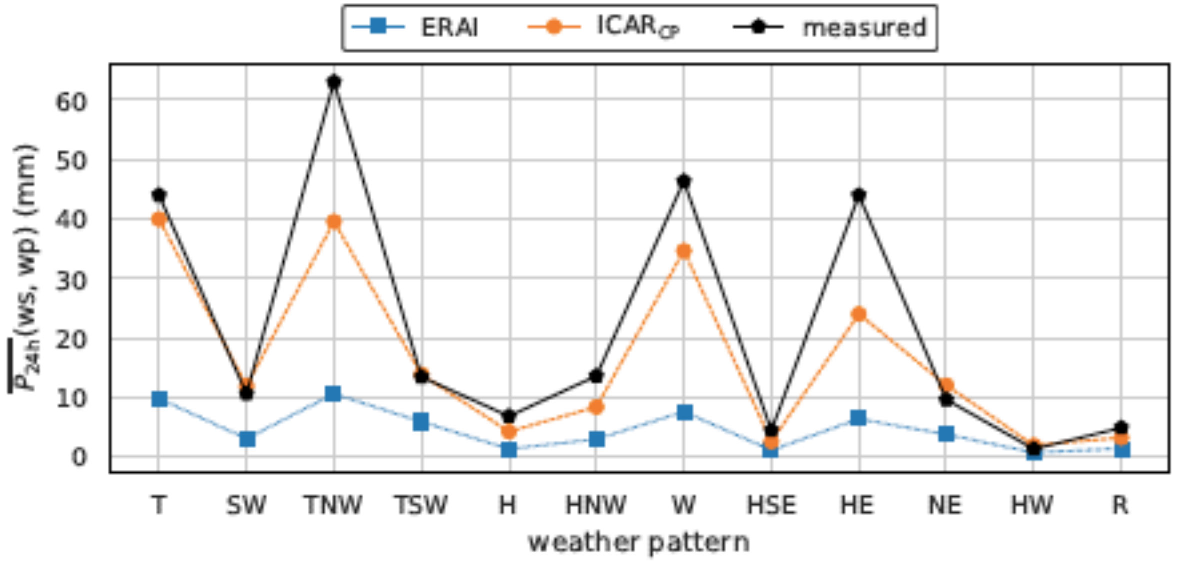
Inland Alaska

Arnold et al (2012)

- Climate services need equally as good information as over flat land (coasts, prairies, cities,...)

Climate diagnostics

- ➢ Example ICAR (physically based downscaling)
  → Intermediate Complexity Atmospheric Research model…
  → combines analytic (wave) solution with thermodynamic and other processes
  → 24 hr precipitation in Southern Alps (NZ)



Horak et al. (in review)

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Air pollution in complex terrain

Valley Smog from Little Cottonwood Canyon, 26-Jan-07 2pm

- Conditions of inhibited exchange
  MBL – free troposphere
  ⟶ air pollution 'within orography'
  ⟶ stable conditions

- Conditions of enhanced exchange
  MBL – free tropophere
  ⟶ export of precursors to oxidants
  ⟶ long-range transport (e.g., Ozone)

- For reactive gases: interaction between chemical reaction and exchange
  ⟶ similar treatment as with turbulent Dahmköhler number:
  mountain exchange Da?

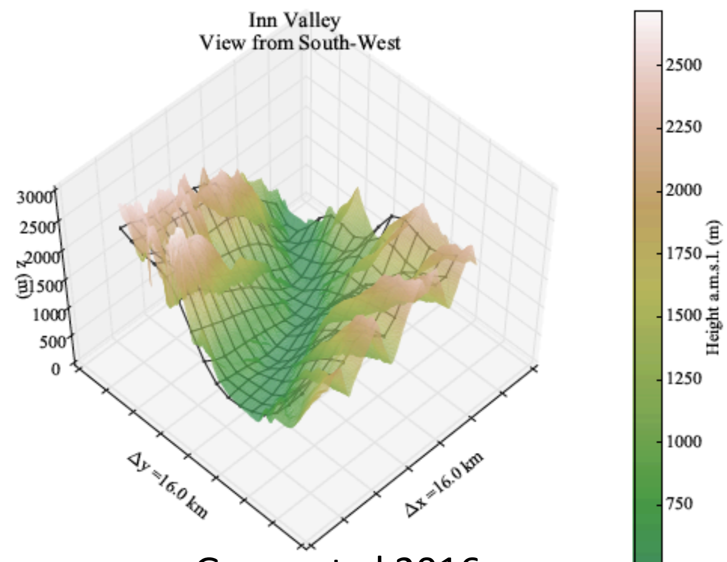
Numerical Modeling

Overall: resolution matters

- better resolution: steeper slopes
  → instabilities (potentially)
  → sfc exchange parameterization gets less appropriate
  → BL parameterization (1d) gets less appropriate
  → external issues (ororaphic shading, 1d radiaion treatment, ..)
  getting more critical
- best resolution: useless, if sfc information is missing

Topics Numerical Modeling

- Coordinates
  → terrain-following (influenced)
  → immersed BC (IBM)
  → leave finite differences?



Goger et al 2016

- physics parameterizations
  → boundary layer and turbulence (grey zone on top!)
  → radiation (1d)
- Initial conditions: most assumptions not met
  → small departures, Gaussian error statistics, unbiased model and observations
  → obs are too often discarded
- Climate models: still 'hydrostatic resolution'
  → need sgs parameterization for heat and mass?

Targets Numerical Modeling

- ‘GABLS’ for complex terrain
  → usually: [observations vs LES] <-> meso-scale
  → reference numerical experiment (what are the biggest problems?)
  → how to include observations?
- same quality of point forecast as for flat terrain
  → not only traditional variables (‘PTU’), but also turbulence (right for the right reason)
- Same robustness of climate scenario information as for flat terrain
  → downscaling in complex terrain (physically based, spatial correlations considered)

Targets Numerical Modeling

- Pollutant dispersion models:
  → 3d treatment (but computationally 'cheap'): revival of mass-consistent models?
  → chemical reactions included (Da...)
- Planning for field experiment
  → positioning of instrumentation
  → flight plans and coordination
  → critical observations?

Observations

Overall target: an internationally coordinated field experiment

→ 2022/23

→ likely in the Alps

→ possibly ‘satellite sites’

- provide data to
  - → test / challenge process understanding
  - → test hypotheses
- validate models
- training data for downscaling (climate services)

Field Experiment

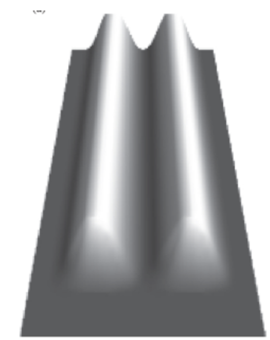
prerequisites

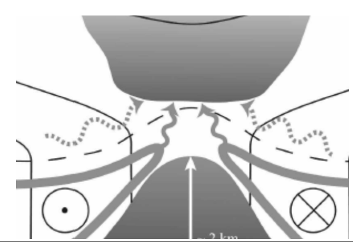
- Solve terrain specific problems for different techniques
  → turbulence: agree on post-processing ‘over slopes’
  → scintillometry: influence of ‘height’ (differet scaling)
  → airborne turbulence: generality /robustness of wavelet approach
  → satellite: spatial data - but quality?
- advance benefits of new technology /terrain specific advantages
  → temperature /humidity (Raman lidars): ‘across’ orography?
  → drones
  → passive T profilers: use sfc data @ different elevations

Field Experiment - target area

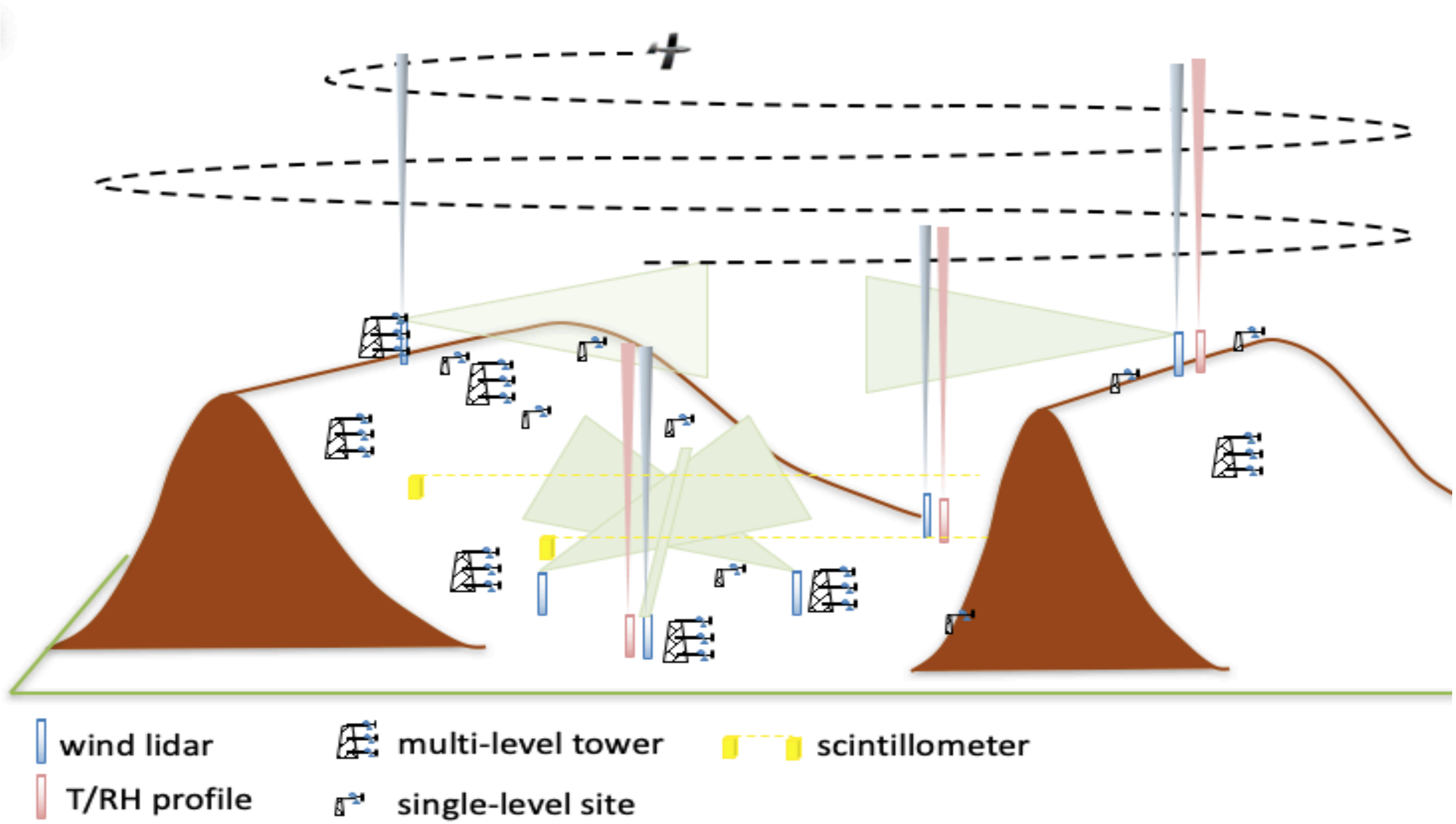
Target area

- Spatial variability
  → need 'many instruments' (many groups)
  → coordination
- IOP several months – EOP < 1 yr
  → cannot meet 'climate needs' (long time series, 30 yrs)
  → presence of 'longterm sites' (especially for 'variables related to exchange') andvantageous
- Generic ‚orography elements'
  → the valley system: curvature? side valleys? Orientation? Mountain-top sites?
  → the isolated mountain
  → others?





Field Experiment - target area



Mountain Weather and Climate Services

Recall targets:

- ➢ Point forecast (weather) / point diagnostics (climate): comparable accuracy of as over 'flat terrain'
- ➢ Weather /climate services: accuracy must not be limited by atmospheric input

→ right for the right reason

→ not only traditional weather and climate variables, but also those required for 'application models'

Mountain Weather and Climate Services

Weather and Climate Services:

- ...are often mountain-specific
  - → flood forecasting (flash floods), hydrological extreme events - safety / natural desasters
  - → avalanche forecast - warnings
  - → hydro power (planning and management) - energy
- …often have particular challenges in regions characterized by orography:
  - → air pollution in valleys – health
  - → wind energy (siting) - energy
  - → transportation (e.g., fog at airports in complex terrain)
  - → agricultural forecasts (e.g., frost)
- climate scenarios: assume that ‘the physics will not change’
  - → thus the physics must be correctly represented in the models

Mountain Weather and Climate Services

Atmosphere-influenced process models (‚applications‘)

- used today (weather) for
  - → warnings
  - → on-demand economy (hydro power, wind, solar)
  - → short-term planning (toursim, health (e.g. pollen)
  - → optimizing operations (traffic etc)
- used in scenario mode for
  - → planning (e.g., 30 yrs planning horizon for hydrological infrastructure)
  - → economic decisions
- often need ‚more than PTU‘:
  - → correct point forecasts / point diagnostics in complex mountainous terrain

Summary

- TEAMx has ‘lifted off’
- Bottom-up project structure
  → no ‘big pot’ for finances
  → but many interesting topics
- Workshop in Rovereto (28-30. August 2019)
  → finalize White Paper
  → processes / numerical modeling / observations
- Scientific goal
  → better understand *exchange processes between orography and the free troposphere*
  → at all scales incl. their interactions
- Target:
  → point forecasts (weather) and diagnostics (climate) at an accuracy comparable to that for flat terrain

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Thank you for your attention!

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