TEAMx

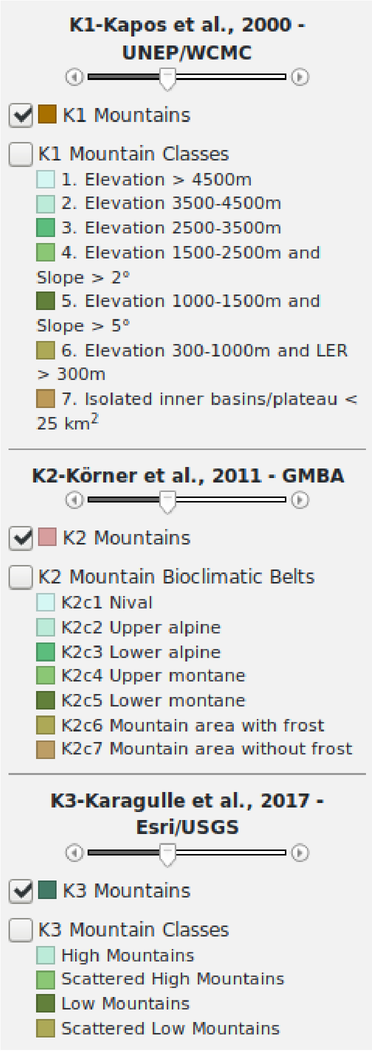
Multi-scale transport and exchange processes in the atmosphere over mountains – programme and experiment

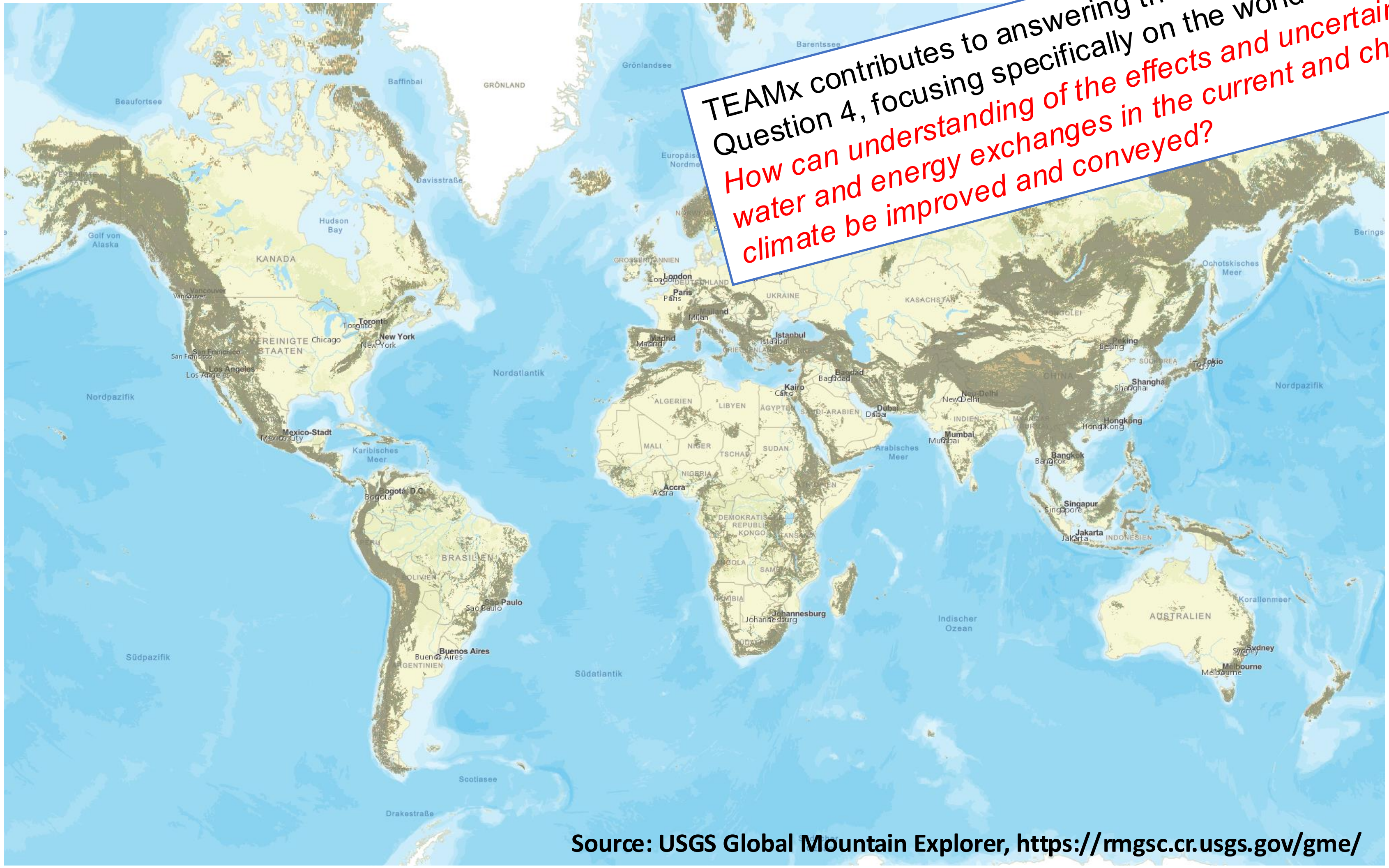
M.W. Rotach[1], M. Arpagaus[2], J. Cuxart[3], S.F.J. De Wekker[4], V. Grubišić[5], N. Kalthoff[6]
D.J. Kirshbaum[7], M. Lehner[1], S.D. Mobbs[8], A. Paci[9], E. Palazzi[10], S. Serafin[1], D. Zardi[11]

[1]University of Innsbruck, [2]MeteoSwiss, [3]University of the Balearic Islands
[4]University of Virginia, [5]NCAR EOL, [6]Karlsruhe Institute of Technology, [7]McGill University
[8]National Centre of Atmospheric Sciences, [9]Meteo France, [10]ISAC CNR, [11]University of Trento

www.teamx-programme.org

Global distribution of mountains





TEAMx contributes to answering the GEWEX Science Question 4, focusing specifically on the world's mountains. *How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?*

Source: USGS Global Mountain Explorer, https://rmgsc.cr.usgs.gov/gme/

Exchange processes over mountains

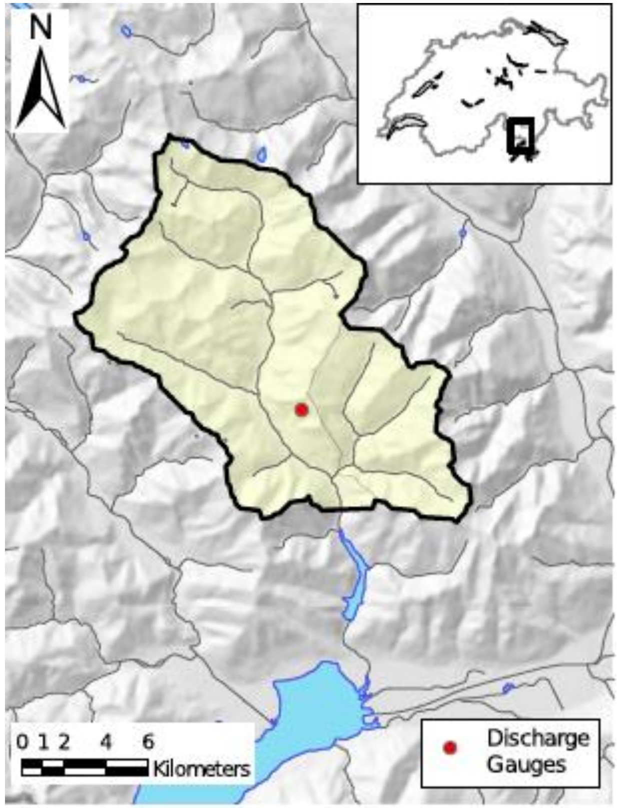
Momentum	Atmospheric flow decelerates over mountains, due to orographic blocking and gravity wave breaking. Orographic drag parameterizations alleviate systematic biases in general circulation models.
Heat	At daytime, mountains heat the atmosphere at high altitudes above sea level, generating breeze systems that favor horizontal and vertical transport and mixing. At night, orography favors cold-air pooling.
Mass: water	Flow over mountains enhances stratiform and convective precipitation, drying up the atmosphere. Mountains are “water towers” for the surrounding plains.
Mass: CO_2	CO_2 uptake by the land surface is the most uncertain term of the global budget, and is often estimated as the residual from other terms. Systematic deviations between modelled uptake and estimated residual reveal inadequacies in CO_2 flux modelling over land. Poorly represented exchange over orography may be one reason.

Relevance of mountain weather and climate

- Goes beyond local weather forecasting.
- Has broad implications on:
  1. Hydrological processes, flooding
  2. Hemispheric circulation
  3. Atmospheric composition
  4. Global carbon budget

1. Hydrological ensemble forecasts

- Small catchment in southern Switzerland: Valle Verzasca (186 km^2)
- Atmospheric EPS: COSMO-E (Klasa et al. 2018); 2.2 km Δx, 21 members.
- Hydrological model: PREVAH (Viviroli et al 2009); semi-distributed, 25 different combinations of physical parameters.
- 21x25=525 simulations per initiation time.
- Ensemble approach shows the dominant contribution to uncertainty (meteo vs hydro model uncertainty).

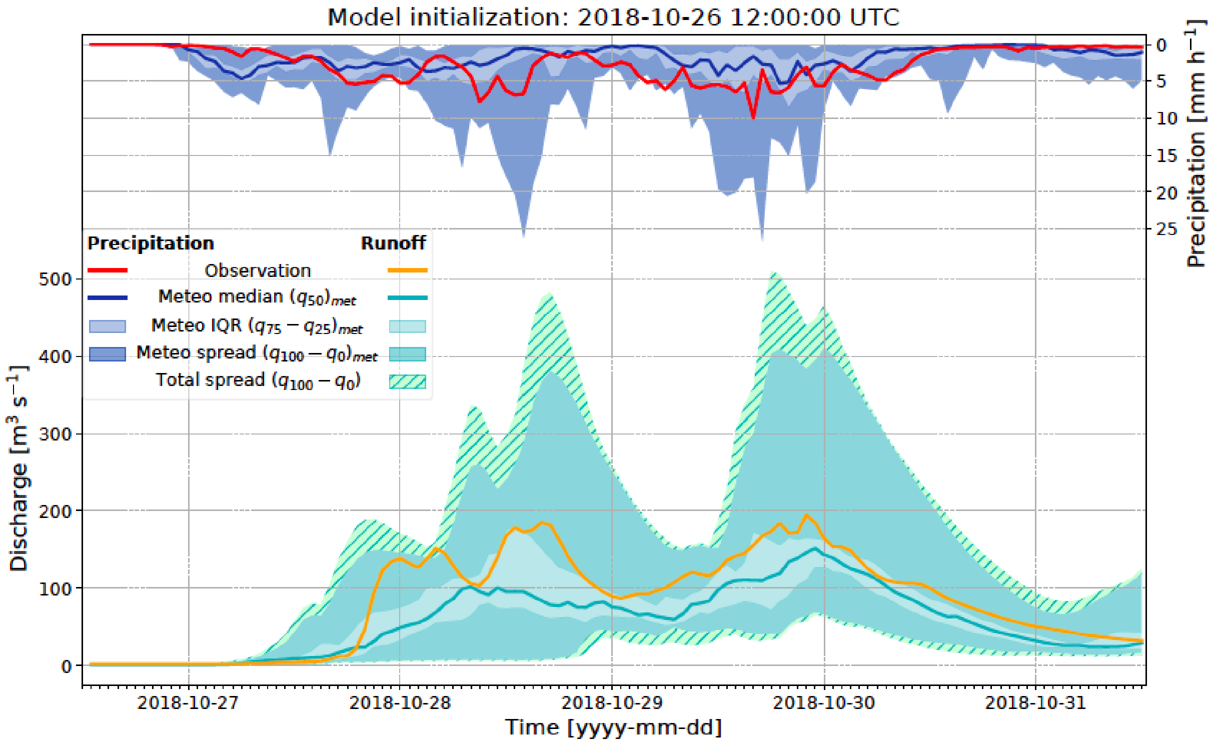


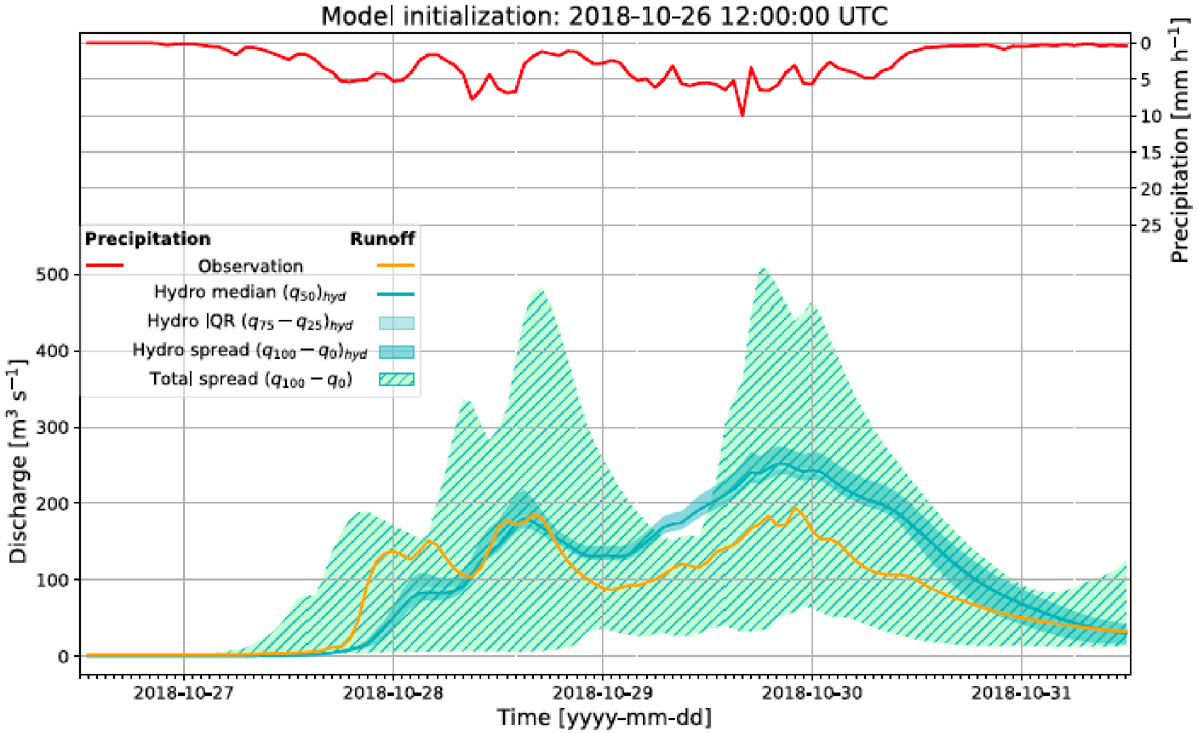
1. Hydrological ensemble forecasts

Example: October 26-31, 2018

Uncertainty from meteorological ensemble

Uncertainty from hydrological ensemble





Giordani (2019), *MSc Thesis at Univ Innsbruck, in collaboration with Massimiliano Zappa, WSL*

2. Hemispheric circulation

- The accuracy of global NWP simulations is heavily affected by orographic drag parameterization.
- Scientific uncertainties in mountain wave dynamics remain, e.g.:
  - Role in transport of water vapour and constituents
  - Tropospheric response to stratospheric gravity wave breaking, e.g. downslope wind/Föhn predictability

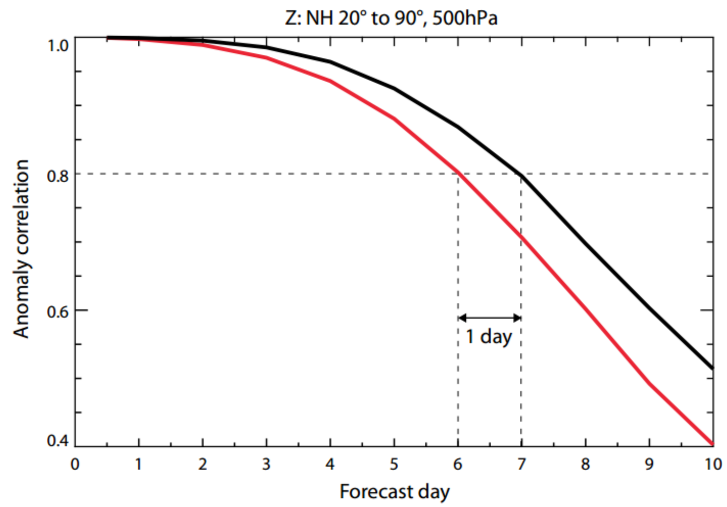
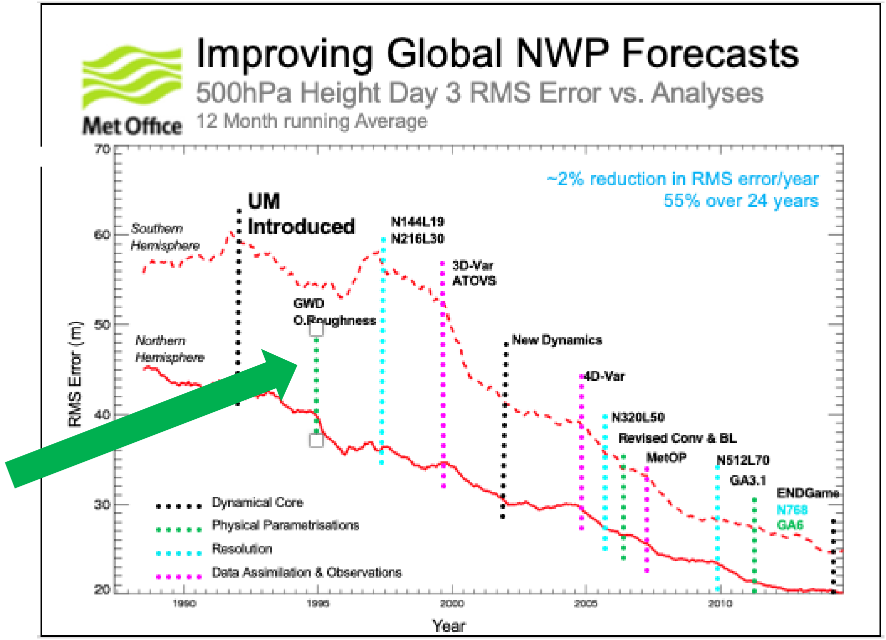


Fig. 4 Almost 1 day of skill is lost when the turbulent orographic form drag parametrization[17] is switched off in global 10-day weather forecasts performed with the Integrated Forecasting System of the European Centre for Medium-Range Weather Forecasts

Sandu et al. 2019



Courtesy A. Brown (ECMWF)

3. Atmospheric composition

- Impacts at different scales:
  - Atmospheric boundary-layer pollution in mountainous terrain, e.g. cold pooling, boundary-layer venting
  - Enhancement of troposphere-stratosphere exchange due to orographically induced motions (e.g., convection, waves).

4. Global carbon budget

FOSSIL FUELS

9.3±0.5 PgC y^{-1}

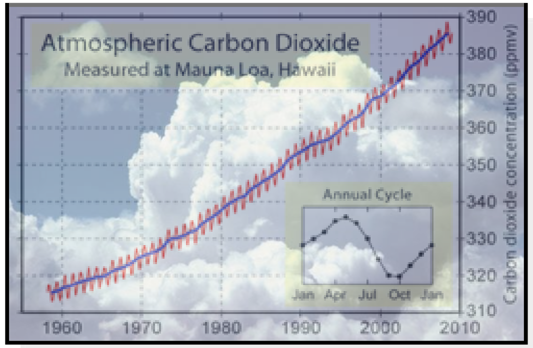
LAND-USE CHANGE

1.0±0.5 PgC y^{-1}

\+

4.5±0.1 PgC y^{-1}

45%



ATMOSPHERE

3.1±0.9 PgC y^{-1}

30%

Calculated as the residual of all other flux components

LAND UPTAKE

26%

2.6±0.5 PgC y^{-1}

Average of 5 models

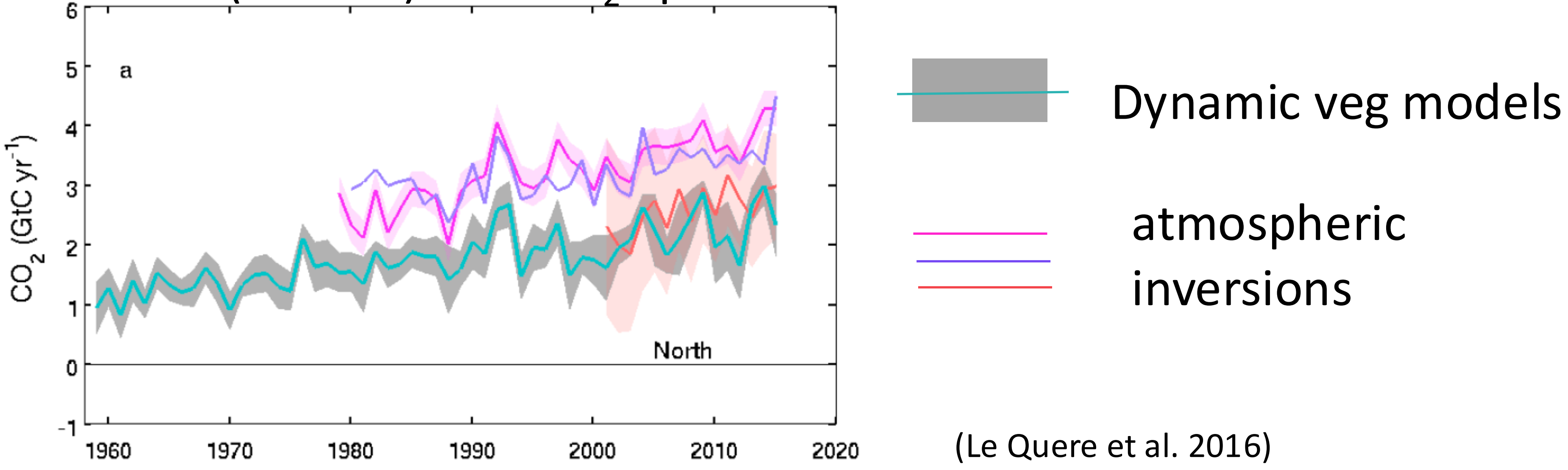
OCEAN UPTAKE

Global Carbon Project 2010; Updated from Le Quéré et al. 2016 – budget: 2006-2015

4. Global carbon budget

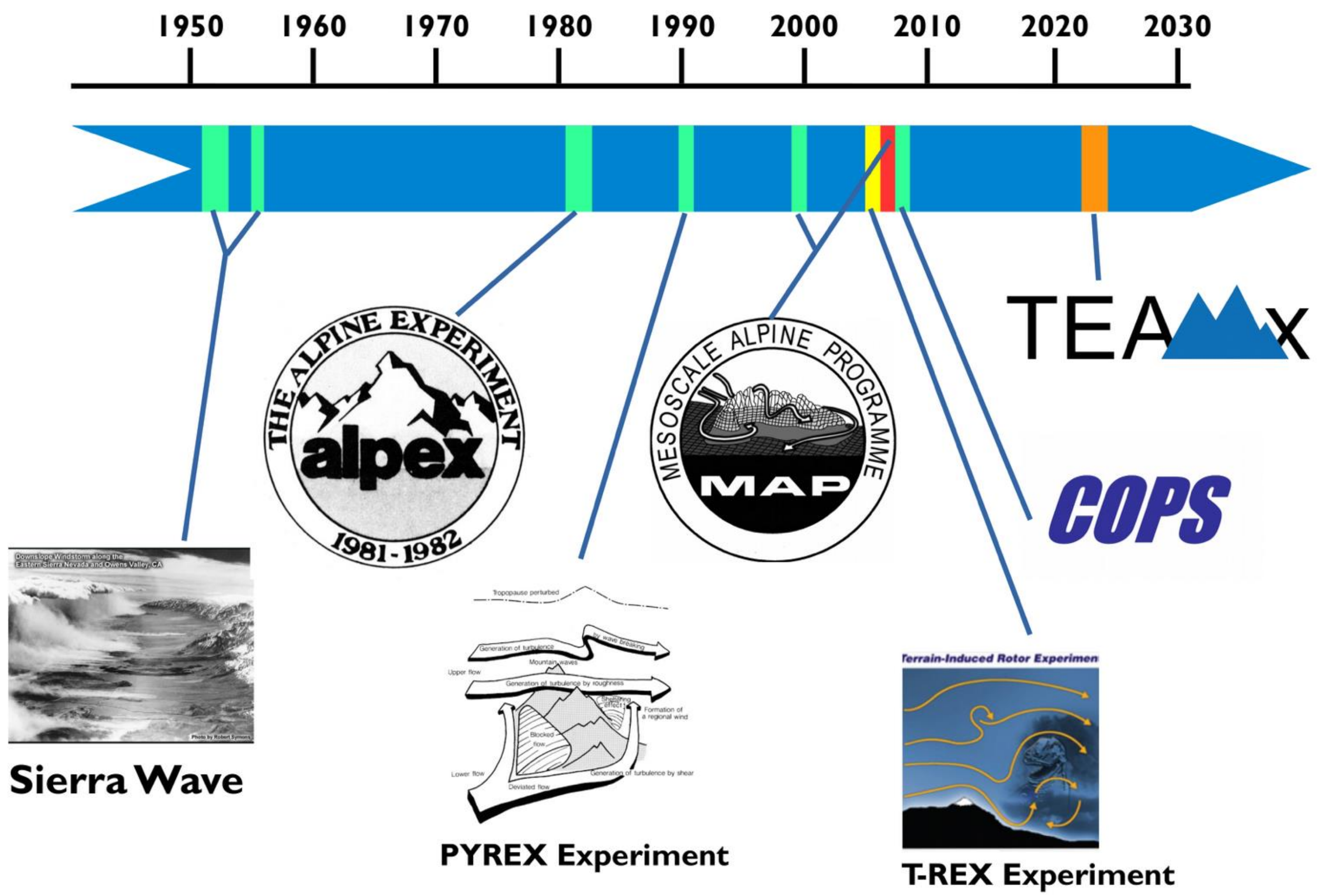
- Land uptake is the most uncertain of all budget components.
- Modelled uptake depends on method (2.3 vs. 2.7/3.8/3.8 PgC y^{-1} for 2006-2015)
- Modelling approaches are based on PBL concepts that do not take into account the terrain

NH (> 30° N) land CO_2 uptake



(Le Quere et al. 2016)

Major experiments in mountain meteorology

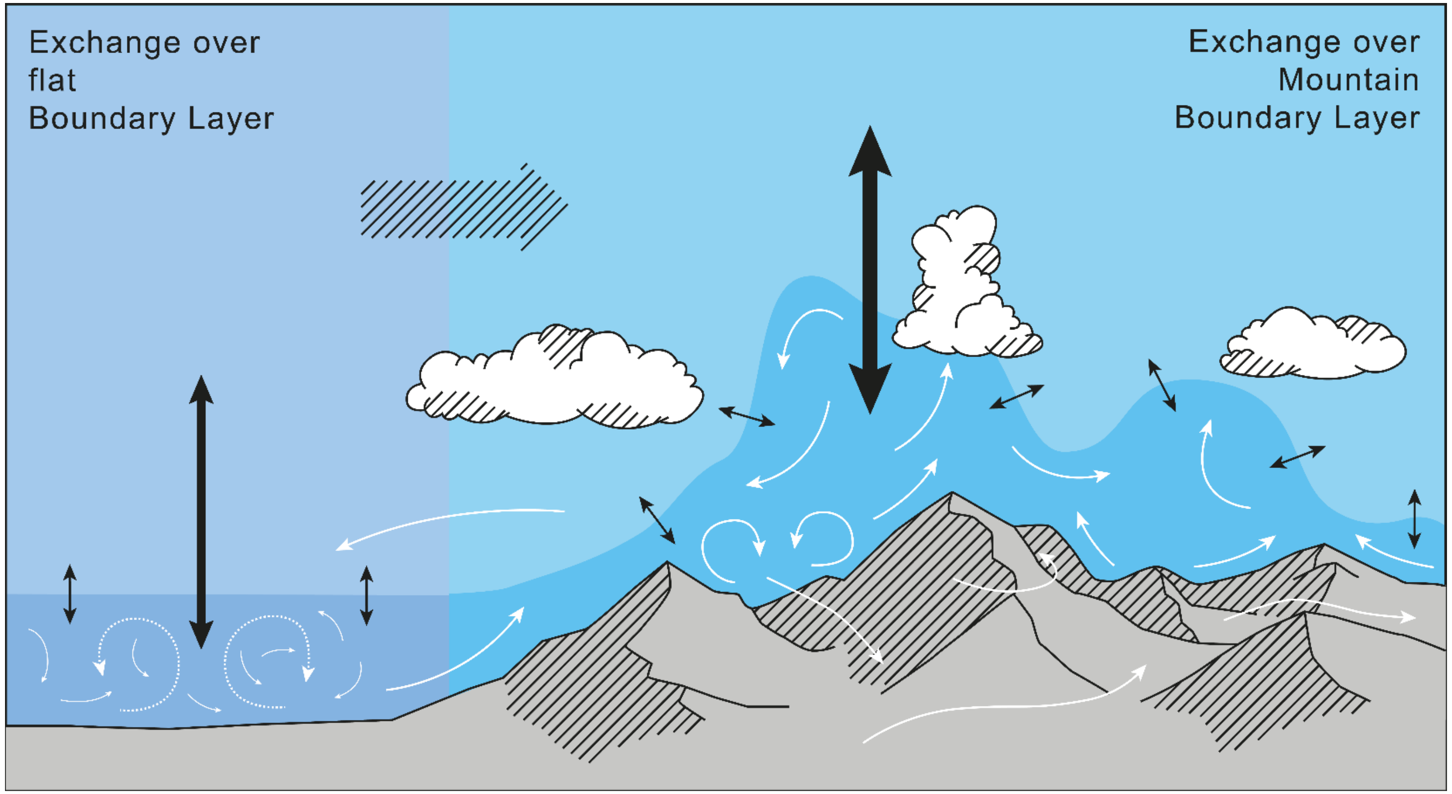


Technological drivers

- Huge technological advances in observational and computational technology since previous large-scale campaigns.
- Observational advances:
  - Remote sensing: ground based (radar, lidar, boundary-layer profiling, tomographic) and satellite-based (resolution, parameters retrieved).
  - Airborne sampling and remote sensing.
- Model advances:
  - Steadily increasing resolution.
  - High resolution implies challenges in model initialisation, parameterization of sub-grid-scale physical processes, model evalution.

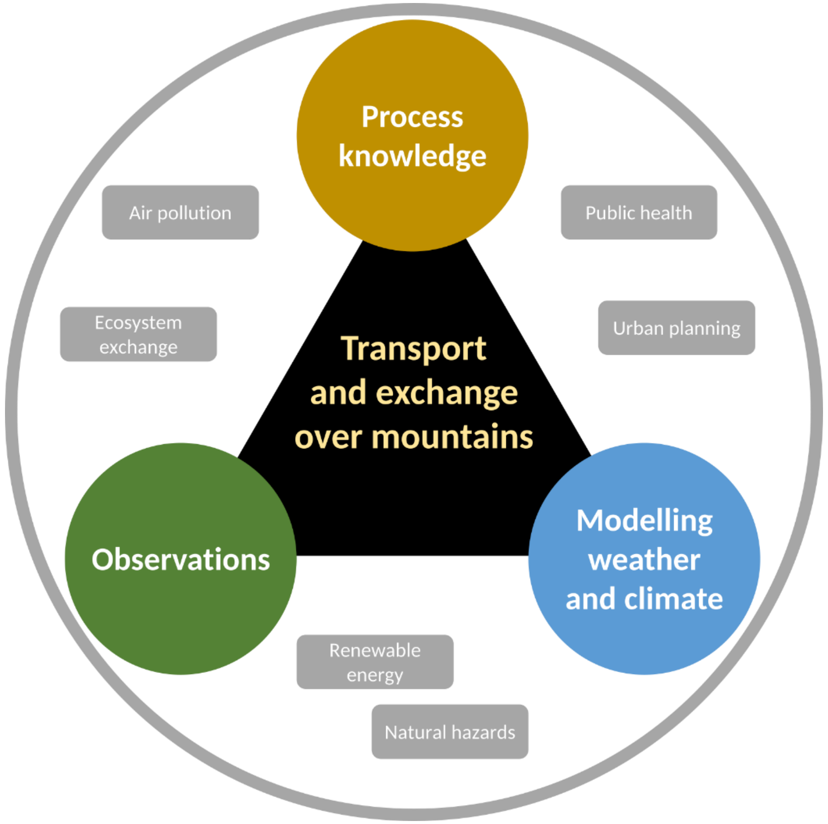
TEAMx

- *Exchange processes induced by mountains*: Transfer of heat, momentum and mass (water, CO_2, aerosols) between the ground, the PBL and the free atmosphere.
- High-resolution observation and modelling possible, but non-trivial. Model spatial resolutions outpacing observations.
- Special challenges over mountains: Spatial heterogeneity, wide range of relevant scales of motion.



Aims

- *Joint experimental efforts* to collect observations of exchange processes in complex-terrain areas. Use them for:
  - Model evaluation.
  - Parameterization improvement/development (SL, PBL, orographic drag, convection).
  - Process understanding.
- Field phase tentatively in 2023-2024.



MoU signed by 9 institutions.
U. Innsbruck / MeteoSwiss / Meteo France / U. Virginia / McGill U. / U. Trento / C2SM / NCAS / KIT
Open to new partners.

Atmosphere special issue on "***Atmospheric Processes over Complex Terrain***" (editors M. Rotach and D. Zardi).
8 papers published, 1 in preparation.

First TEAMx Workshop
28-30 August 2019
Rovereto (Italy).
92 participants.

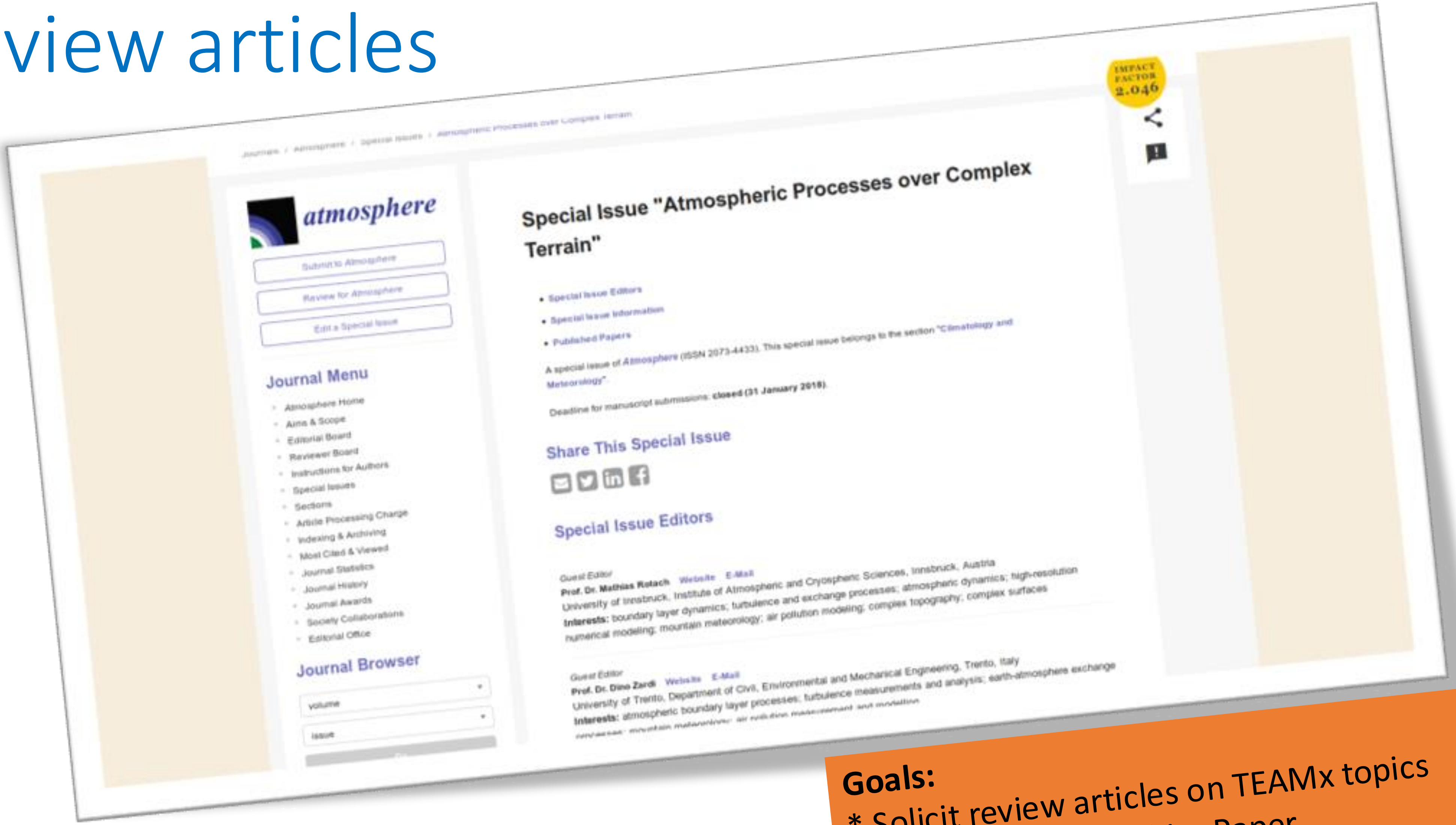
White Paper currently in preparation; finalized after workshop.

Coordination and Implementation Group

- **Mathias Rotach**, University of Innsbruck (Chair)
- **Marco Arpagaus**, MeteoSwiss
- **Joan Cuxart**, University of the Balearic Islands
- **Stephan De Wekker**, University of Virginia
- **Vanda Grubišić**, National Center for Atmospheric Research
- **Norbert Kalthoff**, Karlsruhe Institute of Technology
- **Daniel Kirshbaum**, McGill University
- **Manuela Lehner**, University of Innsbruck
- **Stephen Mobbs**, National Centre for Atmospheric Science
- **Alexandre Paci**, Meteo France
- **Elisa Palazzi**, National Research Council of Italy
- **Stefano Serafin** ⇦ Coordinator
- **Dino Zardi**, University of Trento

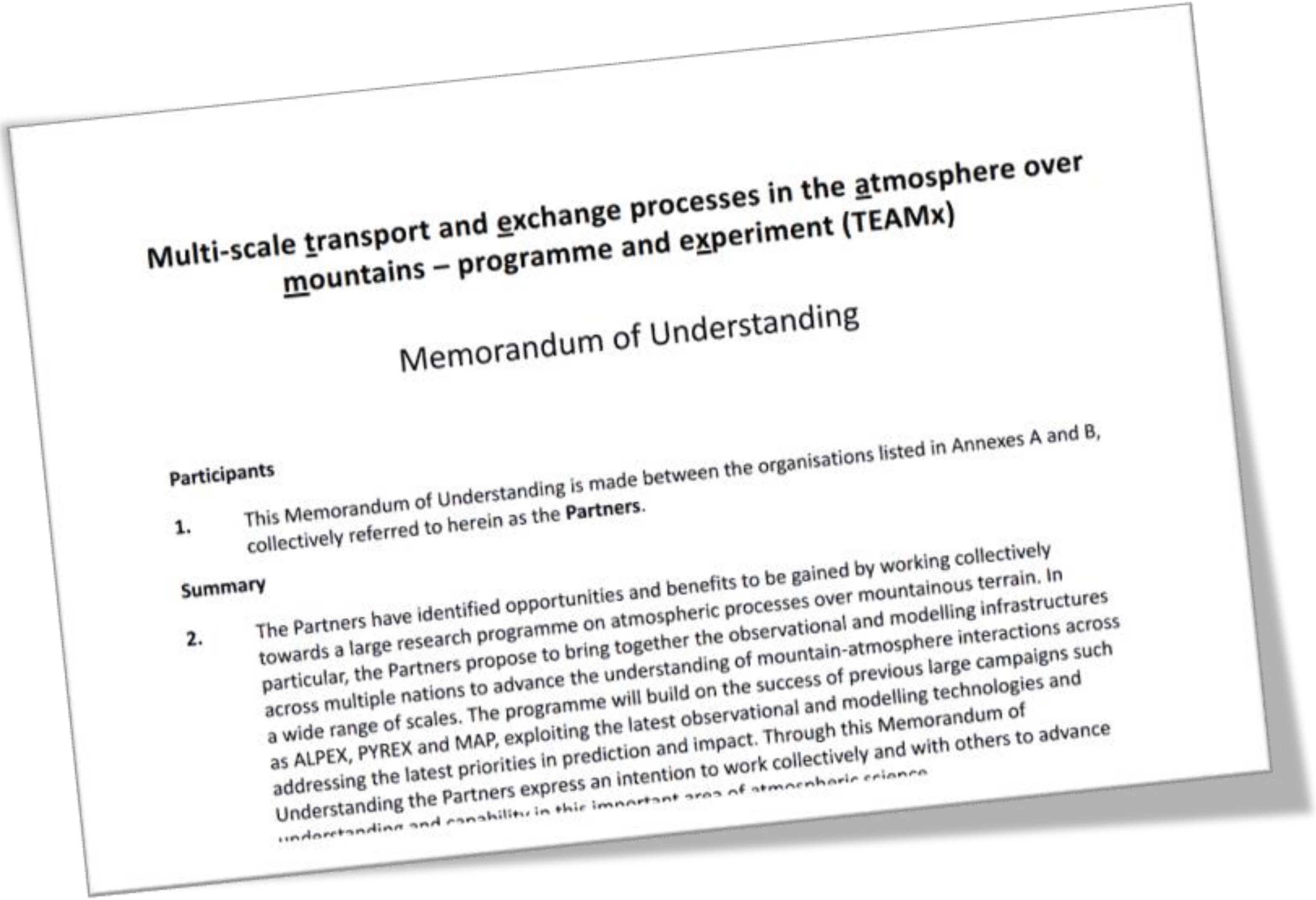
Programme Coordinator Office at the University of Innsbruck
Sponsored by Karlsruhe Institute of Technology KIT, Météo France, MeteoSwiss, National Center for Atmospheric Science (NCAS), University of Innsbruck, University of Trento, ZAMG

Review articles



Goals:
* Solicit review articles on TEAMx topics
* Basis for TEAMx White Paper

Memorandum of Understanding



Multi-scale transport and exchange processes in the atmosphere over mountains – programme and experiment (TEAMx)

Memorandum of Understanding

Participants

1. This Memorandum of Understanding is made between the organisations listed in Annexes A and B, collectively referred to herein as the **Partners**.

Summary

2. The Partners have identified opportunities and benefits to be gained by working collectively towards a large research programme on atmospheric processes over mountainous terrain. In particular, the Partners propose to bring together the observational and modelling infrastructures across multiple nations to advance the understanding of mountain-atmosphere interactions across a wide range of scales. The programme will build on the success of previous large campaigns such as ALPEX, PYREX and MAP, exploiting the latest observational and modelling technologies and addressing the latest priorities in prediction and impact. Through this Memorandum of Understanding the Partners express an intention to work collectively and with others to advance

Partnership

First TEAMx Workshop

28-30 August 2019
Rovereto
Italy

92 participants
11 countries

White paper


TEAMx

MulTi-scale transport and
Exchange processes in the
Atmosphere over
Mountains
Programme and experiment

Version 2
in preparation

Science Plan

Objective	Primary Focus	Target
Process understanding	Micro- and meso-scale processes within and above the *mountain boundary layer* (MoBL); Interaction between scales.	Quantitative understanding of momentum, energy and mass exchange over mountainous terrain
TEAMx Joint Experiment(s)	Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations over and near mountains	Quality-controlled observational data pool, available for process investigation, high-resolution model verification, parameterization development
Improving Weather and Climate Models	*Models right for the right reason*, i.e., identification and reduction of model biases and uncertainties over complex terrain	Weather forecasts and climate simulations over mountains as good as over flat terrain, and less reliant on model output post-processing
Support to Weather and Climate Service Providers	Air pollution, hydrology, climate change scenarios (e.g., elevation-dependent climate change).	Smaller uncertainty of impact models, due to reduced errors in weather and climate information.

Science Plan

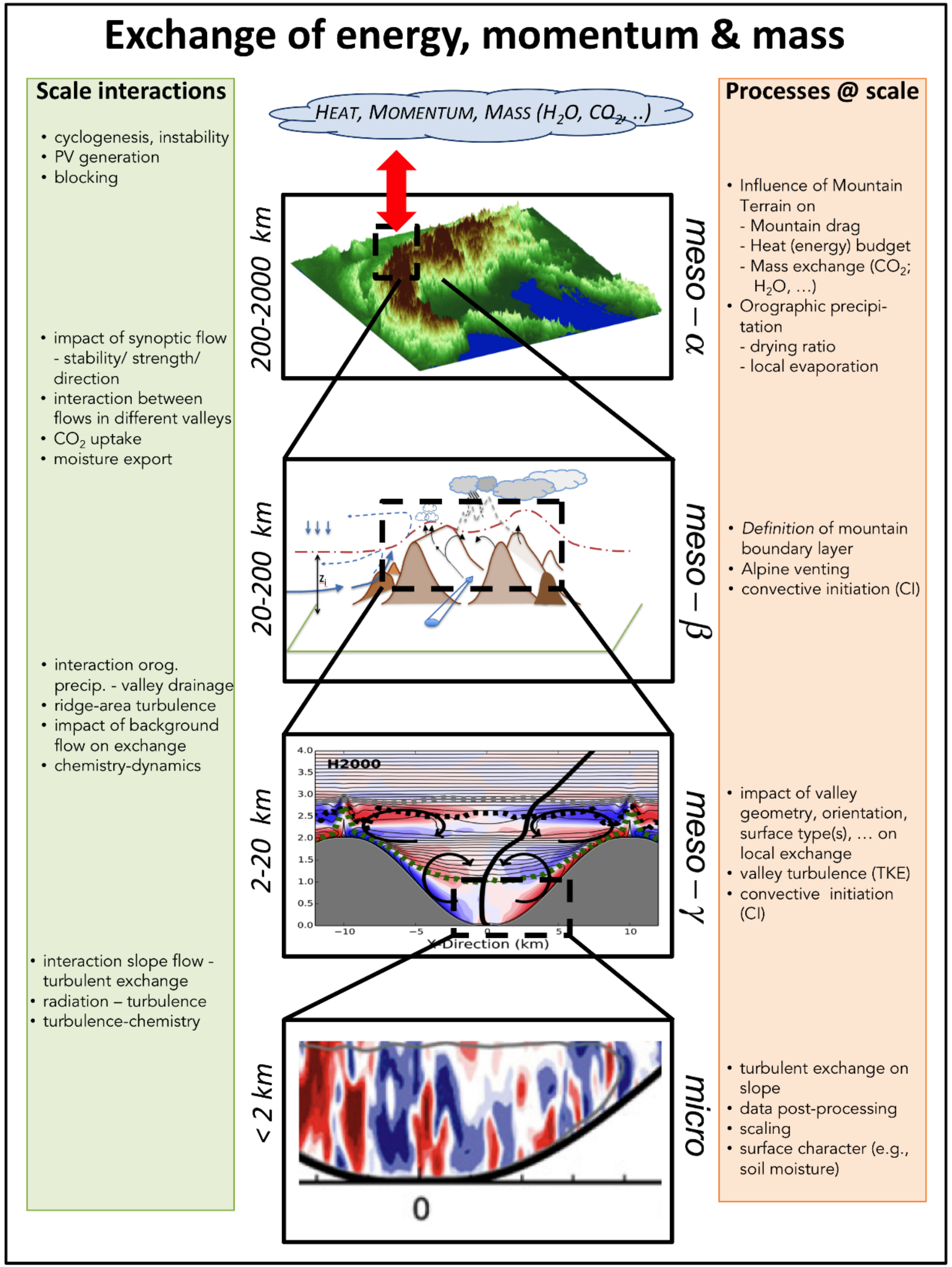
Objective	Primary Focus	Target
Process understanding	Micro- and meso-scale processes within and above the *mountain boundary layer* (MoBL); Interaction between scales.	Quantitative understanding of momentum, energy and mass exchange over mountainous terrain
TEAMx Joint Experiment(s)	Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations over and near mountains	Quality-controlled observational data pool, available for process investigation, high-resolution model verification, parameterization development
Improving Weather and Climate Models	*Models right for the right reason*, i.e., identification and reduction of model biases and uncertainties over complex terrain	Weather forecasts and climate simulations over mountains as good as over flat terrain, and less reliant on model output post-processing
Support to Weather and Climate Service Providers	Air pollution, hydrology, climate change scenarios (e.g., elevation-dependent climate change).	Smaller uncertainty of impact models, due to reduced errors in weather and climate information.

Science Plan

Objective	Primary Focus	Target
Process understanding	Micro- and meso-scale processes within and above the *mountain boundary layer* (MoBL); Interaction between scales.	Quantitative understanding of momentum, energy and mass exchange over mountainous terrain
TEAMx Joint Experiment(s)	Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations over and near mountains	Quality-controlled observational data pool, available for process investigation, high-resolution model verification, parameterization development
Improving Weather and Climate Models	*Models right for the right reason*, i.e., identification and reduction of model biases and uncertainties over complex terrain	Weather forecasts and climate simulations over mountains as good as over flat terrain, and less reliant on model output post-processing
Support to Weather and Climate Service Providers	Air pollution, hydrology, climate change scenarios (e.g., elevation-dependent climate change).	Smaller uncertainty of impact models, due to reduced errors in weather and climate information.

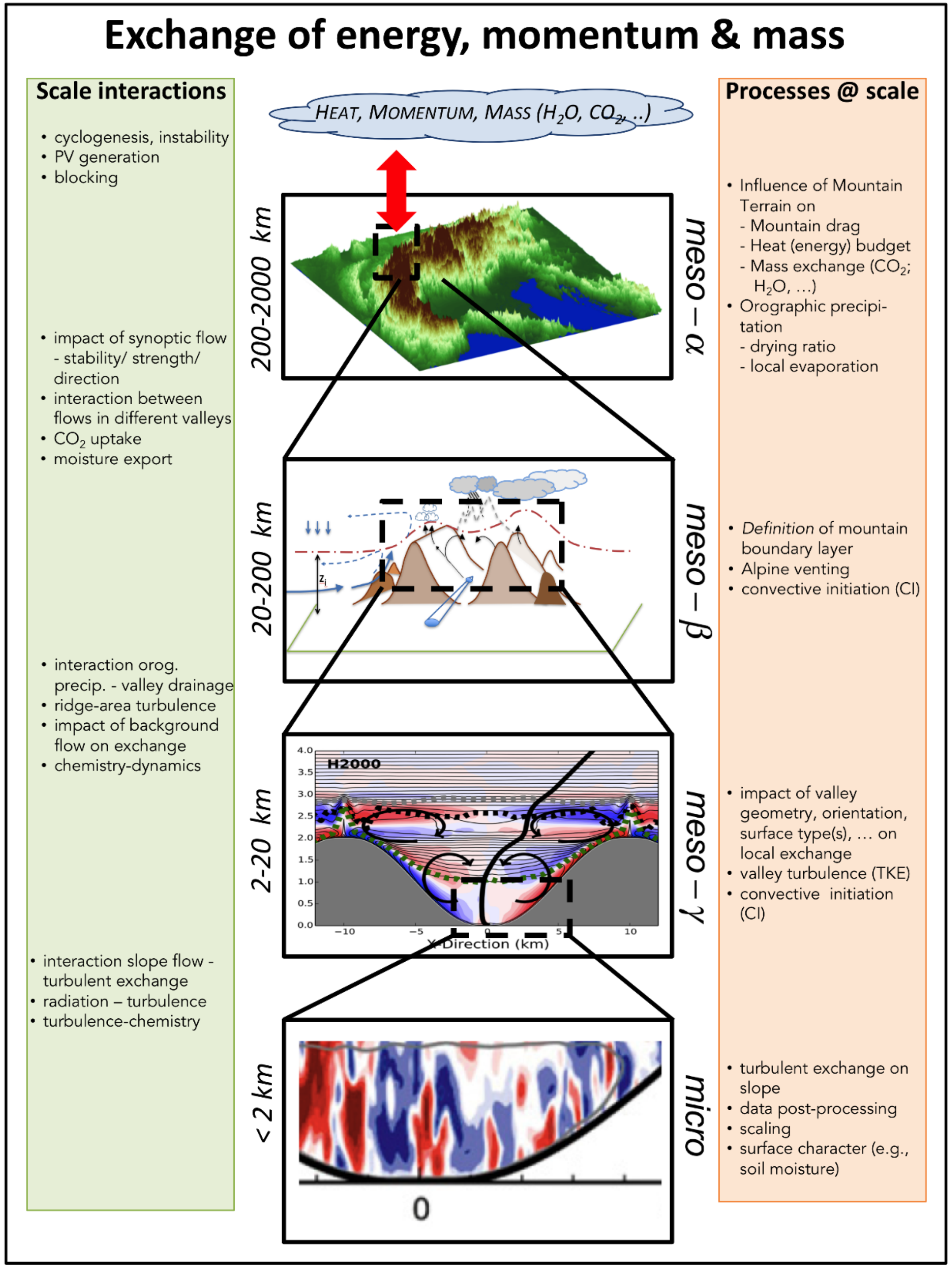
Science Plan

Objective	Primary Focus	Target
Process understanding	Micro- and meso-scale processes within and above the *mountain boundary layer* (MoBL); Interaction between scales.	Quantitative understanding of momentum, energy and mass exchange over mountainous terrain
TEAMx Joint Experiment(s)	Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations over and near mountains	Quality-controlled observational data pool, available for process investigation, high-resolution model verification, parameterization development
Improving Weather and Climate Models	*Models right for the right reason*, i.e., identification and reduction of model biases and uncertainties over complex terrain	Weather forecasts and climate simulations over mountains as good as over flat terrain, and less reliant on model output post-processing
Support to Weather and Climate Service Providers	Air pollution, hydrology, climate change scenarios (e.g., elevation-dependent climate change).	Smaller uncertainty of impact models, due to reduced errors in weather and climate information.

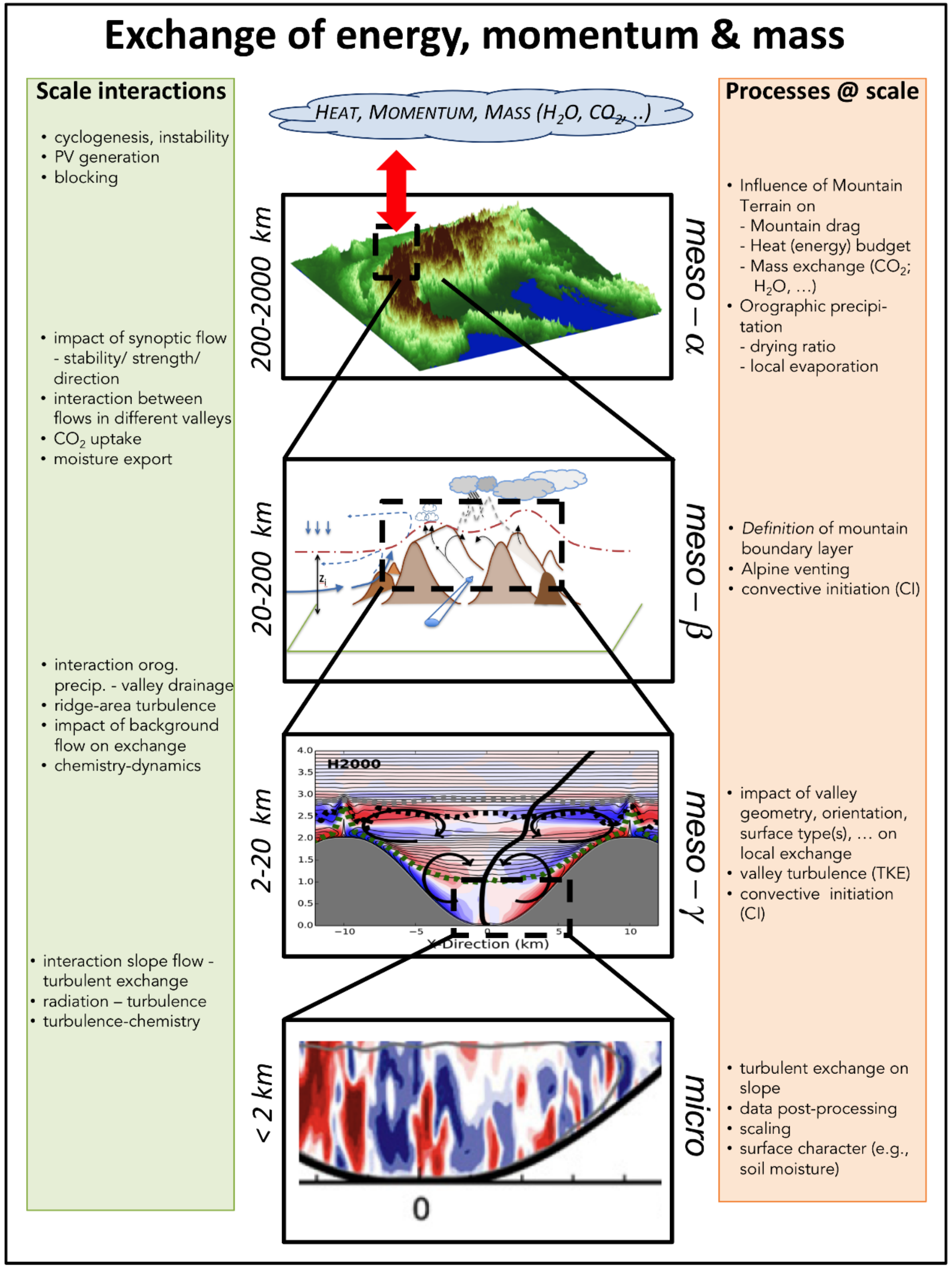


... and their interactions

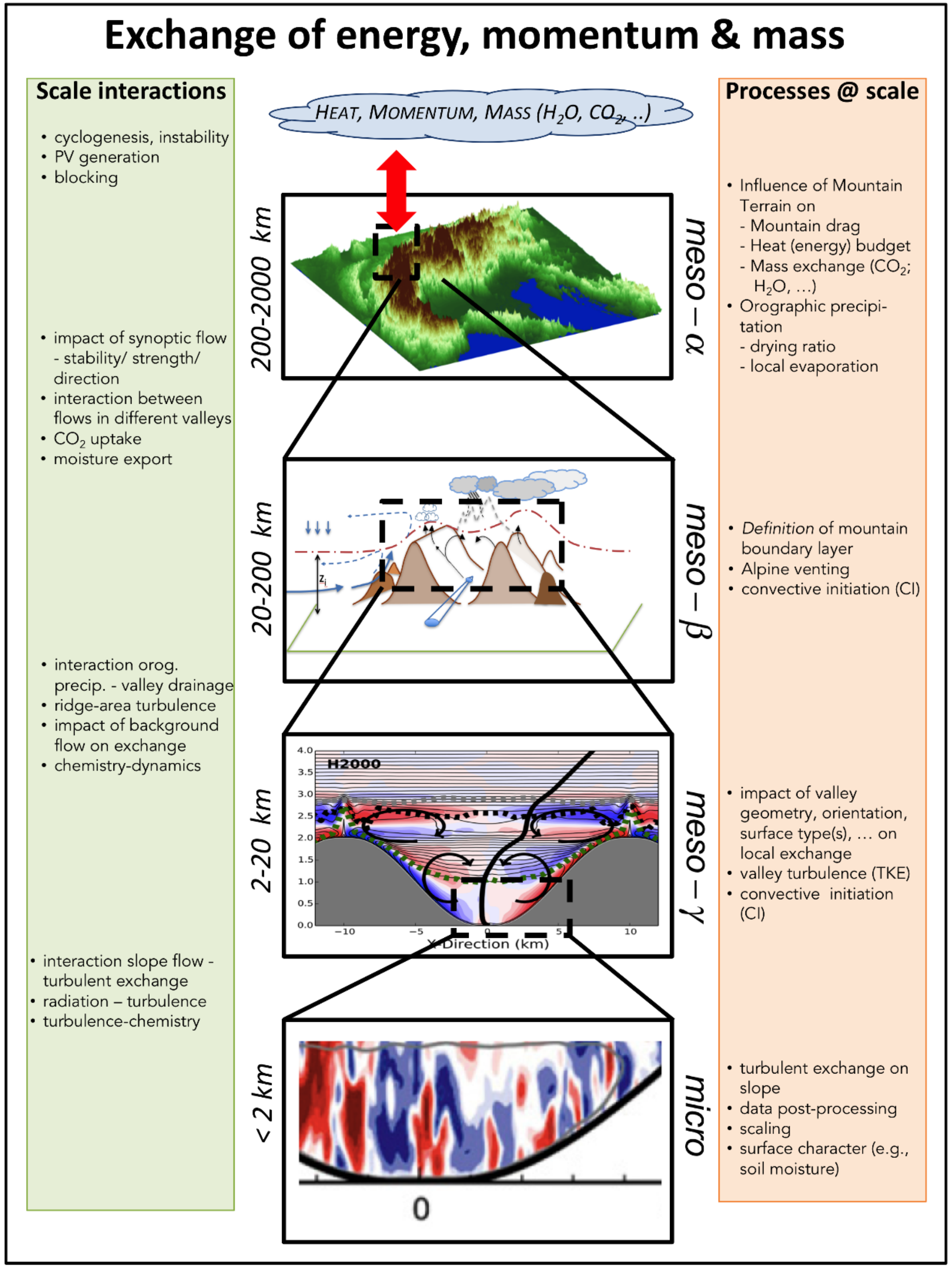
Processes at various spatial scales ...



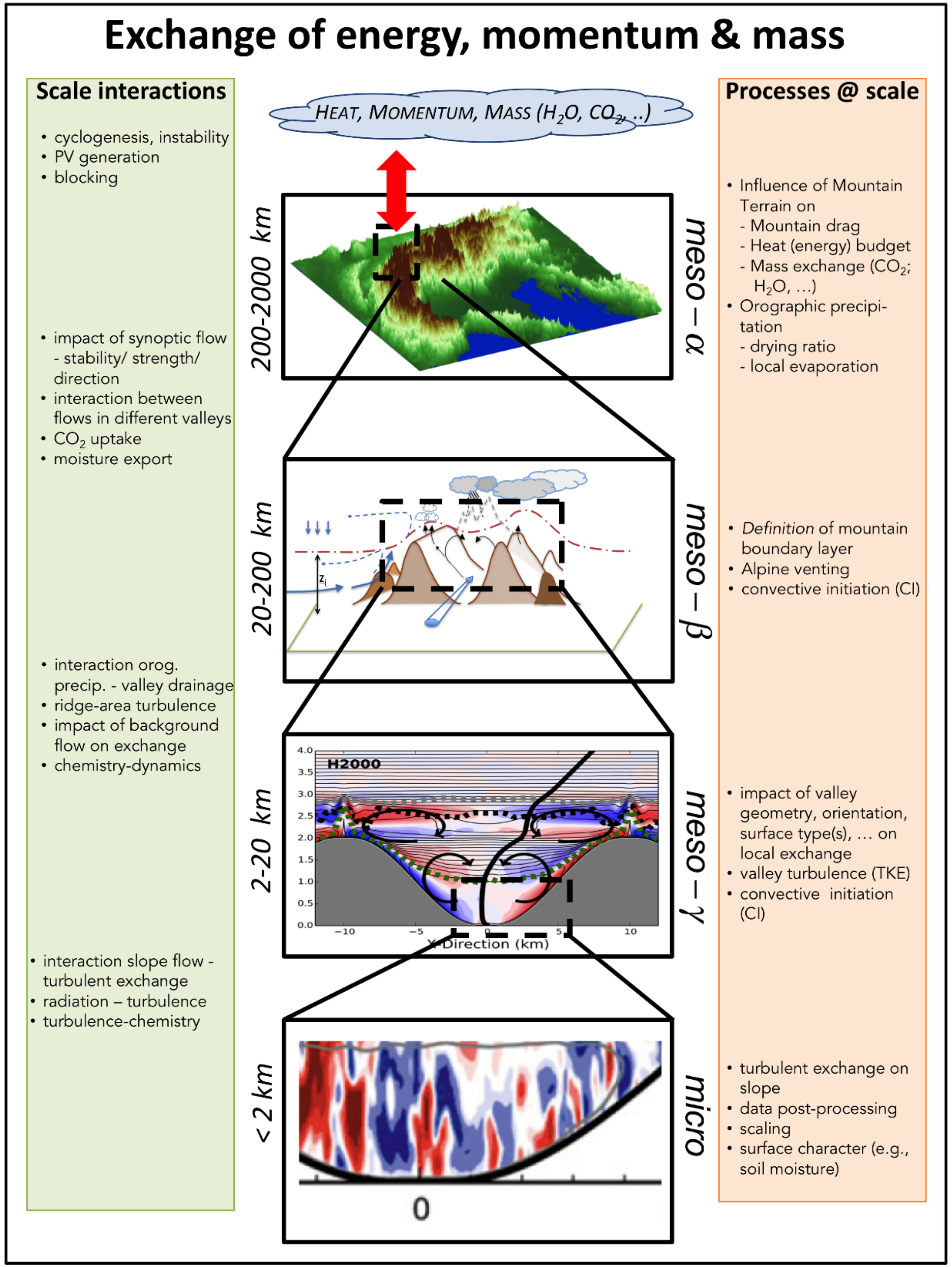
- Influence of mountain terrain on
  - mountain drag
  - heat (energy) budget
  - mass exchange (CO_2; H_2O, …)
- orographic precipitation
  - drying ratio
  - local evaporation



- *Definition* of mountain boundary layer (**MoBL**)
- Alpine venting
- convection initiation (CI)

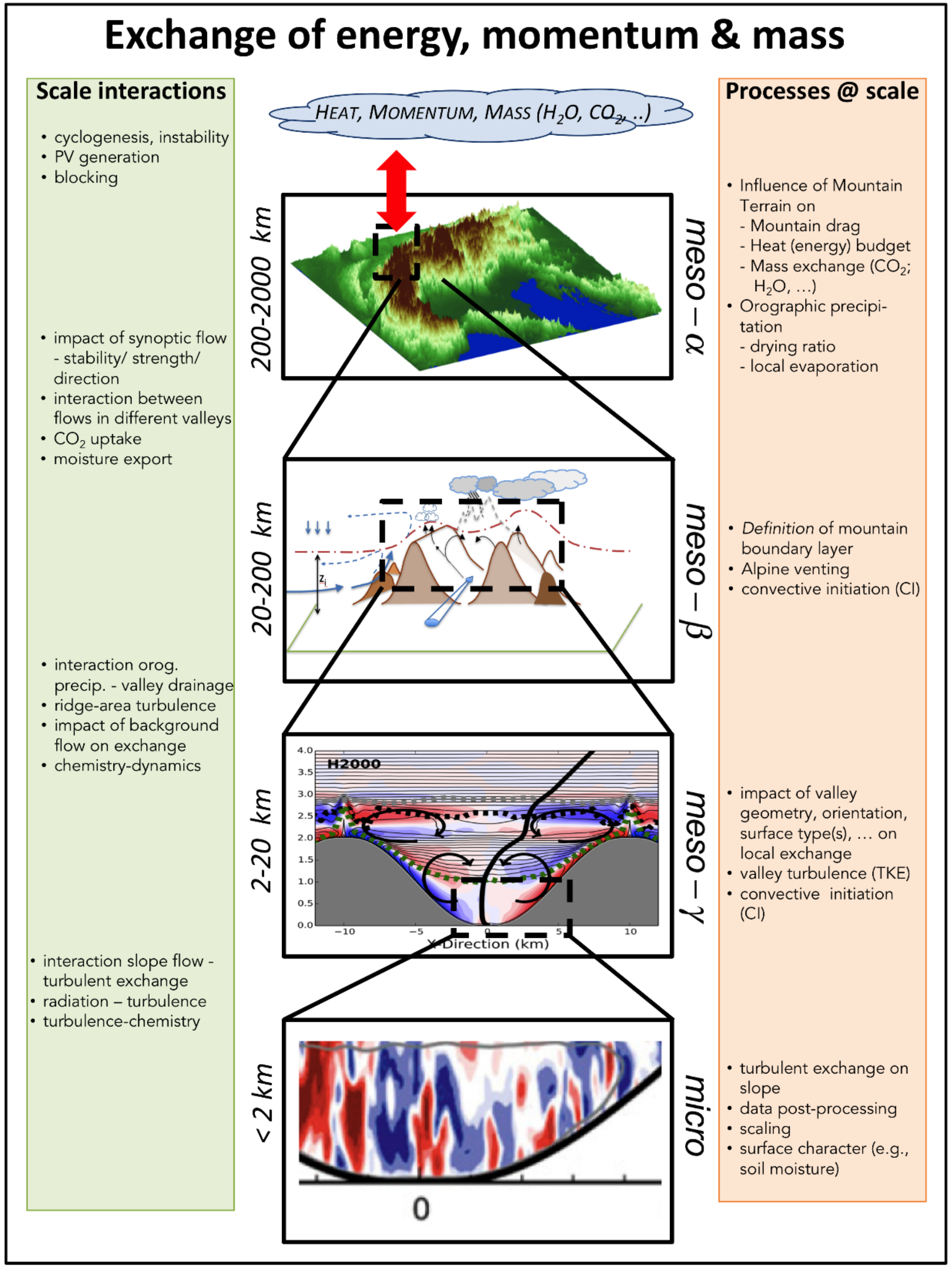


- impact of valley geometry, orientation, surface type(s), … on local exchange
- valley turbulence (TKE)
- convection initiation (CI)

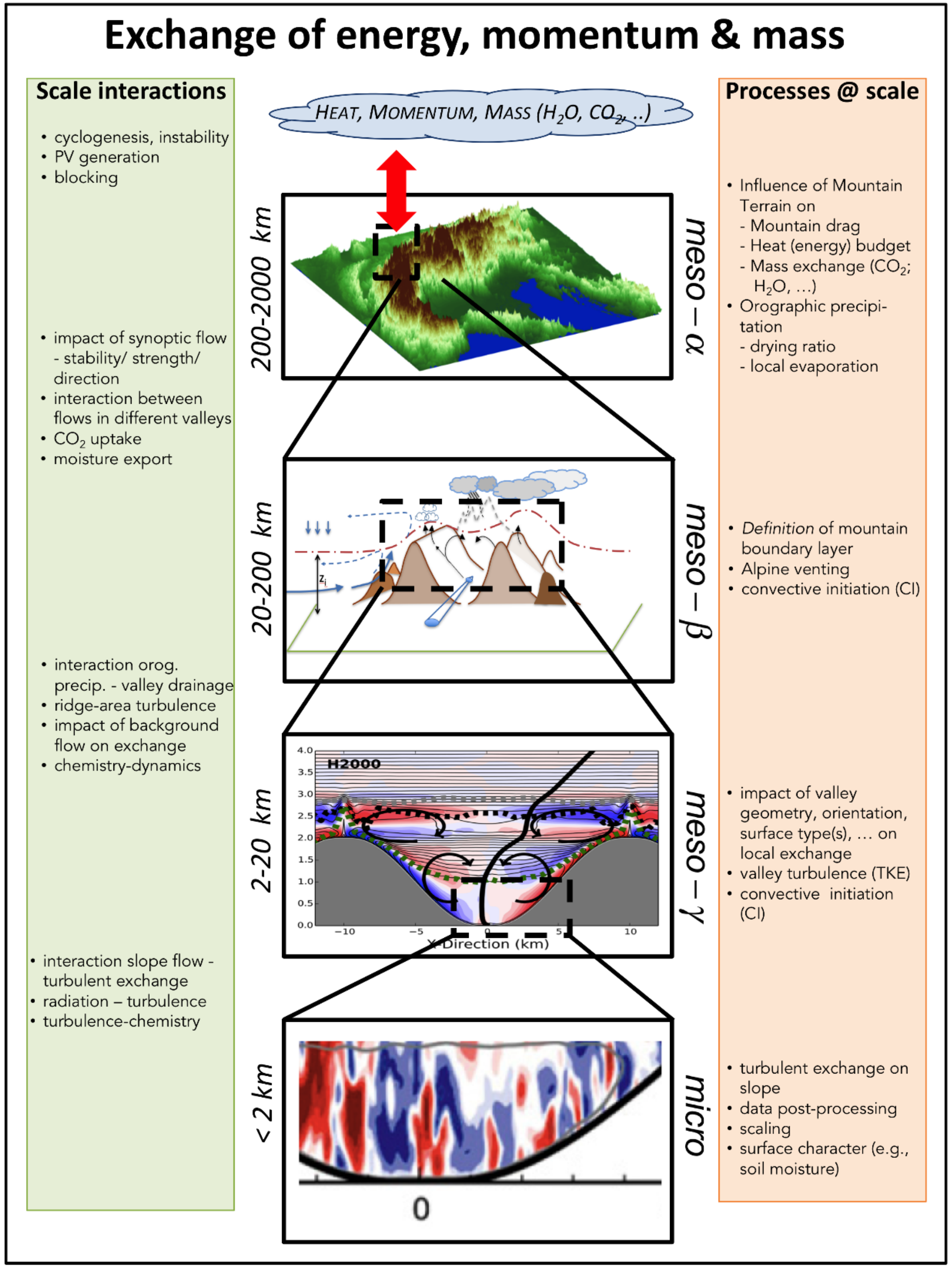


- turbulent exchange on slope
- data post-processing
- scaling
- surface character (e.g., soil moisture)

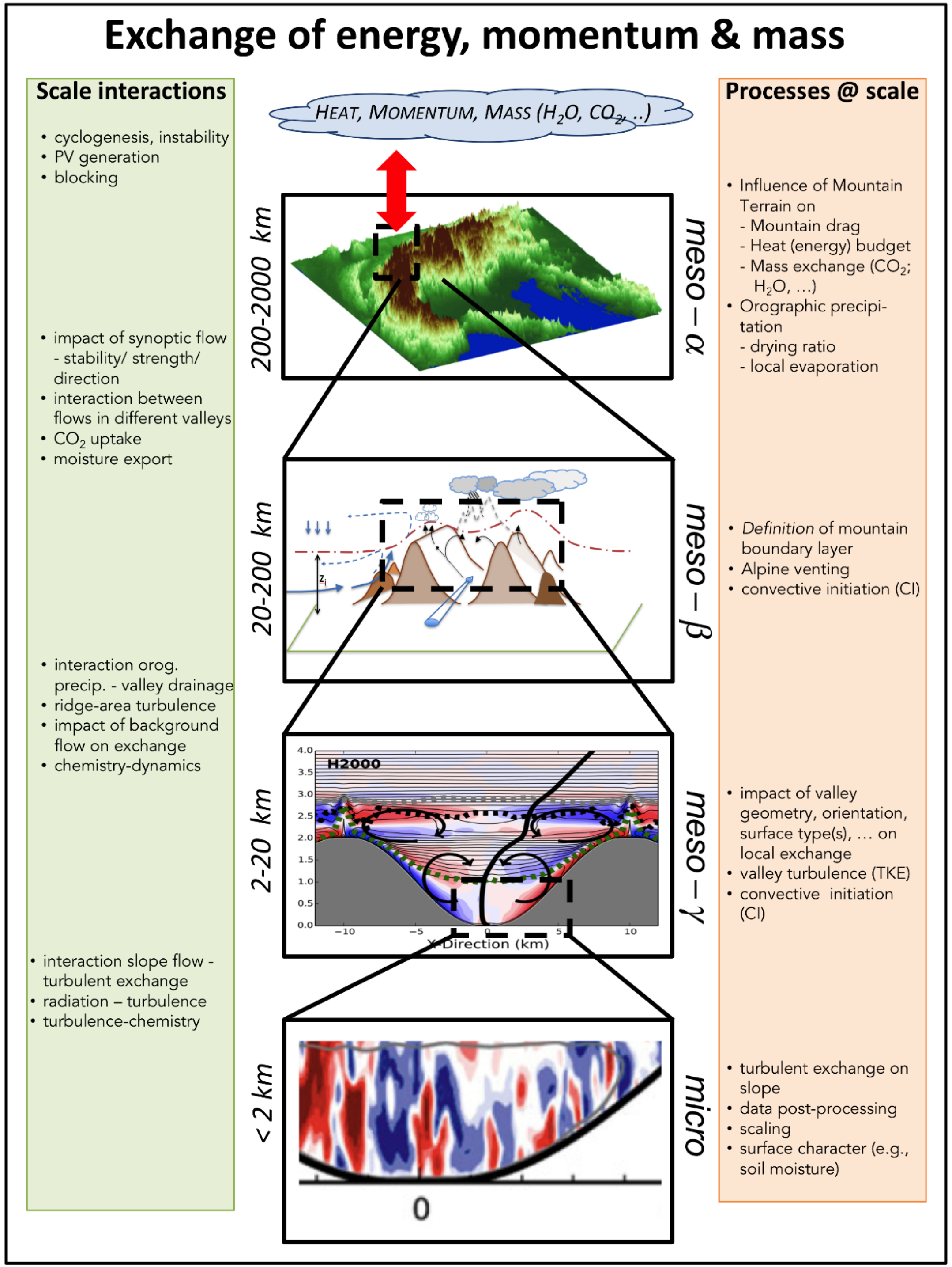
- cyclogenesis, instability
- PV generation
- blocking

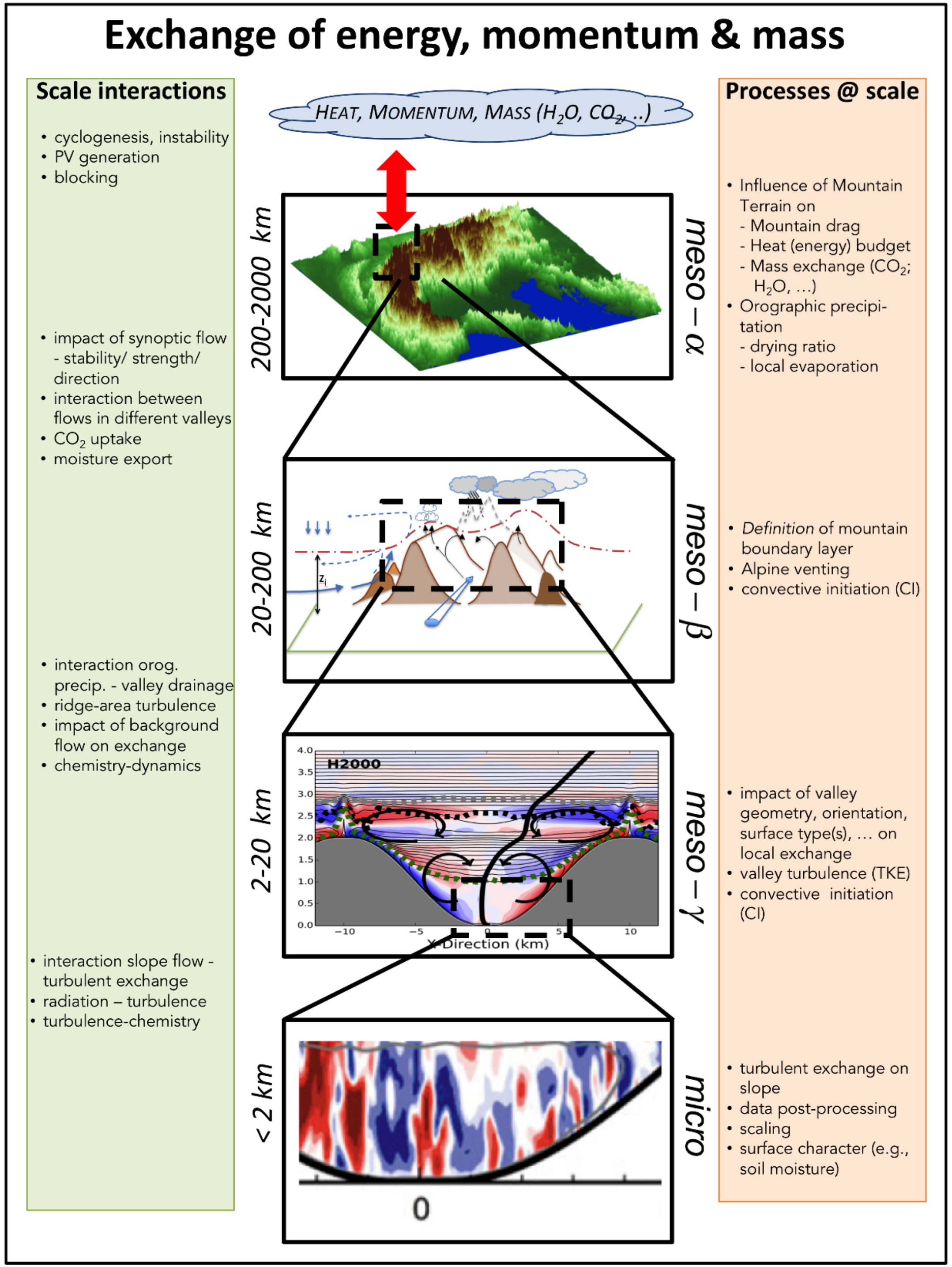


- impact of synoptic flow
  - stability/ strength/ direction
- interaction between flows in different valleys
- CO_2 uptake
- moisture export



- interaction orog. precip. - valley drainage
- ridge-area turbulence
- impact of background flow on exchange
- chemistry-dynamics

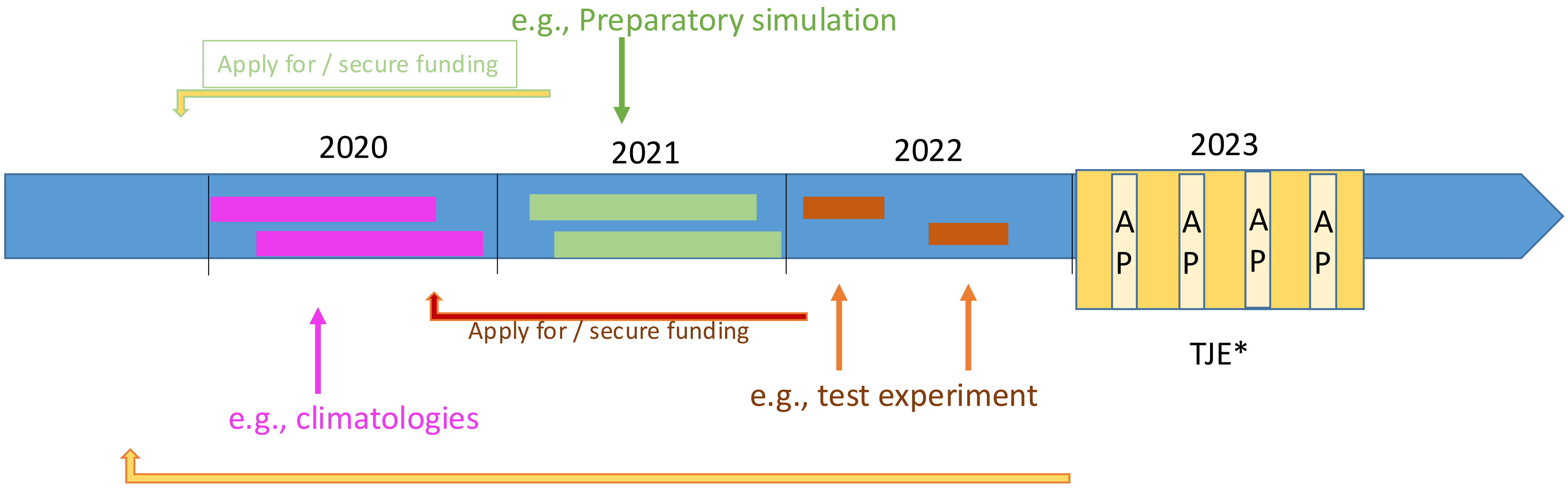




- interaction slope flow - turbulent exchange
- radiation – turbulence
- turbulence-chemistry

When?

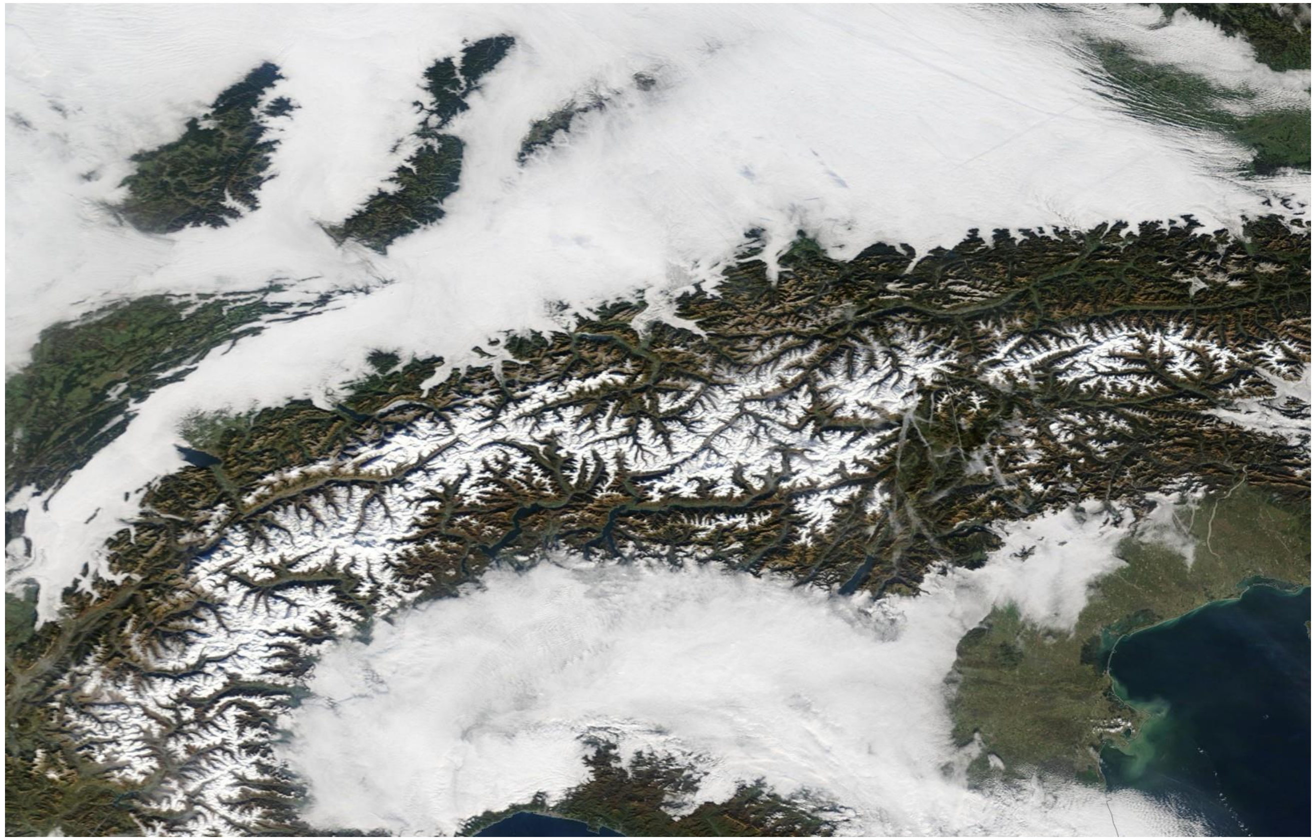
…Towards an intensive field campaign in 2023…



* TEAMx Joint Experiment

Where?

- European Alps
  - Midlatitude region with abundant moisture supply.
  - High spatial heterogeneity in small area.
  - Dense measuerement network.
  - Existing semi-permanent micrometeorological observatories, numerous high-altitude observatories.



Funding

- TEAMx is bottom-up financed.
- While applying for funding, project PIs may request TEAMx “endorsement”. Endorsement implies contributing and accessing to common data pool. Data policy in preparation.
- Projects can be stand-alone, bi- or multi-lateral.
- CIG/PCO supports coordination and initiation of new collaborative projects.
- Two TEAMx projects already running...

ASTER (courtesy of Manuela Lehner)

Atmospheric boundary-layer modeling over complex terrain

Evaluating surface forcing processes *(turbulence parameterizations, land-surface models, and soil and land-use characteristics)* for boundary-layer modeling over complex terrain

WRF model simulations

Idealized simulations:

Quantify the sensitivity of modelled soil, surface, and near-surface parameters to these surface forcing processes.

Real-case simulations: North and South Tyrol

Identify and quantify deficiencies in current representations of these surface forcing processes

Identify those parameters and processes that have a large impact and whose current representation in models is deficient.

Collaborators:

- University of Innsbruck (PI Manuela Lehner)
- University of Trento (PI Lorenzo Giovannini)
- University of Bolzano (PI Massimo Tagliavini)

Project start:

- July 2019

CROSSINN (courtesy of Bianca Adler and Nevio Babic)

KIT
Karlsruher Institut für Technologie

- Cross-valley flow in the Inn Valley investigated by dual-Doppler LiDAR measurements
- Motivation: lack of knowledge of valley-induced circulations and their impacts on exchange of momentum, heat and mass
- Objective: sample the valley atmosphere in a single cross-valley transect with high spatiotemporal resolution
- Innsbruck, Austria – Aug-Oct 2019
- 3 x Doppler LiDAR (Leosphere Windcube), microwave radiometer (HATPRO), i-Box flux towers, DLR Cessna

Possible GEWEX connections

- **GEWEX Process Evaluation Studies, PROES** (shared approach: defining observation-based metrics to understand physical processes and improve models at the fundamental process level).
- **GHP Cross-cutting project INARCH** (The International Network of Alpine Research Catchment Hydrology), due to focus on mountain hydrology and snow.
- **GASS**, due to ongoing activities on surface drag (esp. orographic drag) and momentum transport, in particular the COORDE intercomparison project.
- **GABLS** (GEWEX Atmospheric Boundary Layer Study).

TEAMx and GABLS

- Common approach: Intercomparison between observations, large-eddy simulations and simplified versions of NWP codes.
- GABLS:
  - considered flat/homogenous terrain;
  - dealt primarily with stable boundary layer processes.
- TEAMx:
  - Will have greater focus on daytime, convectively driven exchange.
  - Cannot use single-column model approach due to focus on terrain heterogeneity.
  - Will need to address separately orographic and land-cover complexity.
  - Will need to include models with different grid types (terrain following grids, immersed and embedded boundary methods).

Conclusions

- TEAMx has started: MoU, review papers, workshop.
- Scientific focus on mountain-induced exchange processes. Broad scope including related disciplines such as air chemistry, climate science.
- Combination of field and modelling experiments.
- Plans for field campaign in 2023-2024 in the European Alps.
- Implementation details currently being defined.
- Funding: bottom-up approach, partners fund themselves.
- First two funded projects:
  - CROSSINN (PI Bianca Adler, KIT)
  - ASTER (PI Manuela Lehner, UIBK)

Thank you!

https://worldview.earthdata.nasa.gov

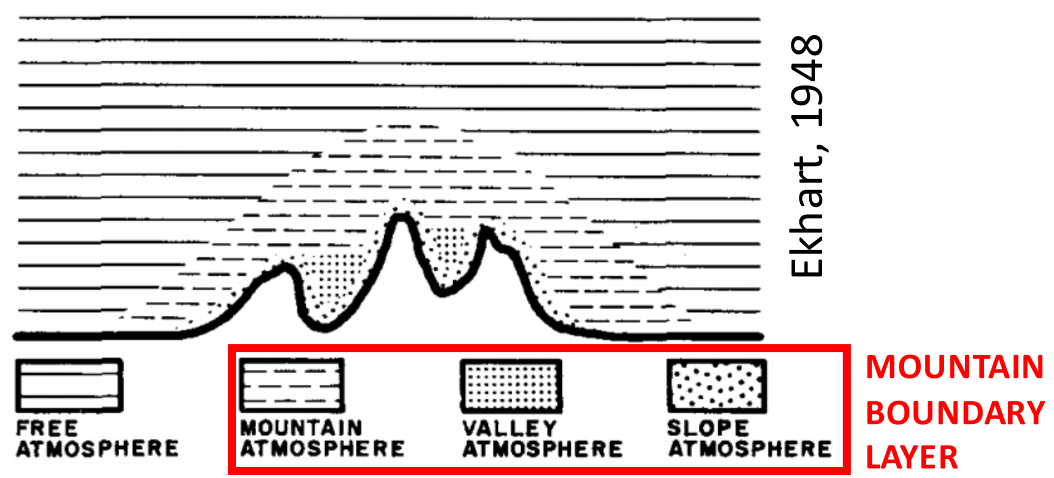


Figure 13: Diagram of the structure of the atmosphere above a mountain range.

1. **Shortcomings of parameterization schemes over mountains**
2. Multi-scale interactions over mountains

Parameterizing exchange processes

- Three examples of gaps between the state-of-the art in parameterizations and the state of knowledge about exchange processes over mountains:
  1. Scaling laws in the surface layer
  2. Planetary boundary layer
  3. Orographic drag

Example 1: MOST scaling laws

How parameterizations work

- SL parameterizations assume that the first model level lies within the constant-flux layer.
- Under this assumption, *surface* fluxes are estimated from model-level variables using bulk transfer relationships.
- Bulk transfer coefficients include adiabatic corrections, based on MOST (Ψ, $\zeta = z/L$).

$$\overline{u'w'}_s = -C_d u_1 U_1$$
$$\overline{v'w'}_s = -C_d v_1 U_1$$
$$\overline{w'T'}_s = -C_h U_1 (T_1 - T_s)$$

$$C_d = k^2 \left[\log\left(\frac{z_1}{z_0}\right) - \Psi_m\left(\frac{z_1}{L}\right) \right]^{-2}$$
$$C_h = k^2 \left[\log\left(\frac{z_1}{z_0}\right) - \Psi_m\left(\frac{z_1}{L}\right) \right]^{-1} \left[\log\left(\frac{z_1}{z_0}\right) - \Psi_h\left(\frac{z_1}{L}\right) \right]^{-1}$$

Example 1: MOST scaling laws

What we know

- Over slopes, turbulent fluxes may change considerably with height above ground.
- Even using *local* scaling, flux-profile relationships are often reported to match observed fluxes and gradients very poorly over complex terrain.
- The example refers to a steep mountain slope.

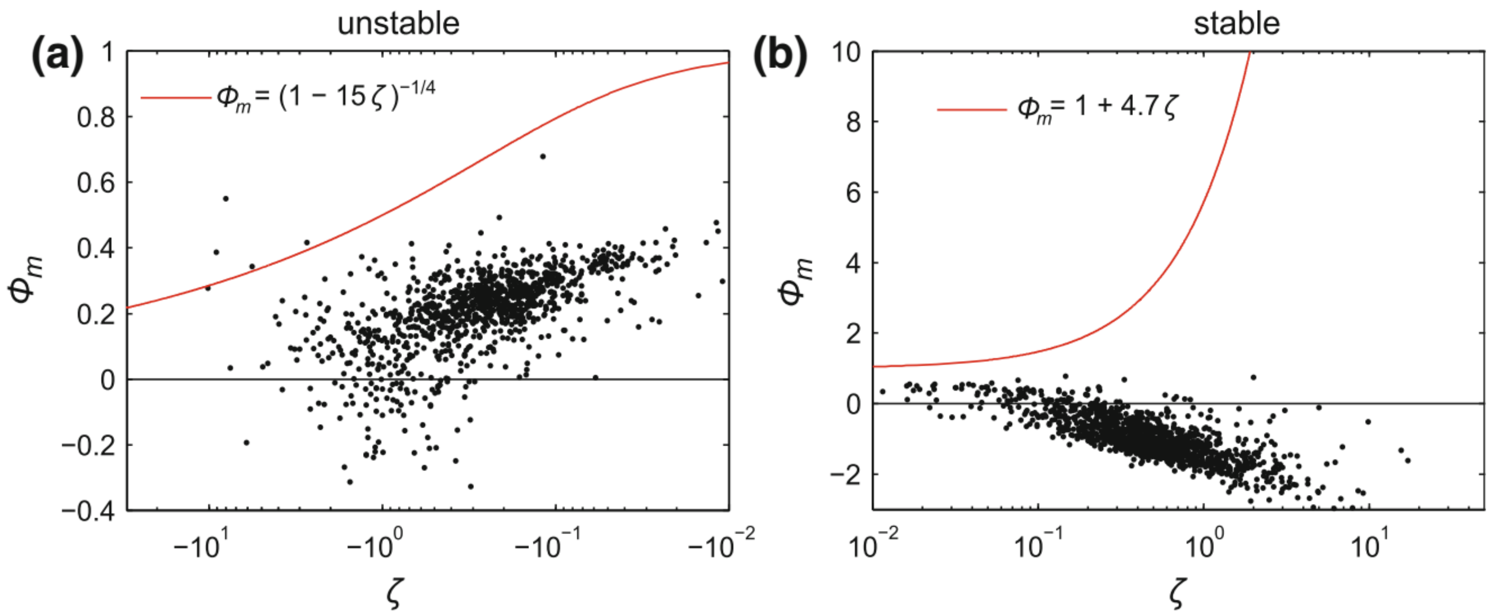


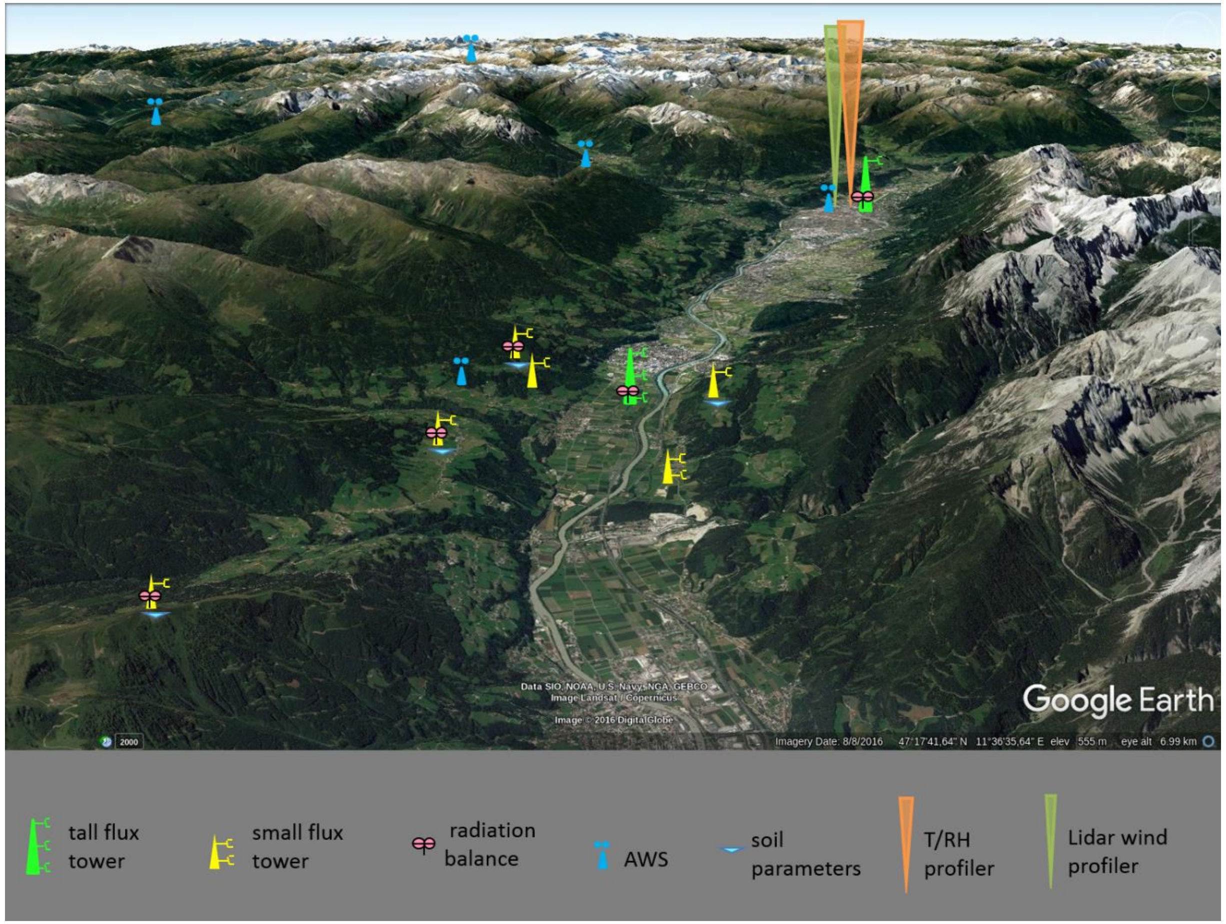
Fig. 10 Dimensionless wind shear ϕ_m for **a** $\zeta < 0$ and **b** $\zeta > 0$ at site T2, 1.5 m normal to the surface. The *solid red lines* represent the Businger–Dyer flux–profile relationships determined over flat and homogeneous surfaces (Businger et al. 1971; Dyer 1974)

Nadeau et al (2013)

Example 1: MOST scaling laws

TEAMx plan

- Observation of the components of the surface energy budget for extended periods in distributed observatories (e.g., i-Box).
- Fundamental investigations on turbulence properties in the atmosphere over complex terrain (e.g., anisotropy, generalization of scaling laws).
- Systematic evaluation of SL parameterization over complex terrain.



2011 – ongoing

Example 1: MOST scaling laws

TEAMx plan

- Observation of the components of the surface energy budget for extended periods in distributed observatories (e.g., i-Box).
- Fundamental investigations on turbulence properties in the atmosphere over complex terrain (e.g., anisotropy, generalization of scaling laws).
- Systematic evaluation of SL parameterization over complex terrain.

2011 – ongoing

Example 2: PBL structure

Troen and Mahrt (1986)

How parameterizations work

- Regardless of the closure type (K-profile or TKE-based), the BL height (z_i) is a key parameter in determining the eddy transfer coefficients.
- z_i is determined in a variety of ways (e.g., gradient or Ri_b methods).
- PBL closures are often 1D (they only model vertical exchange).

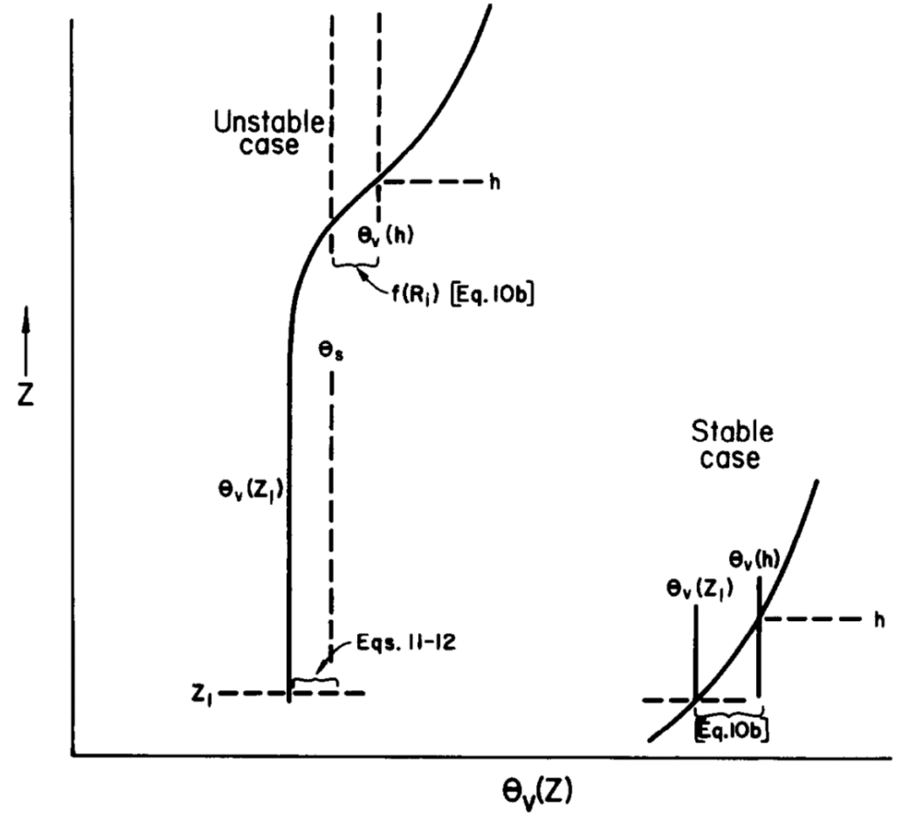


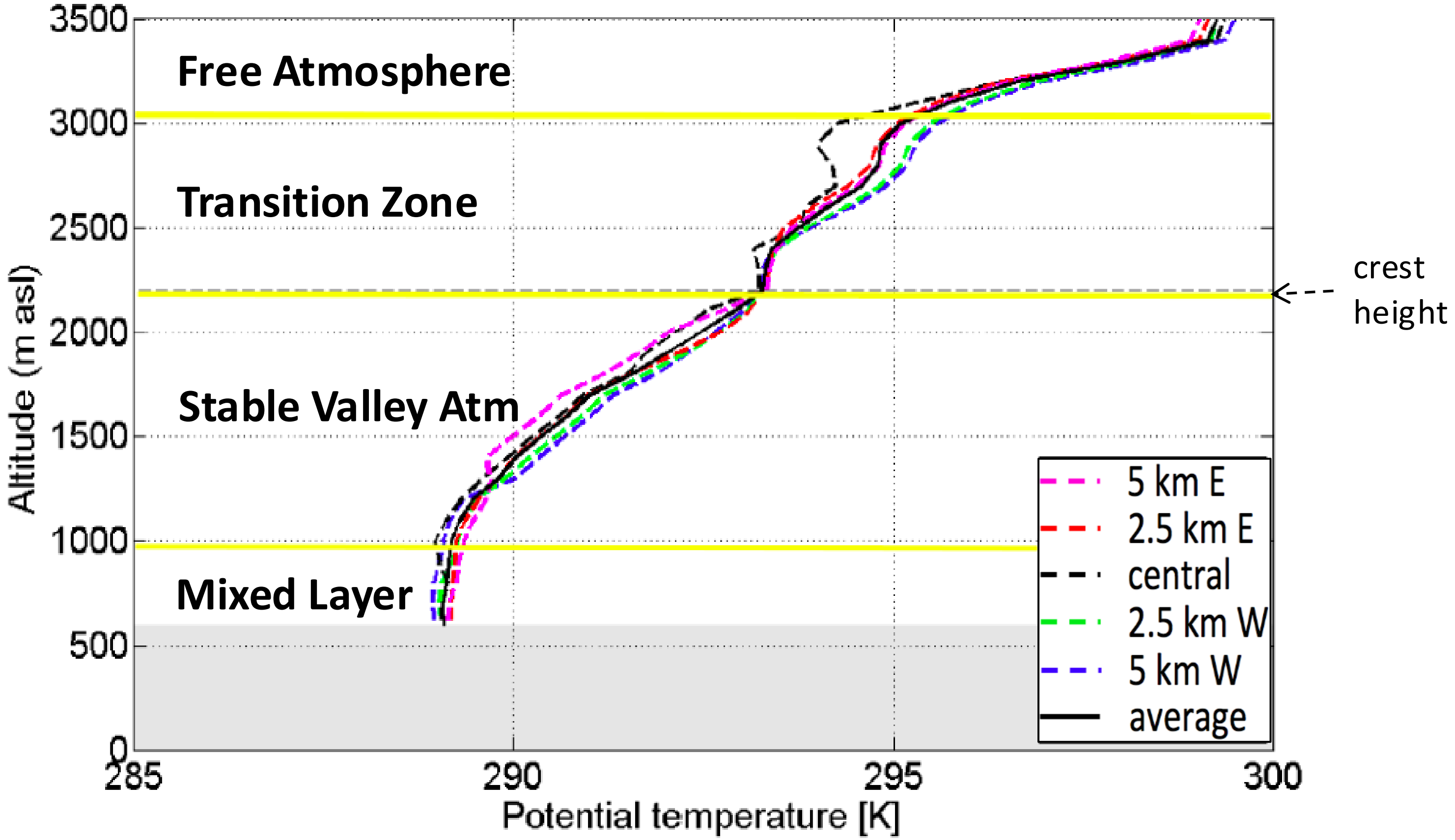
Fig. 1. Geometric sketch of the boundary-layer depth relationship to the profile of potential temperature above the surface layer (solid profile). For the unstable case, the first vertical broken line to the right of the profile indicates the potential temperature after enhancement due to the temperature excess associated with surface heating (11–12). The vertical broken line on the right indicates the potential temperature at the boundary-layer top after deepening due to shear-generated mixing as formulated in terms of a modified bulk Richardson number (10b). The latter mechanism completely determines the depth of the stable boundary layer.

Example 2: PBL structure

What we know

- The vertical structure of the MBL is more complex than that of the CBL (evidence from both *observations* and numerical modelling).
- Different ways to estimate z_i perform very differently over complex terrain.
- Horizontal exchange is important over complex terrain.

Markl et al (2017)



Wagner et al (2015)

Example 2: PBL structure

What we know

- The vertical structure of the MBL is more complex than that of the CBL (evidence from both observations and *numerical modelling*).
- Different ways to estimate z_i perform very differently over complex terrain.
- Horizontal exchange is important over complex terrain.

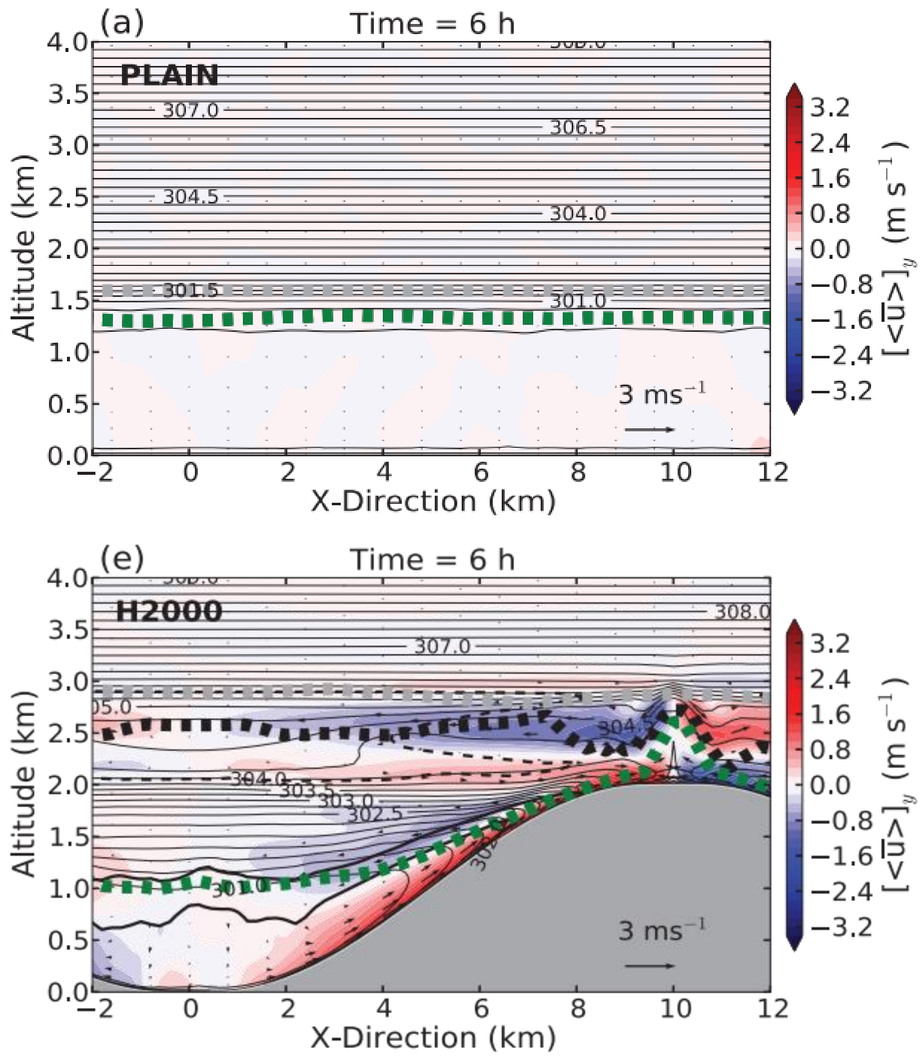


Figure 4. (a)–(e) Cross-sections of potential temperature (thin contour lines), cross-valley (colour shading) and along-valley wind speed (thick contour lines, negative values dashed, interval 1.0 m s^{-1}, the zero line is not shown) averaged between $y = 5$ and $y = 15$ km after 6 h of simulation. Boundary-layer heights PBL1, PBL2 and PBL3 are plotted with thick dashed green, black and grey lines, respectively.

Example 2: PBL structure

What we know

- The vertical structure of the MBL is more complex than that of the CBL (evidence from both observations and numerical modelling).
- Different ways to estimate z_i perform very differently over complex terrain.
- Horizontal exchange is important over complex terrain.

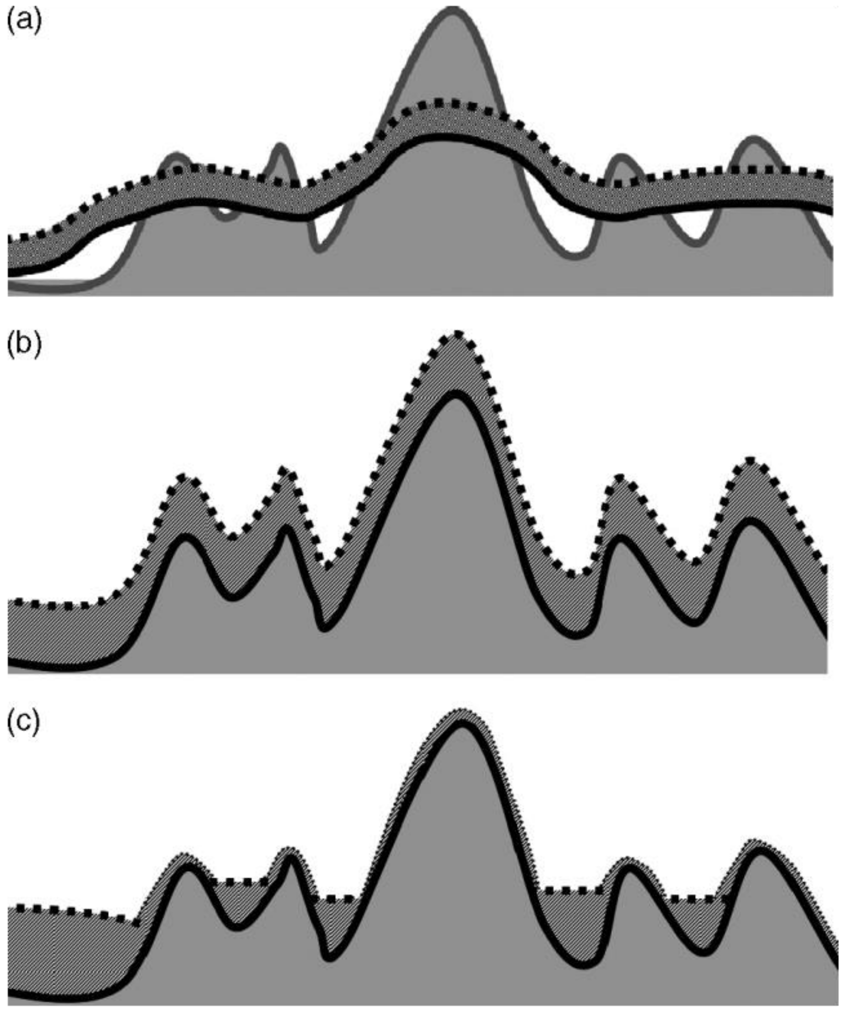
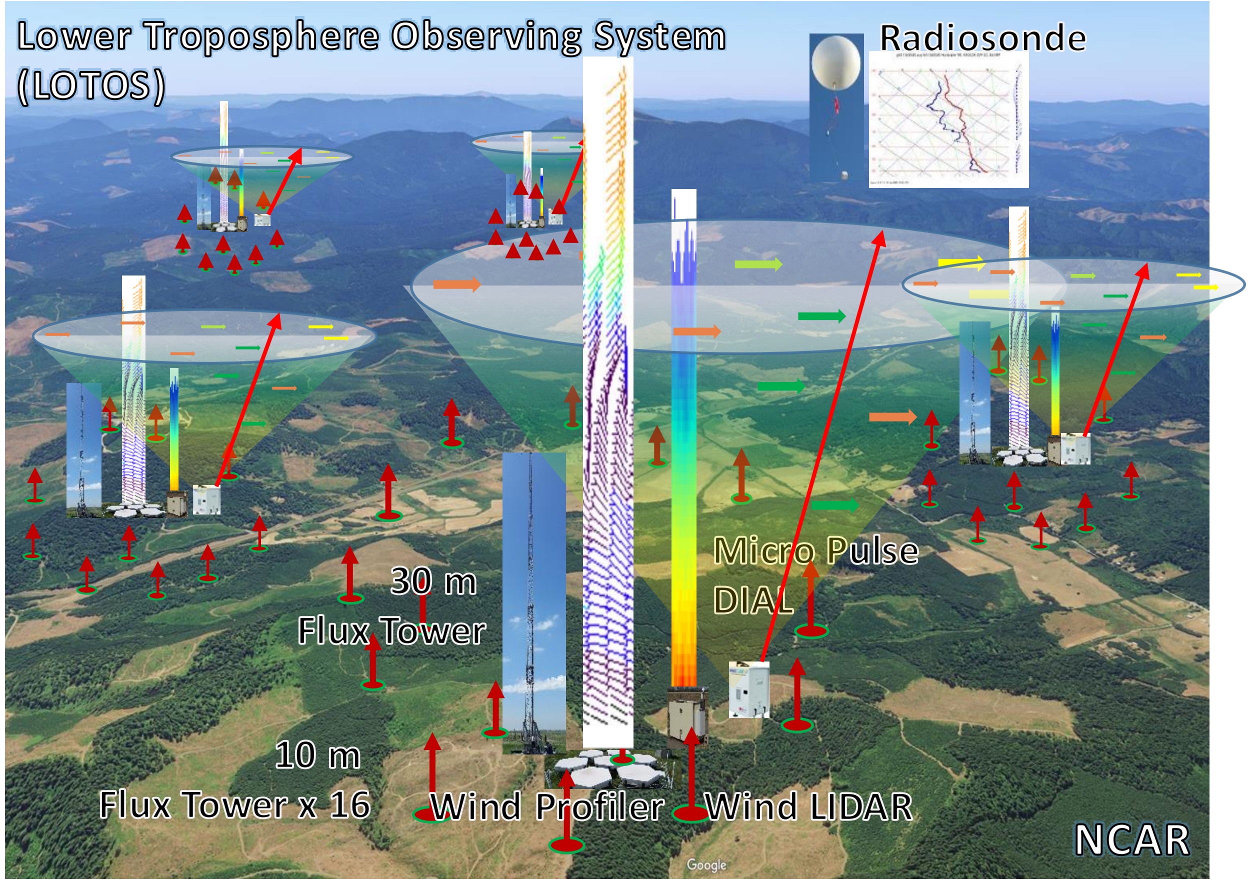


Figure 5. Schematic representation of the boundary layer in (a) a low-resolution numerical model, (b) a high-resolution operational numerical model, and (c) the turbulent boundary layer as found from different MAP boundary-layer studies.

Example 2: PBL structure

TEAMx plan

- Comprehensive measurements of the MoBL: ground-based remote sensing to map 3D kinematic and thermodynamic structure and fluxes within PBL over valleys/mountains (flux towers+remote sensors; e.g. Doppler wind and Raman lidars, wind profilers). Possible use of light aircraft or UAVs for gap-filling measurements over wide areas.
- Systematic evaluation of PBL parameterization over complex terrain.
- Testing recent advances in numerics (e.g. immersed- and embedded-boundary methods to represent orography).



Example 3: Orographic drag

How parameterizations work

- Two components: blocked-flow drag and gravity-wave drag.
- Both are estimated from vertically-averaged values of U, N and ρ, e.g. in the layer between σ and 2σ (of the SGS orography).
- Consequence: orographic drag parameterizations are unaware of low-level wind shear and inversion layers.

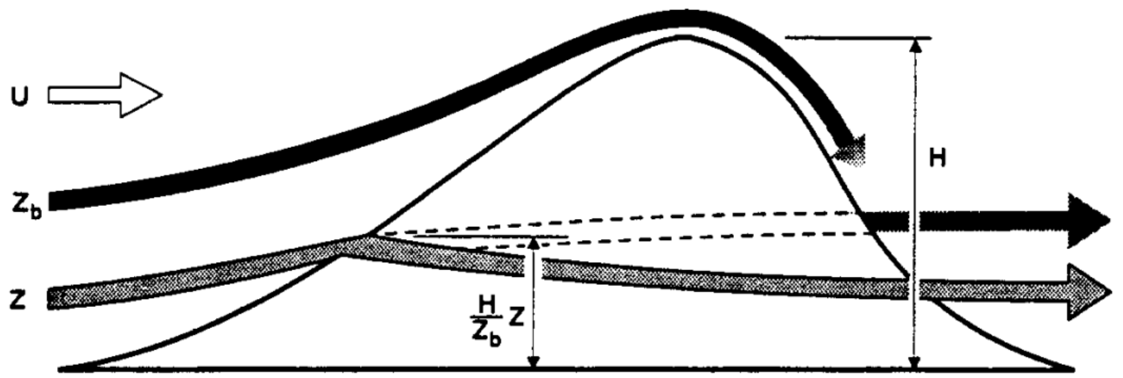


Figure 1. Schematic representation of the low-level flow behaviour parametrized in the new scheme (see text for details.

Lott and Miller (1997)

Example 3: Orographic drag

Teixeira (2014)

What we know

- Vertical variation of wind and stability in mountain flows can lead to a rich variety of flow realizations.
- Drag is not only affected by terrain anisotropy but also by vertical wind shear, presence of total and partial critical levels, vertical wave reflection and resonance, and non-hydrostatic effects such as trapped lee waves.

TEAMx plan

- Extend theory and parameterization of orographic drag to complex flows.

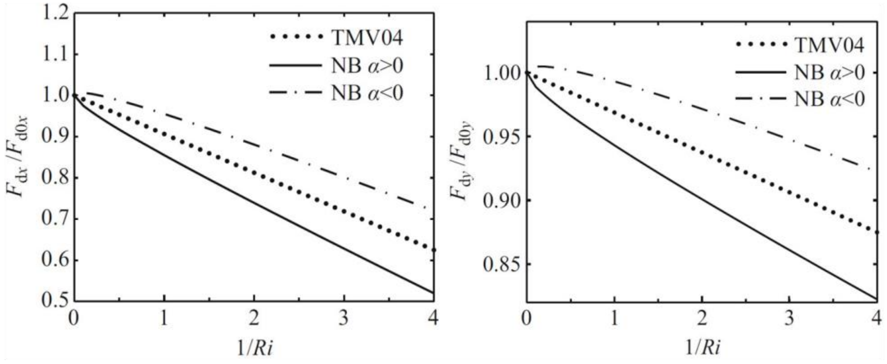


FIGURE 4 | Normalized *x* (left) and *y* (right) components of the drag as a function of *Ri* for the wind profile (45). The solid and dash-dotted lines correspond to non-Boussinesq calculations (with different signs of α – see legend), and the dotted line is the original Boussinesq result (46). Reproduced from Figure 1 of Tang et al. [69] with kind permission from Springer Science and Business Media.

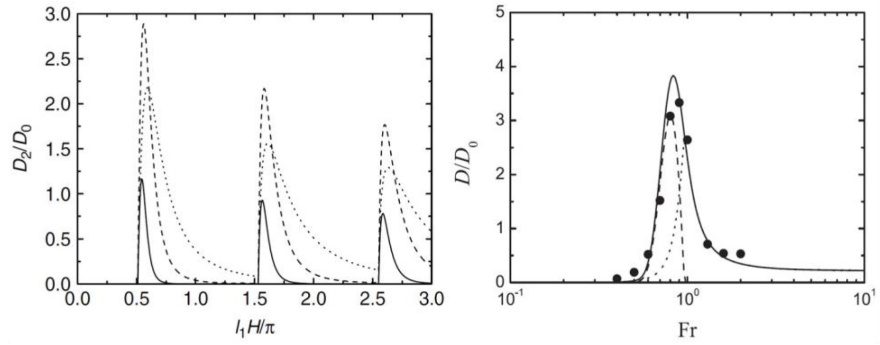


FIGURE 11 | Left: trapped lee wave drag (here denoted by D_2) normalized by (30) as a function of $l_1 H/\pi$. Solid line: $l_1 a = 10$, dashed line: $l_1 a = 5$, dotted line: $l_1 a = 2$. Reproduced from Figure 6 of Teixeira et al. [111]. Copyright © 2012 Royal Meteorological Society. **Right:** Drag normalized by (30) as a function of Fr for $l_2 H = 0.5$ and $l_2 a = 1$. Solid line: total drag, dotted line: internal gravity wave drag, dashed line: trapped lee wave drag, all from theory; symbols: numerical simulations. Reproduced from Figure 9 of Teixeira et al. [112]. © American Meteorological Society. Used with permission.

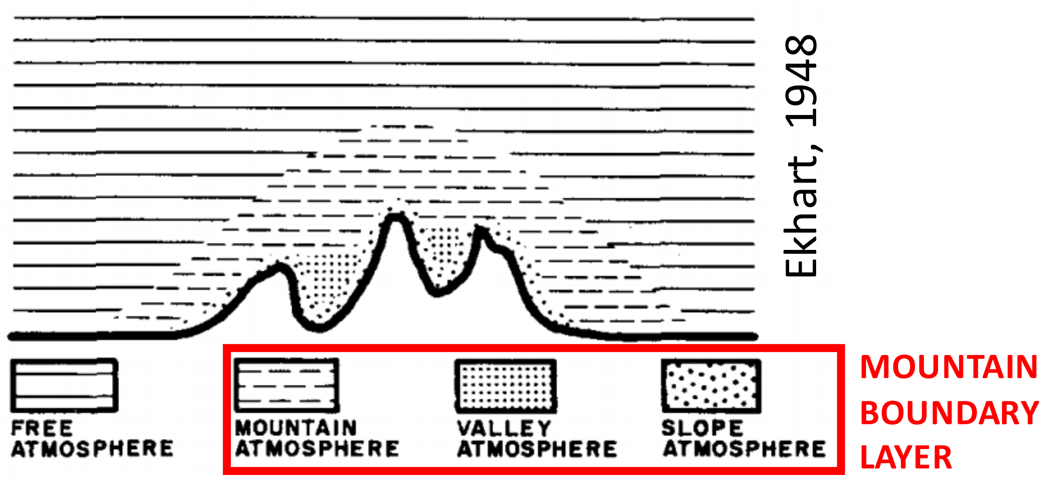
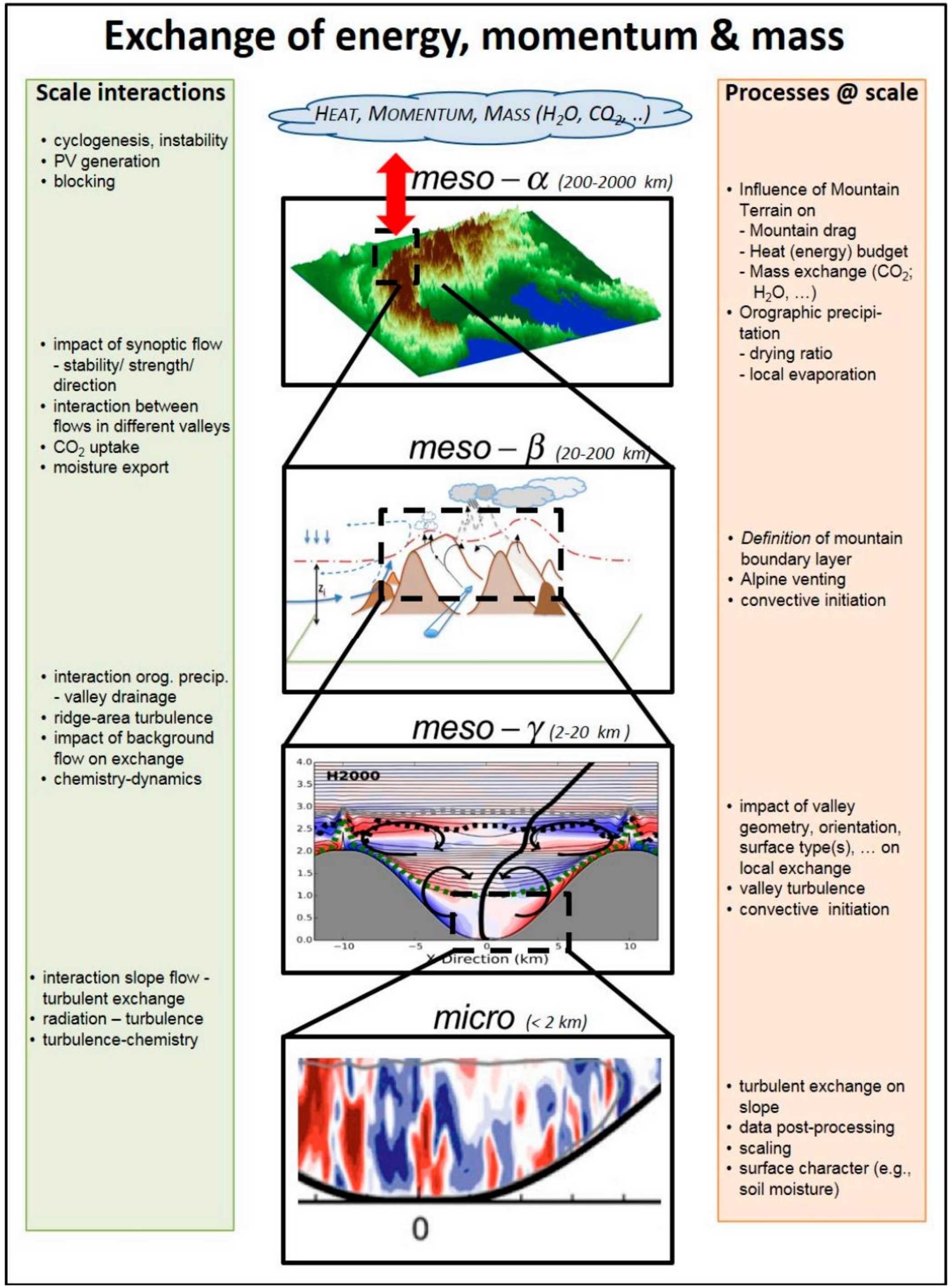


Figure 13: Diagram of the structure of the atmosphere above a mountain range.

1. Shortcomings of parameterization schemes over mountains
2. **Multi-scale interactions over mountains**

Multi-scale interactions

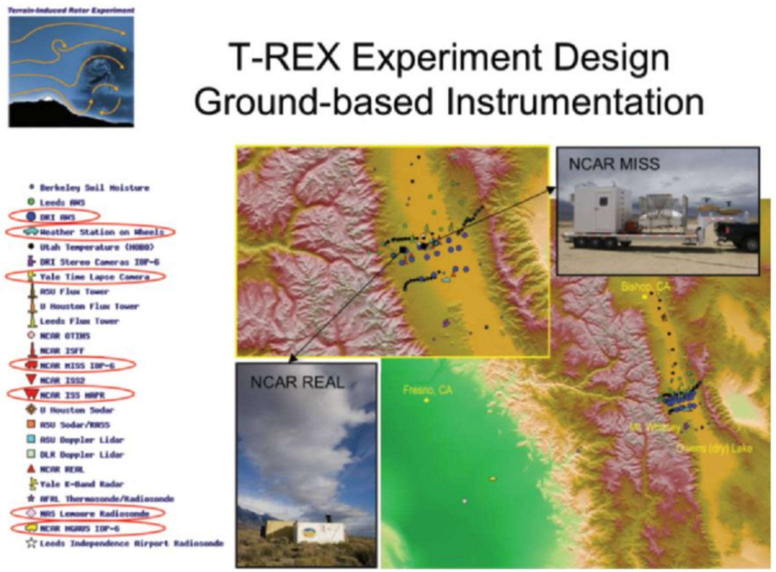
- Orographically-induced circulations (breezes, foehn, cold-air pooling etc.) span a wide range of temporal and spatial scales.
- Spatial scales from meso-α to micro.
- Processes and their interactions are complex and often strongly non-linear. Small differences in initial or boundary conditions may cause very different response.



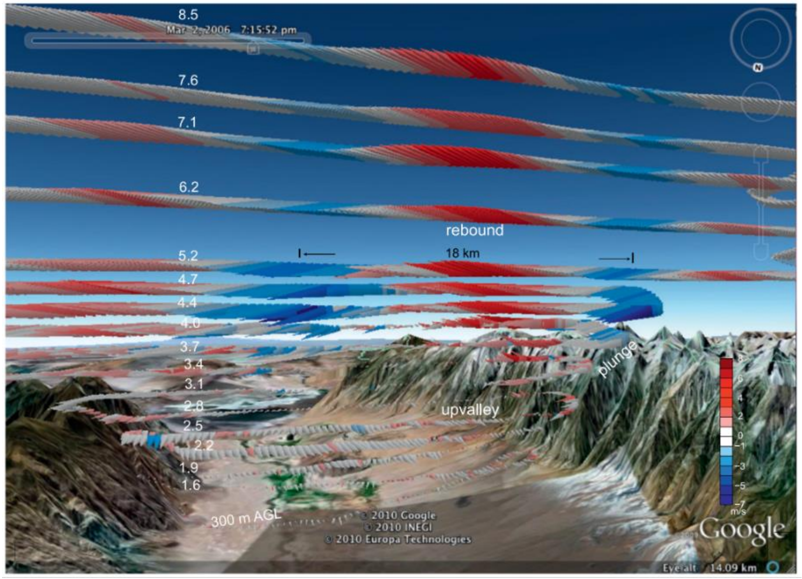
Lehner and Rotach (2018)

Example: a T-REX event

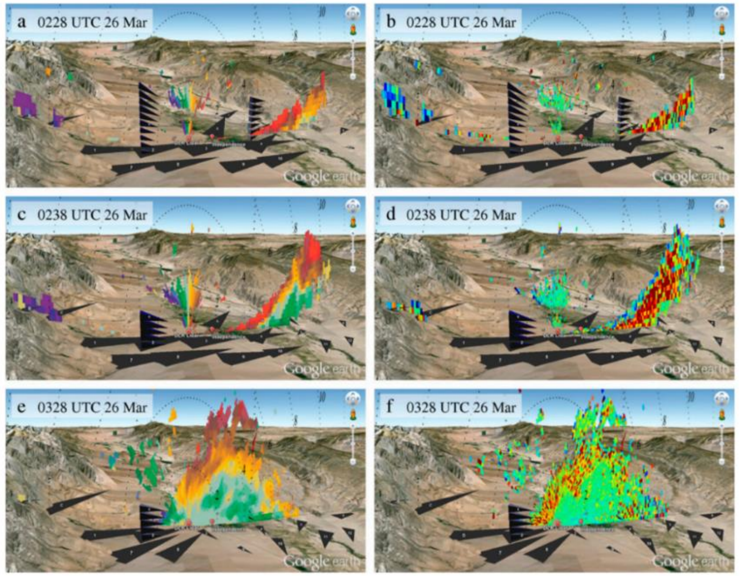
- T-Rex field phase in March-April 2006, Owens Valley (California).
- Major focus: Atmospheric rotors.



Grubišić et al. (2008)

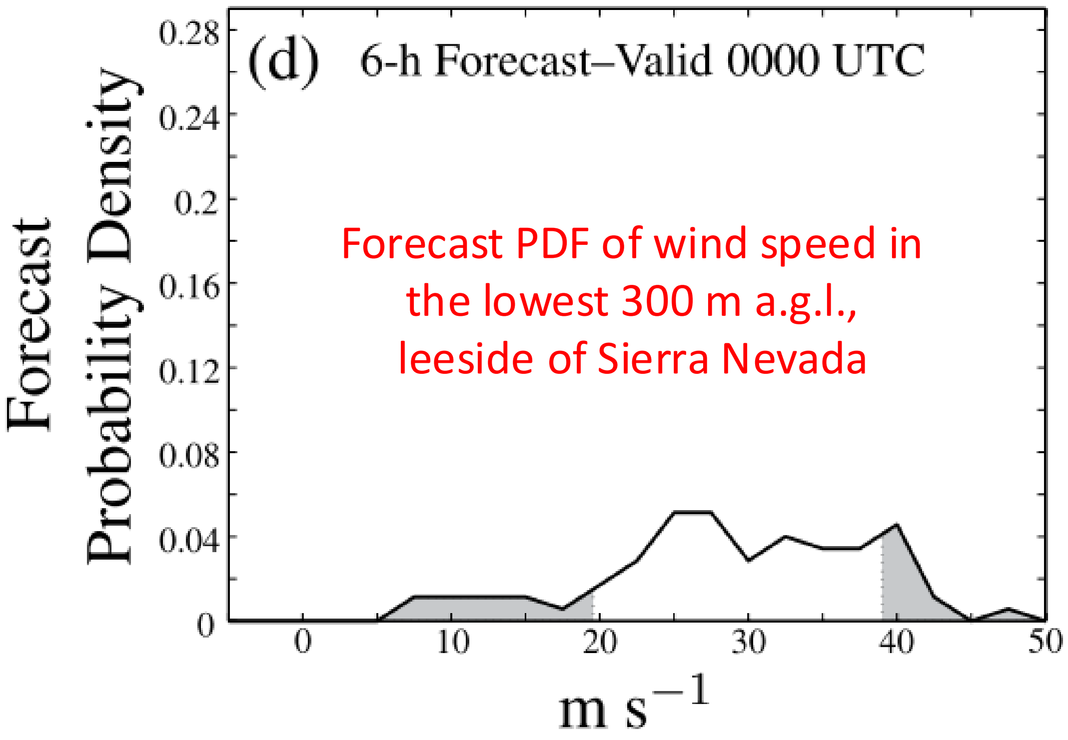


Mayr and Armi (2010)

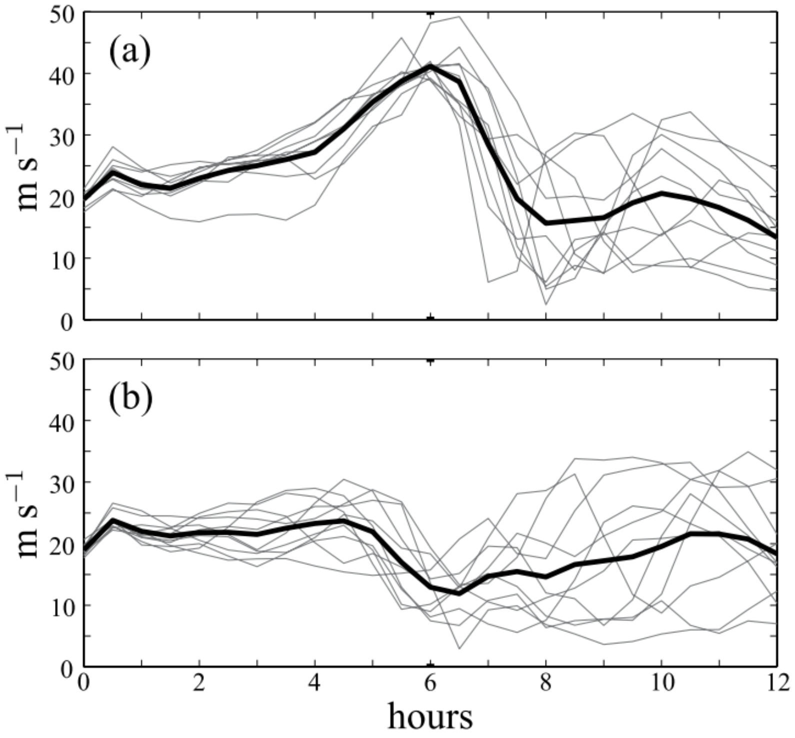


Strauss et al. (2016)

Multi-scale interactions in orographic flows



Forecast PDF of wind speed in the lowest 300 m a.g.l., leeside of Sierra Nevada



10 strongest members

10 weakest members

FIG. 7. The evolution of the zonal wind averaged over the Owens Valley metric box during the IOP 6 simulation for the (a) 10 strongest and (b) 10 weakest ensemble members. The thick line shows the mean of each 10-member subset.

Reinecke and Durran (2009)

Multi-scale interactions in orographic flows

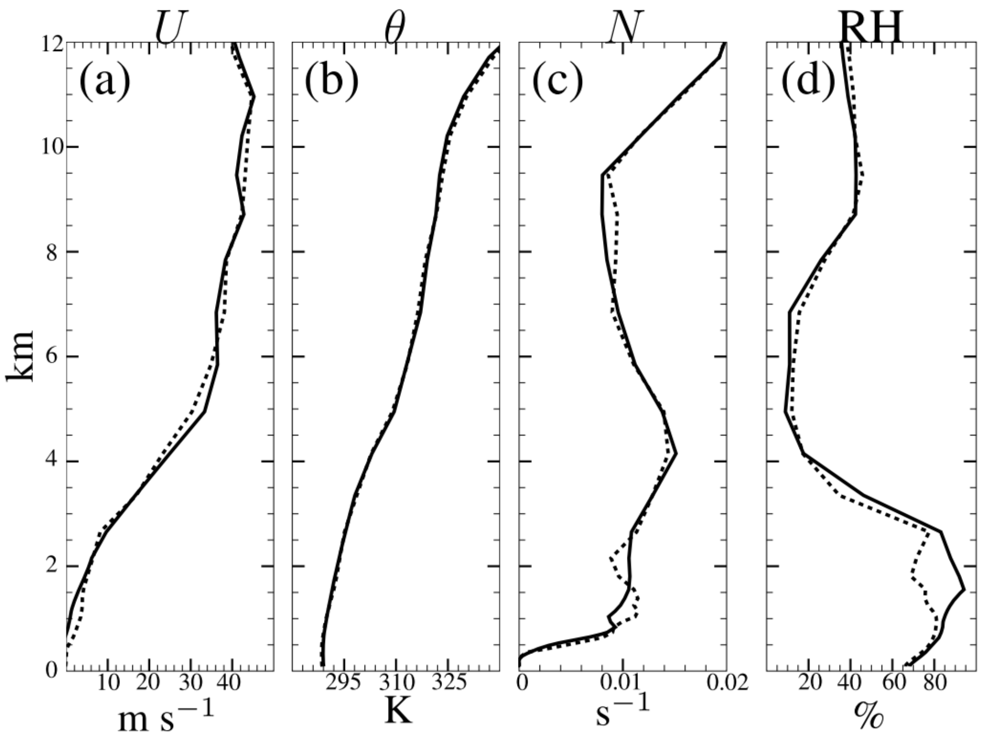
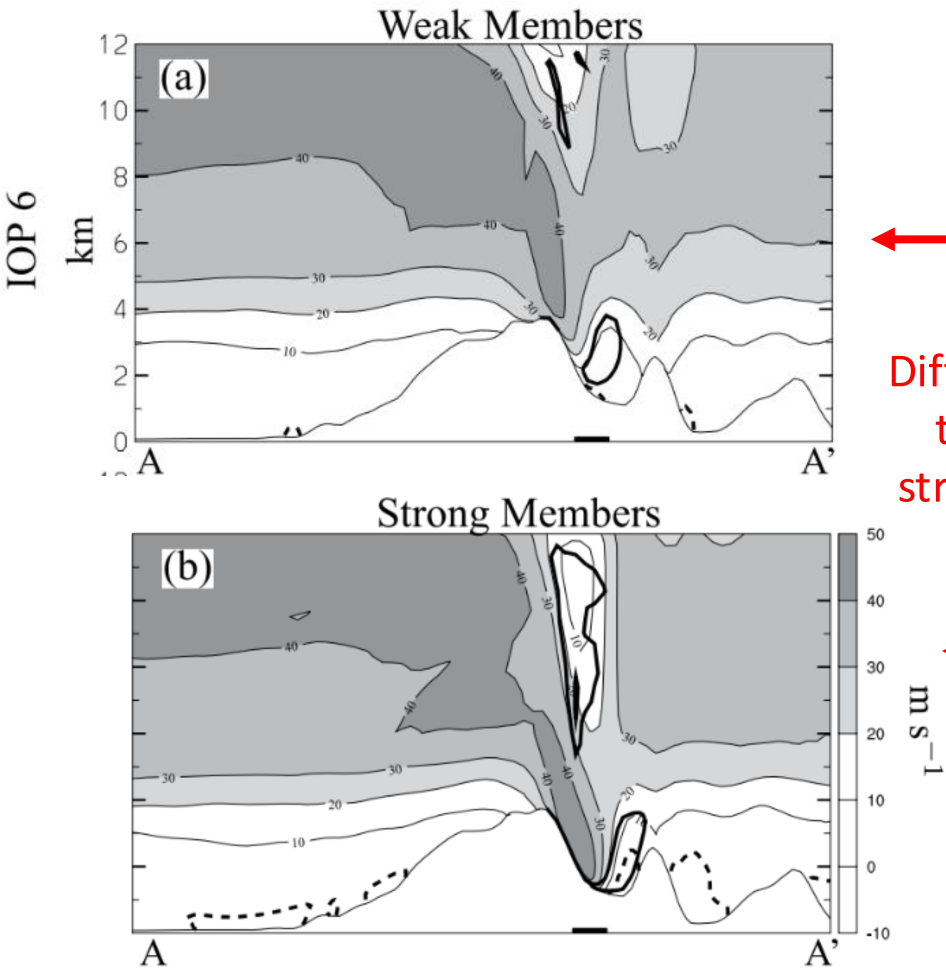


FIG. 11. Composite model soundings for the strong subset (solid) and weak subset (dashed) for IOP 6. The soundings are valid at forecast hour 5 (one hour before the time of maximum wind) and taken at the upstream edge of the A–A' cross section depicted in Fig. 1c. Plotted is the (a) cross-barrier component of the wind U, (b) potential temperature θ, (c) Brunt–Väisälä frequency N, and (d) RH.



Difference lies in the thermal structure of the valley

Reinecke and Durran (2009)

Multi-scale interactions in orographic flows

- A subtle interplay between large-scale and local-scale processes determines whether or not:
  - Foehn winds will break through to valley floors;
  - Mountain waves will reach large amplitude.
- **TEAMx plan**
  - Expand observational evidence, currently limited to a few events from previous field campaigns. E.g., ongoing PIANO project (PI Alexander Gohm, UIBK). Observing system design must cover a broad range of scales.
  - Evaluate implications on orographic drag and larger-scale impacts on synoptic flow.
  - Advance knowledge on the predictability of orographically-forced flow.

References

- Ekhart, E. (1948). De la structure thermique de l'atmosphere dans la montagne [On the thermal structure of the mountain atmosphere]. La Meteorologie 4, 3–26.
- Grubišić, V., J.D. Doyle, J. Kuettner, S. Mobbs, R.B. Smith, C.D. Whiteman, R. Dirks, S. Czyzyk, S.A. Cohn, S. Vosper, M. Weissmann, S. Haimov, S.F. De Wekker, L.L. Pan, and F.K. Chow, 2008: THE TERRAIN-INDUCED ROTOR EXPERIMENT. Bull. Amer. Meteor. Soc., 89, 1513–1534.
- Lehner, M. and M.W. Rotach (2018): Current Challenges in Understanding and Predicting Transport and Exchange in the Atmosphere over Mountainous Terrain Atmosphere, 9, 276.
- Lott, F. and Miller, M. J. (1997), A new subgrid-scale orographic drag parametrization: Its formulation and testing. Q.J.R. Meteorol. Soc., 123: 101-127
- Markl, Y., L. Laiti, M. Rotach (2017): The spatial variability of the temperature structure in a major east-west oriented valley in the Alps. 34th International Conference 0n Alpine Meteorology. 18-23 June 2017, Reykjavik, Iceland.
- Mayr, G.J. and L. Armi, 2010: The Influence of Downstream Diurnal Heating on the Descent of Flow across the Sierras. J. Appl. Meteor. Climatol., 49, 1906–1912.
- Nadeau, D.F., Pardyjak, E.R., Higgins, C.W. et al. (2013) Similarity Scaling Over a Steep Alpine Slope Boundary-Layer Meteorol 147: 401.
- Reinecke, P.A. and D.R. Durran, 2009: Initial-Condition Sensitivities and the Predictability of Downslope Winds. J. Atmos. Sci., 66, 3401–3418.
- Rotach, M. W. and Zardi, D. (2007), On the boundary-layer structure over highly complex terrain: Key findings from MAP. Q.J.R. Meteorol. Soc., 133: 937-948.
- Strauss, L., S. Serafin, and V. Grubišić, 2016: Atmospheric Rotors and Severe Turbulence in a Long Deep Valley. J. Atmos. Sci., 73, 1481–1506.
- Teixeira MAC (2014) The physics of orographic gravity wave drag. Front. Phys. 2:43. Wagner, J. S., Gohm, A. and Rotach, M. W. (2015), The impact of valley geometry on daytime thermally driven flows and vertical transport processes. Q.J.R. Meteorol. Soc., 141: 1780-1794.
- Troen, I.B. & Mahrt, L. (1986): A simple model of the atmospheric boundary layer; Sensitivity to surface evaporation. Boundary-Layer Meteorol 37: 129.
- Wagner, J.S.; Gohm, A.; Rotach, M.W., 2015: Influence of along-valley terrain heterogeneity on exchange processes over idealized valleys. Atmos. Chem. Phys. 15, 6589–6603.

Mountain meteorology: key programmes

1981-1982: Alpine Experiment (ALPEX)

Lee cyclogenesis

1990: Pyrenees Experiment (PYREX)

Gravity wave drag

1999: **Mesoscale Alpine Programme** (MAP; first WWRP research and development project).

Heavy rainfall, PV streamers, gap flows

Wet and dry MAP

Primary scientific objectives ("MAP Design Proposal", 1/1995)

1a To improve the **understanding of orographically influenced precipitation events** and related flooding episodes involving deep convection, frontal precipitation and runoff.

1b To improve the **numerical prediction of moist processes** over and in the vicinity of complex topography, including interactions with land-surface processes.

2a To improve the understanding and forecasting of the life cycle of **Foehn-related phenomena**, including their three-dimensional structure and associated boundary layer processes.

2b To improve the understanding of **three-dimensional gravity wave breaking and associated wave drag** in order to improve the parametrization of gravity wave drag effects in numerical weather prediction and climate models.

3 To provide **data sets** for the validation and improvement of high-resolution numerical weather prediction, hydrological and coupled models in mountainous terrain.

Sub-projects ("MAP Science Plan", 6/1998)

P1 Orographic precipitation mechanisms;

P2 Incident upper tropospheric PV anomalies;

P3 Hydrological measurements for flood forecasting;

P4 Dynamics of gap flow;

P5 Unstationary aspects of Foehn in a large valley;

P6 Three-dimensional gravity wave breaking;

P7 Potential vorticity banners;

P8 Planetary boundary layer structure.

MAP field campaign (1999)

- Preparations began in 1995
- Field phase between 15 September and 15 November 1999
- 17 Intensive Observation Periods
- 485 flight hours

- Approx. 220 articles on peer-reviewed journals in 1997-2006
- Approx. 45 doctoral dissertations in 1996-2007
- Peak of scientific production: 4-5 years after field campaign

MAP research output (Volkert and Gutermann, 2007)

Table I. Distribution of 220 MAP related articles in peer-reviewed journals over the years 1997–2006 and 30 research journals. The journals are grouped by the publishing learned societies (AMS: American Meteorological Society; AGU: American Geophysical Union; RMS: Royal Meteorological Society; D-A-CH: consortium of meteorological societies of Germany, Austria, Switzerland; EGU: European Geophysical Union; IMI: International Meteorological Institute, Stockholm) or companies (Springer, Elsevier). The journal abbreviations are explained in the appendix, part B alongside the complete inventory of counted articles. Entries in bold contain the MAP related articles of the special issues in *Meteorol. Atmos. Phys.* **72**, issue no. 2–4, 2000; *Q. J. R. Meteorol.Soc.* **129**, issue no. 588, 2003; *Hydrol. Earth System Sci.* **7**, issue no. 6, 2003; and *Meteorol. Z.* **13**, issues no. 1–3, 2004.

society/publisher	**journal(*s*)**	year **97**	year **98**	year **99**	year **00**	year **01**	year **02**	year **03**	year **04**	year **05**	year **06**	**Sum**
AMS	JAS, MWR		2		2	2	5	1	8	6	5	**31**
	JAOT, WF				3	6	3		1			**13**
	BAMS, JAM, JC, JHyM				2	4	2	1	1	1	3	**14**
AGU	GRL, JGR		1	1				4	1	1		**8**
RMS	**QJ**					4	5	**30**	11	7	10	**67**
	IJCli, MA		1		1		1				1	**4**
D-A-CH	BPA, **MZ**			2		4	1	3	**12**		1	**23**
EGU	ACP, AG, **HESS**				1			**9**		1		**11**
IMI	Tellus-A				1	1		1	1		1	**5**
Springer	AP-B, BLM, EFM, IA, **MAP**	1			**11**	2	1	4	7	3	4	**33**
Elsevier	AE, JHyd, PCE				2	2	1	2	1			**8**
others	AsGs, Geof, HydP						1	2				**3**
Sum		**1**	**4**	**3**	**23**	**25**	**20**	**57**	**43**	**19**	**25**	**220**

Q. J. R. Meteorol. Soc. **133**: 949–967 (2007)
DOI: 10.1002/qj

MAP funding (Volkert and Gutermann, 2007)

Table A I. Investments for MAP made by countries and international bodies divided into project funds, extra investment (mostly for infrastructure during the SOP), and estimated in-kind investment from the base budgets of the participating institutions.

Country or international body	Sponsoring agencies[l]	Project funds (M€)	Extra investment (M€)	In-kind investment (M€; estim.)	Total (M€)
Austria	Fed. Min., FWF, ZAMG	1.4	0.3[a]	0.7	2.4
Canada	MSC, NRC	0.1	–	0.2	0.3
Croatia	DHMZ	0.1	0.1[b]	0.1	0.3
France	CNRS, Météo-France, CNES, EDF	1.0	1.0[c]	4.9	6.9
Germany	DLR, DFG, DWD	0.4	0.4[d]	1.3	2.1
Italy	CNR, AMI	1.1	0.6[e]	0.6	2.3
Slovenia	ARSO	0.1	0.1[b]	0.1	0.3
Switzerland	SNF, MeteoSwiss, CSCS, ETH	3.3	–	1.5	4.8
United Kingdom	Met Office, NERC	0.1	0.3[f]	0.7	1.1
United States[g]	NSF, ONR, NCAR	7.2	1.4[h]	4.8	13.4
EUMETNET	National Meteorological Services	–	2.2[i]	–	2.2
European bodies	EU, ECMWF	1.4[j]	–	0.1[k]	1.5
Total		16.2	6.4	15.0	37.6

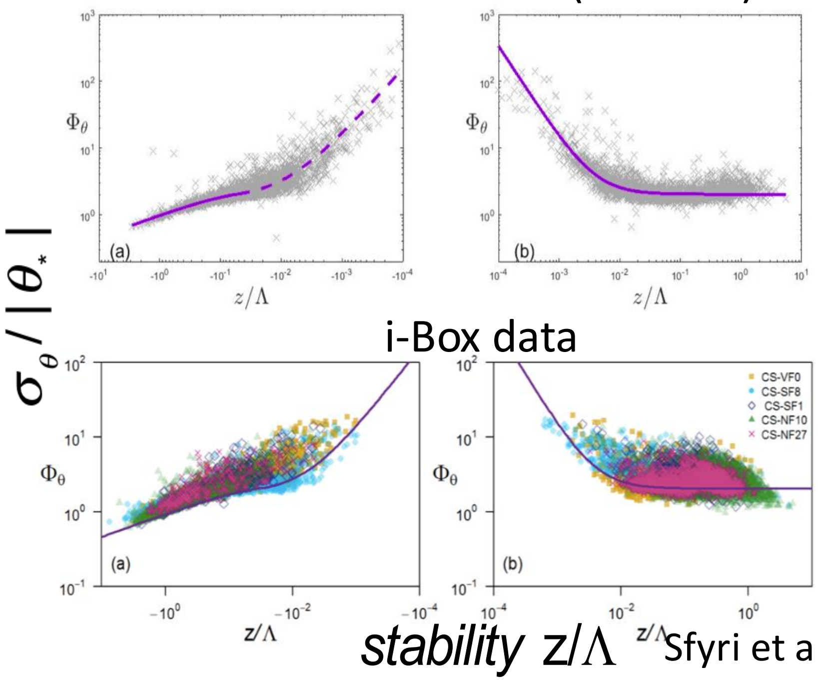
[a] Basic contribution to run the mission operation centre (MOC) in Innsbruck during SOP.
[b] Enhancement of routine measurements.
[c] Basic costs for SOP deployments.
[d] Basic costs for research aircraft and enhanced observations.
[e] Basic contribution for the precipitation operation centre (POC) in Milano and for enhanced measurements.
[f] Deployment of research aircraft.
[g] USA figures where provided in US$; 1 US$ = 1 € is used as average conversion rate for the MAP period.
[h] Basic costs for US MAP-office and field deployments (*e.g.* two research aircraft, Doppler radar).
[i] 14 national meteorological services contributed to basic infrastructure (e.g. programme office, data centre) via EUMETNET administered by MeteoSwiss.
[j] EU contribution to the MAP-related research projects HERA and RAPHAEL.
[k] ECMWF contribution to reanalysis costs in addition to EUMETMET payment.
[l] See Appendix D for acronyms.

Q. J. R. Meteorol. Soc. **133**: 949–967 (2007)
DOI: 10.1002/qj

Land-atmosphere exchange

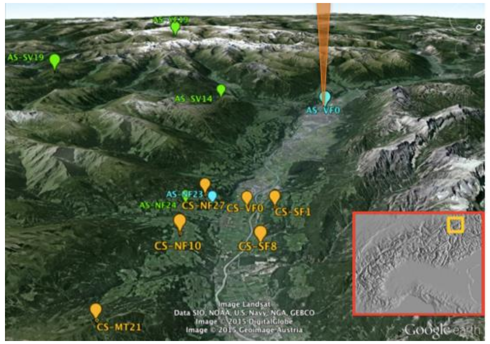
- Near-surface exchange (MOST or no-MOST)

ideal reference (Cabauw)



Sfyri et al. (2018)

i-Box sites



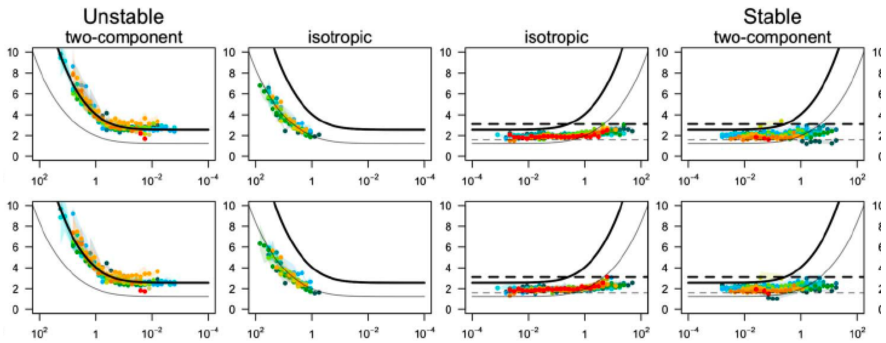
- each site is different (all are higher than ref)
- not dependent on slope angle

→ scaling (*local* is not really satisfying)

→ data post-processing

→ differences to 'HHF terrain'?

Land-atmosphere exchange

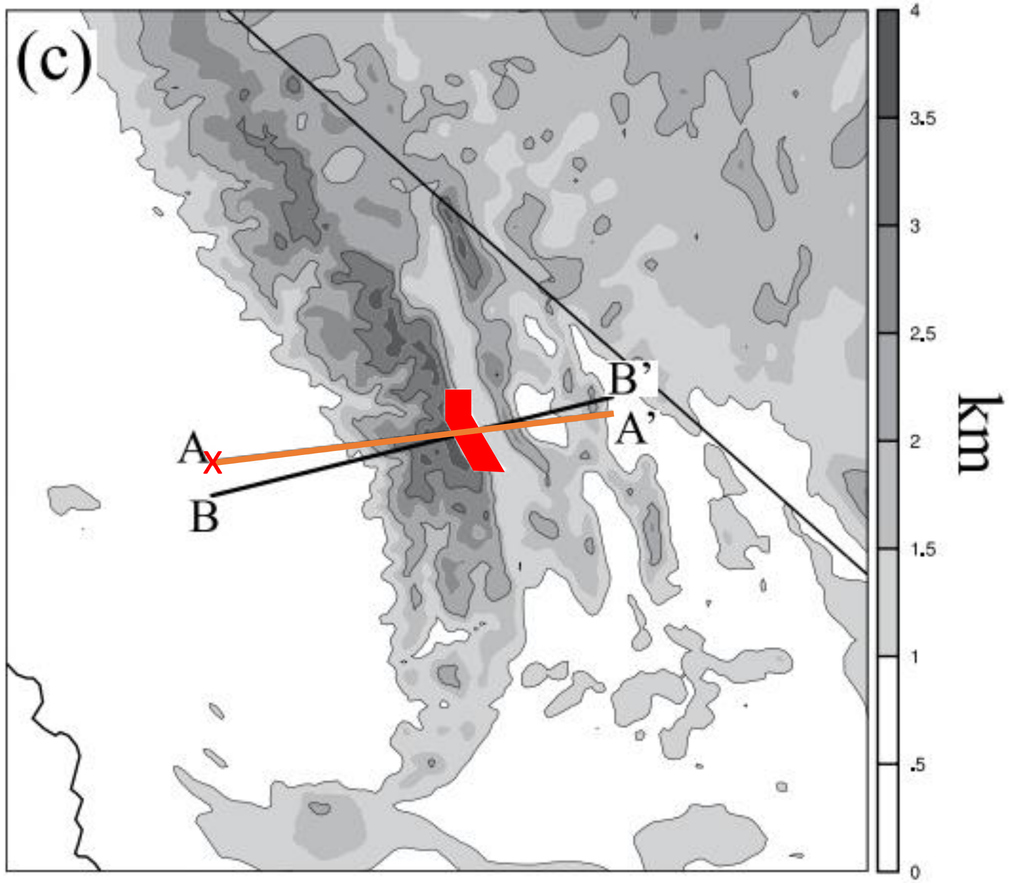


- Scaling
  → value of local scaling?
  → how to address spatial inhomogeneity
  → isotropy scaling (Stiperski et al. 2019)
- Data treatment
  → 'slope normal' or vertical
  → data post-processing, DQ
- Advection, EB closure

BL approximation!
(Oldroyd et al. 2015)

Multi-scale interactions in orographic flows

- T-Rex IOP 6 simulated with a 70-member EnKF ensemble.
- Dx = 3 km in innermost domain
- 40 vertical levels
- Focus on downslope windstorms, lowest 300 m of atmosphere in the red area.
- Cross-sections along A-A’
- Upstream profiles at A



Reinecke and Durran (2009)

Multi-scale interactions in orographic flows

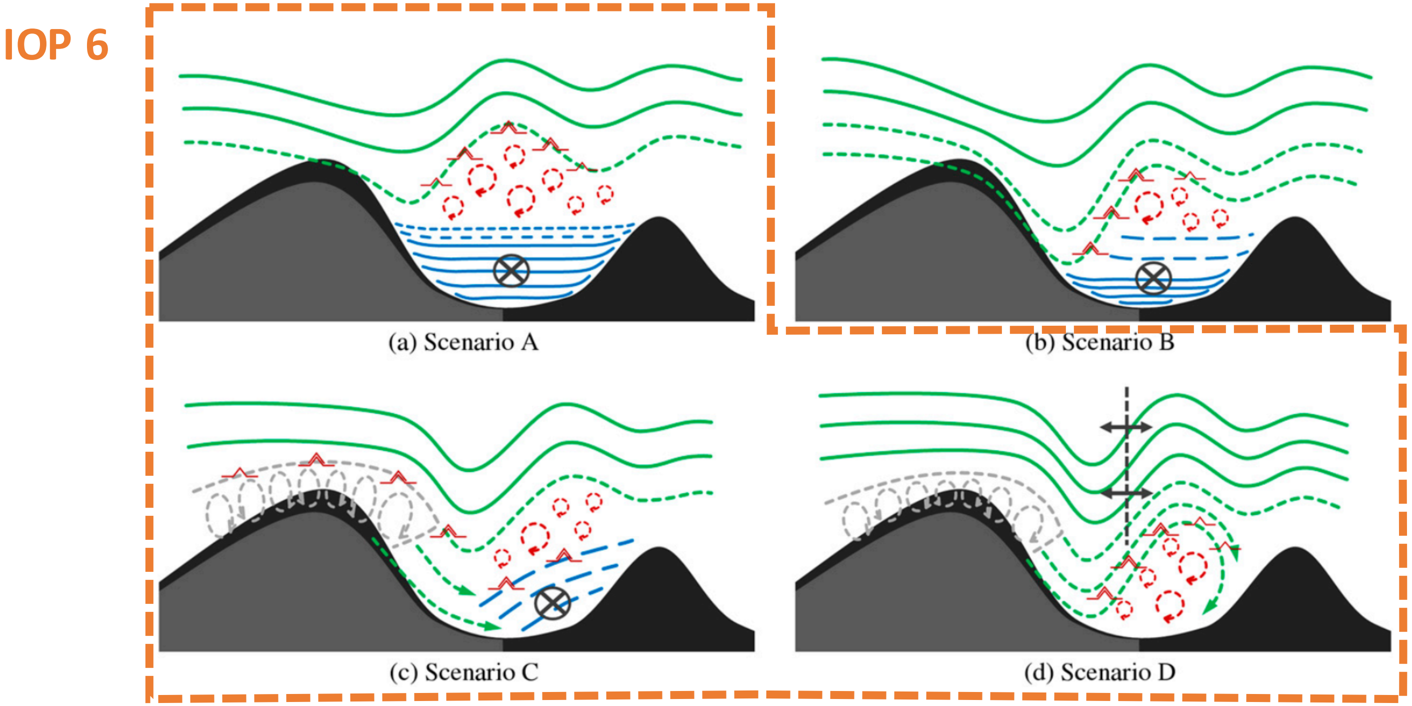


FIG. 16. Schematic diagrams of four different scenarios of wave formation and low-level turbulence generation in Owens Valley: (a) elevated turbulence zone, (b) flow separation at a low-level valley inversion, (c) turbulent interaction of in-valley westerlies with along-valley flows, and (d) transient mountain waves and rotors. Flow is from the left. The lower gray-shaded terrain indicates the presence of a mountain pass. Green lines depict streamlines of the flow in laminar (solid) and turbulent (dashed) flow regions. Red turbulence symbols and eddies mark regions of moderate and severe turbulence and mixing. The cap cloud over the Sierra Nevada is indicated with gray eddies and delimited by a dashed gray line. Beyond cap clouds, roll clouds and lenticular wave clouds are frequently present in the wave crests over the valley; here, they are omitted for clarity. In the valley, blue lines represent isentropes in undisturbed (solid) and disturbed (dashed) regions. Up-valley flow is indicated by into-the-page circular symbols. In (d), arrows pointing left and right illustrate the movement of the wave and rotor.

Strauss et al (2016)

Multi-scale interactions in orographic flows

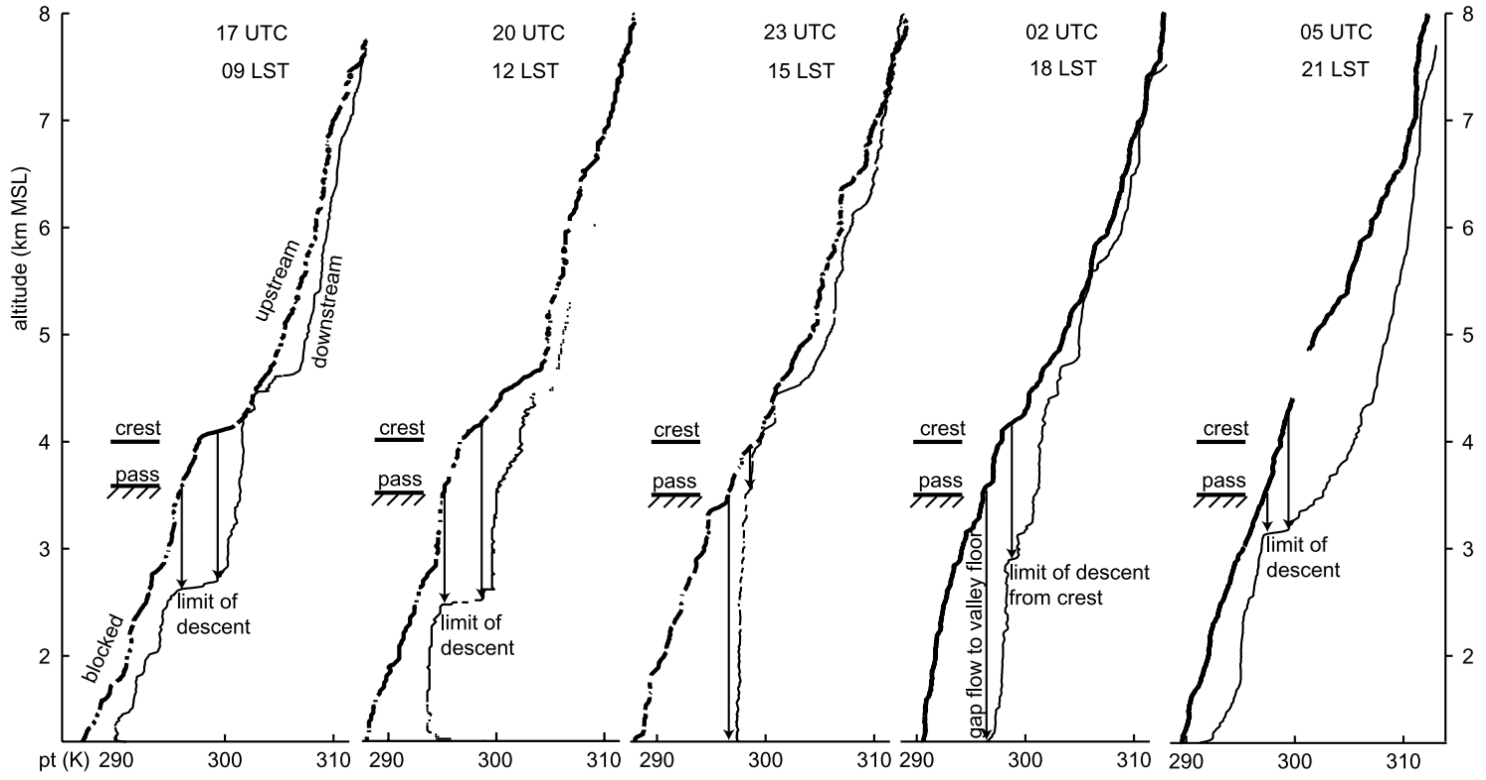


FIG. 4. Potential temperature of radio soundings upstream (thick) and downstream (thin) of the Sierra Nevada, with added altitude of the Sierra Nevada crest and Kearsarge Pass and launch times. Arrows show adiabatic descent of upstream air from gap and crest height, respectively, to the downstream air mass.

Mayr and Armi (2010)