TEAMx

Multi-scale Transport and Exchange processes in the Atmosphere over Mountains – programme and experiment

www.teamx-programme.org

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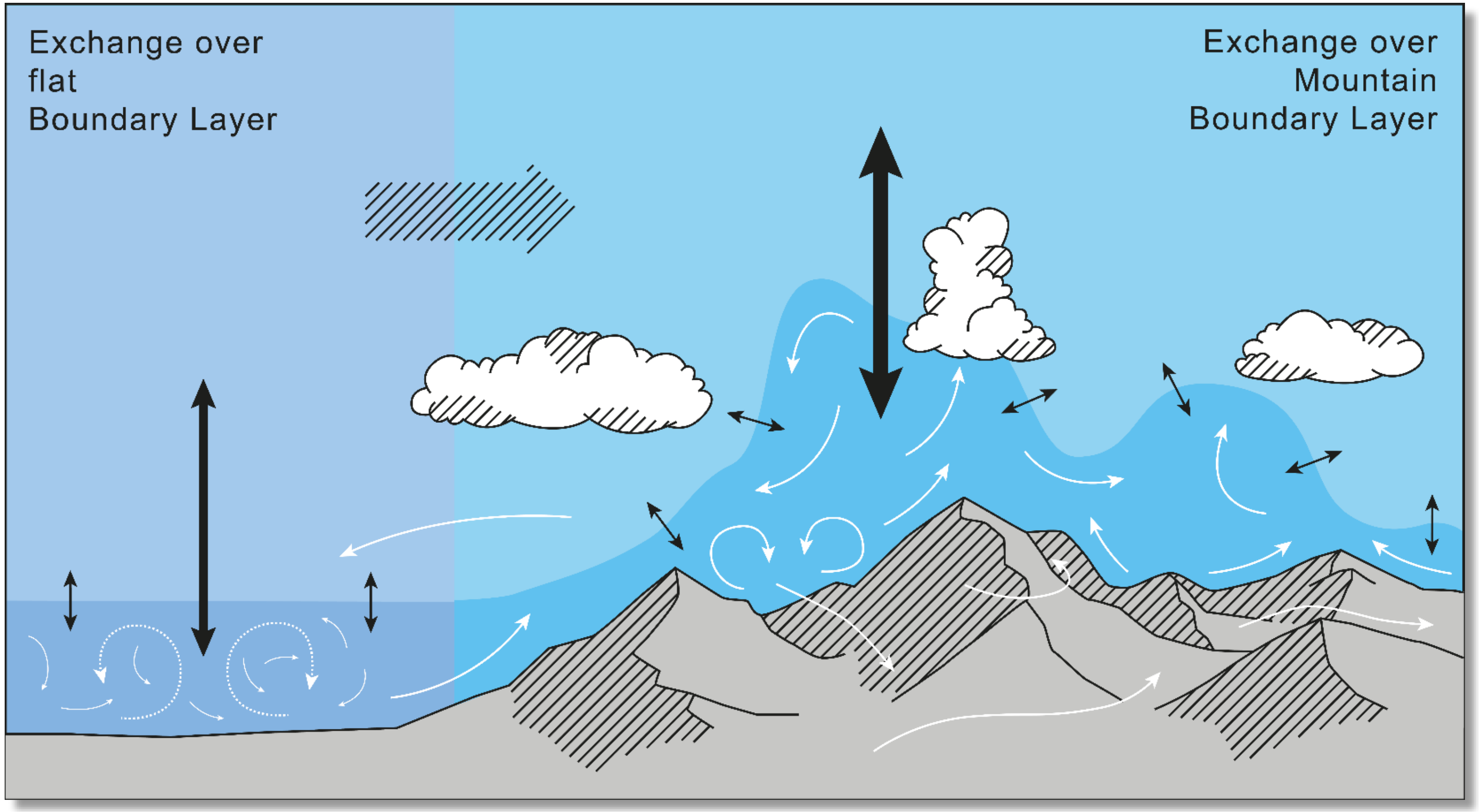
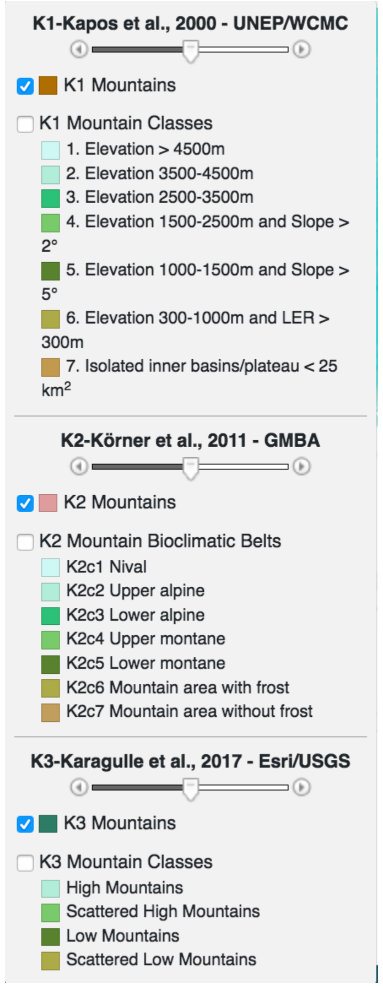
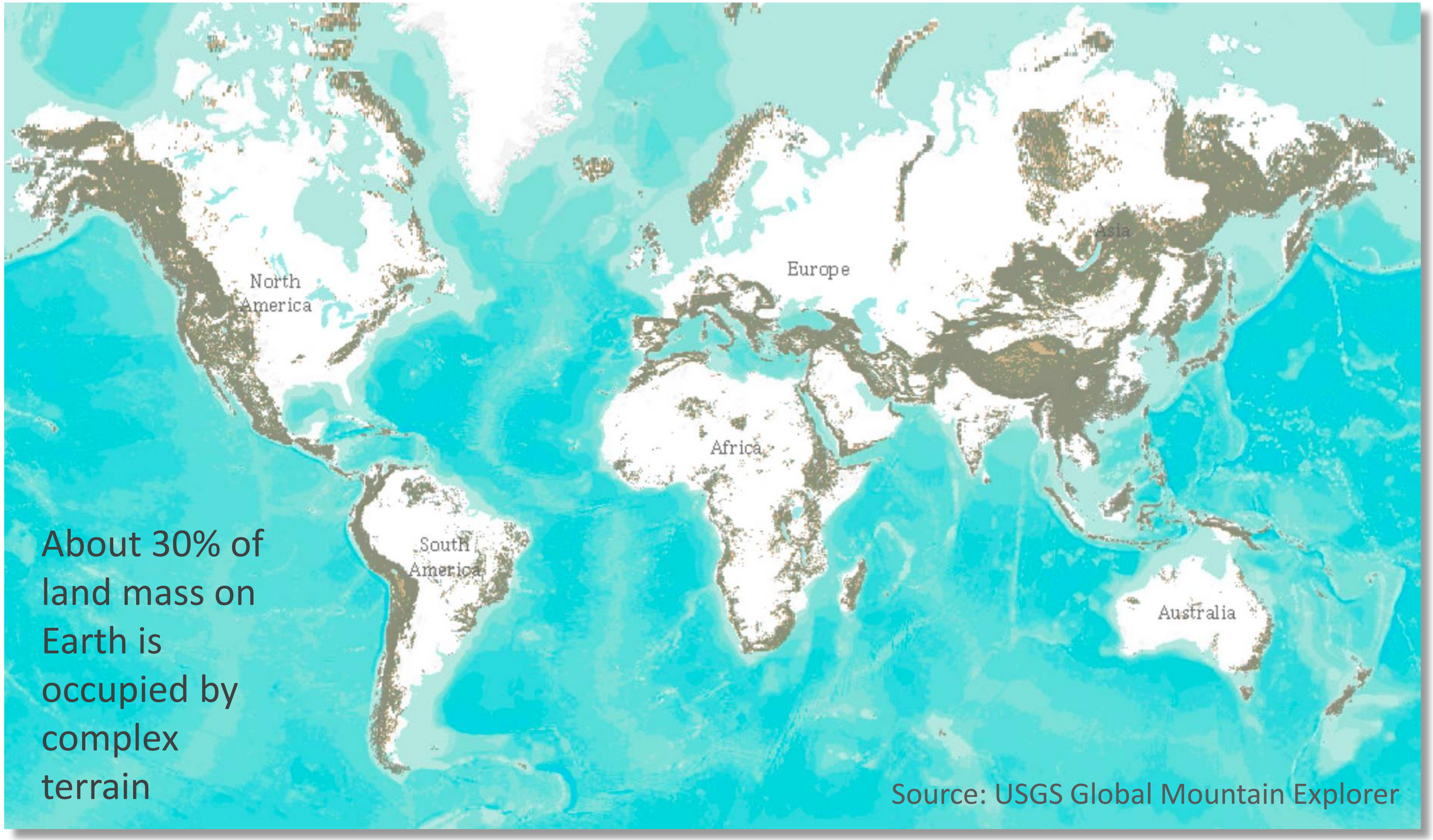
TEAMx

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



Global Distribution of Mountains



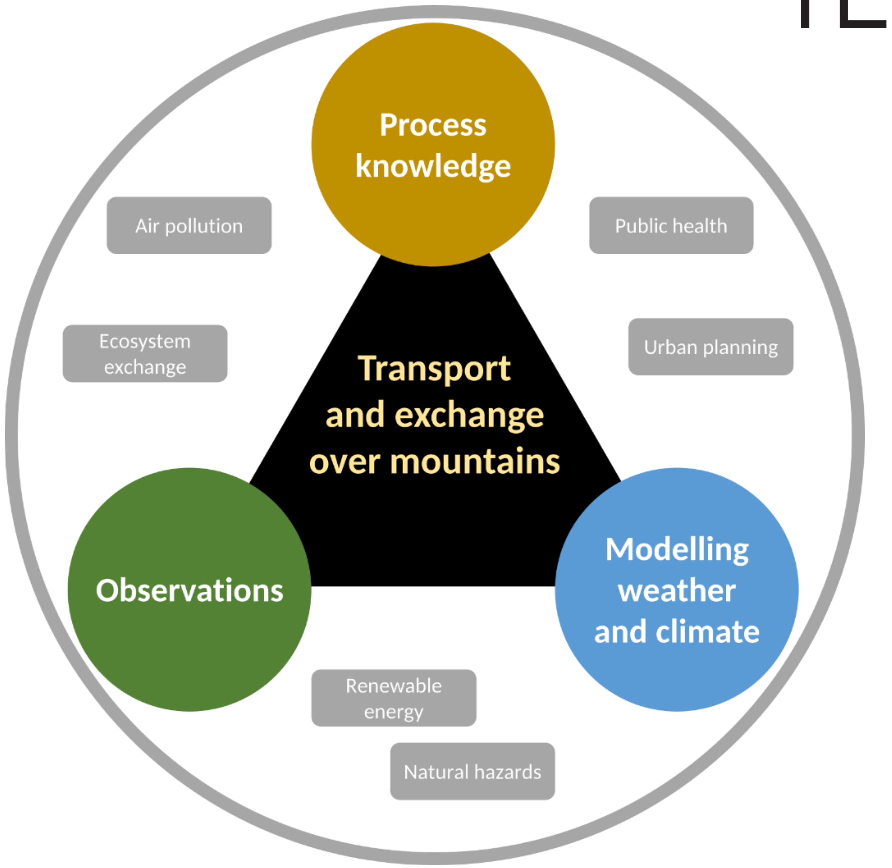


About 30% of land mass on Earth is occupied by complex terrain

Source: USGS Global Mountain Explorer

TEAMx: Aims

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



TEAMx 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).
87 registered participants

White Paper currently in preparation; to be finalized after the Workshop.

TEAMx: Some Research Questions

- Do we have a *quantitative* grasp of exchange processes and their interactions over complex terrain?
  (e.g., scaling laws in the surface layer; entrainment rates)
- Do current NWP, regional climate and pollutant transport and dispersion models adequately account for the processes within mountain BL?
  (e.g., dependence of mountain-induced fluxes on model resolution)
- Is SGS parameterization of orography-induced exchange of heat and mass necessary for O(10 km) grid-spacing models?
  (e.g., similar to orographic drag)
- How do BL processes over mountains impact convection initiation, air quality, etc.?

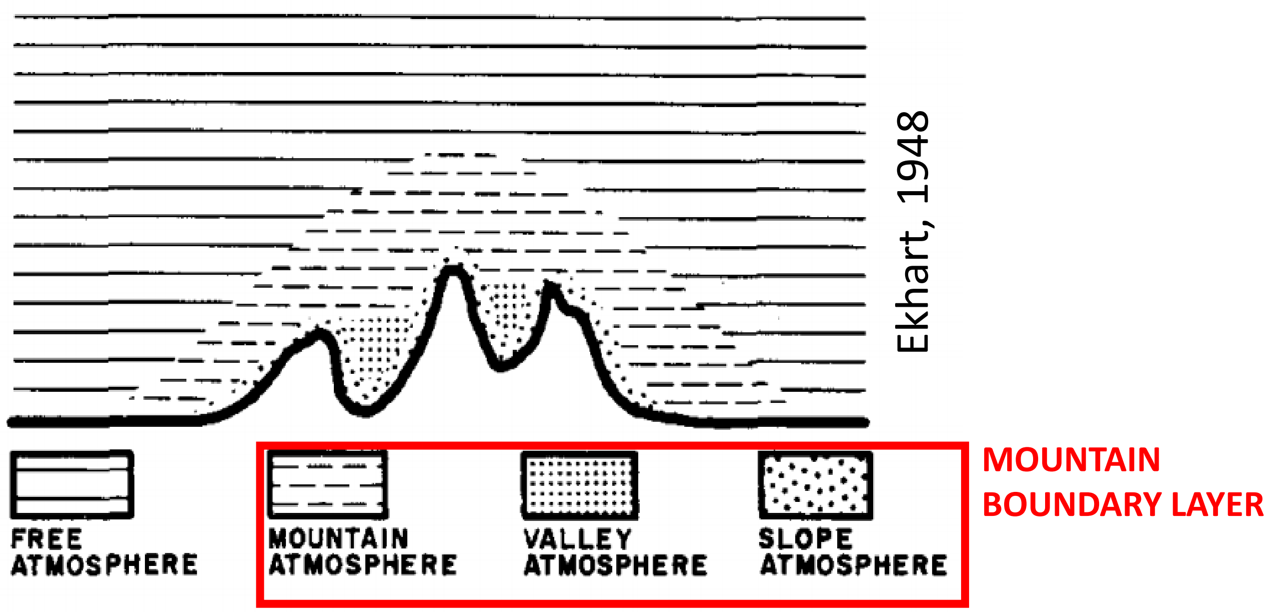


Figure 13: Diagram of the structure of the atmosphere above a mountain range.

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

Parameterizing Exchange Processes

- Three examples of gaps between the state of knowledge about exchange processes over mountains and the state-of-the art in parameterizations:
  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,
- *Surface* fluxes are estimated from model-level variables using bulk transfer relationships,
- Under this assumption, bulk transfer coefficients include adiabatic corrections, based on MOST (Ψ, ζ=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 the ground,
- Even using *local* scaling, flux-profile relationships are often reported to match poorly observed fluxes and gradients over complex terrain,
- The example illustrates a case over a steep mountain slope under weak synpotic flow and clear-sky conditions.

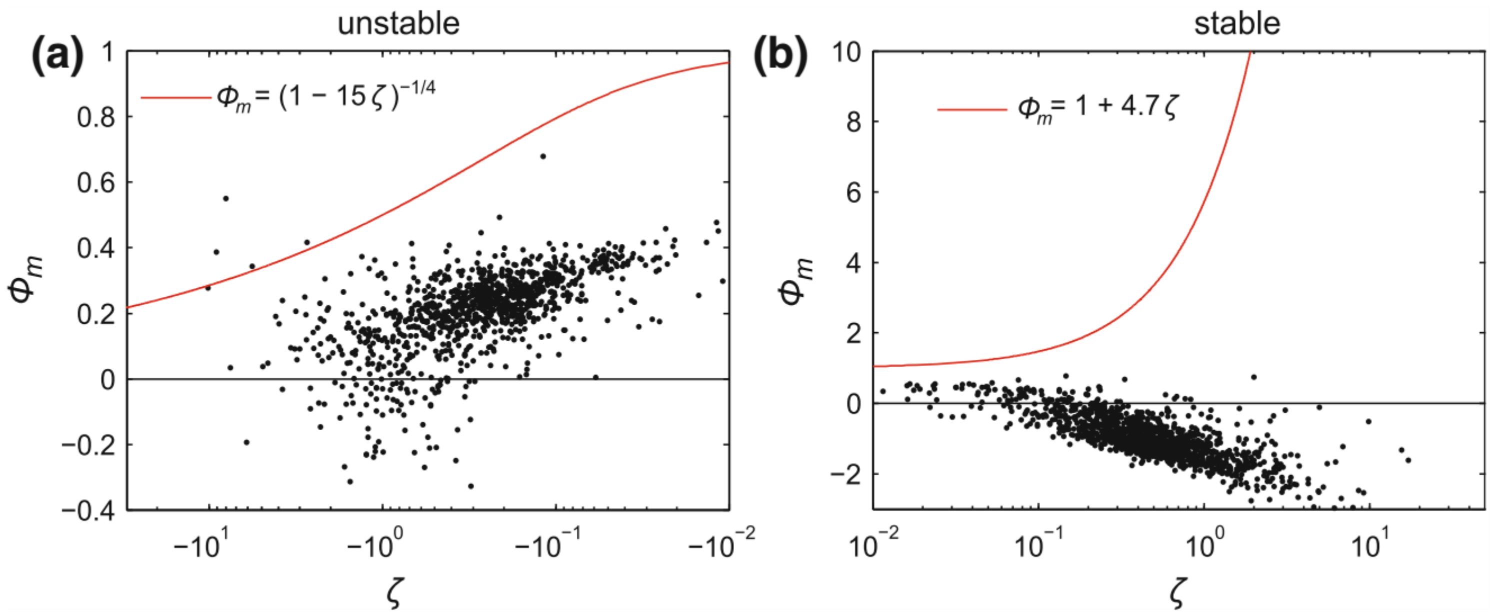


Fig. 10 Dimensionless wind shear ϕ_m for **a** $\zeta < 0$ and **b** $\zeta > 0$ at site T2, 1.5 m normal to the surface. The *solid red lines* represent the Businger–Dyer flux–profile relationships determined over flat and homogeneous surfaces (Businger et al. 1971; Dyer 1974)

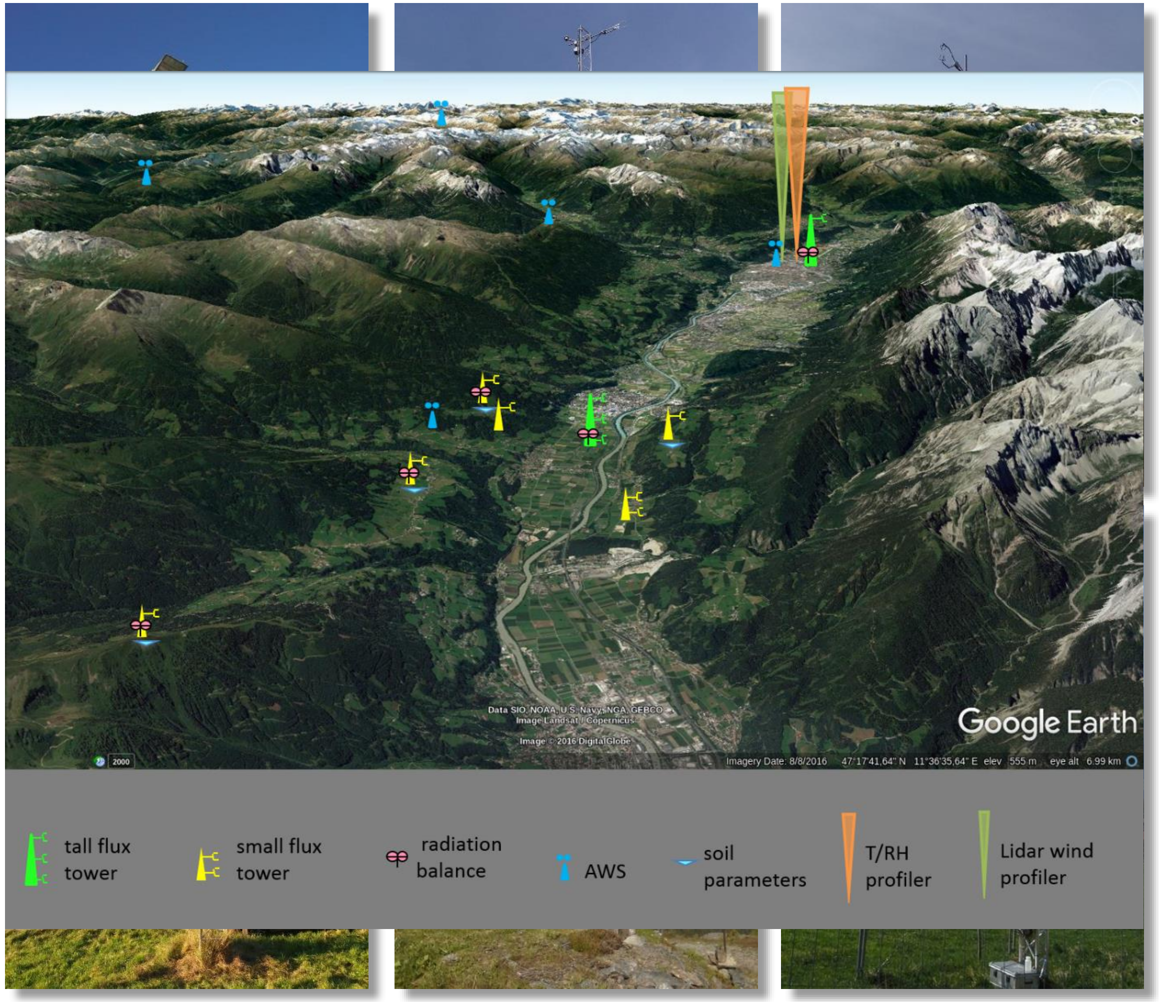
Nadeau et al (2013)

Example 1: MOST Scaling Laws

2011 – ongoing

TEAMx Plan

- Observations 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.



Poster: Modelling and Observing the Atmospheric Boundary Layer over Mountains by Serafin et al.

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).

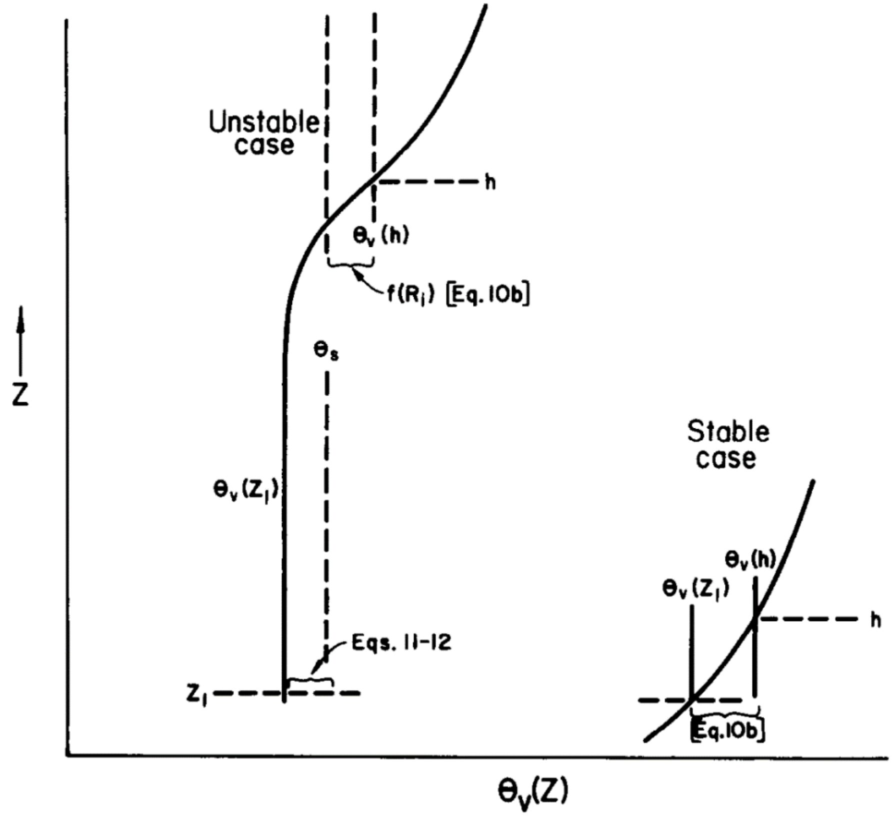


Fig. 1. Geometric sketch of the boundary-layer depth relationship to the profile of potential temperature above the surface layer (solid profile). For the unstable case, the first vertical broken line to the right of the profile indicates the potential temperature after enhancement due to the temperature 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.

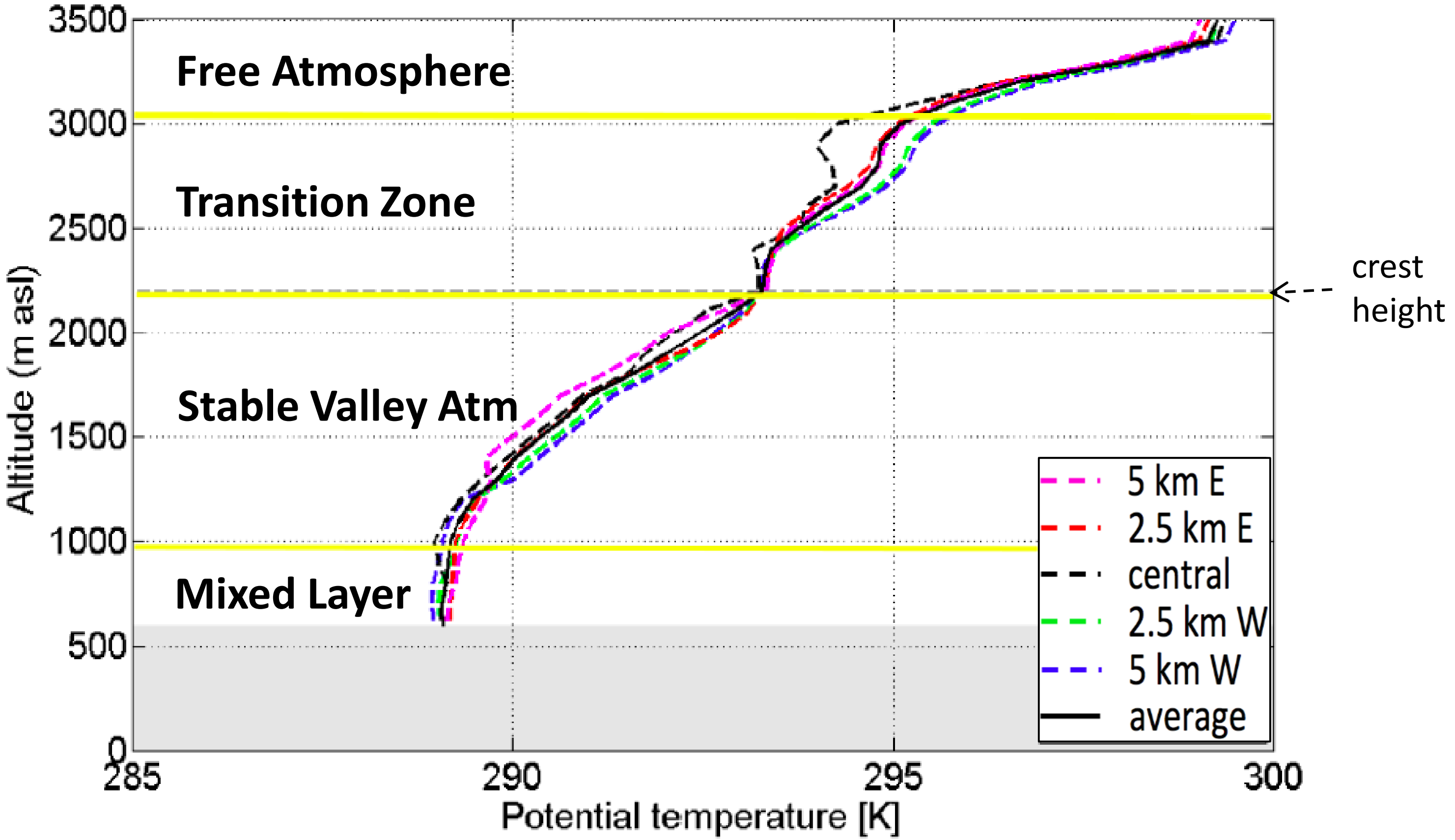
Example 2: PBL Structure

What we know

- The vertical structure of the MBL is more complex than that of the CBL (evidence from both *observations* and numerical modelling),

Daytime BL in the Inn Valley

Markl et al (2017)



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 of estimating z_i yield varying results over complex terrain,

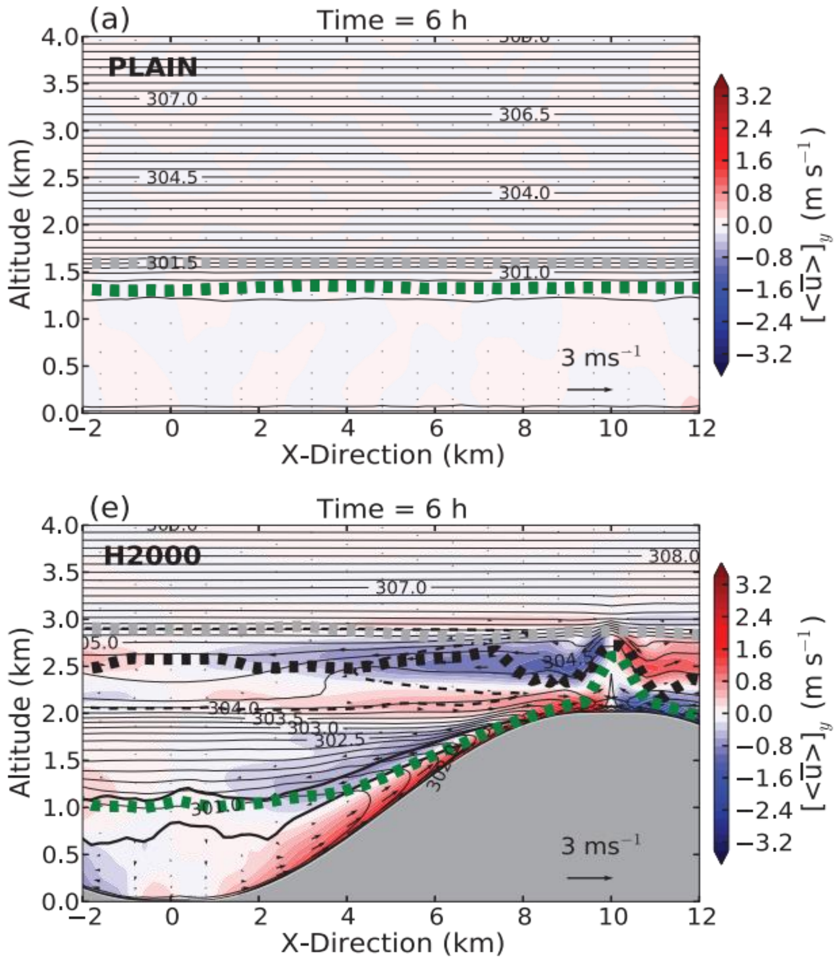


Figure 4. (a)–(e) Cross-sections of potential temperature (thin contour lines), cross-valley (colour shading) and along-valley wind speed (thick contour lines, negative values dashed, interval 1.0 m s^{-1}, the zero line is not shown) averaged between $y = 5$ and $y = 15$ km after 6 h of simulation.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

Example 2: PBL Structure

Rotach and Zardi (2007)

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 of estimating z_i yield varying results over complex terrain,
- Horizontal exchange is important over complex terrain.

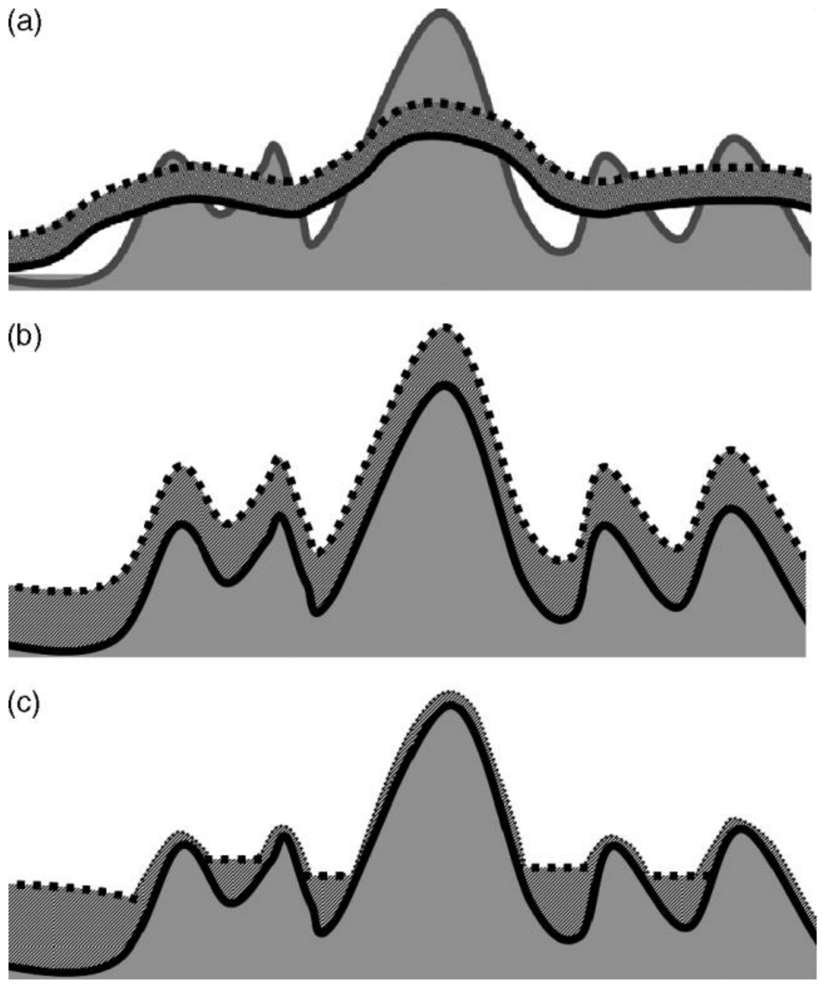
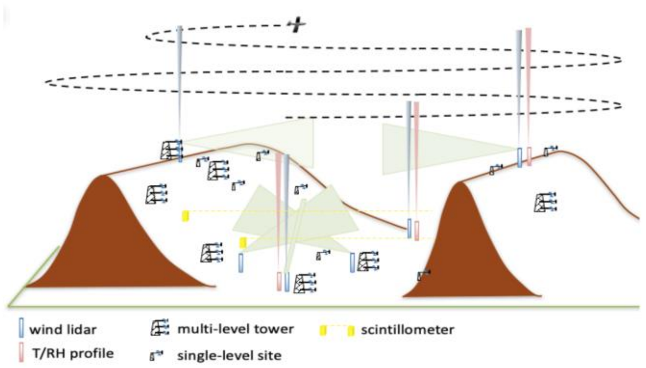


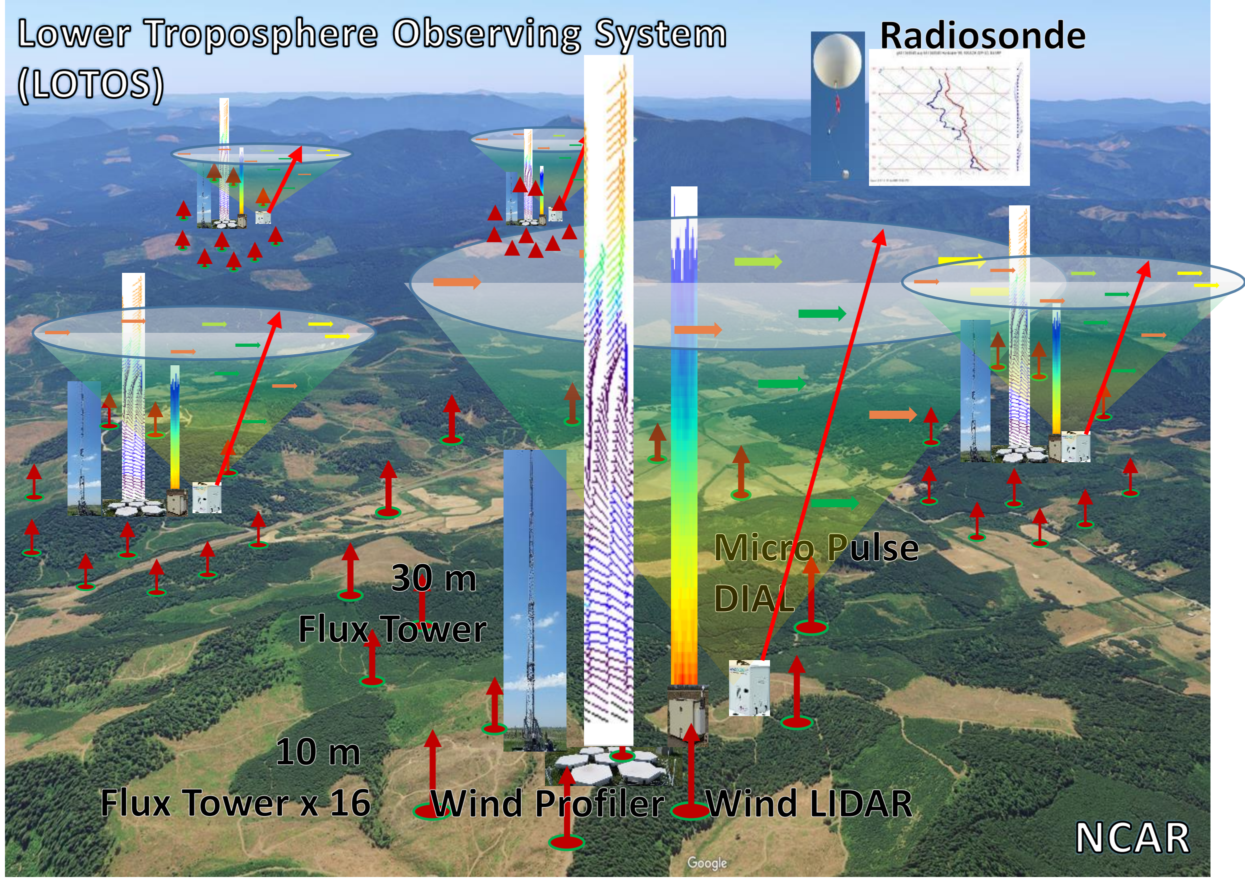
Figure 5. Schematic representation of the boundary layer in (a) a low-resolution numerical model, (b) a high-resolution operational numerical model, and (c) the turbulent boundary layer as found from different MAP boundary-layer studies.

Example 2: PBL Structure



TEAMx plan

- Obtain comprehensive measurements of mountain boundary layer
- Use 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 sUAS for gap filling measurements over wide areas,
- Systematic evaluation of PBL parameterizations 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 2*σ* (of the SGS orography).
- Consequence: Orographic drag parameterizations are unaware of low-level wind shear and inversion layers.

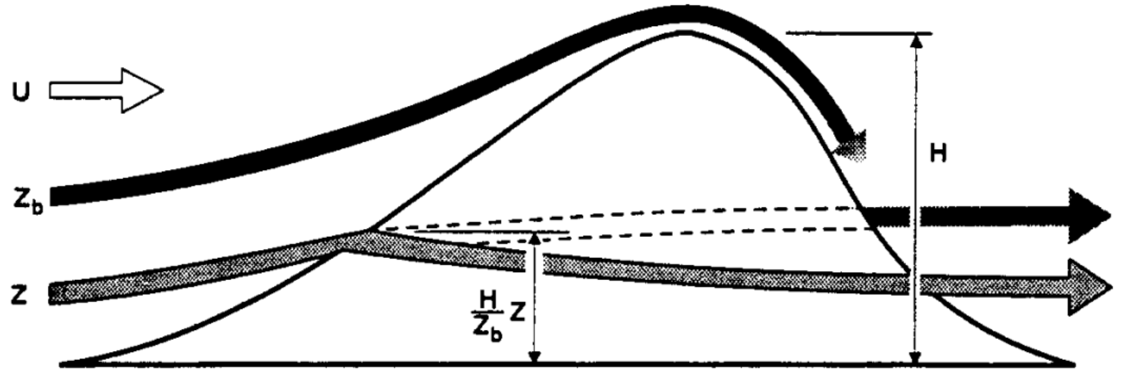


Figure 1. Schematic representation of the low-level flow behaviour parametrized in the new scheme (see text for details.

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

- Advance the physically based approach to parameterizing drag by extending theoretical predictions to more complex flows.

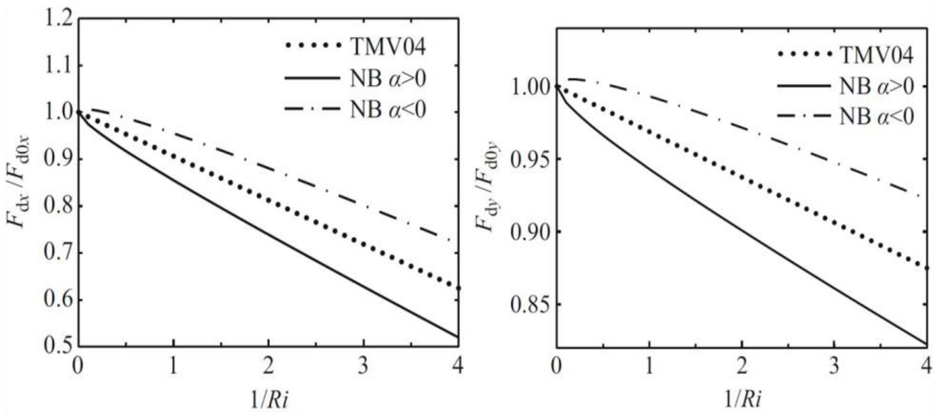


FIGURE 4 | Normalized *x* (left) and *y* (right) components of the drag as a function of *Ri* for the wind profile (45). The solid and dash-dotted lines correspond to non-Boussinesq calculations (with different signs of α – see legend), and the dotted line is the original Boussinesq result (46). Reproduced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

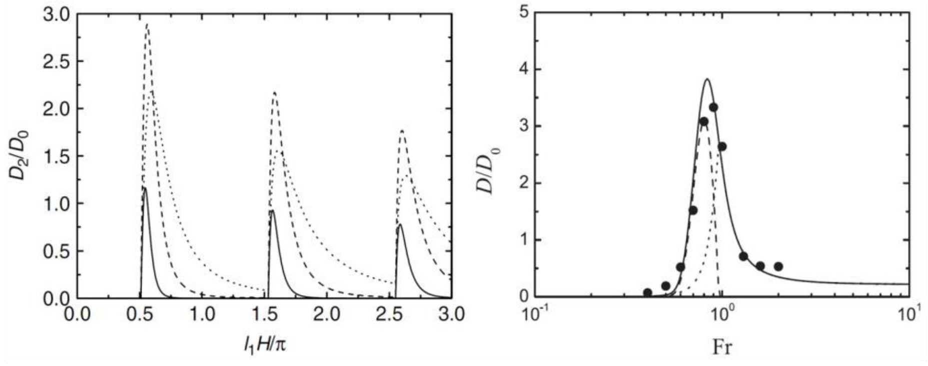


FIGURE 11 | Left: trapped lee wave drag (here denoted by D_2) normalized by (30) as a function of l_1H/π. Solid line: $l_1a = 10$, dashed line: $l_1a = 5$, dotted line: $l_1a = 2$. Reproduced from Figure 6 of Teixeira et al. [111]. Copyright © 2012 Royal Meteorological Society. **Right:** Drag normalized by (30) as a function of Fr for $l_2H = 0.5$ and $l_2a = 1$. 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.

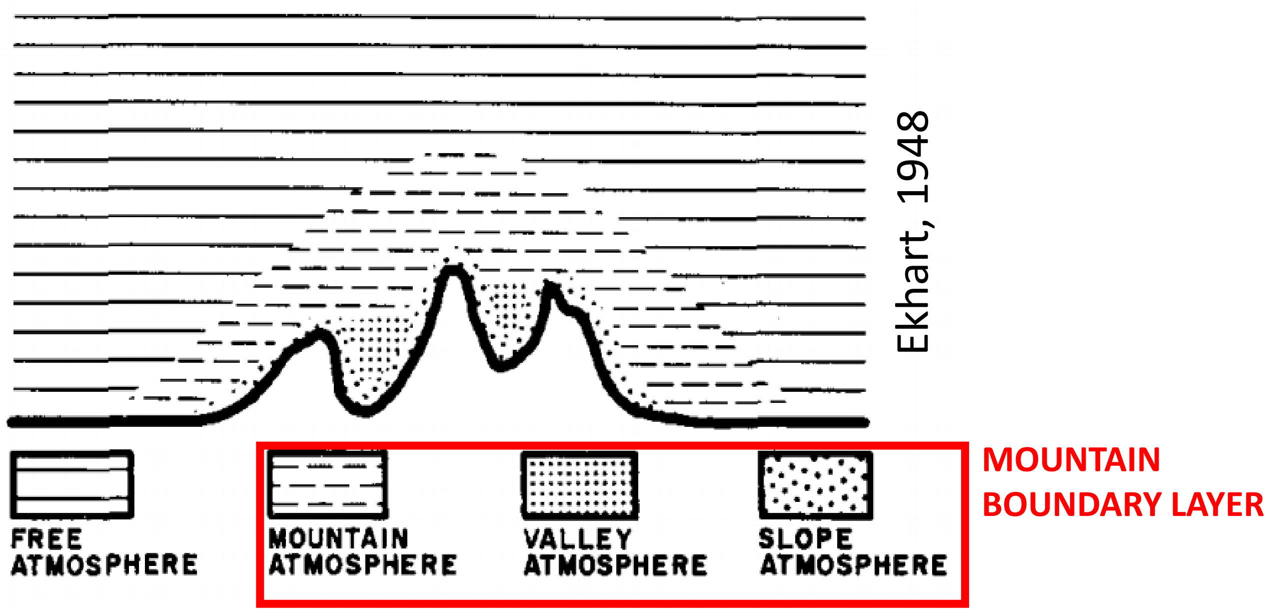
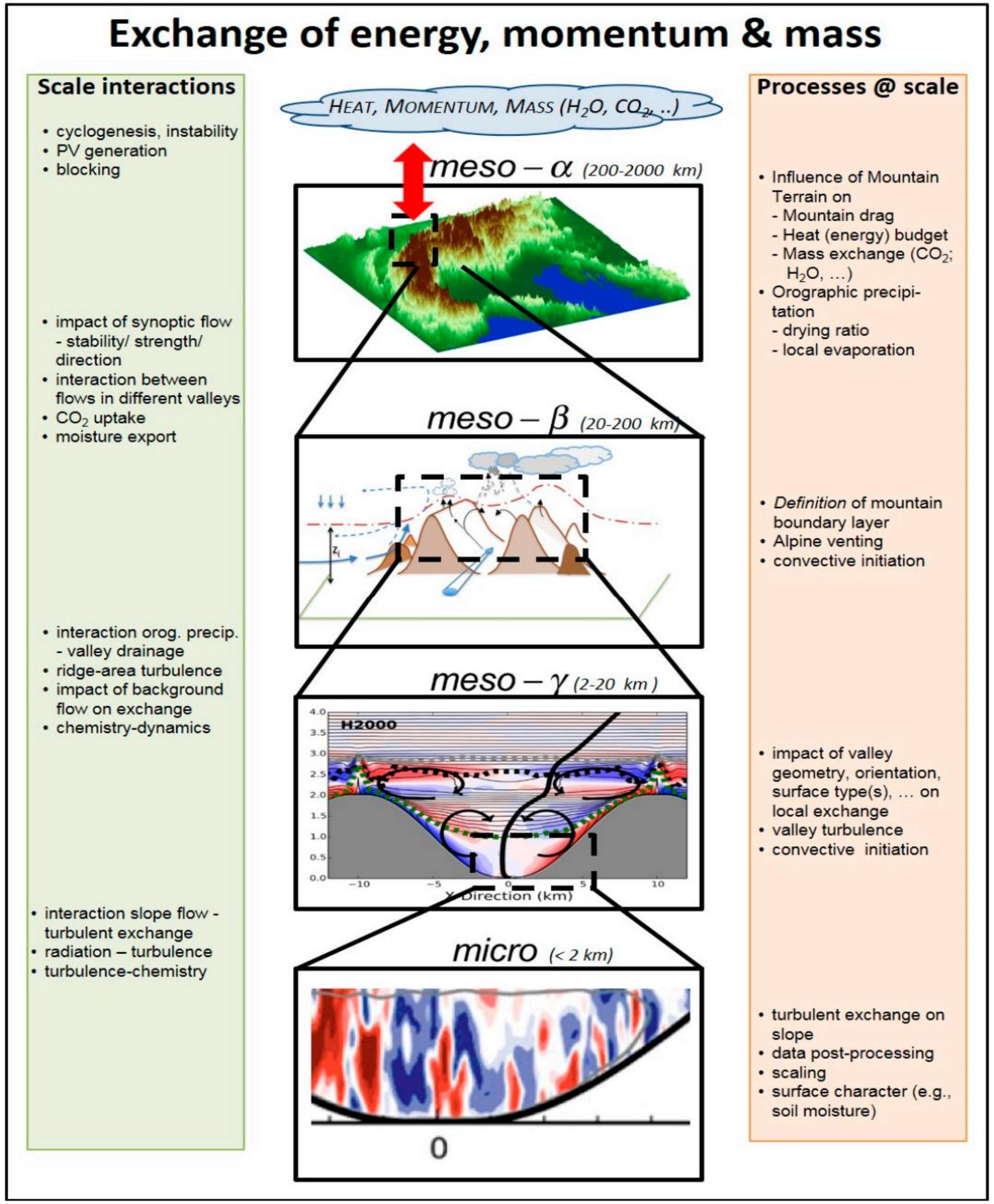


Figure 13: Diagram of the structure of the atmosphere above a mountain range.

1. Shortcomings of parameterization schemes over mountains
2. Multi-scale interactions in the atmosphere over mountains

Multi-scale Interactions in Orographic Flows

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

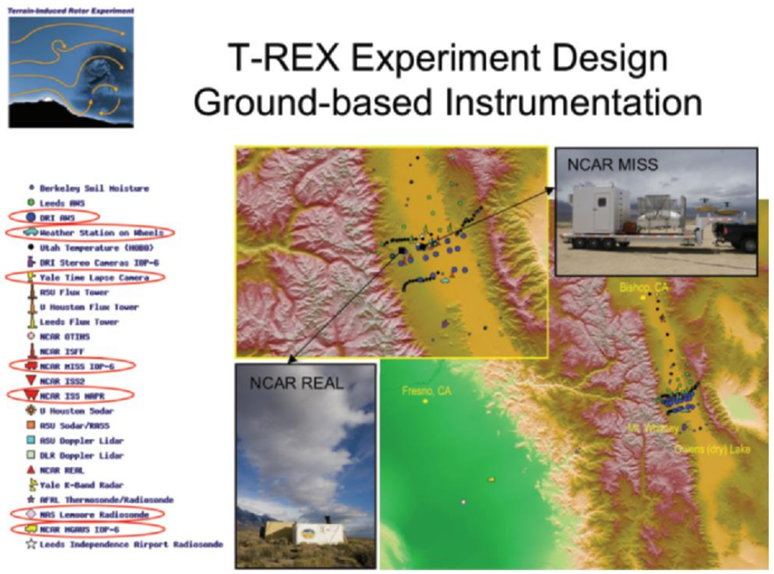


Lehner and Rotach (2018)

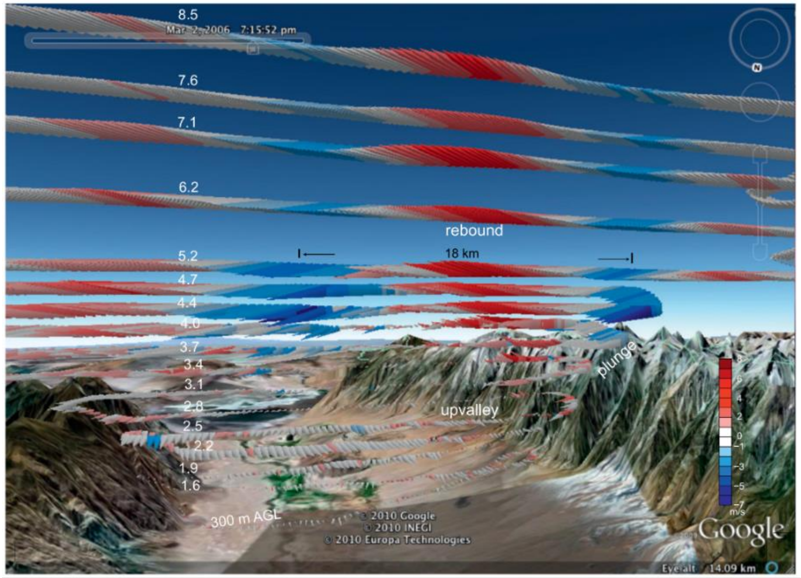
Multi-scale Interactions in Orographic Flows

- T-REX (March-April 2006, Owens Valley, CA)
- Focus on atmospheric wave-induced rotors (mountain wave - BL coupling)

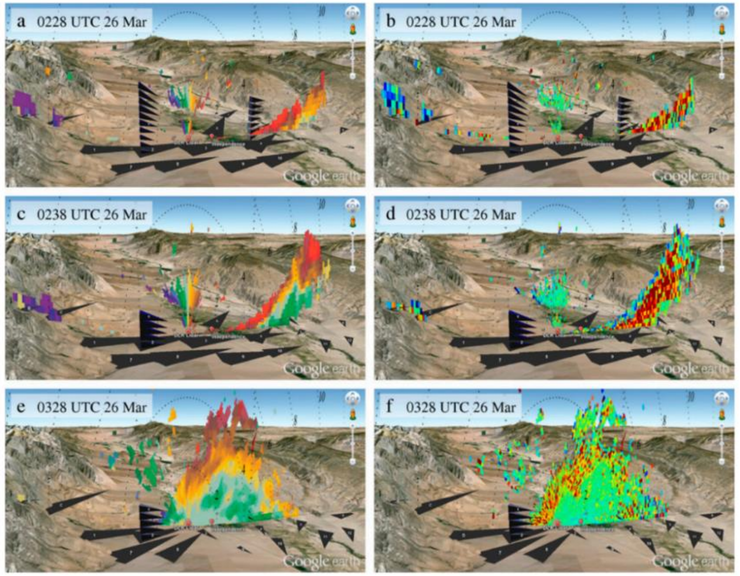
Strong wave/rotor event of IOP 6, March 25, 2006



Grubišić et al. (2008)



Mayr and Armi (2010)



Strauss et al. (2016)

How Sensitive are Downslope Winds to Small Variations in Upstream Conditions?

T-REX IOP 6 (March 25, 2006)
Reinecke and Durran (2009)

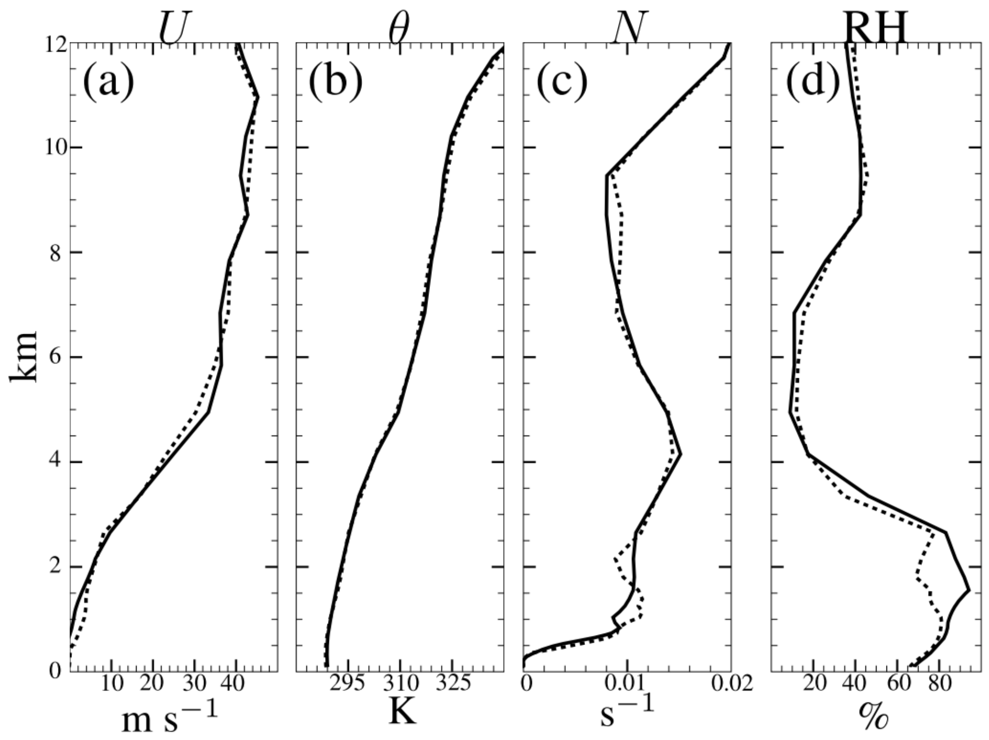
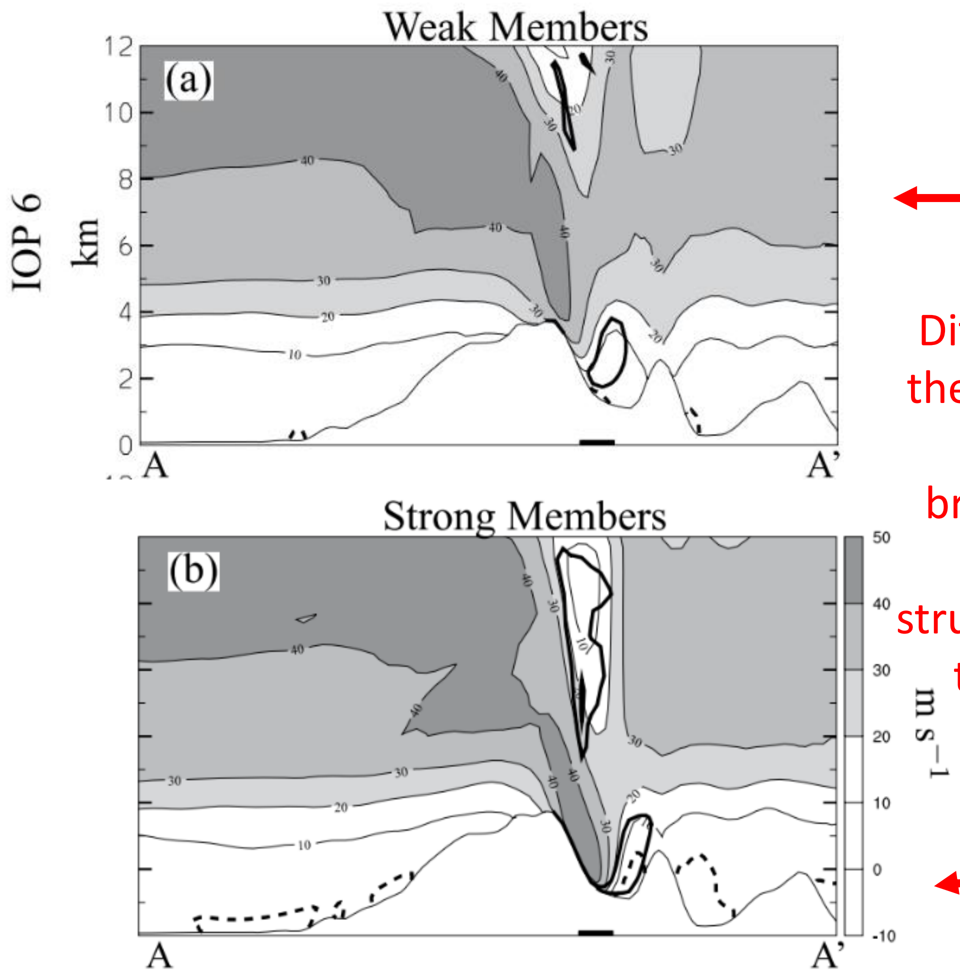


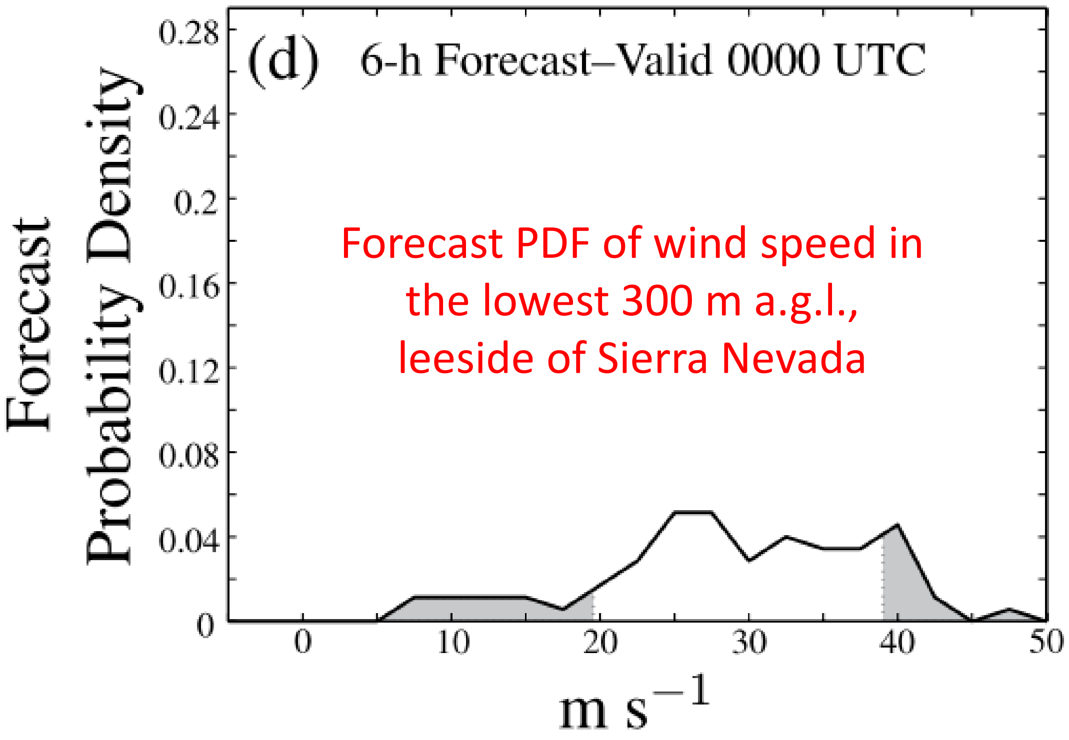
FIG. 11. Composite model soundings for the strong subset (solid) and weak subset (dashed) for IOP 6. The soundings are valid at forecast hour 5 (one hour before the time of maximum wind) and taken at the upstream edge of the A–A' cross section depicted in Fig. 1c. Plotted is the (a) cross-barrier component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



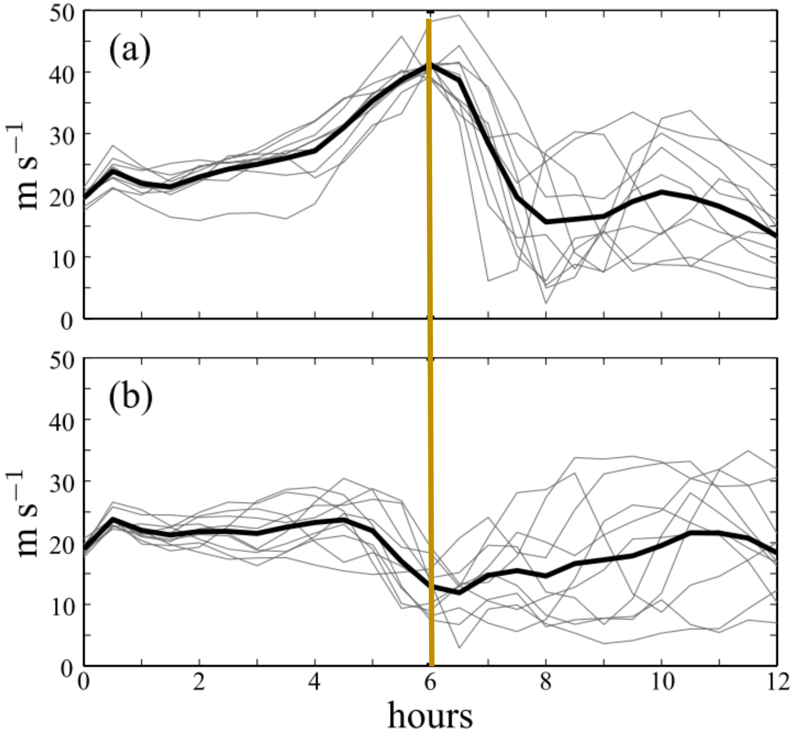
Differences in the strength of the wave breaking and thermal structure within the valley.

How Sensitive are Downslope Winds to Small Variation in Upstream Conditions?

T-REX IOP 6 (March 25, 2006)



Reinecke and Durran (2009)



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.

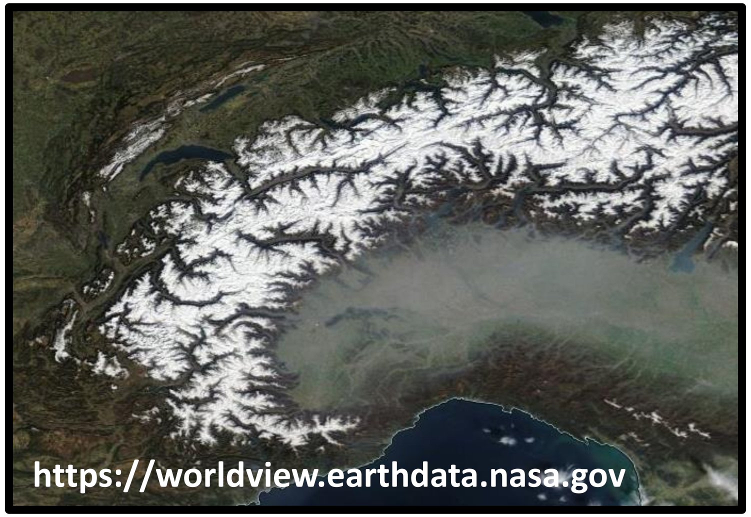
Multi-Scale Interactions and Predictability of Orographic Flows

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

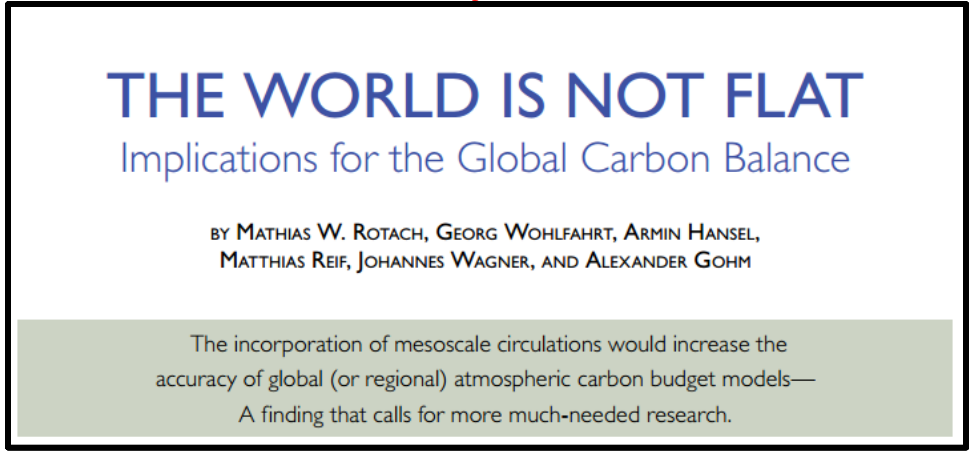
Related Research Areas

- TEAMx has started: MoU, review papers, workshop.
- Scientific scope centered on mountain boundary-layer (MBL) exchange processes.
- Implementation details and connections with related research areas (atmospheric convection, trace gas transport) currently being defined.
- Funding: bottom-up approach, partners fund themselves.
- First two funded projects:
  - CROSSINN (PI Bianca Adler, KIT)
  - ASTER (PI Manuela Lehner, UIBK)

1. Air Pollution



2. Global Carbon Cycle



THE WORLD IS NOT FLAT

Implications for the Global Carbon Balance

BY MATHIAS W. ROTACH, GEORG WOHLFAHRT, ARMIN HANSEL, MATTHIAS REIF, JOHANNES WAGNER, AND ALEXANDER GOHM

The incorporation of mesoscale circulations would increase the accuracy of global (or regional) atmospheric carbon budget models— A finding that calls for more much-needed research.

Summary

TEAMx

- TEAMx has started: MoU, review papers, pre-campaign projects, Workshop,....
- Scientific focus on mountain-induced exchange processes,
- Accurate representation of these processes essential for quality of short- and long-term predictions over complex terrain,
- Signficiant impact on societaly relevant problems (harvesting wind energy, air pollution/air quality, hydrology, regional climate change impacts),
- Funding: bottom-up approach, partners bringing their own funding,
- Newly funded projects:
    - CROSSINN (PI Bianca Adler, KIT)
    - ASTER (PI Manuela Lehner, UIBK)

Objectives and methods	Primary focus	Target
Process knowledge	Micro- and meso-scale processes in the mountain boundary layer.	Quantitative understanding of regional water, energy and mass exchange, basis for parameterization design.
Observations; TEAMx joint experiment(s)	Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations.	Quality-controlled observational data pool, available for high-resolution model verification and for parameterization development.
Modelling weather and climate	*Models right for the right reason*, that is: identification and reduction of model biases and uncertainties over complex terrain.	Local forecasts over mountains with similar quality as over flat terrain, and less reliant on model output post-processing.
Weather and climate services	Air quality, hydrology, climate change scenarios (e.g., elevation-dependent warming)	Quality of services over complex terrain not limited by the accuracy of weather and climate information.

TEAMx

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Thank you!

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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)

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

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.

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