Why you should remember what TEAMx means

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

Part I

- Motivation
- TEAMx

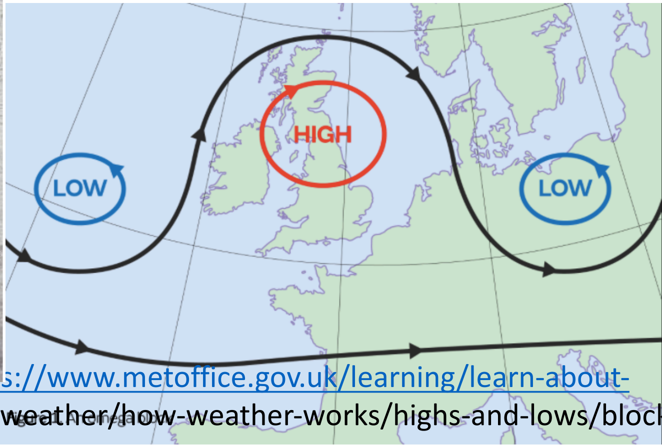
Part II

- ACINN activites
- i-Box & some results....

Mountain Weather and Climate

- long tradition
  - → orographic precipitation
  - → gravity waves, ~ breaking
  - → blocking
  - → Föhn, Bora & co
  - → dynamic features
- Alpex, Pyrex, MAP

http://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

Mountain Weather and Climate

- common interest
  → impact of mountains on state of the atmosphere
  → e.g., how does ‘a mountain’ change the production of rain?
  → how does ‘a mountain’ modify the flow?
  etc., etc. ...
- mountain → atmosphere perspective
- from a global perspective:
  → ‘mountain’ is part of the surface
  → character of the surface

Exchange

- character of the surface
  → determines the *exchange* between the atmosphere and the earth
  → *coupling* of the atmosphere with the surface
- mountain ↔ atmosphere perspective
- traditionally: this is the role of the boundary layer
  → exchange of heat, mass and momentum *at the surface*
  → transport to the ground / away from the ground
- example: CO_2 budget

Fate of Anthropogenic CO_2 Emissions

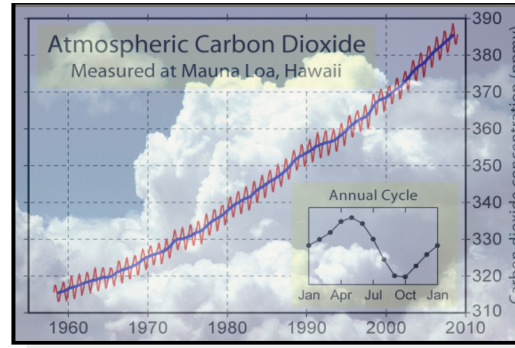
9.3 ± 0.5 PgC y^{-1}

+

1.0 ± 0.5 PgC y^{-1}

4.5 ± 0.1 PgC y^{-1}

45%



3.1 ± 0.9 PgC y^{-1}

30%

Calculated as the residual of all other flux components

26%

2.6 ± 0.5 PgC y^{-1}

Average of 5 models

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

Land surface carbon uptake

Overall:

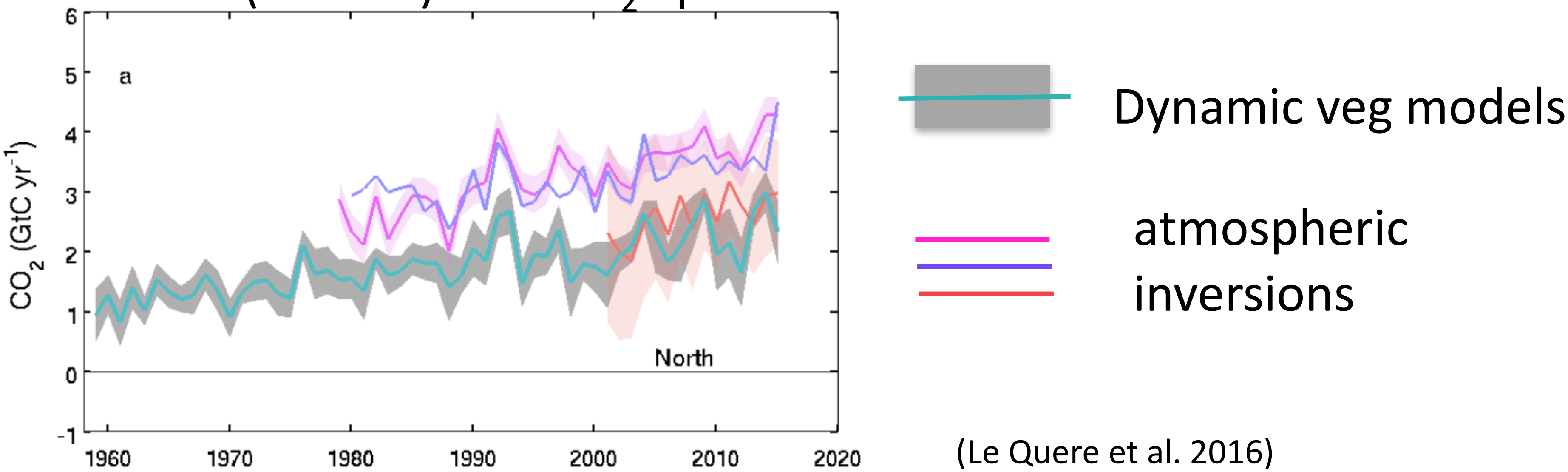
→ about equal shares go to oceans / land surface

→ uncertainty of land uptake the largest

→ land uptake modeled depends on method (2.3 vs. 2.7/3.8/3.8 PgC y^{-1} for 2006-2015)

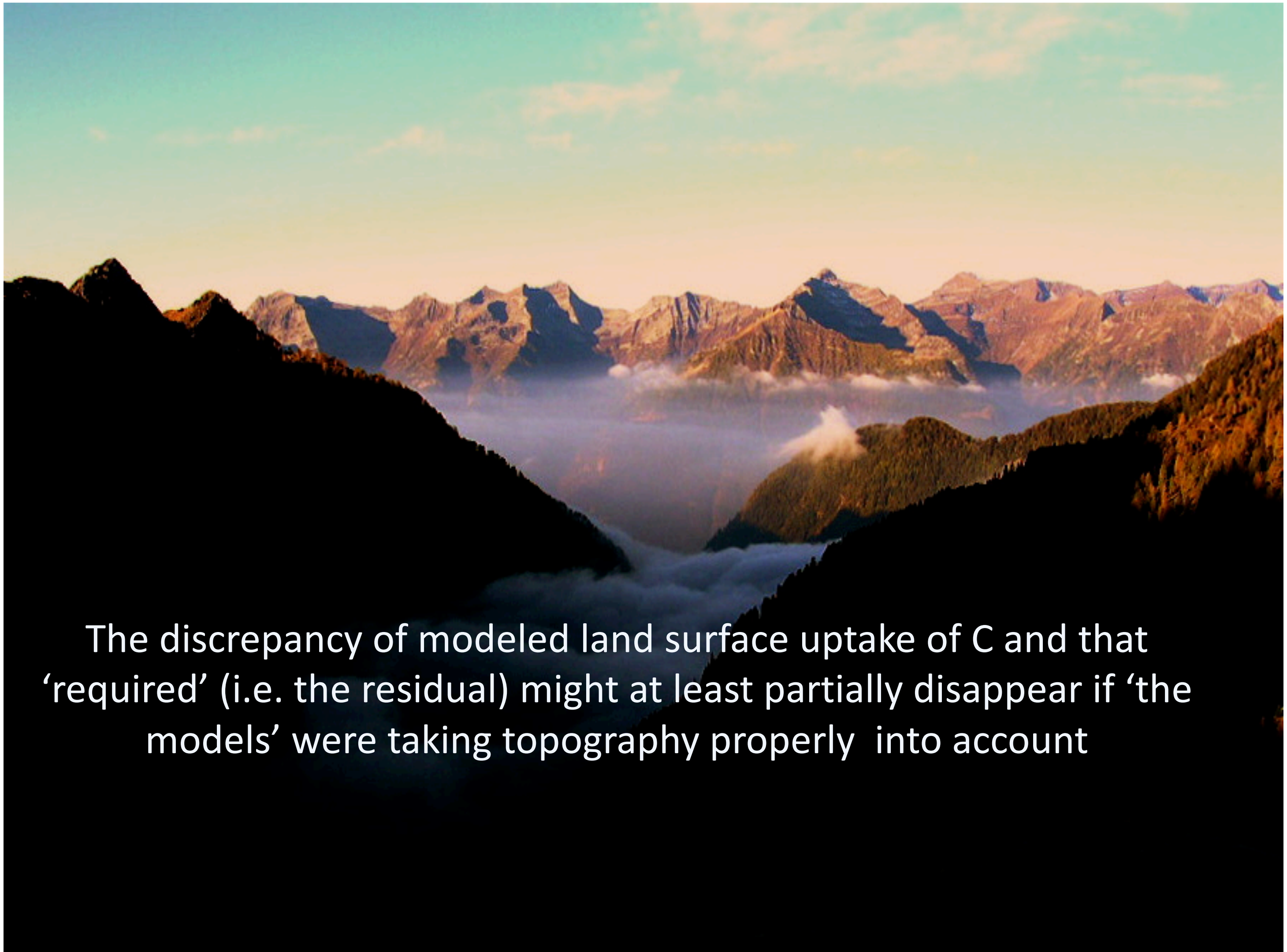
→ *modeled*: does not take into account terrain

NH (> 30° N) land CO_2 uptake



(Le Quere et al. 2016)

Hypothesis


The discrepancy of modeled land surface uptake of C and that
'required' (i.e. the residual) might at least partially disappear if 'the
models' were taking topography properly into account

Modeled land surface uptake

model approaches:

- atmospheric inverse modeling

  vs:

- dynamic global vegetation models, including

  → ecosystem modeling

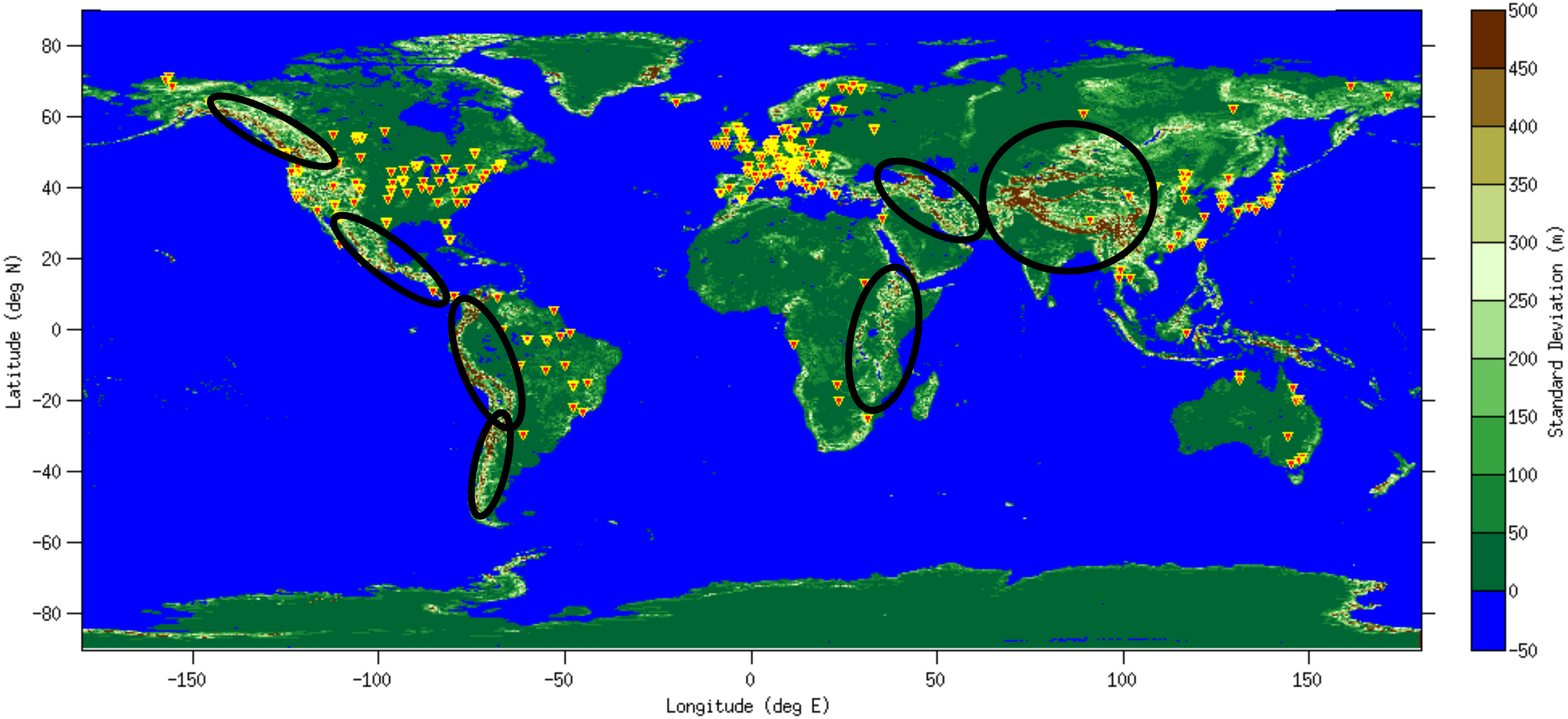
  → inventories

  → upscaling from ‘flux towers’

all rely on measurements: [CO_2] or $\overline{w'CO_2'}$

Flux tower sites

Standard deviation subgrid-scale topography (20km)

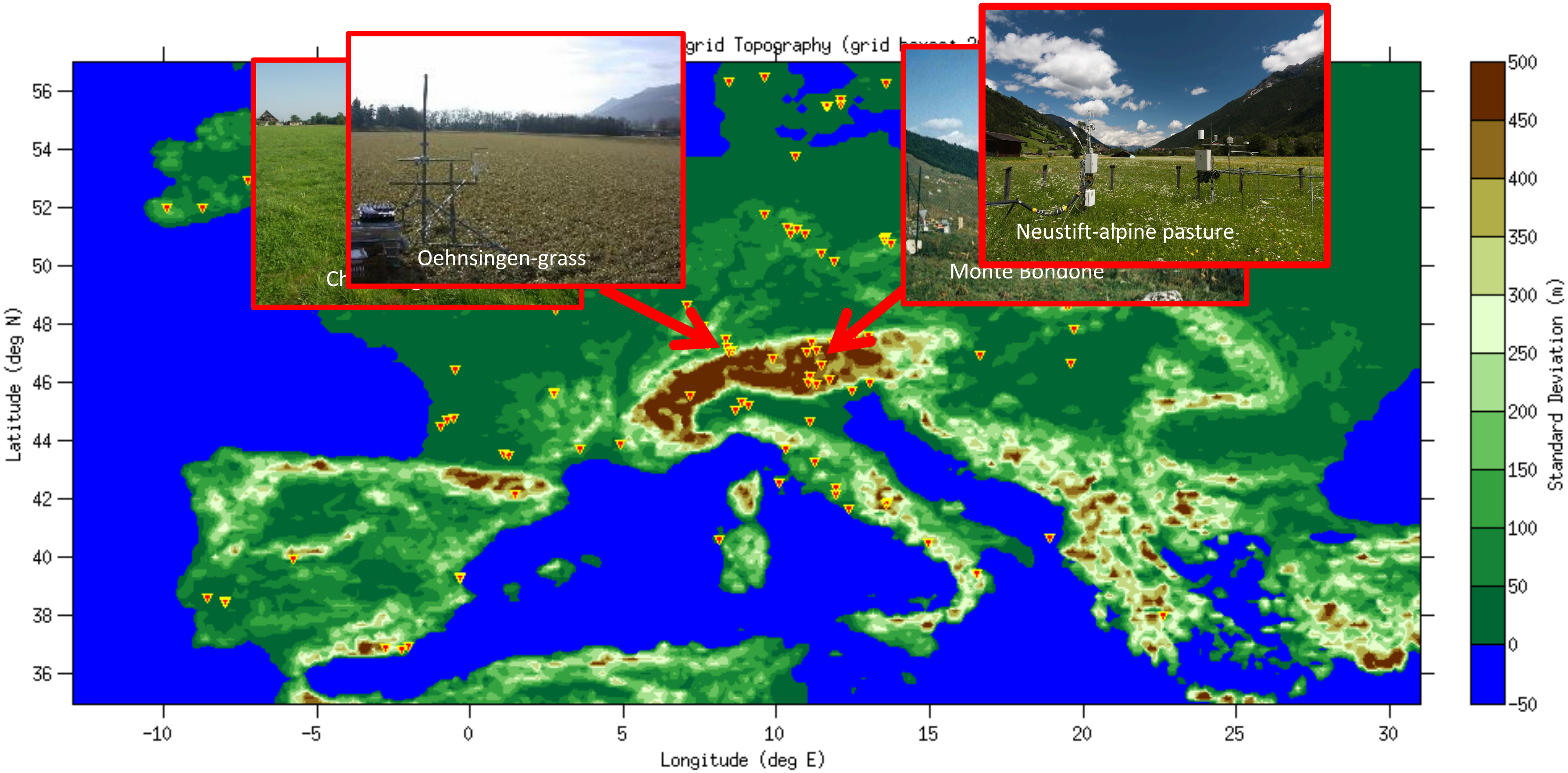


→ represent ecosystems

→ but not topography

Rotach et al. (2014), BAMS

Flux tower sites



→ represent ecosystems

→ but not topography

universität innsbruck

Modeled land surface uptake

model approaches:

- atmospheric inverse modeling

  vs:

- dynamic global vegetation models, including

  → ecosystem modeling

  → inventories

  → upscaling from ‘flux towers’

→ rely on ‘boundary layer exchange’

Exchange over topography

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.

JULY 2014 BAMS | 1021

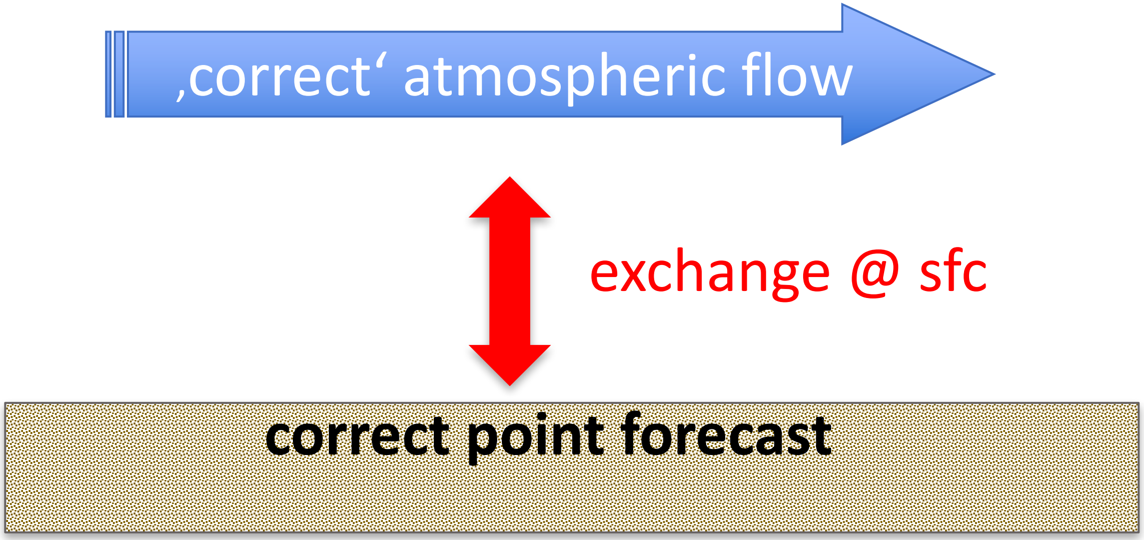
AMERICAN METEOROLOGICAL SOCIETY

Recent developments (since MAP)

- better model resolution
  → e.g., COSMO-1 for NWP
  → EURO-CORDEX: 12.5 km grid spacing for regional climate
  → 2.2 km grid spacing: decade-long climate simulations (Ban et al. 2014)
- more realistic terrain
  → need to treat steep(er) slopes
  → parameterizations are not devised for non-flat terrain
- climate change
  → requires impact modeling
  → need: the right temperature at mtn. surface (not only the mtn. sfc temperature that yields the 'best precipitation')

A Change in the Perspective

- atmospheric models (weather and climate)
  → goal: use output as input for *Earth System Services / Climate services*
  → hydrological / agricultural / health / air pollution / …. **applications**



A Change in the Perspective

atmospheric flow: **right for the right reason**

→ if related to traditional (prognostic) variables:
downscaling (diagnosing)

→ for example: heat wave (temperature ...), wind power

→ if application model needs more: such as *turbulence, PBL height ?*

→ for example: air pollution modeling (friction velocity, TKE, PBL height, ...)

A new international initiative

TEAMx

Transport and Exchange processes in the Atmosphere over Mountainous terrain

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


Innsbruck, 4.9. 2015

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

Exchange of energy, momentum & mass

Scale interactions

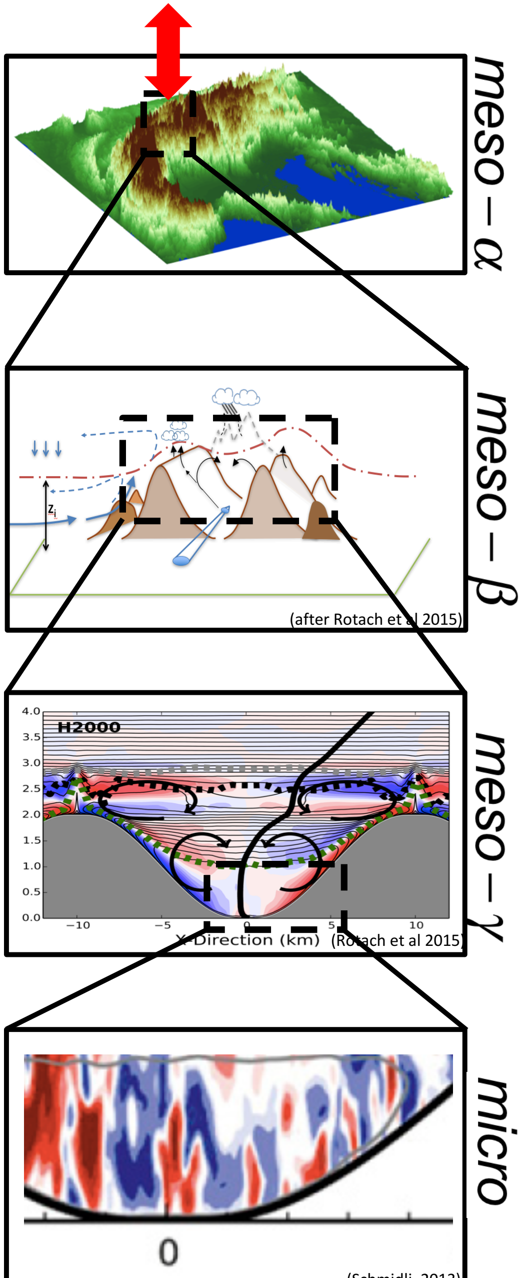
- cyclogenesis, instability
- PV
- blocking

- impact of synoptic flow
  - stability/ strength/ direction
- interaction between 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

θ, u, H_2O, CO_2,...



Processes @ scale

- How does MT influence
  - Mountain drag (u)
  - Heat (energy) budget (θ)
  - Mass exchange (CO_2; H_2O)
- Orographic precipi-tation
  - specific questions

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

- valley geometry, orientation
- surface type(s)
- valley turbulence (TKE)
- convective initiation (CI)

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

topics:

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

→ ***and their interactions***

Exchange of energy, momentum & mass

Scale interactions

- cyclogenesis, instability
- PV
- blocking

- impact of synoptic flow
  - stability/ strength/ direction
- interaction between different valleys
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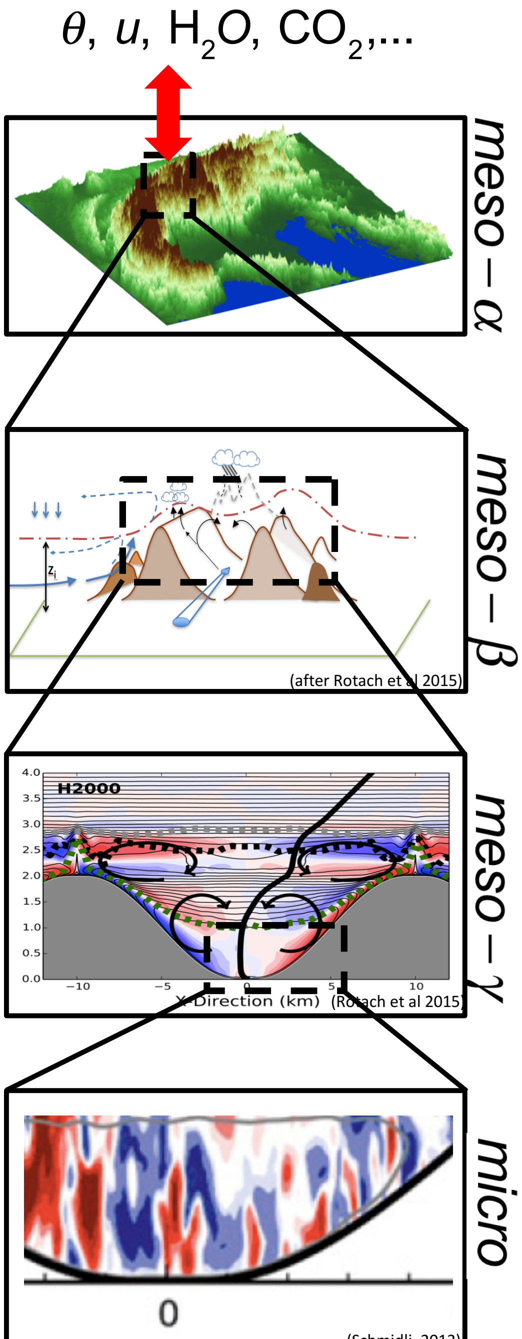

Processes @ scale

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

methods:

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

goal:

→ coordinated *experiment*

TEAMx

Research questions

$\longrightarrow$ how does mountainous terrain impact exchange to the free atmosphere of energy, mass and momentum? (which processes, interaction, abundance, ...)

$\longrightarrow$ do we understand the relevant processes quantitatively?

$\longrightarrow$ are current models (regional climate, NWP) able to adequately reproduce these processes?

$\longrightarrow$ do we need a sgs-parameterization (*as gravity wave drag*) for $\mathcal{O}$(10 km) grid spacing models?

$\longrightarrow$ how does mountainous terrain affect air quality?

TEAMx

partners (so far…)**:**

[+/- represented in CIG]

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

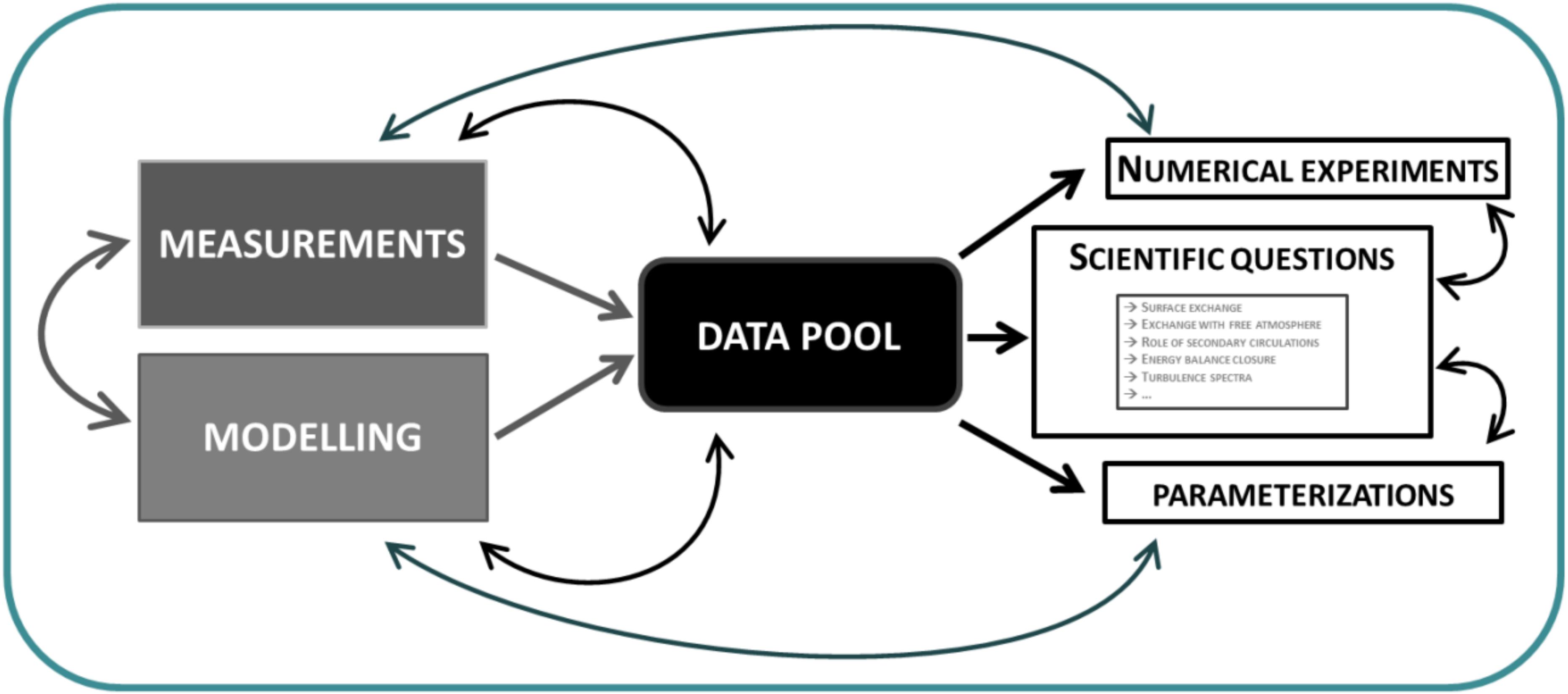
- ZAMG
- MeteoSwiss
- Meteo France
- NCAR

Part II

ACINN activities (wrt TEAMx):

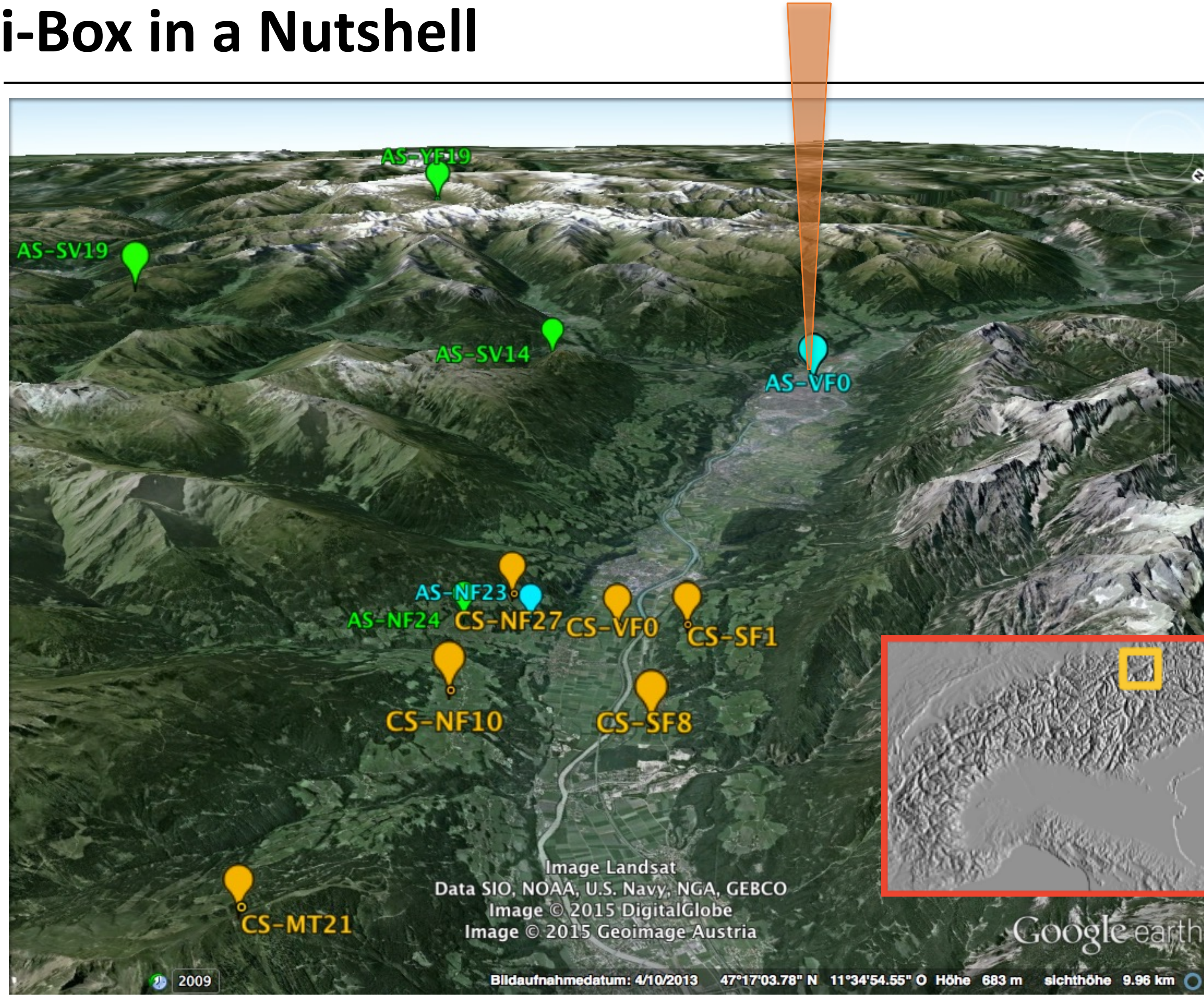
- i-Box
  → cluster of various projects
  → observational network *plus* numerical modeling
  → recent BAMS paper (Rotach et al. 2017, DOI:10.1175/BAMS-D-15-00246.1)
- idealized-terrain simulations
  → Project QUEMONT (Alexander Gohm)

i-Box in a Nutshell



Rotach et al. (2017)

i-Box in a Nutshell



How important are 3D effects for the simulation of TKE structure in a major Alpine valley?

Brigitta Goger[1]

M. W. Rotach[1], A. Gohm[1], O. Fuhrer[2], I. Stiperski[1], A. A. M. Holtslag[3]

[1]Institute of Atmospheric and Cryospheric Sciences, University of Innsbruck, Austria

[2]Federal Office for Meteorology and Climatology (Meteo Swiss), Zürich, Switzerland

[3]Meteorology and Air Quality Section, Wageningen University, The Netherlands

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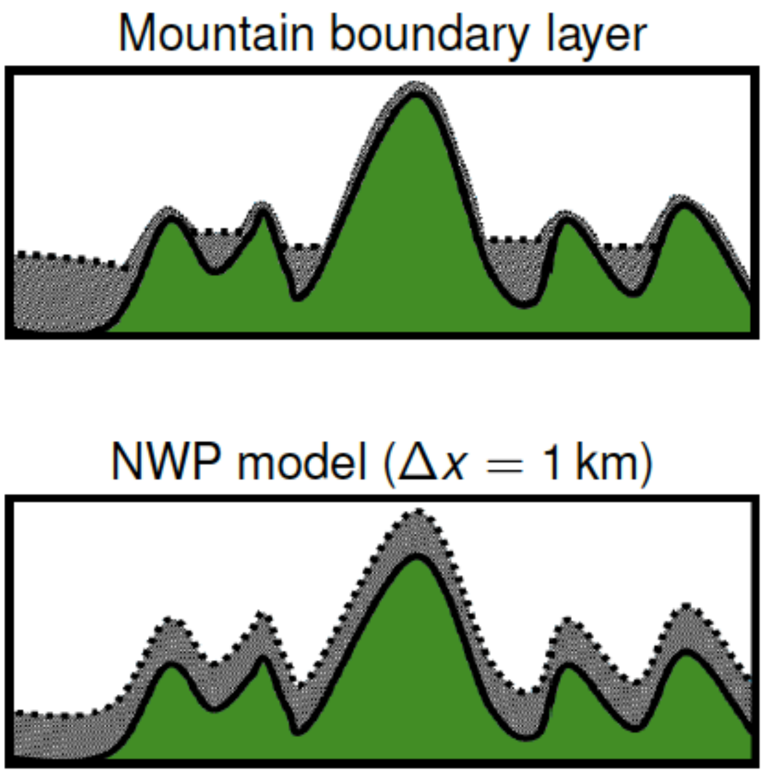
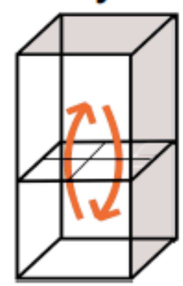
Motivation & Goals



Rotach and Zardi (2007)

Common Turbulence Parameterizations

- Developed for hhf terrain
- 1D turbulence parameterizations
- Only vertical exchange

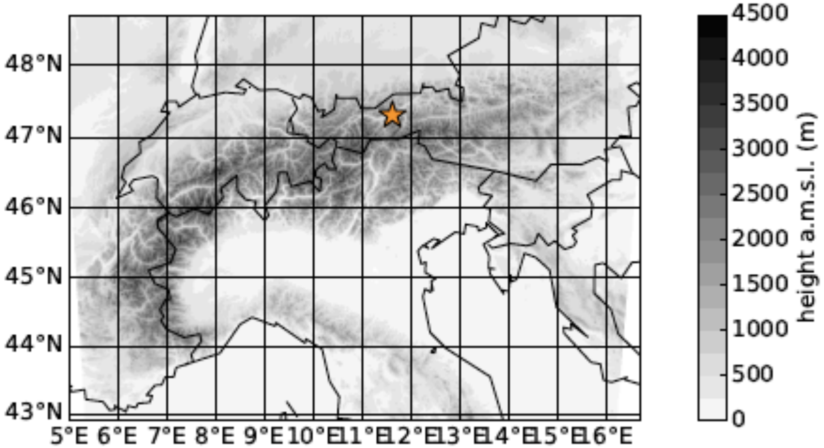


- TKE underestimation

How do 3D effects influence the simulation of TKE in complex terrain?

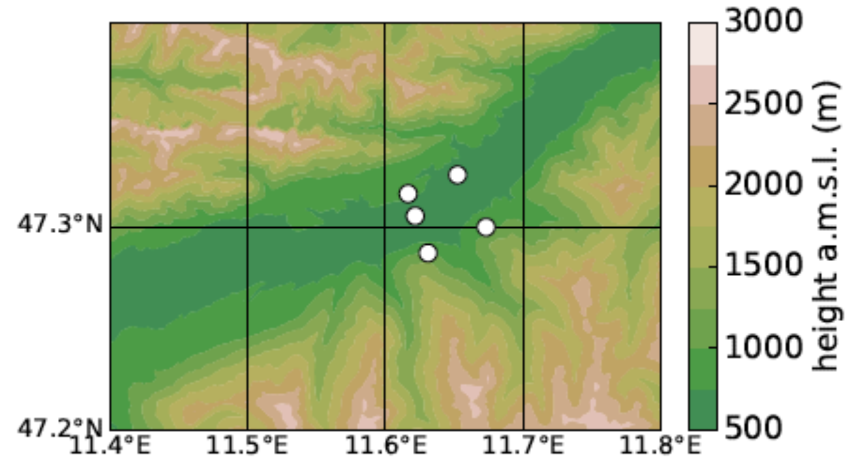
Turbulence Parameterization Evaluation

NWP Model COSMO



- Similar to operational setup of MeteoSwiss (MCH)
- Initial & boundary conditions fom MCH
- $\Delta x = 1.1\,\mathrm{km}$
- 80 vertical levels ($\Delta z_{min} = 10\,\mathrm{m}$)

i-Box Observations



- 5 flux towers
- TKE observations
- TKE budget terms:
  Buoyancy production
  Shear production
  Dissipation
  Turbulent Transport

1D Turbulence Parameterization

- 1.5-order turbulence closure (Mellor-Yamada)
- Prognostic equation for auxiliary variable q^2=2TKE

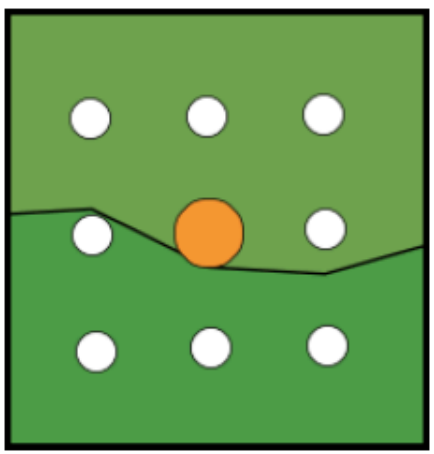
$$\underbrace{\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)}_{\text{tendency}} = - \underbrace{K_H \frac{g}{\theta}\frac{\partial \theta}{\partial z}}_{\substack{\text{buoyancy} \\ \text{production/consumption}}} + \underbrace{K_M \left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right]}_{\text{vertical shear production}}$$

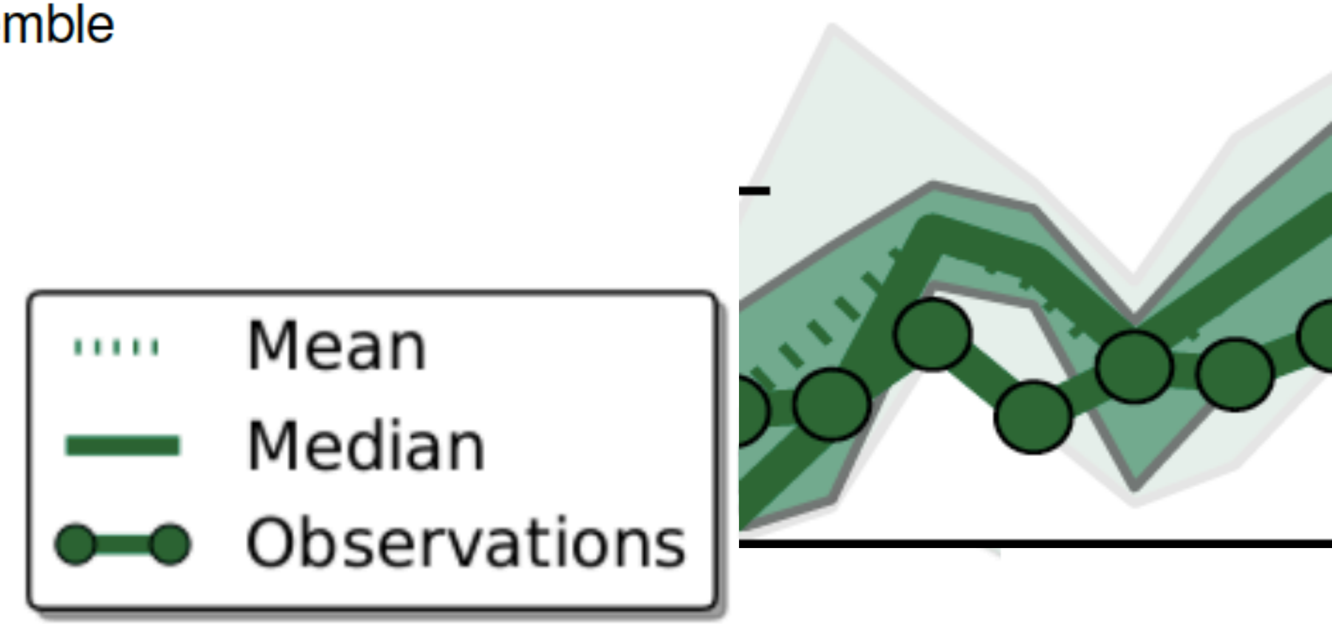
$$+ \underbrace{\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\left[\alpha_{\mathrm{tke}}\overline{\rho}\lambda_l q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right]}_{\text{vertical turbulent transport}} - \underbrace{\frac{q^3}{B_1 \lambda_l}}_{\text{dissipation}} \qquad (1)$$

Hybrid Turbulence Parameterization

Methods

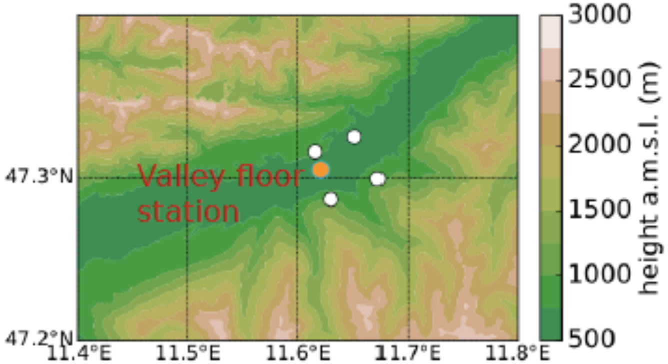
- Case studies:
  Daytime up-valley wind
  Nighttime down-slope flows
- TKE budget evaluation of both turbulence parameterizations
- Grid point ensemble





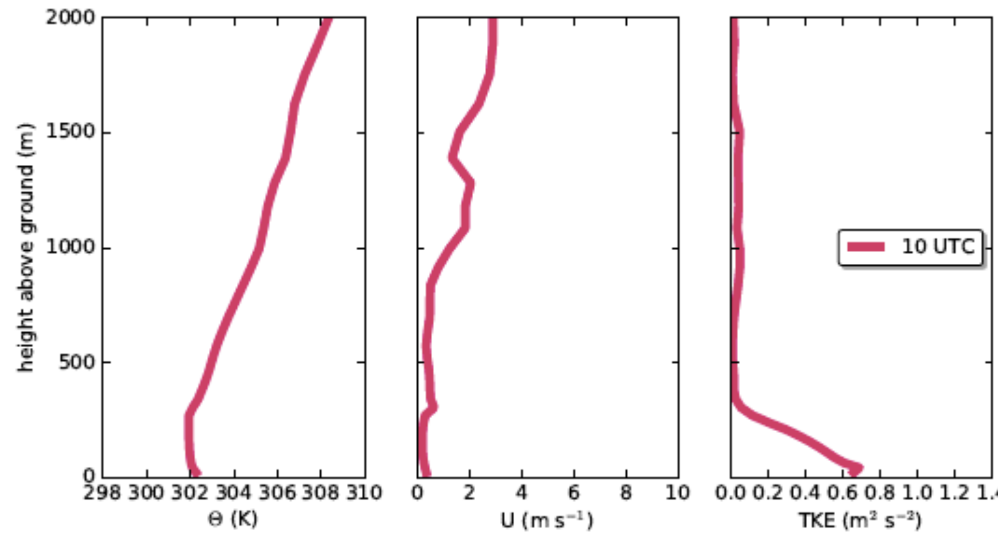
Valley Floor Station | Daytime

ACINN

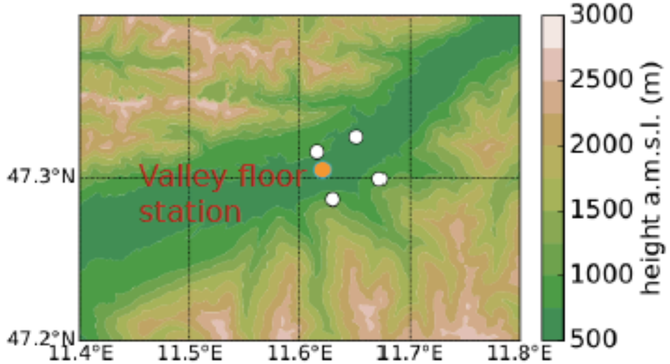


July 01, 2015 init 00 UTC

Before noon: convective boundary layer

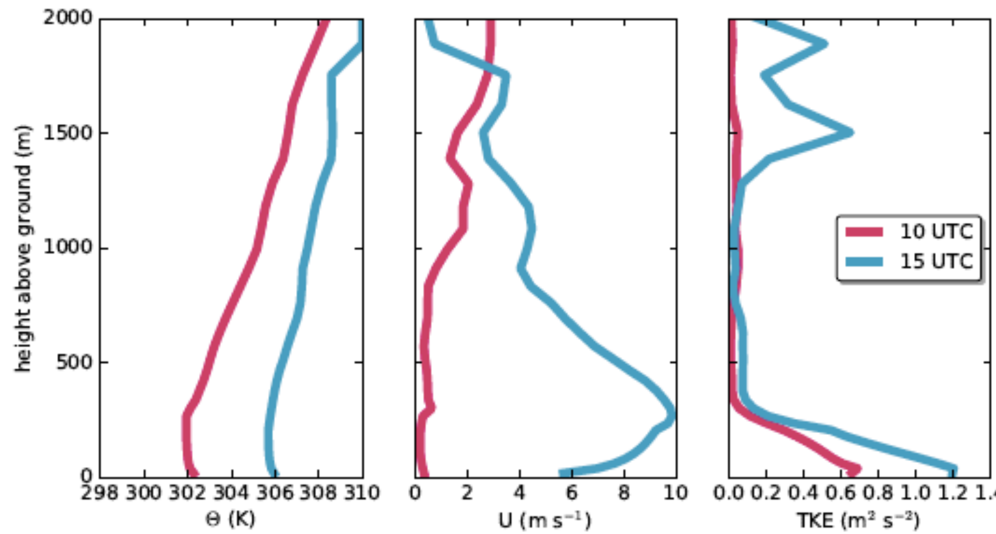


Valley Floor Station | Daytime

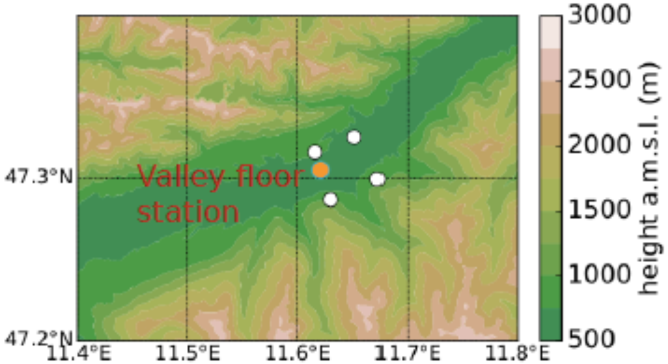


July 01, 2015 init 00 UTC

Afternoon: strong up-valley wind



Valley Floor Station | Daytime



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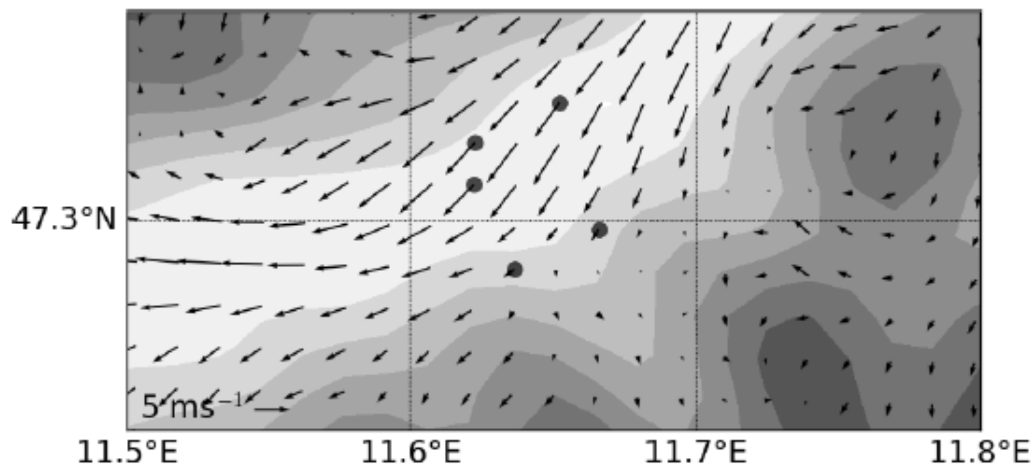
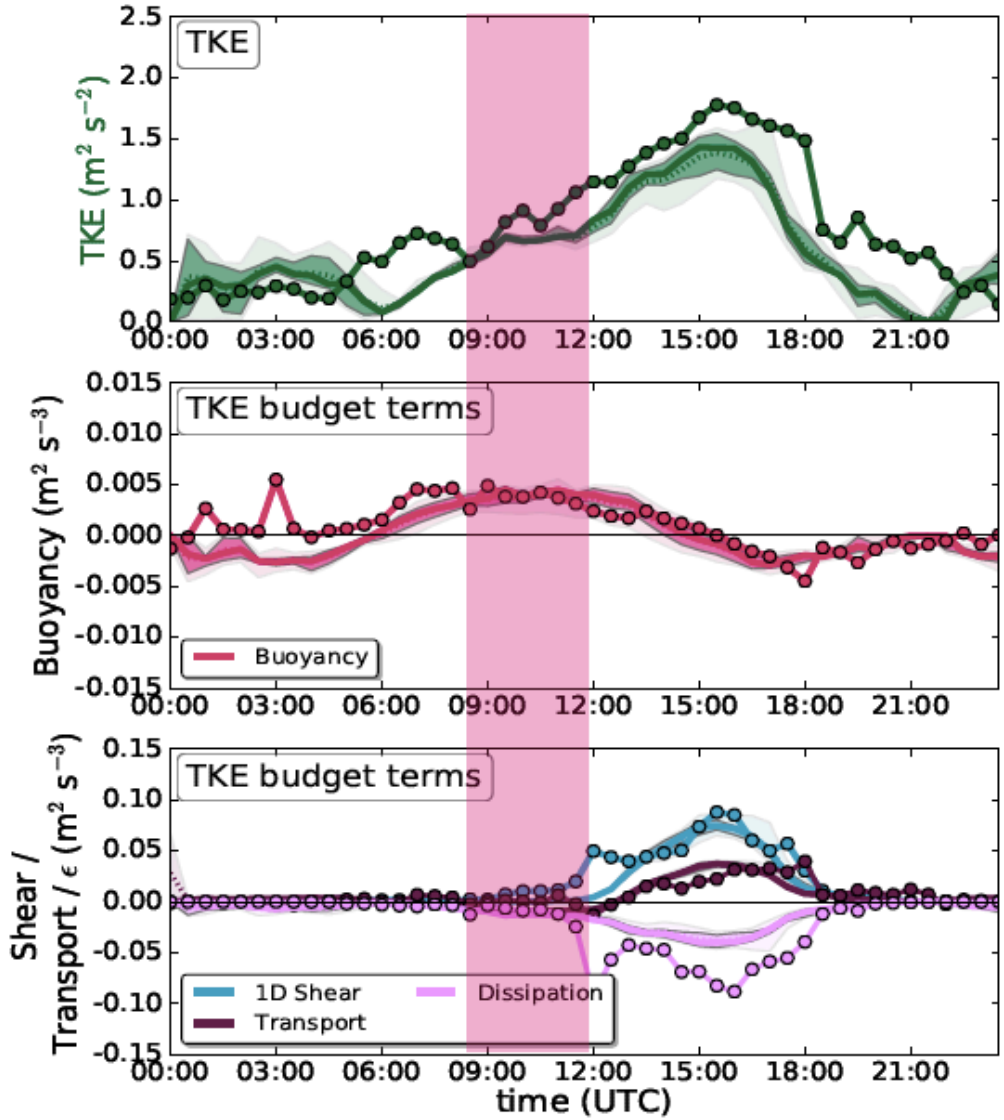
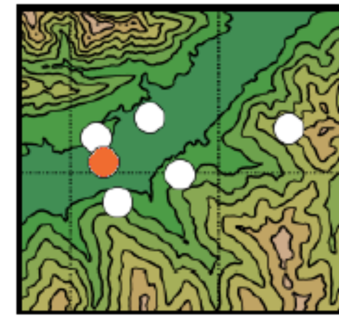


Wind field at 15 UTC

Daytime TKE | 1D Turbulence





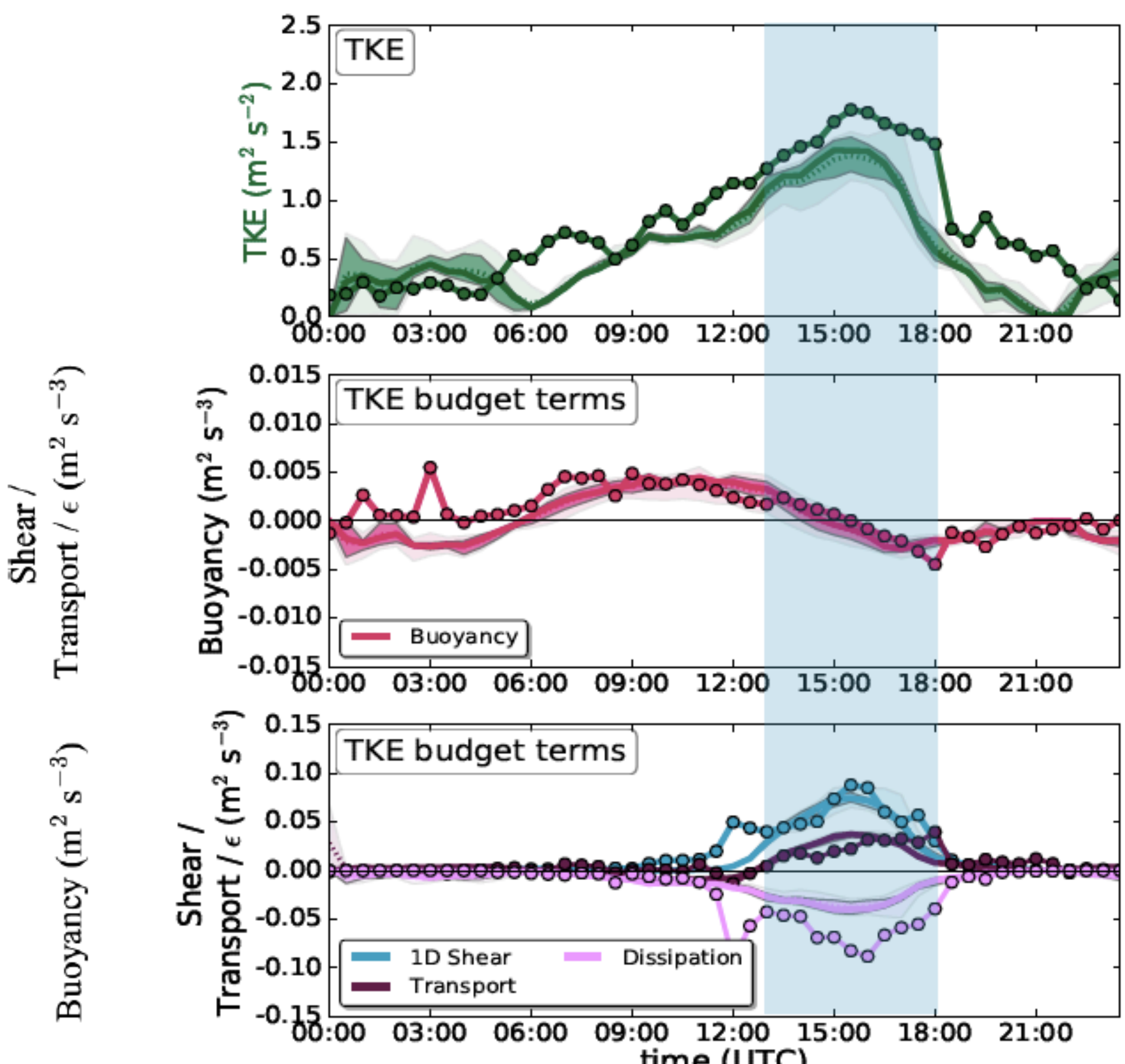
Before noon:

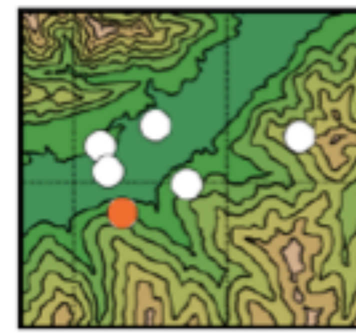
Buoyant production dominates

TKE well simulated by the model

Daytime TKE | 1D Turbulence

ACINN



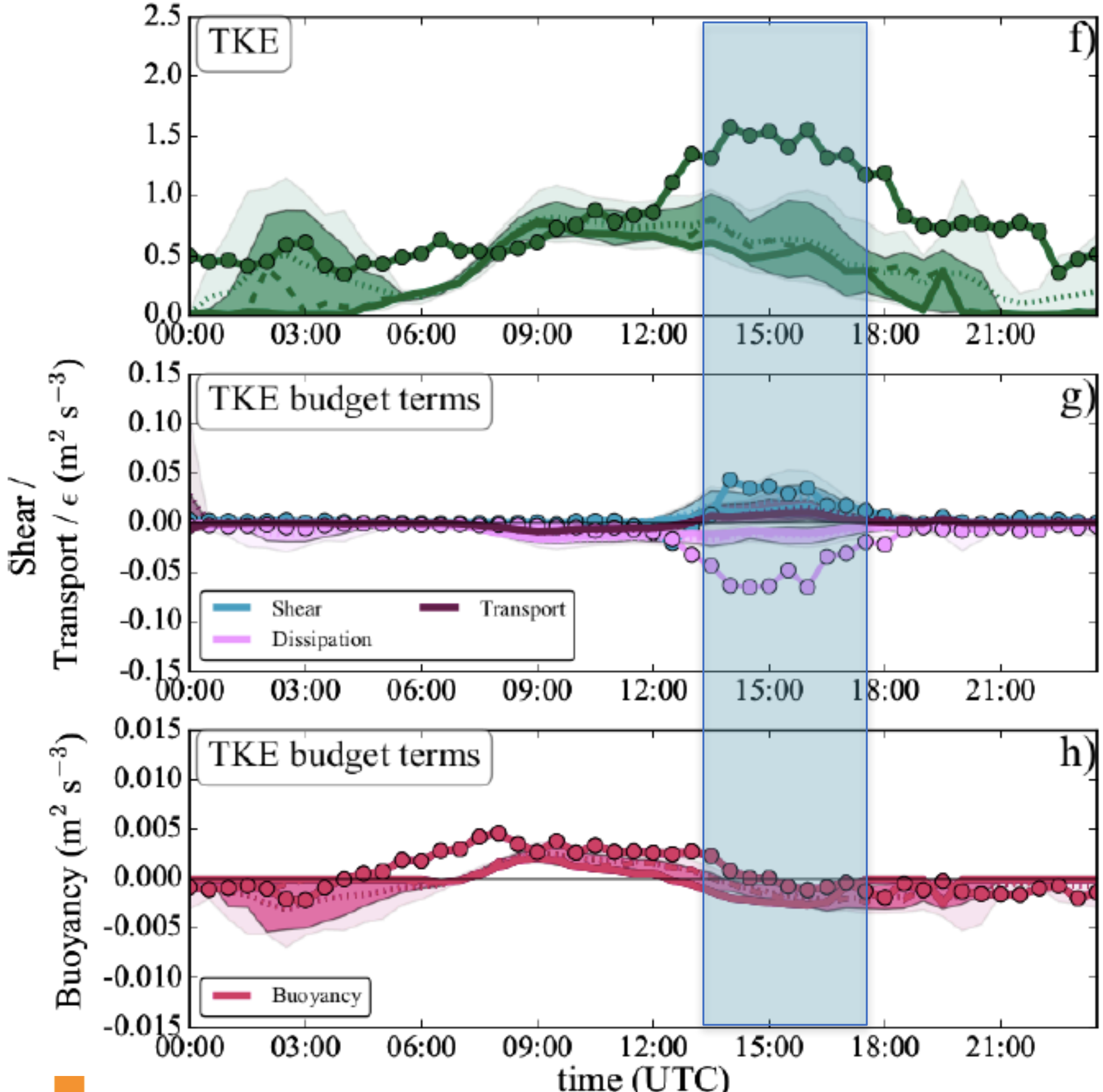


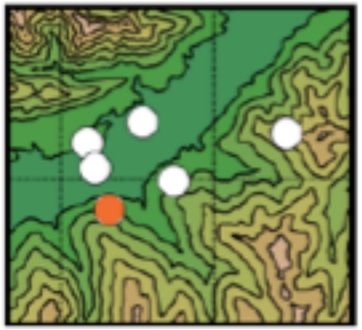
Afternoon:

Vertical shear generation together with valley wind

TKE underestimated

Daytime TKE | 1D Turbulence





Afternoon:

Vertical shear generation together with valley wind

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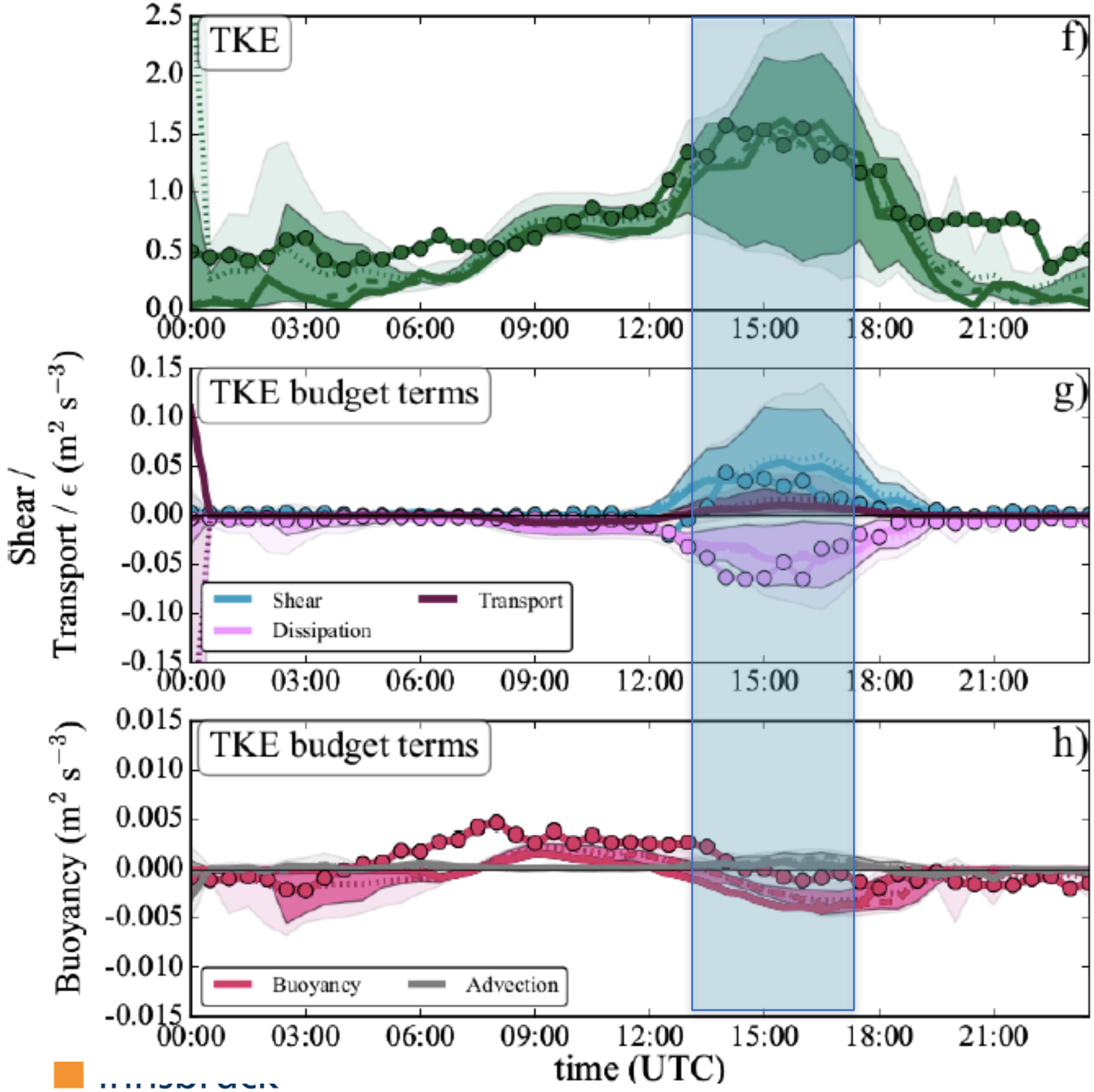
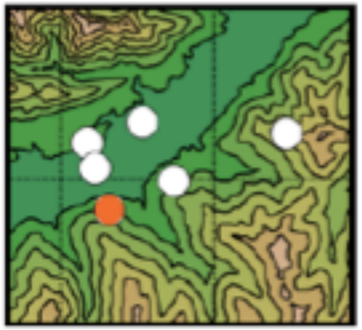
Daytime TKE | Hybrid Turbulence



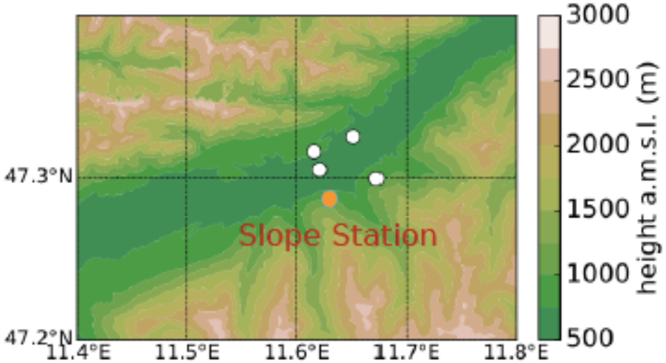


Afternoon:

3D shear production

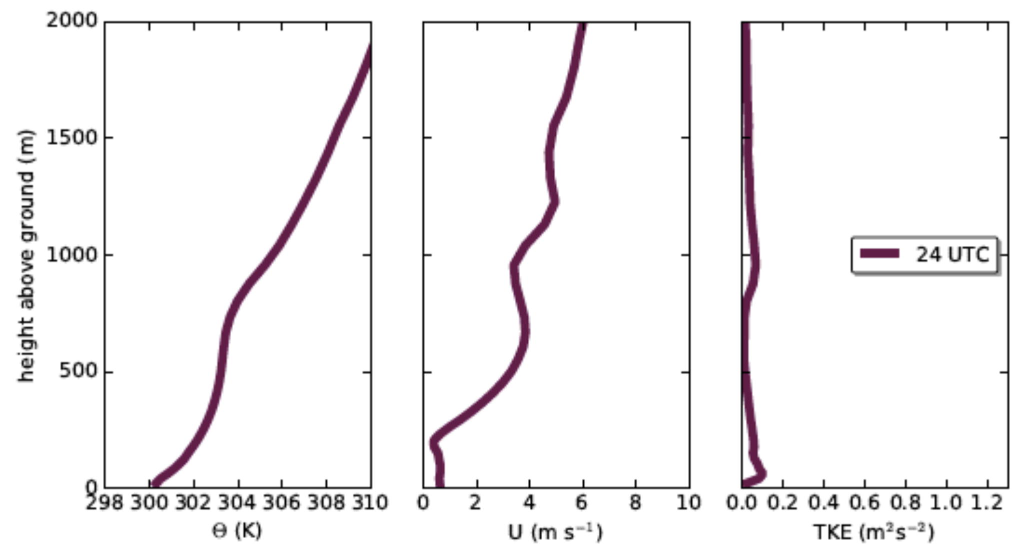
Correct TKE simulation

Steep Slope Station | Nighttime

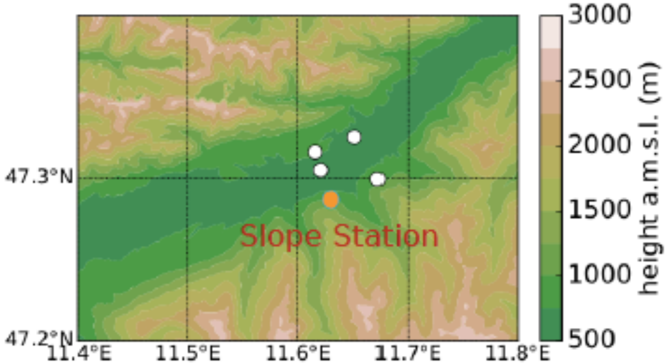


July 01, 2015 init 12 UTC

Nighttime: stable boundary layer

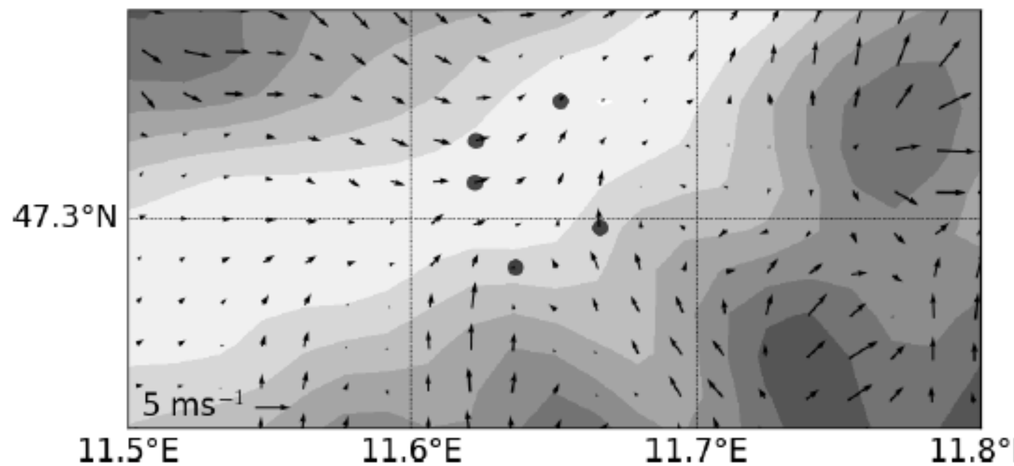


Steep Slope Station | Nighttime



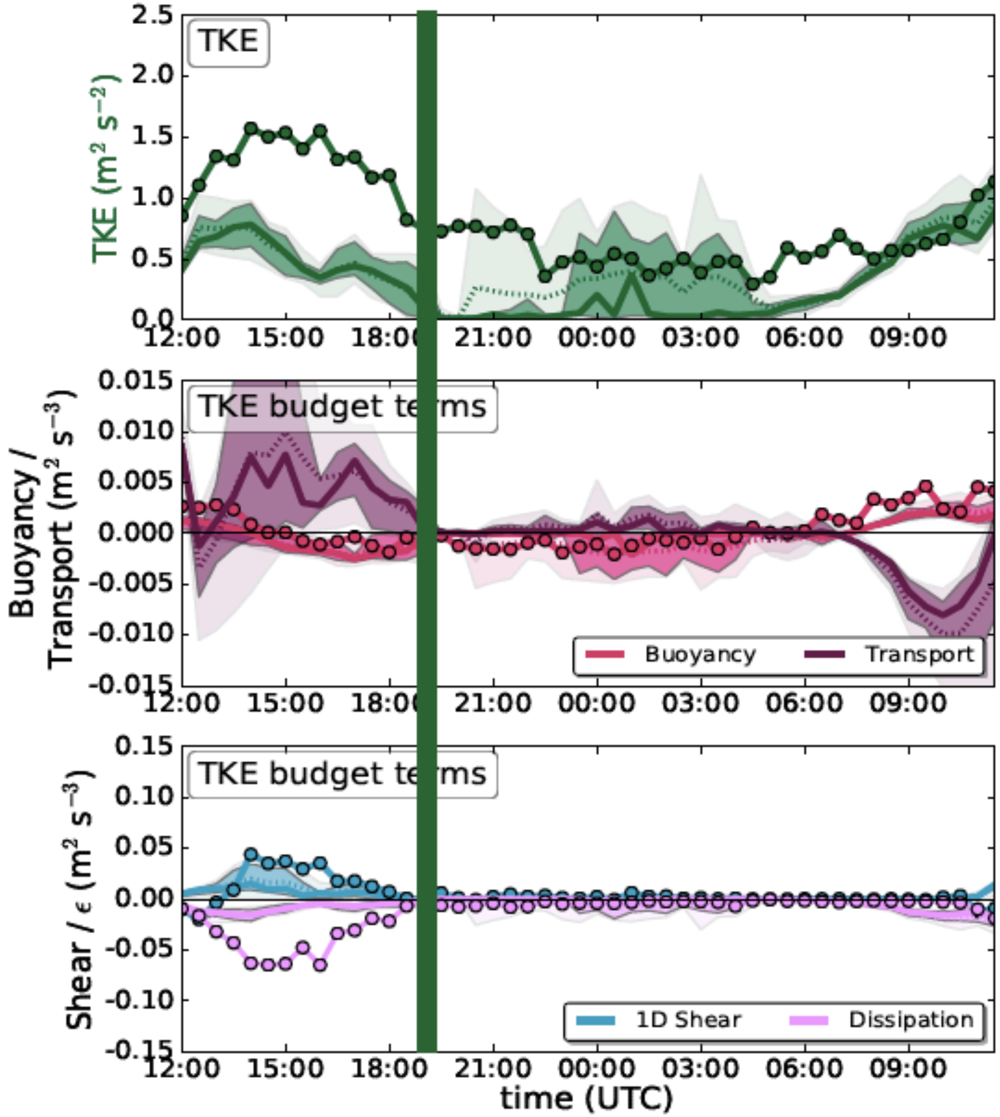
July 01, 2015 init 12 UTC

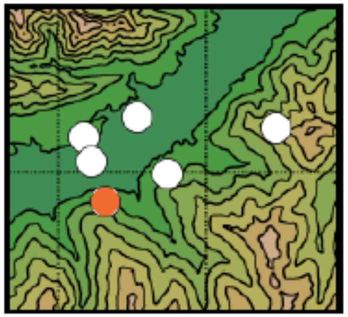
Nighttime: Down-slope flows / Drainage flows



Wind field at 00 UTC

Nighttime TKE | 1D Turbulence

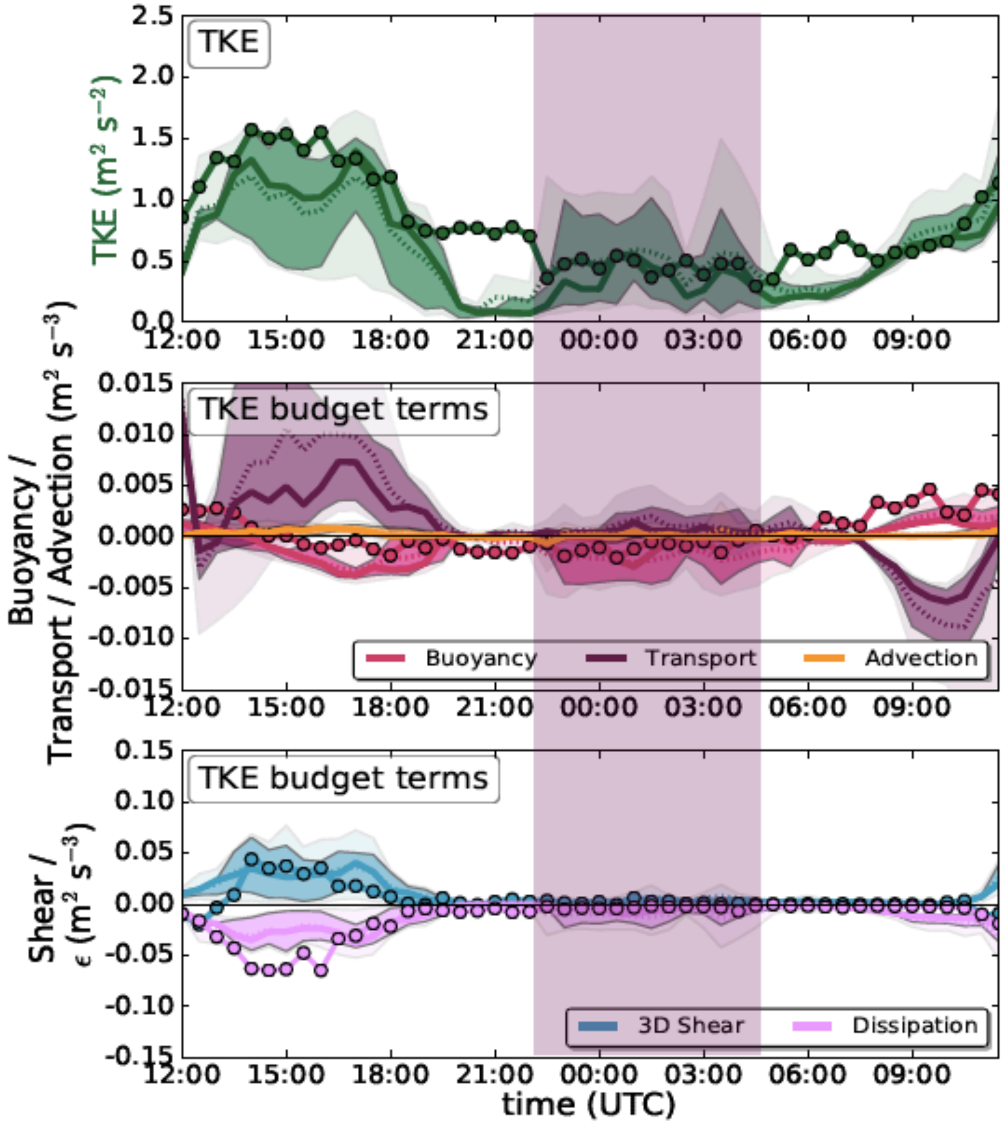


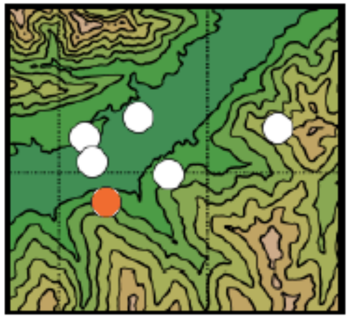


Nighttime:

Model is not able to simulate nighttime TKE

Nighttime TKE | Hybrid Turbulence





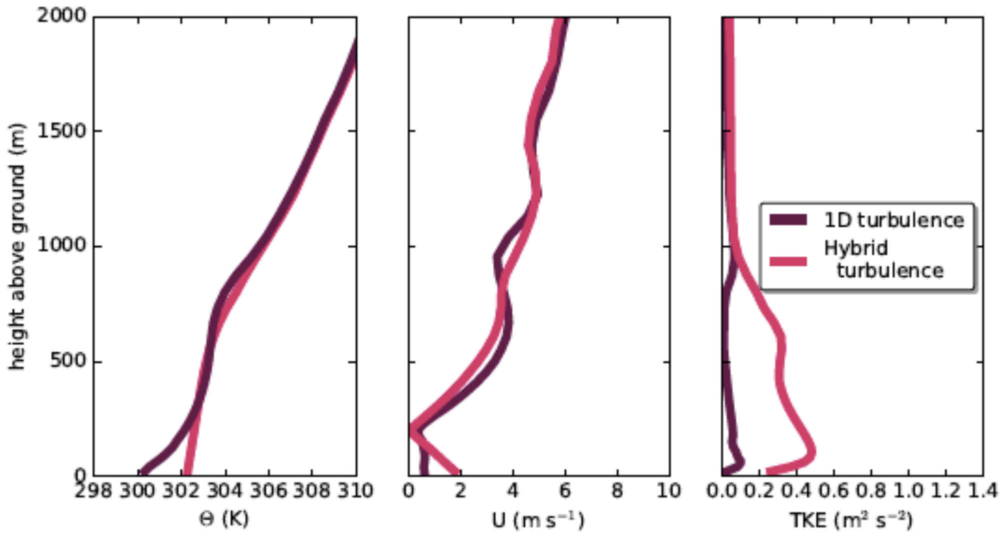
Nighttime:

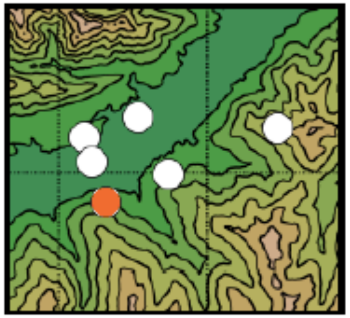
Successful TKE simulation

Transport-dominated

Minor role of TKE advection

Nighttime TKE | Vertical Profiles 24 UTC





Modified TKE structure also at higher elevations

Summary & Conclusions

1D Turbulence Parameterization

- Buoyancy (before noon): 1D turbulence sufficient
- Vertical shear (afternoon): TKE underestimation
- Turbulent Transport (night): no realistic TKE simulation

Hybrid Turbulence Parameterization

- 3D shear (afternoon): Crucial for correct simulation of TKE
- Turbulent Transport (night): Model is able to simulate TKE accordingly
- TKE Advection: plays minor role

Goger et al.: *The Impact of 3D Effects on the Simulation of Turbulence Kinetic Energy Structure in a Major Alpine Valley*, in press BLM

ACINN activities (wrt TEAMx):

- i-Box
  → cluster of various projects
  → observational network *plus* numerical modeling
  → recent BAMS paper (Rotach et al. 2017, DOI:10.1175/BAMS-D-15-00246.1)
- idealized-terrain simulations
  → Project QUEMONT (Alexander Gohm)

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Towards generalizing the impact of surface heating, stratification and terrain geometry on the daytime heat export from and idealized valley.

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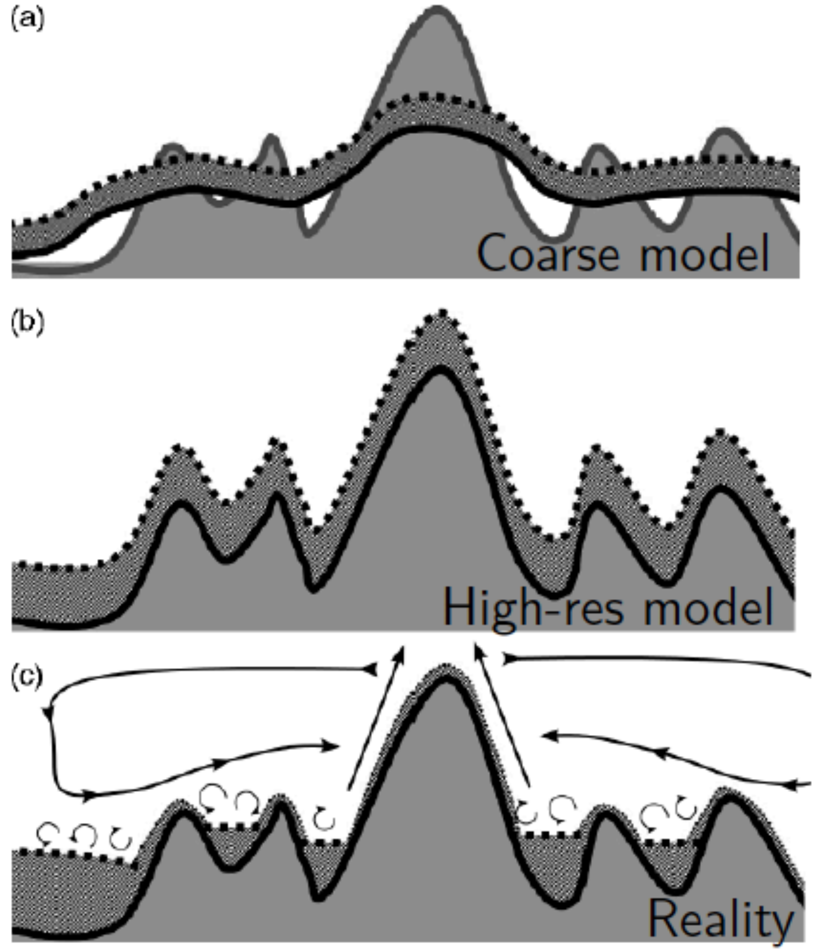
5th of December 2016

Formulation of the Problem

- Global models: too coarse grid for complex terrain
- Unrealistic PBL structure
- Local circulations are not resolved

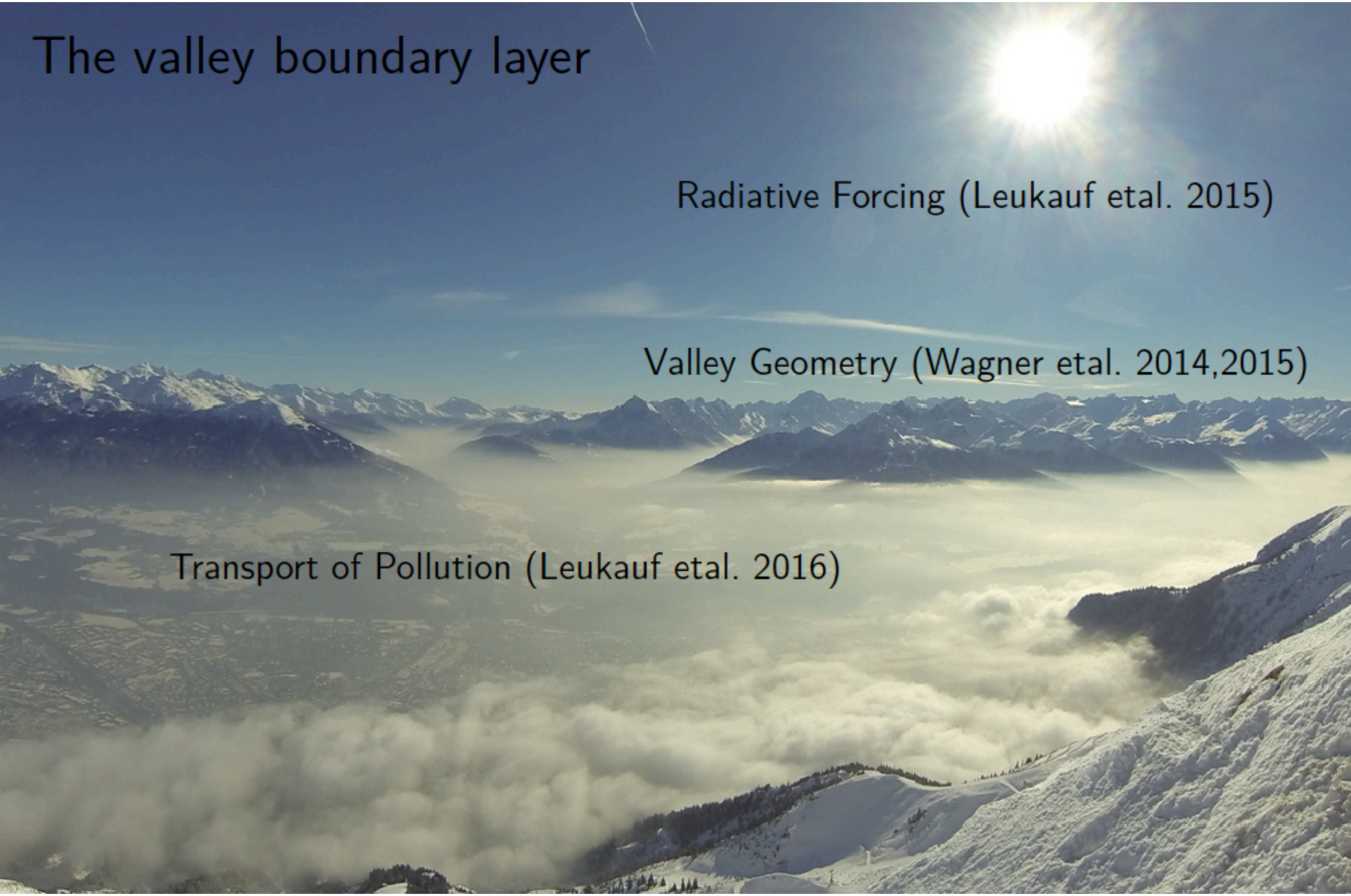
- **Important exchange mechanisms are missing**



After Rotach and Zardi 2007

Alexander Gohm
Quantifying **E**xchange Processes in **Mount**ainous Terrain

The valley boundary layer



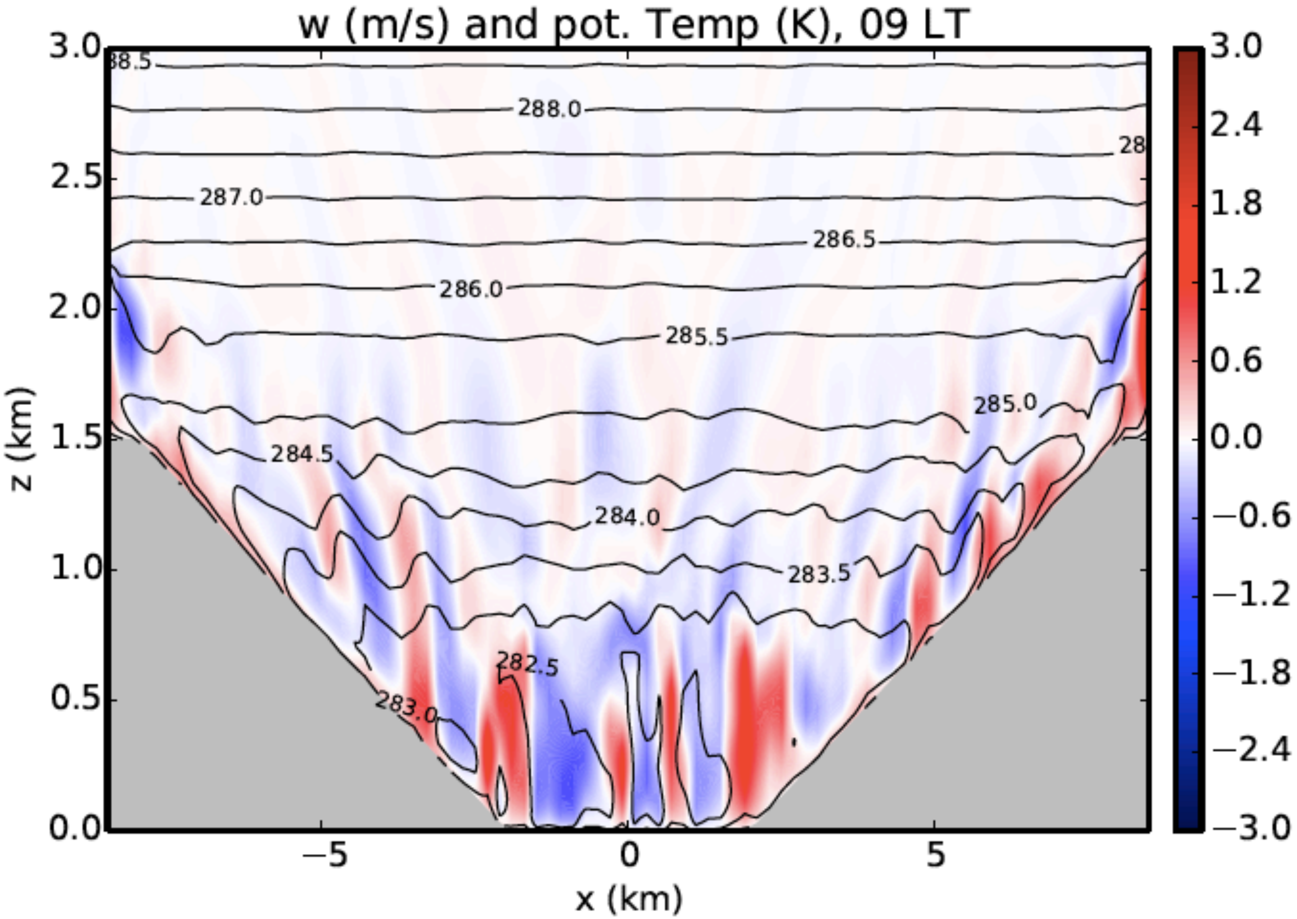
In this talk...

1. Focus on the export of heat
2. Dependence on Stability and Forcing
3. Daytime conditions
4. Impact of Residual Layers

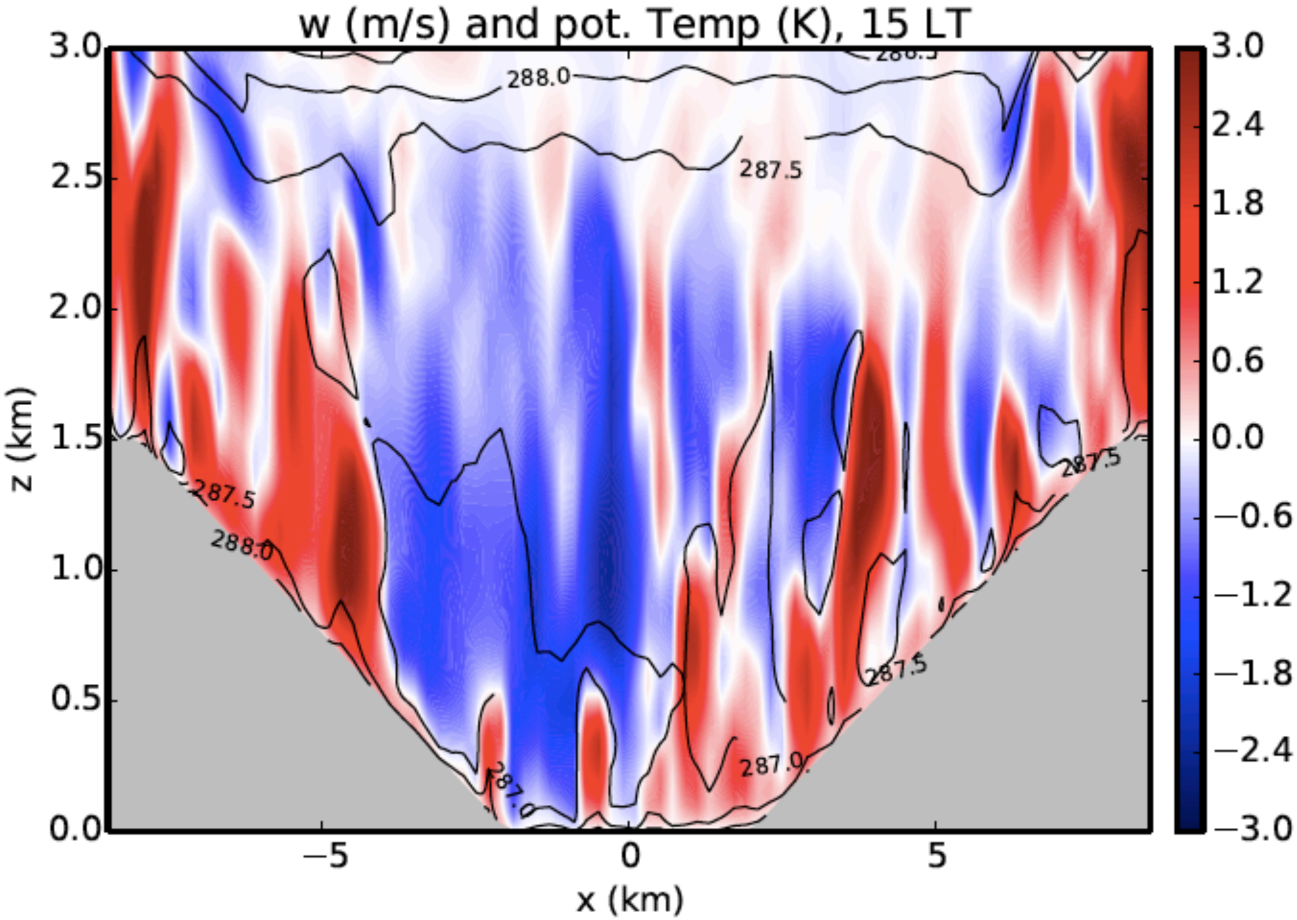
Breakup of a valley inversion

After Whiteman and McKee (1982): Breakup is reached as the valley atmosphere becomes **neutral**

Impact of the breakup



Impact of the breakup



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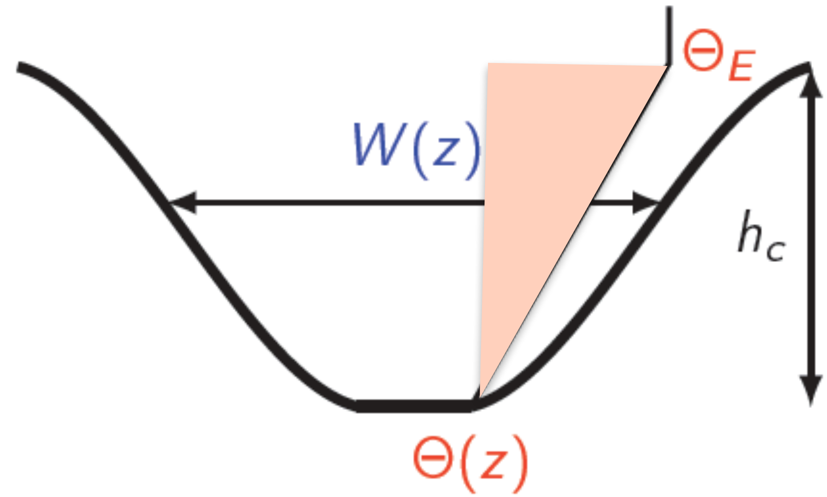
Required, provided and exported energy

At sunrise:

$$Q_{\mathrm{req}} = L_y c_p \int_0^{h_c} \rho(z)[\Theta_E - \Theta(z)]W(z)dz$$



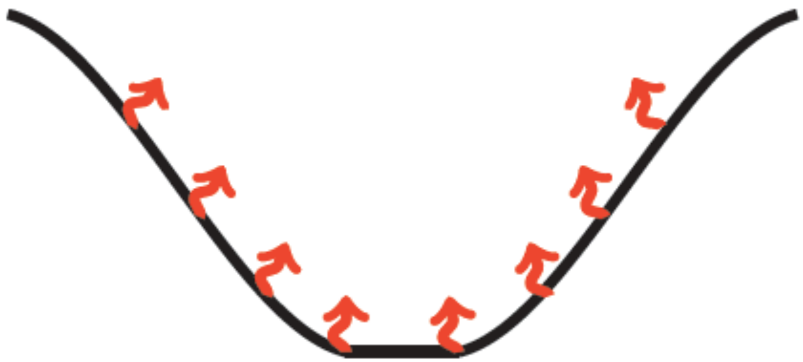
Required, provided and exported energy

At sunrise:

$$Q_{\mathrm{req}} = L_y c_p \int_0^{h_c} \rho(z)[\Theta_E - \Theta(z)] W(z) dz$$

During daytime:

$$Q_{\mathrm{prov}} = \int_{t_r}^{t_s} \int_A H_s(t, x, y) dx\, dy\, dt$$



Required, provided and exported energy

At sunrise:

$$Q_{\mathrm{req}} = L_y c_p \int_0^{h_c} \rho(z)[\Theta_E - \Theta(z)] W(z) dz$$

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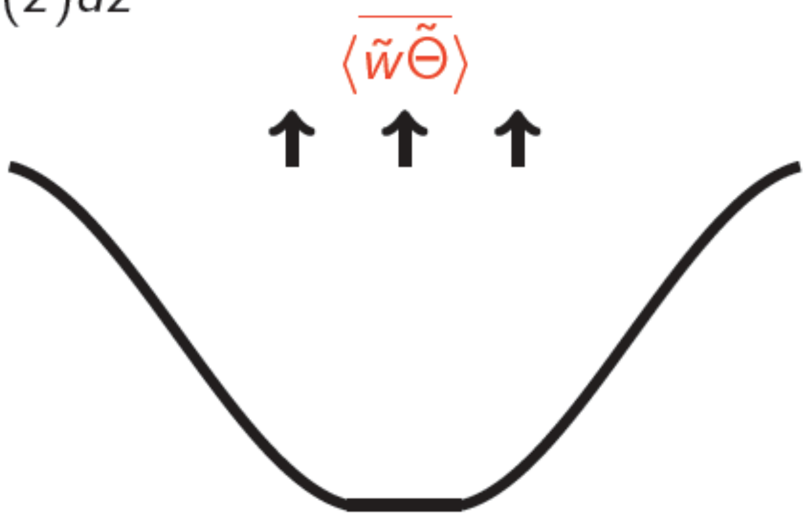


$$Q_{\mathrm{exp}} = c_p \int_{t_r}^{t_s} \int_A \langle \bar{\rho} \rangle \overline{\langle \tilde{w} \tilde{\Theta} \rangle} \Big|_{z=h_c} dx\, dy\, dt$$

The Breakup Parameter

$$B = \frac{Q_{\mathrm{req}}}{Q_{\mathrm{prov}}}$$

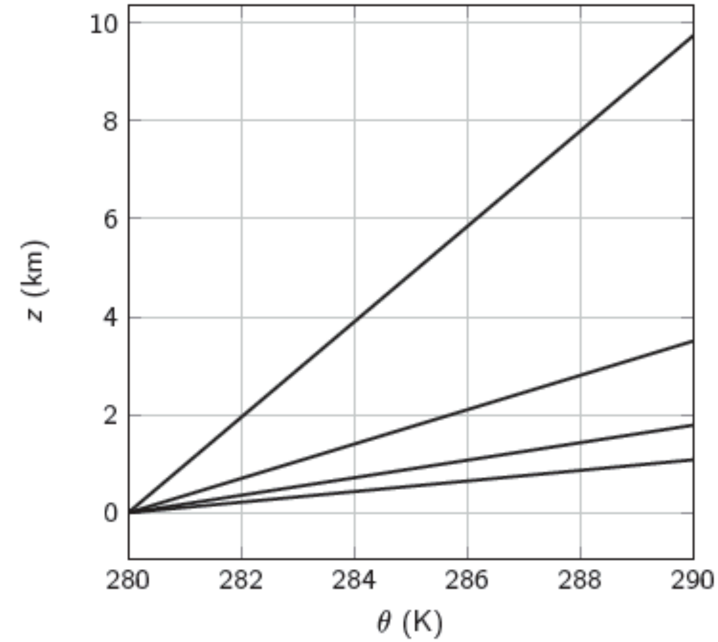
Approximately:
$B > 1$: Breakup is never reached
$B = B_c = 1$: Breakup barely reached
$B < 1$: Breakup is reached

Due to heat export:
Breakup reached for $B_c < 1$. ($B_c \approx 0.65$)

Expectation: Vertical export depends strongly on B

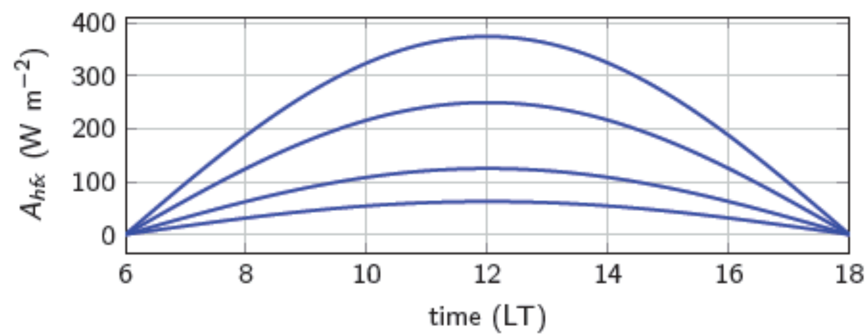
A virtual lab: **WRF model**

- LES: small meshsize ($\Delta x = 200$ m)
- no PBL parametrization
- no soil model
- MO-theory for u* and momentum fluxes
- u = v = 0 m/s

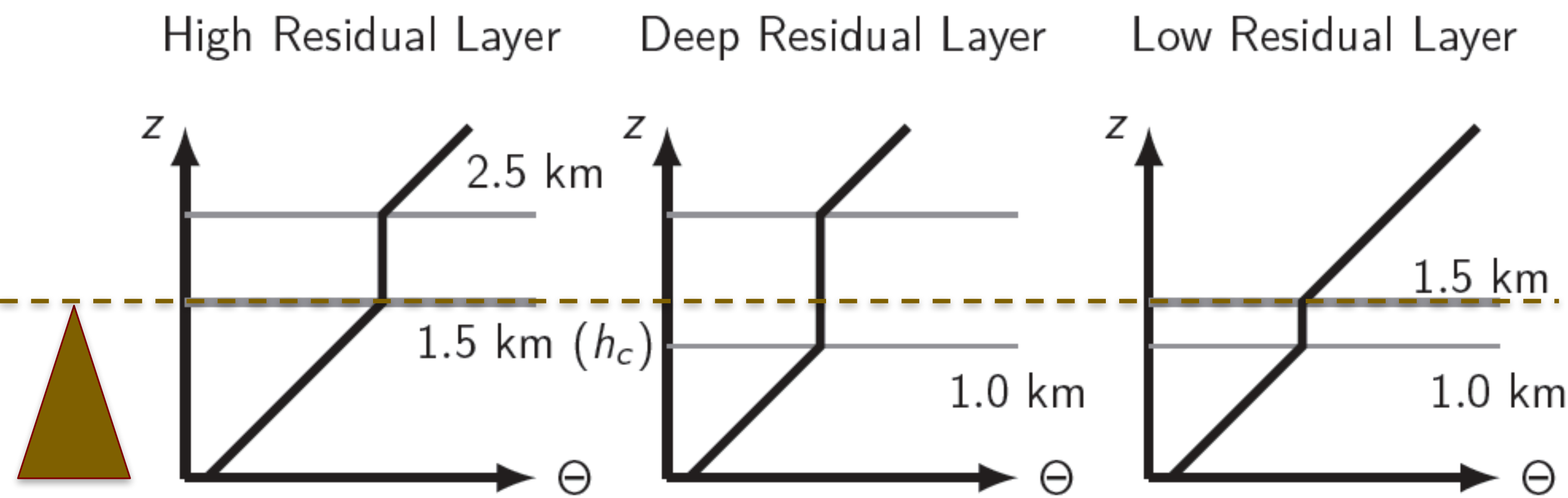


Variables

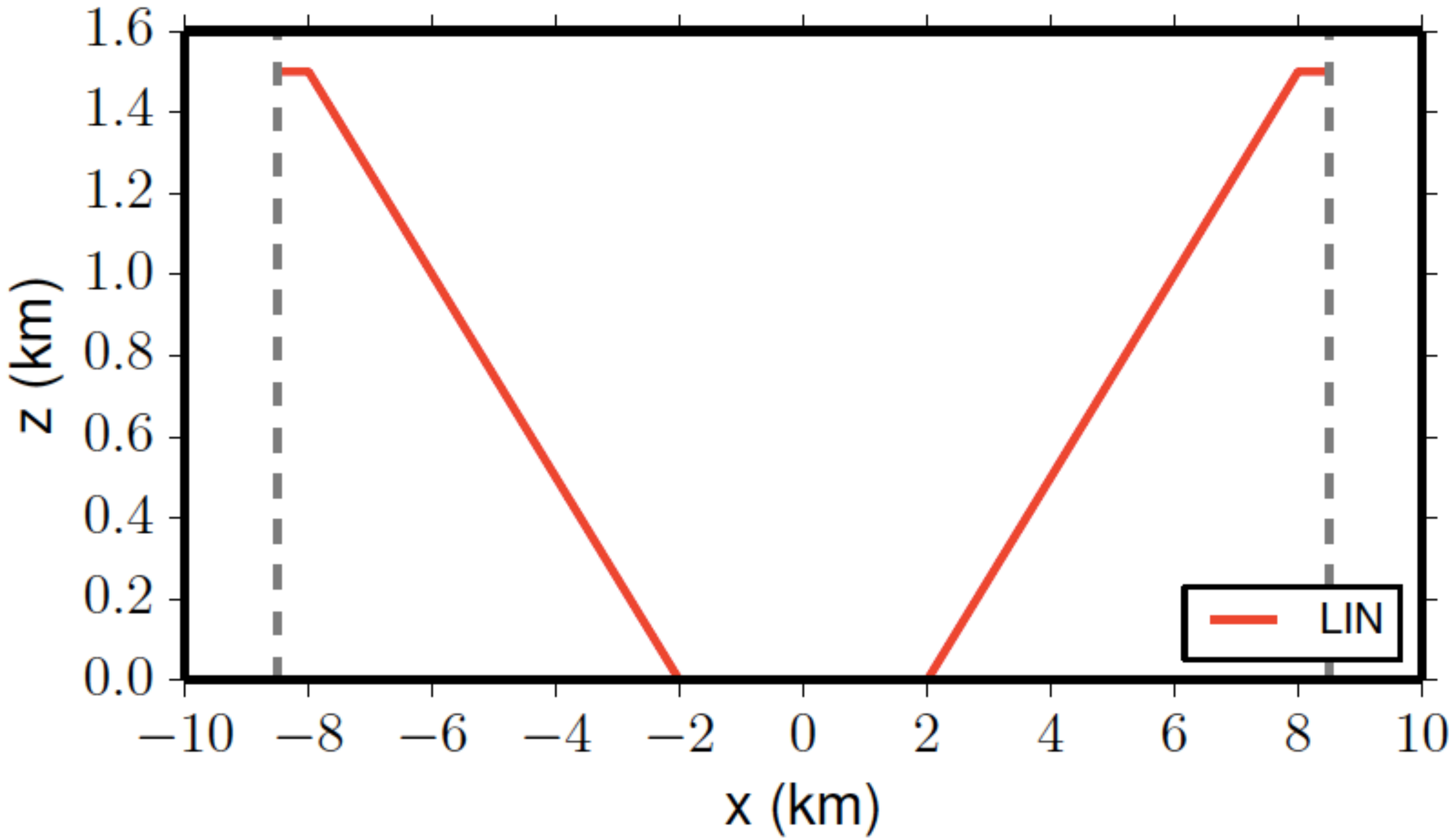
- $N = 0.006\text{-}0.018\ s^{-1}$
- $A_{hfx} = 62.5\text{-}375$ W m^{-2}
- Residual Layers



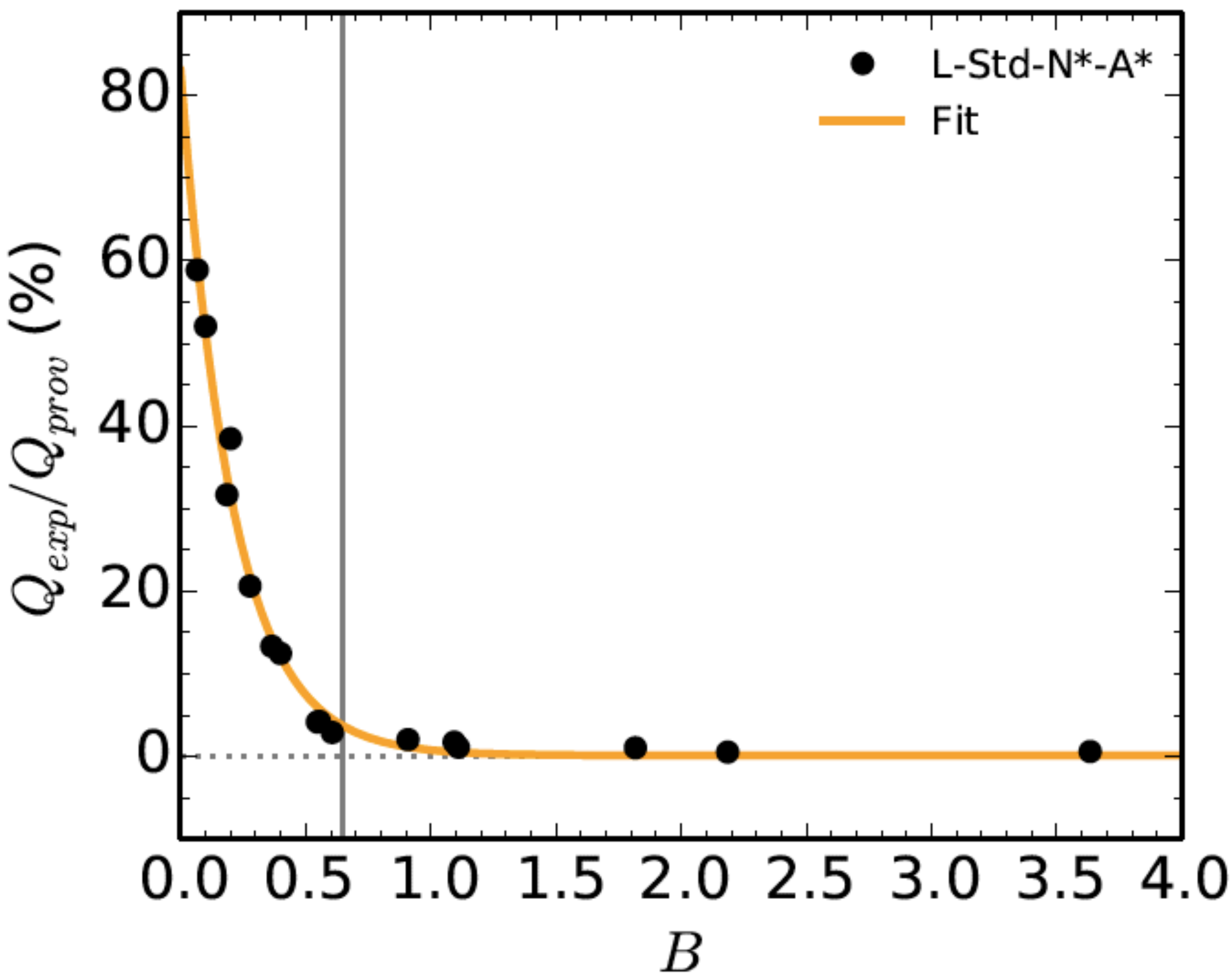
Residual Layers



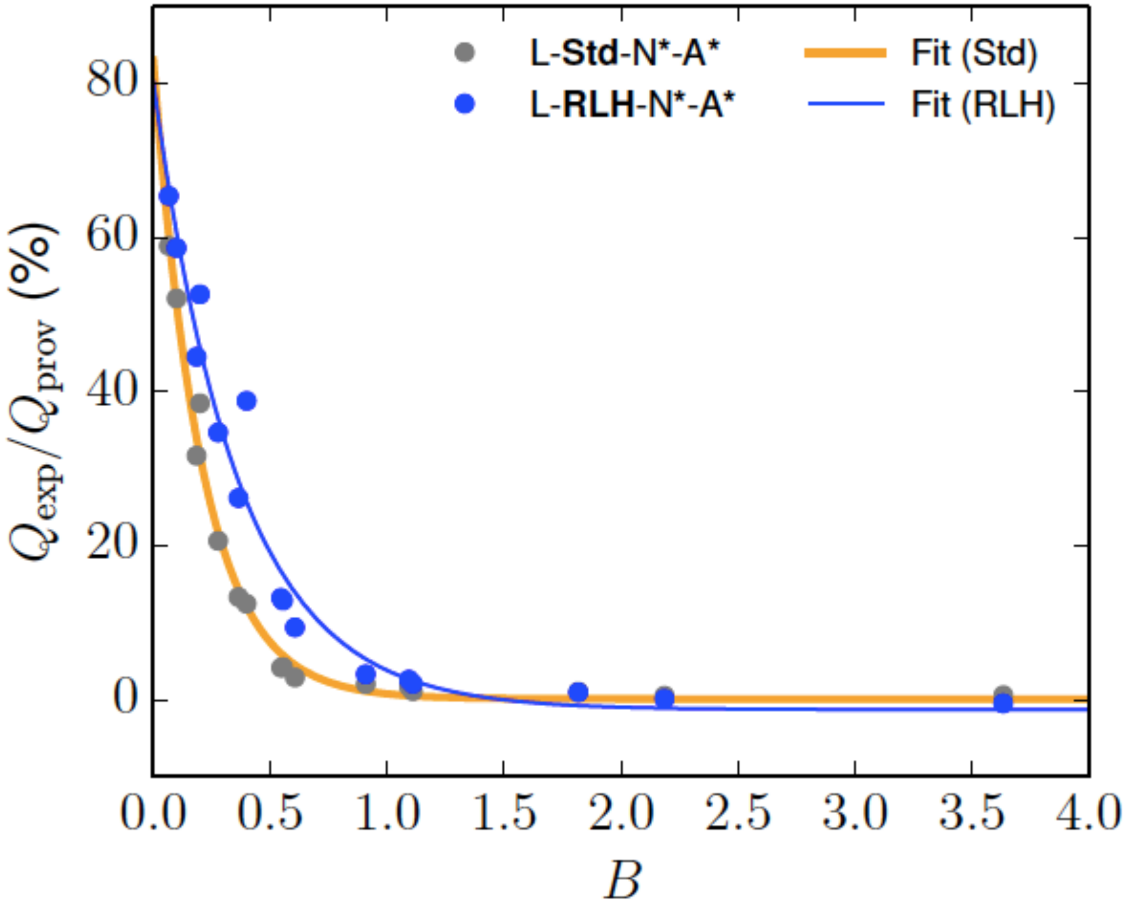
Topography



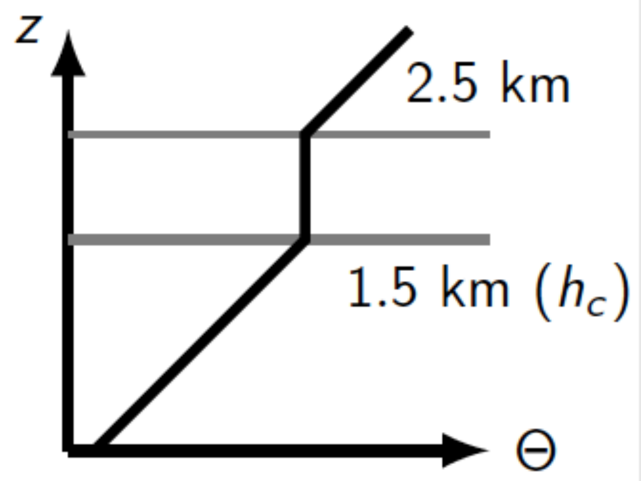
Export of heat – Reference



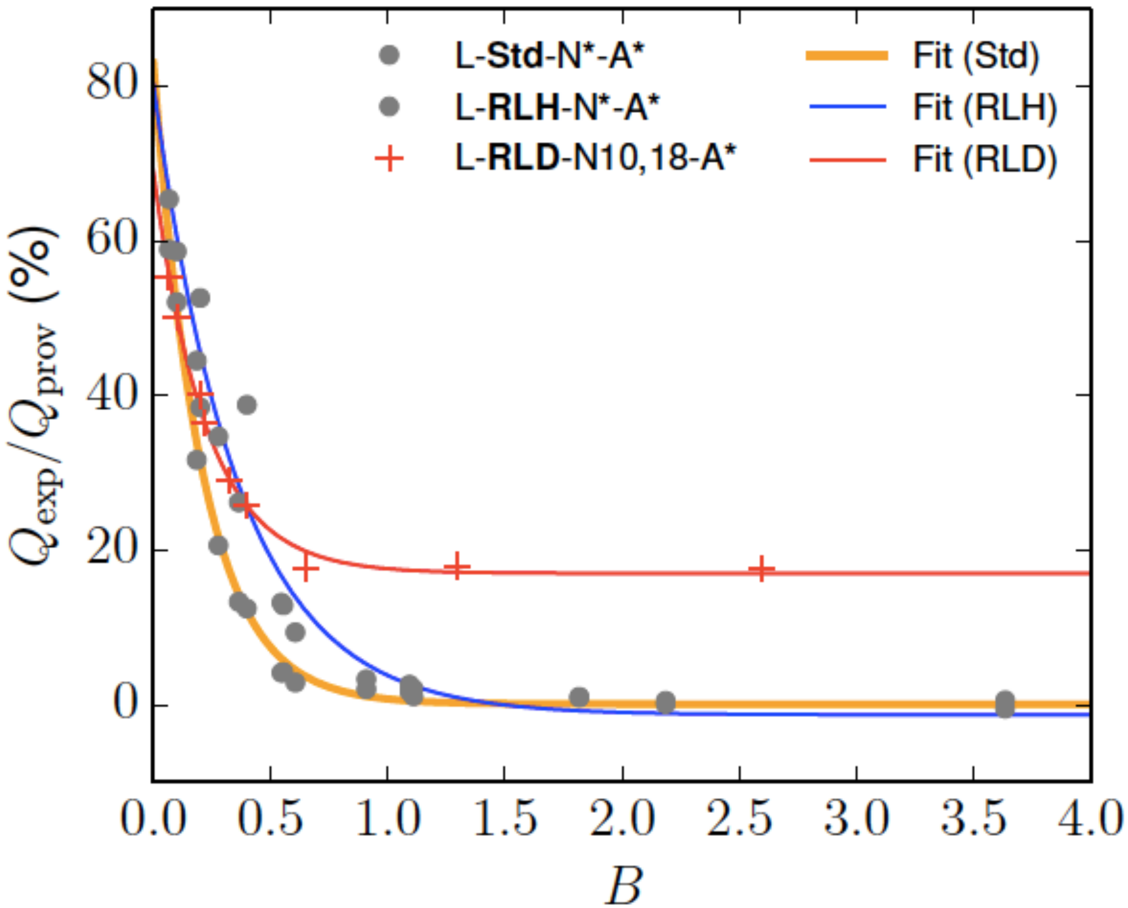
Export of heat – Impact of Residual Layers



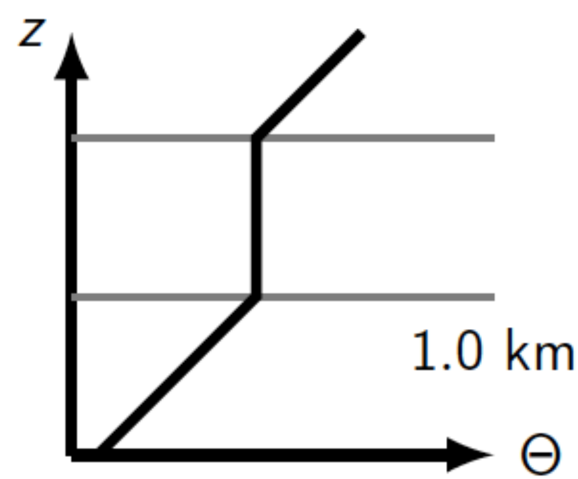
High Residual Layer



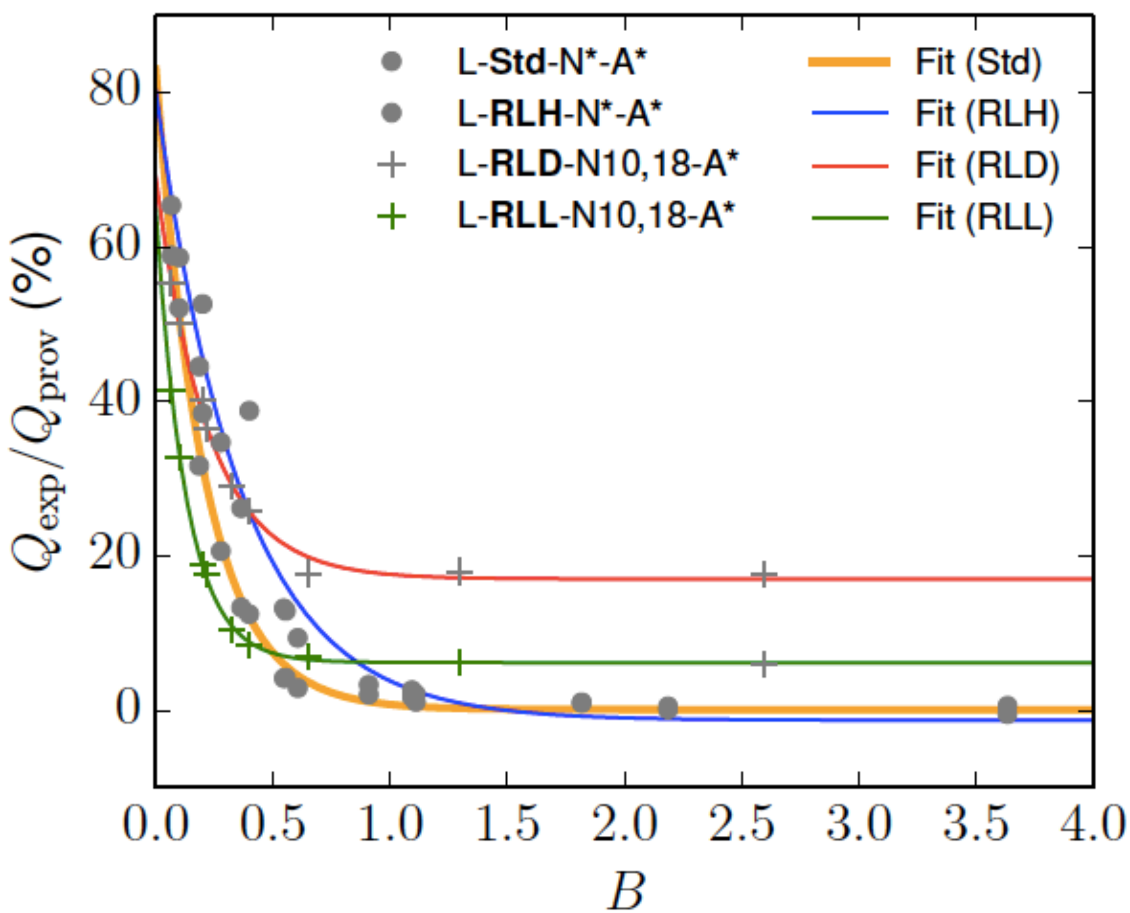
Export of heat – Impact of Residual Layers



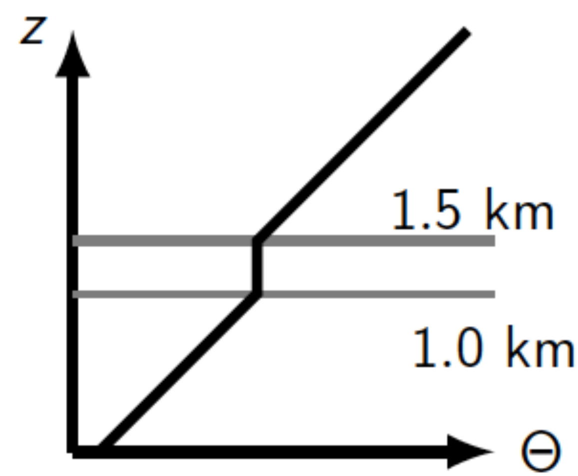
Deep Residual Layer



Export of heat – Impact of Residual Layers



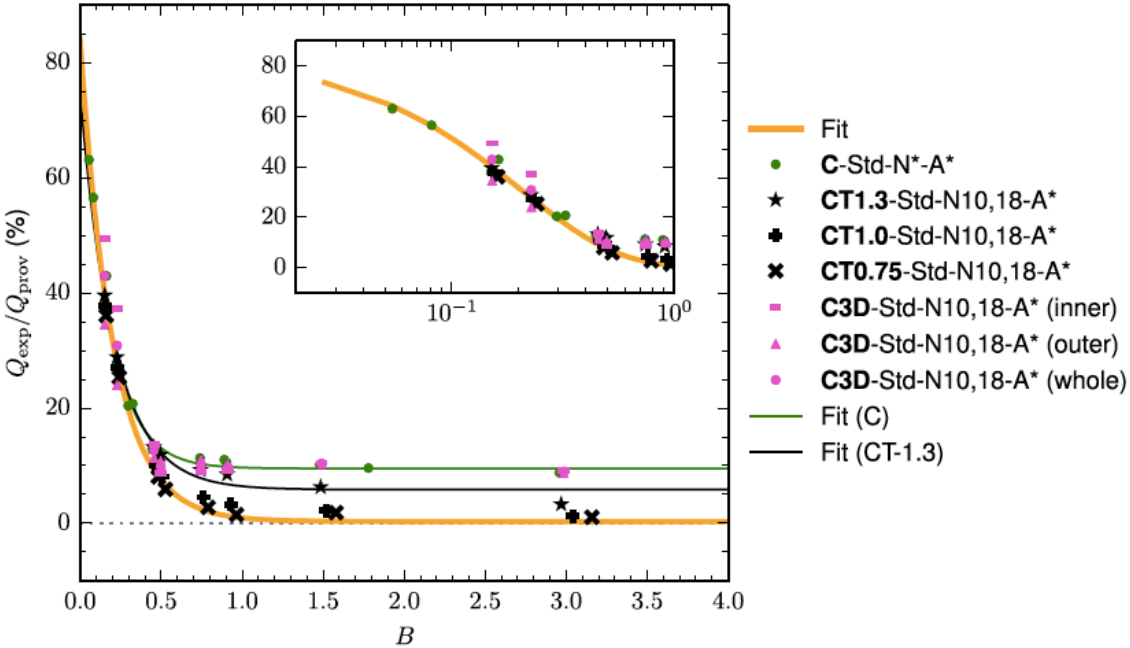
Low Residual Layer



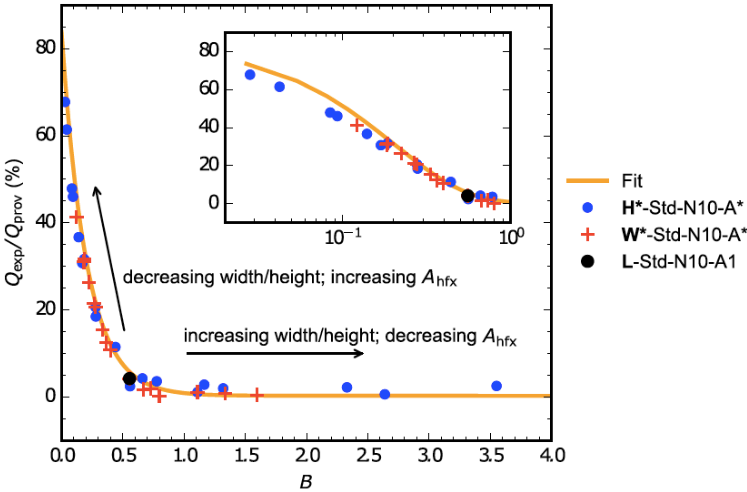
Impact of other parameters

- terrain geometry H / W, terrain form
- 2d – 3d
- elevated plateau's

cosine shape (‚C'), elev. plateau

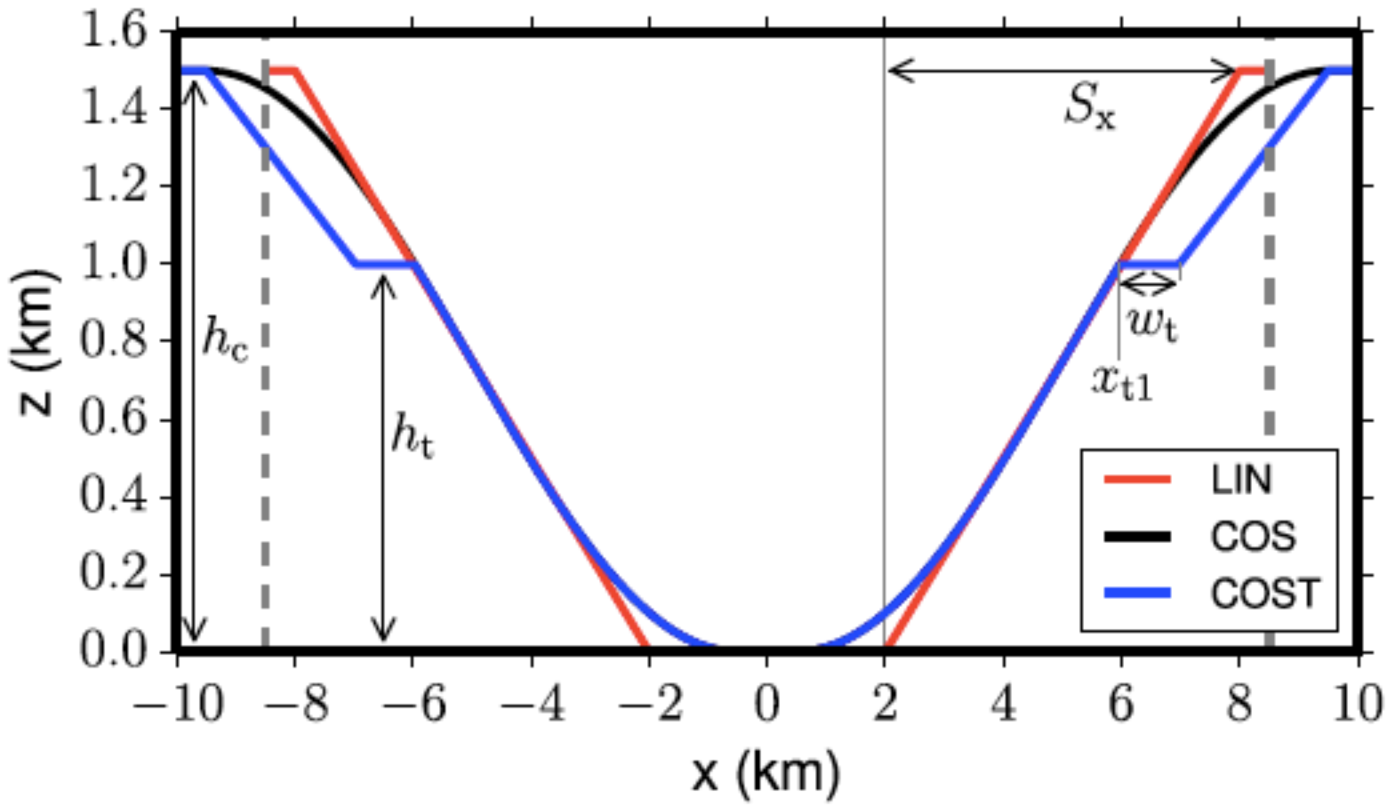


H/W ratio, length (L)

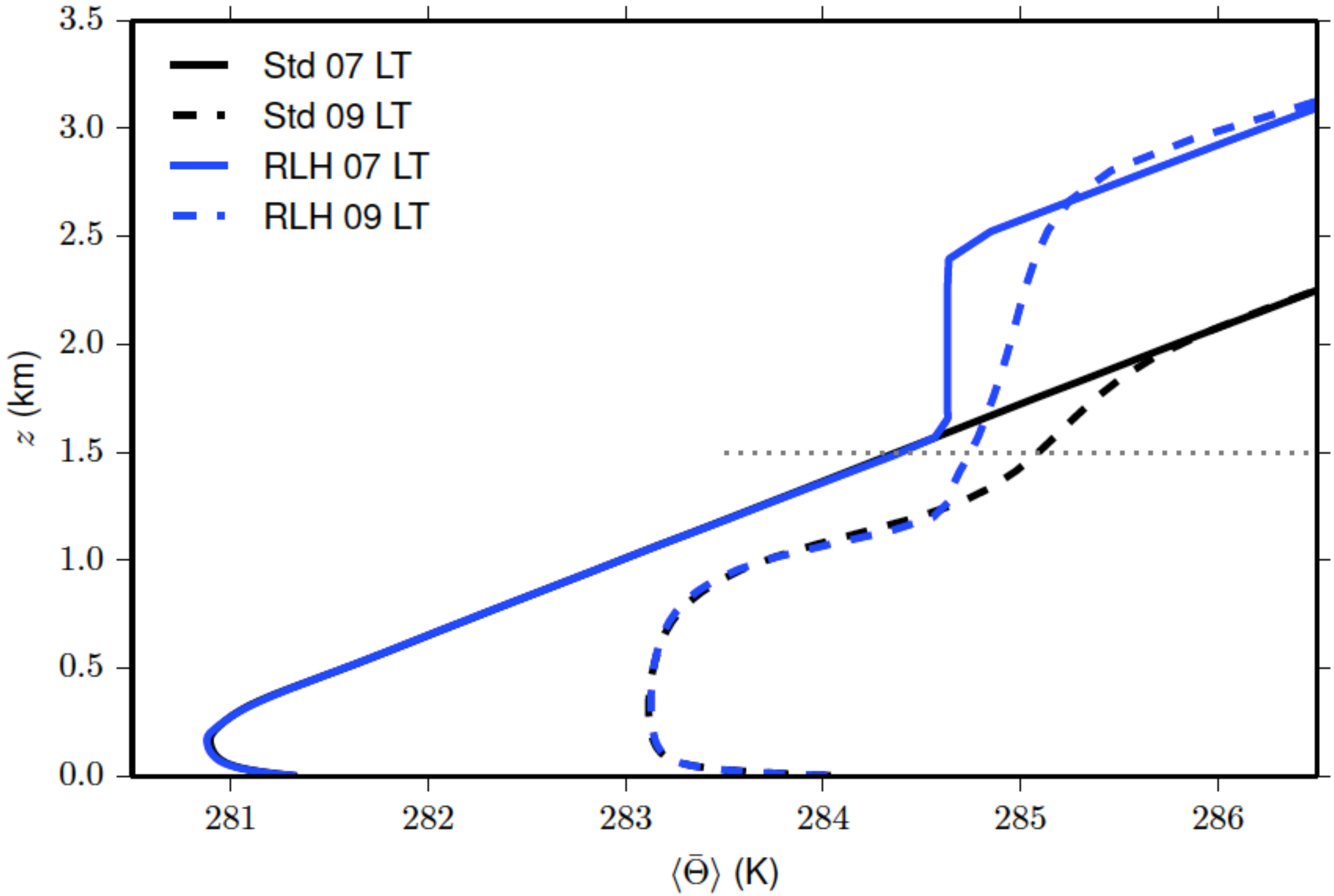


Impact of other parameters

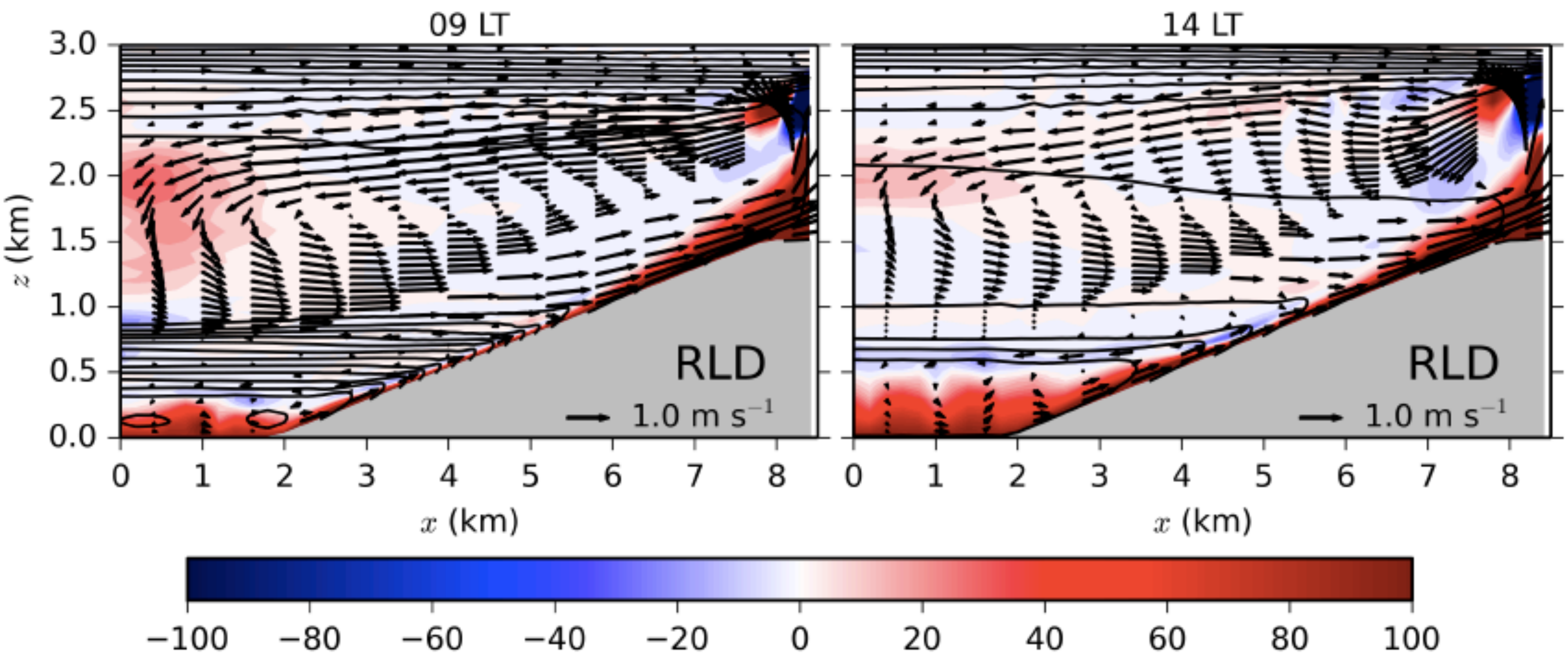
- terrain geometry H / W, terrain form
- 2d – 3d
- elevated plateau‘s



High Residual Layer

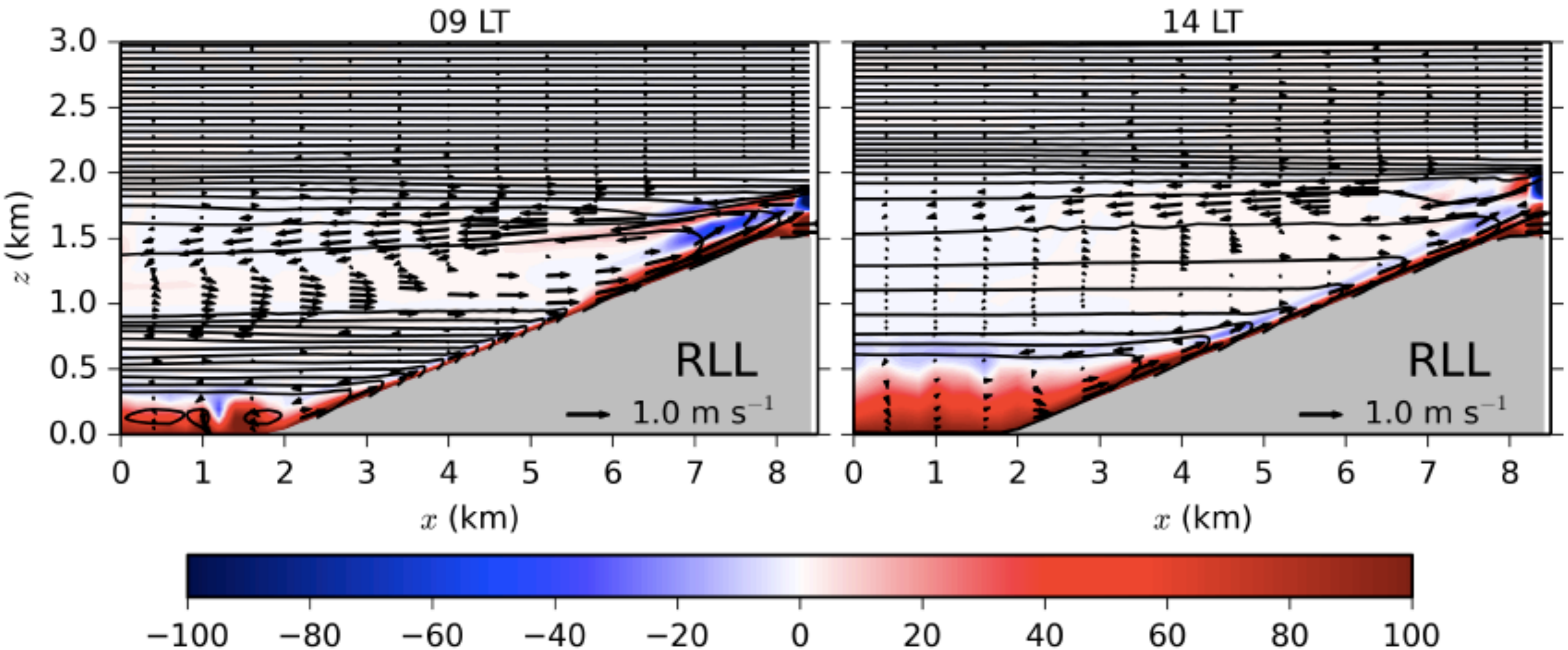


Deep Residual Layer



Vertical heat flux (W m^{-2})

Low Residual Layer



Vertical heat flux (W m^{-2})

Conclusions

- Breakup parameter determines how fast the valley BL evolves
- Total export of heat decreases exponentially with increasing B
- Residual Layers impact the vertical distribution of heat
- Lead to an increase or decrease export of heat

→ Leukauf et al. (2017), JAMC

Summary

- exchange of energy, mass and momentum
  → impact of mountainous terrain
  → right for the right reason (climate & NWP *services*)
- **TEAMx**
  → coordinated international effort
  → partners welcome
- COSMO TKE parameterization (1d vs. 'hybrid')
  → is hybrid good enough? (LES needed?)
  → seek more general formulation
- idealized valley simulations
  → breakup parameter: towards a sgs-parameterization?
  → initial stratification most relevant

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Title

TKE forcing	Location	bias [1D] ($m^2\,s^{-2}$)	bias [hybrid] ($m^2\,s^{-2}$)	rmse [1D] ($m^2\,s^{-2}$)	rmse [hybrid] ($m^2\,s^{-2}$)
Buoyancy	Valley floor	-0.32	-0.30	0.36	0.34
	Slopes	0.03	0.04	0.16	0.15
Shear	Valley floor	-0.44	0.08	0.48	0.33
	Slopes	-0.45	-0.22	0.51	0.34
Transport	Valley floor	-0.22	-0.12	0.25	0.16
	Slopes	-0.35	-0.32	0.38	0.36

Table 2 Bias and rmse for TKE for simulations with both `turb_1D` and `turb_hybrid`. The

Title

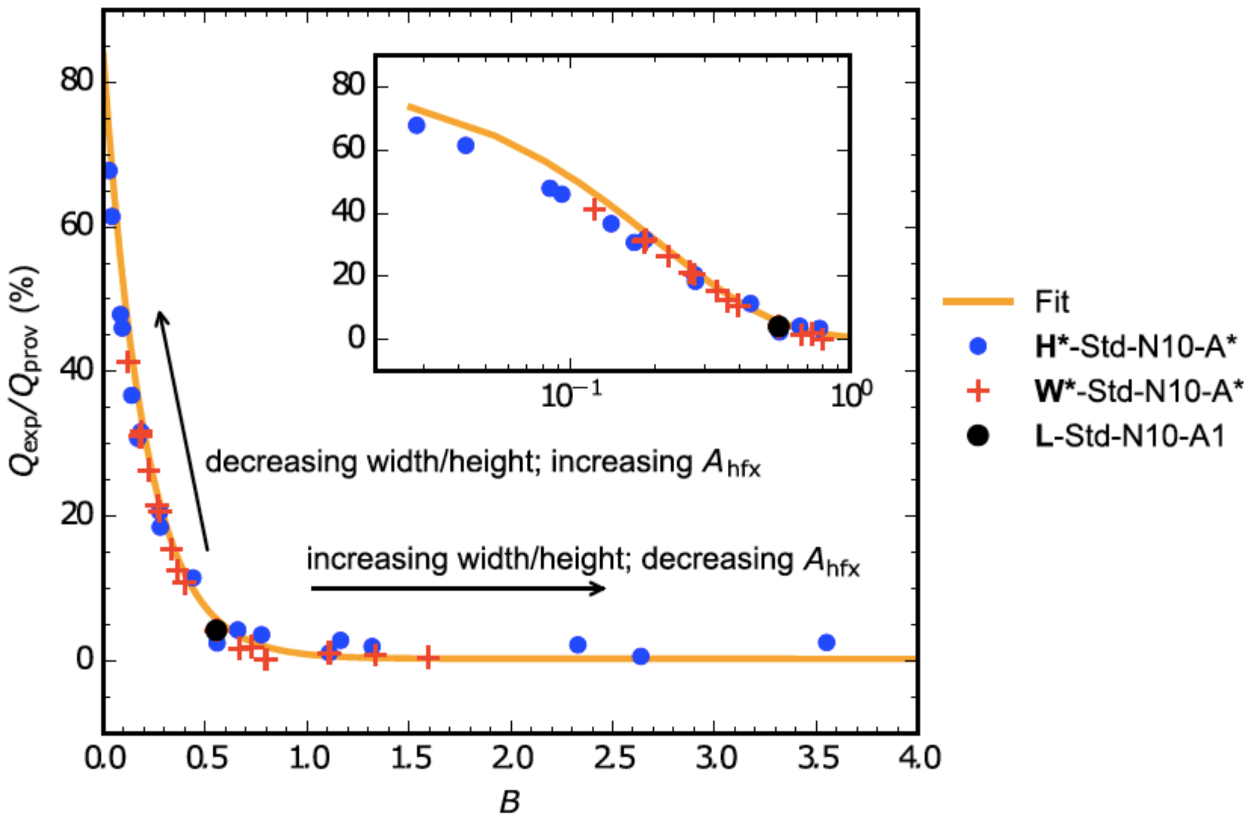

FIG. 7. As in Fig. 2, but for the simulation sets H*-Std-N10-A* and W*-Std-N10-A*. The simulation L-Std-N10-A1 is identical to H1.5-Std-N10-A1 and to W2-Std-N10-A1.

→ no impact of valley width / valley depth

Title

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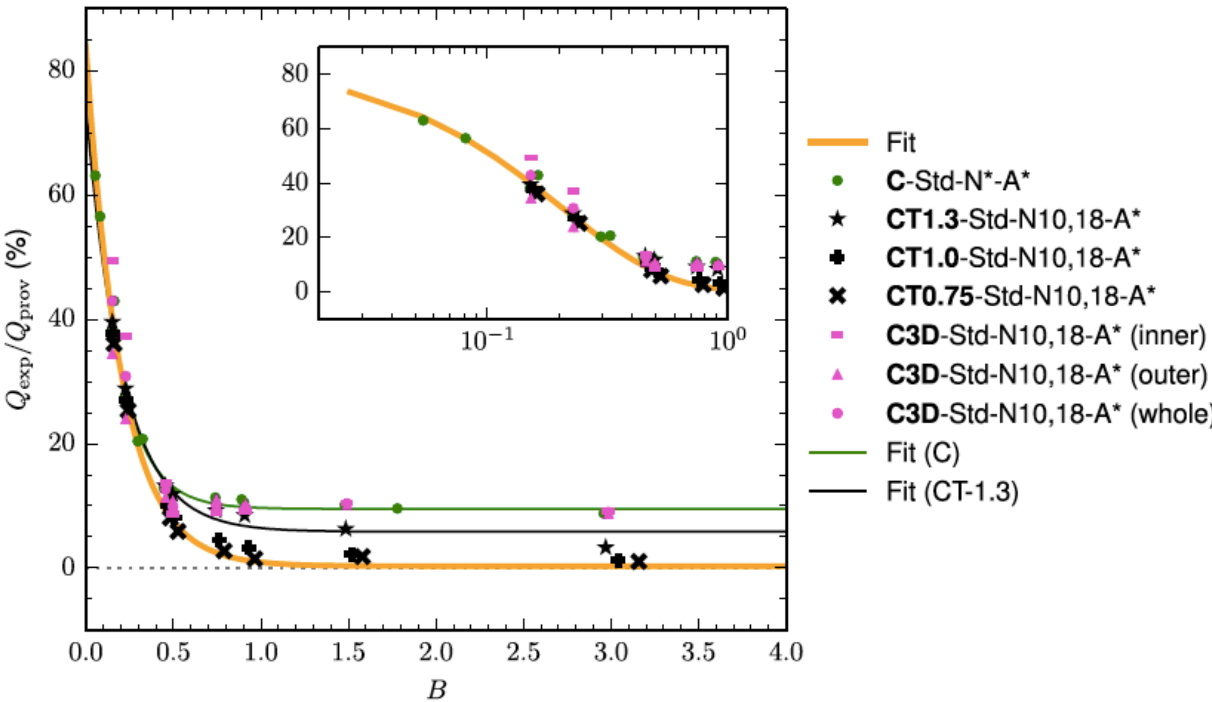


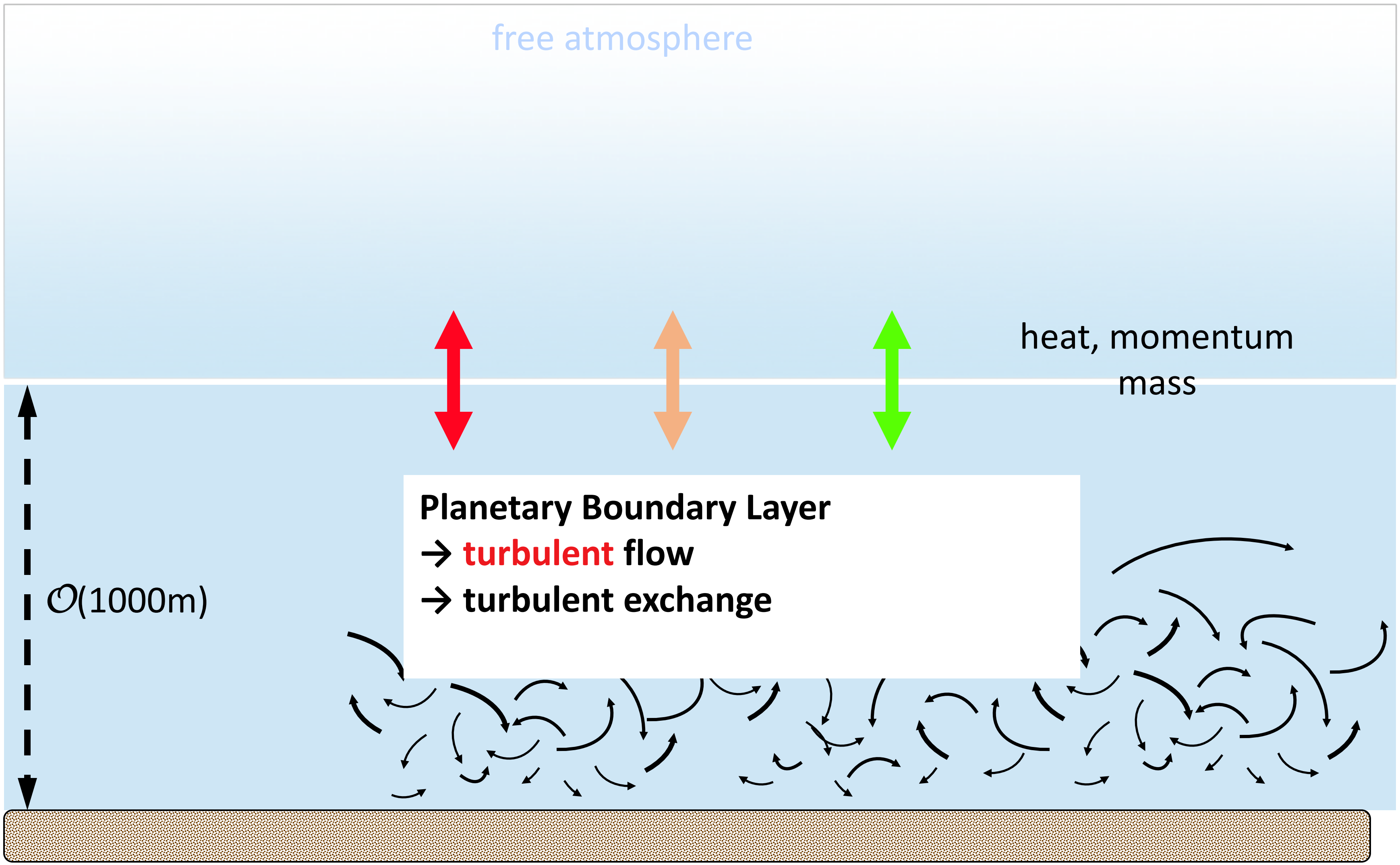
FIG. 8. As in Fig. 2, but for the simulation sets C-Std-N*-A*, CP1.3-Std-N*-A*, CP1.0-Std-N*-A*, CP0.75-Std-N*-A*, and C3D-Std-N10,18-A*. The vertical heat flux over the three-dimensional valley has been averaged over the innermost 10 km (inner), the 10 km nearest to the valley entrance (outer), and over the whole valley (whole).

→ impact of valley form (cosine instead of linear), 3d (instead of 2d) and ‘elevated plateaus’

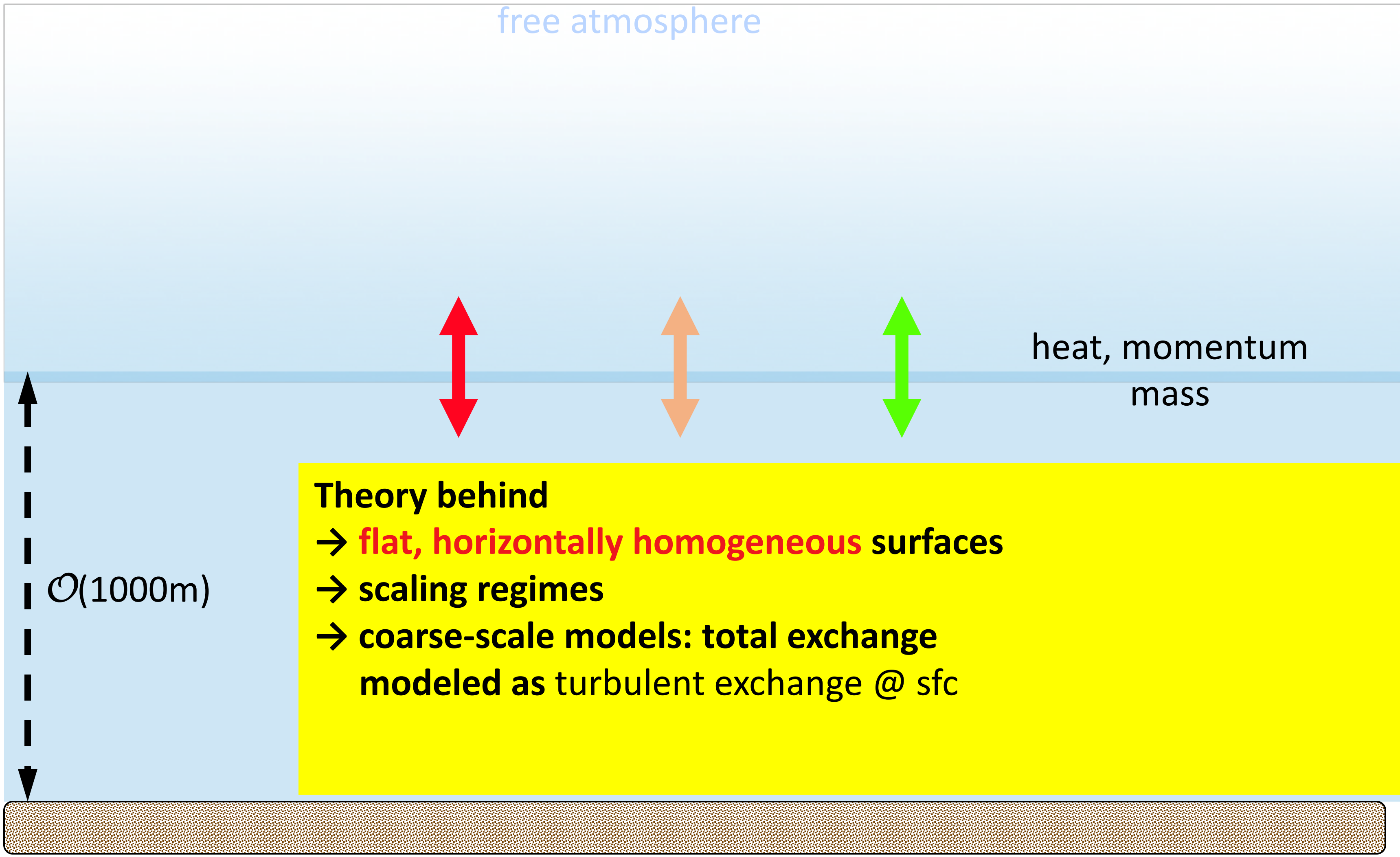
GAPS in knowledge

→ project @ UIBK will start soon ...

‚Near-surface‘ exchange



‚Near-surface‘ exchange



Theory behind

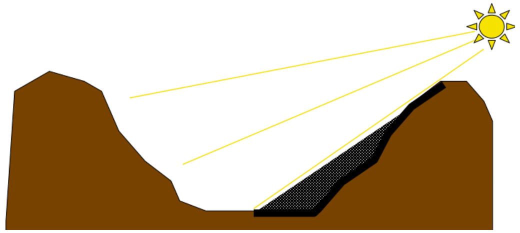
→ **flat, horizontally homogeneous surfaces**

→ **scaling regimes**

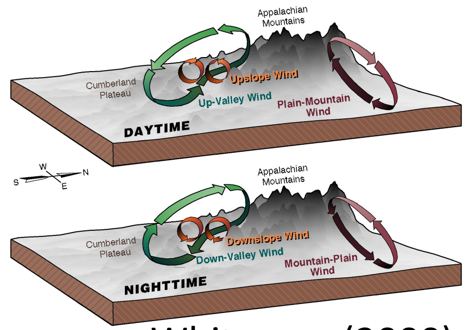
→ **coarse-scale models: total exchange modeled as** turbulent exchange @ sfc

Exchange over topography

- Boundary layer is inhomogeneous by construction

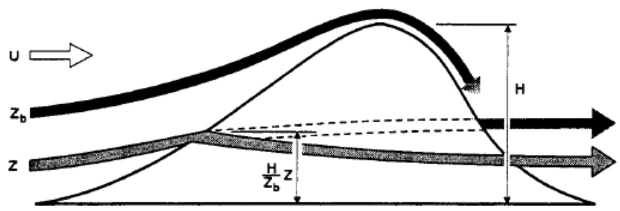


- thermally induced circulations
  → slope / valley flows
  → mountain venting



Whiteman (2000)

- dynamic modification (gravity wave drag, etc)

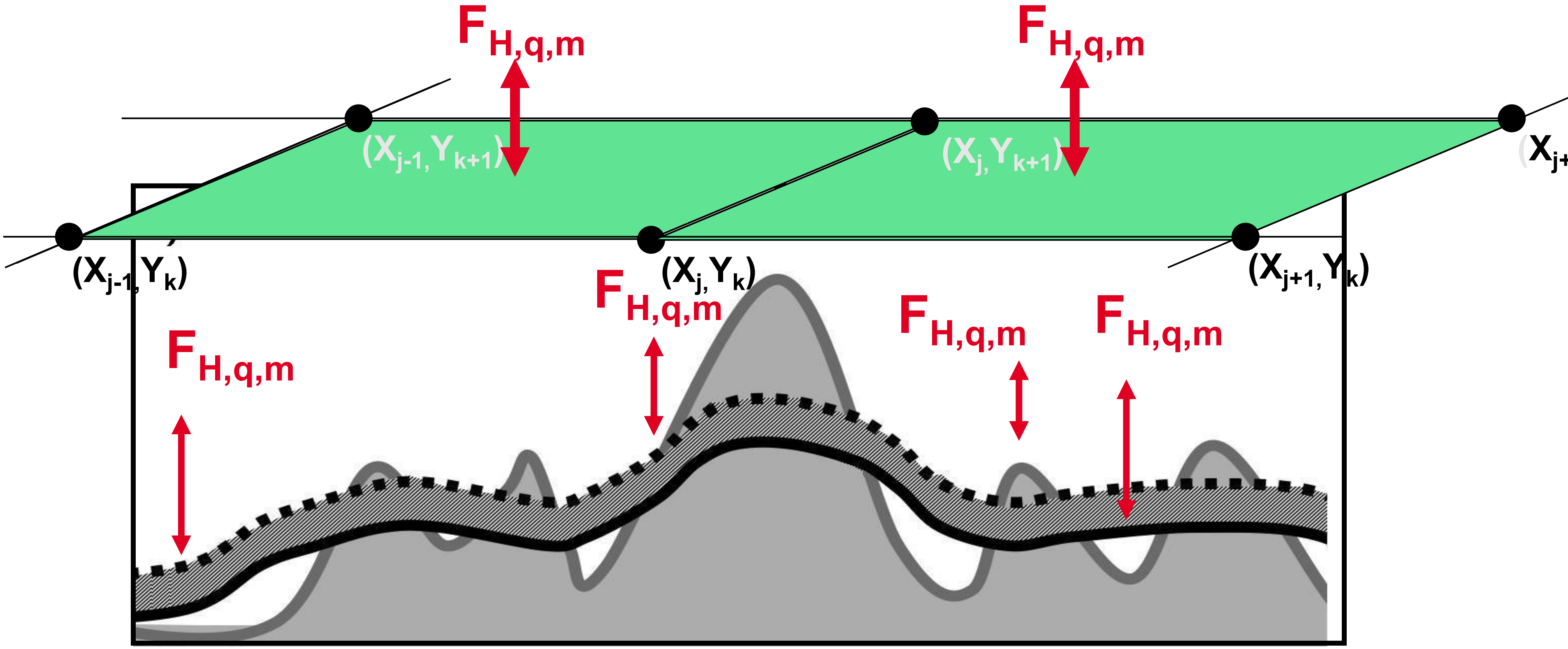


Lott and Miller (1996)

- geometrical effects (e.g., narrowing / widening) for mass

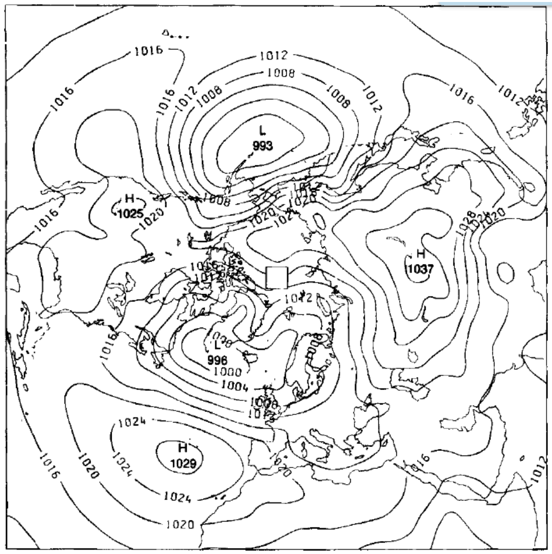
Coarse models

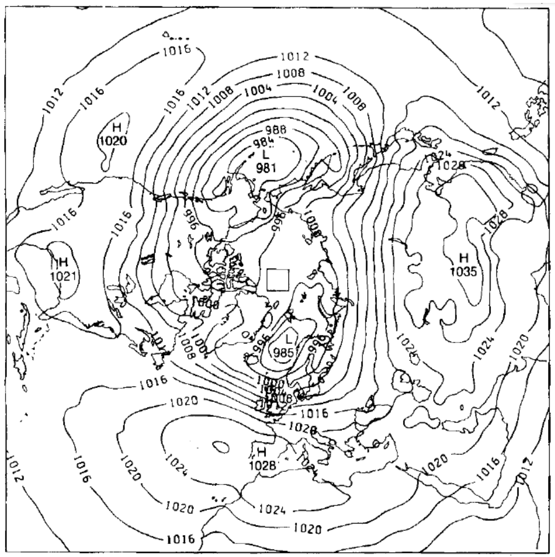
→ high spatial resolution required $\mathcal{O}$(100m)
→ climate modeling: $\mathcal{O}$(100km) ….



Rotach and Zardi (2007)

Momentum exchange





no gravity wave drag

Palmer et al 1986 (QJ)

mean Jan NH SLP (84-86)

→ **total exchange:** subgrid-scale contribution para-meterized

Subgrid parameterization

✓ **Momentum**

→ orographic drag (e.g. Palmer et al. 1986)

Heat

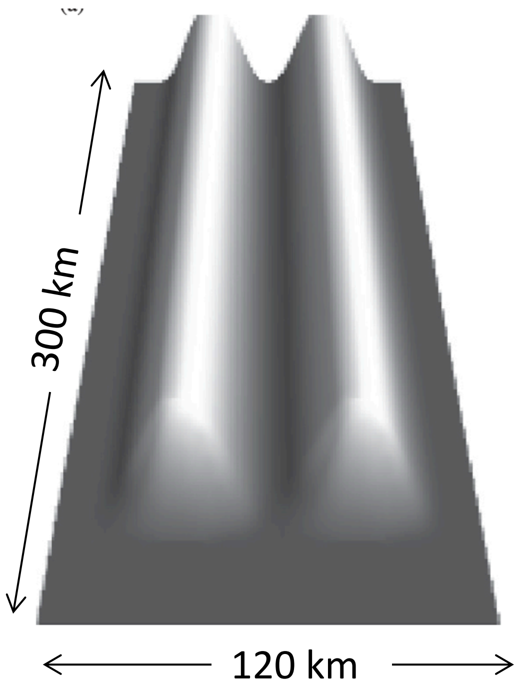
→ Noppel and Fiedler (2002)

→ …..

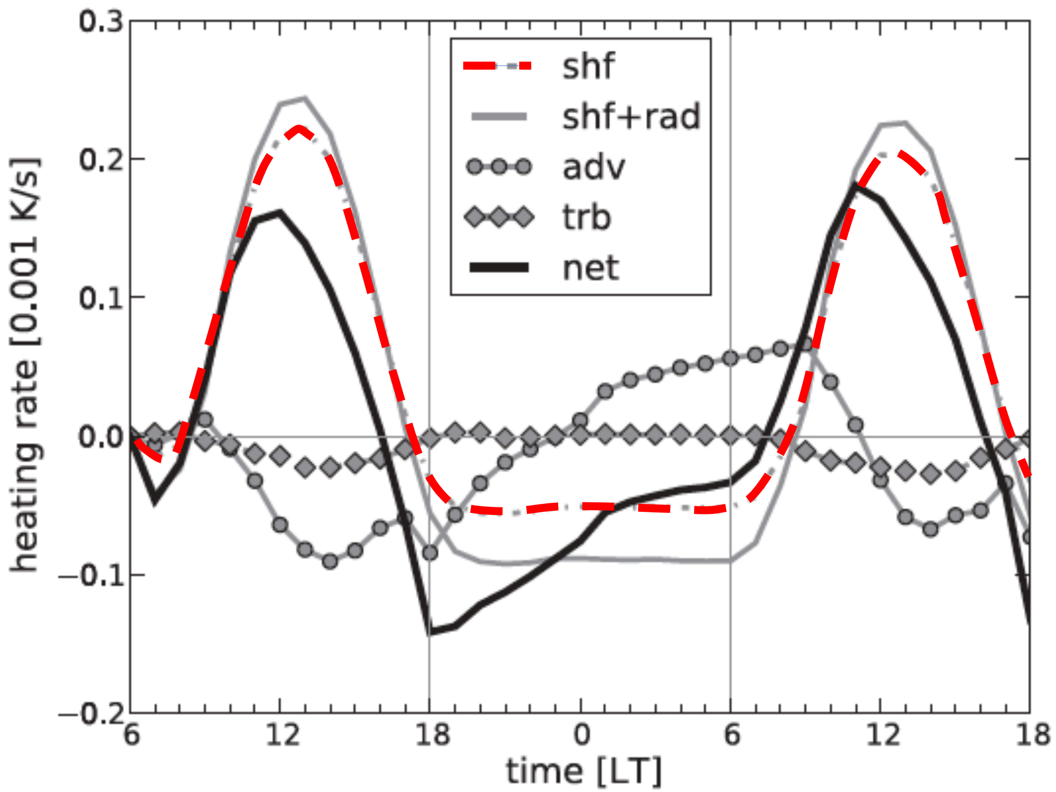
→ Schmidli and Rotunno (2012)

>idealized modeling
>systematic
>no parameterization yet

Heat exchange



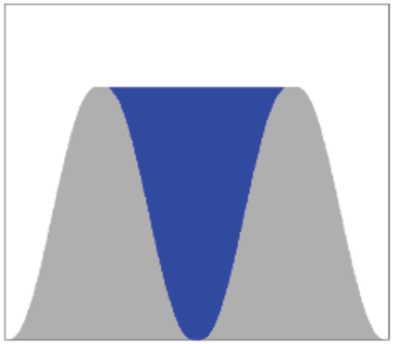
Δx=1km, ARPS



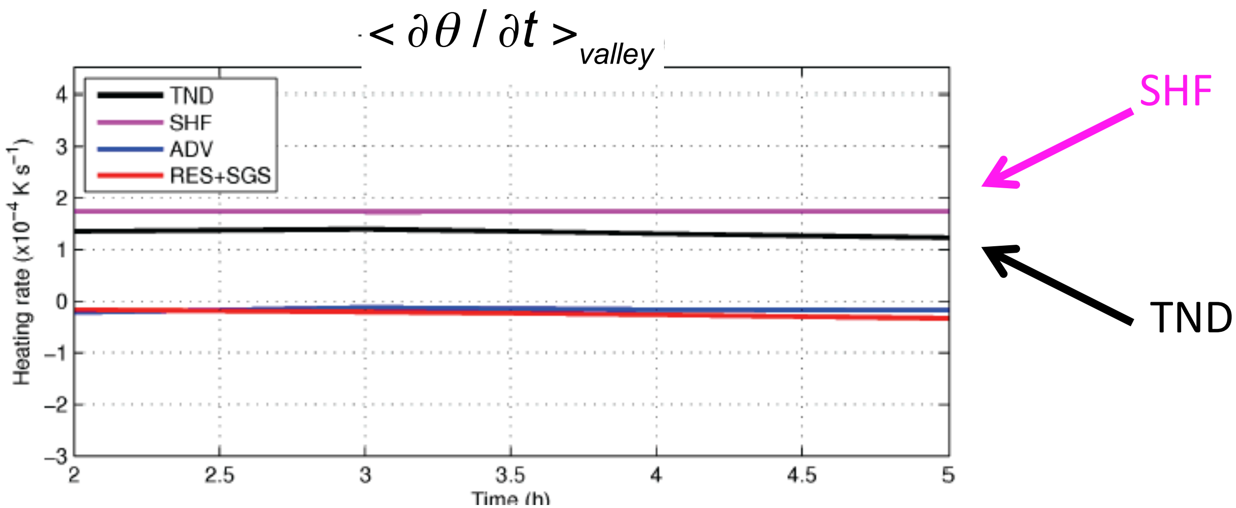
→ perfectly ideal
→ influence of surrounding topography
→ influence of geometry

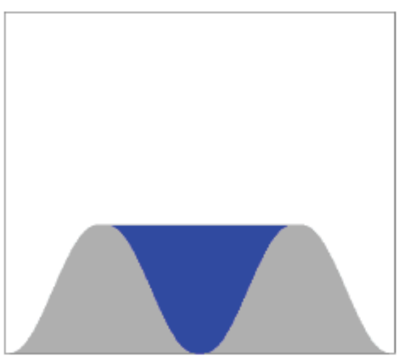
Schmidli and Rotunno 2010

Heat exchange - geometry

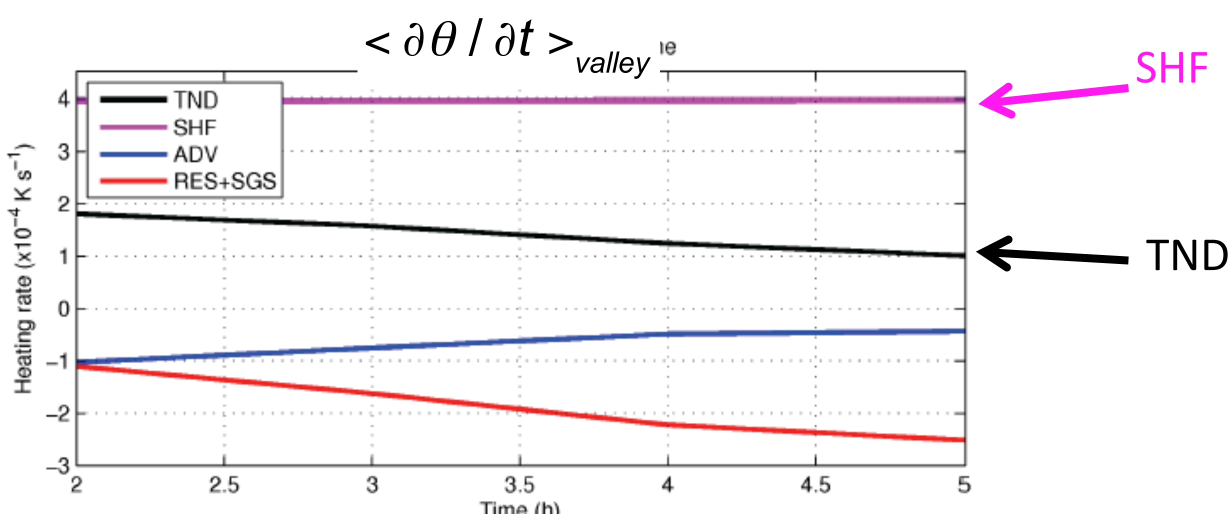


Volume **V**





Volume $\frac{1}{3}$**V**
HGT = 0.5 km



Johannes Wagner, IMGI

Subgrid parameterization

✓ **Momentum**

→ orographic drag (e.g. Palmer et al. 1986)

(✓) **Heat**

→ Noppel and Fiedler (2002)

→ .....

→ Schmidli and Rotunno (2012)

>idealized modeling
>systematic
>no parameterization yet

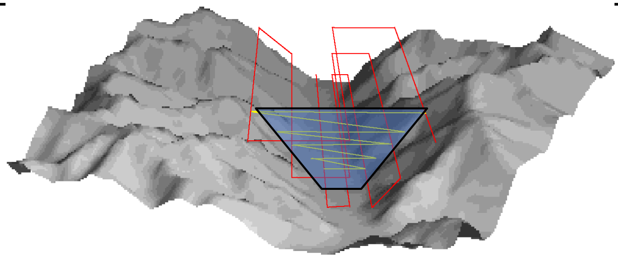
Mass

→ Weigel et al. (2007)

Numerical Modeling

- MAP Riviera example
- three days with weak synoptic forcing
- ARPS, LES, high resolution, several nests
  - → (very) good correspondence to observations
  - → different (all) variables simultaneously in correspondence

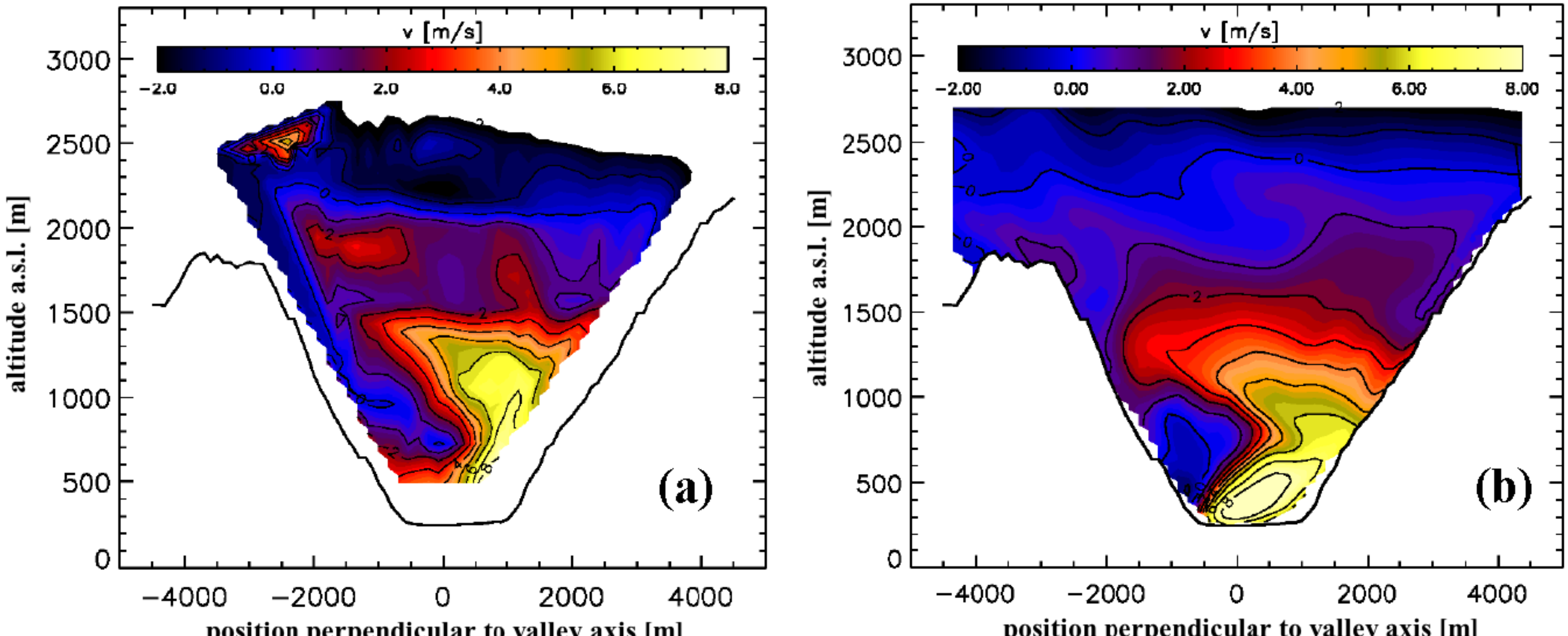
Wind along valley



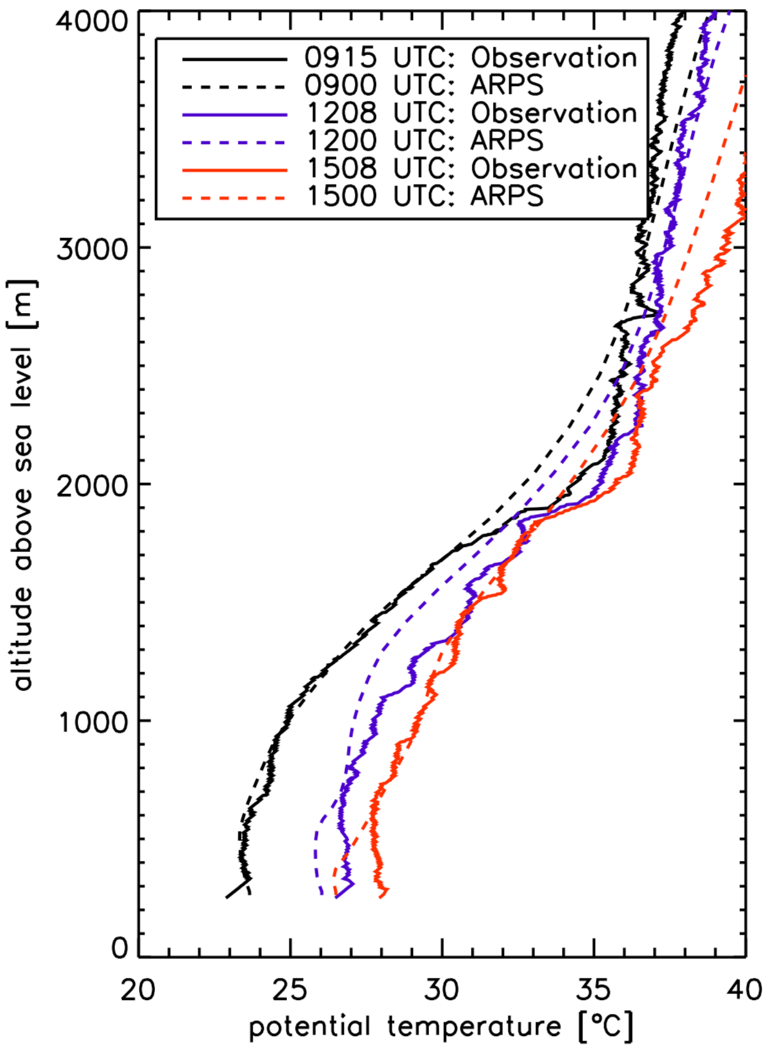
25. August (1300 UTC)

observation

simulation



Profile Potential Temperature



example:
25. August 1999

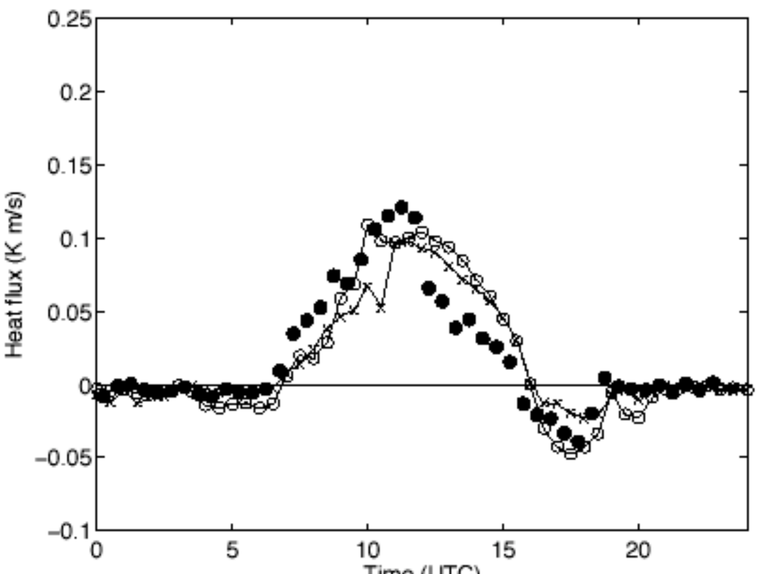
kinematic heat flux

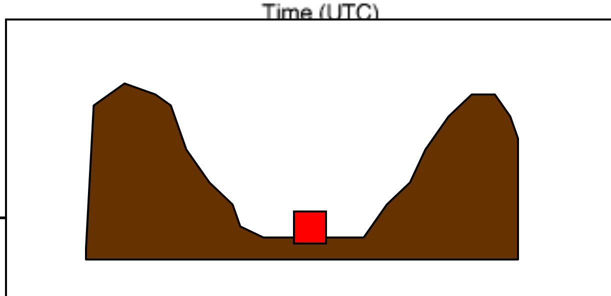
● ● ● observation

x x x simulation - reference

○ ○ ○ land use and soil moisture

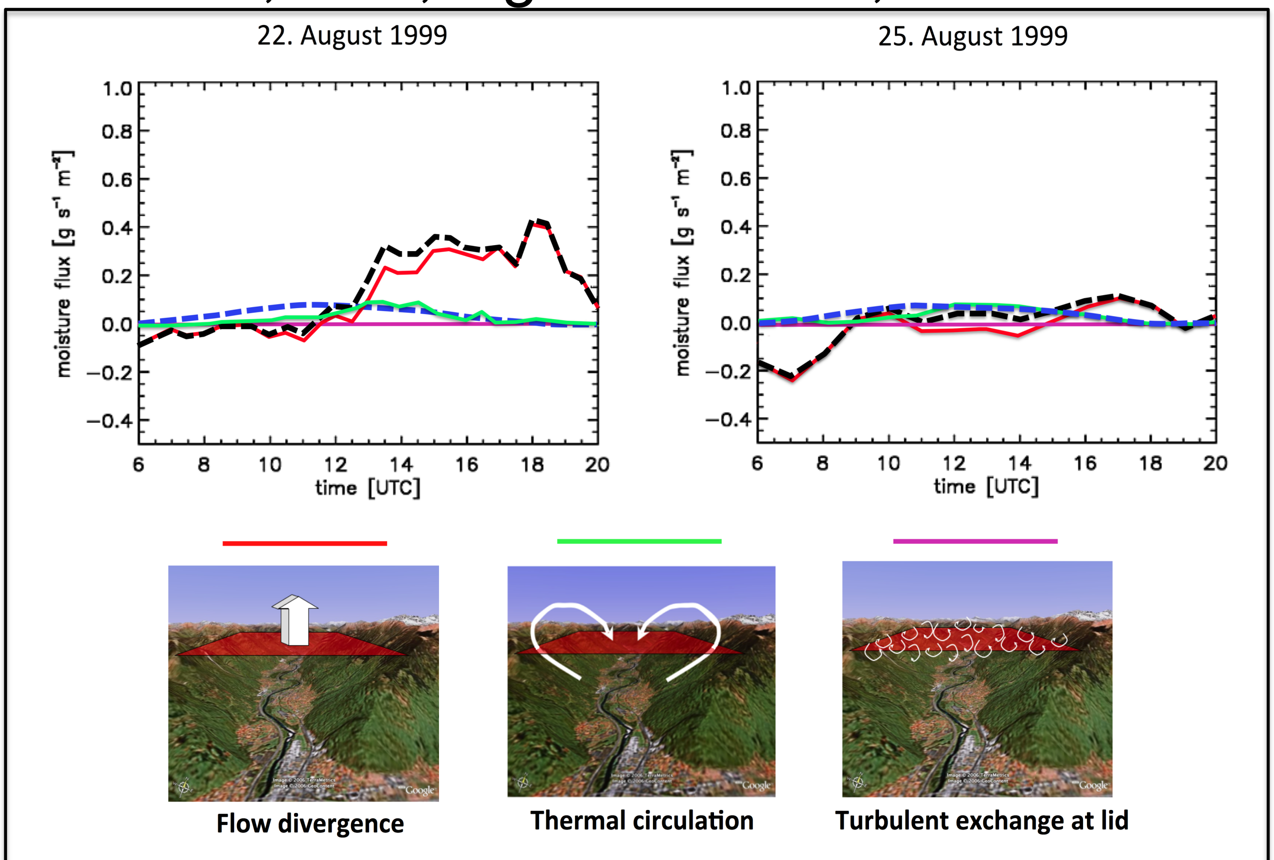
Chow et al. 2006, JAM
Weigel et al. 2006, JAM





Moisture exchange

- MAP Riviera example
- three days with weak synoptic forcing
- ARPS, LES, high resolution, several nests



LES (350m):

(= + +)

Coarse model:

Weigel et al (2007)

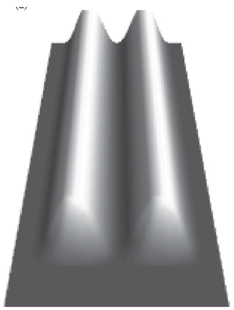
Exchange of CO_2

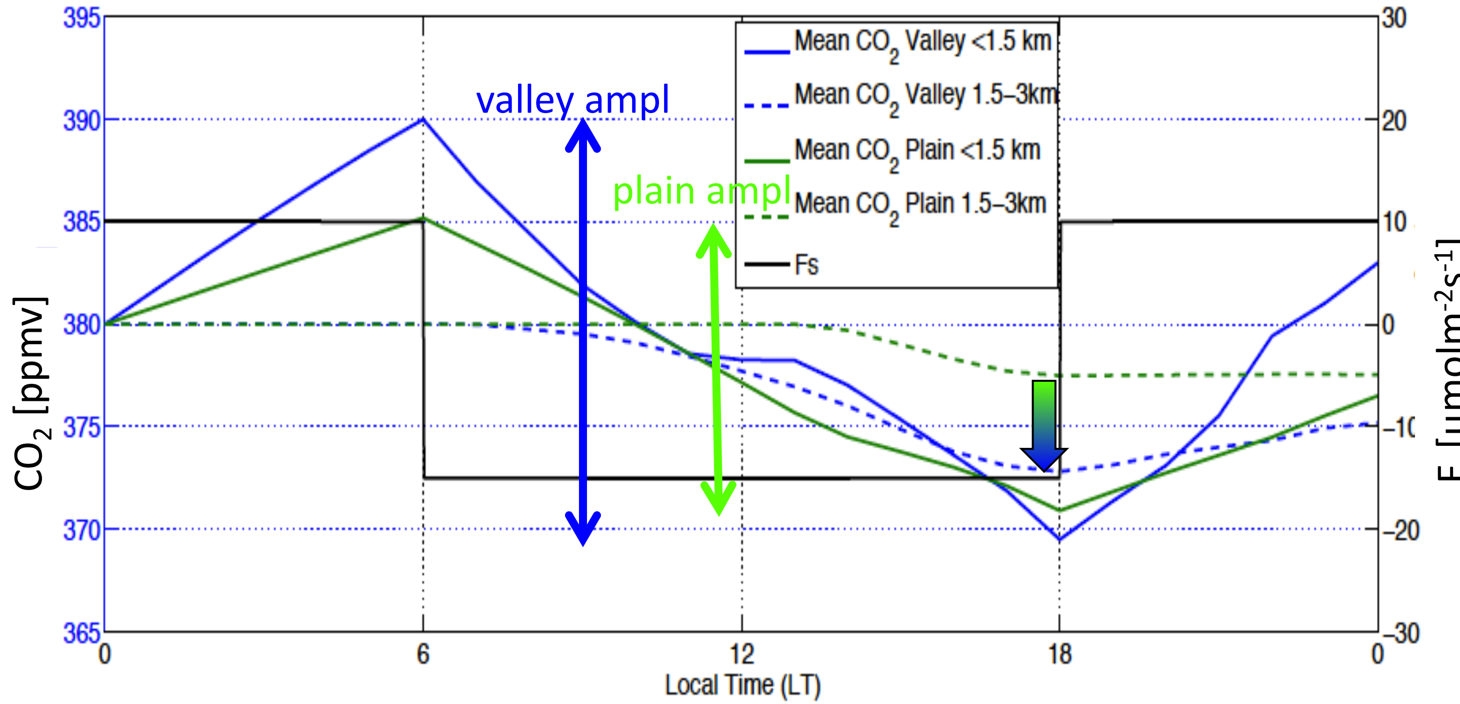
- different source/sink characteristics than moisture
- ‘active’ during the night as well
- importance of SBLs/drainage flows

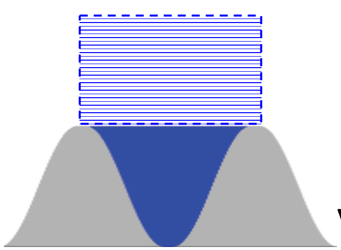
Some pioneering studies:

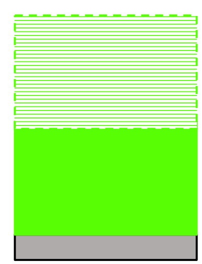
- carbon budgeting methods yield inconsistent results
  → Niwot Ridge AmeriFlux site (Desai et al. 2011)
- mountain induced circulation with significant impact on regional carbon budget
  → Airborne Carbon in the Mountains Experiment (Sun and De Wekker 2011)
- meso-scale circulations contribute to total exchange
  → Regional carbon budget models (e.g., Perez-Landa et al. 2007; Pillai et al. 2011)

CO_2 exchange






valley


plain

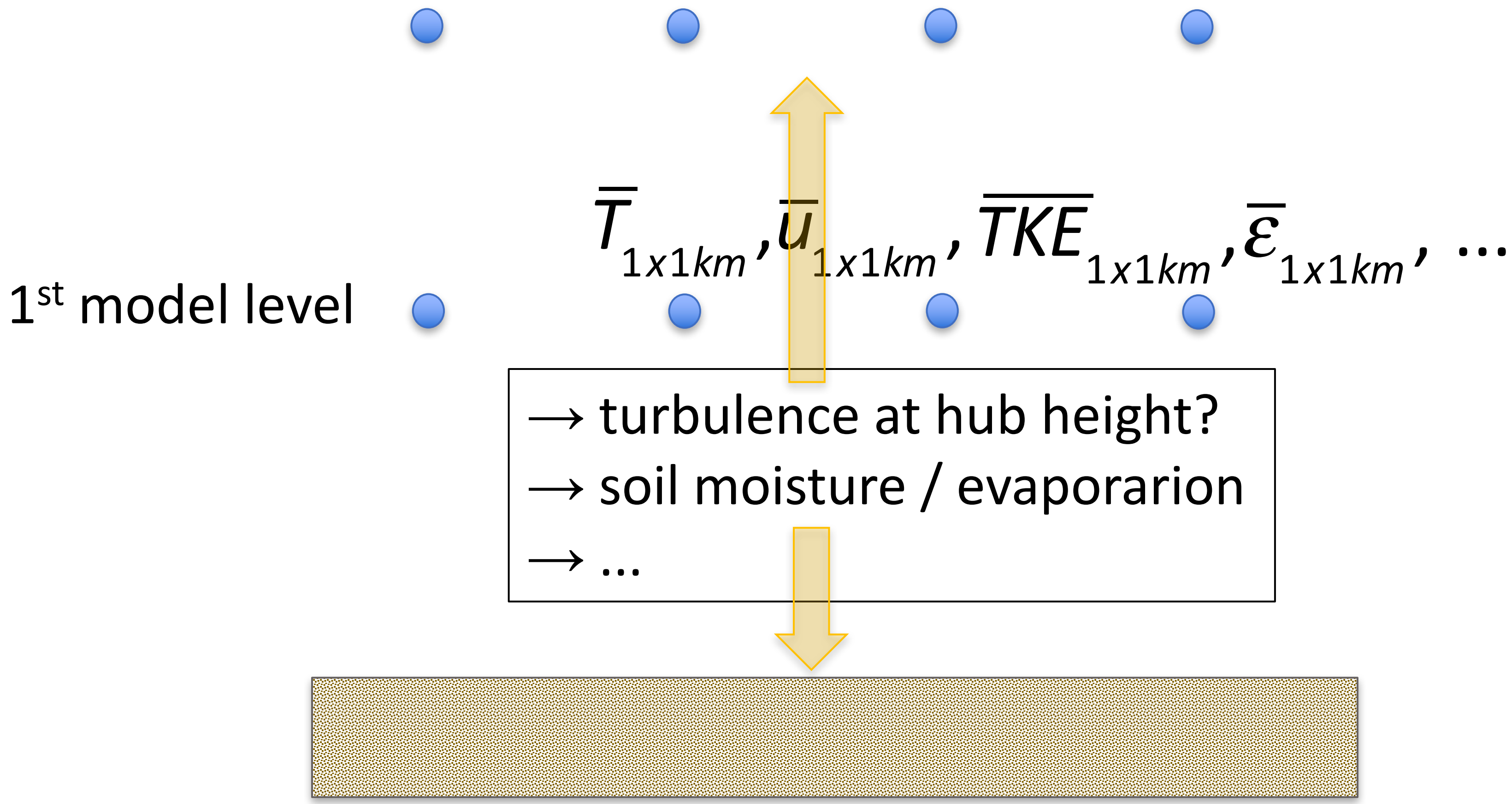
Summary

- Boundary layer structure in complex terrain
  → impact on overall exchange to FT
  → turbulent exchange *plus* meso-scale circulations
  plus terrain effects

- parameterizations exist for momentum
  → not for heat
  → nor for mass

- need to understand relative importance of processes
  → comprehensive data sets: more than a few episodes / spatial coverage
  → high-resolution numerical modeling
  → combined observations/modeling testbed

Atmospheric point informtion



→ boundary layer structure

→ bundary layer scaling

Boundary Layer challenges

- *Non-horizontally homogeneous*
- *Large roughness elements (plants, rocks, trees, houses)*
- *Topography*