A coordinated effort to investigate transport and exchange processes in the Atmosphere over mountains

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

- Transport and exchange processes over mountains

  → relevance

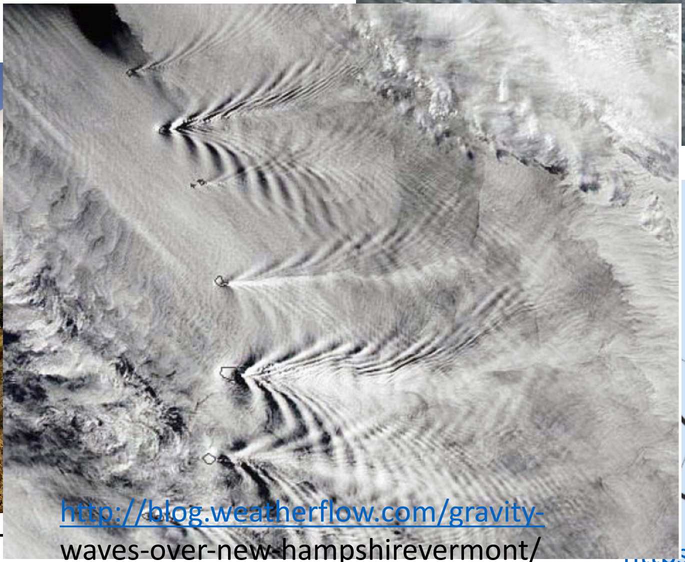
  → what do we know / need to know?

- TEAMx – a new international program

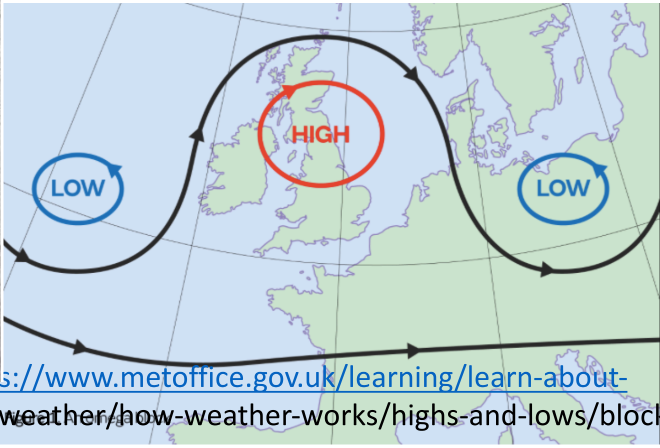
  ALPEX – MAP - TEAMx

Mountain Weather and Climate

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



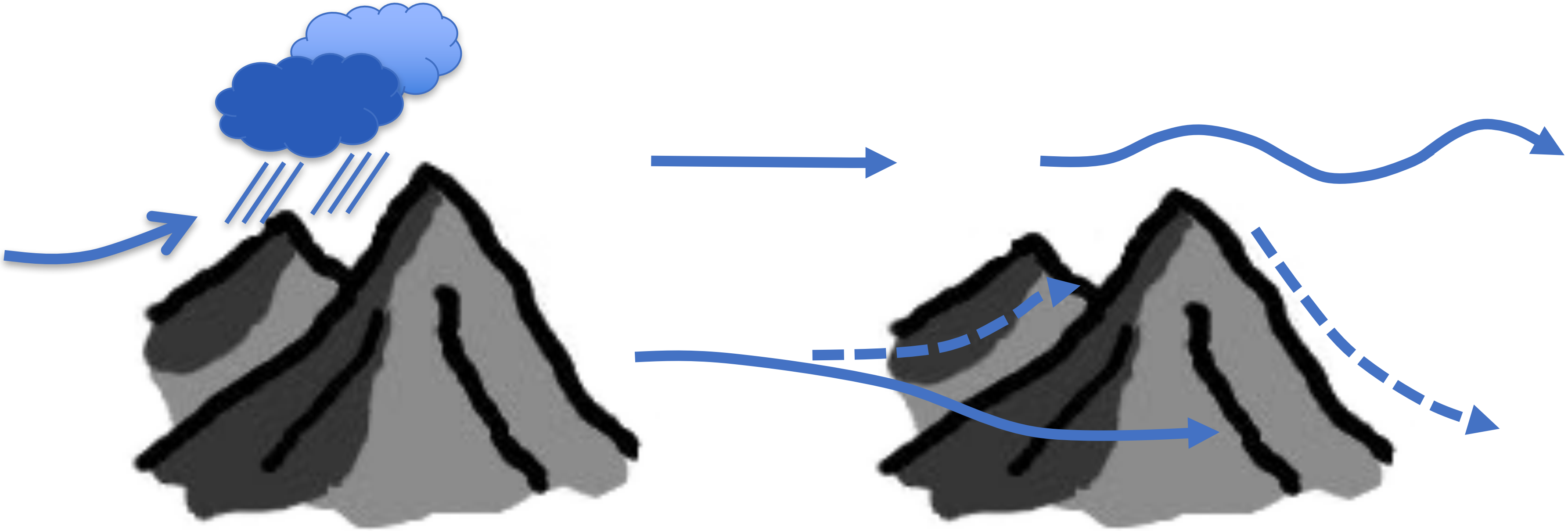
http://blog.weatherflow.com/gravity-waves-over-new-hampshirevermont/



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. ...



Which effect has the presence of the mountain **on the atmosphere**?

Mountain Weather and Climate

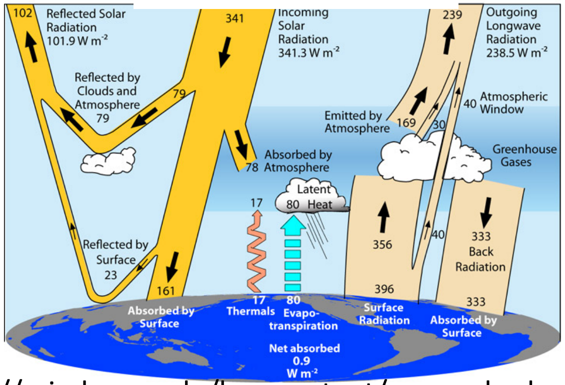
- common interest
  → impact of mountains on state of the atmosphere
  → e.g., how does ‘a mountain’ change the production of rain?
  → how does ‘a mountain’ modify the flow?
  etc., etc. ...
- mountain → atmosphere perspective
- from a global point of view:
  → ‘mountain’ is part of the surface
  →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

http://www.panoramio.com/photo/1724212

Exchange

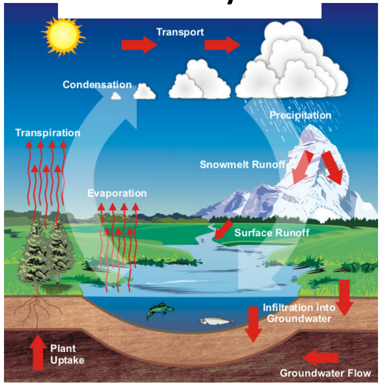
- character of the surface
  → determines the *exchange* between the atmosphere and the earth
  → *coupling* of the atmosphere with the surface
- mountain ↔ atmosphere perspective
  → how does the atmophere – which has been modified by the mountain – execute this exchange?

energy budget



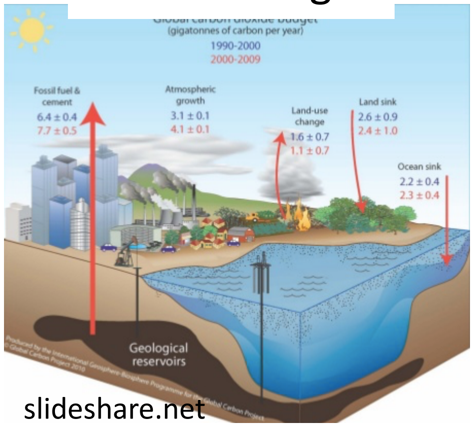
https://scied.ucar.edu/longcontent/energy-budget

water cycle



http://www.algebralab.org/practice/practice.aspxfile=Reading_WaterCycle.xml

carbon budget



slideshare.net

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  → how does the atmophere – which has been modified by the mountain – execute this exchange?
- 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

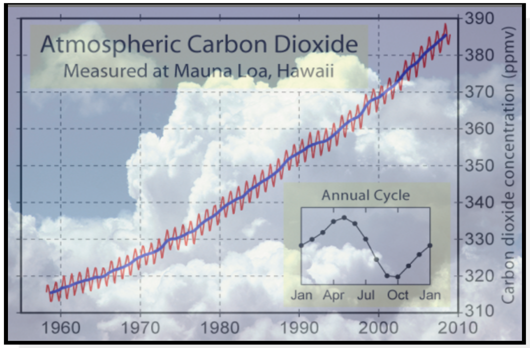
9.3±0.5 $PgC\ y^{-1}$

+

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:

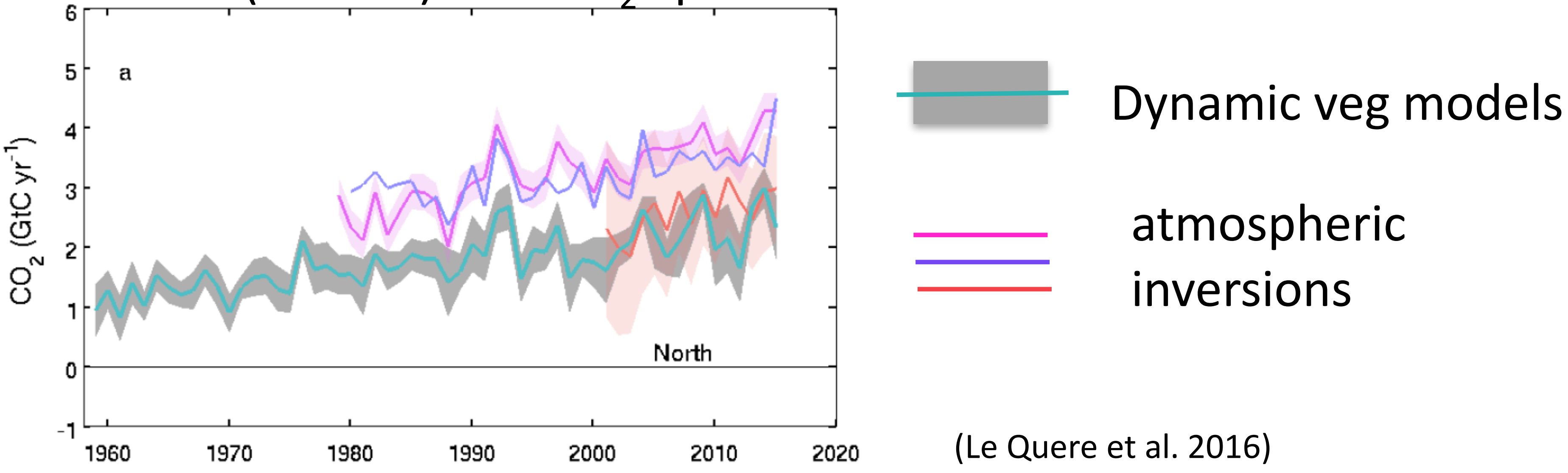
→ about equal shares go to oceans / land surface

→ 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)

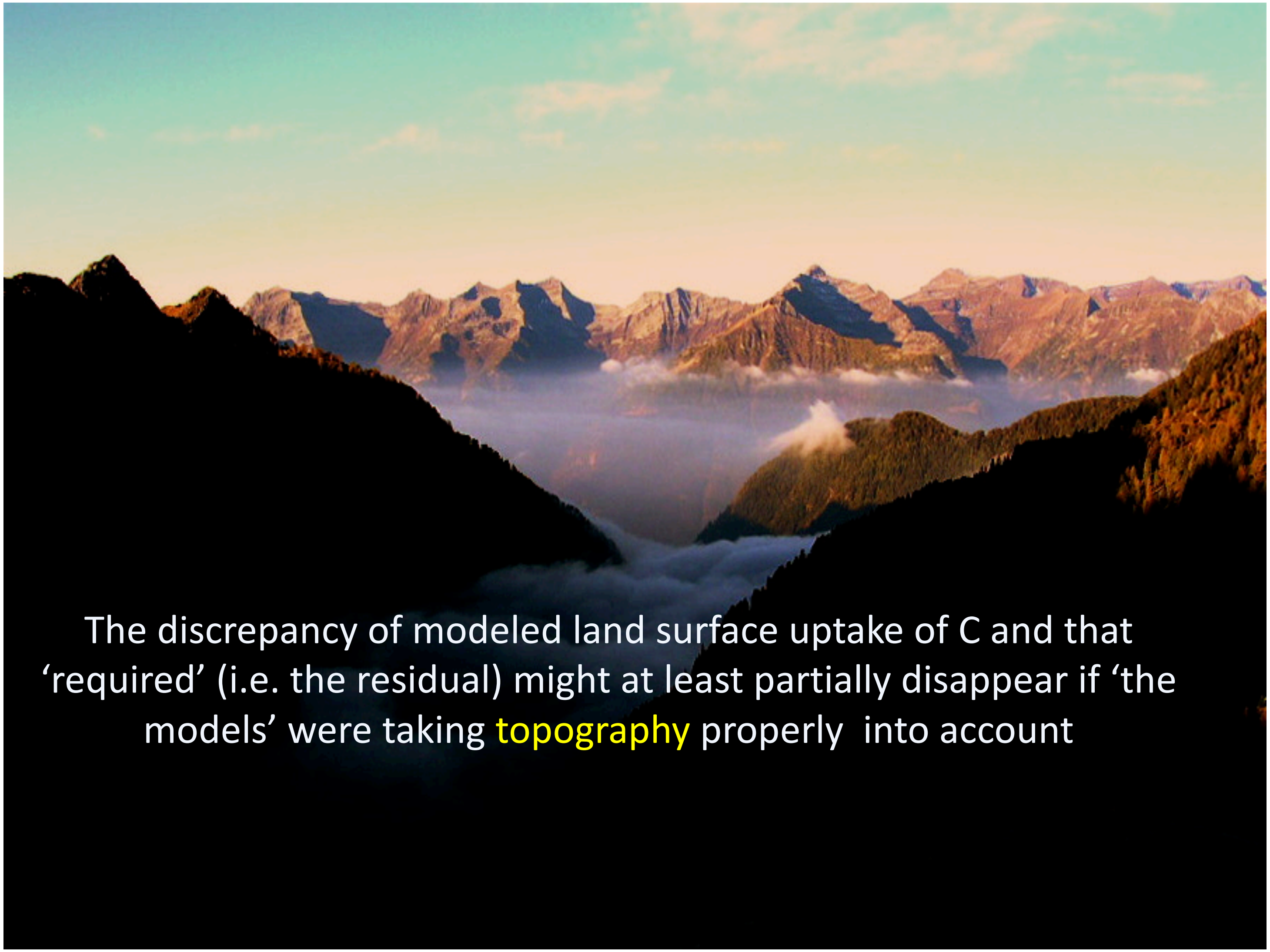
→ *modeled*: does not take into account terrain

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

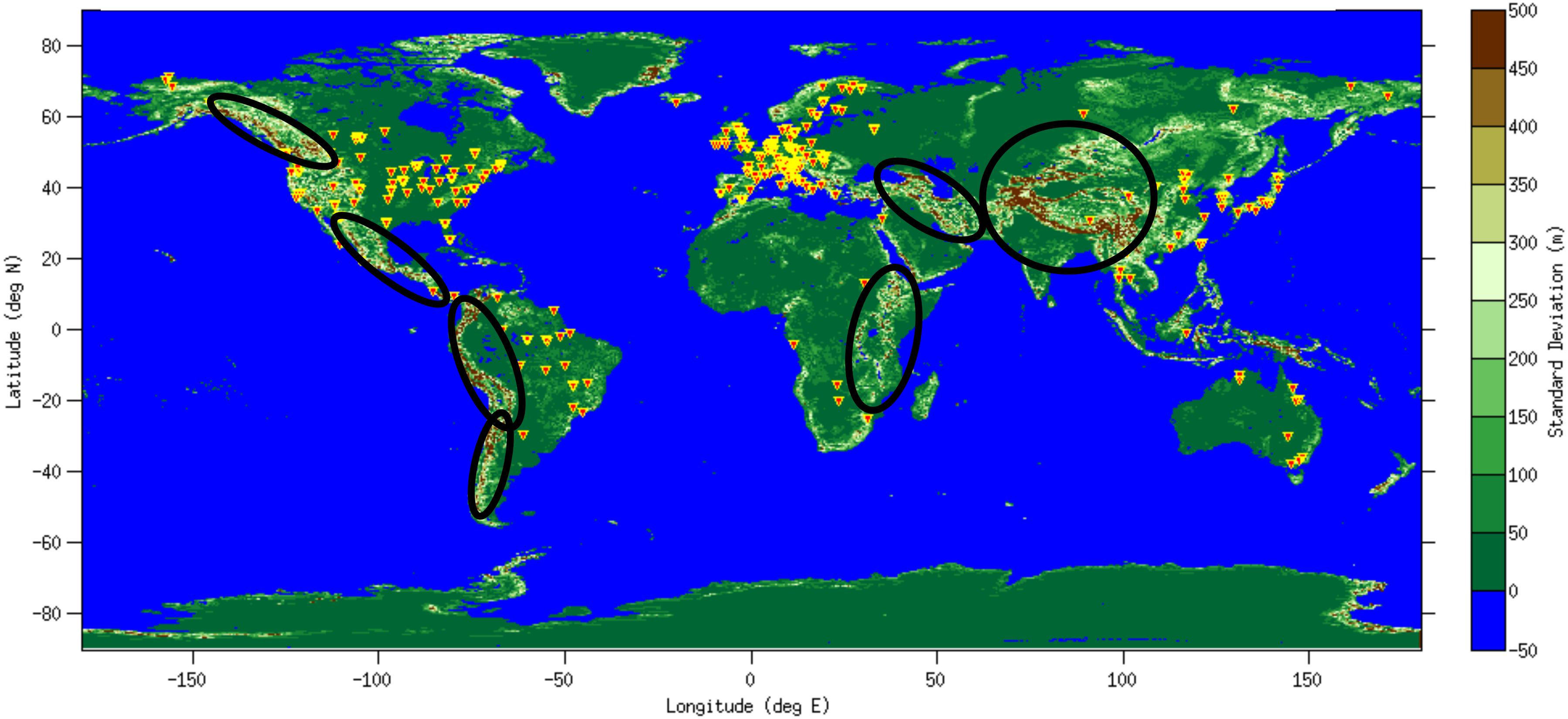
→ inventories

→ upscaling from ‘flux towers’

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

Flux tower sites

Standard deviation subgrid-scale topography (20km)

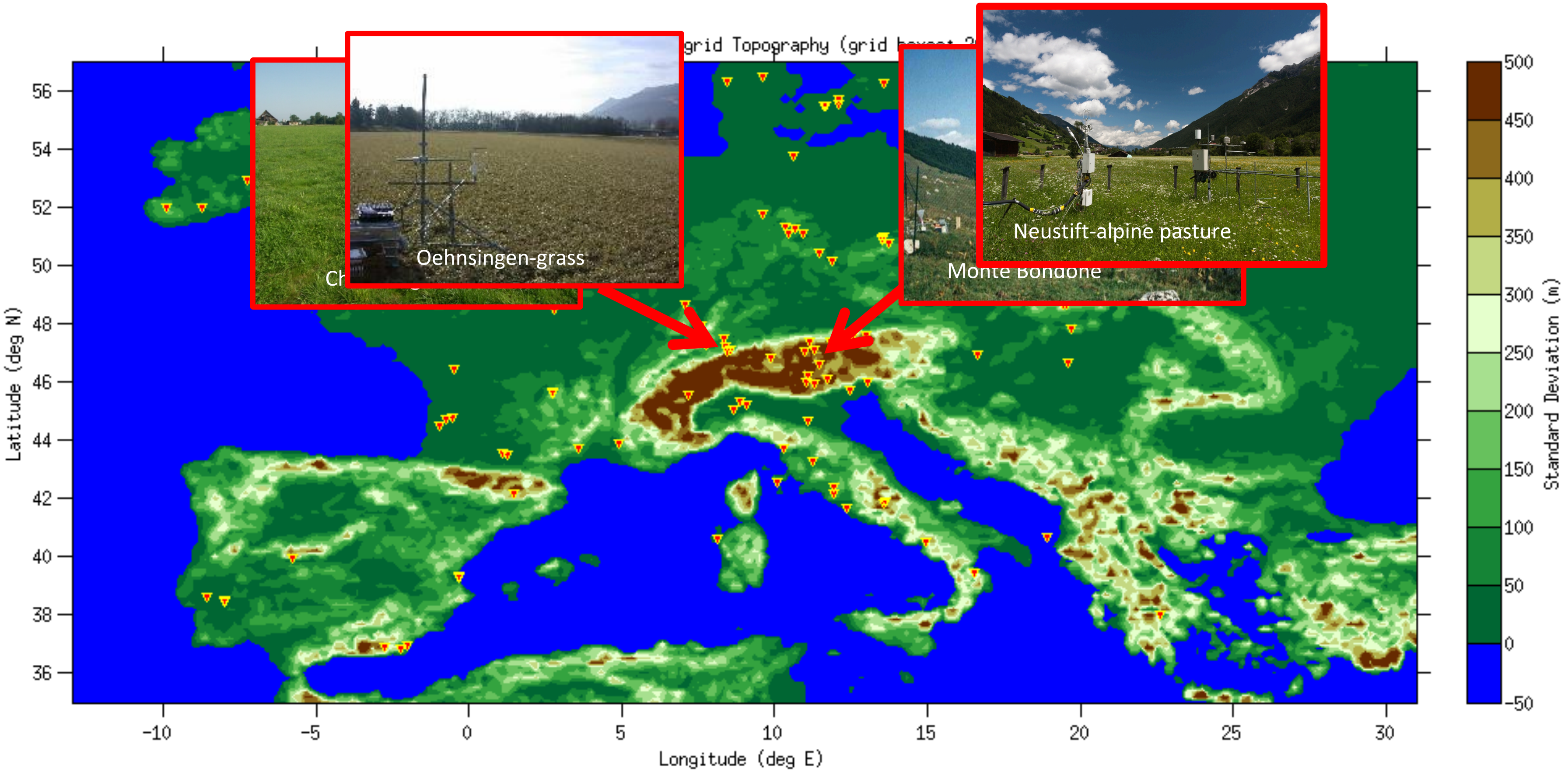


→ represent ecosystems

→ but not topography

Rotach et al. (2014), BAMS

Flux tower sites



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Modeled land surface uptake

model approaches:

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  vs:

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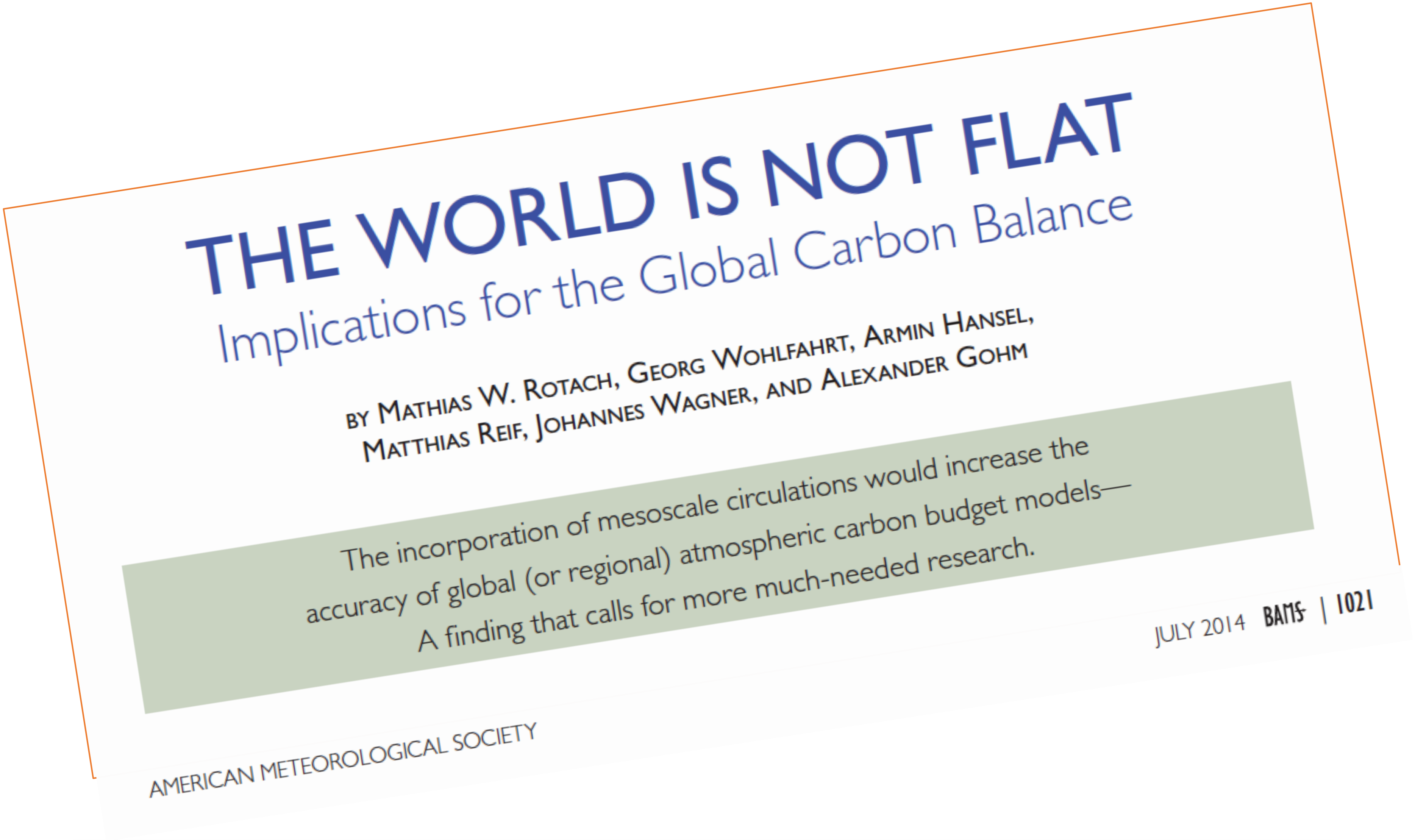
  → ecosystem modeling

  → 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.

AMERICAN METEOROLOGICAL SOCIETY

JULY 2014 BAMS | 1021

Exchange

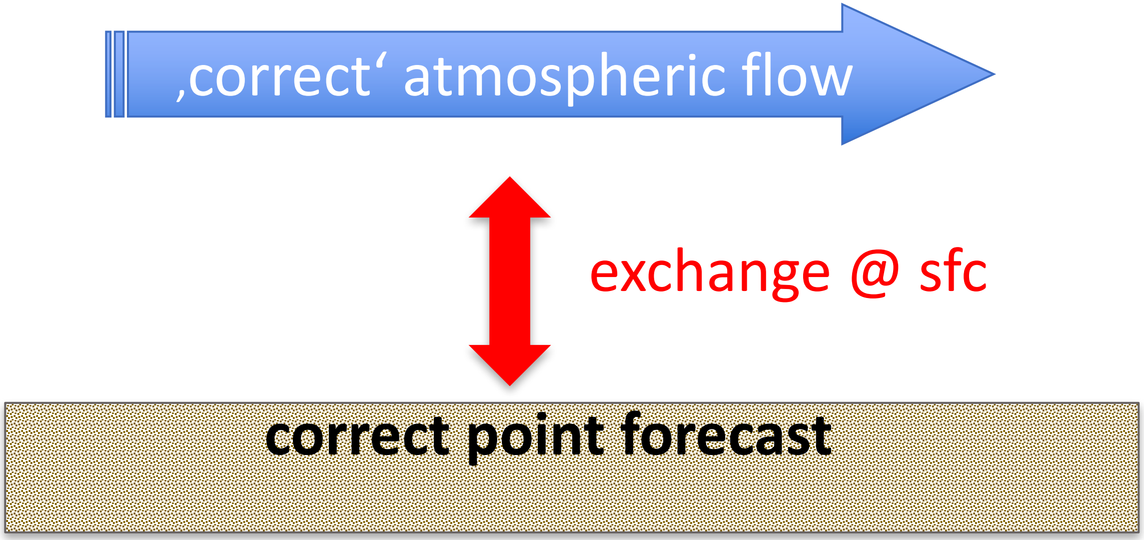
- character of the surface
  ⟶ determines the *exchange* between the atmosphere and the earth
  ⟶ *coupling* of the atmosphere with the surface
- mountain ⟷ atmosphere perspective
  ⟶ how does the atmophere – which has been modified by the mountain – execute this exchange?
- traditionally: this is the role of the *boundary layer*
  ⟶ exchange of heat, mass and momentum *at the surface*
  ⟶ transport to the ground / away from the ground
- (first) challenge: Mountain Boundary Layer
  ⟶ where (what) is it?
  ⟶ how does it interact with meso-scale flows?

Recent developments (since MAP)

- better model resolution
  - → e.g., COSMO-1 for NWP, AROME @2.5 km
  - → 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)
  - → physics parameterizations are not devised for non-flat terrain
- huge jump in observational systems
  - → lidar, commercially available (beginning: also Raman for H_2O)
  - → satellites
- climate change
  - → requires impact modeling
  - → need: the right temperature at mtn. surface (not only the mtn. sfc temperature that yields the 'best precipitation')

The 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**



‚correct‘ atmospheric flow

exchange @ sfc

correct point forecast

A Change in the Perspective

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

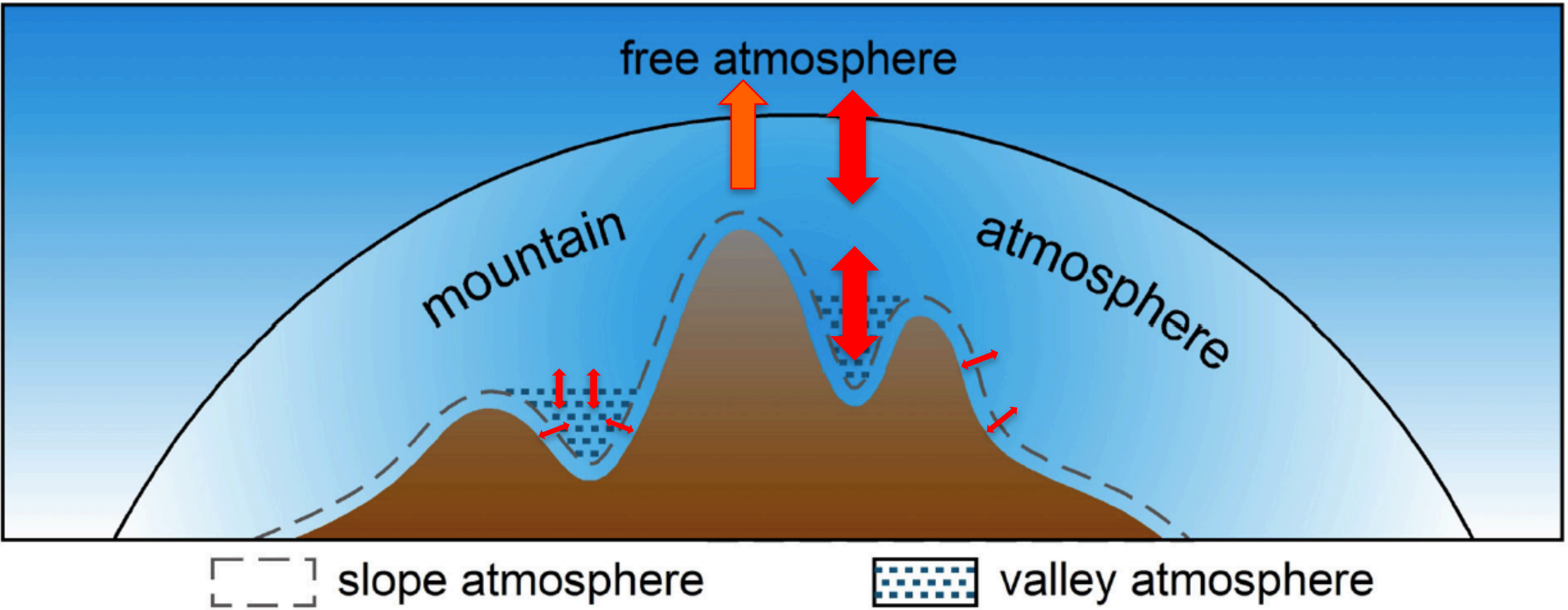
→ if related to traditional (prognostic) variables:
downscaling (diagnosing)

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

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

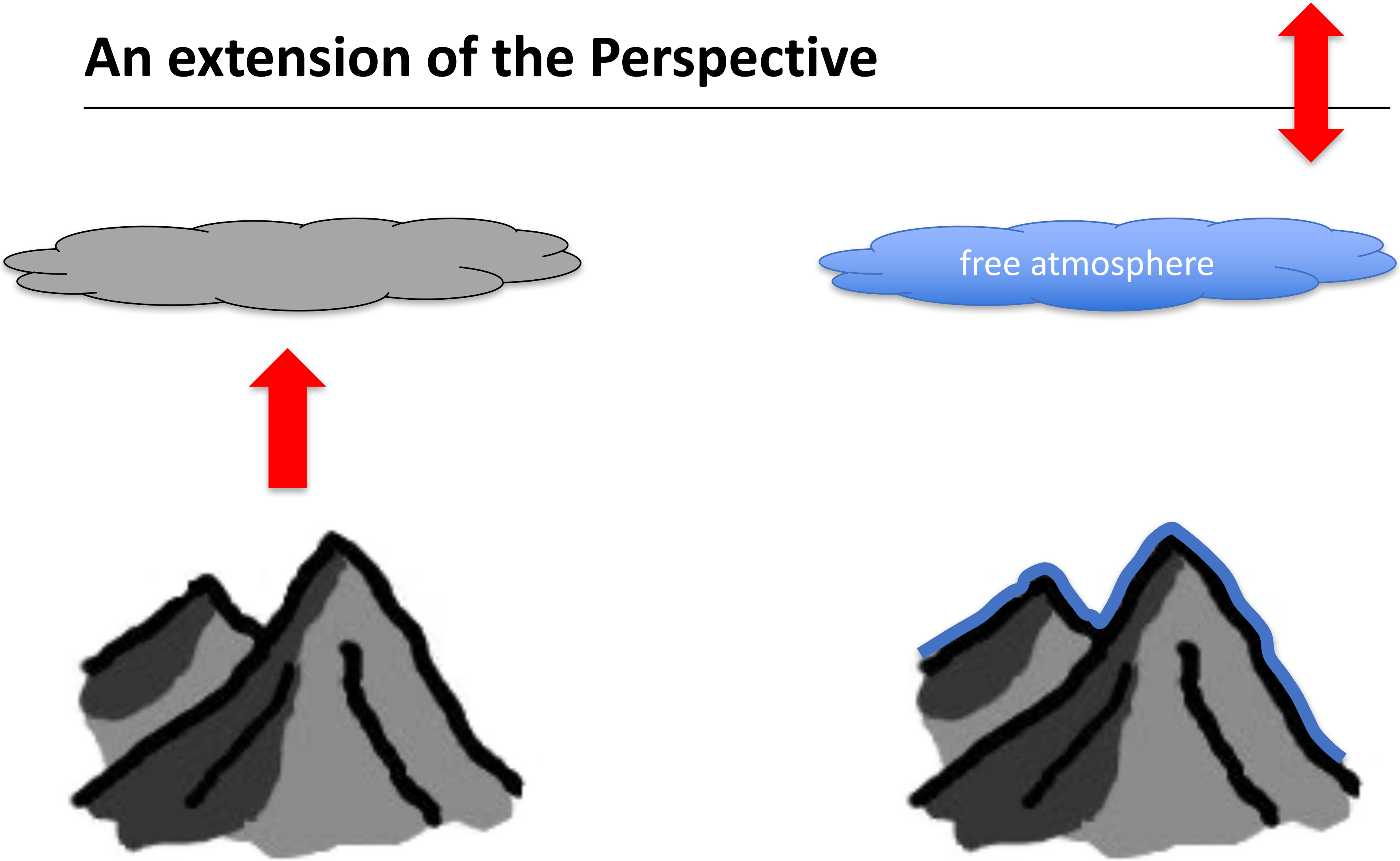
→ for example: air pollution modeling (friction velocity, TKE, PBL height, ...)

An extension of the Perspective



DeWekker and Kossman(2015), after Eckhart (1948)

An extension of the Perspective



Mountain meteorology

Correct point forecast

- mountain ↔ atmosphere perspective
  → how does the atmophere – which has been modified by the mountain – execute this exchange?
  → translates to ‘correct point forecast’
- radiation, turbulence, boundary layer state
  → direct input to *impact models*
  → hydrological [evaporation, sfc EB]; vegetation (agriculture) [sfc EB, canopy]; wind power [TKE]; solar power [net SW]; avalanche [sfc EB, albedo]; air pollution [PBL height, TKE, stability]; pollen [PBL height, TKE, stability]
  → for reliable point weather forecast / warnings / planning (now): *Earth System Services*
  → for downscaling of climate data (future): *Climate Services*
- interaction with meso-scale flow (not PBL alone)

Earth-atmosphere interaction

Exchange of

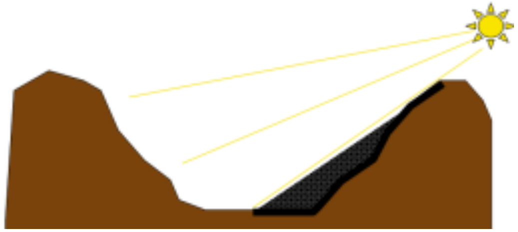
- heat, momentum
- mass (water vapor, others, [CO_2], …)

... determined through

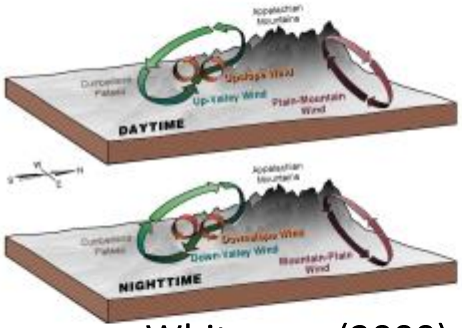
- availability
- efficiency of exchange

Exchange over topography

- Boundary layer is *inhomogeneous* by construction

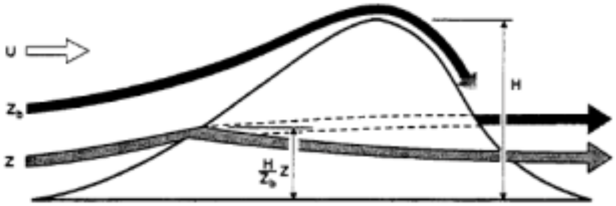


- thermally induced circulations
  → slope / valley flows
  → mountain venting



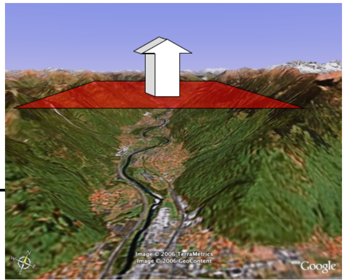
Whiteman (2000)

- dynamic modification (gravity wave drag, etc.)



Lott and Miller (1996)

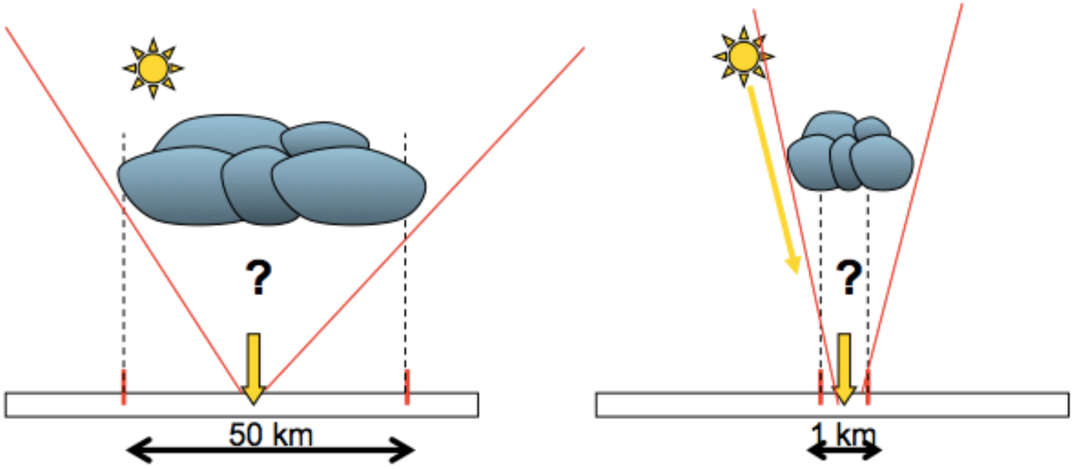
- geometrical effects (e.g., narrowing / widening) for mass



Exchange over topography

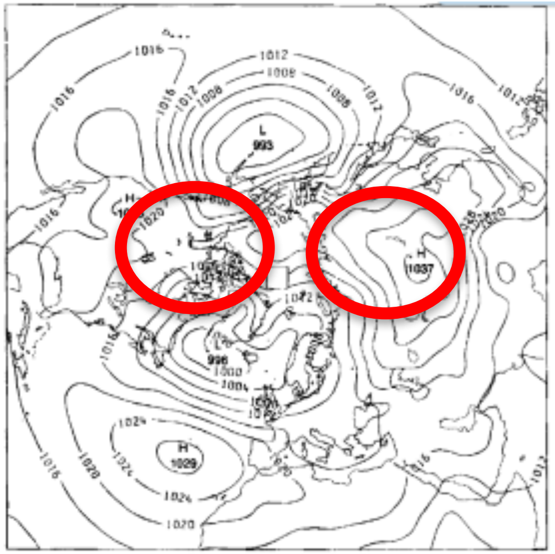
- do the (current) atmospheric models appropriately represent this?
  → depends on resolution...
  → state of the Art: $\mathcal{O}$(1 km) grid spacing for NWP, $\mathcal{O}$(10 km) gs for regional climate

- physical processes
  → turbulent exchange
  → radiation
  → both usually 1d

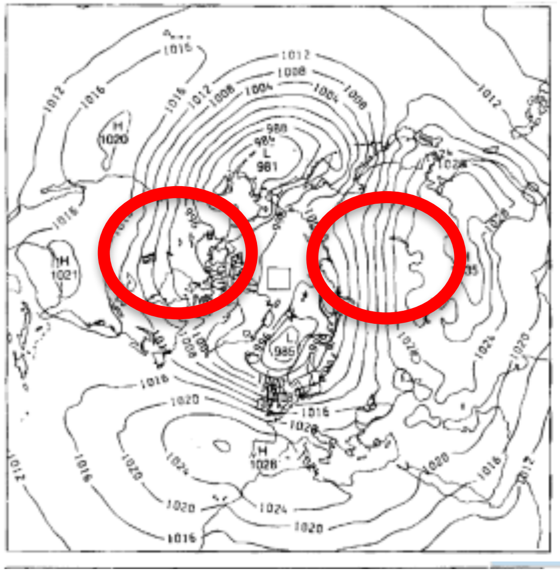


- appropriate meso-scale flow (thermodynamic) field?
  → do low resolution models need a sgs parameterization?

Momentum exchange



Palmer et al 1986 (QJ)



no gravity wave drag

mean Jan NH SLP (84-86)

→ **total exchange:** subgrid-scale contribution parameterized

Subgrid parameterization

✓ **Momentum**

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

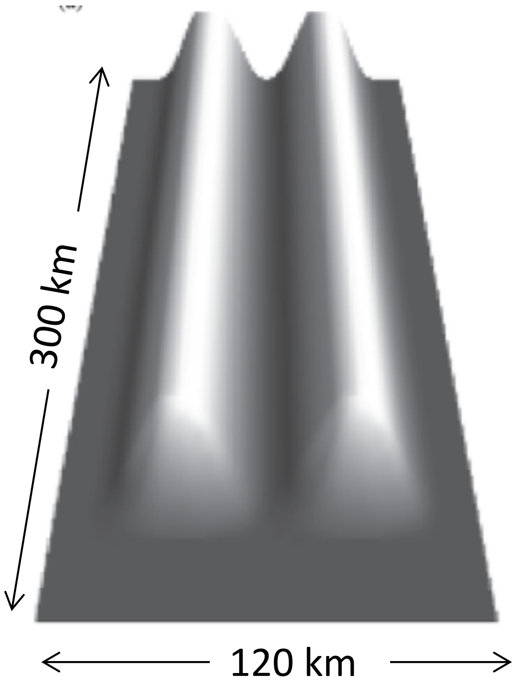
Heat

→ Noppel and Fiedler (2002)

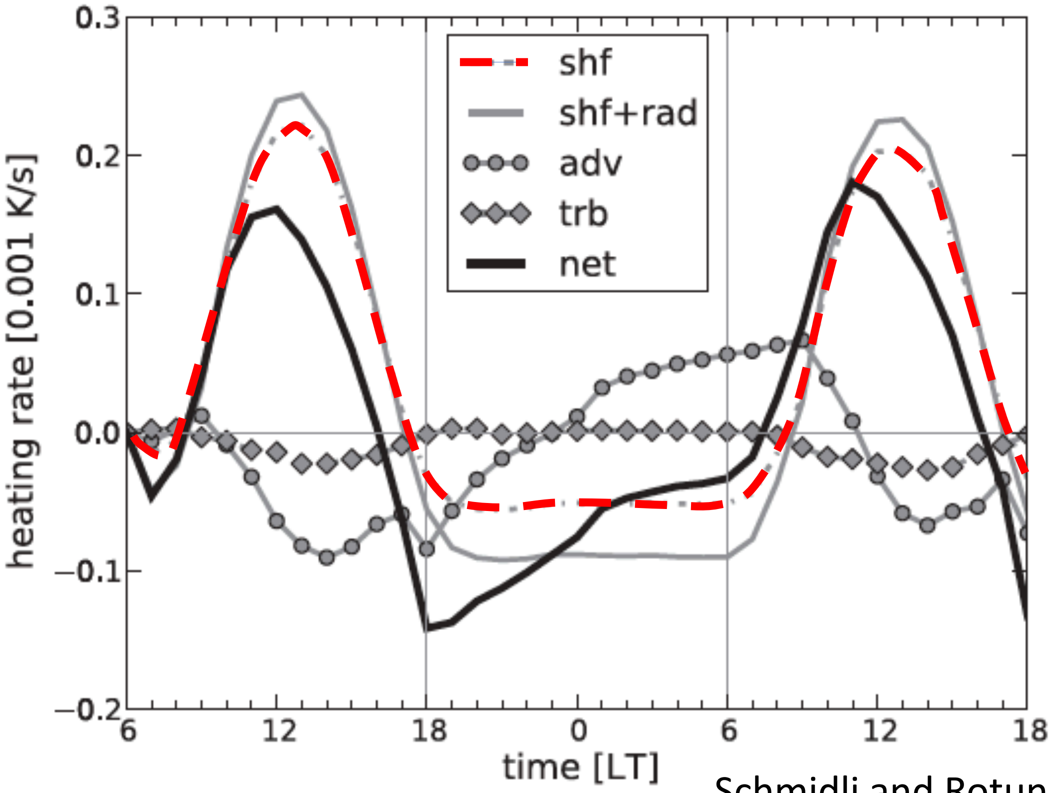
→ …..

→ Schmidli and Rotunno (2010, 2012)

Heat exchange



Δx =1km, ARPS



Schmidli and Rotunno 2010

→ perfectly ideal

→ influence of surrounding topography

→ influence of geometry / initial stratification / ….

(Johannes Wagner) (Daniel Leukauf)

Subgrid parameterization

✓ **Momentum**

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

(✓) **Heat**

→ Noppel and Fiedler (2002)

→ …..

→ Schmidli and Rotunno (2012)

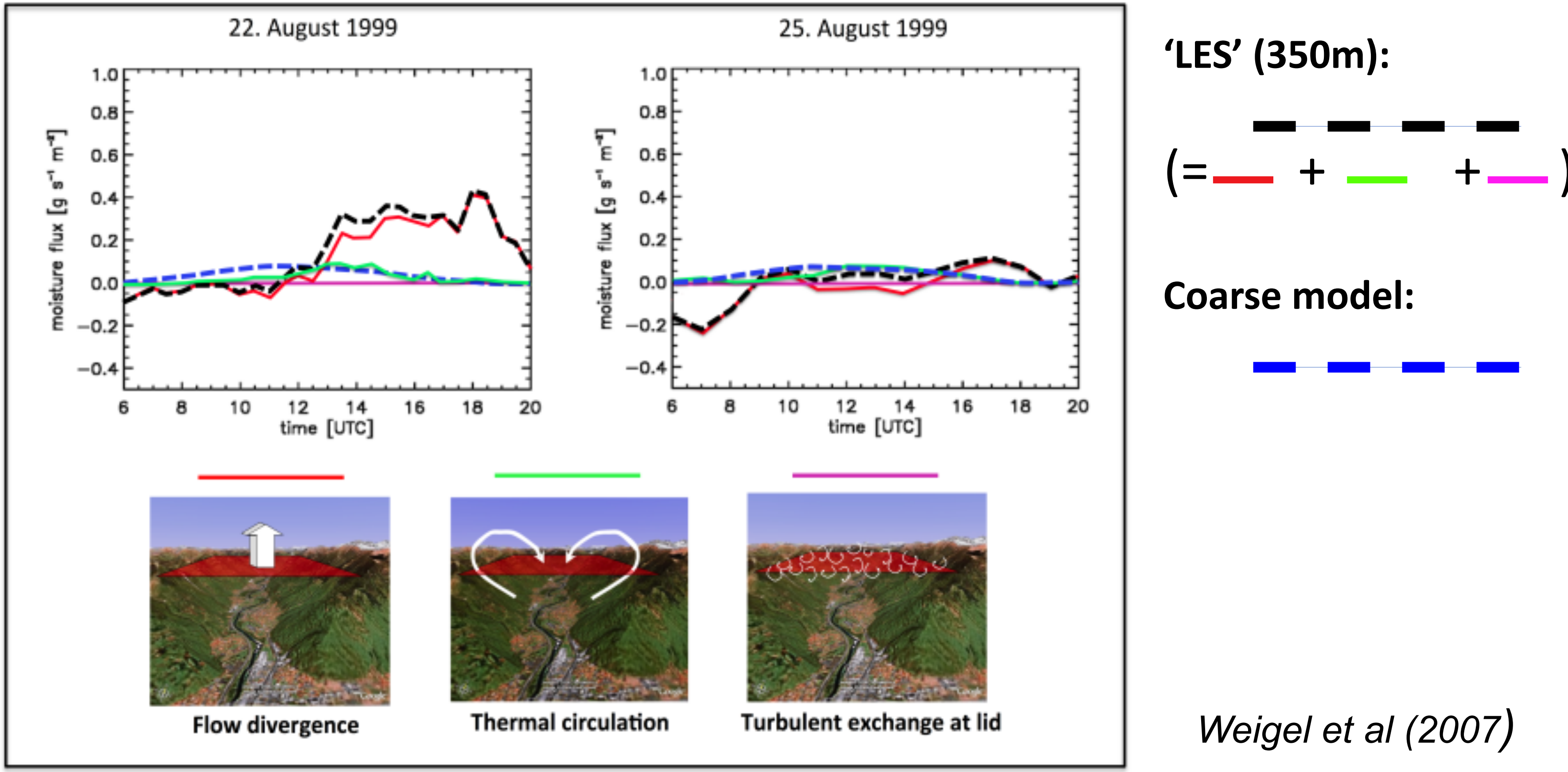
>idealized modeling
>systematic
>no parameterization yet

Mass

→ Weigel et al. (2007)

Moisture exchange

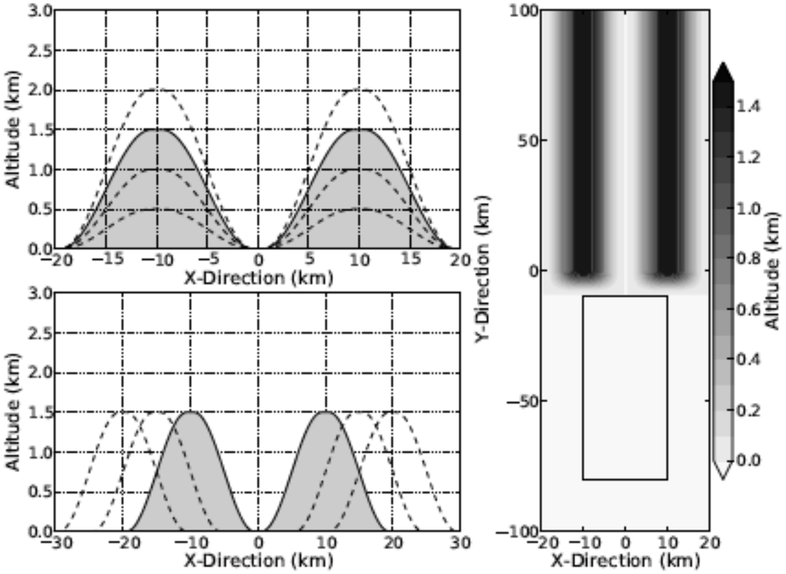
- MAP Riviera example
- two (example) days with weak synoptic forcing
- ARPS, excellent correspondence to measurements

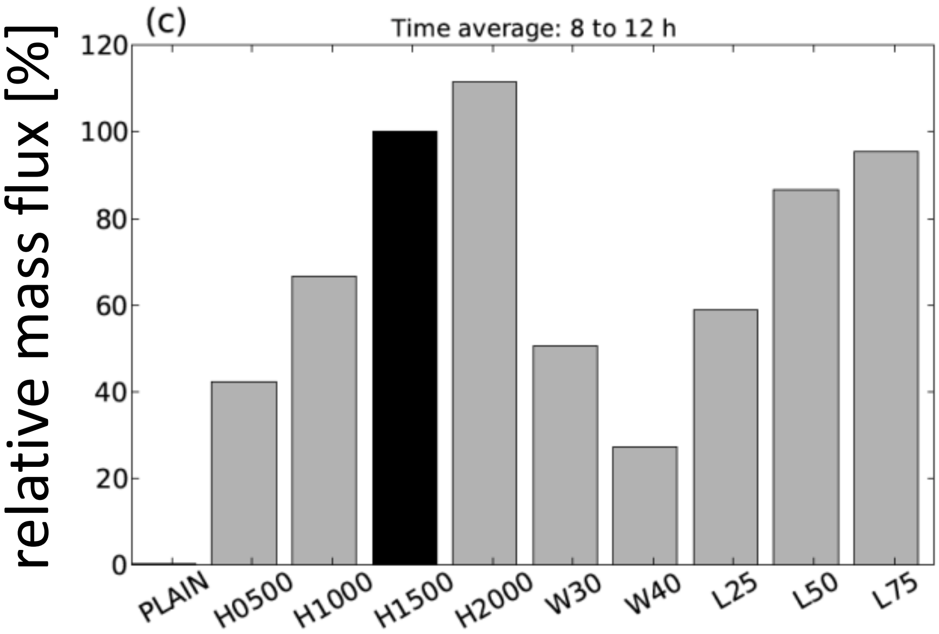


Weigel et al (2007)

Mass exchange

- Idealized numerical modeling
- WRF, 200m horizontal mesh size
- different geometries





Wagner et al, QJ 2015

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**

→ moisture

→ CO_2

A new international programme

TEAMx

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

ALPEX → *MAP* → *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

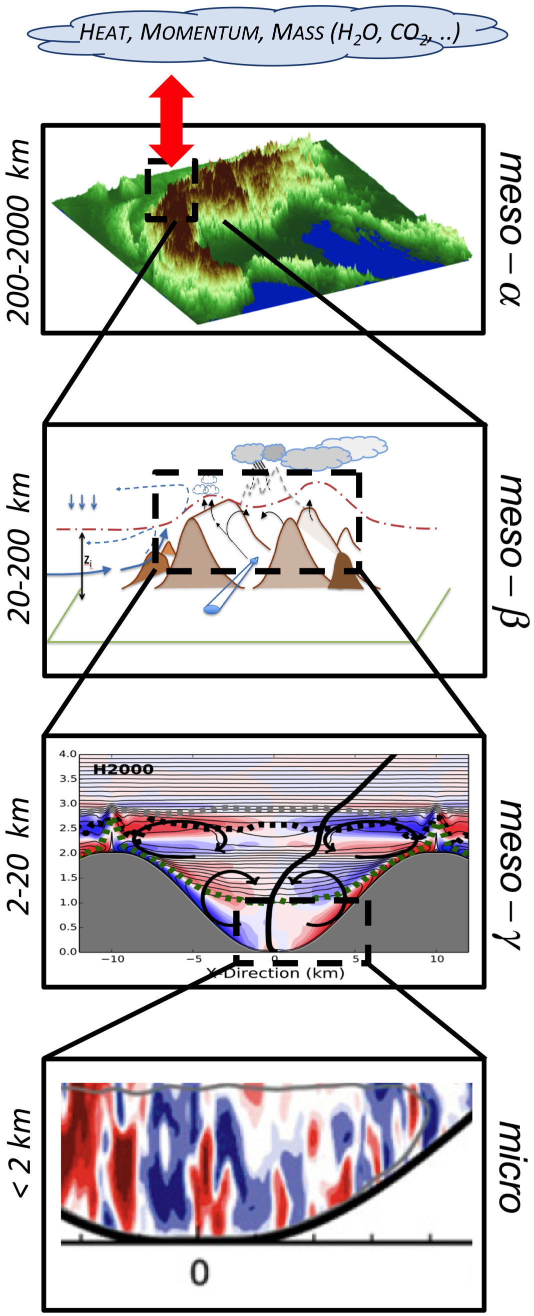
Scale interactions

- cyclogenesis, instability
- PV 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



Processes @ scale

- 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
- Alpine venting
- convective initiation (CI)

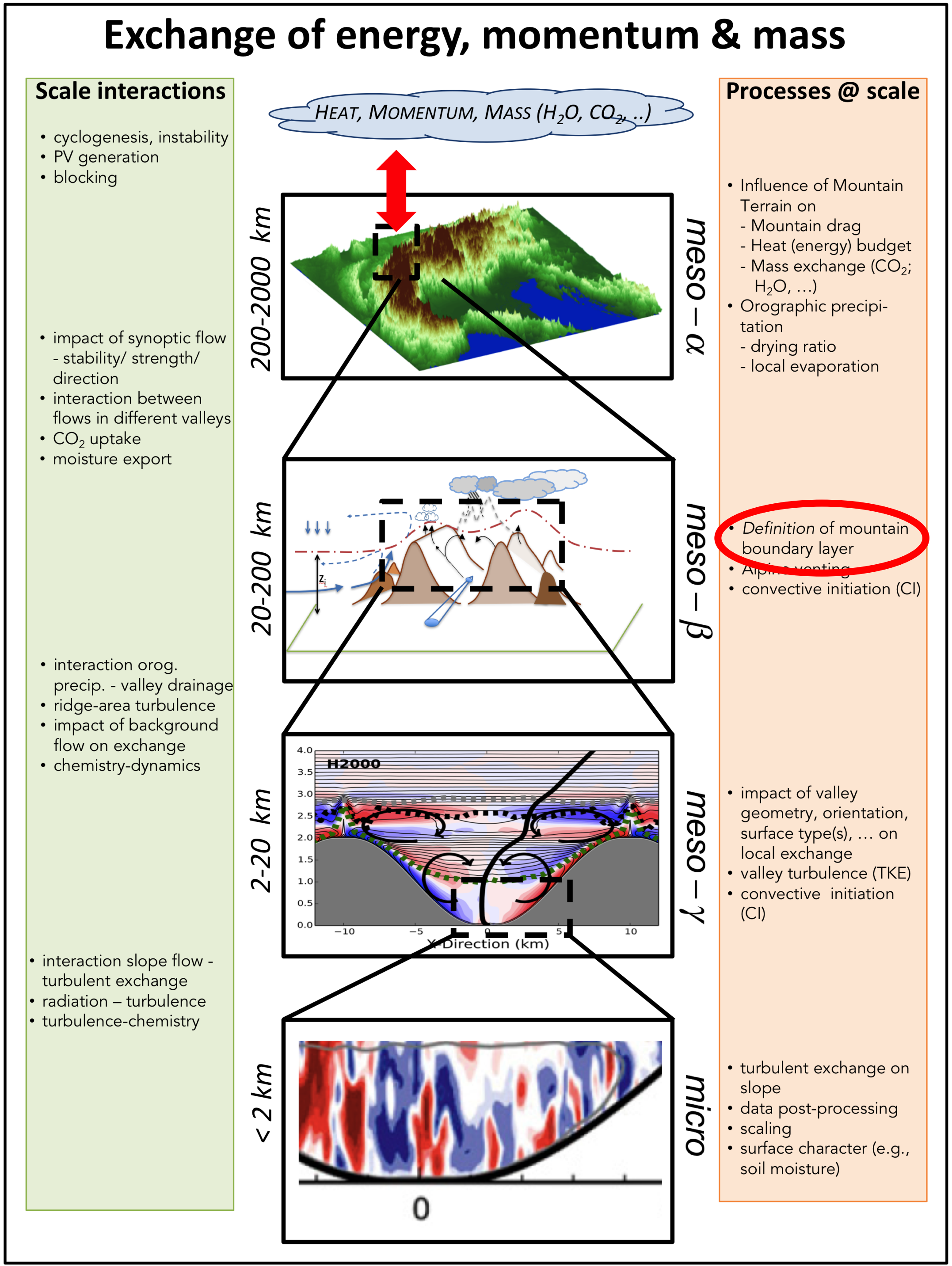
- impact of valley geometry, orientation, surface type(s), … on local exchange
- valley turbulence (TKE)
- convective initiation (CI)

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



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methods:

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

goal:

→ coordinated *experiment* *(2022-23)*

Specific research questions

Where (what) is the MBL?

‘The *Atmospheric Boundary Layer* is that part of the troposphere that is **directly influenced** by the presence of the **earth's surface**, and responds to surface forcing with a **timescale of about an hour or less**’. Stull (1988)

diagnostics, ABL height:

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

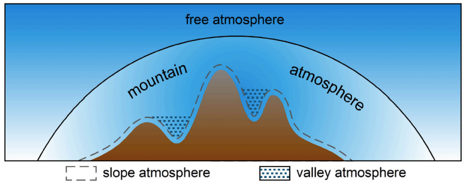
→ based on turbulence state of ABL (e.g., Ri / TKE criterion)

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

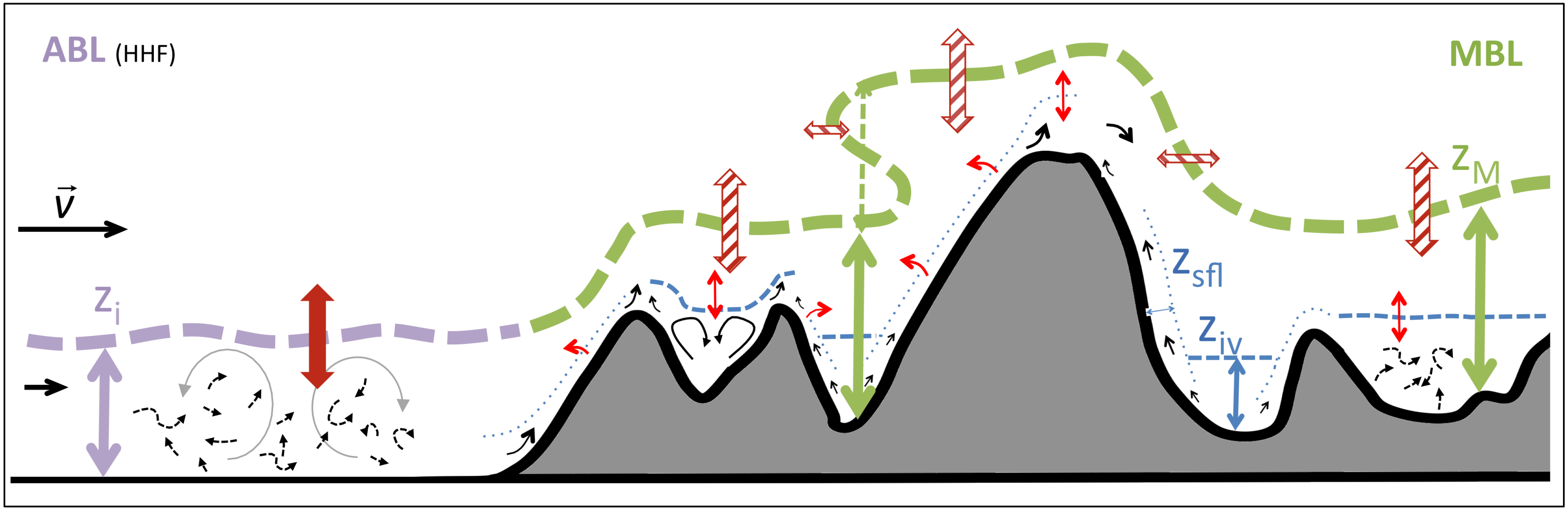
→ dependent on application (even in HHF terrain)

Mountain Boundary Layer (MBL)

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



a) unstable stratification (daytime)



Lehner and Rotach (tbs)

Mountain Boundary Layer (MBL)

Suggested definition **Mountain Boundary Layer**

The Mountain Boundary Layer (MBL) is *the lowest part of the troposphere that is directly influenced by the mountainous terrain, responds to surface and terrain forcings with timescales of order one hour (*$\mathcal{O}$[1 h]), *and is responsible for the exchange of energy, mass, and momentum between the mountainous terrain and the free troposphere.*

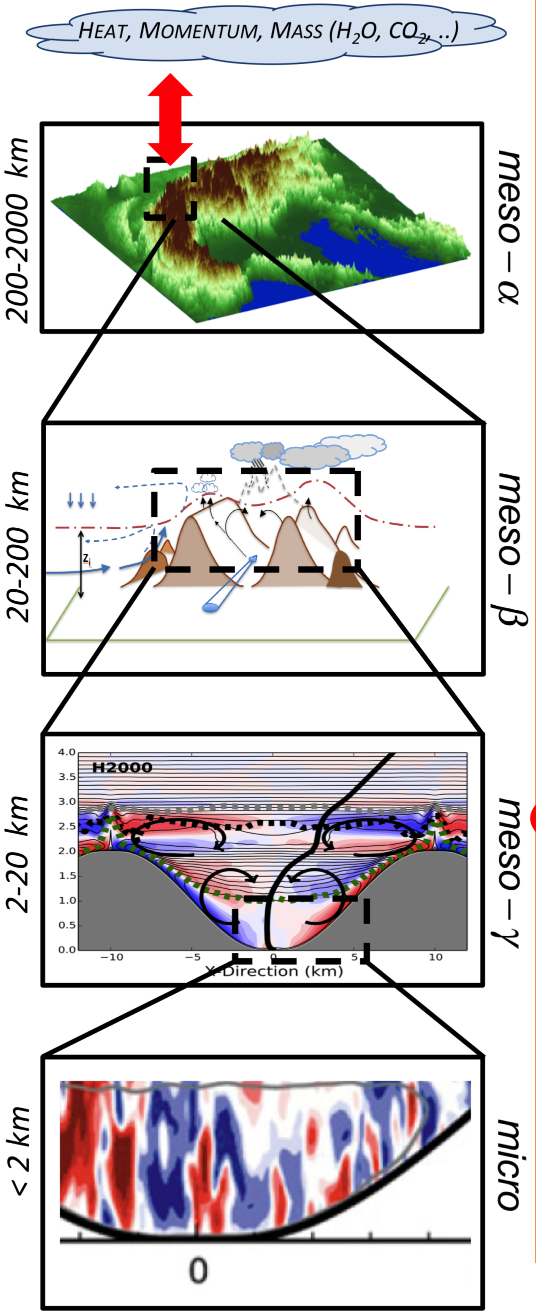
Lehner and Rotach (tbs)

explicit research questions:

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

→ 'general' structure feasible?

Exchange of energy, momentum & mass



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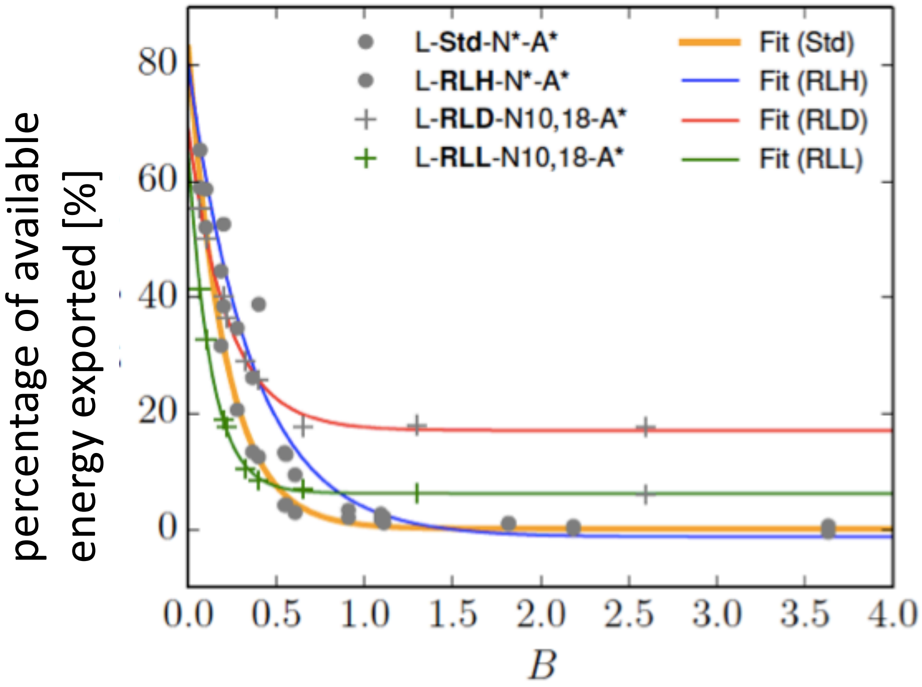
Heat export from idealized valley

Dissertation Daniel Leukauf



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

idealized WRF simulations:

→ dx = 200 m

→ different (solar) forcing

→ different initital stratification

→ different geometry

→ how much heat is exported?

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

Leukauf et al. (2017)

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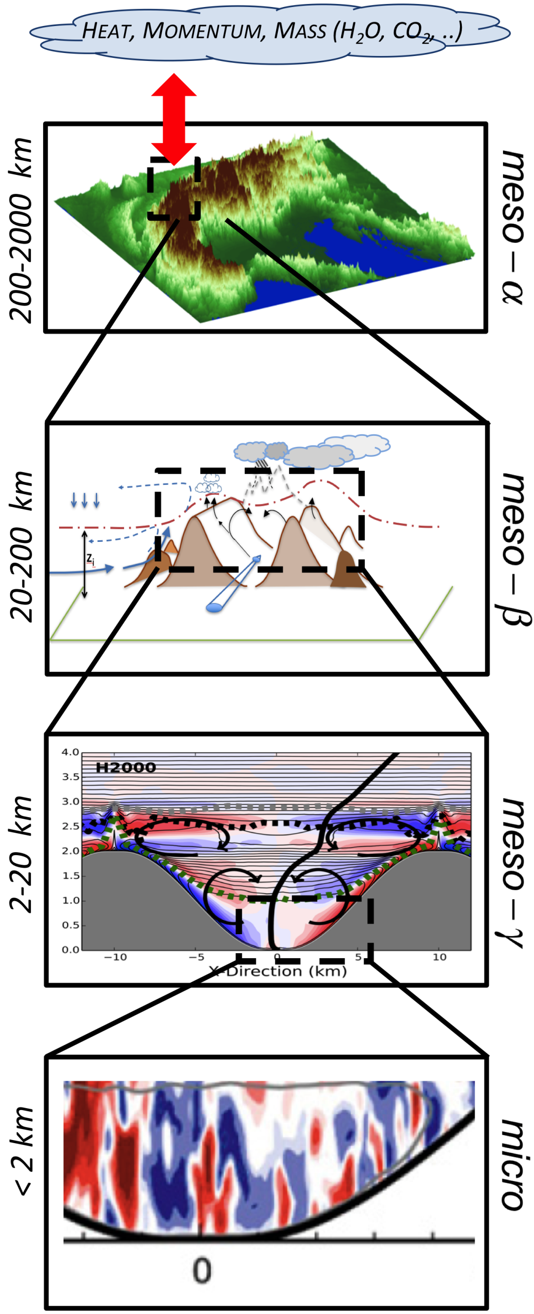
- interaction slope flow - turbulent exchange
- radiation – turbulence
- turbulence-chemistry



Processes @ scale

- 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
- Alpine venting
- convective initiation (CI)

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

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

methods:

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

goal:

→ coordinated *experiment (2022-23)*

Flow structure in idealized valley

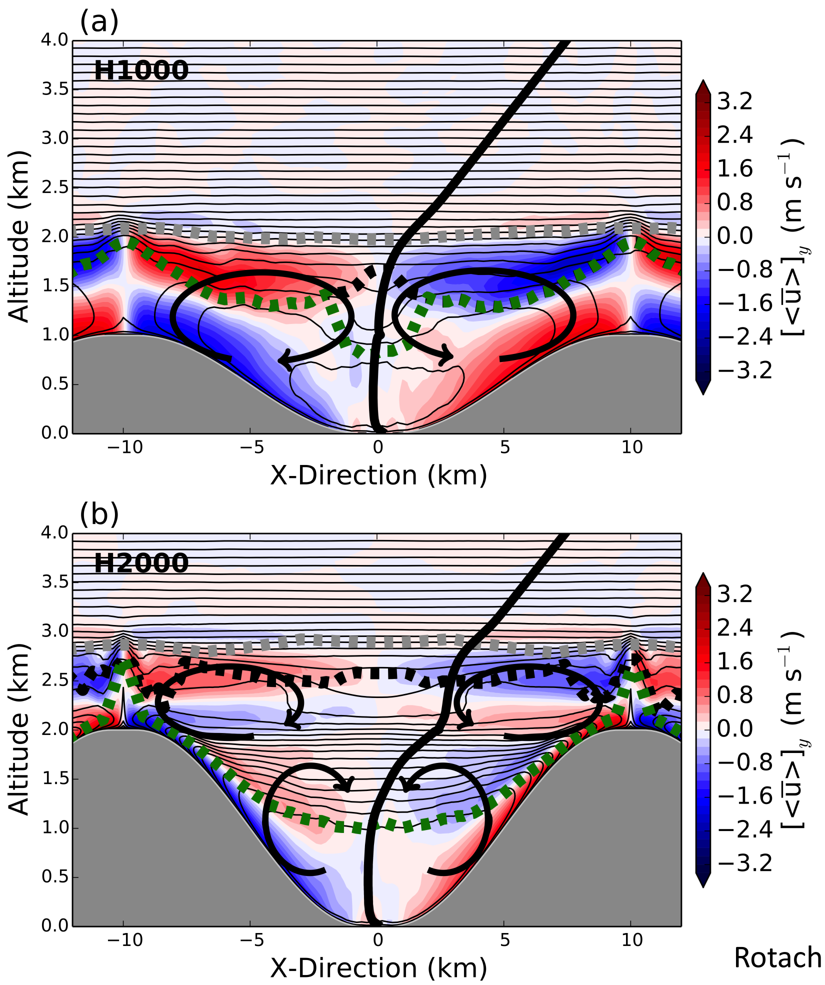
Dissertation Johannes Wagner

idealized WRF simulations:

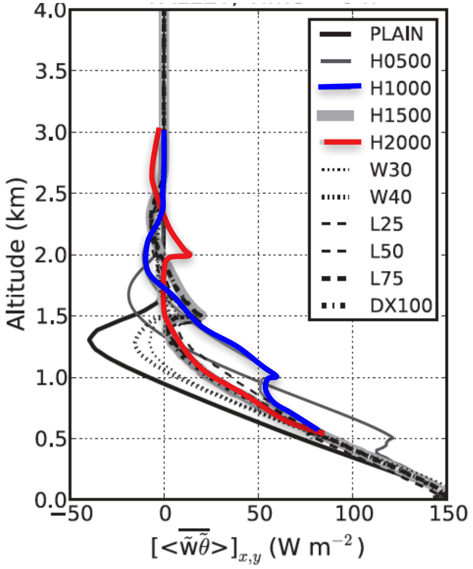
→ dx = 200 m

→ different valley geometry

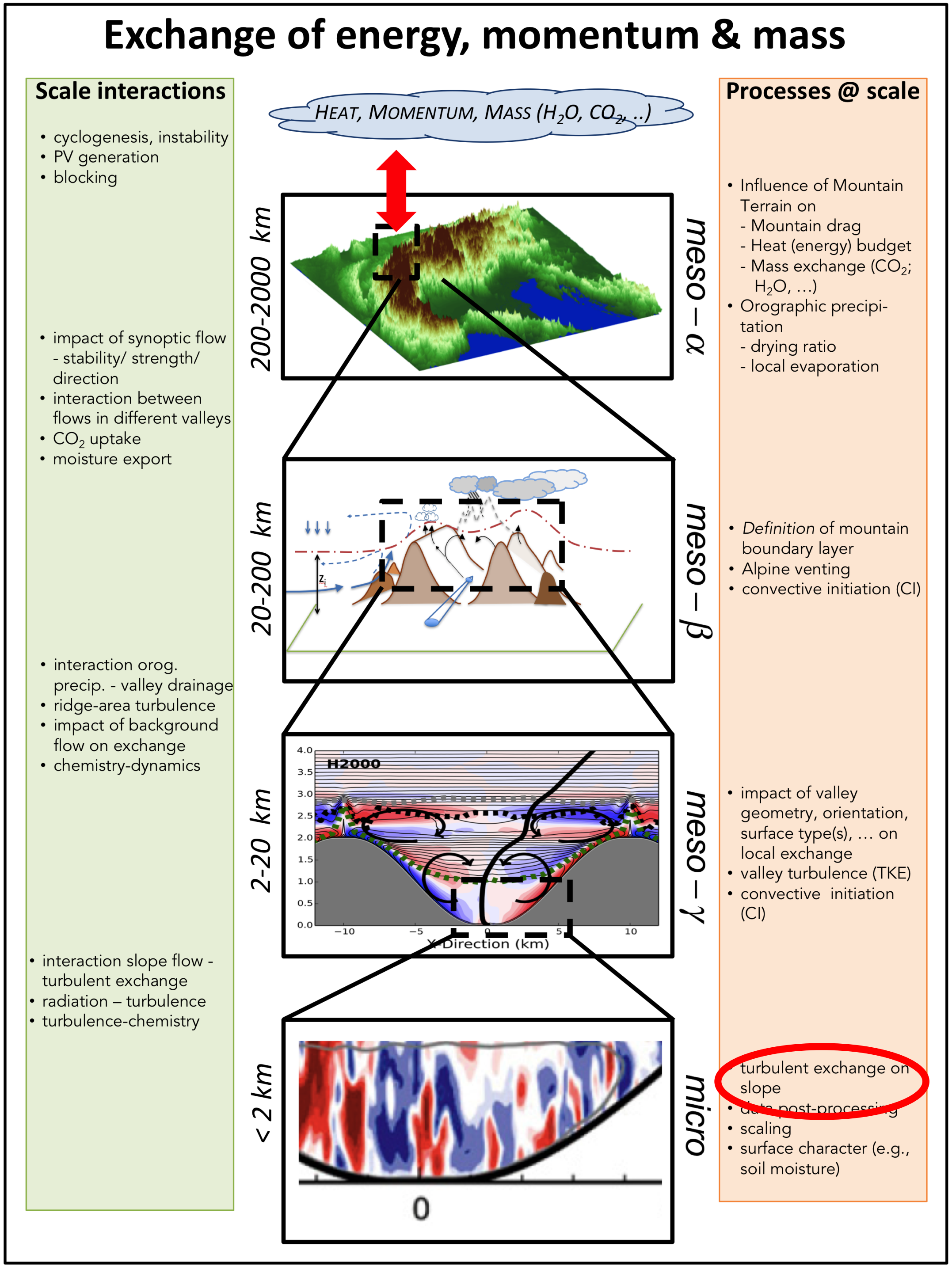
→ slope circulation - exchange



total vertical heat flux
(average valley cross-sect)



Rotach et al. 2015, based on Wagner et al. 2015



Exchange of energy, momentum & mass

Scale interactions

- 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
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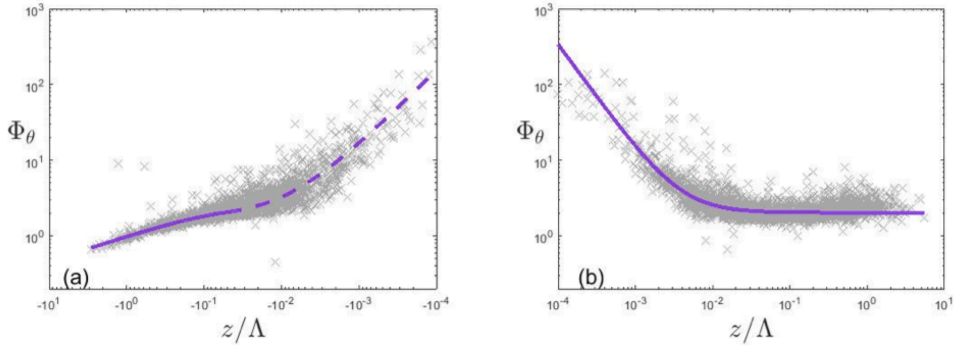
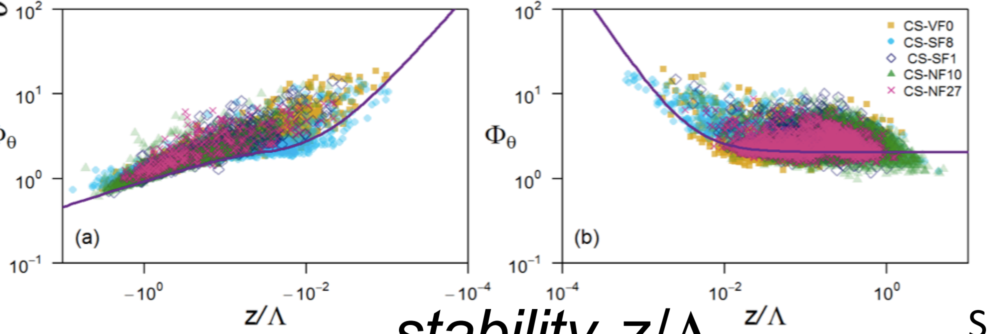
Turbulent exchange on slopes

Dissertation Eleni Sfyri

ideal reference (Cabauw)



i-Box data



$\sigma_\theta / |\theta_*|$

stability z/Λ

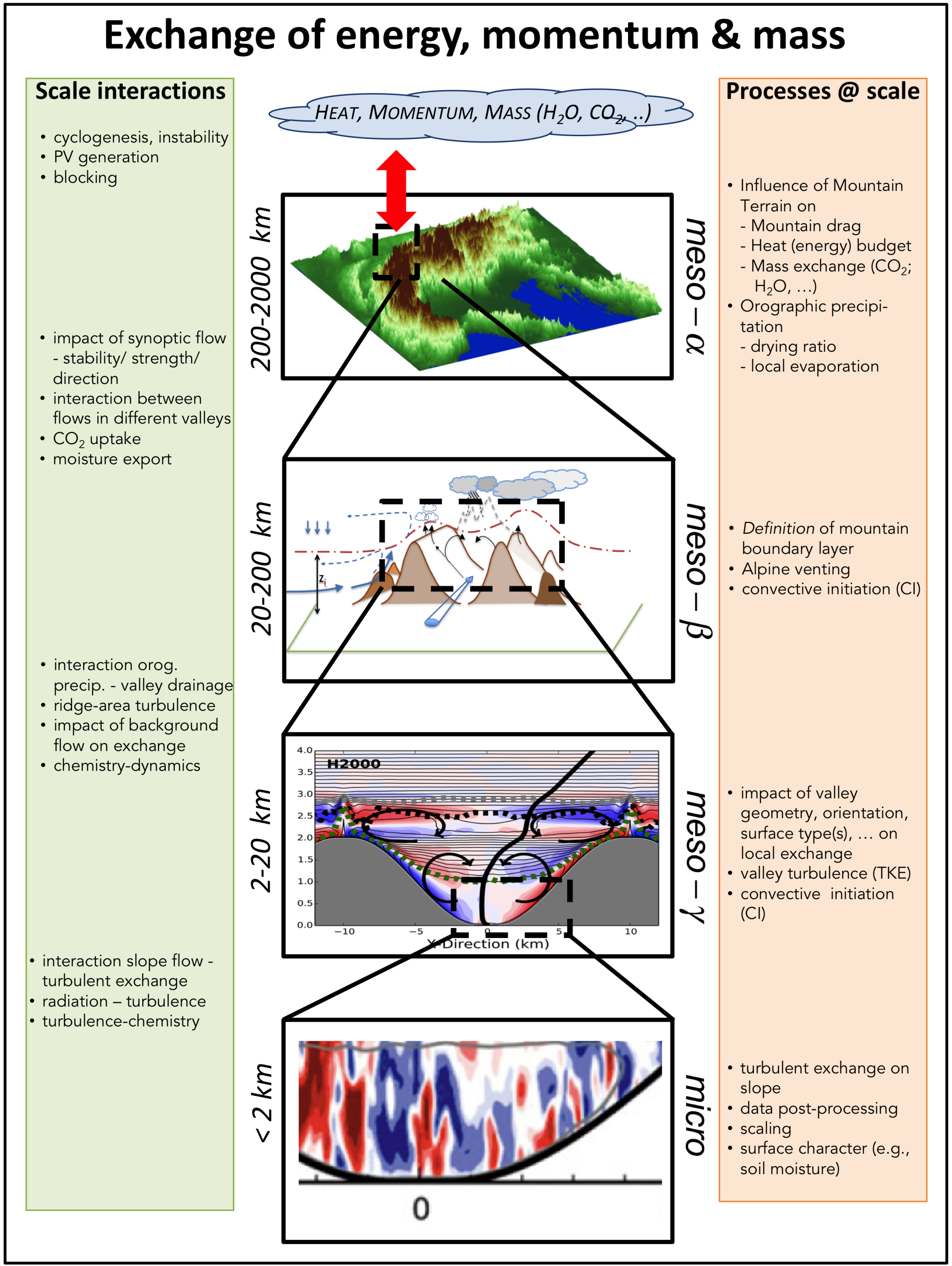
Sfyri et al. (2018)

i-Box measurements:
→ flux-scalar relations
→ non-dimensional temperature variance

→ differences to 'HHF terrain'?

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

only one example….



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goal:

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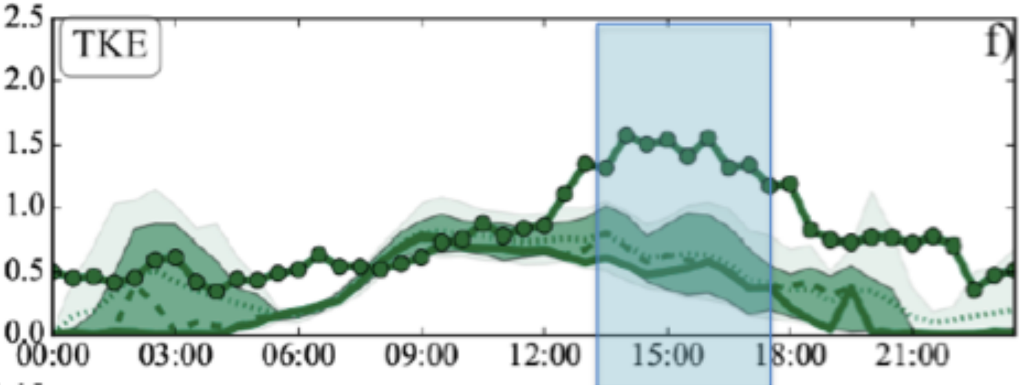
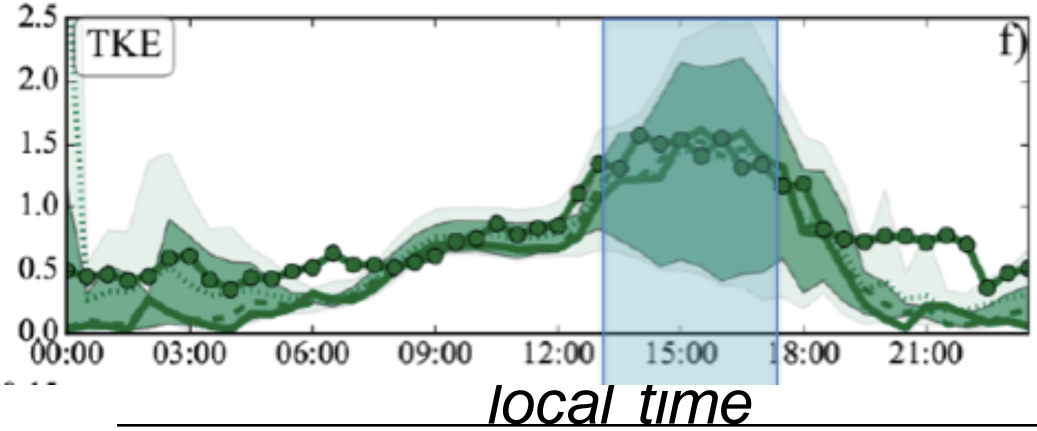
Numerical models

Dissertation Brigitta Goger

1-dimensional TKE closure



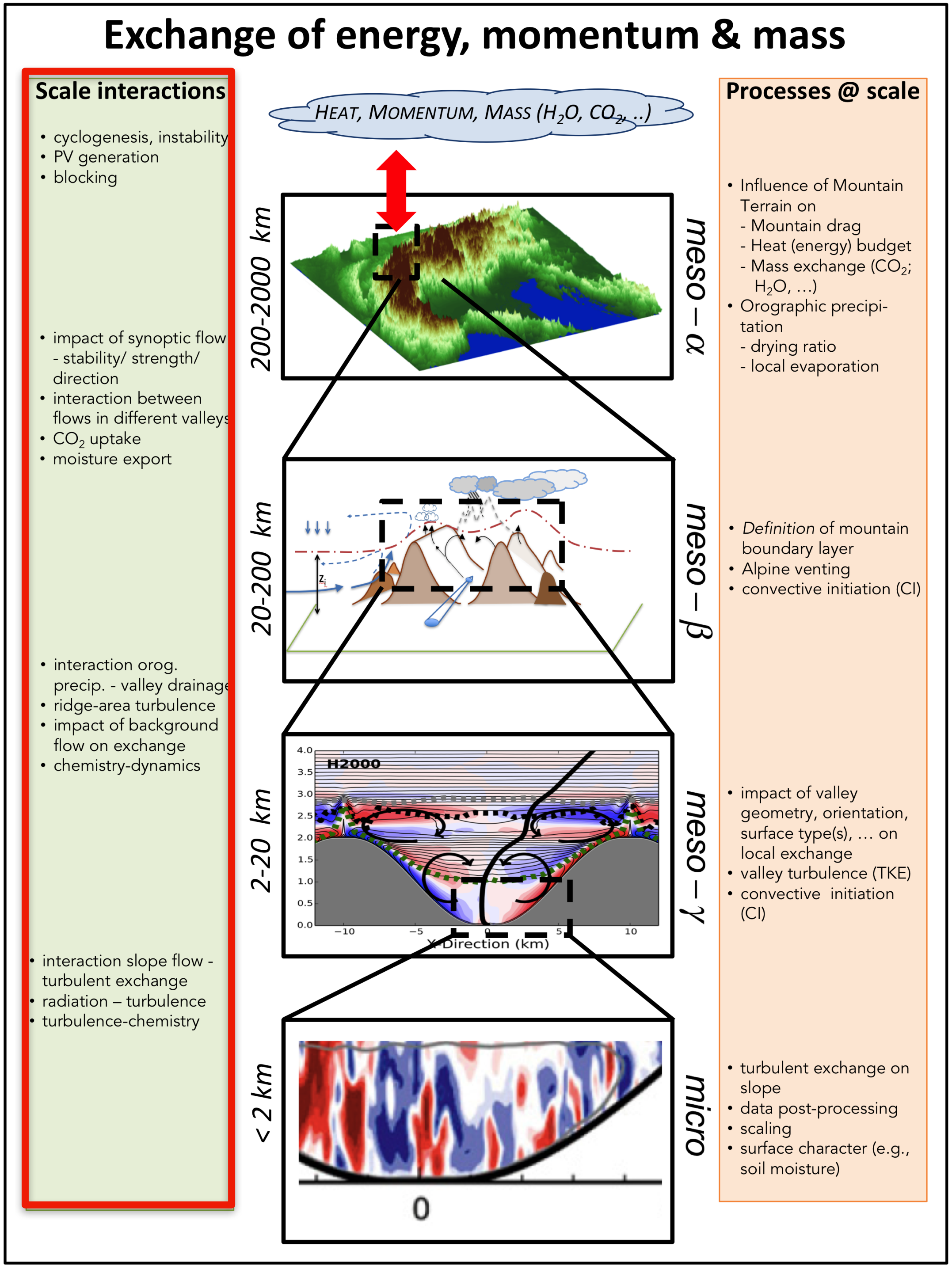
horizontal shear added



TKE closure of COSMO model:
→ 1d enough?
→ add horizontal shear production

→ compare @ different i-Box sites (here: slope site)

Goger et al. (2018)



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- data post-processing
- scaling
- surface character (e.g., soil moisture)

→ interactions relevant

→ much to be done

TEAMx

Overarching research questions

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

TEAMx

partners (so far…)**:**

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

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

Additioal partners with innovative ideas and commitment (very) welcome!

Summary

- exchange of energy, mass and momentum
  → relevant in atmosphere / climate system
  → impact of mountainous terrain
  → [must be] right for the right reason (climate & NWP *services*)

- **TEAMx**
  Multi-scale transport and exchange processes in the atmosphere over mountains - programme and experiment
  → coordinated international effort
  → partners welcome
  → will entertain us for the years to come...

Thank you for your attention!

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

Part II

ACINN activities (wrt TEAMx):

- ➢ i-Box

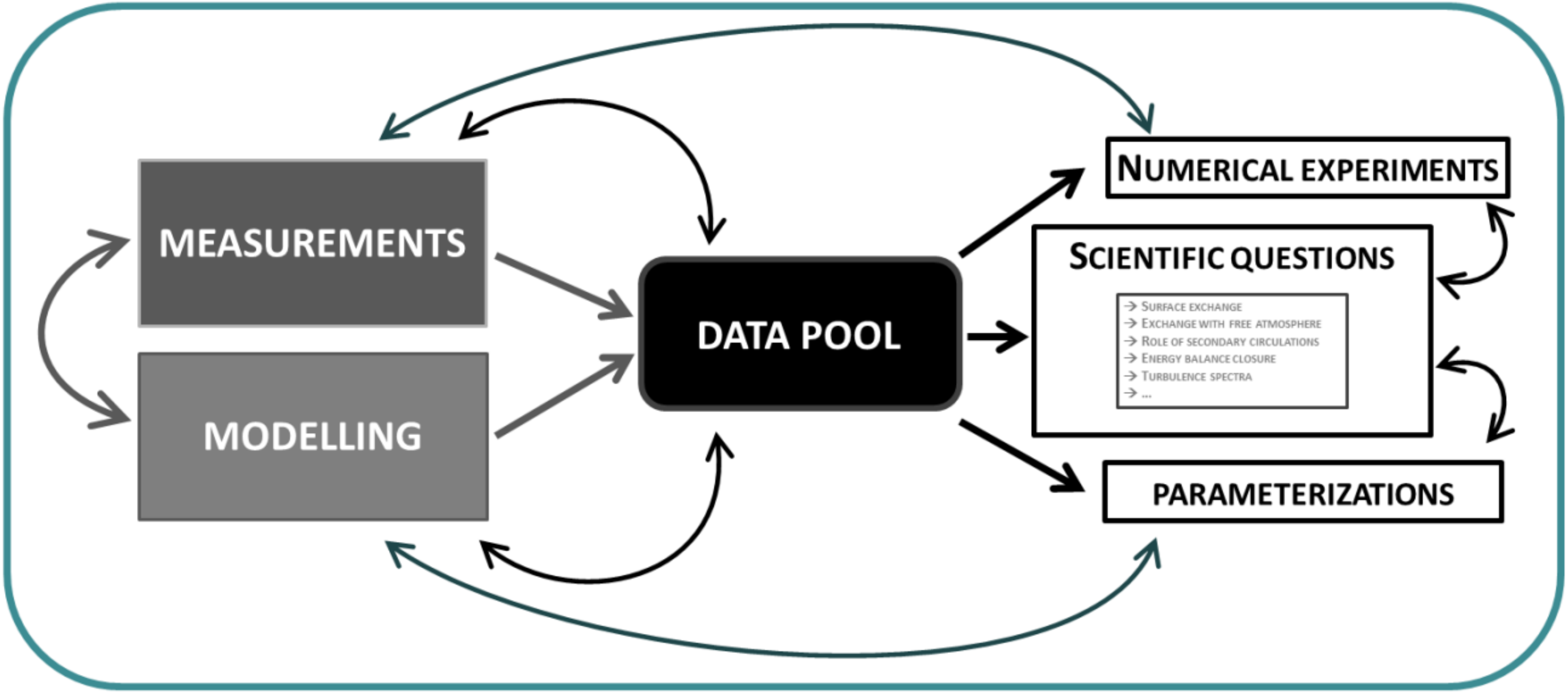
  ⟶ cluster of various projects

  ⟶ 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



MEASUREMENTS

MODELLING

DATA POOL

NUMERICAL EXPERIMENTS

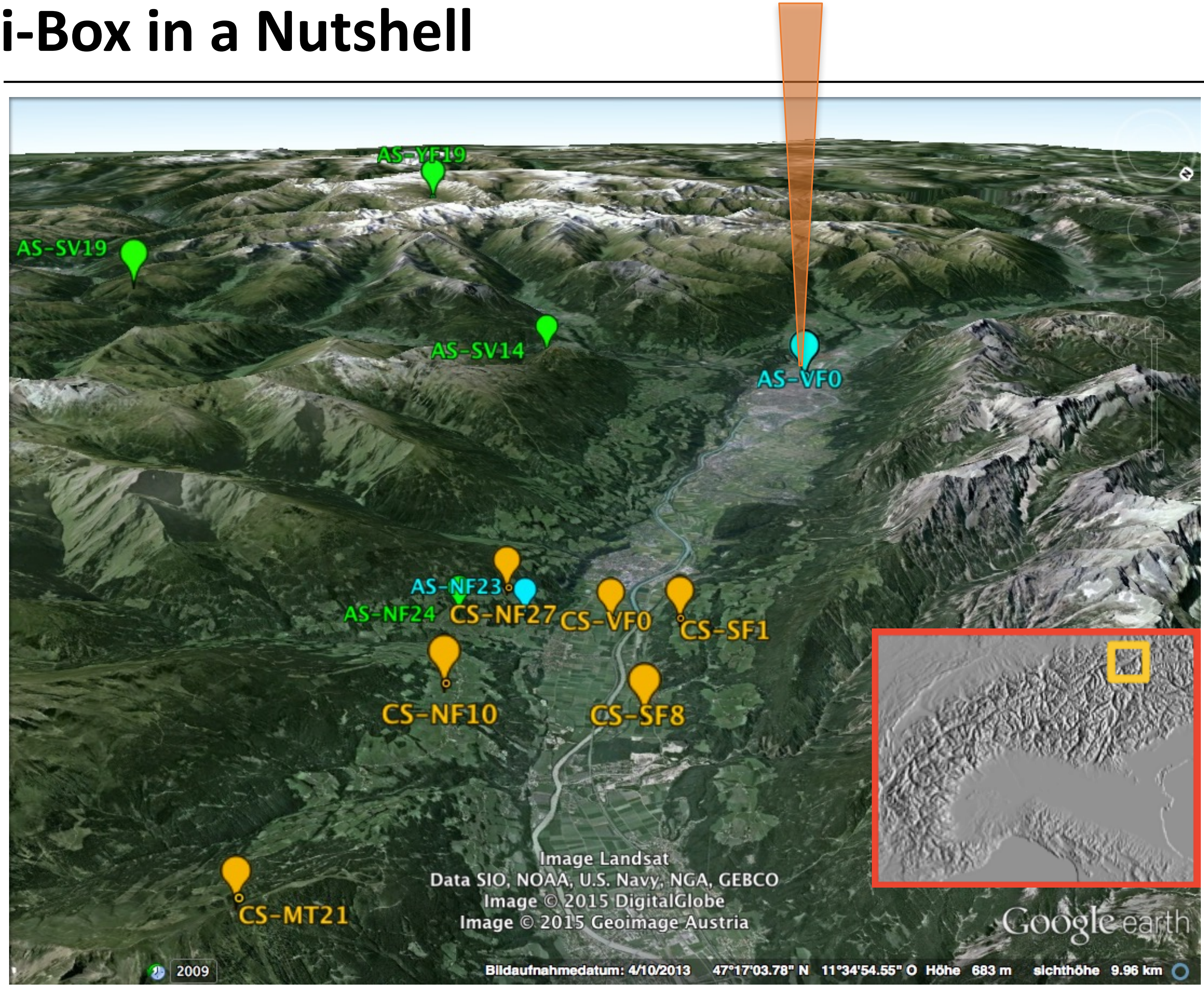
SCIENTIFIC QUESTIONS

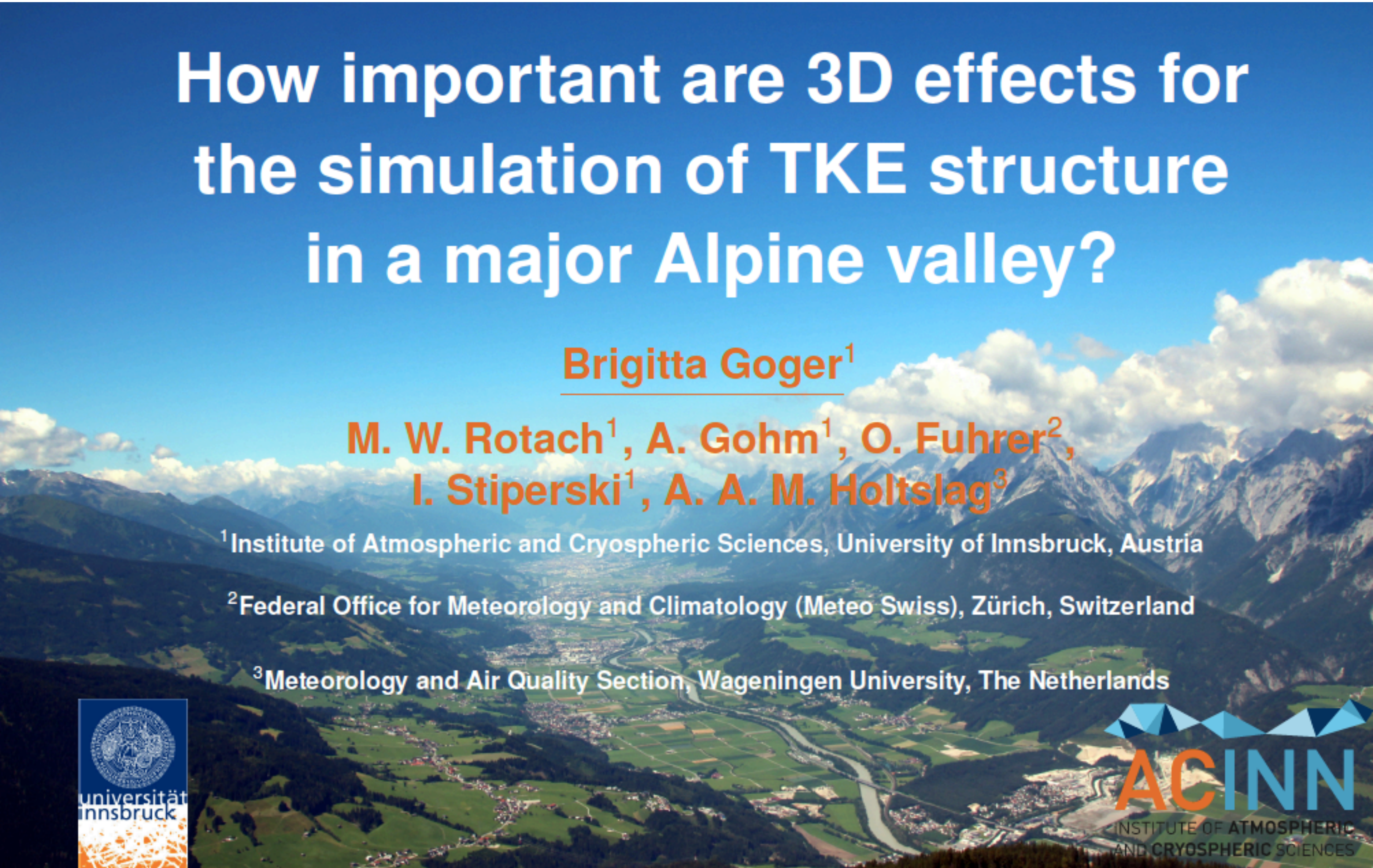
- → Surface exchange
- → Exchange with free atmosphere
- → Role of secondary circulations
- → Energy balance closure
- → Turbulence spectra
- → …

PARAMETERIZATIONS

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

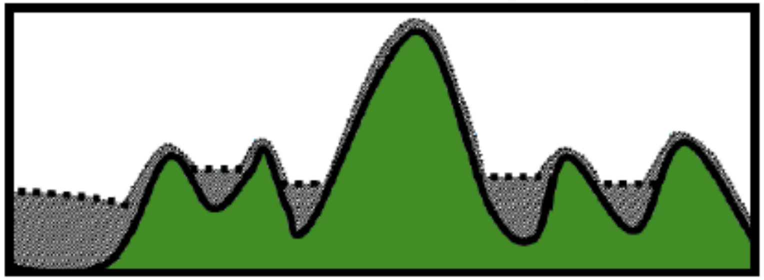
[3]Meteorology and Air Quality Section, Wageningen University, The Netherlands

universität innsbruck

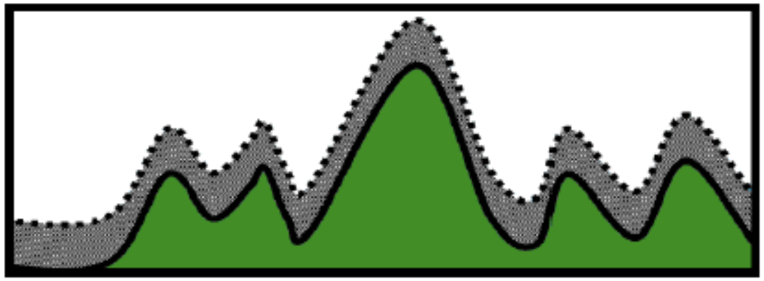
ACINN
INSTITUTE OF ATMOSPHERIC AND CRYOSPHERIC SCIENCES

Motivation & Goals

Mountain boundary layer



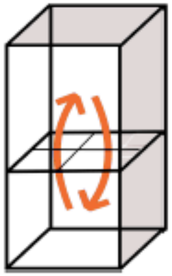
NWP model ($\Delta x = 1$ km)



Rotach and Zardi (2007)

Common Turbulence Parameterizations

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

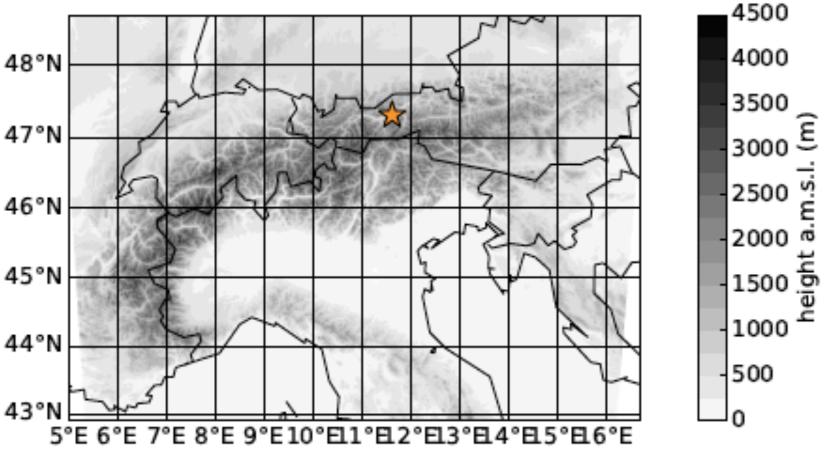


- TKE underestimation

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

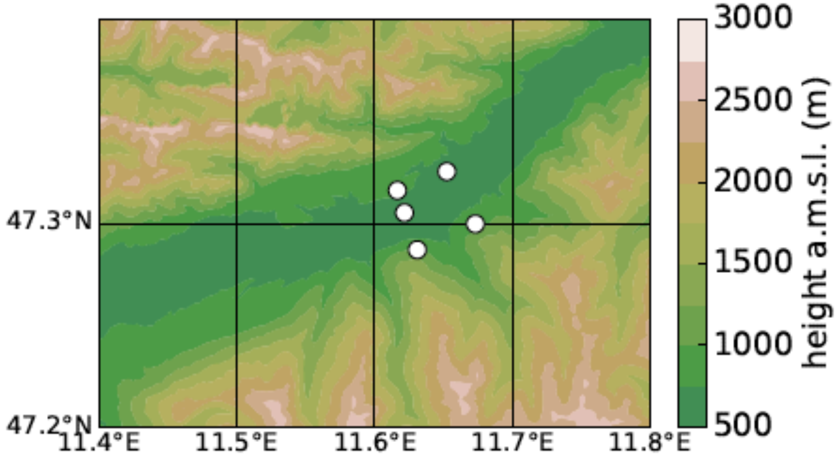
Turbulence Parameterization Evaluation

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

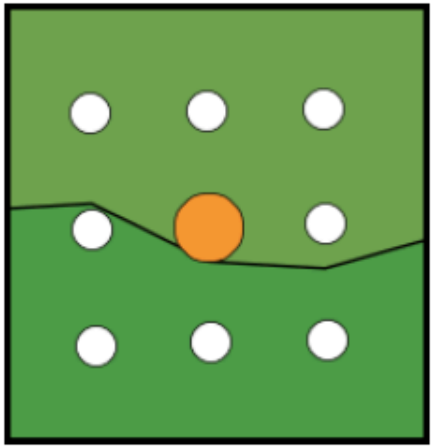
$$\underbrace{\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)}_{\text{tendency}} = -\underbrace{K_H \frac{g}{\theta}\frac{\partial \theta}{\partial z}}_{\substack{\text{buoyancy}\\ \text{production/consumption}}} + \underbrace{K_M \left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial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

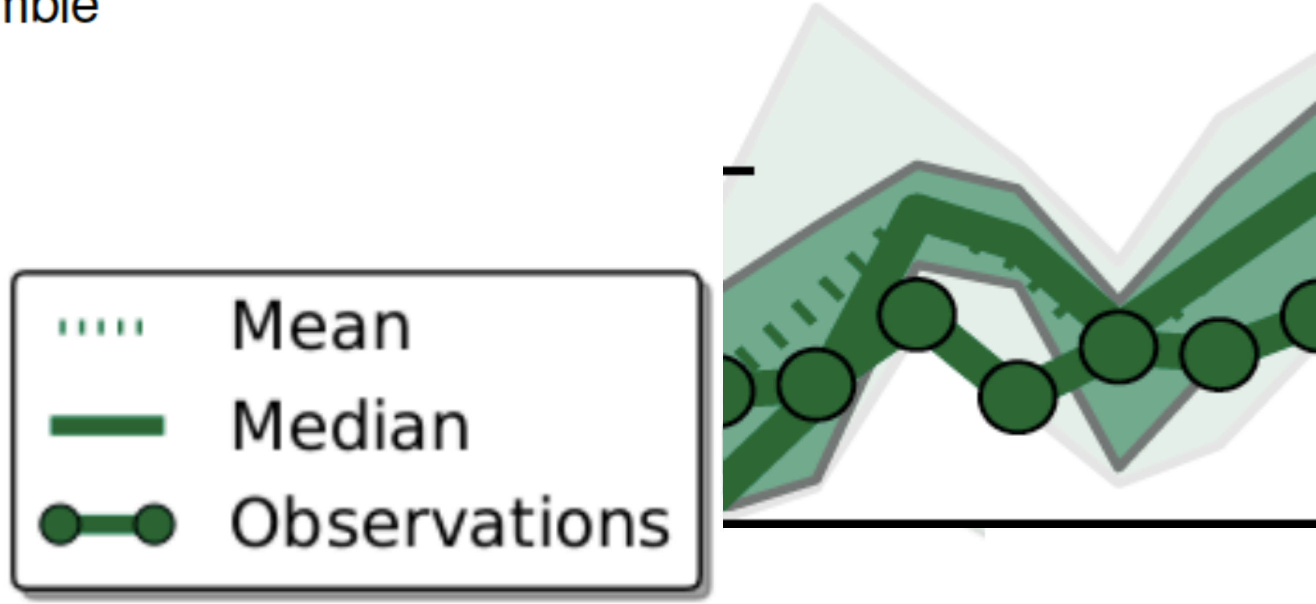
$$+ \underbrace{\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\left[\alpha_{\mathrm{tke}}\overline{\rho}\lambda_l q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right]}_{\text{vertical turbulent transport}} - \underbrace{\frac{q^3}{B_1 \lambda_l}}_{\text{dissipation}} \qquad (1)$$

Hybrid Turbulence Parameterization

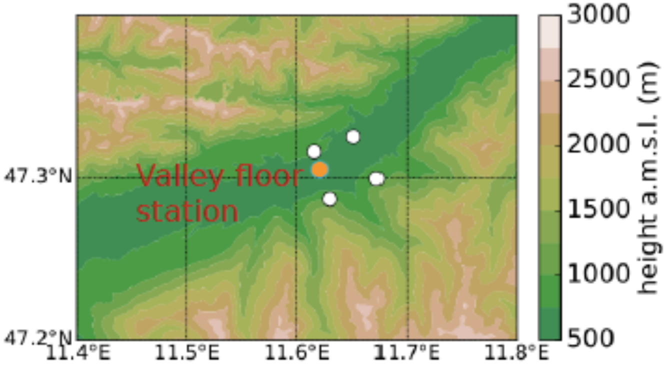
Methods

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



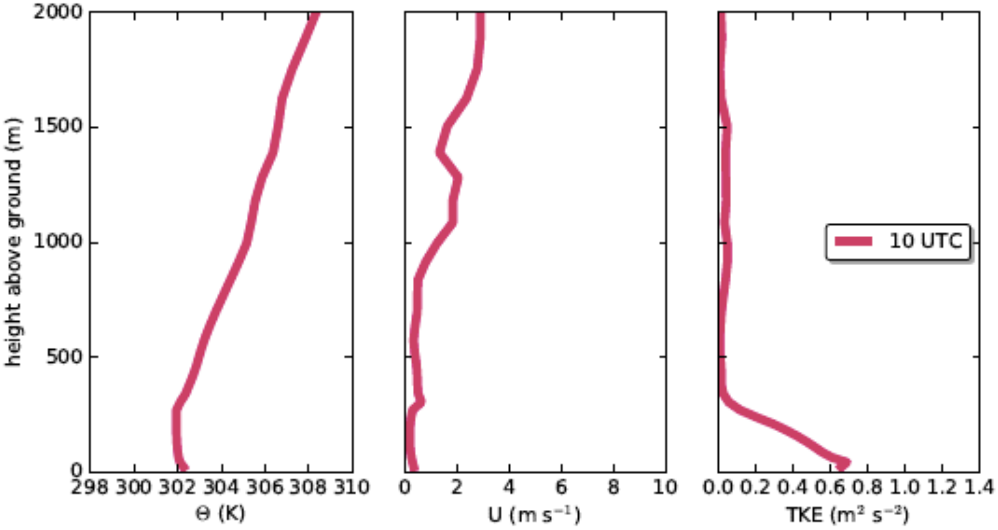


Valley Floor Station | Daytime



July 01, 2015 init 00 UTC

Before noon: convective boundary layer



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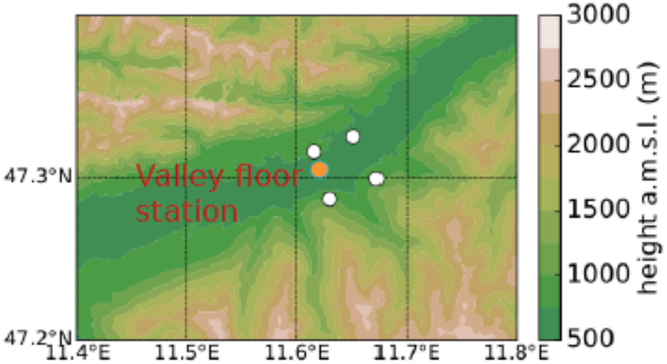
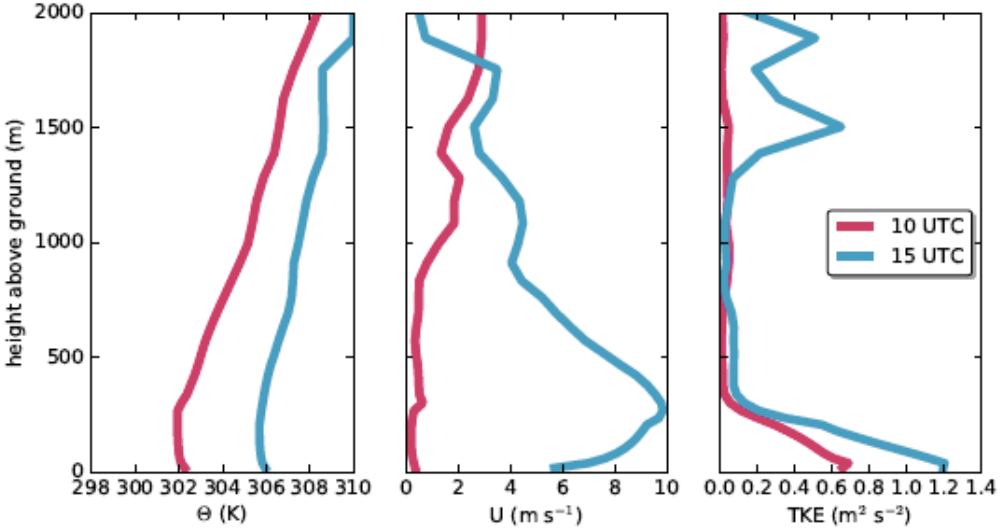


July 01, 2015 init 00 UTC

Afternoon: strong up-valley wind



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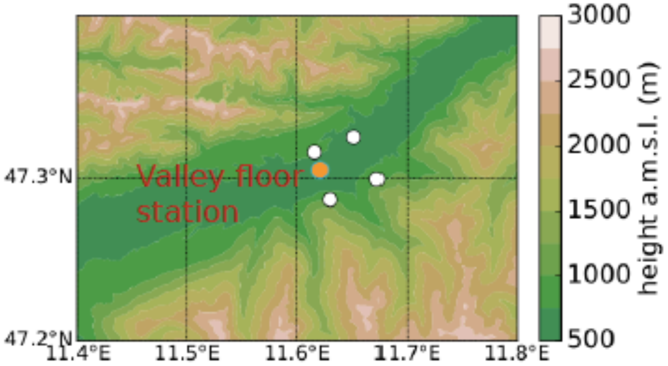

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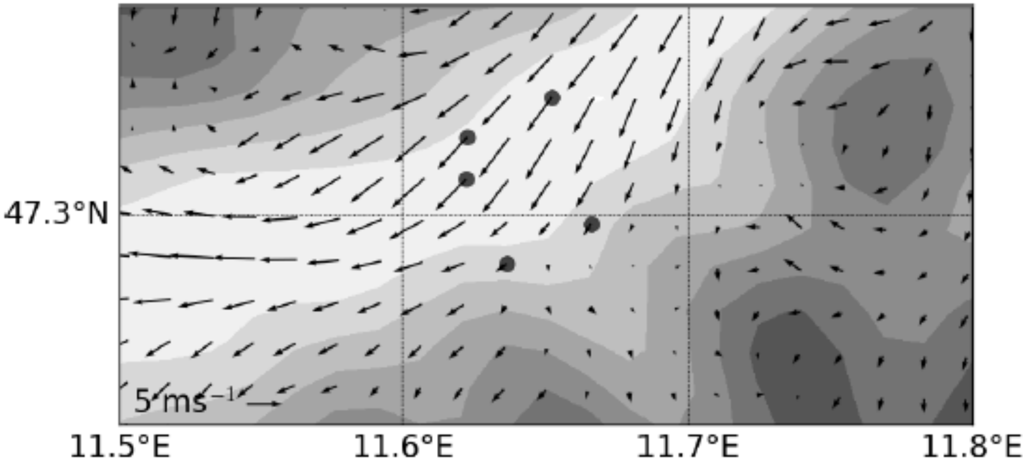
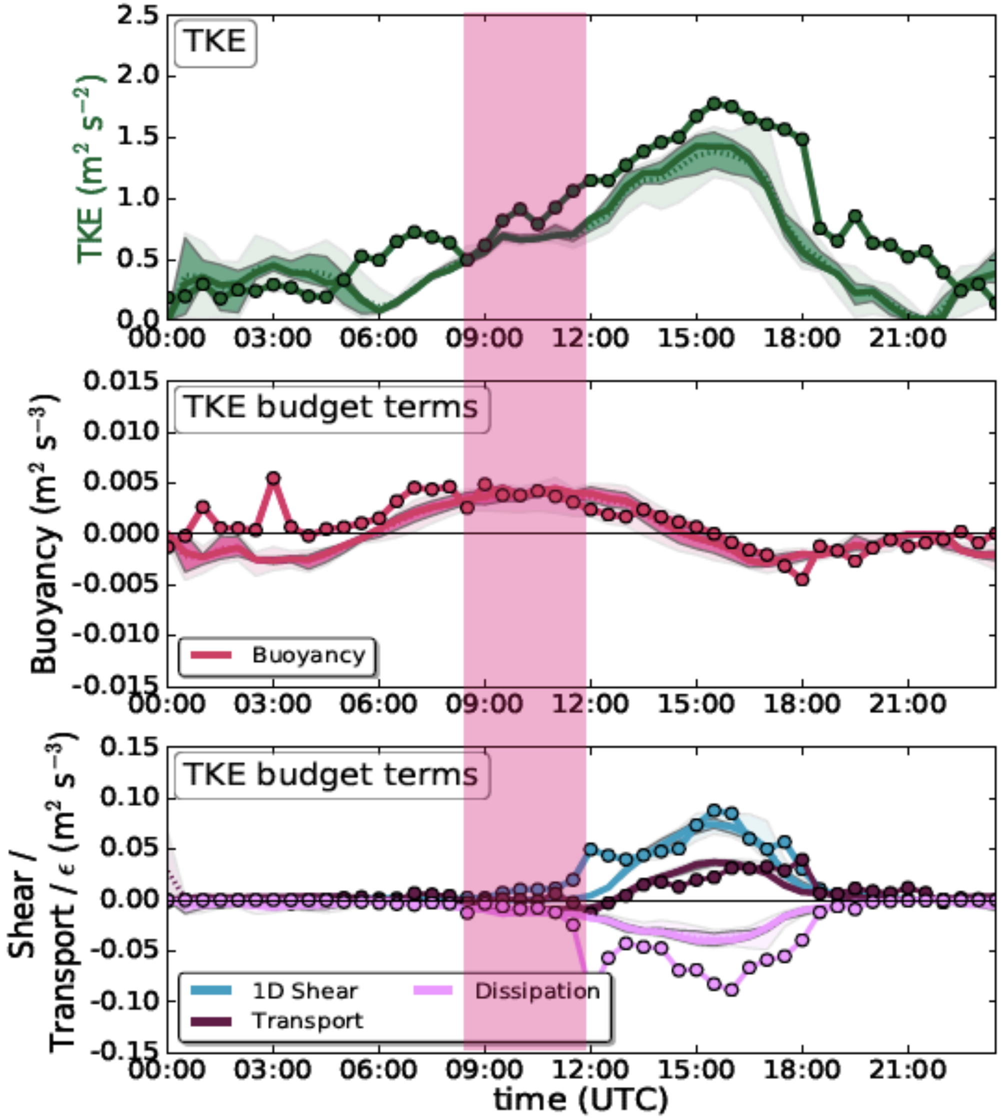
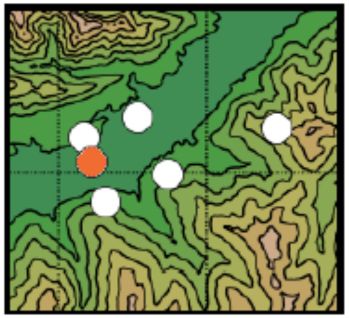


Wind field at 15 UTC

Daytime TKE | 1D Turbulence



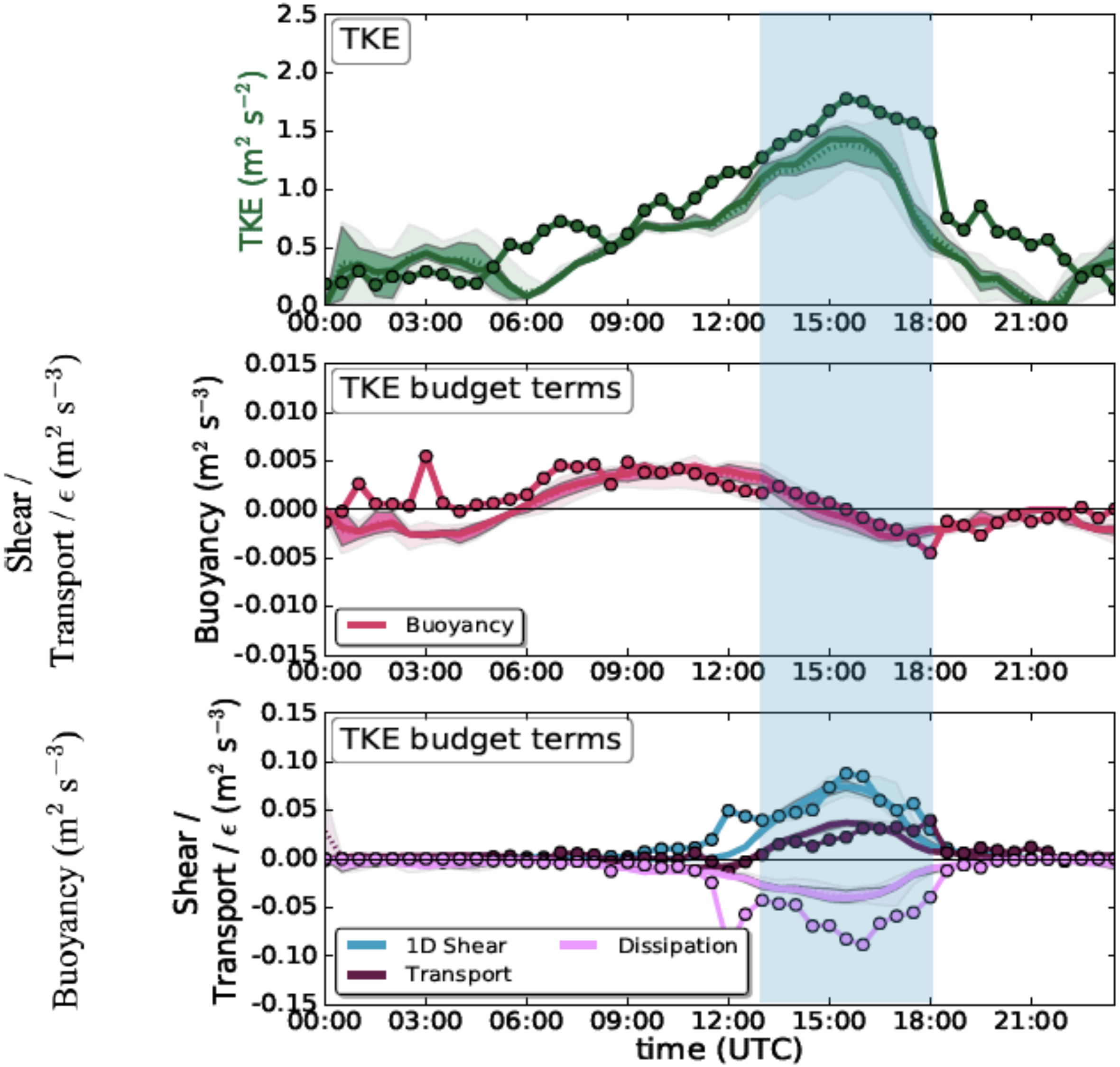


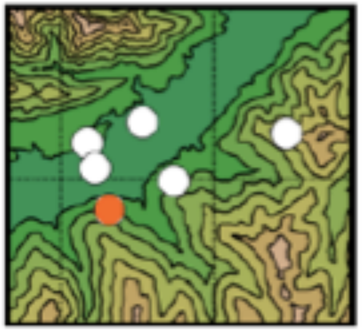
Before noon:

Buoyant production dominates

TKE well simulated by the model

Daytime TKE | 1D Turbulence



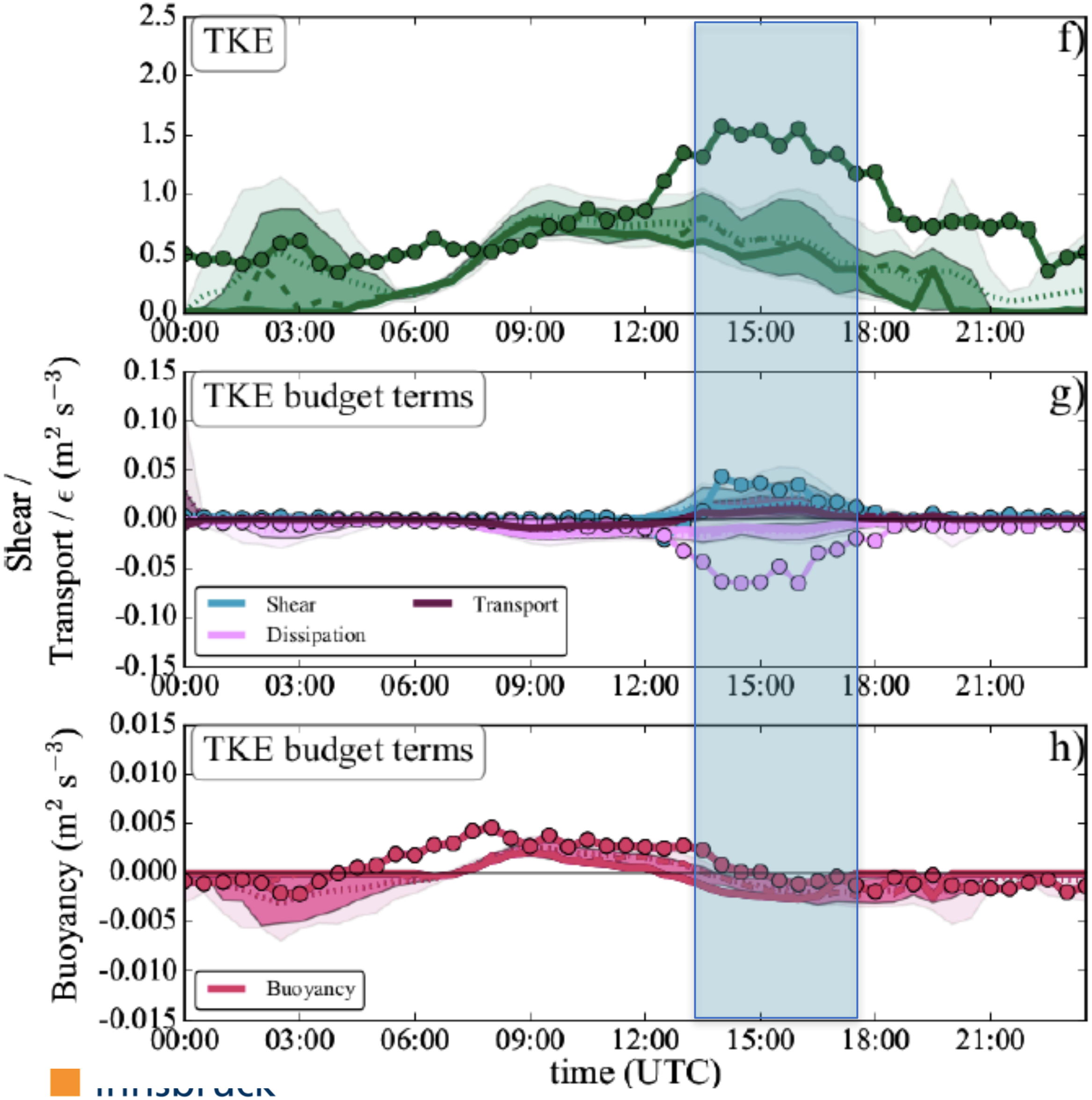


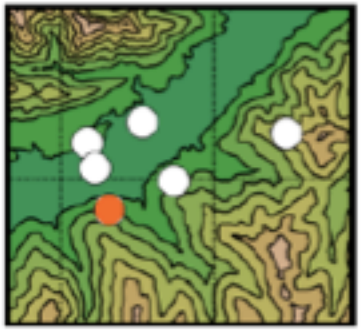
Afternoon:

Vertical shear generation together with valley wind

TKE underestimated

Daytime TKE | 1D Turbulence





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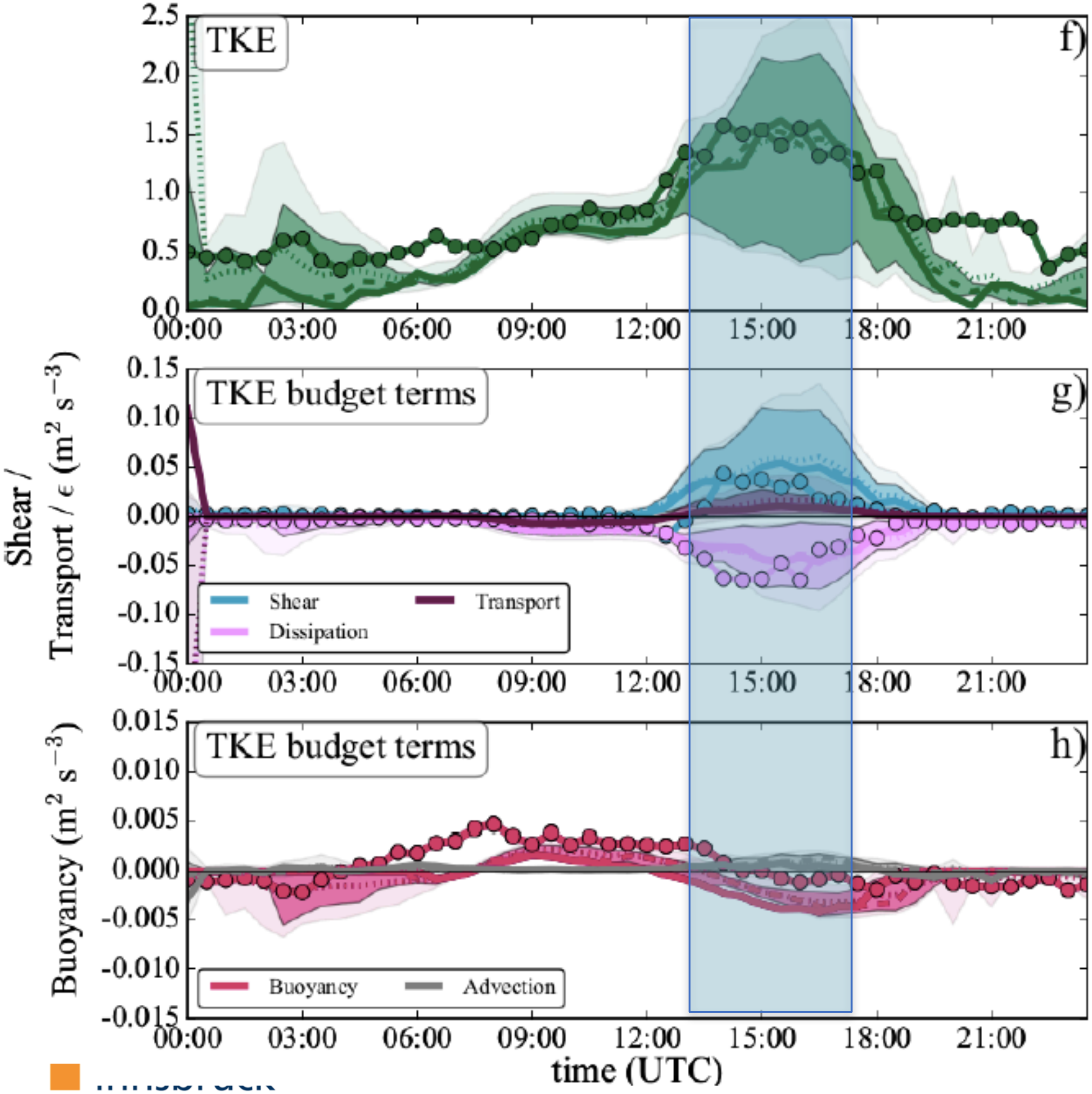
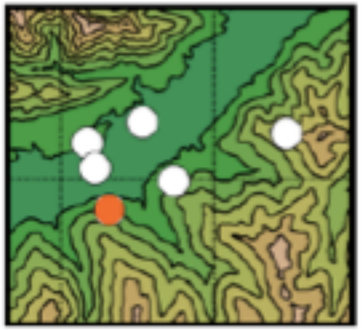
Daytime TKE | Hybrid Turbulence



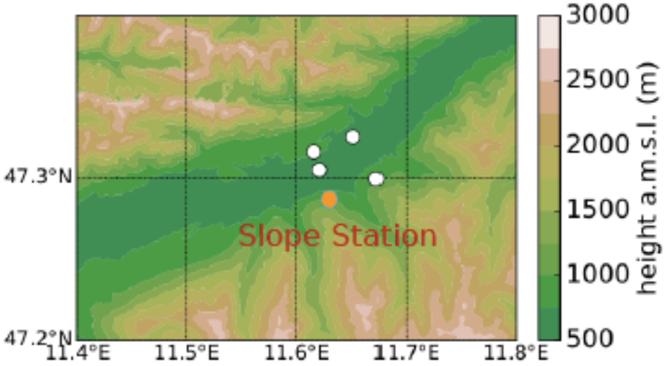


Afternoon:

3D shear production

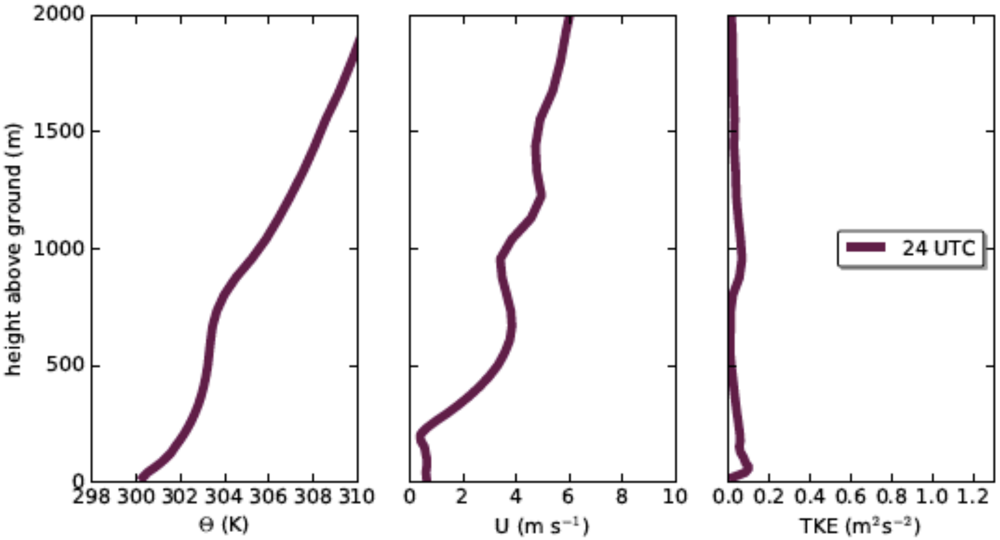
Correct TKE simulation

Steep Slope Station | Nighttime

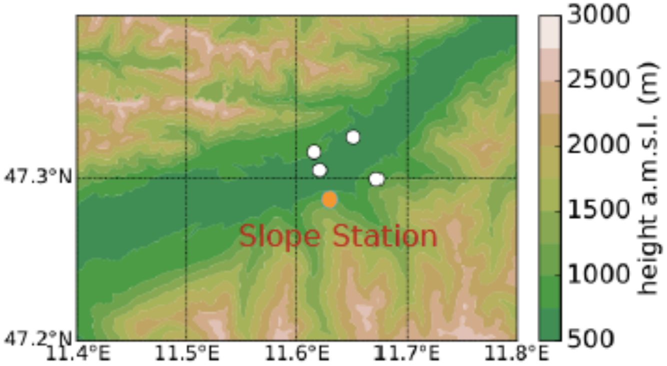


July 01, 2015 init 12 UTC

Nighttime: stable boundary layer

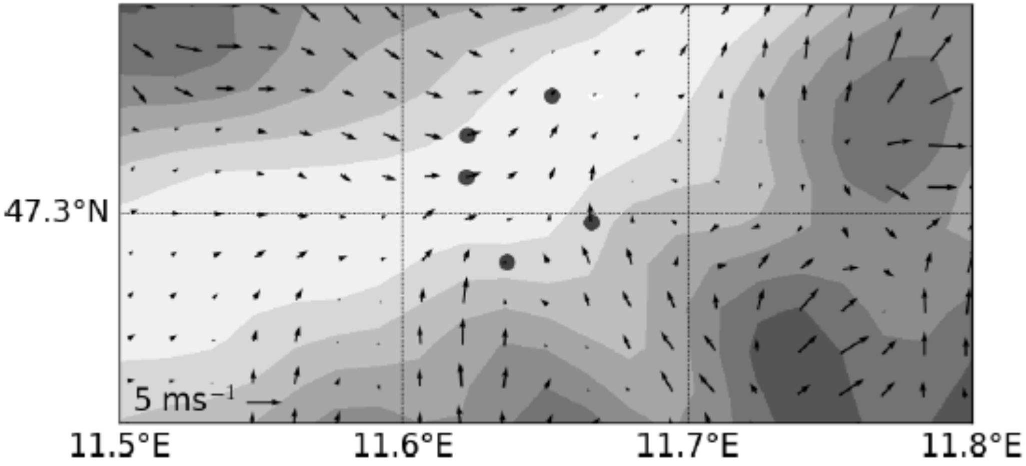


Steep Slope Station | Nighttime



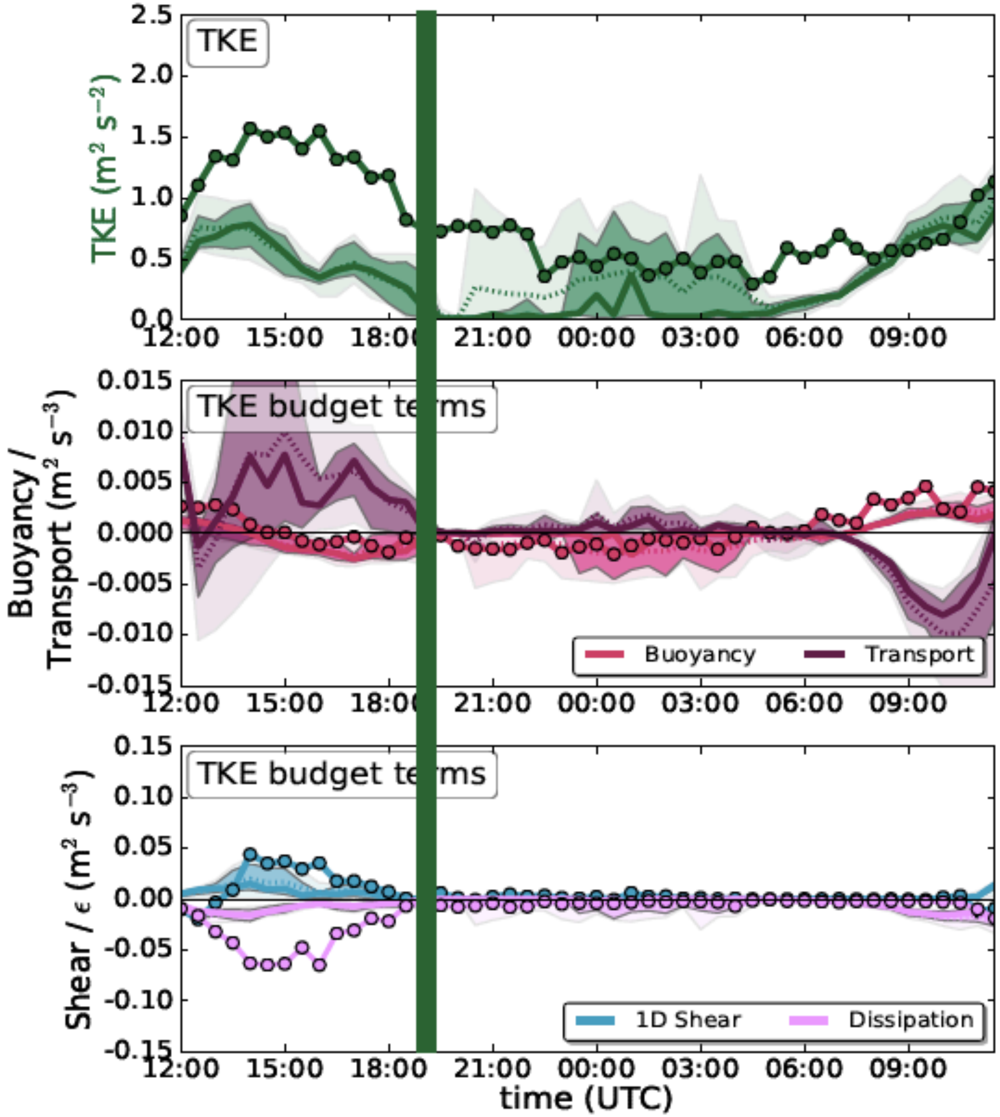
July 01, 2015 init 12 UTC

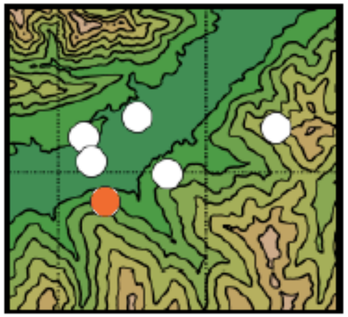
Nighttime: Down-slope flows / Drainage flows



Wind field at 00 UTC

Nighttime TKE | 1D Turbulence

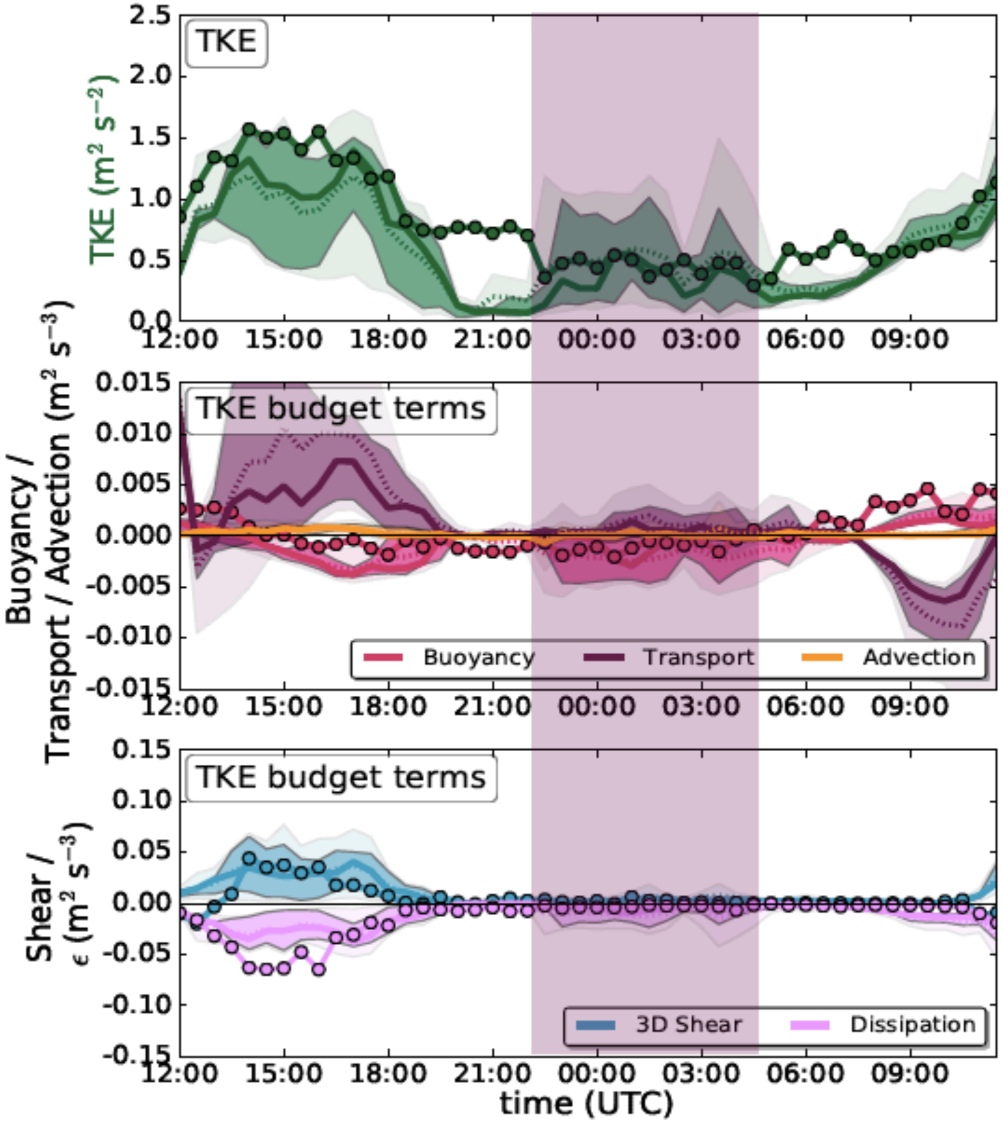


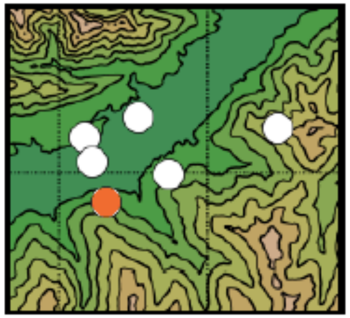


Nighttime:

Model is not able to simulate nighttime TKE

Nighttime TKE | Hybrid Turbulence





Nighttime:

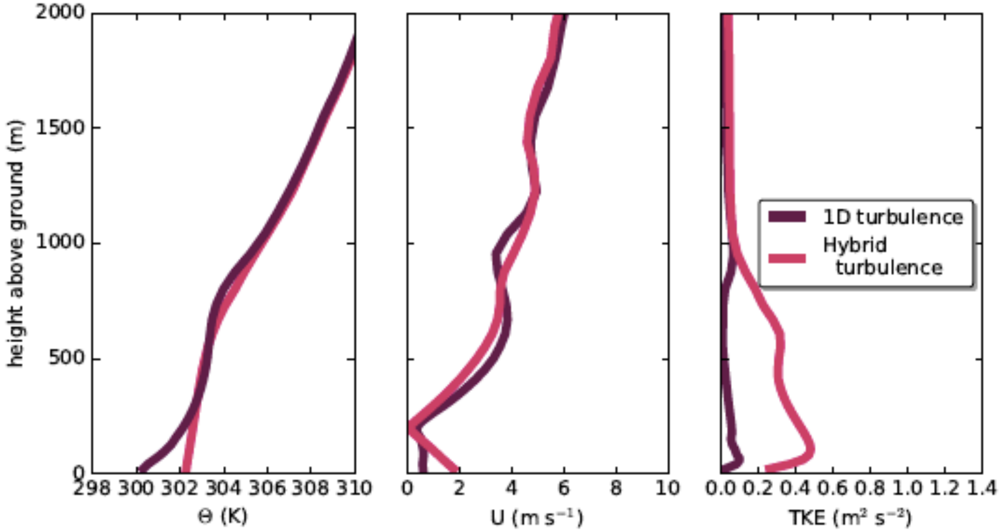
Successful TKE simulation

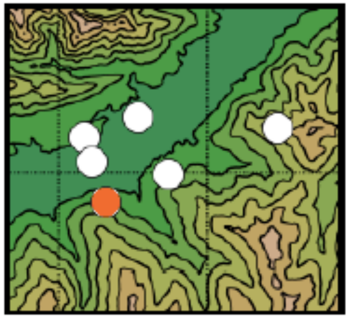
Transport-dominated

Minor role of

TKE advection

Nighttime TKE | Vertical Profiles 24 UTC





Modified TKE structure also at higher elevations

Summary & Conclusions

ACINN

1D Turbulence Parameterization

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

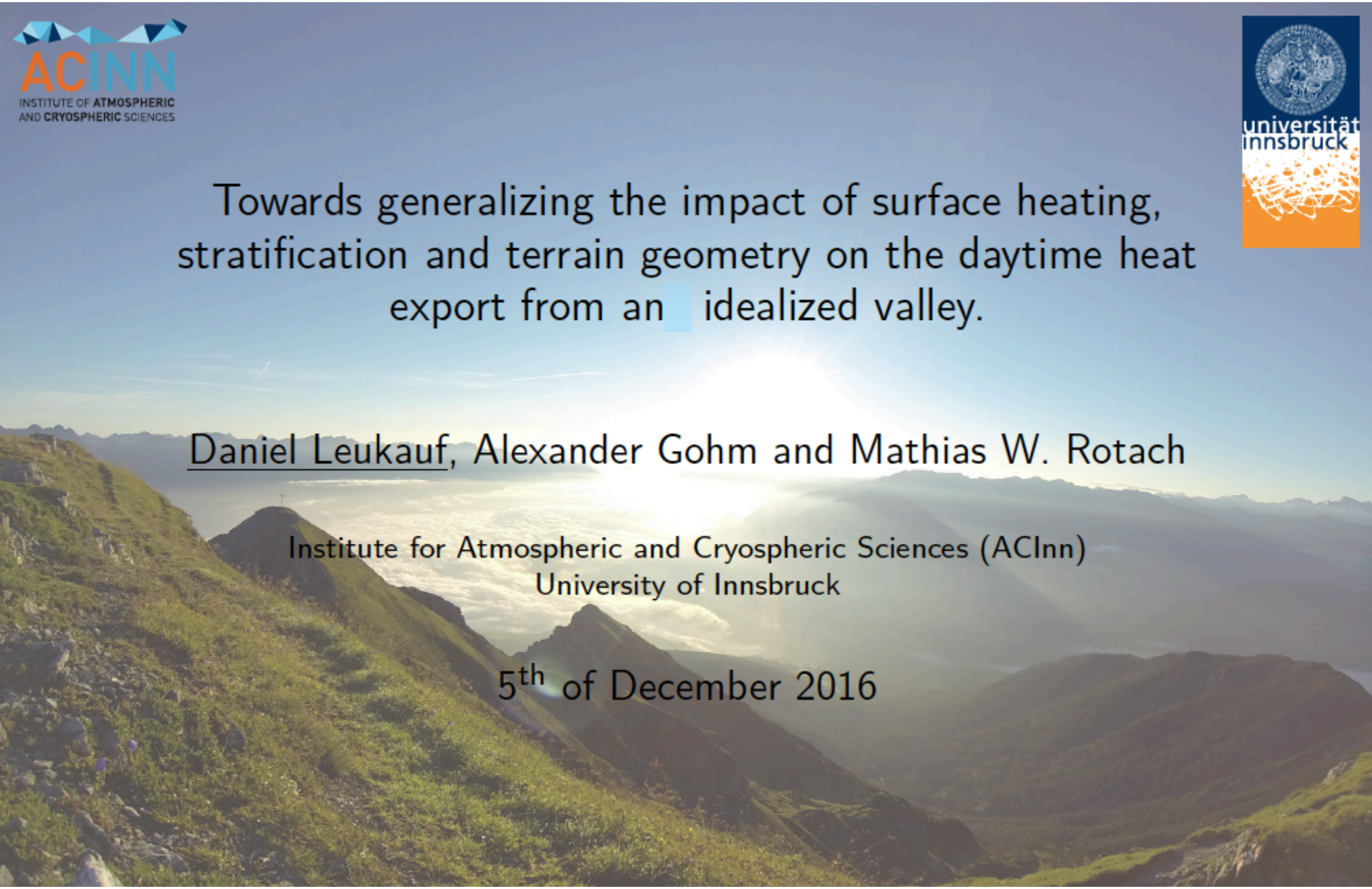
Hybrid Turbulence Parameterization

- 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)



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

Daniel Leukauf, Alexander Gohm and Mathias W. Rotach

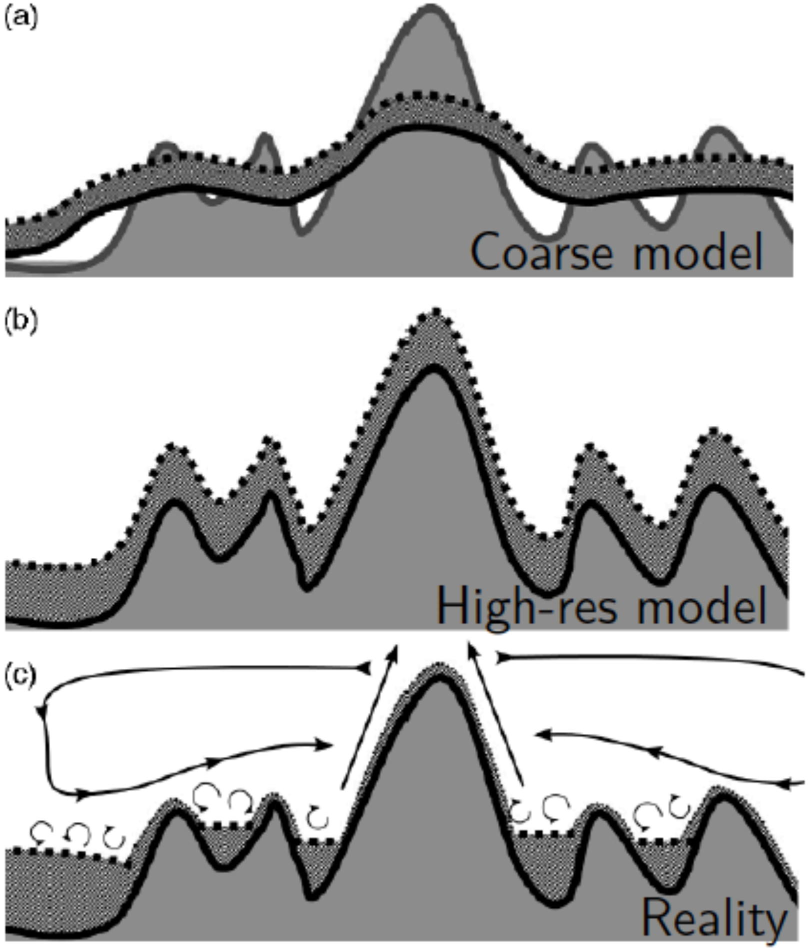
Institute for Atmospheric and Cryospheric Sciences (ACInn)
University of Innsbruck

5th of December 2016

Formulation of the Problem

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

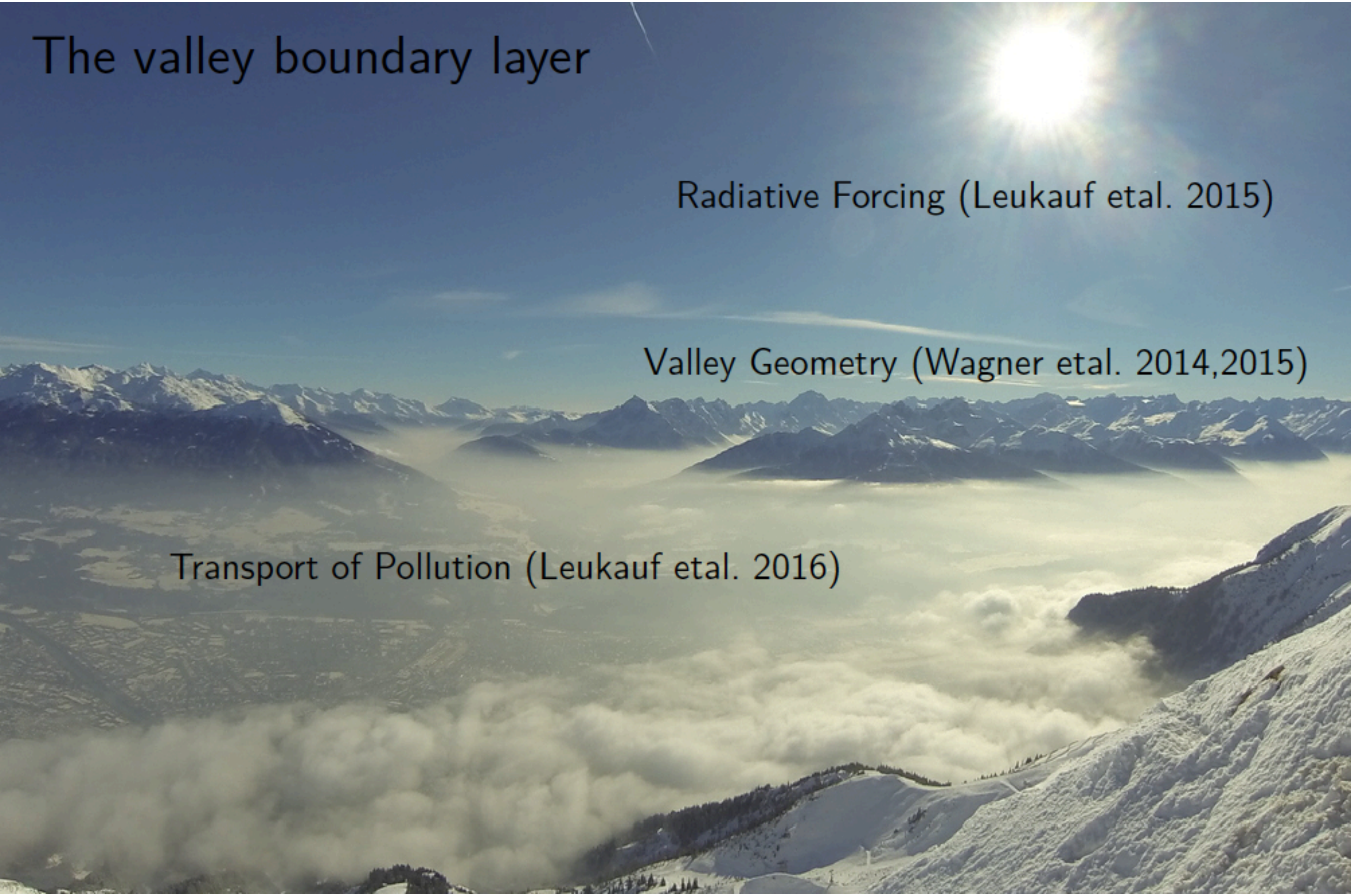
- **Important exchange mechanisms are missing**



After Rotach and Zardi 2007

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

The valley boundary layer



Radiative Forcing (Leukauf etal. 2015)

Valley Geometry (Wagner etal. 2014,2015)

Transport of Pollution (Leukauf etal. 2016)

In this talk...

❶ Focus on the export of heat

❷ Dependence on Stability and Forcing

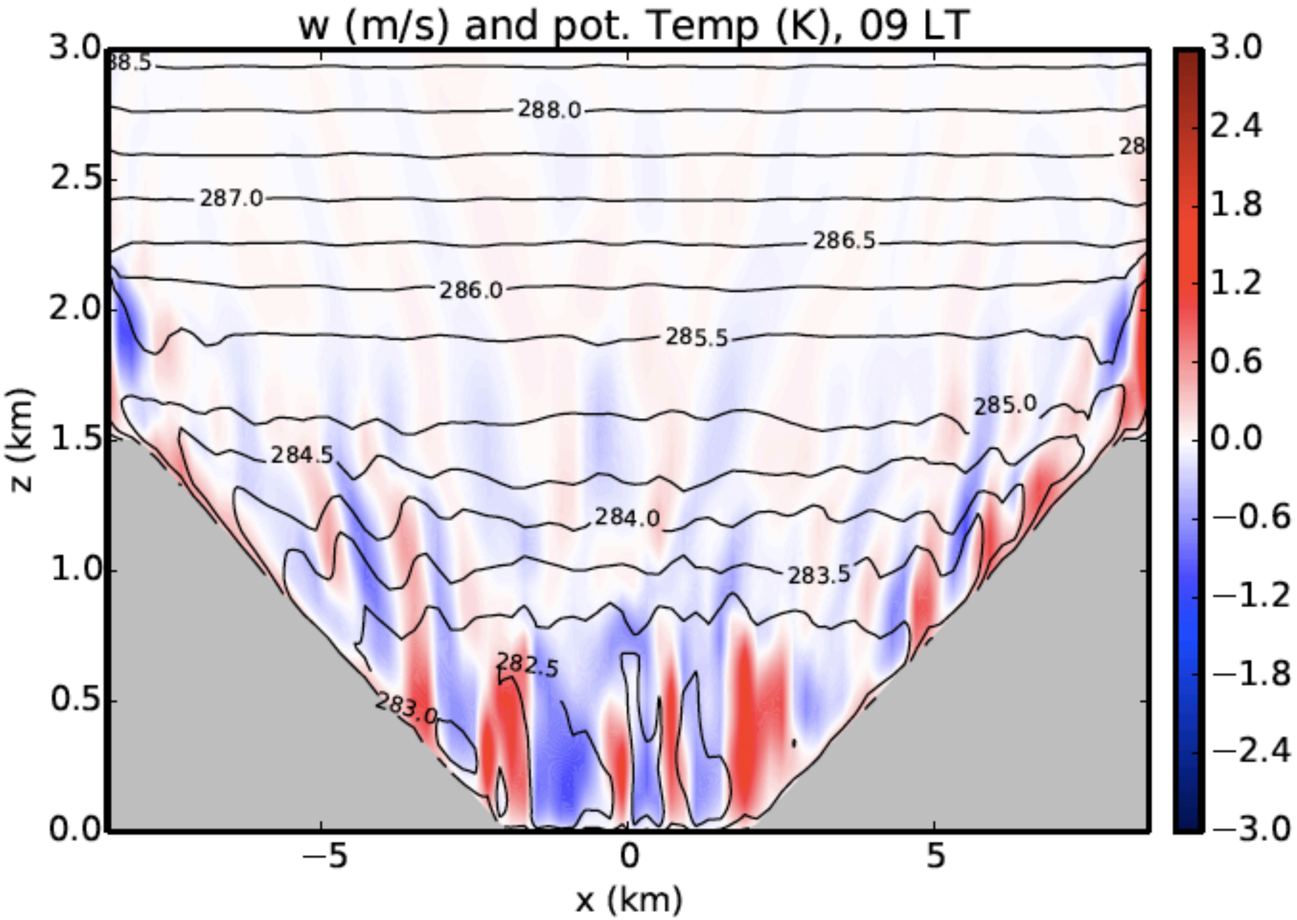
❸ Daytime conditions

❹ Impact of Residual Layers

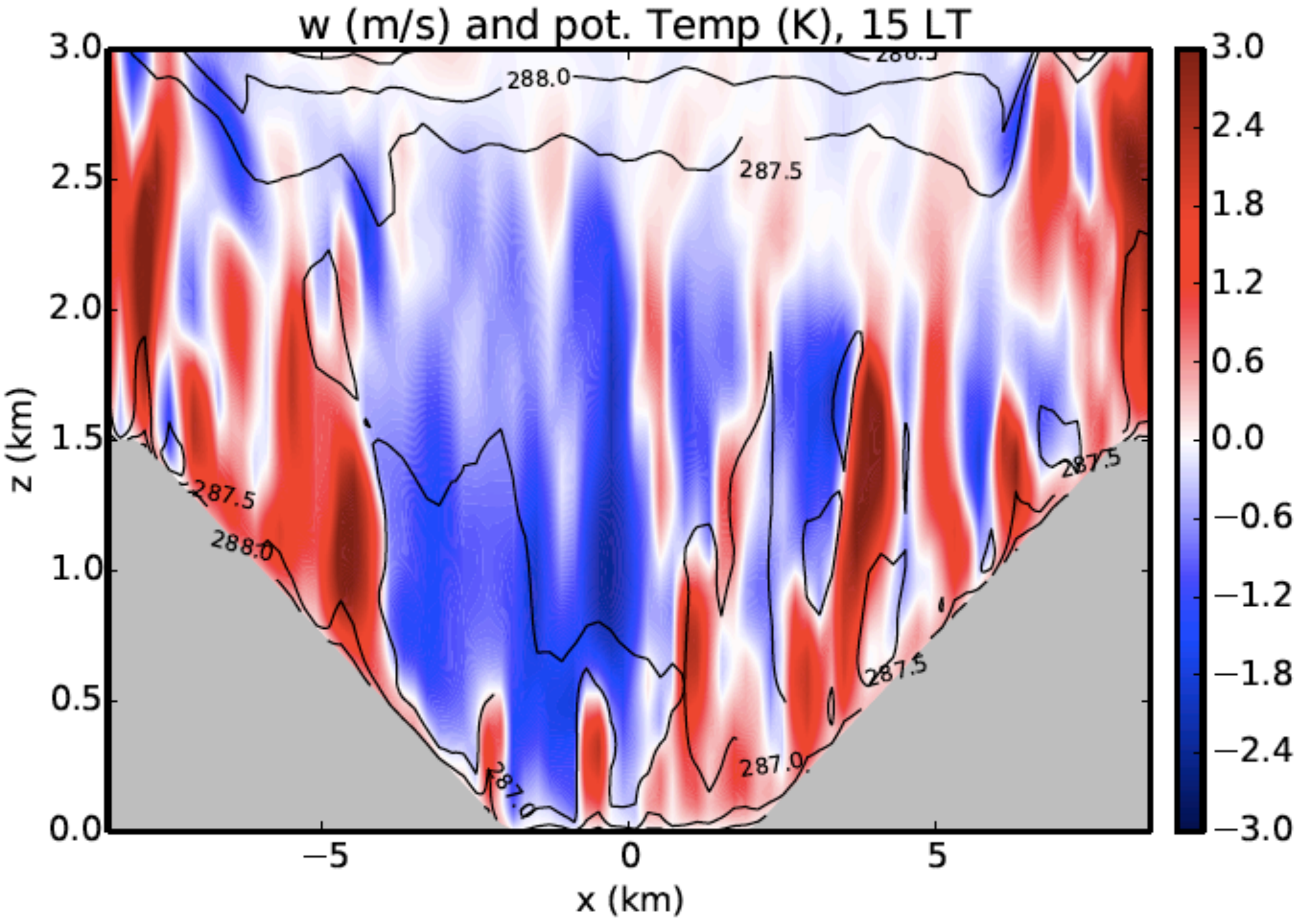
Breakup of a valley inversion

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

Impact of the breakup



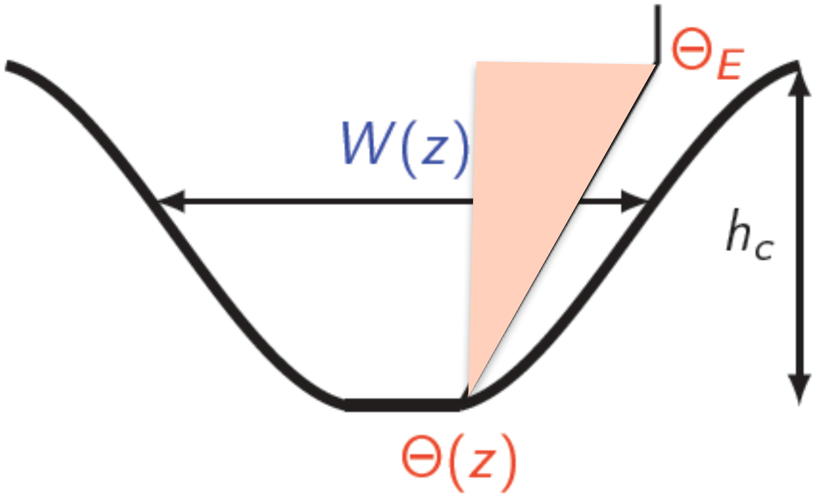
Impact of the breakup



Required, provided and exported energy

At sunrise:

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



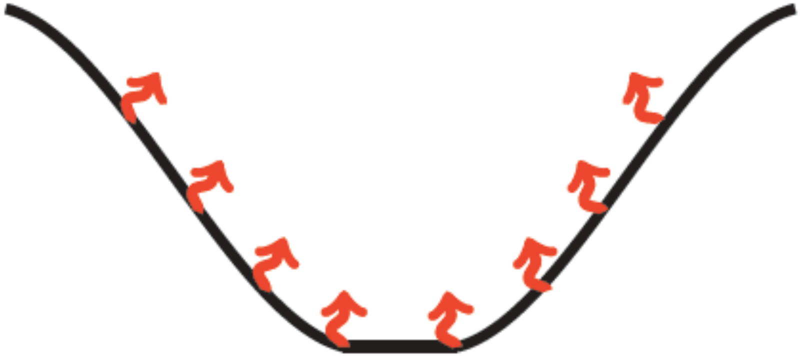
Required, provided and exported energy

At sunrise:

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

During daytime:

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

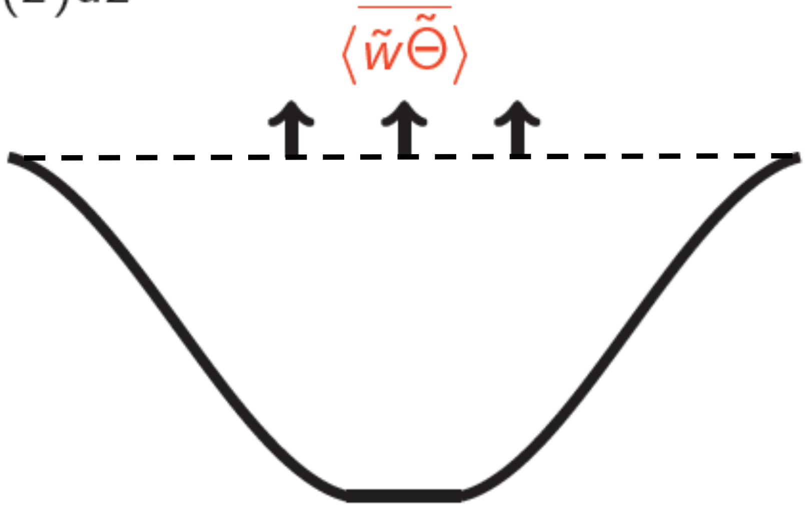


surf. sens. Heat flux H_s

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:

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

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

The Breakup Parameter

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

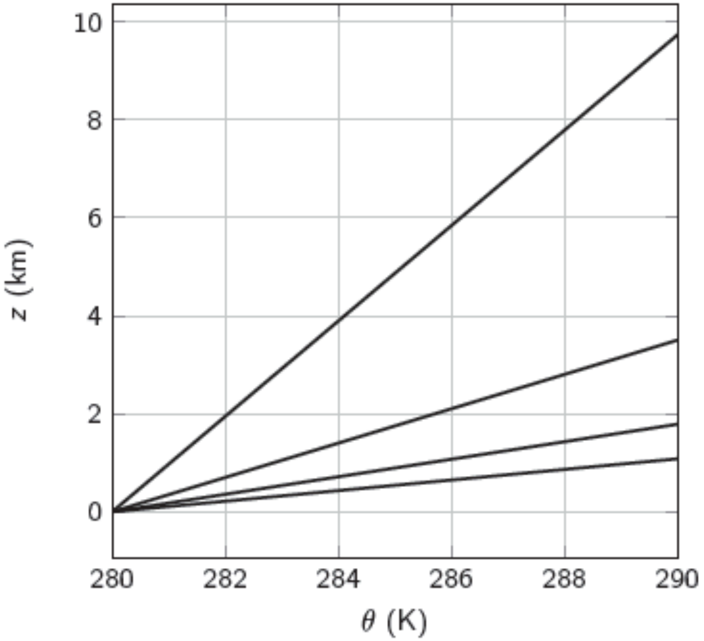
Approximately:
$B > 1$: Breakup is never reached
$B = B_c = 1$: Breakup barely reached
$B < 1$: Breakup is reached

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

Expectation: Vertical export depends strongly on B

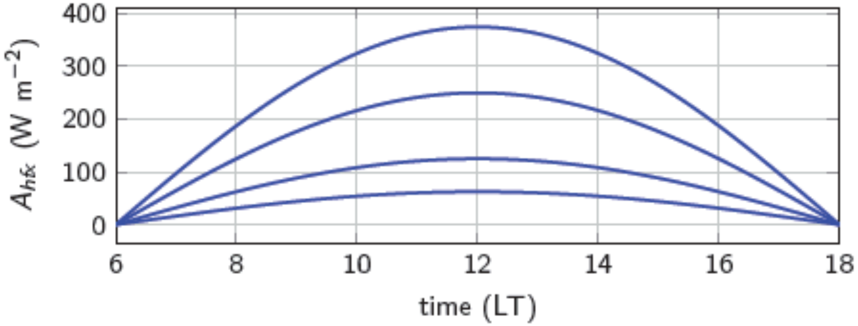
A virtual lab: **WRF model**

- 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

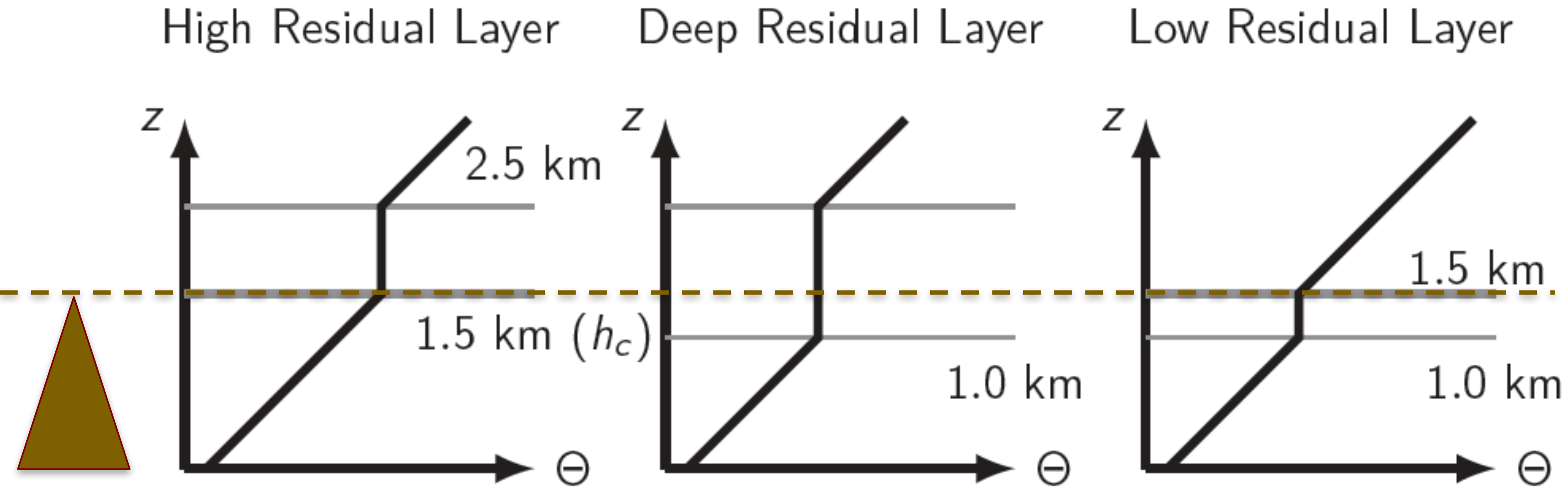


Variables

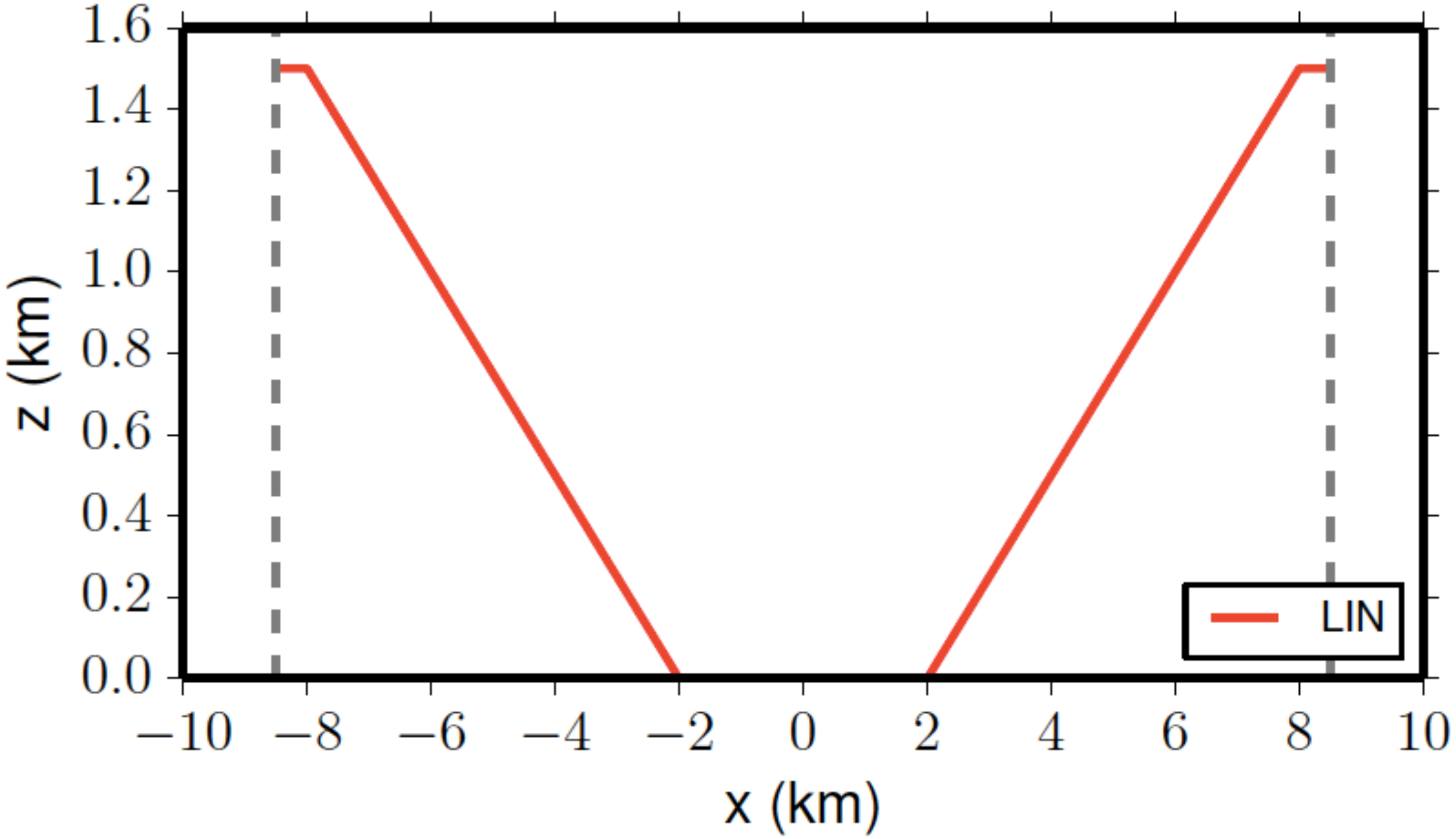
- $N = 0.006\text{-}0.018\ s^{-1}$
- $A_{hfx} = 62.5\text{-}375\ \mathrm{W\ m^{-2}}$
- Residual Layers



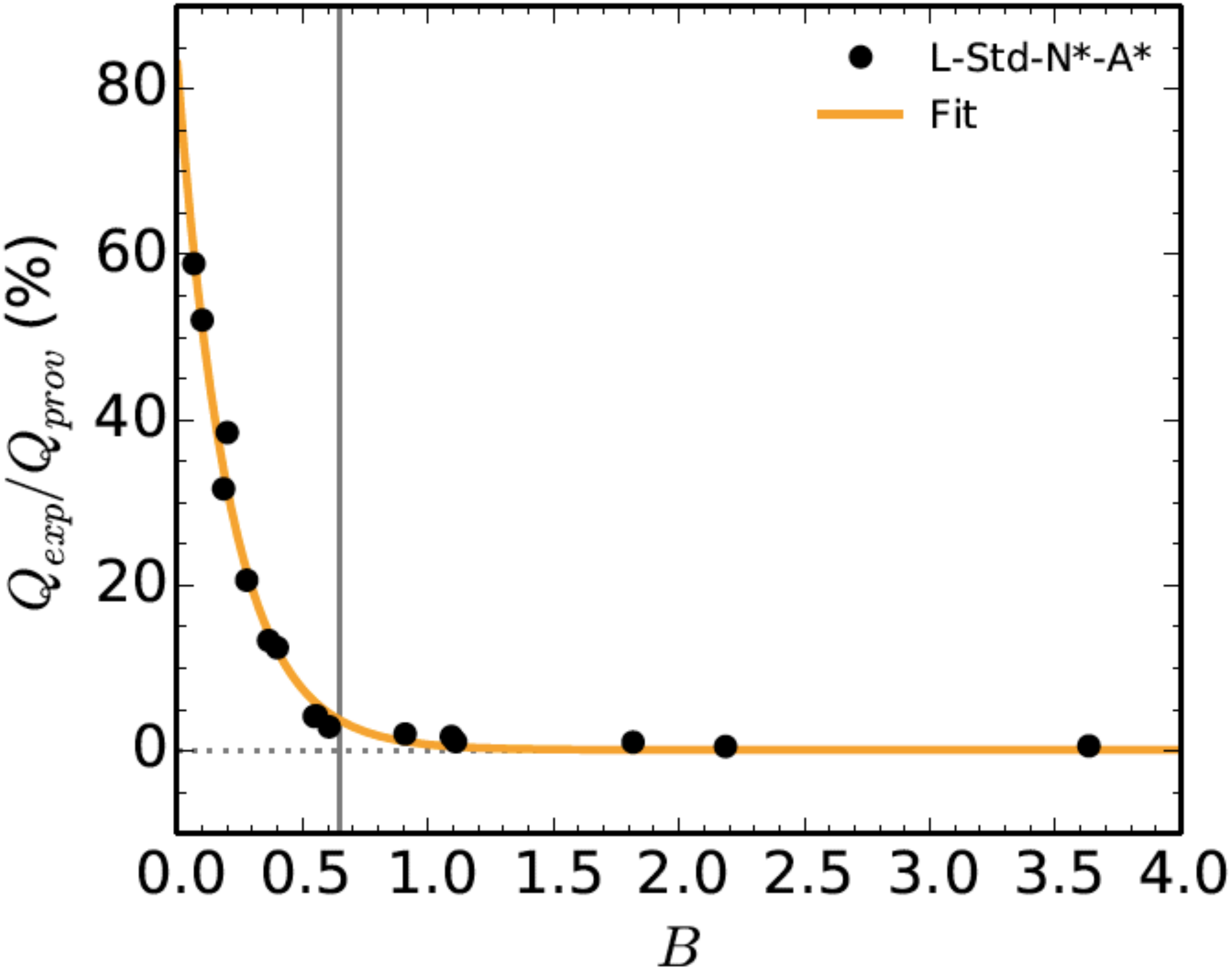
Residual Layers



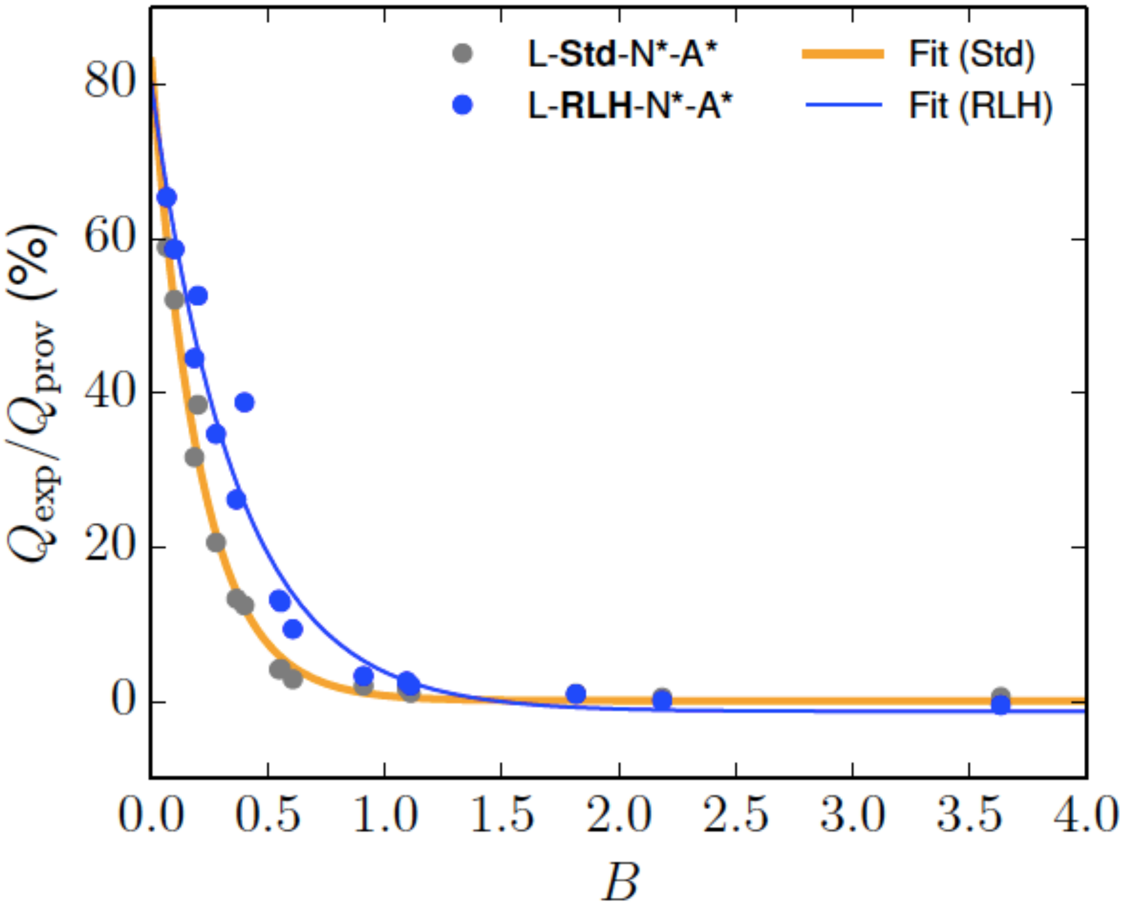
Topography



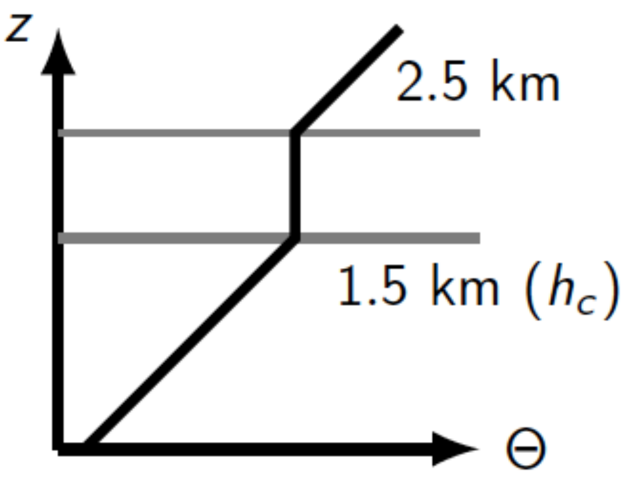
Export of heat – Reference



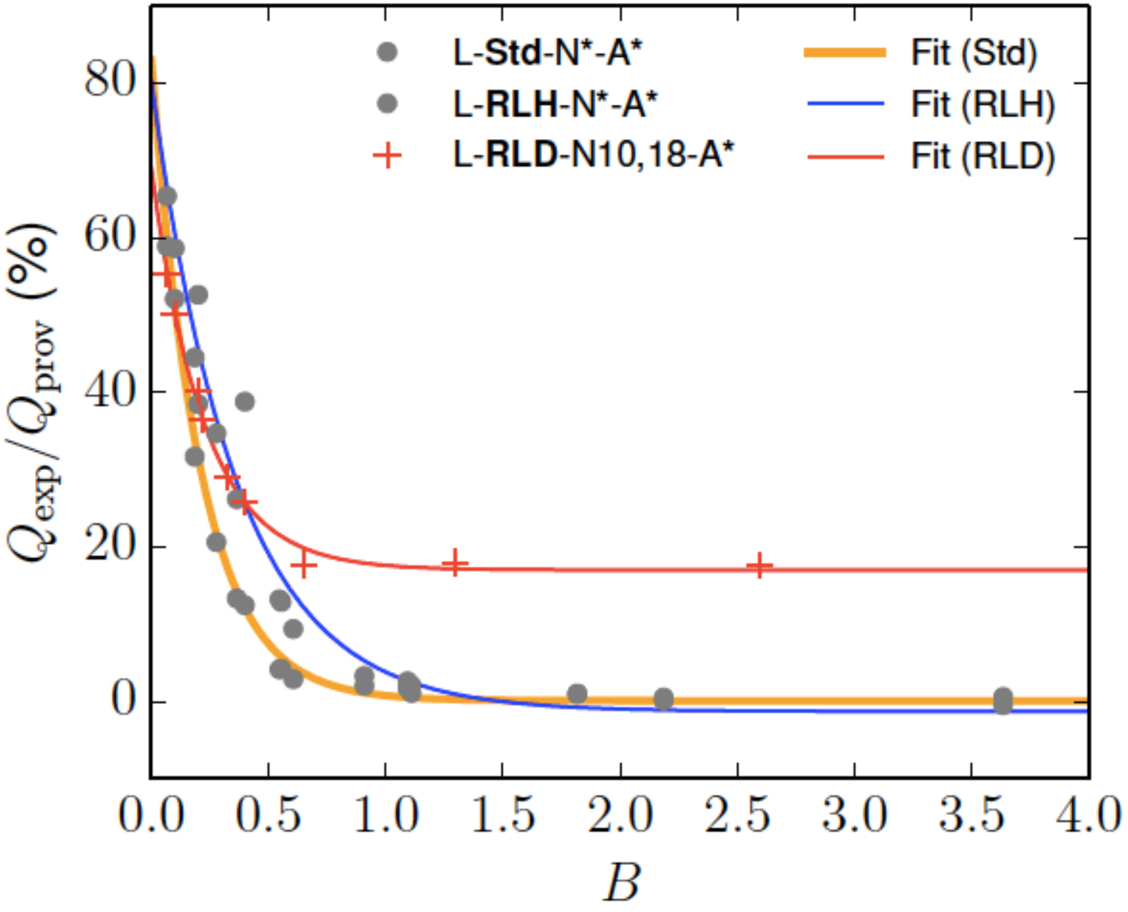
Export of heat – Impact of Residual Layers



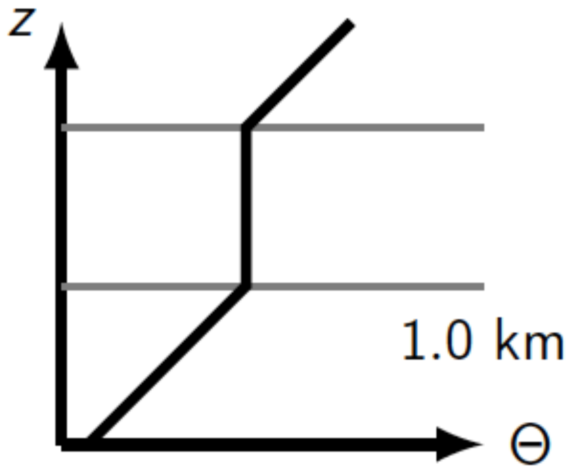
High Residual Layer



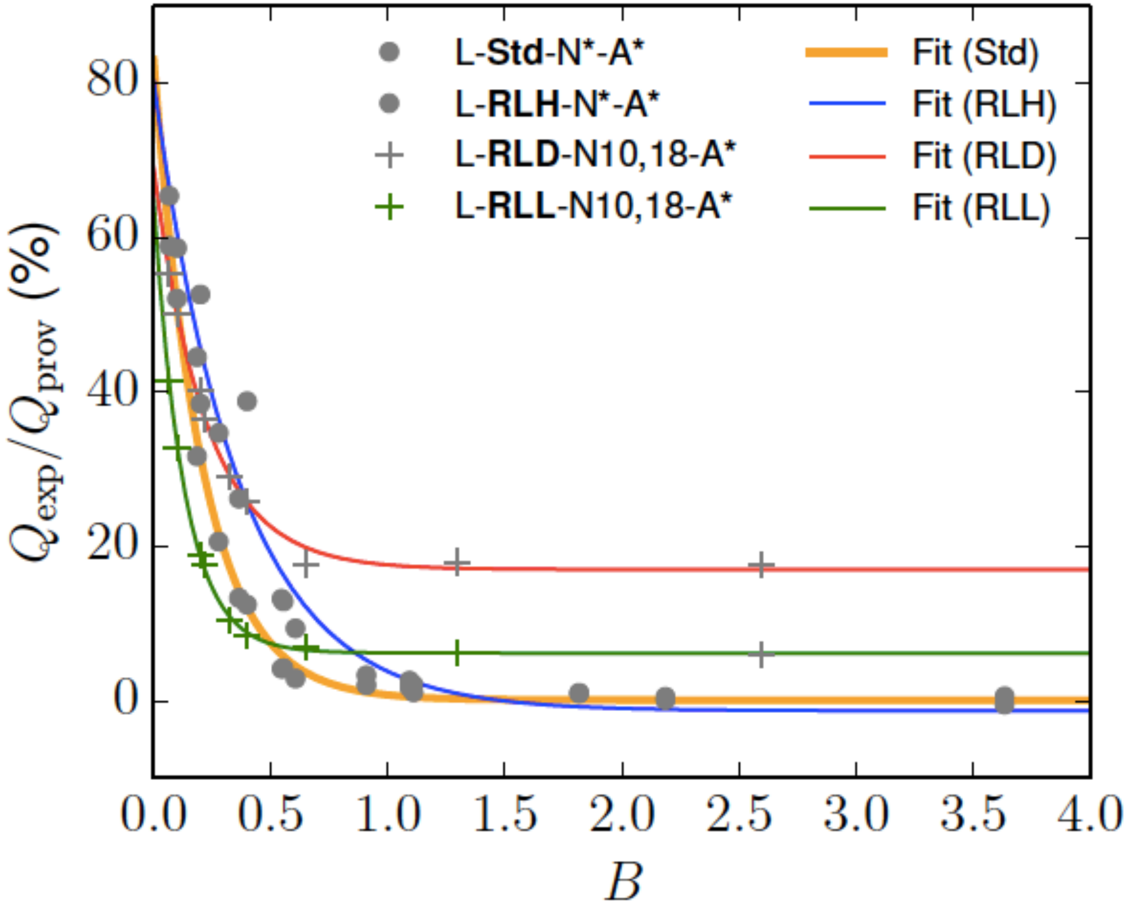
Export of heat – Impact of Residual Layers



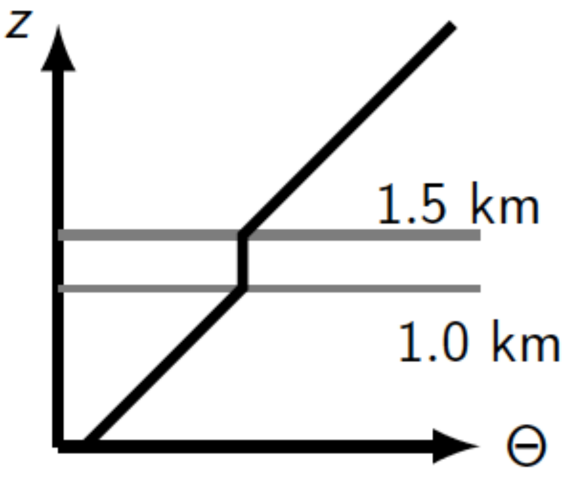
Deep Residual Layer



Export of heat – Impact of Residual Layers



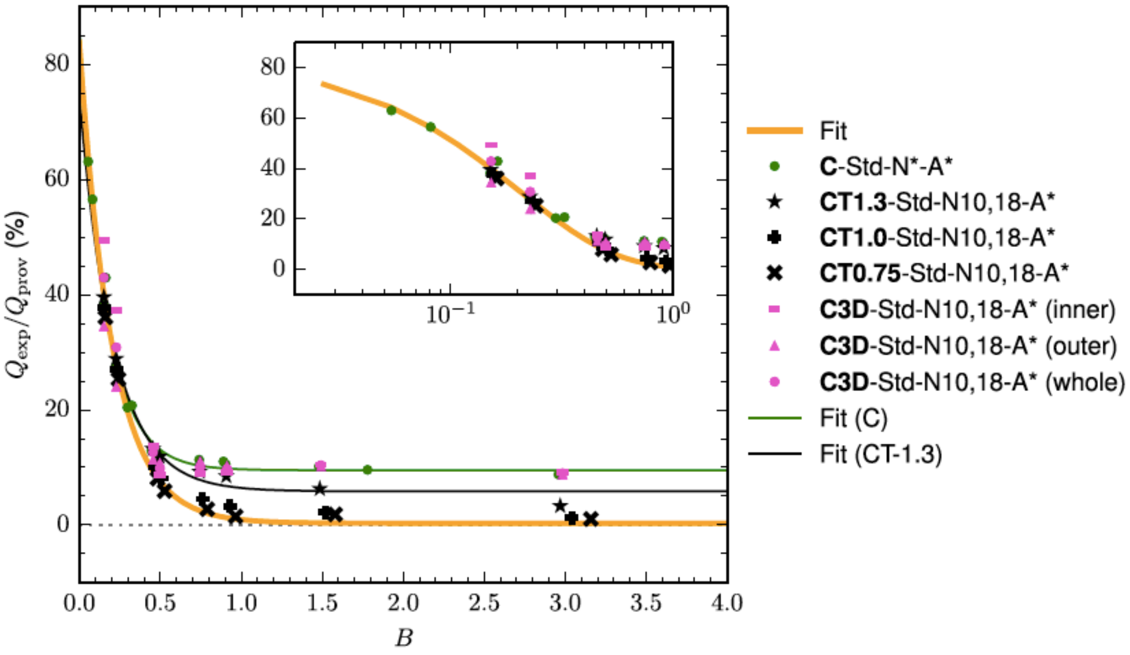
Low Residual Layer



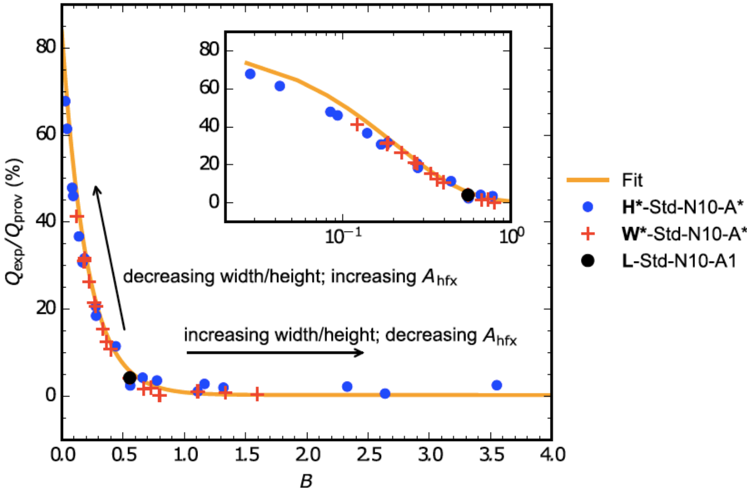
Impact of other parameters

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

cosine shape (‚C‘), elev. plateau

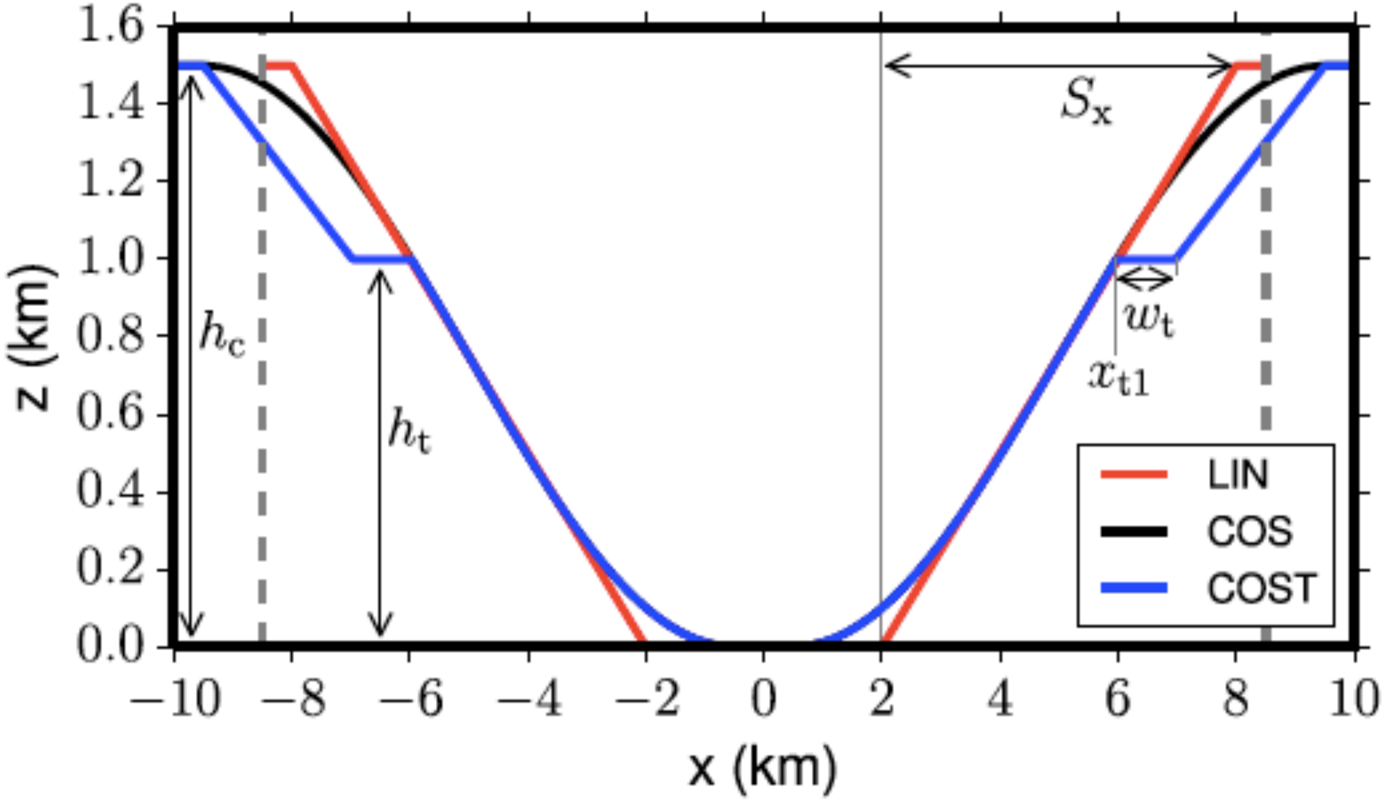


H/W ratio, length (L)

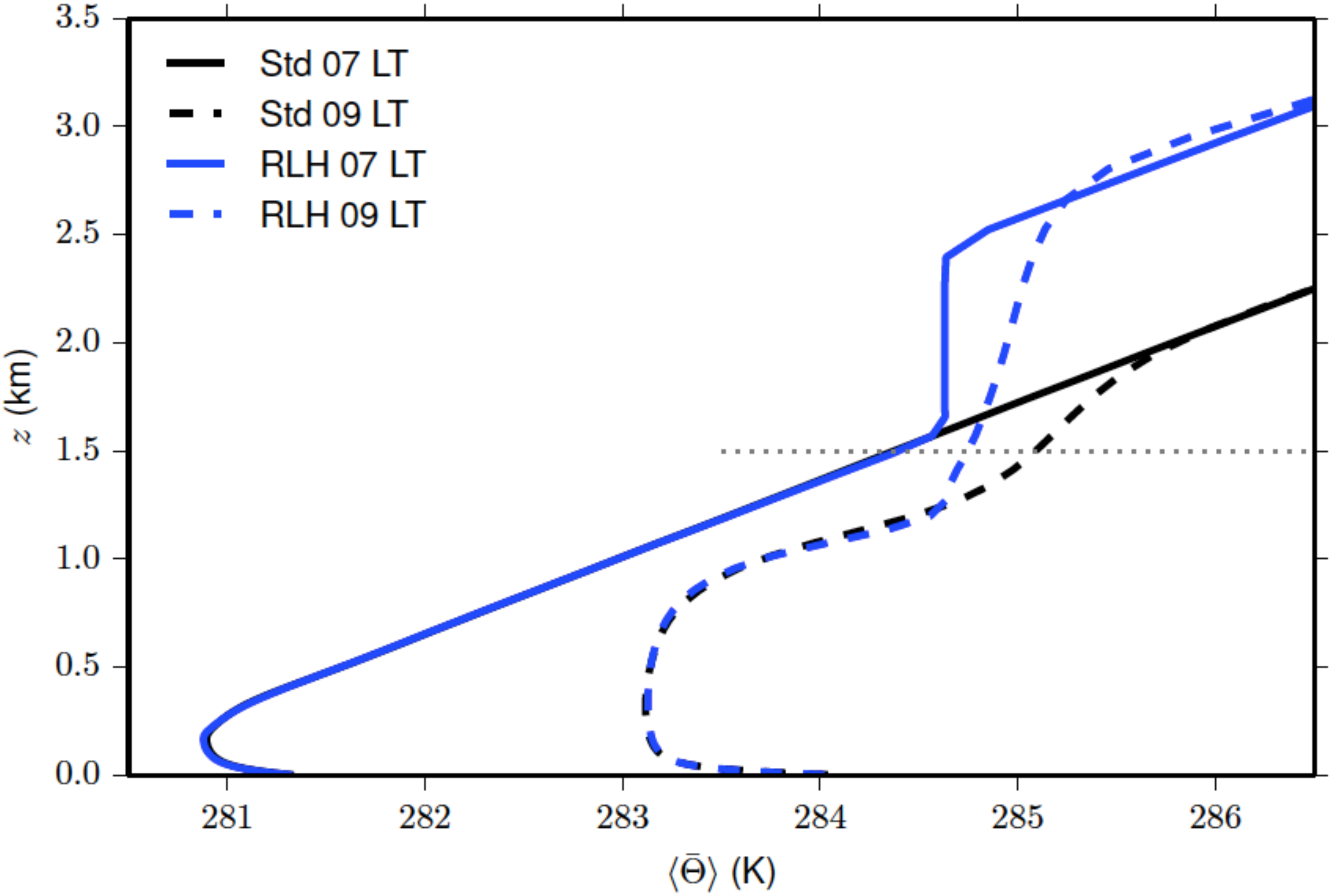


Impact of other parameters

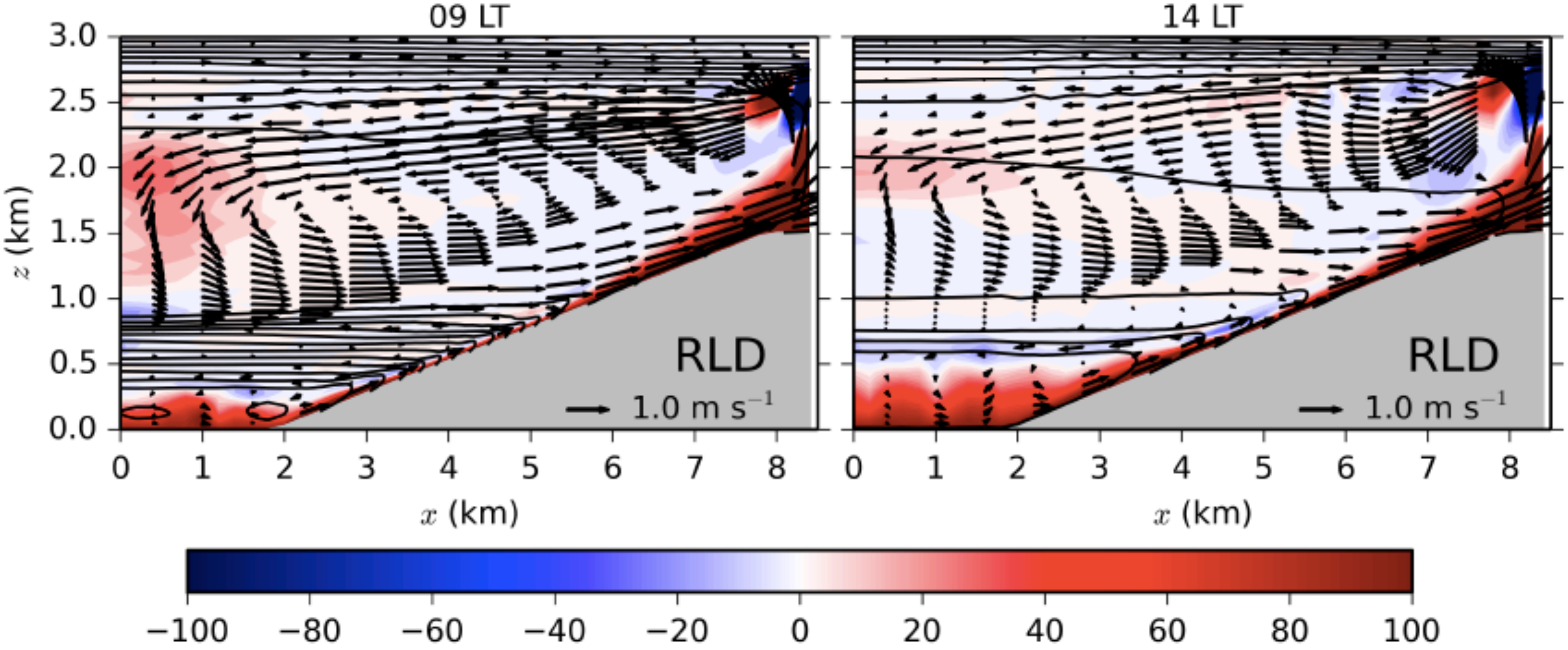
- terrain geometry H / W, terrain form
- 2d – 3d
- elevated plateau‘s



High Residual Layer

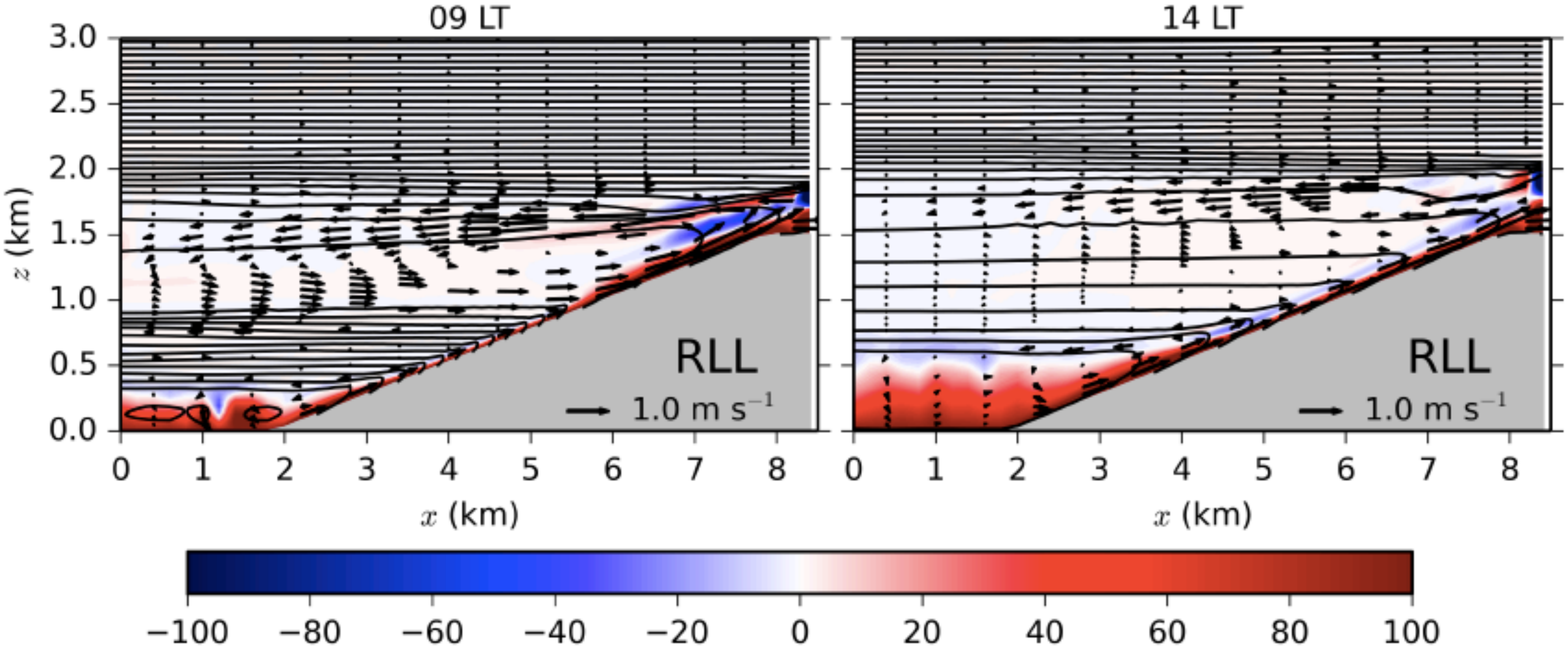


Deep Residual Layer



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

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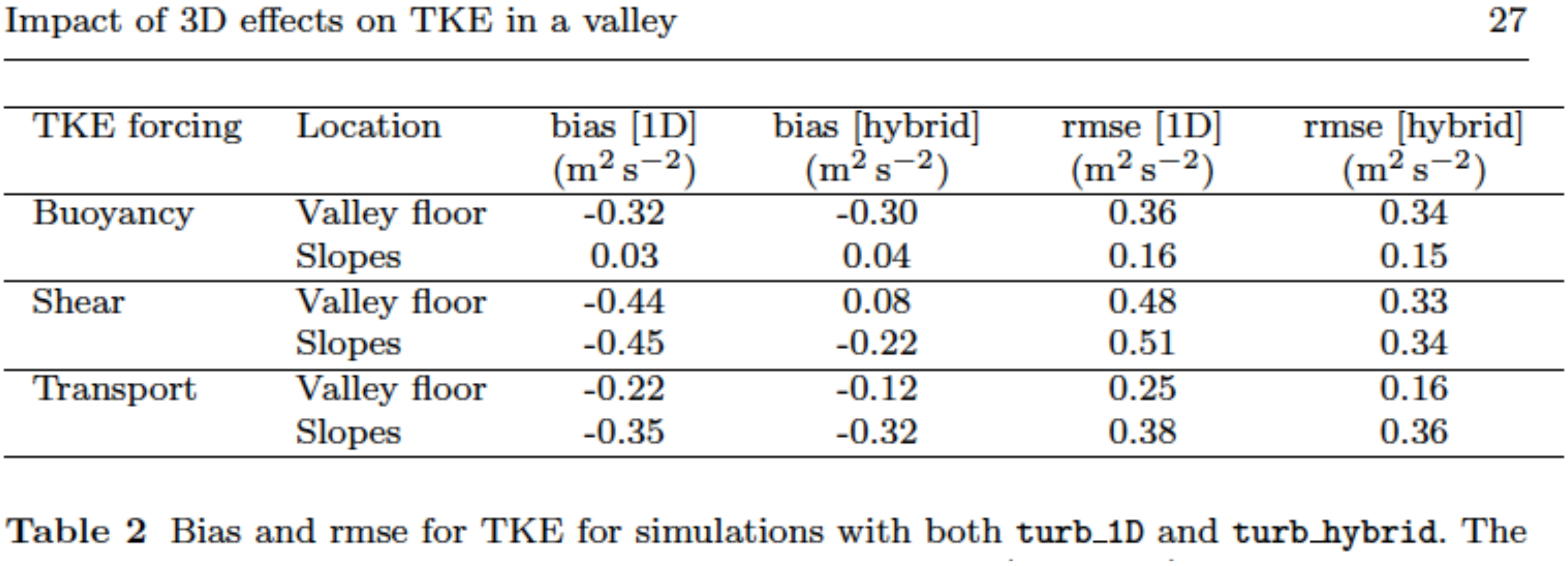
Wagner JS, Gohm A, Rotach MW: 2015, Influence of along-valley terrain heterogeneity on exchange processes over idealized valleys, *Atmos Chem Phys*, 15, 6589-6603 15, 415-451, doi: 10.5194/acp-15-6589-2015

Wagner JS, Gohm A, Rotach MW: 2015, The impact of valley geometry on daytime thermally driven flows and vertical transport processes, *Quart J Roy Meteorol Soc,* **141** (690), 1780-1794, part: A, doi: 10.1002/qj.2481

Title

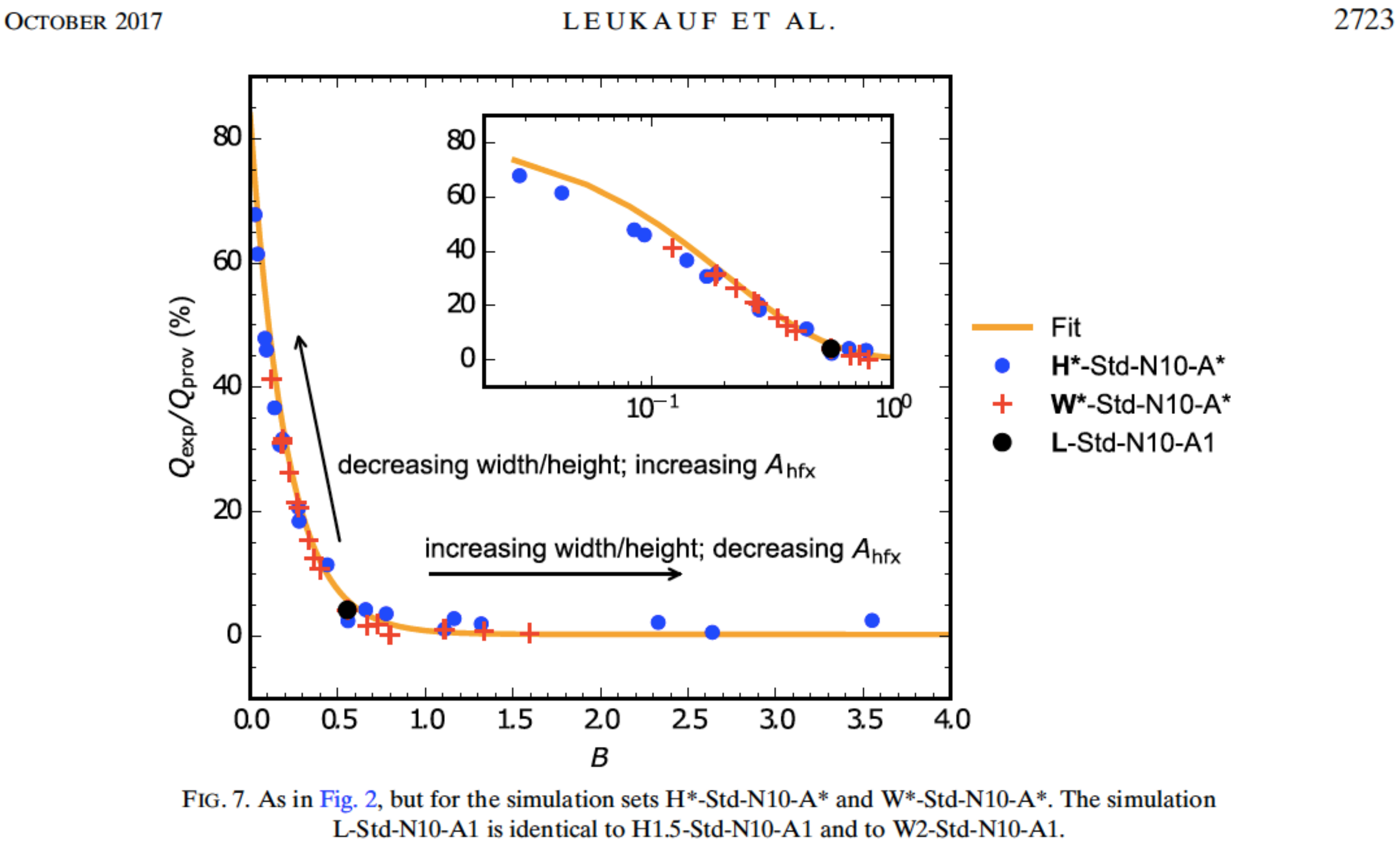


Impact of 3D effects on TKE in a valley 27

TKE forcing	Location	bias [1D] $(\mathrm{m^2\,s^{-2}})$	bias [hybrid] $(\mathrm{m^2\,s^{-2}})$	rmse [1D] $(\mathrm{m^2\,s^{-2}})$	rmse [hybrid] $(\mathrm{m^2\,s^{-2}})$
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



OCTOBER 2017 LEUKAUF ET AL. 2723

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

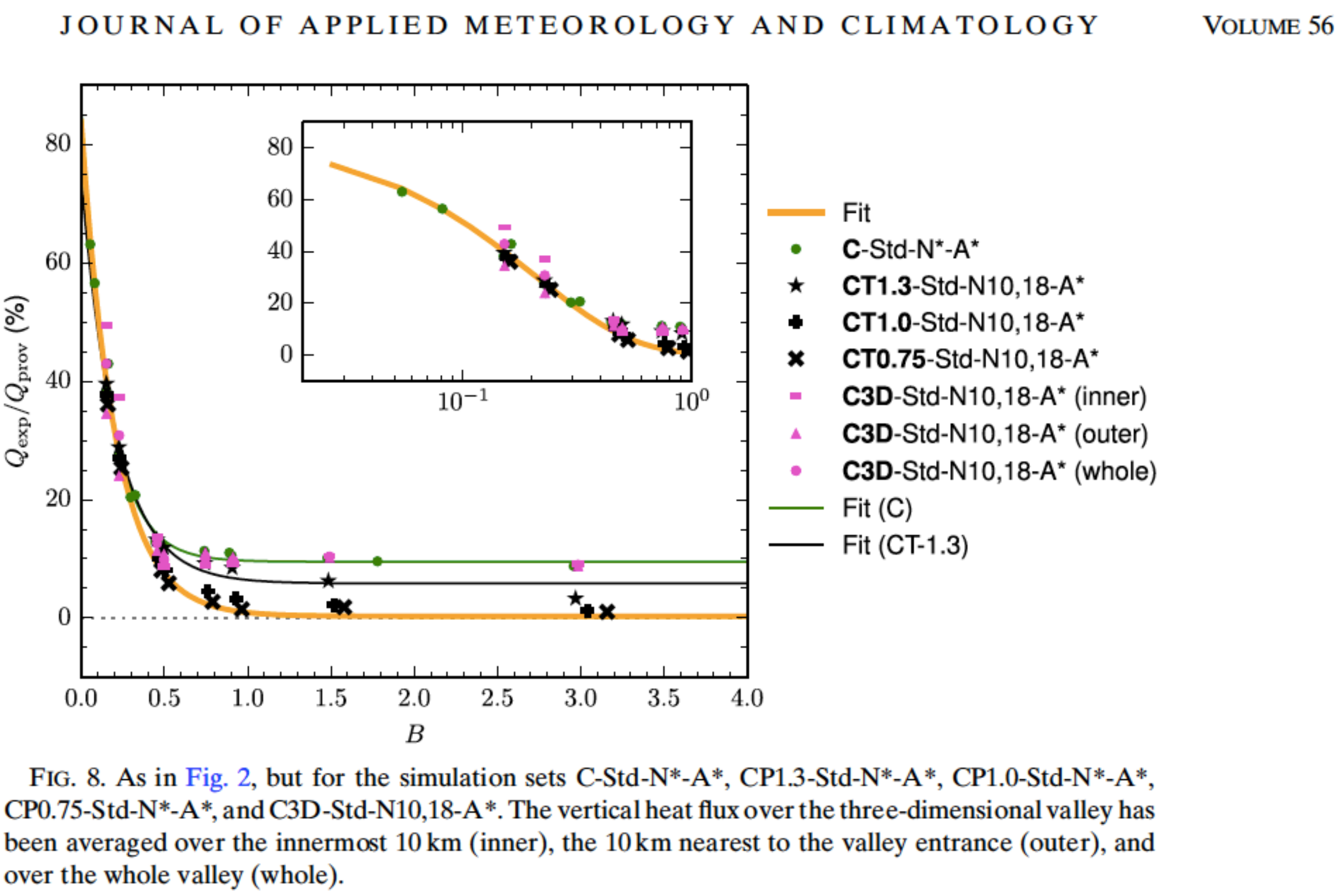


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FIG. 8. As in Fig. 2, but for the simulation sets C-Std-N*-A*, CP1.3-Std-N*-A*, CP1.0-Std-N*-A*, CP0.75-Std-N*-A*, and C3D-Std-N10,18-A*. The vertical heat flux over the three-dimensional valley has been averaged over the innermost 10 km (inner), the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

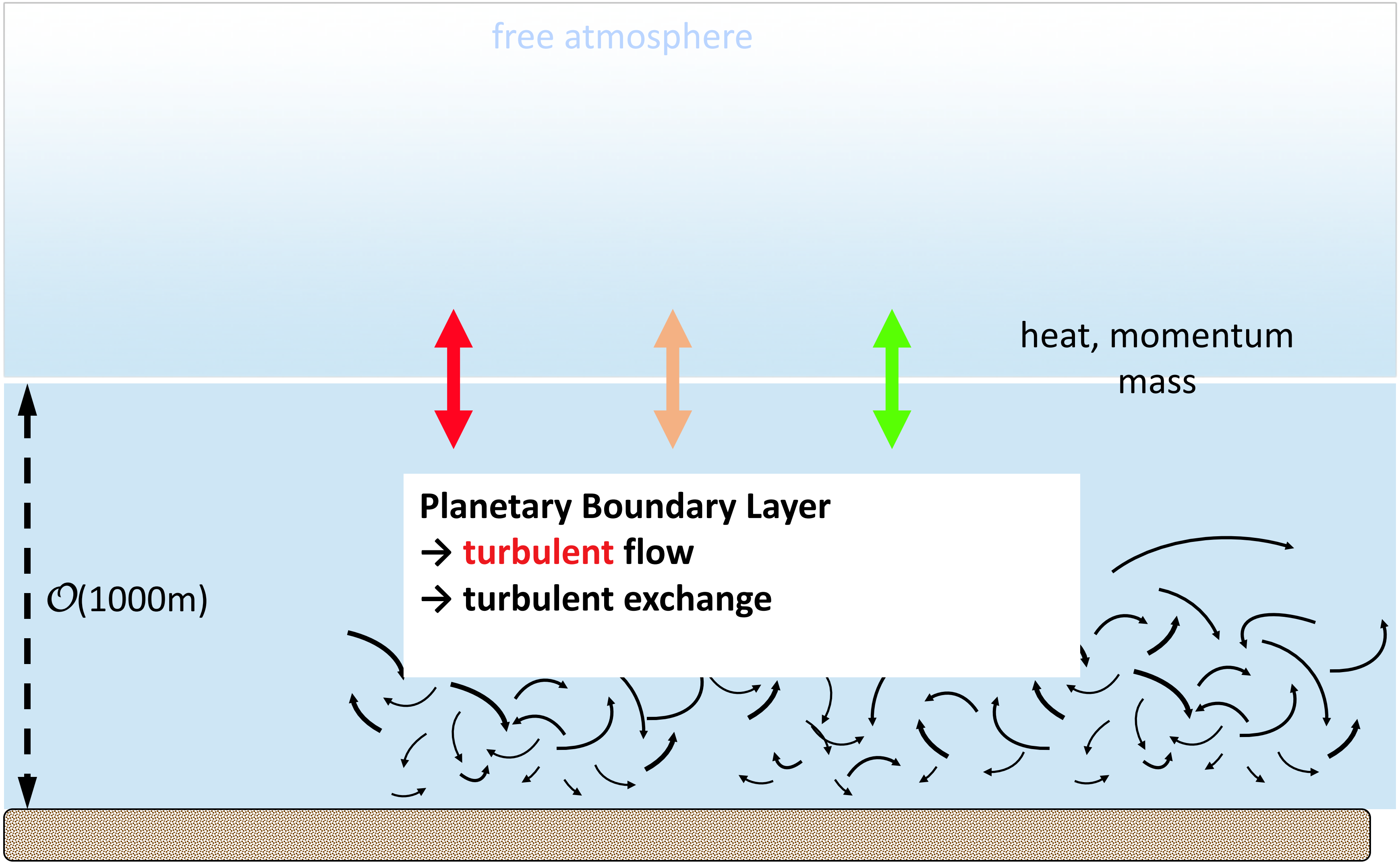
→ impact of valley form (cosine instead of linear), 3d (instead of 2d) and ‘elevated plateaus’

GAPS in knowledge


© Janick Entremont

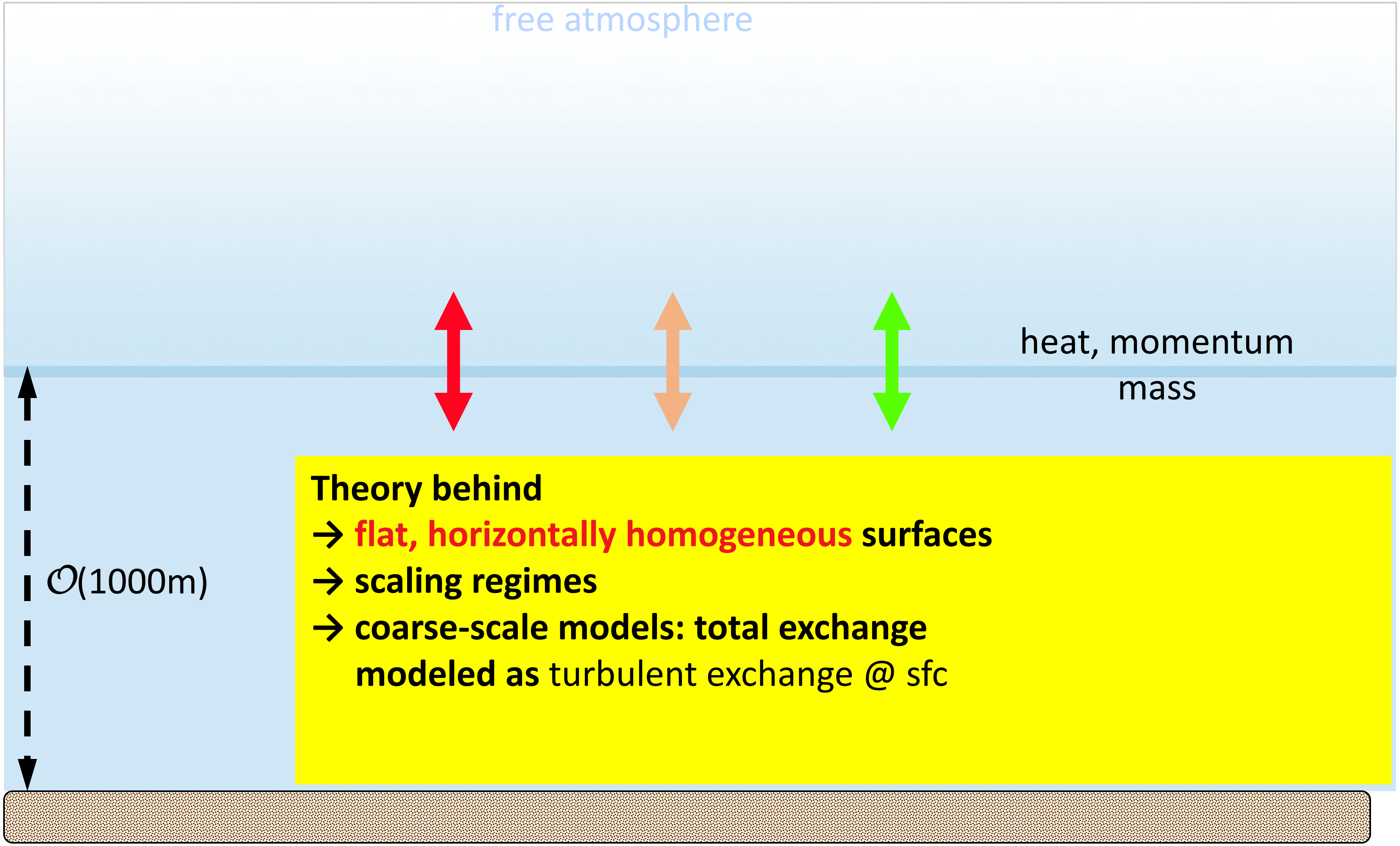
→ project @ UIBK will start soon ...

‚Near-surface' exchange



Planetary Boundary Layer
→ **turbulent flow**
→ **turbulent exchange**

‚Near-surface‘ exchange



Theory behind

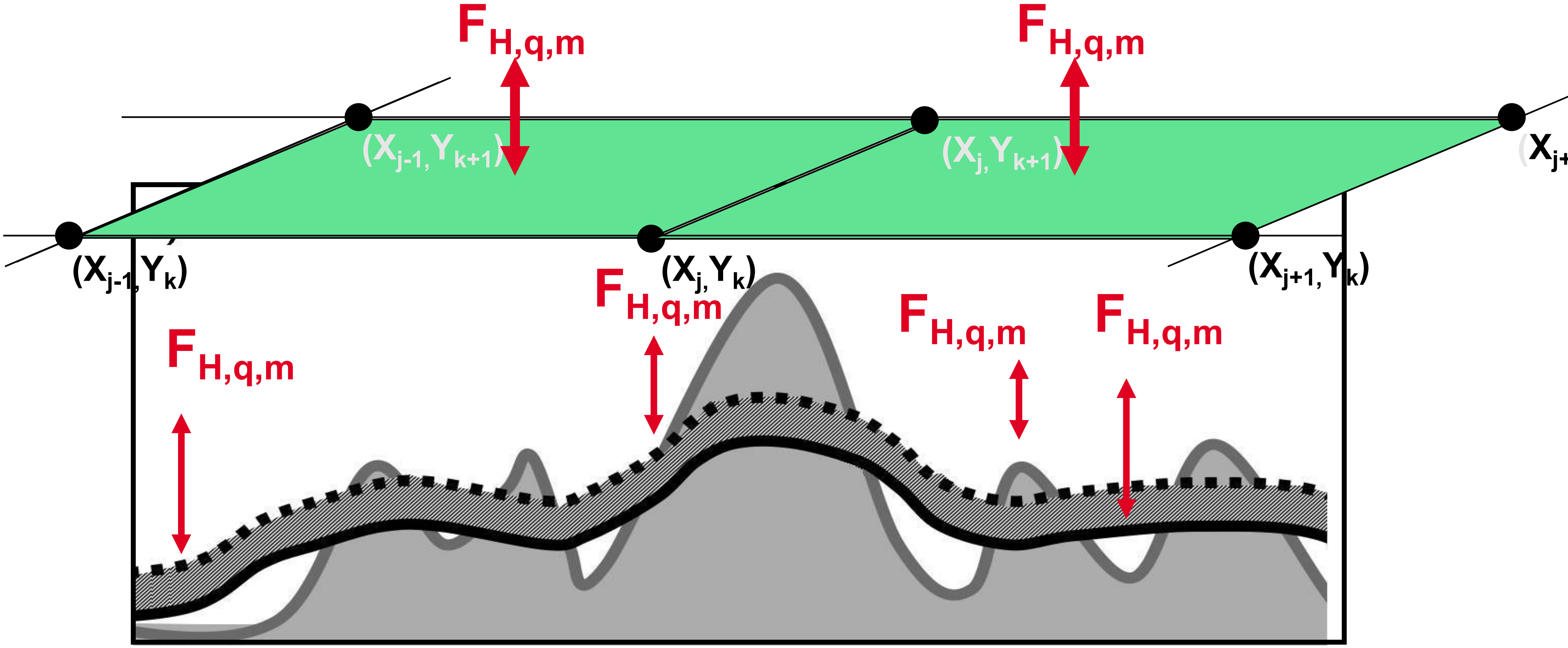
→ **flat, horizontally homogeneous surfaces**

→ **scaling regimes**

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

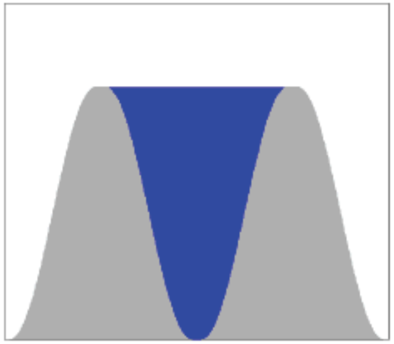
Coarse models

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

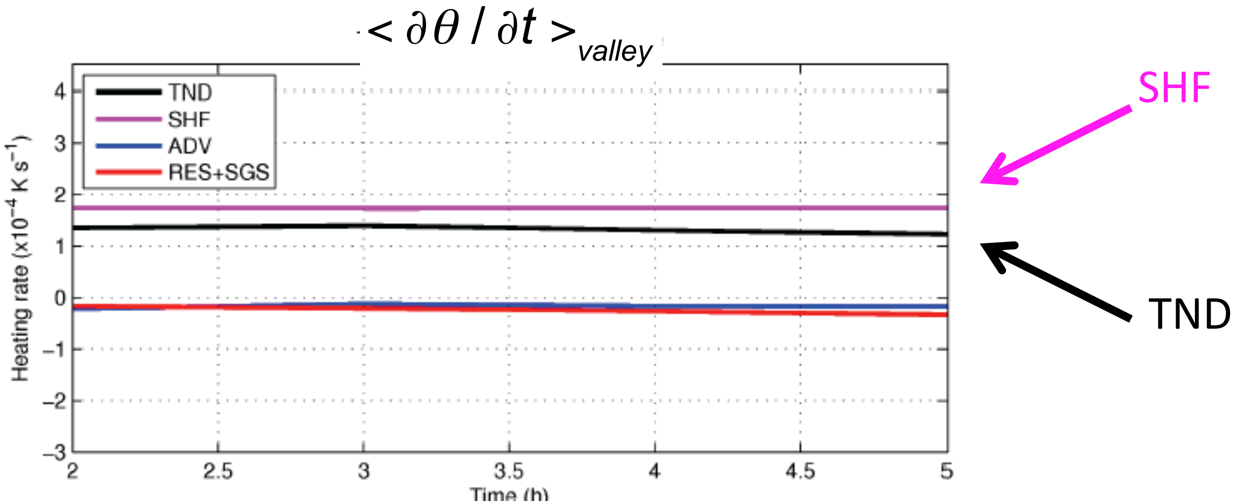


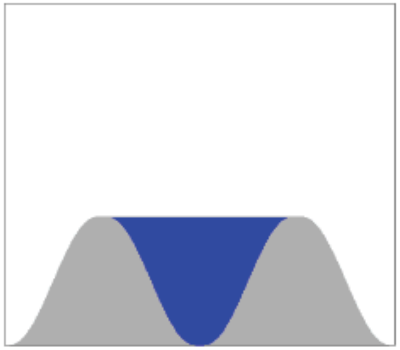
Rotach and Zardi (2007)

Heat exchange - geometry

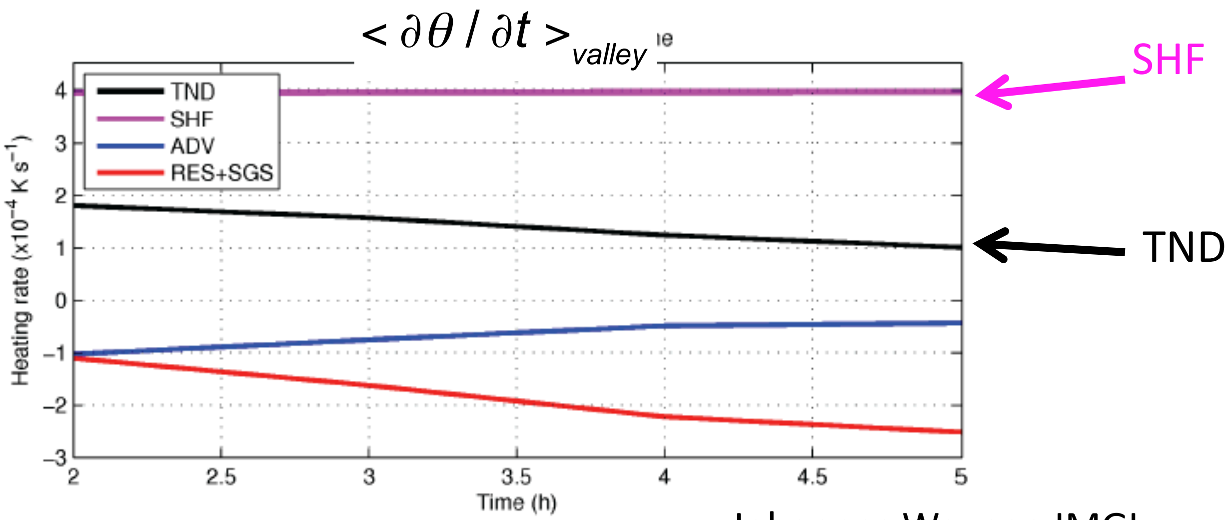


Volume V





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

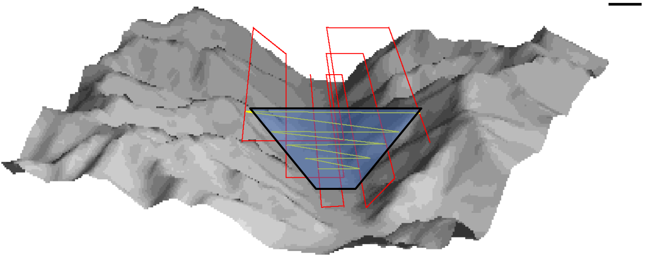


Johannes Wagner, IMGI

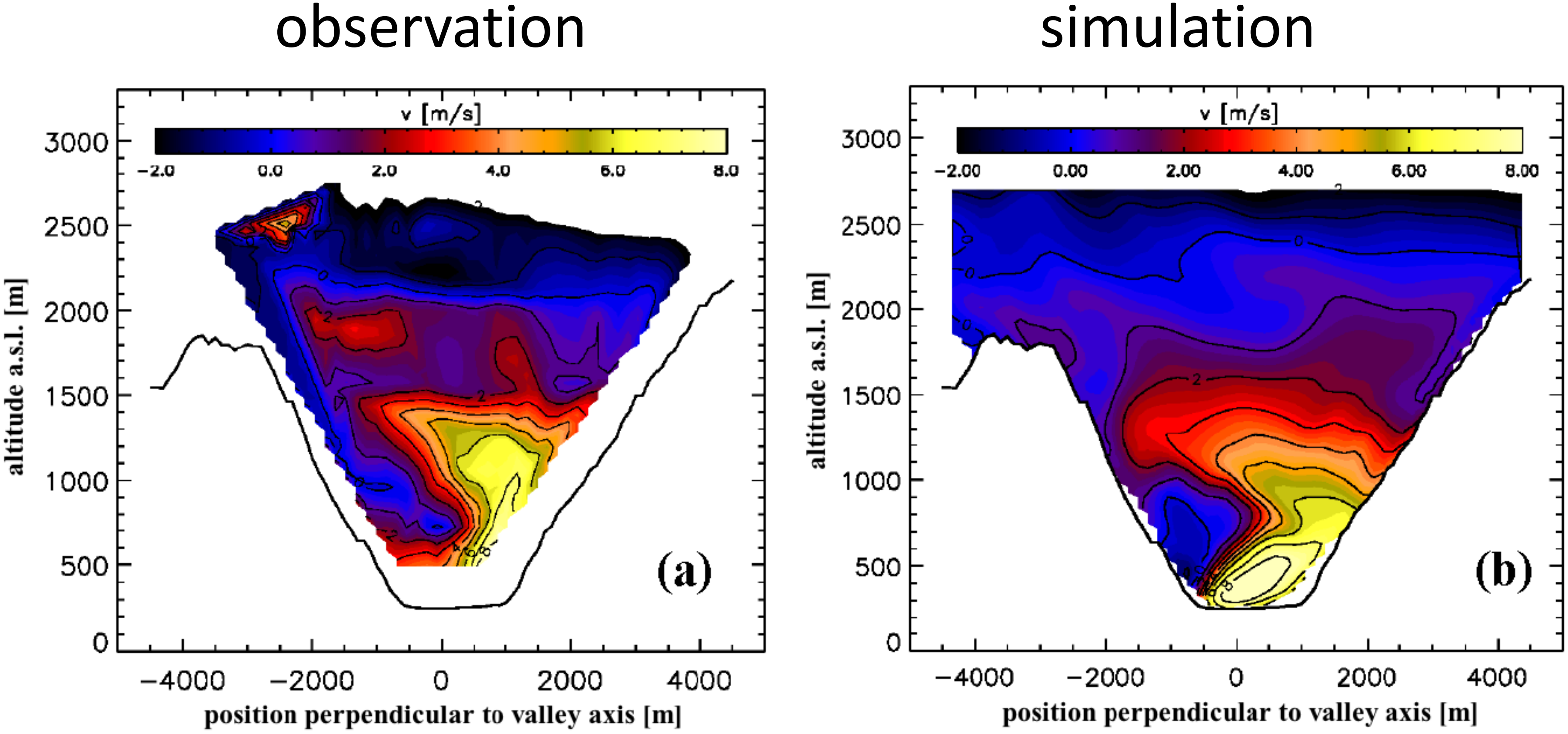
Numerical Modeling

- 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

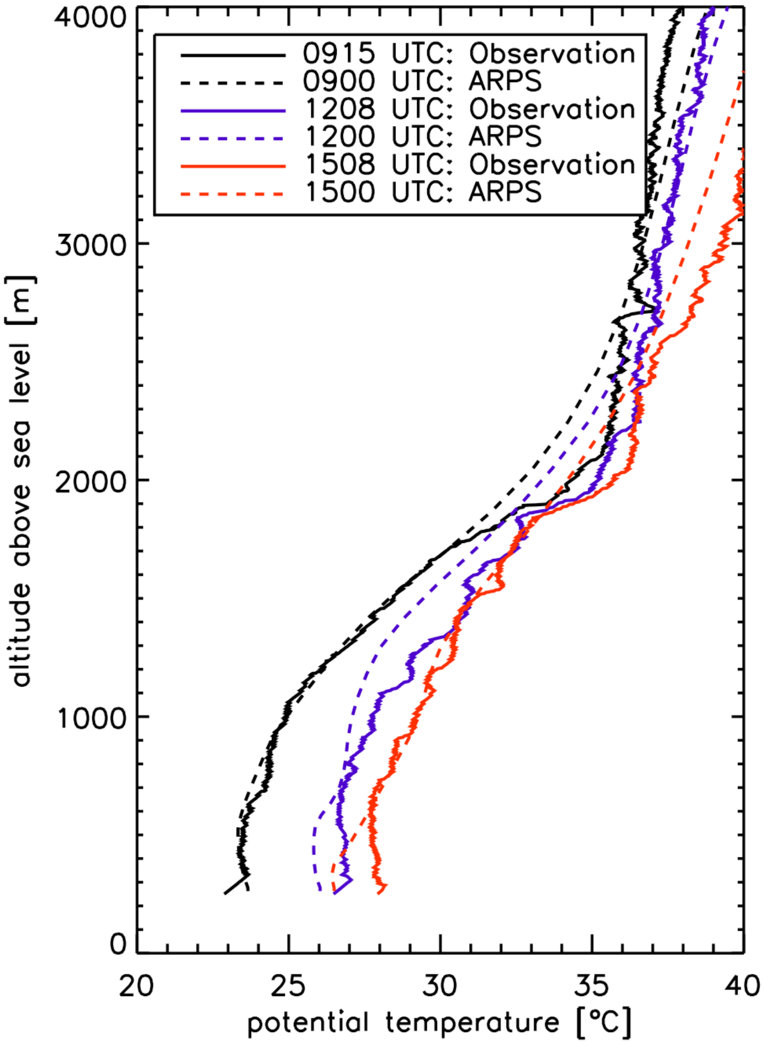
Wind along valley



25. August (1300 UTC)



Profile Potential Temperature



example:
25. August 1999

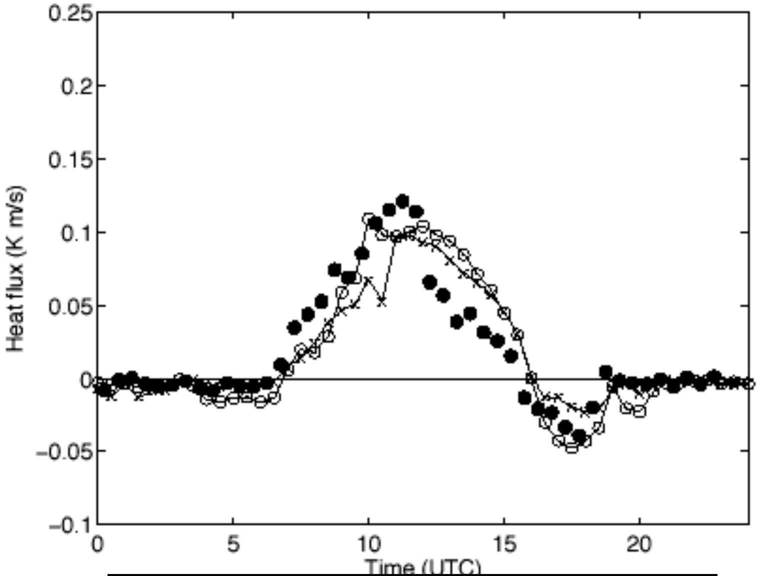
kinematic heat flux

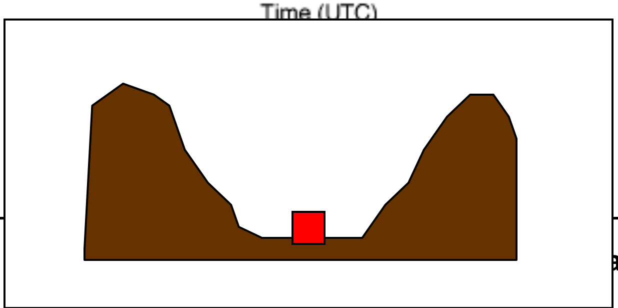
● ● ● observation

x x x— simulation - reference

○ ○ ○ land use and soil moisture

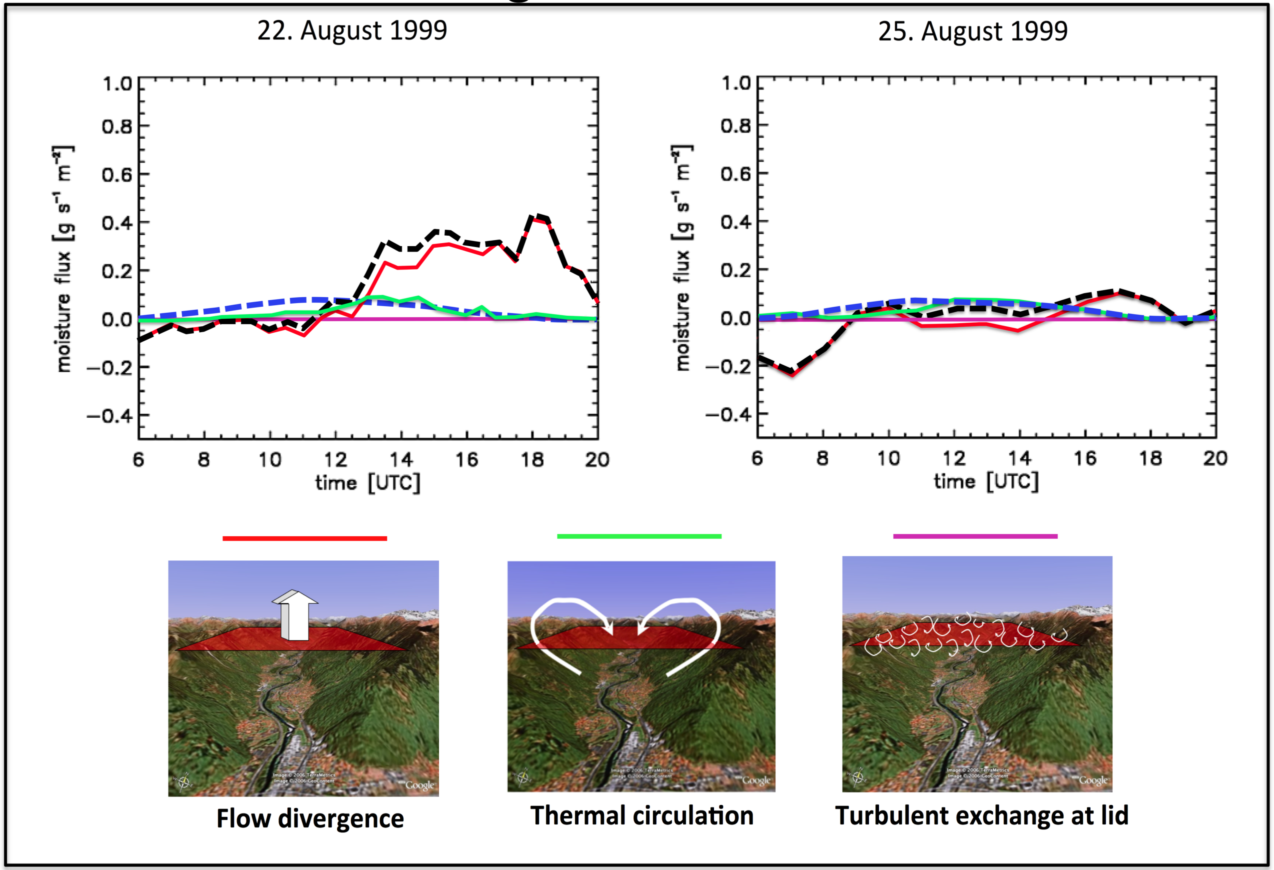
Chow et al. 2006, JAM
Weigel et al. 2006, JAM





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)

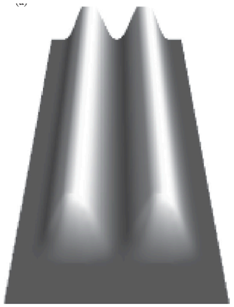
Exchange of CO_2

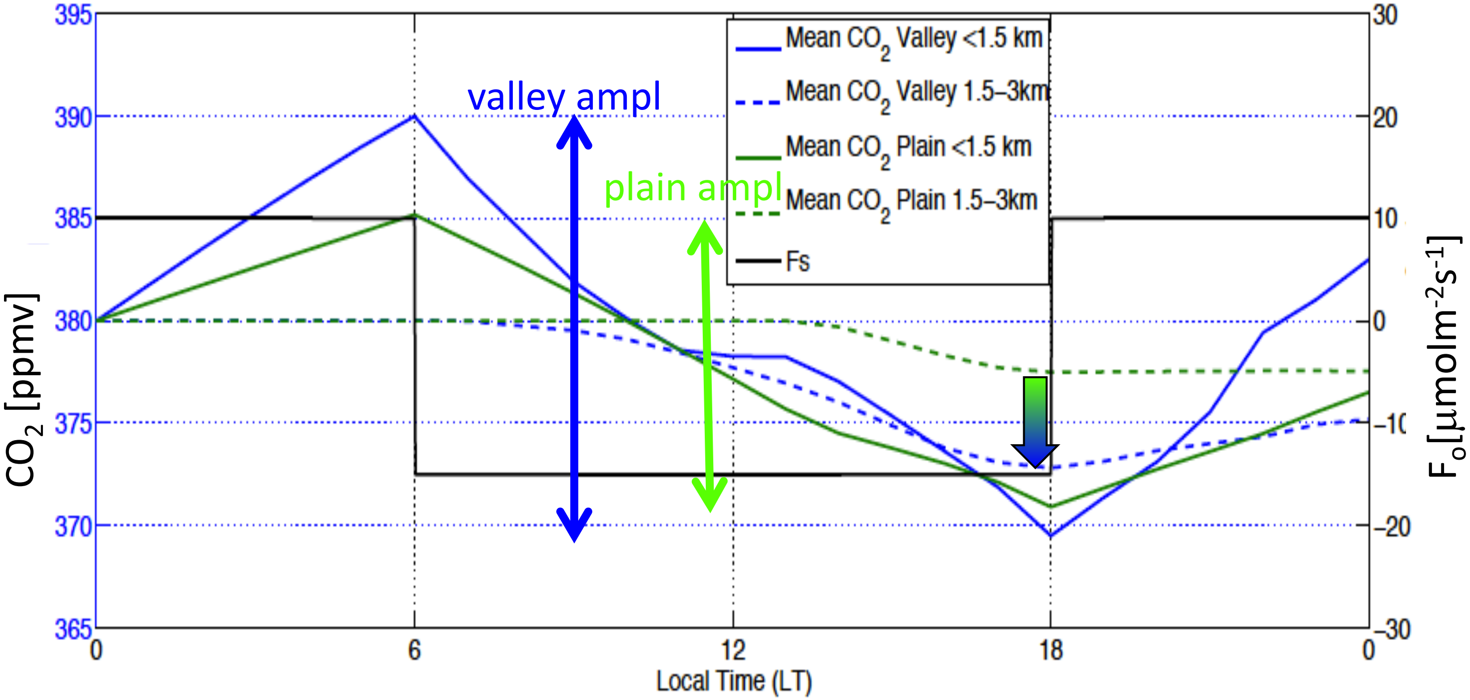
- different source/sink characteristics than moisture
- ‘active’ during the night as well
- importance of SBLs/drainage flows

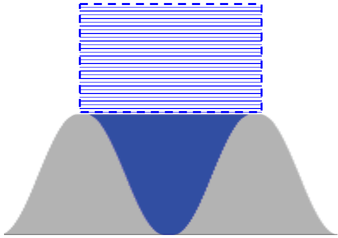
Some pioneering studies:

- 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)

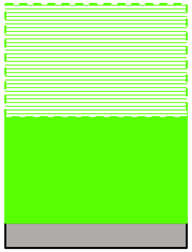
CO_2 exchange







valley



plain

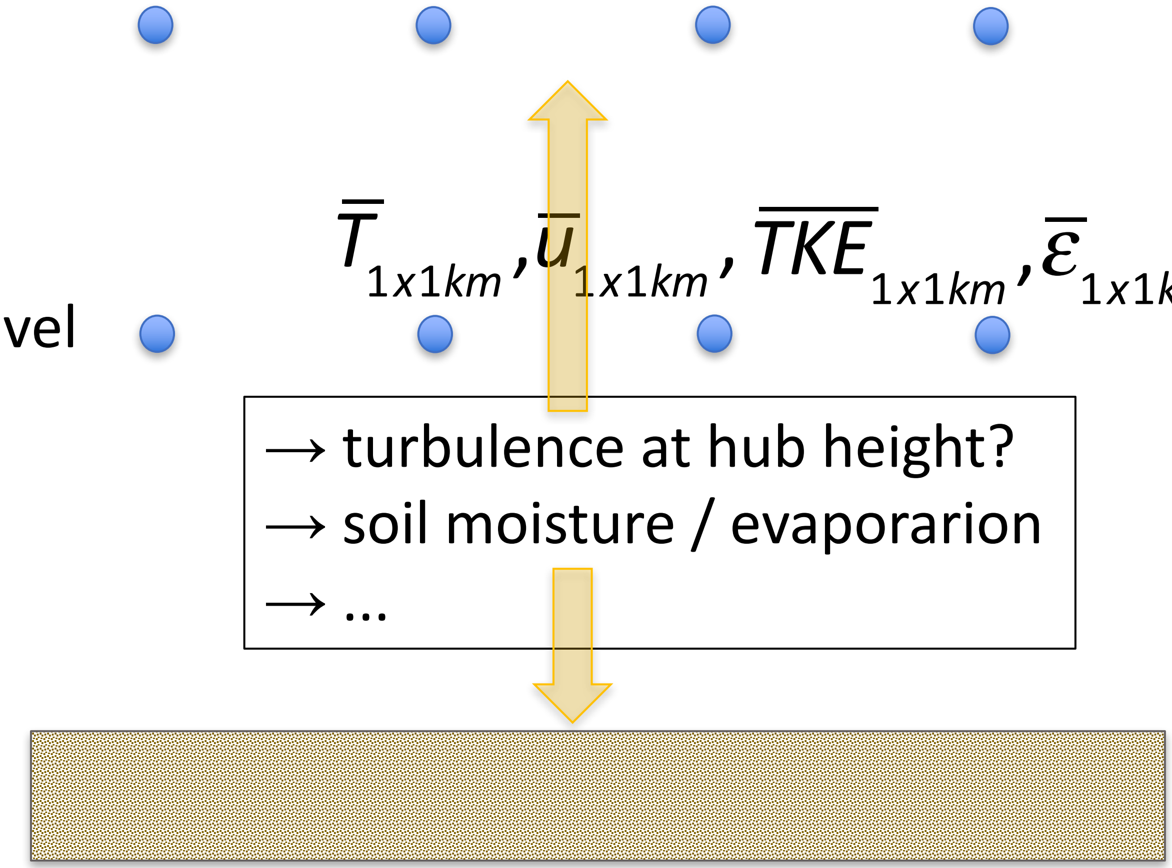
Summary

- 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



$\overline{T}_{1x1km}, \overline{u}_{1x1km}, \overline{TKE}_{1x1km}, \overline{\varepsilon}_{1x1km}, \ldots$

1st model level

→ turbulence at hub height?
→ soil moisture / evaporarion
→ …

→ boundary layer structure
→ bundary layer scaling