universität innsbruck

TEAMx – a New international Research Programme on Weather and Climate in the Mountains

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Outline

- Atmospheric transport and exchange processes over mountains

  → relevance:

  weather / climate / air pollution

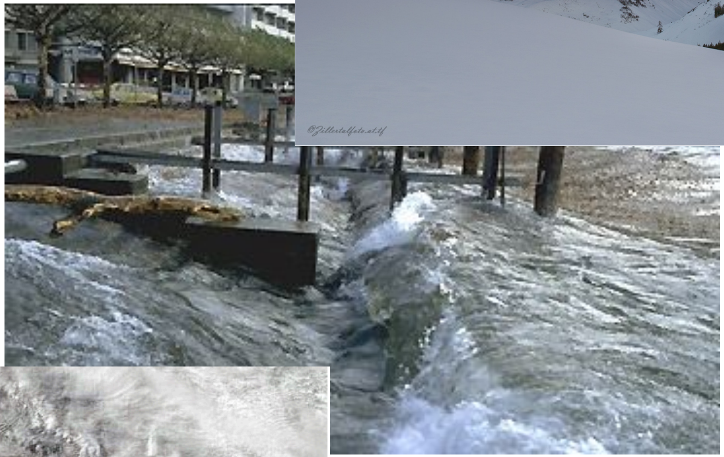
  → what do we know / need to know?

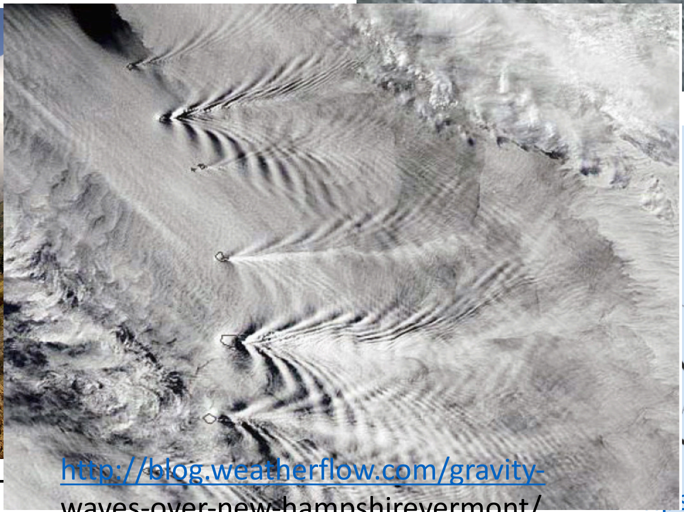
- TEAMx – a new international program

  ALPEX – MAP - TEAMx

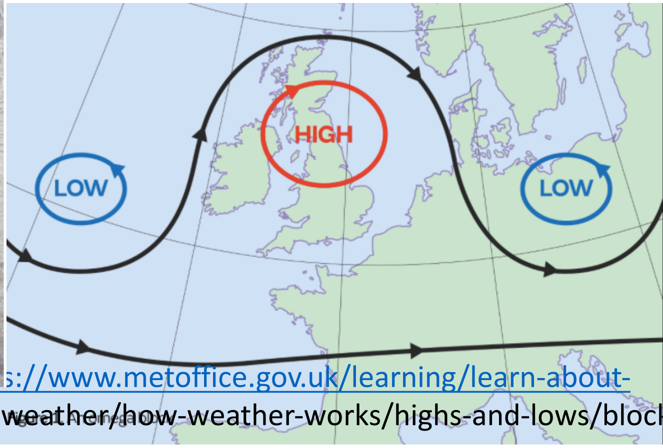
Mountain Weather and Climate

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





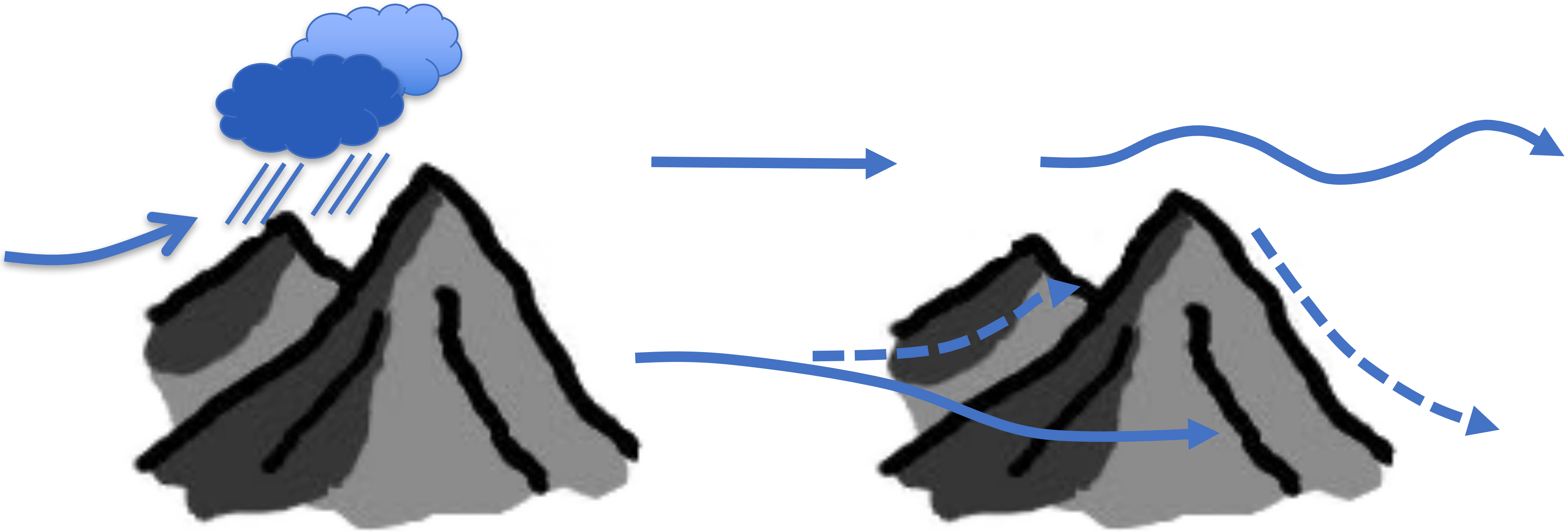
http://blog.weatherflow.com/gravity-waves-over-new-hampshirevermont/



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

Mountain Weather and Climate

- common interest, traditional
  - → 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, traditional
  → 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

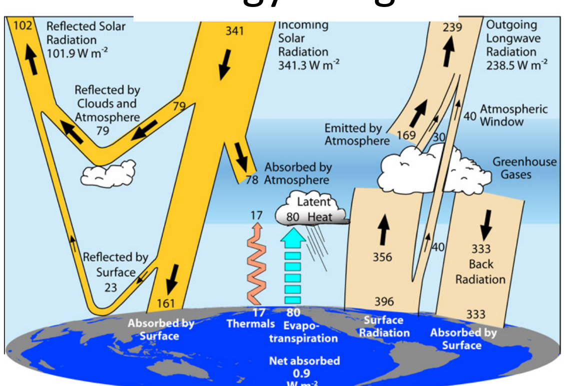
- from a global point of view:

  → 'mountain' is part of the surface
  → character of the surface

Exchange

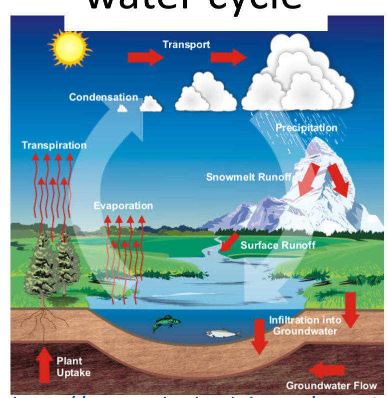
- character of the surface
  → determines the *exchange* between the atmosphere and the earth
  → *coupling* of the atmosphere with the surface
- mountain ↔ atmosphere perspective
  → how does the atmophere – which has been modified by the mountain – execute this exchange?

energy budget



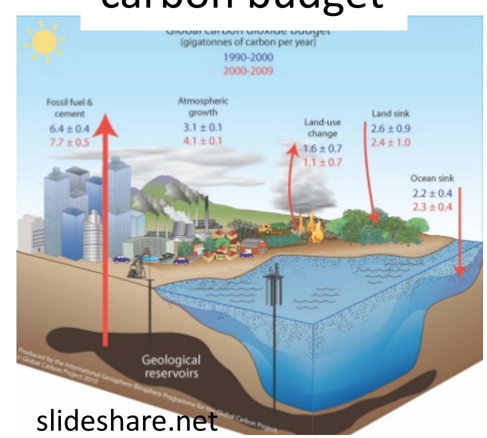
https://scied.ucar.edu/longcontent/energy-budget

water cycle



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

carbon budget



slideshare.net

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
- example: CO_2 budget

Fate of Anthropogenic CO_2 Emissions

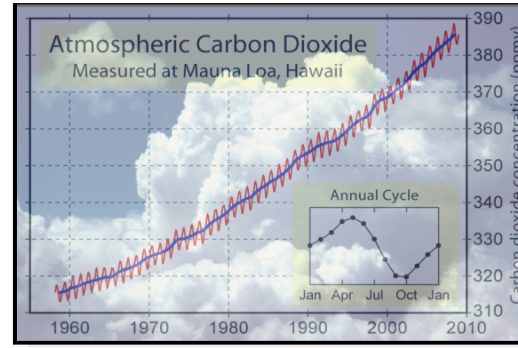
9.3 ± 0.5 PgC y^{-1}

+

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

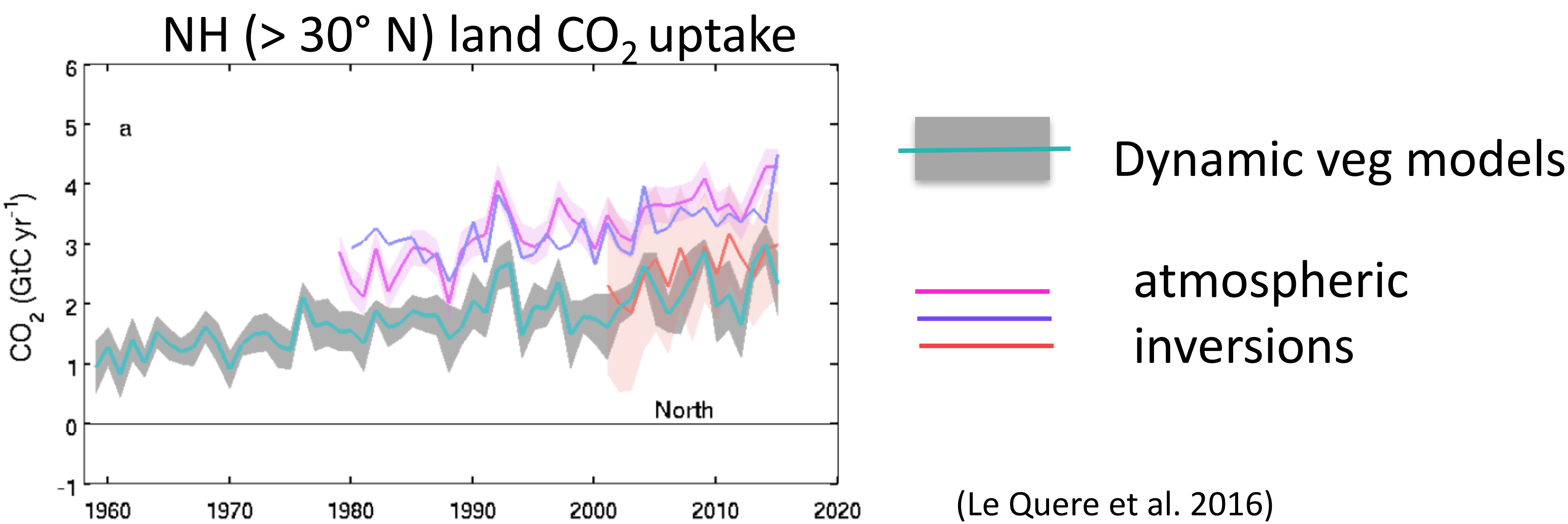
Overall:

→ about equal shares go to oceans / land surface

→ uncertainty of land uptake the largest

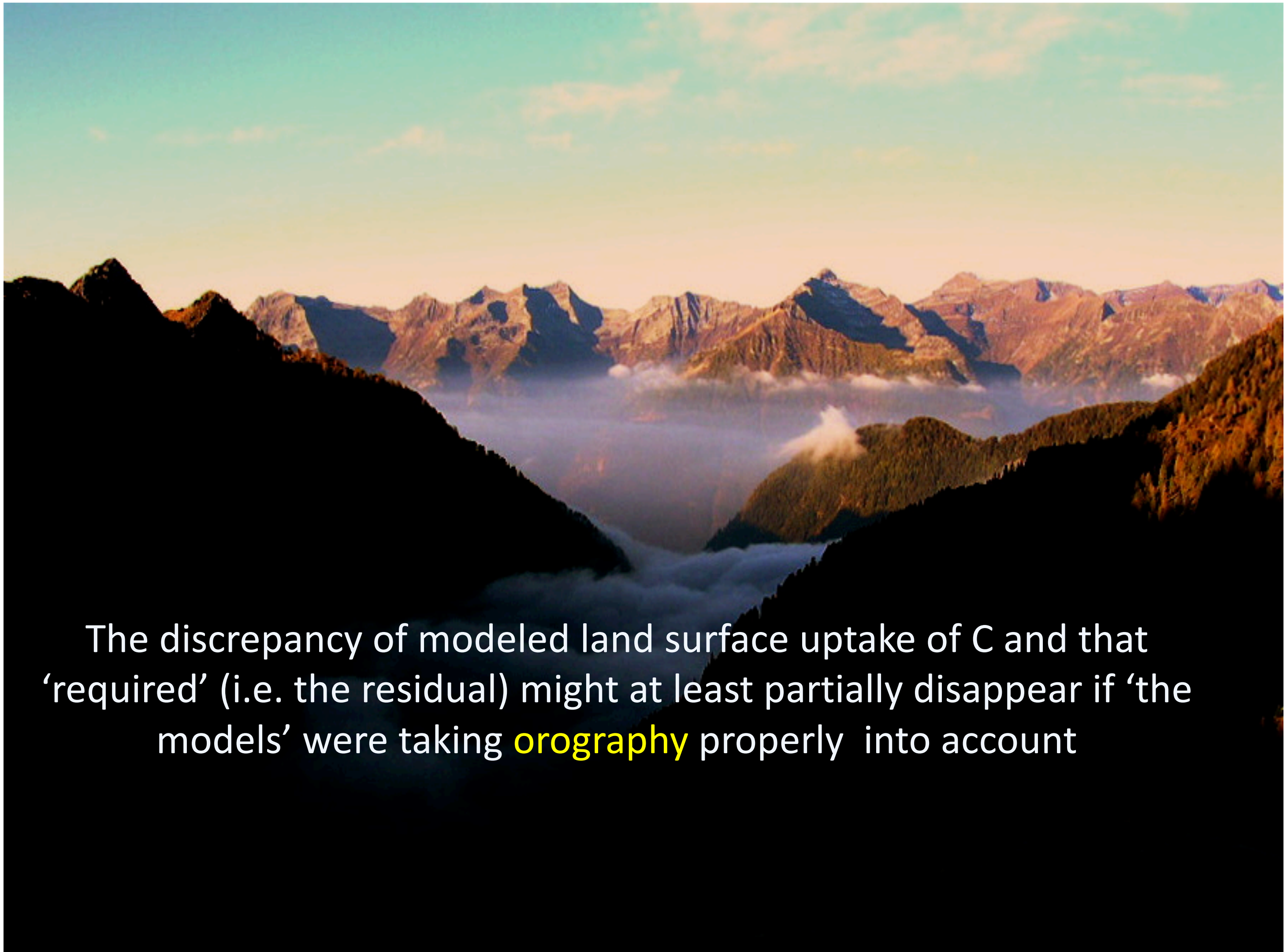
→ land uptake modeled depends on method
(2.3 vs. 2.7/3.8/3.8 PgC y^{-1} for 2006-2015)

→ *modeled*: does not take into account terrain



(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 orography properly into account

Modeled land surface uptake

model approaches:

- atmospheric inverse modeling

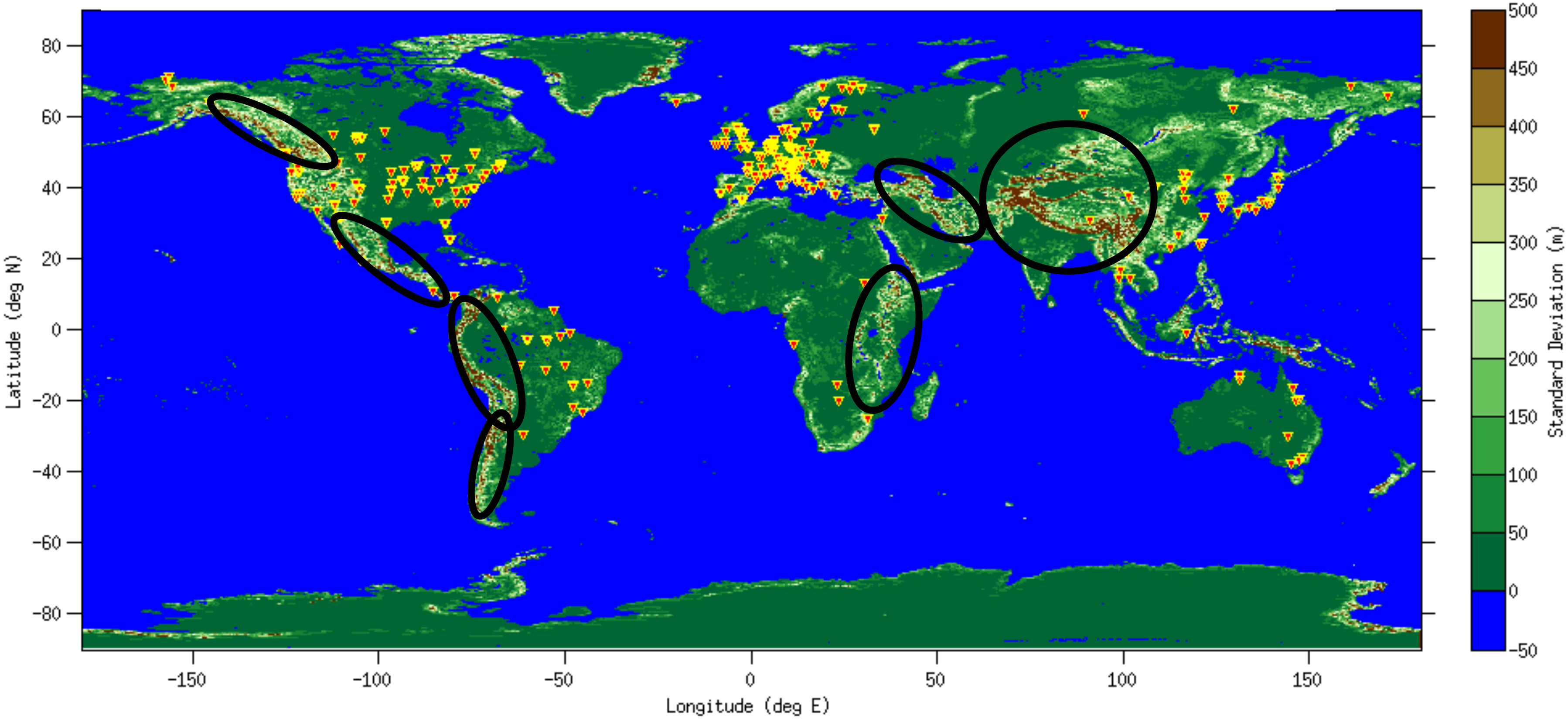
vs.

- 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 orography (20km)

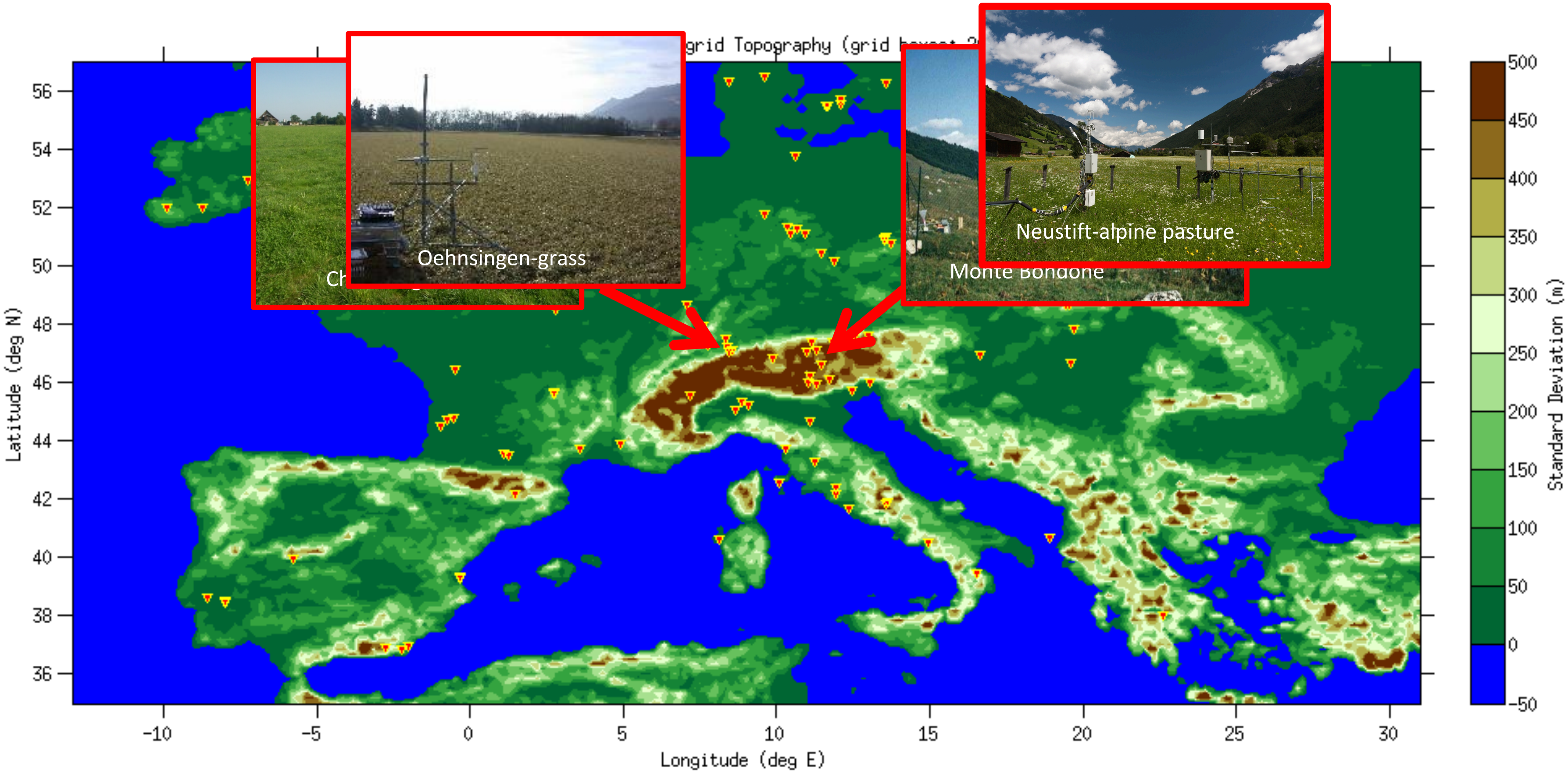


→ represent ecosystems

→ but not orography

Rotach et al. (2014), BAMS

Flux tower sites



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Modeled land surface uptake

model approaches:

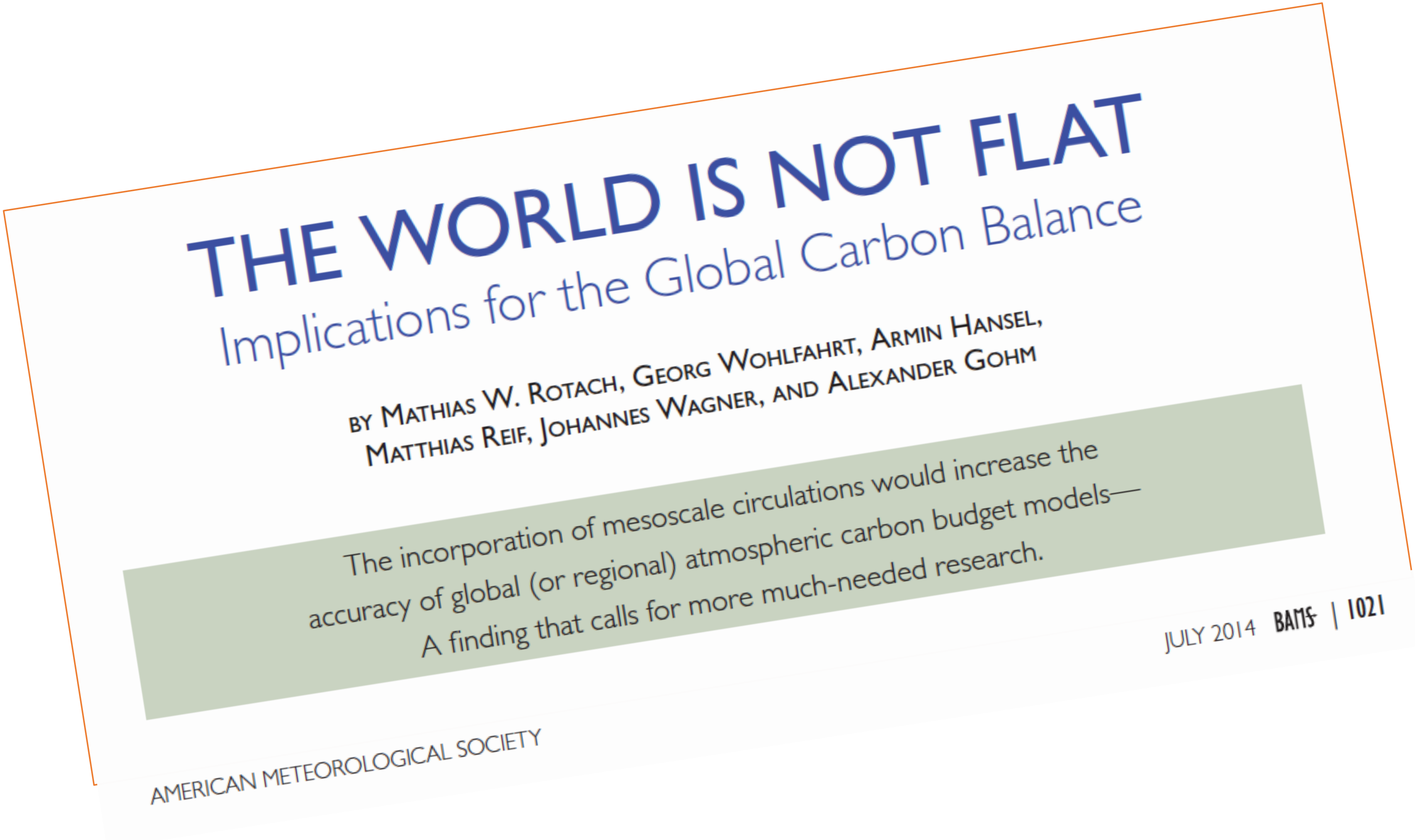
- atmospheric inverse modeling

  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.

AMERICAN METEOROLOGICAL SOCIETY

JULY 2014 BAMS | 1021

Exchange

- character of the surface
  $\longrightarrow$ determines the *exchange* between the atmosphere and the earth
  $\longrightarrow$ *coupling* of the atmosphere with the surface

- mountain $\longleftrightarrow$ atmosphere perspective
  $\longrightarrow$ how does the atmophere – which has been modified by the mountain – execute this exchange?

- traditionally: this is the role of the *boundary layer*
  $\longrightarrow$ exchange of heat, mass and momentum *at the surface*
  $\longrightarrow$ transport to the ground / away from the ground

- (first) challenge: Mountain Boundary Layer
  $\longrightarrow$ where (what) is it?
  $\longrightarrow$ how does it interact with meso-scale flows?

Recent developments (since MAP - 1999)

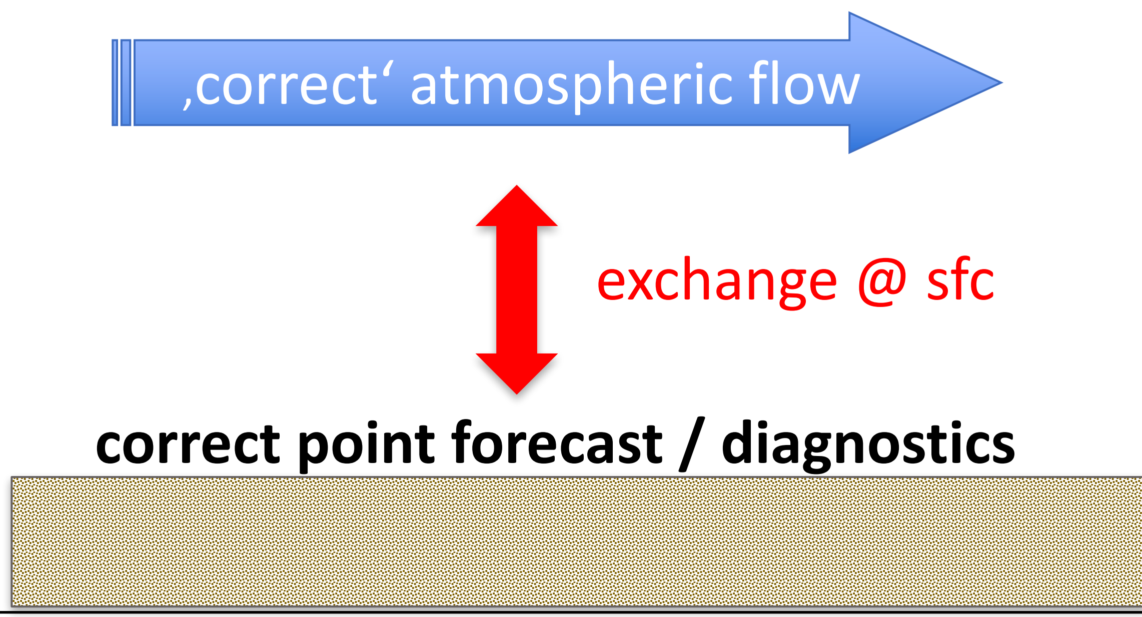
- better atmospheric model resolution
  → weather: $\mathcal{O}$(1 km) grid spacing
  → climate: $\mathcal{O}$(10 km) grid spacing (regional climate)

- huge jump in observational systems
  → lidar, commercially available (beginning: also Raman for H_2O)
  → satellites
  → turbulence information
  → PTr-TOFS

- climate change
  → requires impact modeling
  → need: the right temperature at mtn. surface (not only the mtn. sfc temperature that yields the 'best precipitation')
  → climate diagnostics

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



A Change in the Perspective

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

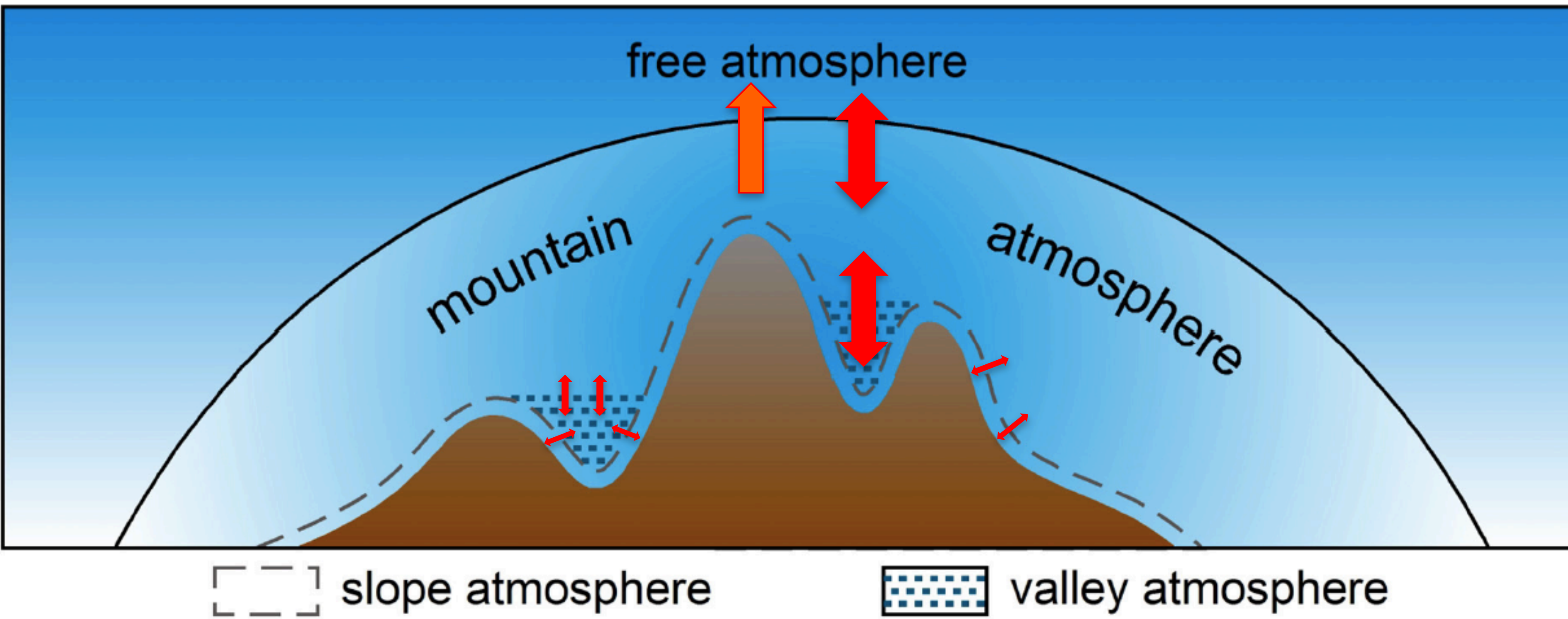
→ if related to traditional (prognostic) variables:
downscaling (diagnosing)

→ 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)

Correct point forecast

- mountain ⟷ atmosphere perspective
  → how does the atmosphere – 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

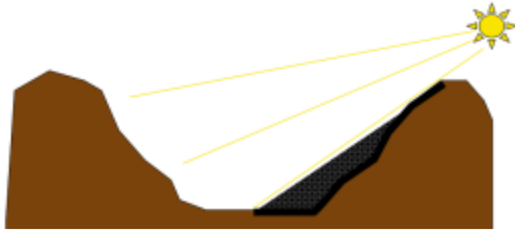
- heat, momentum
- mass (water vapor, others, [CO_2], …)

... determined through

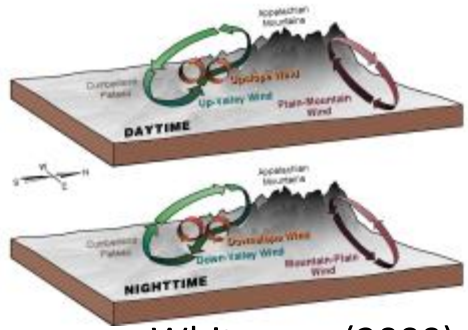
- availability
- efficiency of exchange

Exchange over Orography

- Boundary layer is *inhomogeneous* by construction

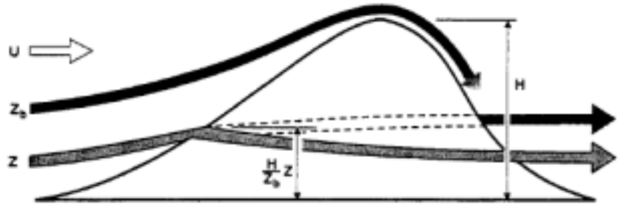


- thermally induced circulations
  → slope / valley flows
  → mountain venting



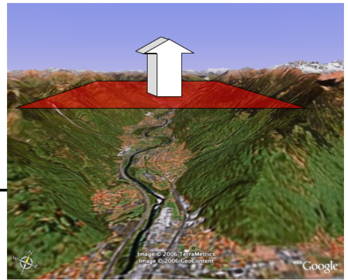
Whiteman (2000)

- dynamic modification (gravity wave drag, etc.)



Lott and Miller (1996)

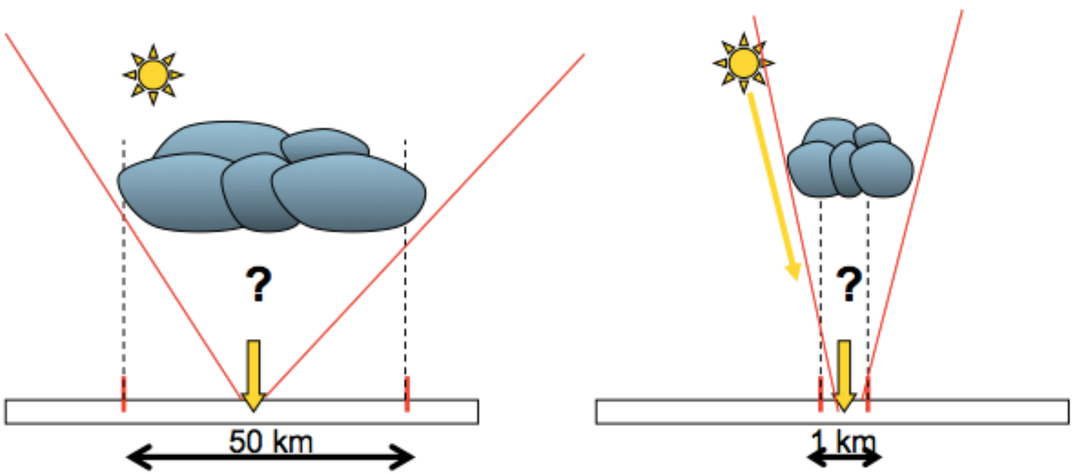
- geometrical effects (e.g., narrowing / widening) for mass



Exchange over Orography

- 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*?

Subgrid parameterization

→ to take into account unresolved sub-grid scale exchange processes

→ necessary today?

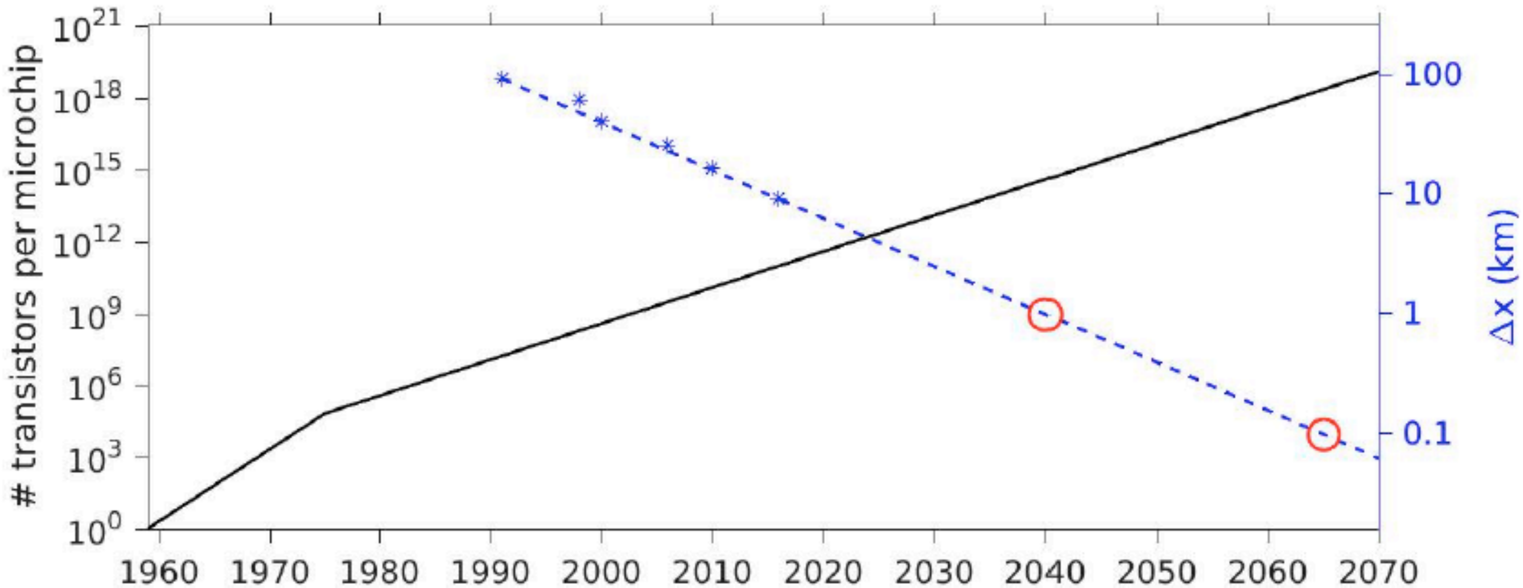


Figure 6. Number of transistors per microchip predicted by Moore's Law [139] (solid line, left scale) and horizontal grid spacing of the ECMWF IFS (asterisks, right scale). The dashed blue line is a fit that assumes dividing the grid spacing by two every 7.5 years and the red circles indicate the years when a grid spacing of 1 km and 100 m will be reached based on this fit.

Lehner and Rotach 2018

Subgrid parameterization

→ to take into account unresolved sub-grid scale exchange processes

→ necessary today?

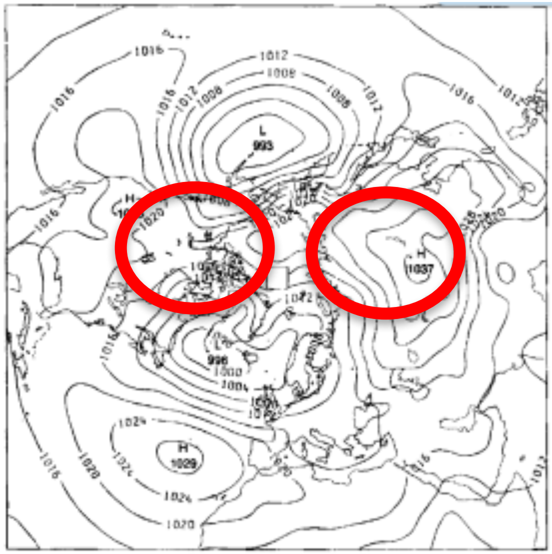
Momentum

→ zonal flow (globally) strongly overestimated in 'early days' of NWP

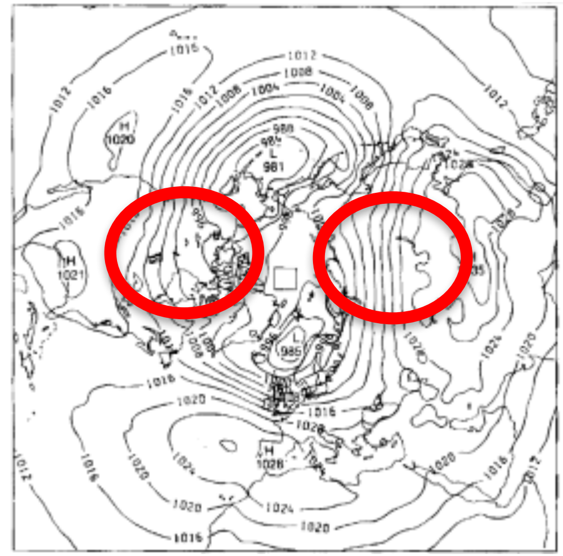
→ exchange due to (sgs) orography (gravity waves) not taken into account

Momentum exchange

observed



modeled



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)

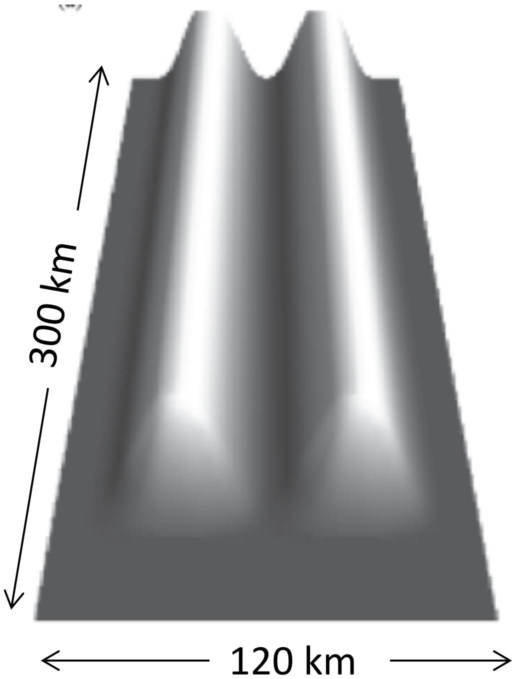
Heat

→ Noppel and Fiedler (2002)

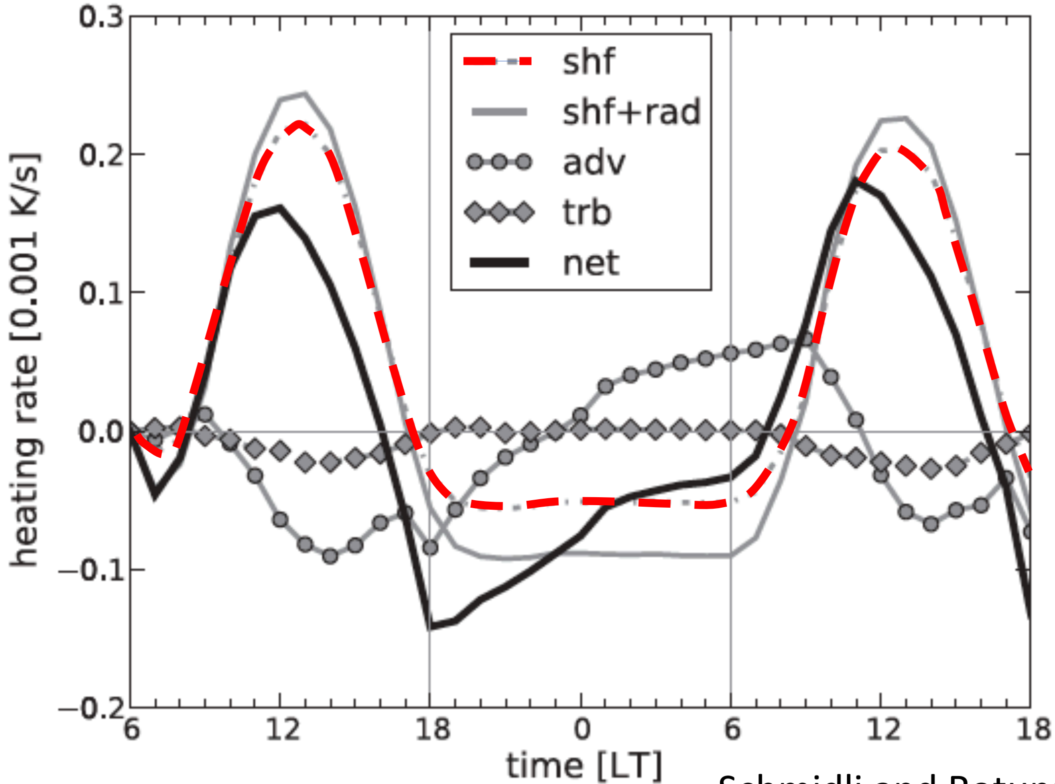
→ …..

→ Schmidli and Rotunno (2010, 2012)

Heat exchange



Δx =1km, ARPS



Schmidli and Rotunno 2010

→ perfectly ideal

→ influence of surrounding orography

→ influence of geometry / initial stratification / ....

Subgrid parameterization

✓ **Momentum**

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

(✓) **Heat**

→ Noppel and Fiedler (2002)

→ .....

→ Schmidli and Rotunno (2012)

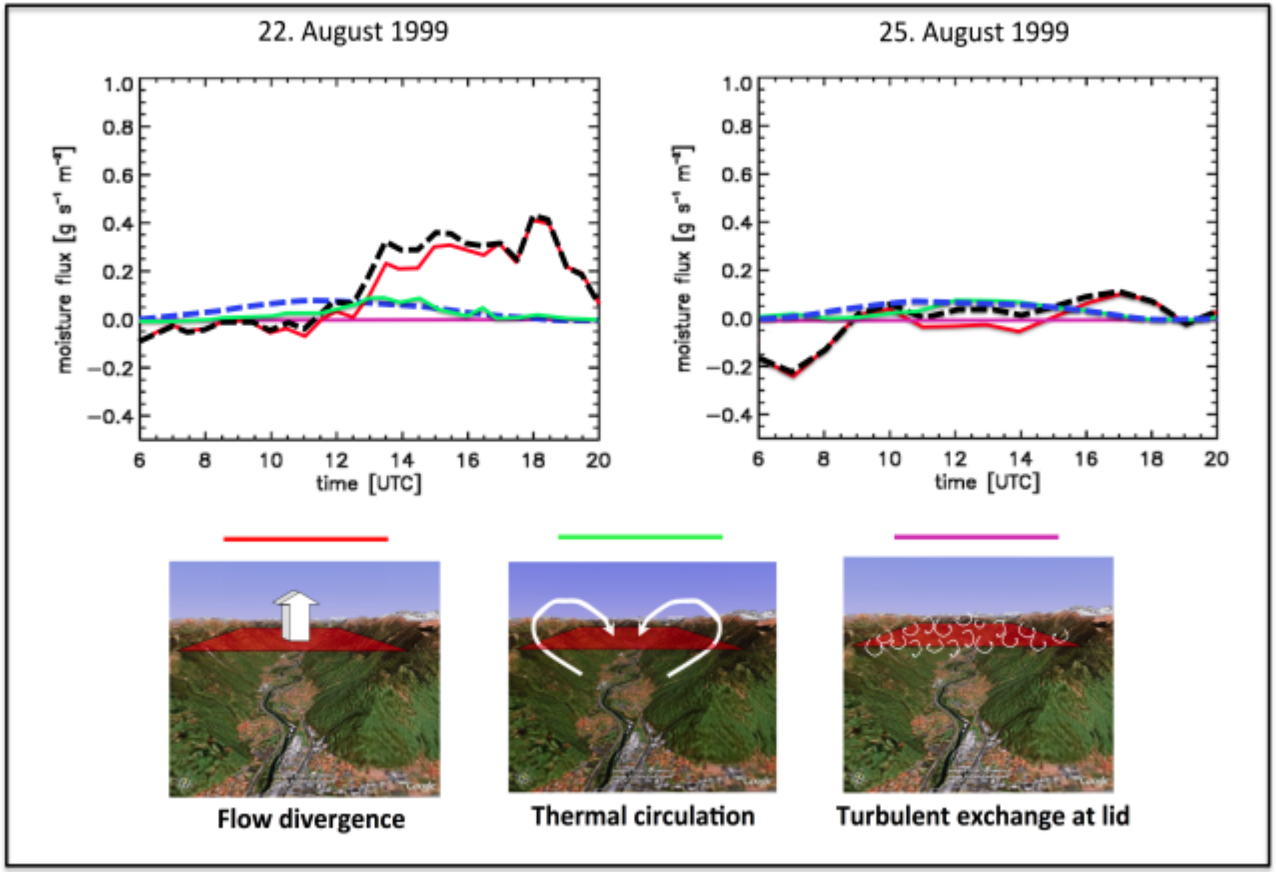
} > idealized modeling
> systematic
> no parameterization yet

Mass

→ Weigel et al. (2007)

Moisture exchange

- MAP Riviera example
- two (example) days with weak synoptic forcing
- ARPS (excellent correspondence to measurements, not shown)



'LES' (350m):

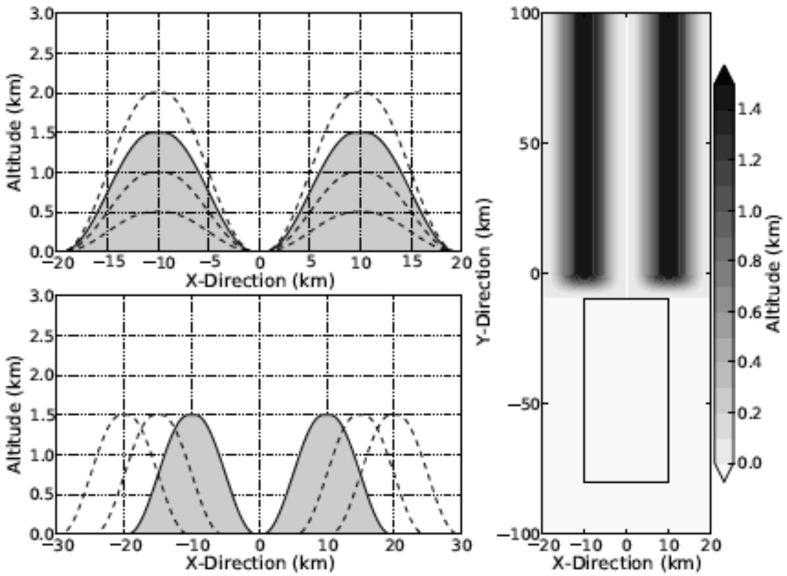
(= + +)

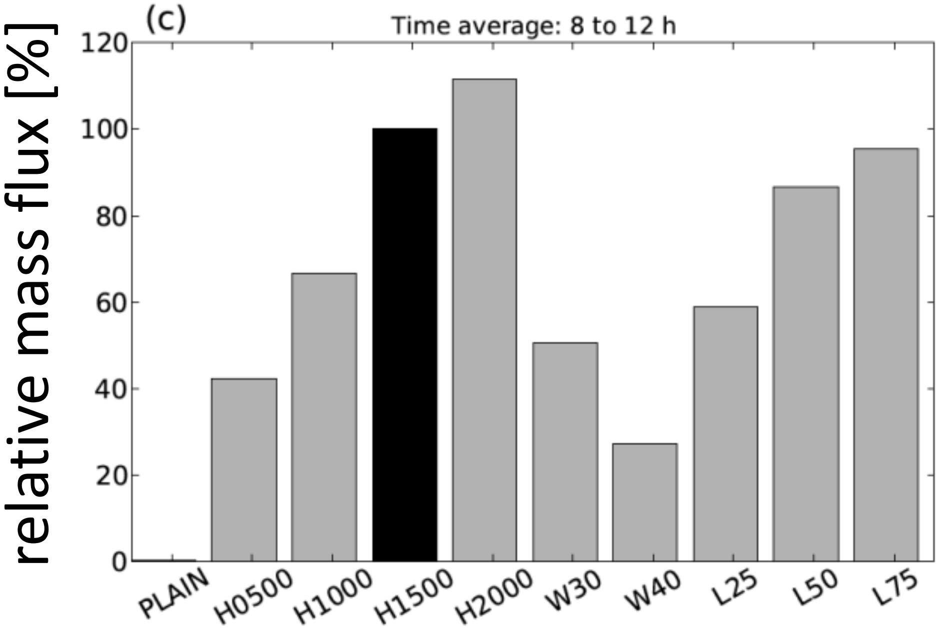
Coarse model:

Weigel et al (2007)

Mass exchange

- Idealized numerical modeling, passive tracer
- 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 (not shown)

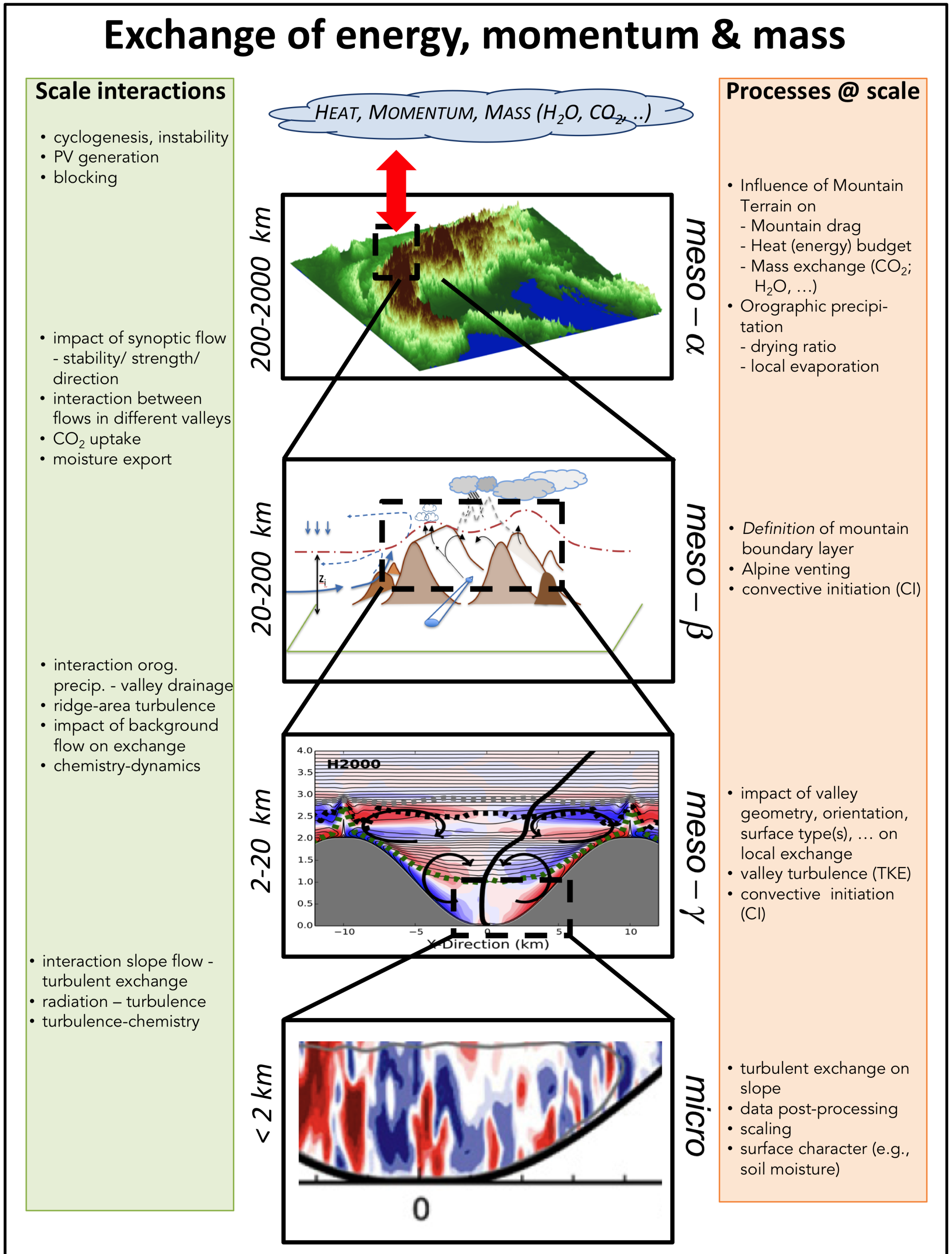
A new international programme

TEAMx

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

ALPEX → MAP → TEAMx

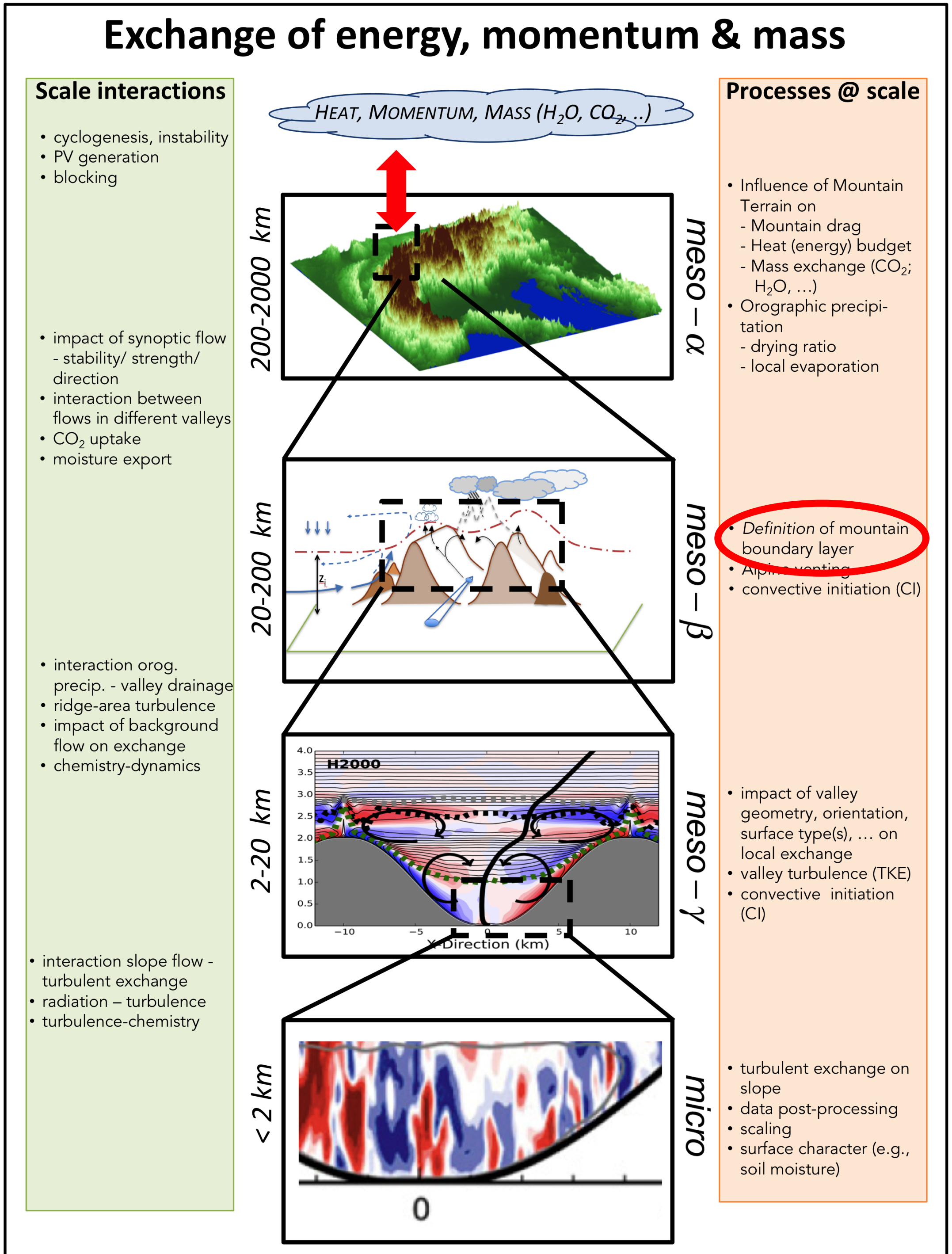
- discussion started: after ICAM-2015
- meetings aside conferences
- **C**oordination and **I**mplementation **G**roup established (9/2017)
- White Paper in preparation



topics:

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

→ ***and their interactions***



methods:

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

goal:

→ coordinated *experiment (2022-23)*

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:

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

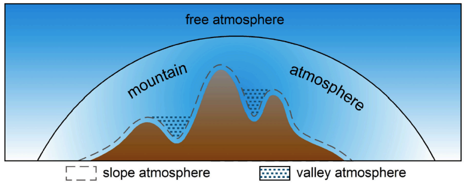
$\longrightarrow$ based on *turbulence state* of ABL (e.g., Ri / TKE criterion)

$\longrightarrow$ based on other influences (such as aerosol / water vapor mixing / concentrations)

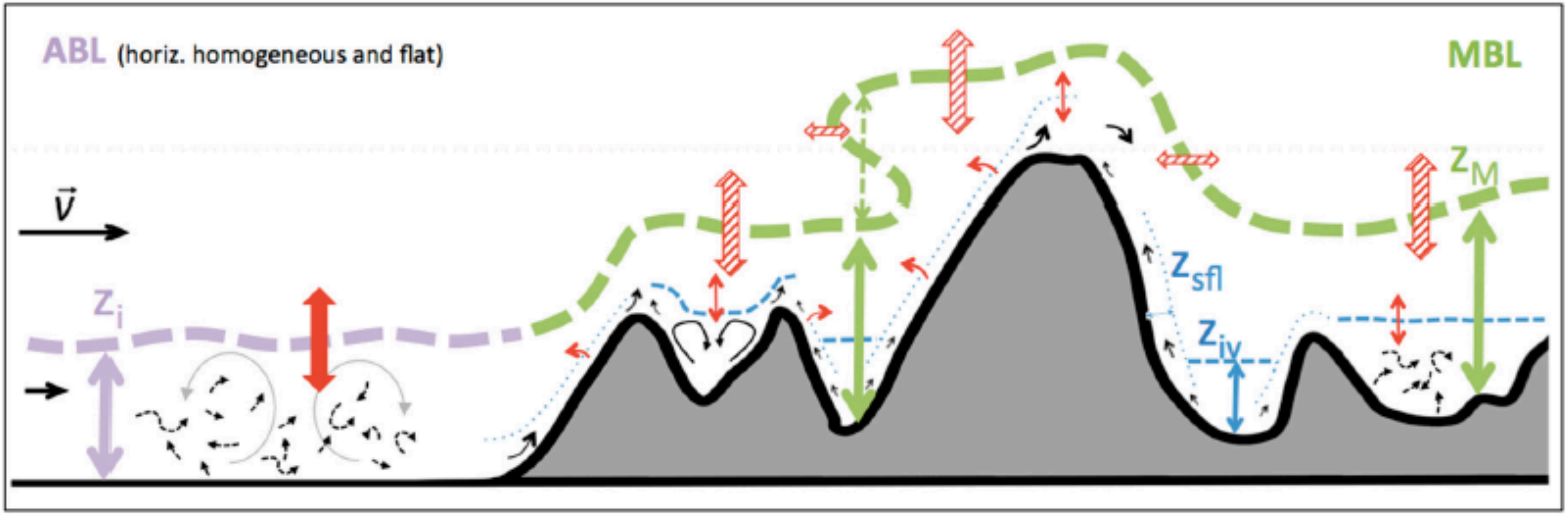
$\longrightarrow$ dependent on application (even in HHF terrain)

Mountain Boundary Layer (MBL)

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



unstable stratification (daytime)



Lehner and Rotach (2018)

Mountain Boundary Layer (MBL)

Suggested definition **Mountain Boundary Layer**

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

Lehner and Rotach (2018)

explicit research questions:

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

→ 'general' structure feasible?

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 - goals and targets

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

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TEAMx

partners (so far…)**:**

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

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

TEAMx – organization

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

TEAMx

Forms of getting involved

PI's / institutions

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

Summary

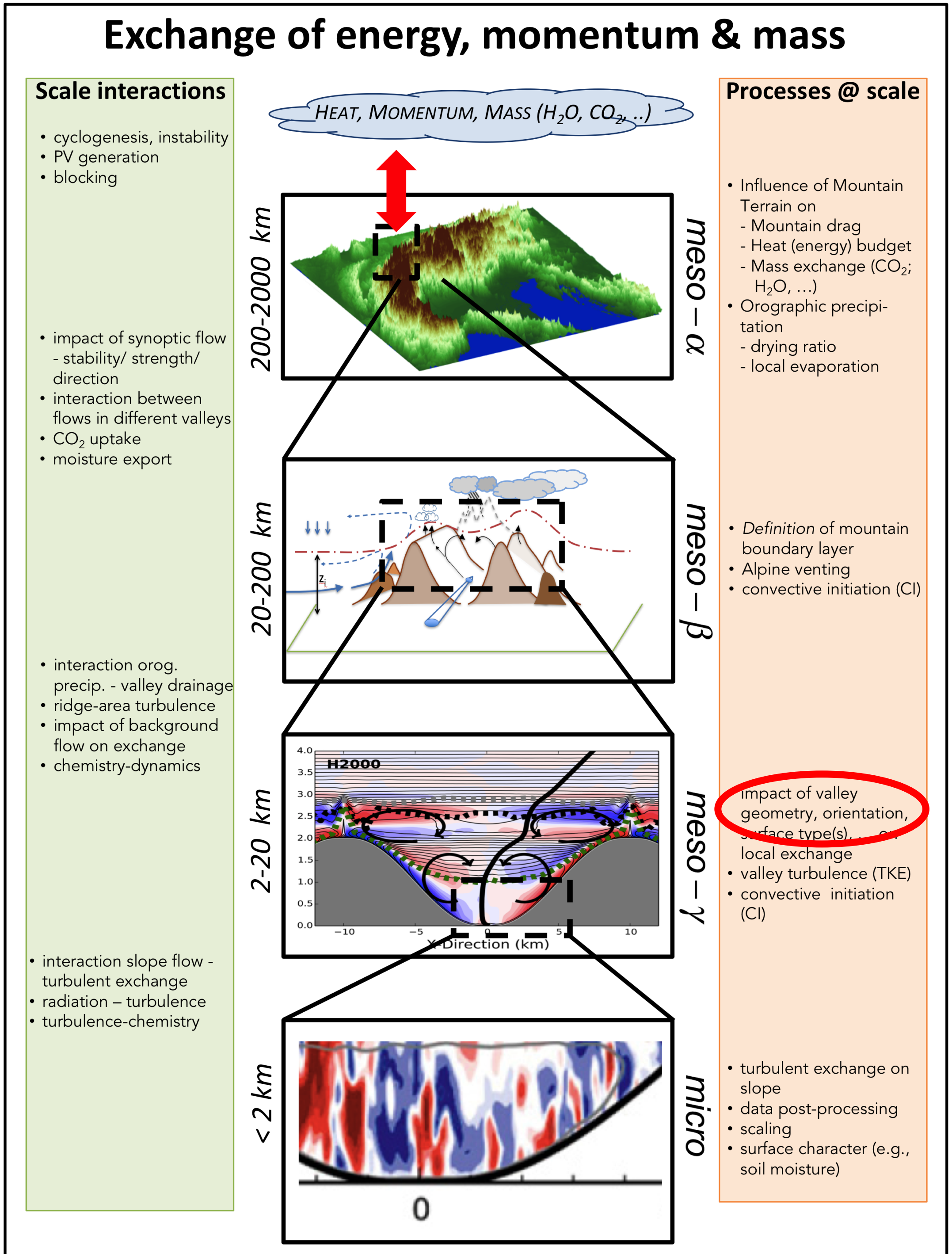
- exchange of energy, mass and momentum
  → relevant in atmosphere / climate system
  → impact of mountainous terrain
  → [must be] right for the right reason (climate & NWP *services*):
  correct point forecasts (weather) & point dignostics (climate)

- **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...

universität innsbruck

Thank you for your attention!

Mathias W. Rotach
Department of Atmospheric and Cryospheric Sciences



methods:

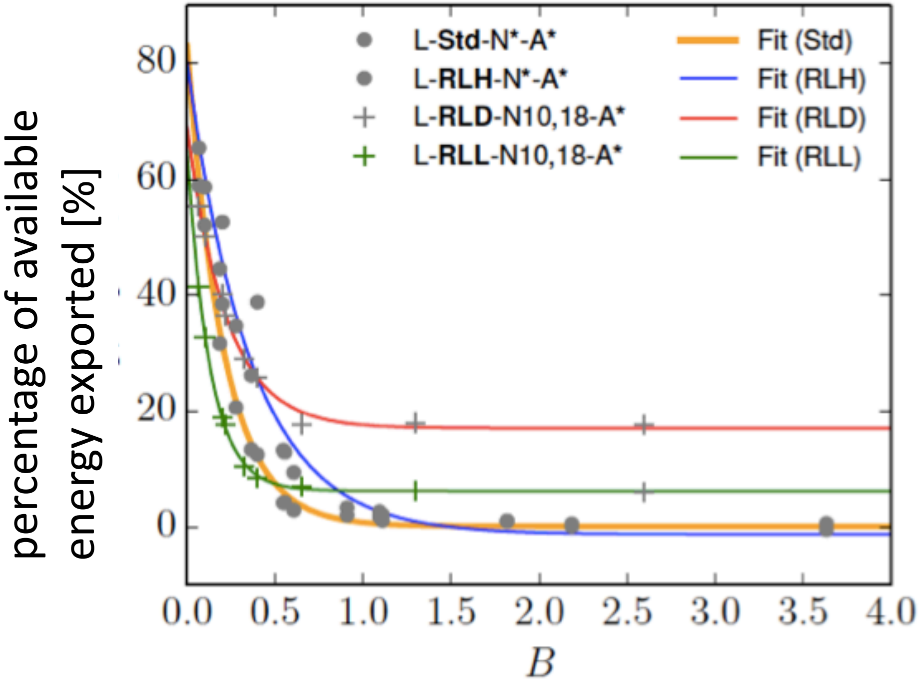
- numerical modeling
  - → NWP (km scale)
  - → regional climate
  - → processes and parameterizations
- observations
  - → turbulent exchange
  - → Lidar, scintillometer
  - → obs strategies

goal:

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

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

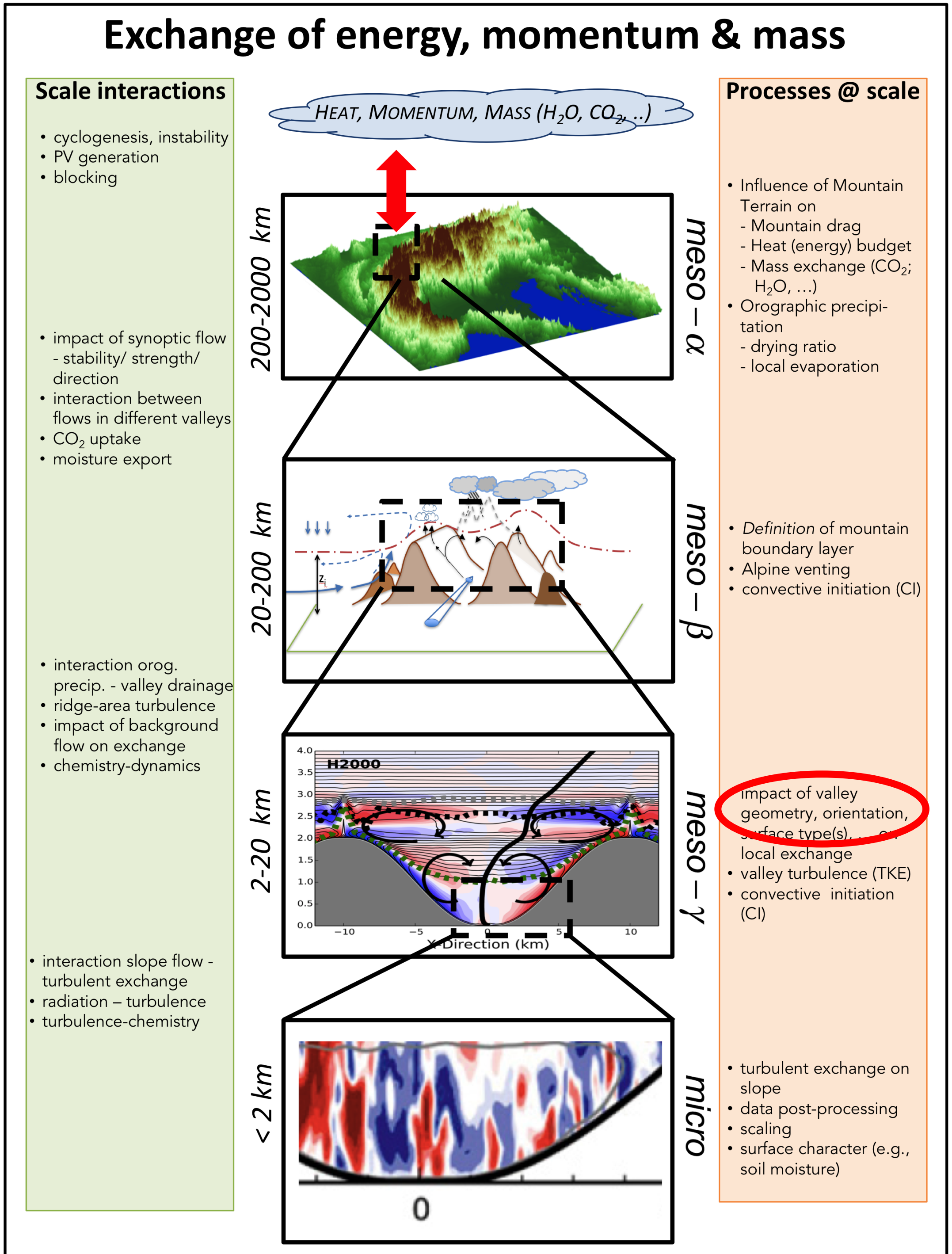
→ different initital stratification

→ 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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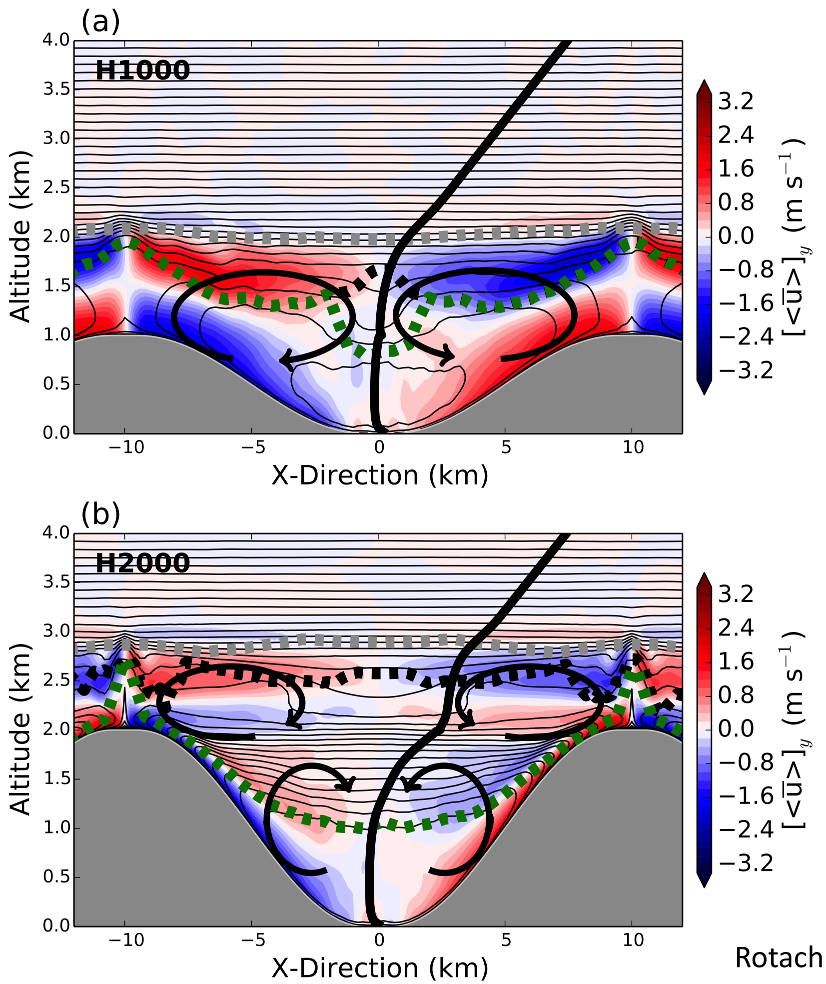
Flow structure in idealized valley

Dissertation Johannes Wagner



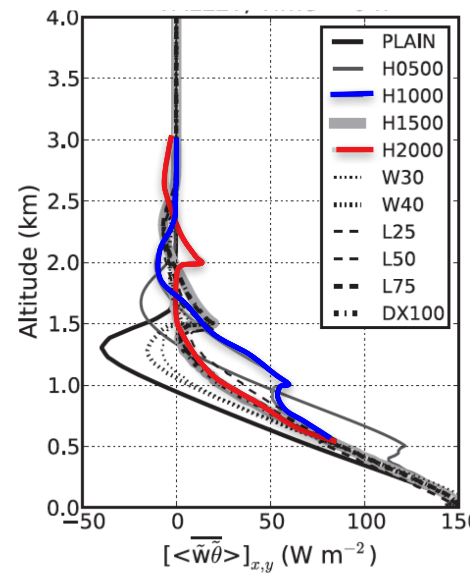
idealized WRF simulations:

→ dx = 200 m

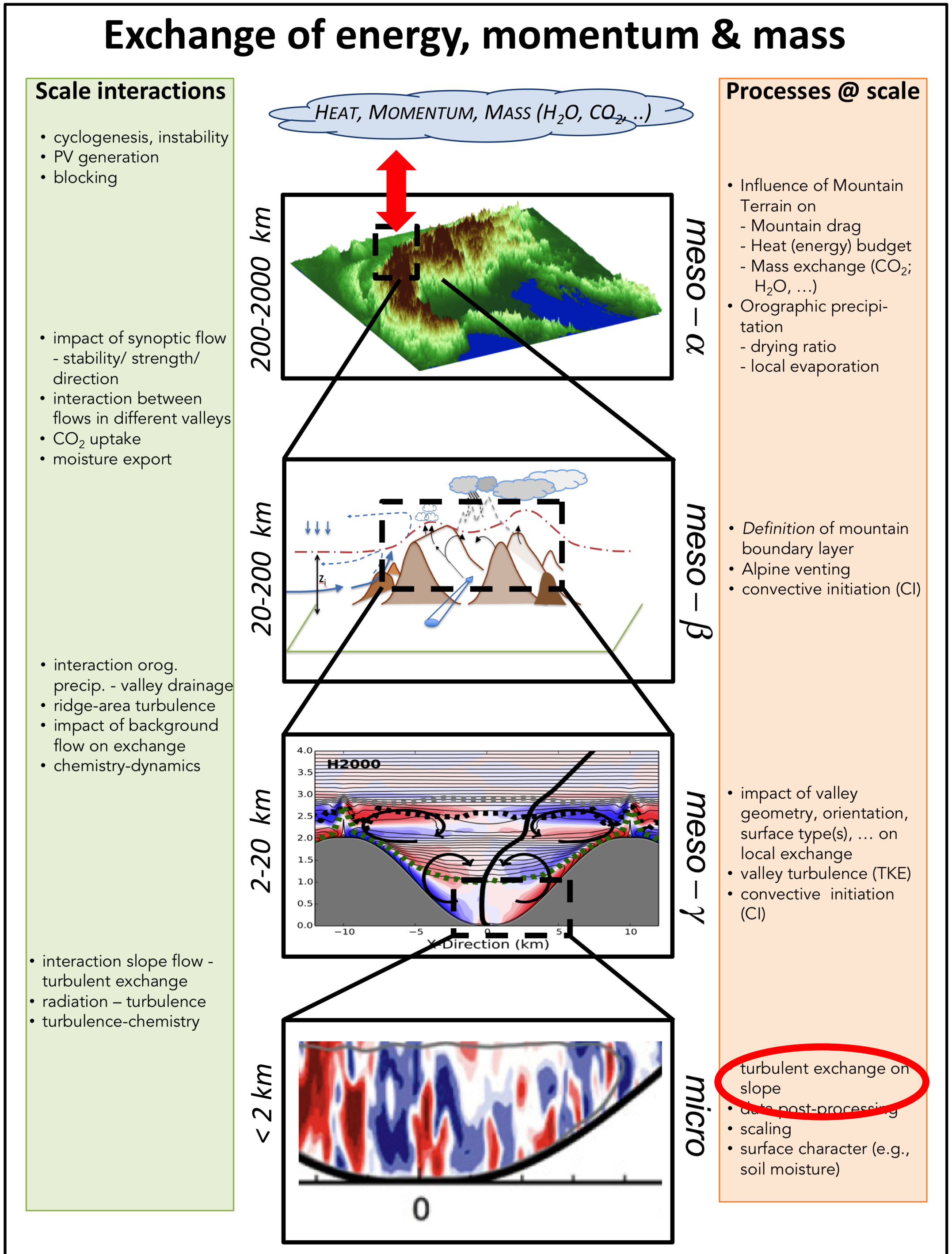
→ different valley geometry

→ slope circulation - exchange

total vertical heat flux
(average valley cross-sect)



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



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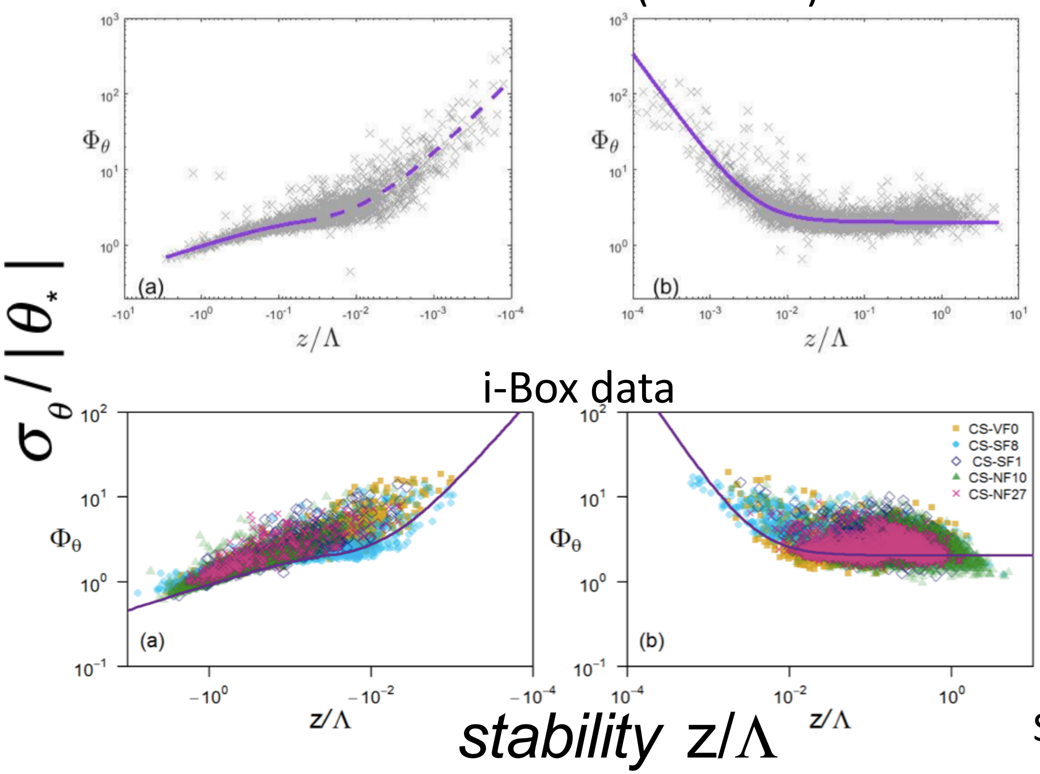
Turbulent exchange on slopes

Dissertation Eleni Sfyri

ideal reference (Cabauw)



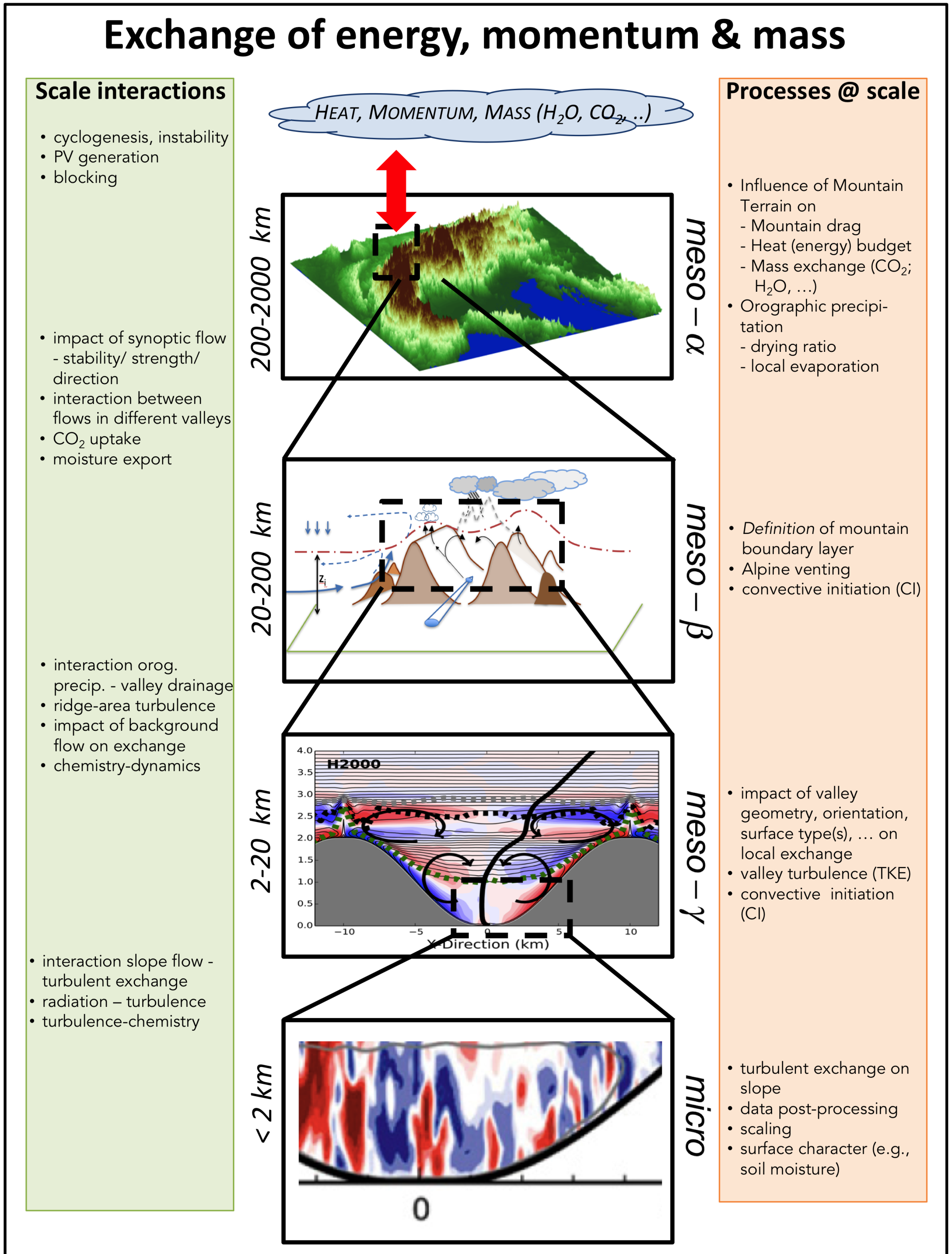
Sfyri et al. (2018)

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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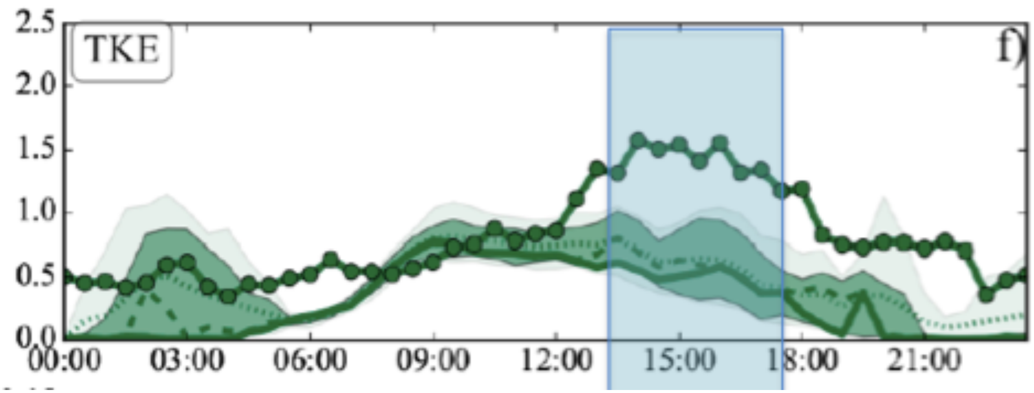
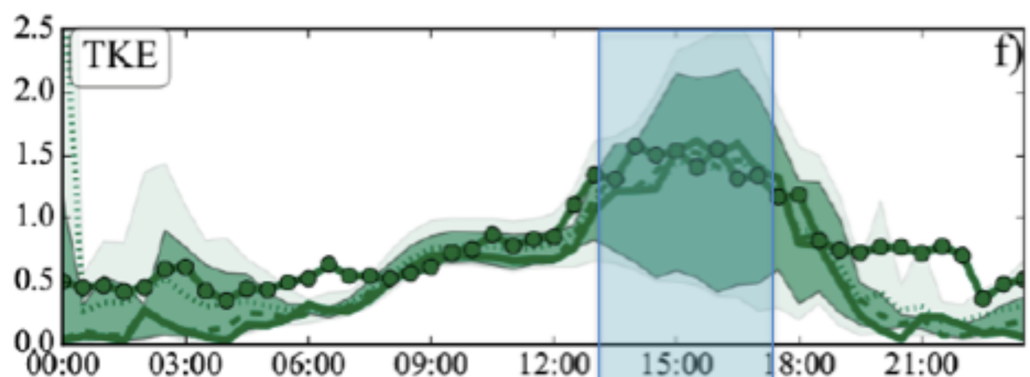
Numerical models

Dissertation Brigitta Goger

1-dimensional TKE closure



horizontal shear added



local time

TKE closure of COSMO model:

→ 1d enough?

→ add horizontal shear production

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

Goger et al. (2018)

Exchange of energy, momentum & mass

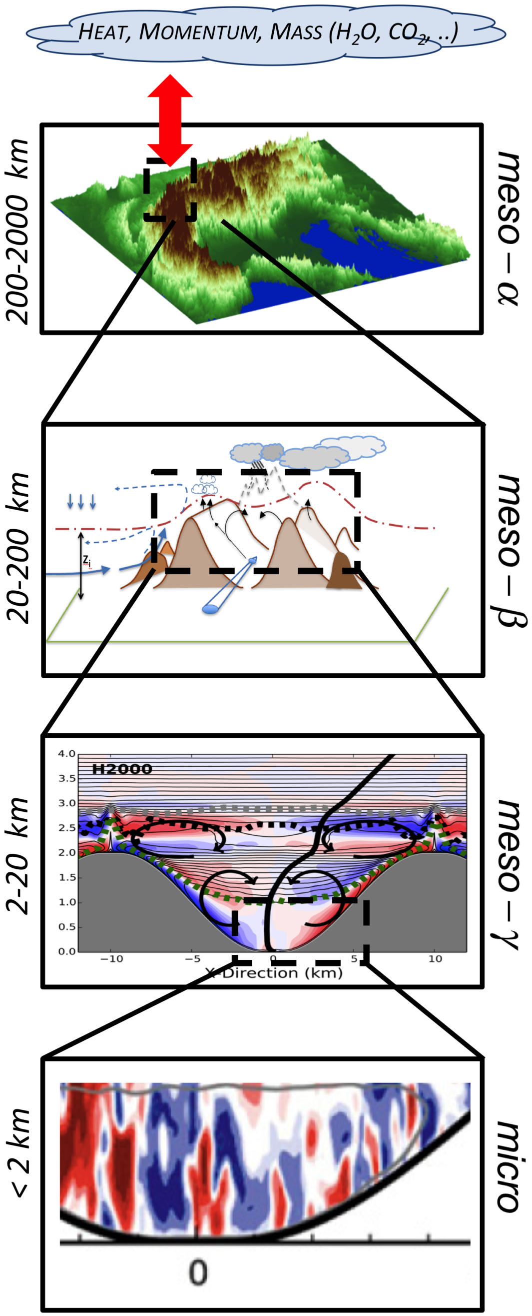
Scale interactions

- 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 precipi-tation
  - 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)

→ interactions relevant

→ much to be done