ETH zürich

Center for Climate Systems Modeling (C2SM)

Modelling turbulence and boundary-layer processes in valleys and over mountains

Brigitta Goger

The Atmospheric Boundary Layer (ABL)...

... is that part of the troposphere that is **directly influenced** by the presence of the **Earth's surface**, and directly responds to surface forcings with a **timescale of about an hour or less**. (Stull, 1988)

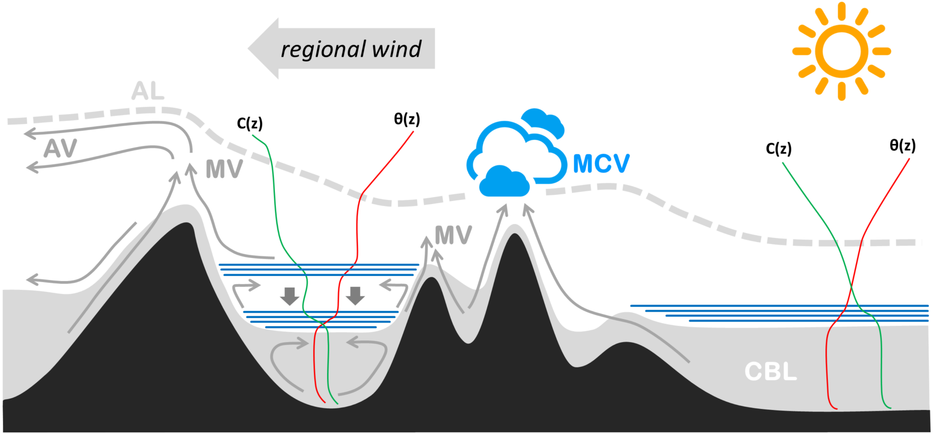
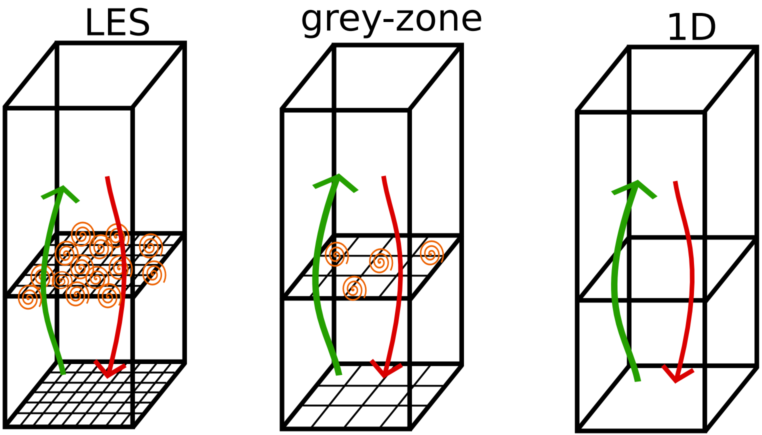


Image from Serafin et al. (2018)

Representation of Atmospheric Turbulence in Numerical Weather Prediction



adapted from Honnert et al. (2011)

Two Study Regions in the Austrian Alps

1) The Inn Valley
Peak-to-peak valley width ≈ 10 km

COSMO: NWP @ $\Delta x = 1.1$ km
Parameterized turbulence

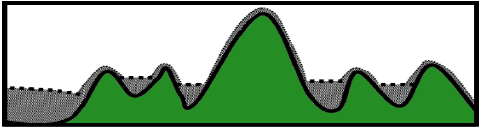
2) The Hintereisferner Glacier
Peak-to-peak valley width ≈ 3 km

WRF: LES @ $\Delta x = 48$ m
(Partly) resolved turbulence

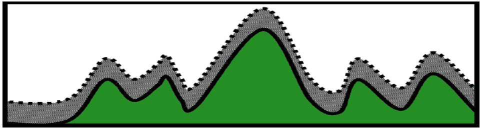
Mountain Boundary Layers (MoBL) in NWP Models

Problem: Common ABL theories and turbulence parameterizations were developed for horizontally homogeneous and flat terrain.

MoBL in reality



Representation in NWP model ($\Delta x = 1\,\text{km}$)



Rotach and Zardi (2007)

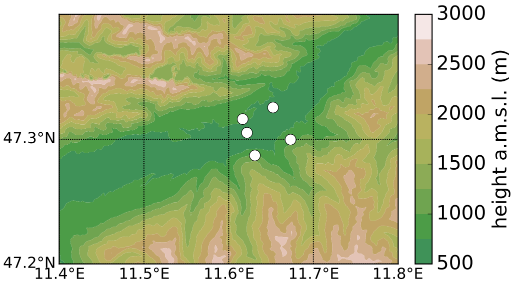
Turbulence Parameterizations:

- 1D turbulence parameterizations consider vertical exchange only
- Missing 3D contributions (e.g. horizontal shear production)
- Turbulence kinetic energy (TKE) underestimation $\rightarrow$ incorrect MoBL representation

Process-based Model Evaluation (Focus on Turbulence)

Does the model produce the **right fields** for the **right reasons**?

i-Box Observations (since 2013)



- Turbulence Flux Towers
- **TKE** + budget terms

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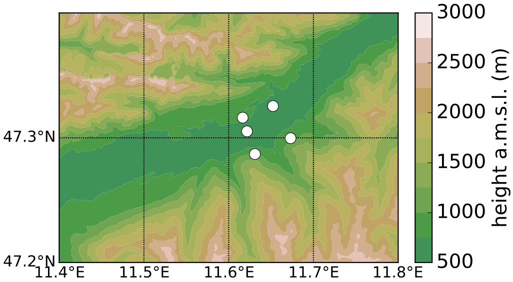
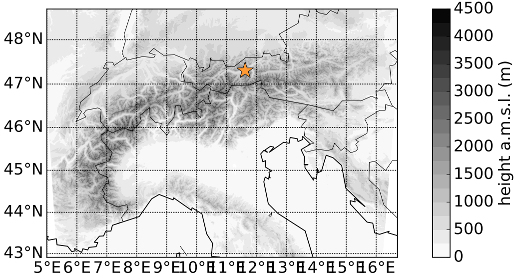


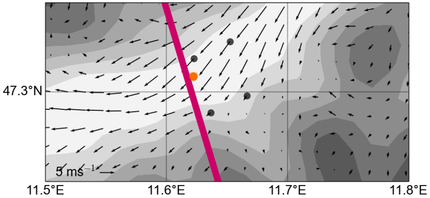
- Turbulence Flux Towers
- **TKE** + budget terms
- Case studies: "Valley wind days"

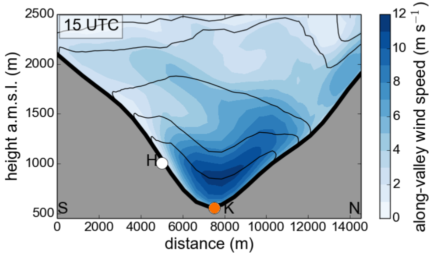
NWP Model COSMO

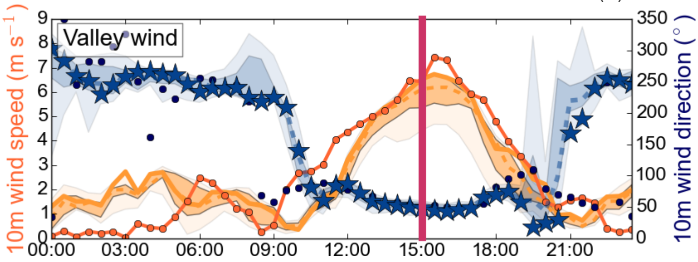


- $\Delta x = 1.1$ km
- 1D Mellor-Yamada type turbulence parameterization (**TKE-based**)

Mountain ABL Case Study: Daytime up-valley wind (Jul 1, 2015)







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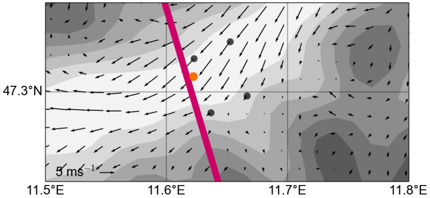
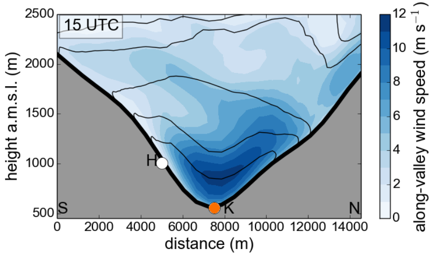
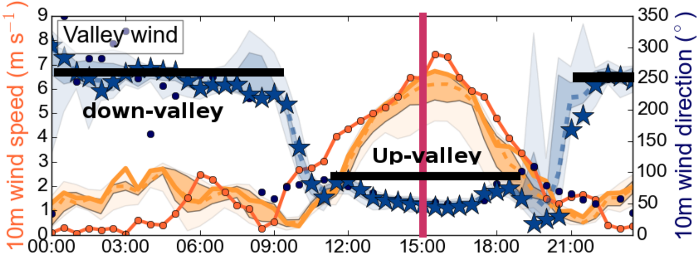






Prognostic TKE Equation in COSMO

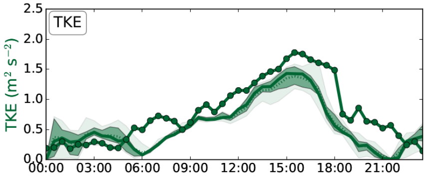
TKE is a measure for turbulence intensity and the current state of the boundary layer

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

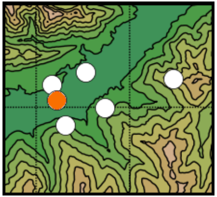
$$+ \underbrace{\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\left[\alpha_{\text{tke}}\overline{\rho}\lambda_l q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right]}_{\text{vertical turbulent transport}} - \underbrace{\frac{q^3}{B_1\lambda_l}}_{\text{dissipation}} \qquad (1)$$

- 1.5-order turbulence closure (Mellor-Yamada)
- Prognostic equation for help variable $q^2 = 2\overline{e}$

TKE - 1D Turbulence Scheme

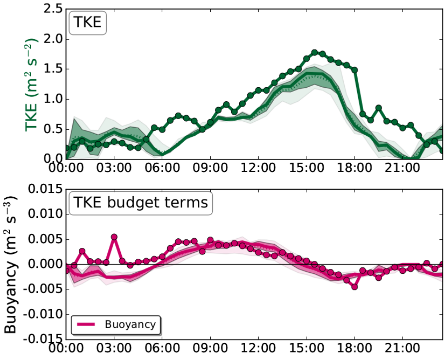


Valley floor



Connected points:
Observations
Straight line:
Model Output
(closest grid point)
'clouds': next closest grid points

TKE - 1D Turbulence Scheme



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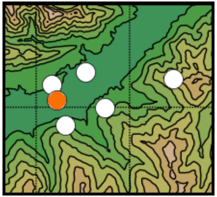

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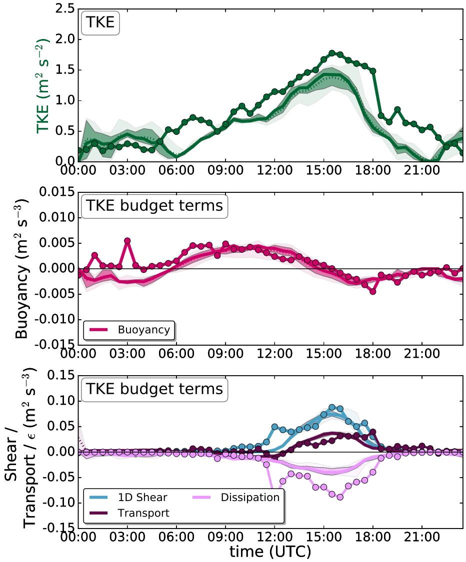

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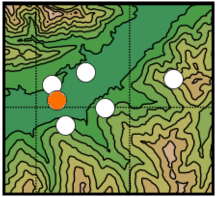

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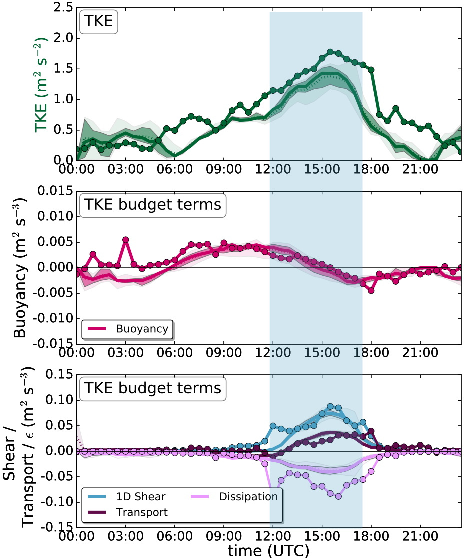
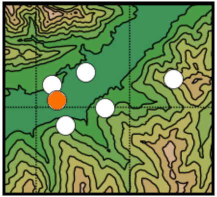


Valley floor



Afternoon:

- Only vertical shear production together with valley wind
- TKE underestimated
- ***Something is missing!***

Let's add horizontal shear production...

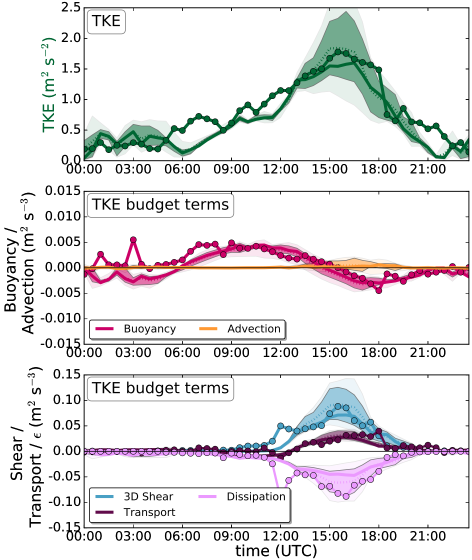
...to the 1D TKE equation:

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)_{HSP} = (c\Delta x)^2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right]^{\frac{3}{2}} \tag{2}$$

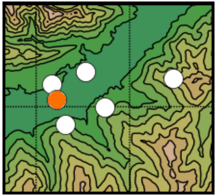
$c = 0.25$... Smagorinsky constant
Δx.... horizontal grid spacing

Hybrid turbulence parameterization: 1D vertical exchange + horizontal shear production

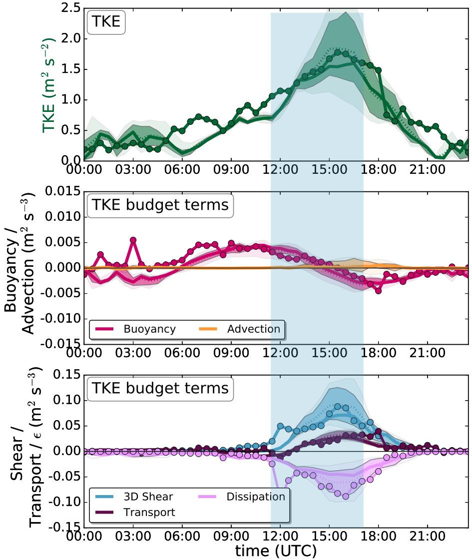
TKE - Hybrid turbulence parameterization



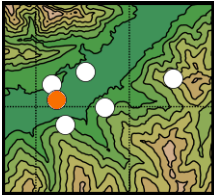
Valley floor



TKE - Hybrid turbulence parameterization



Valley floor



Afternoon:

- 3D shear production
- Correct TKE simulation!

Were we just lucky? Yes.

- $c\Delta x$ as a length scale is unphysical for NWP simulations, because it is directly related to the model grid.
- The horizontal length scale $c\Delta x$ fits the width and scale of phenomena in the Inn Valley
- The afternoon shear maximum is strongly connected to the up-valley wind - a physical phenomenon

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- The afternoon shear maximum is strongly connected to the up-valley wind - a physical phenomenon

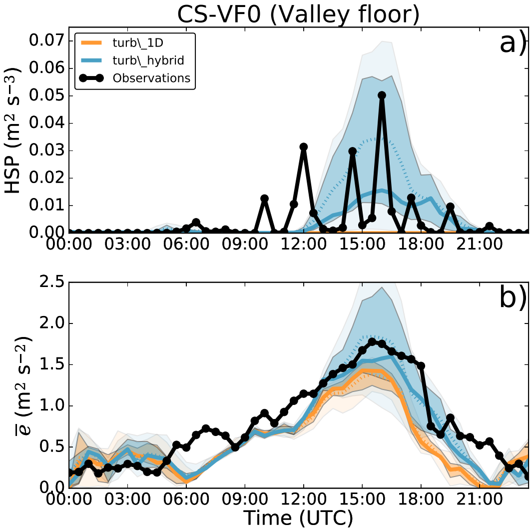
$\rightarrow$ Replace $c\Delta x$ with a new horizontal length scale with a physical background:

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)_{HSP} = U^2 T_{\mathrm{L,u}} T_{\mathrm{L,v}} \left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right]^{\frac{3}{2}} \quad (3)$$

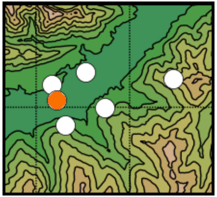
- T_L...Lagrangian Integral Timescale (parameterized); U...horizontal wind speed

Now we want to utilize the model to learn more about glacier ABL processes.

A closer look at Horizontal Shear Production and TKE

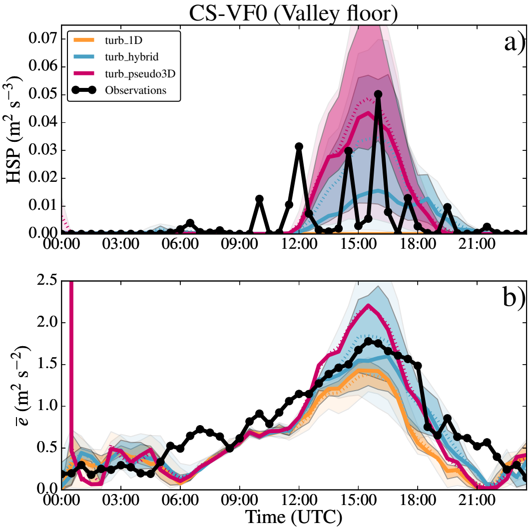


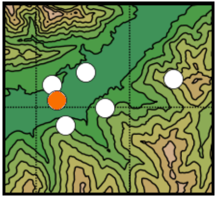
Valley floor



- 1D Turbulence:
  TKE underestimation
- Hybrid Turbulence:
  “lucky choice”

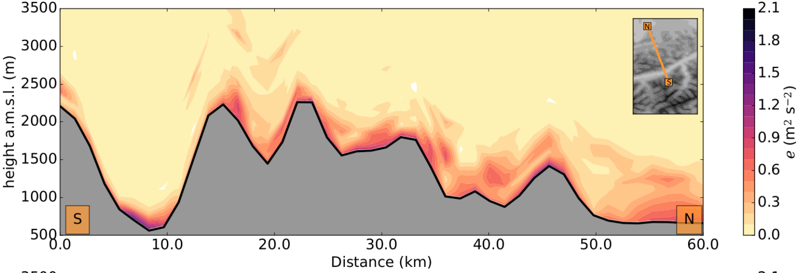
A closer look at Horizontal Shear Production and TKE



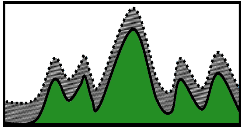


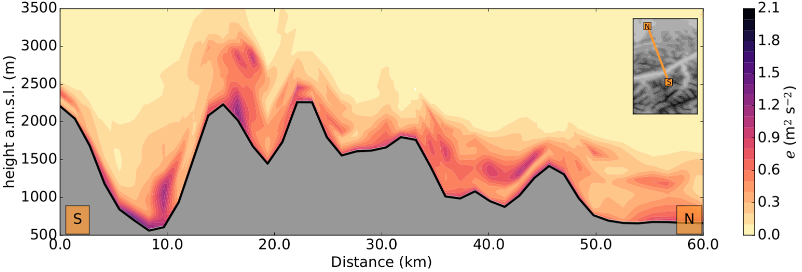
New length scale:
Realistic simulation
of 3D shear and TKE

North-South Cross-section of TKE

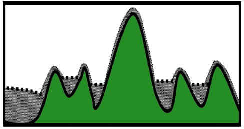


1D shear

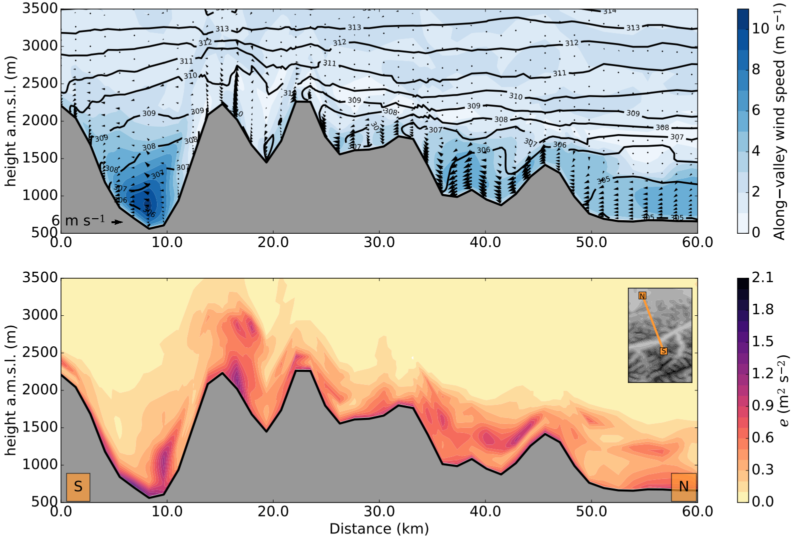




3D shear

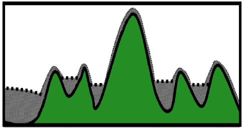


North-South Cross-section of Wind and TKE



TKE maximum related to horizontal wind speed gradient of the valley wind!

3D shear



Key Findings - Turbulence Representation in NWP Models

- Evaluate the model with a well-known case study, where boundary-layer processes dominate
- 3D shear is essential for the correct simulation of TKE in complex terrain (Goger et al., 2018)
- Maxima in TKE and horizontal shear production are related to the up-valley wind
- A real physical background of the horizontal length scale is necessary for a realistic mountain boundary layer representation (Goger et al., 2019)

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Parameterized turbulence

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Peak-to-peak valley width ≈ 3 km

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(Partly) resolved turbulence

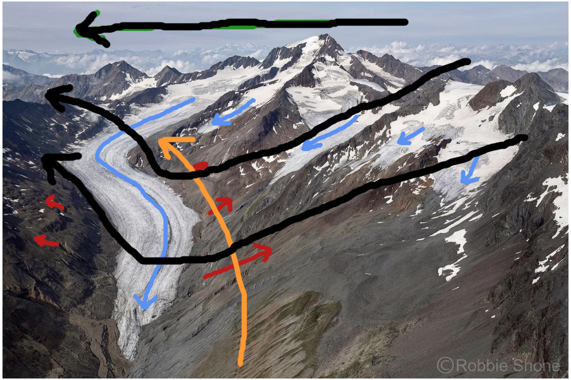
Motivation and Research Questions

Do small-scale ABL processes such as quick changes in sensible heat flux have a major impact on glacier surface mass balance?

Hintereisferner: One of the World Glacier Monitoring Service's reference glaciers with mass balance observations since 1953.

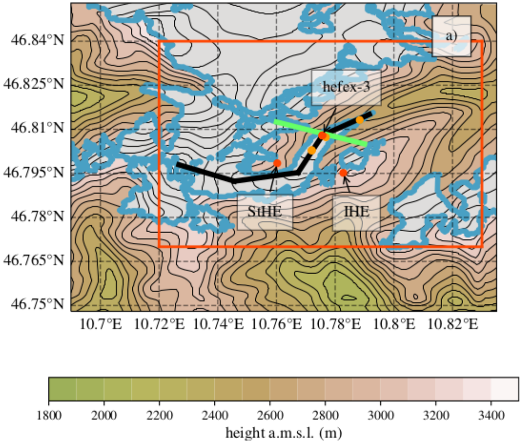
Motivation and Research Questions

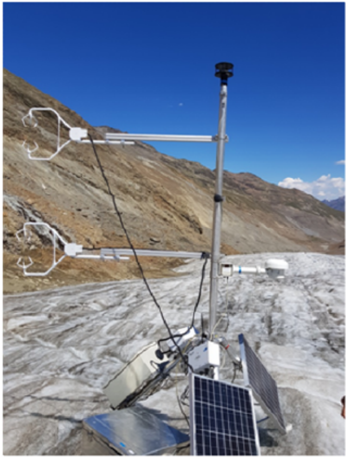
Complex, thermally- as well as dynamically-induced flow structures possible.



Hintereisferner: One of the World Glacier Monitoring Service's reference glaciers with mass balance observations since 1953.

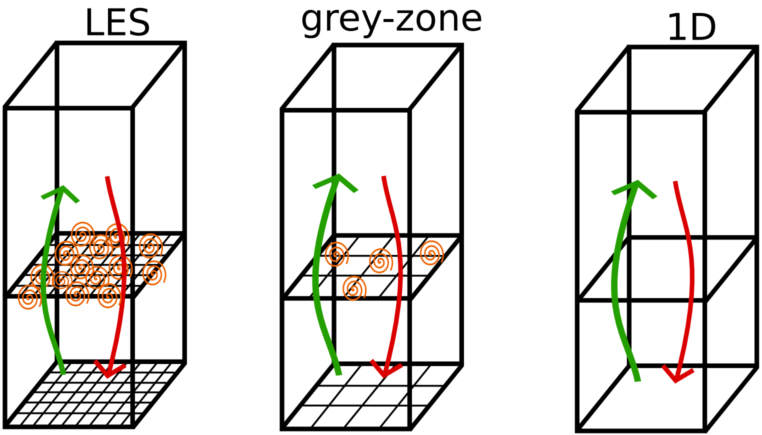
Observations: HEFEX Campaign, August 2018





- HEFEX stations: EC stations on the glacier tongue
- Down-glacier wind is often "disturbed" by NW flow → **Why?**

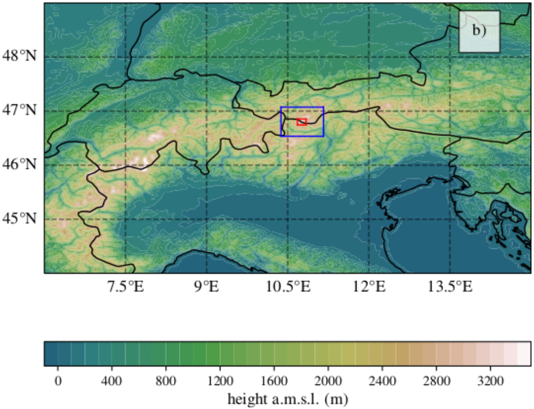
Now we need Large-eddy Simulations!



adapted from Honnert et al (2011)

Modelling: Large-eddy simulations with the WRF Model

Now we want to utilize the model to learn more about glacier ABL processes.



- ERA5 input data, Nested Set-up, 4 domains
- Innermost LES domain @ $\Delta x = 48\,\text{m}$
- No boundary-layer parameterization
- 86 vertical levels, lowest level at $z = 7\,\text{m}$ a. g.
- 2 case studies: Synoptic flow from **South-West** or **North-West**

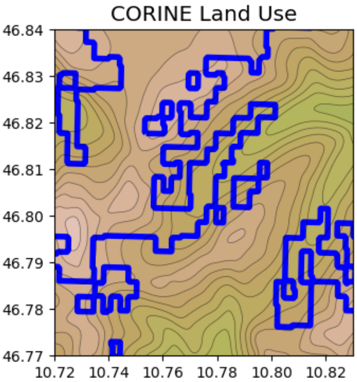
Give the model a chance to perform well!

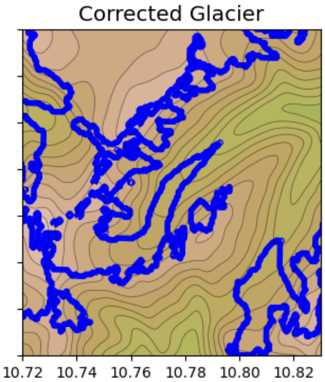
Topography

- Topography
  - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global topography dataset
  - Topography smoothing: Slope angles should not exceed 30° (model stability)
  - $\rightarrow$ Keep this in mind for flow structure
- Topographic shading (radiation)
- Terrain smoothing at domain boundaries (inflow)

Land Use Categories

- High-resolution Static Input Data necessary
  Land use data set: CORINE land use ($\Delta x = 100$ m)
- Correction with glacier shapefiles (Randolph Glacier Inventory)





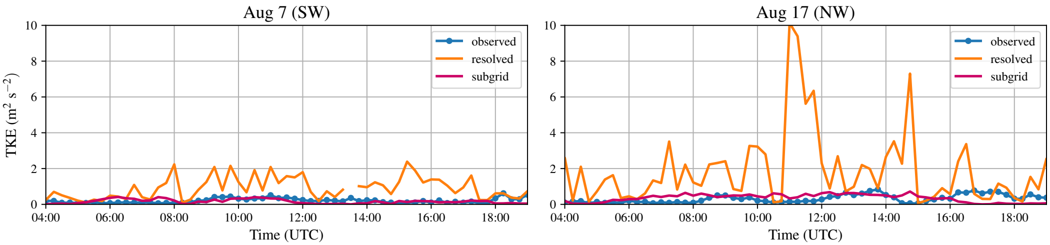
Turbulence Representation

- LES: The largest turbulent eddies are already resolved
- Subgrid-scale turbulence closure after Deardorff
- Online averaging of chosen variables in WRF (15 min averages)
- Calculate the averaged velocity variances:

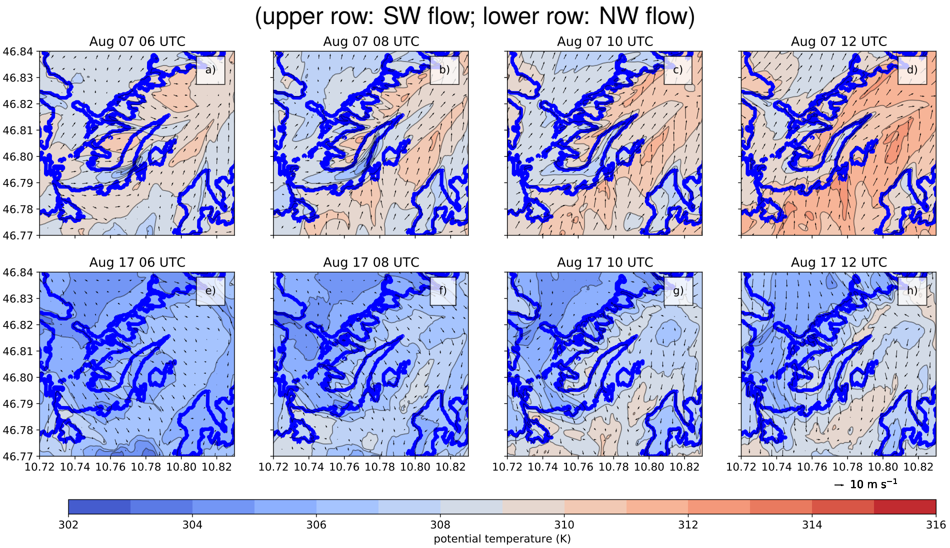
$$\overline{u'^2}_{RES} = \overline{\tilde{u}\tilde{u}} - U^2, \overline{v'^2}_{RES} = \overline{\tilde{v}\tilde{v}} - V^2, \overline{w'^2}_{RES} = \overline{\tilde{w}\tilde{w}} - W^2 \quad (4)$$

and resolved Turbulence Kinetic Energy follows:

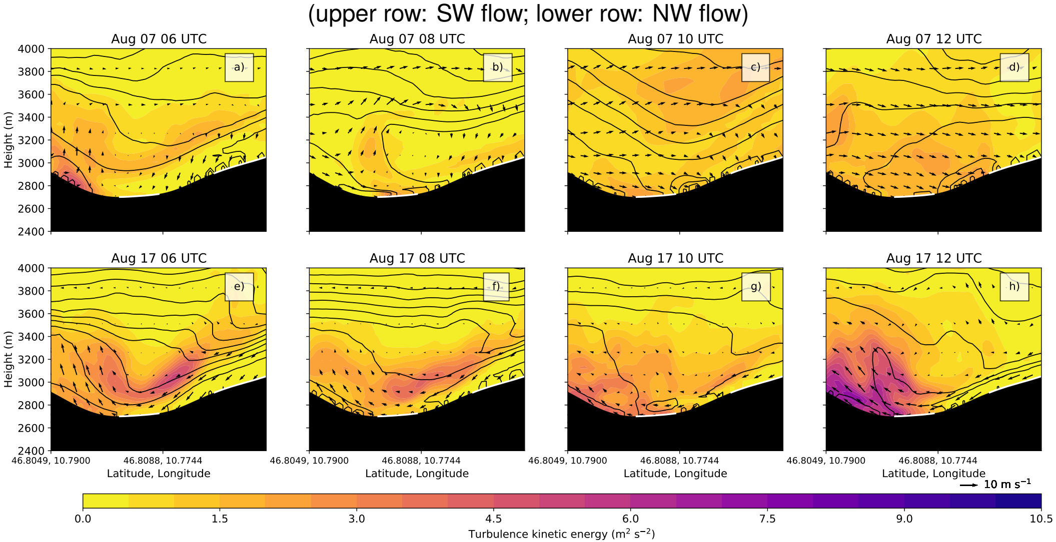
$$TKE_{RES} = \frac{1}{2}(\overline{u'^2}_{RES} + \overline{v'^2}_{RES} + \overline{w'^2}_{RES}) \quad (5)$$



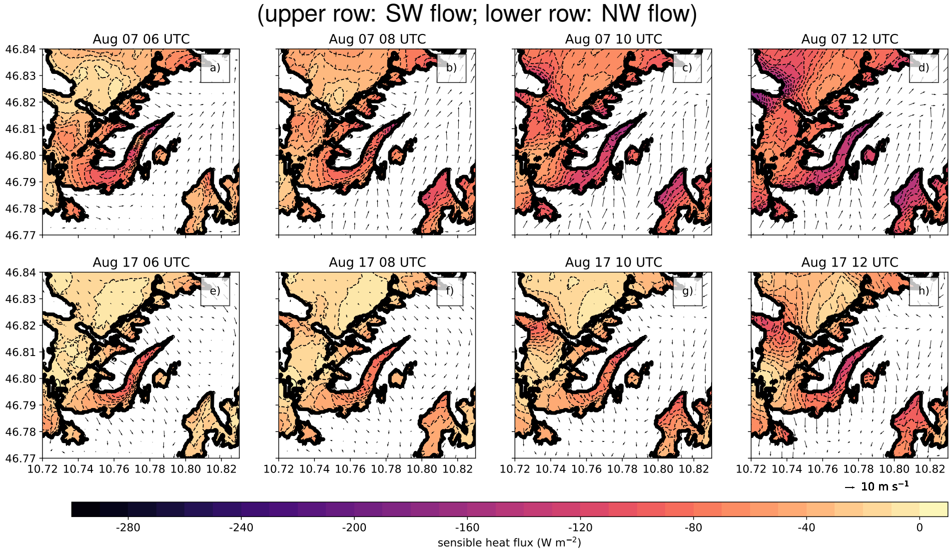
Potential Temperature and Wind Field



Vertical Cross-section across the Glacier

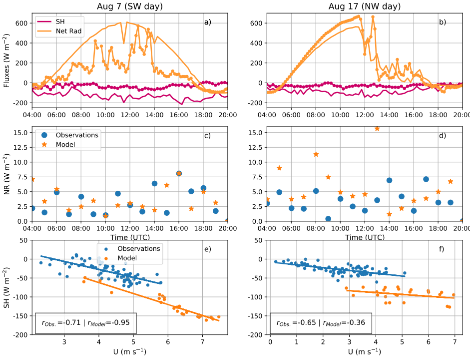


Sensible Heat Flux over the Glacier

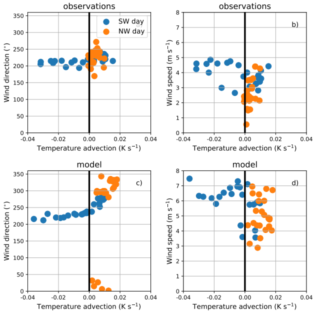


Use the LES to learn more about 3D glacier boundary layer structure

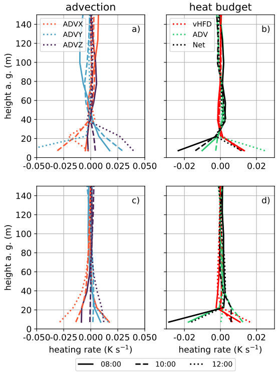
Sensible heat flux stationarity



Horizontal temperature advection (T_{ADV})



Vertical heat budget



- Good agreement for magnitude and “kind” of phenomena
- The model is able to simulate the mesoscale processes affecting the glacier boundary layer

The added value of Large-eddy simulations over Complex Terrain

- Be aware of the scale of the phenomena you would like to simulate $\rightarrow$ Choice of Δx
- Choose high-resolution static input data (topography, land use, etc)
- WRF was able to simulate the general meteorogical situation and mesoscale phenomena over the glacier (Goger et al., 2022)
- Synoptic flow direction either supports or erodes the glacier boundary layer
- Learn more about ABL and mesoscale processes governing the sensible heat flux heterogeneity and stationarity
- However: Horizontal grid spacing is not (yet) fine enough to simulate small-scale down-glacier winds

Overall Conclusions: Modelling Turbulence over Complex Terrain

- Turbulence over mountainous terrain needs "special attention"
- 3D effects (e.g., 3D shear production) should not be disregarded even at the kilometric range
- Turbulence Parameterizations considering 3D effects are able to simulate a more realistic mountain boundary layer

- Array-like arranged eddy-covariance stations are essential for model evaluation → What's going on *inside* the model?
- Process-based analysis of model results → learn more about 3D MoBL structure
- Be aware of the length scale of the processes you want to simulate to give your model a "chance" to perform well

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Model Validation: TKE

TABLE 2. Bias and rmse of TKE of four simulated valley wind days with the three schemes turb_1D, turb_hybrid, and turb_pseudo3D for the time period of the up-valley wind phase (between 1200 and 1800 UTC). "Valley floor" includes the averaged values of sites CS-VF0, CS-SF8, and CS-SF1; "slopes" includes the values of CS-NF10 and CS-NF27. The averaged values over all five stations are summarized in "Overall."

	Bias ($m^2 s^{-2}$)			Rmse ($m^2 s^{-2}$)		
	turb_1D	turb_hybrid	turb_pseudo3D	turb_1D	turb_hybrid	turb_pseudo3D
Valley floor	−0.42	0.09	0.25	0.47	0.38	0.47
Slopes	−0.51	0.27	−0.15	0.53	0.47	0.42
Overall	−0.46	0.10	0.08	0.51	0.37	0.43

Model Validation: Meteorological Variables

TABLE 3. Rmse of three standard meteorological variables (2-m temperature, 2-m relative humidity, and 10-m wind speed from diagnostic model output) of four simulated valley wind days with the three schemes (turb_1D, turb_hybrid, and turb_pseudo3D) for the whole simulation time of 24 h. Stations with an SSO standard deviation below 50 m are classified as "flat terrain,"; stations with and SSO standard deviation larger than 50 m are classified as "HCT." The averaged values over all 88 stations across Austria are summarized in "Overall."

	Terrain	Rmse turb_1D	Rmse turb_hybrid	Rmse turb_pseudo3D
2-m temperature (K)	HCT	2.09	2.07	2.09
	Flat terrain	1.49	1.48	1.48
	Overall	1.72	1.71	1.71
2-m relative humidity (%)	HCT	10.95	10.58	10.40
	Flat terrain	8.92	8.91	9.17
	Overall	9.70	9.55	9.65
10-m wind speed ($m\,s^{-1}$)	HCT	1.12	1.12	1.14
	Flat terain	1.05	1.06	1.06
	Overall	1.08	1.08	1.09

Timeseries: Glacier Tongue and Surroundings