Large-Eddy Simulation of the Daytime Boundary Layer and Heat Transfer Processes over an Idealized Valley

Jürg Schmidli (jschmidli@env.ethz.ch)

Introduction and Motivation

- Transport and mixing of heat, moisture and other constituents over complex terrain determined by evolution of mountain boundary layer, its turbulence and associated thermally-driven flows
- Quantifying these processes important for many applications such as initiation of deep convection, air pollution studies, or parameterization in coarse-resolution models
- Mechanisms governing heating of valleys not clear. Role of valley volume effect and subsidence heating debated in recent literature (e.g. Rampanelli et al., 2004; Schmidli and Rotunno, 2010; Serafin and Zardi, 2011)

Objectives

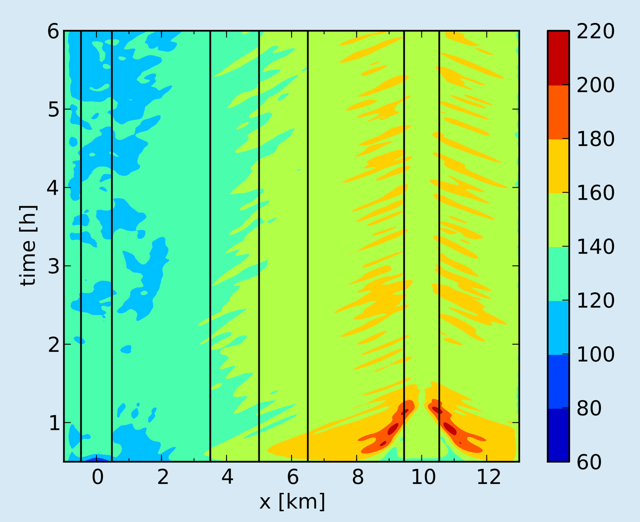
- **Clarify role of volume effect and subsidence**
- **Quantify heat transfer associated with mean flow (thermally-driven circulations) and turbulence**
- **Key principles of heat transfer in stratified fluids?**

Experimental setup

LES simulation

- 2D valley: width 20 km; depth 1.5 km; length: 9.6 km
- Atmosphere at rest with $\frac{\partial \theta}{\partial z} = 3\,\mathrm{K\,km^{-1}}$
- **Constant shortwave forcing** $SW_d = 400\,\mathrm{W\,m^{-2}}$
- Deardorff-type TKE closure (Deardorff, 1980) with SGS length scale $l_0 = \Delta x$
- Monin-Obukhov surface layer with $z_0 = 0.16\,\mathrm{m}$
- Domain: 40 km×9.6 km×5 km
- Grid: $\Delta x = \Delta y = 50$ m; $\Delta z = 8\ldots20(50)$ m
- 6 hours integration
- Double periodic lateral BCs
- Model: ARPS Version 5.2.12+

Surface sensible heat flux forcing



Reynolds flow decomposition

- Perturbation a defined as

$$a(\mathbf{x},t) = \tilde{a}(\mathbf{x},t) - A(\mathbf{x},t)$$

- Average $A = \overline{\tilde{a}}$ defined as

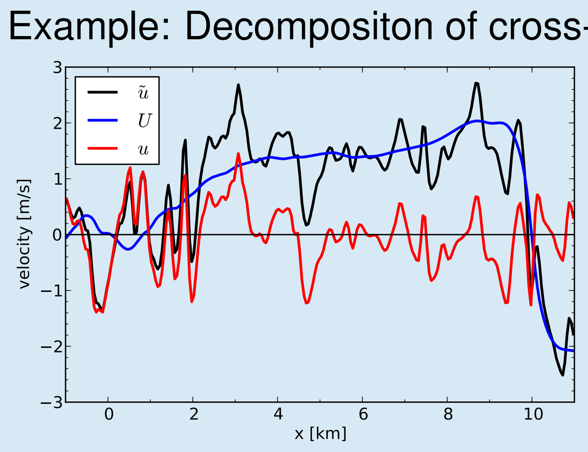
$$A(\mathbf{x},t) = \frac{1}{T L_y} \int_{t-T/2}^{t+T/2} \int_0^{L_y} \tilde{a}(x,y',z,t)\,dy'\,dt'$$

with $T = 40$ min and $L_y = 9.6$ km.

- Covariances and turbulent fluxes

$$\overline{\tilde{a}\tilde{b}} = \overline{AB} + \overline{ab}$$
$$= \text{mea} + \text{trb}$$
$$= \text{mea} + \text{trb\_r} + \text{trb\_s}$$

- Example: Decompositon of cross-valley wind (20m AGL)



- Results are shown for time $= 4$ h.

References

Deardorff, J. W., 1980: Stratocumulus-capped mixed layers derived from a 3-dimensional model. *Bound.-Layer Meteor.*, **18**, 495–527.

Rampanelli, G., D. Zardi, and R. Rotunno, 2004: Mechanisms of up-valley winds. *J. Atmos. Sci.*, **61**, 3097–3111.

Schmidli, J., and R. Rotunno, 2010: Mechanisms of along-valley winds and heat exchange over mountainous terrain. *J. Atmos. Sci.*, **67**, 3033–3047.

Serafin, S., and D. Zardi, 2011: Daytime development of the boundary layer over a plain and in a valley under fair weather conditions: A comparison by means of idealized numerical simulations. *J. Atmos. Sci.*, **68**, 2128–2141.

Flow evolution

Instantaneous flow fields and hourly potential temperature profiles

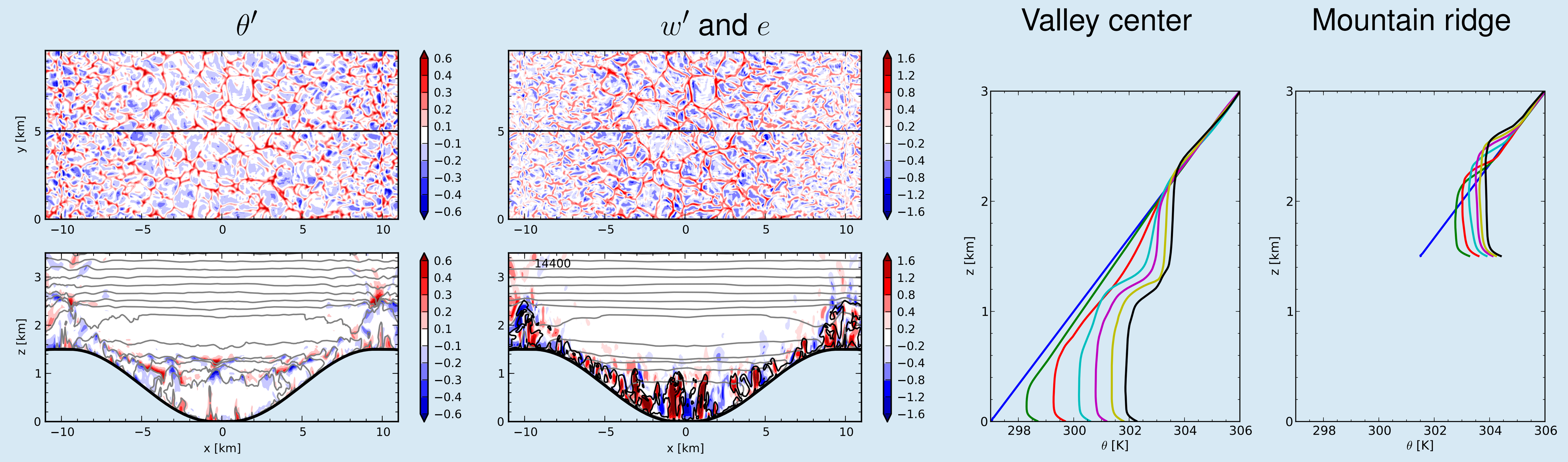


Figure 1: Horizontal cross sections at 40 m AGL (upper panels) and west-east cross sections at $y = 5$ km (lower panels).

First- and second-moment statistics

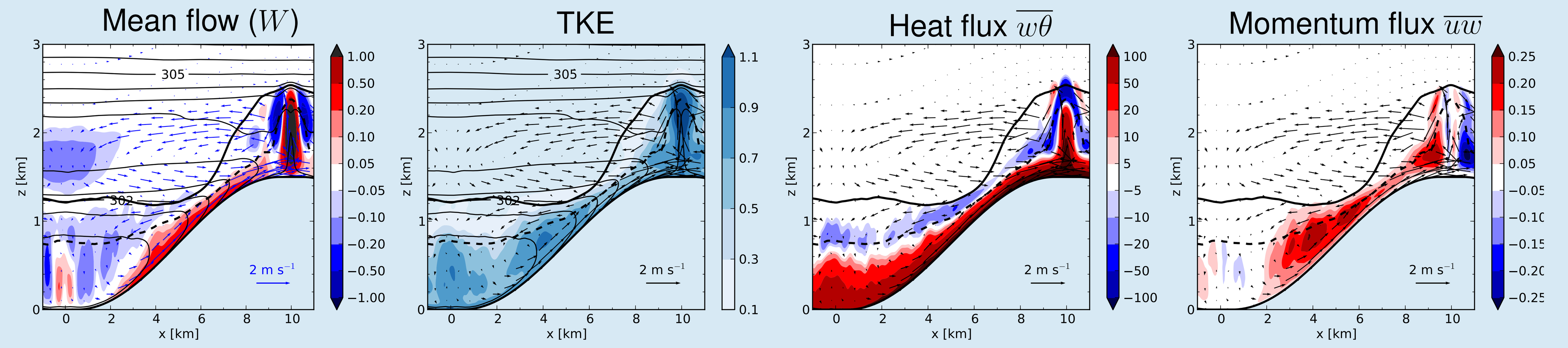


Figure 2: Cross sections of flow statistics, potential temperature (0.5 K interval), boundary layer height (thick solid line), and mixed layer height (dashed line).

Local perspective on valley heating

Decompose temperature tendency into mean and turbulent component

$$\underbrace{\frac{\partial \Theta}{\partial t}}_{\text{net}} = \underbrace{-\mathbf{V}\cdot\nabla\Theta}_{\text{mea}} \underbrace{-\mathbf{v}\cdot\nabla\theta}_{\text{trb}}$$

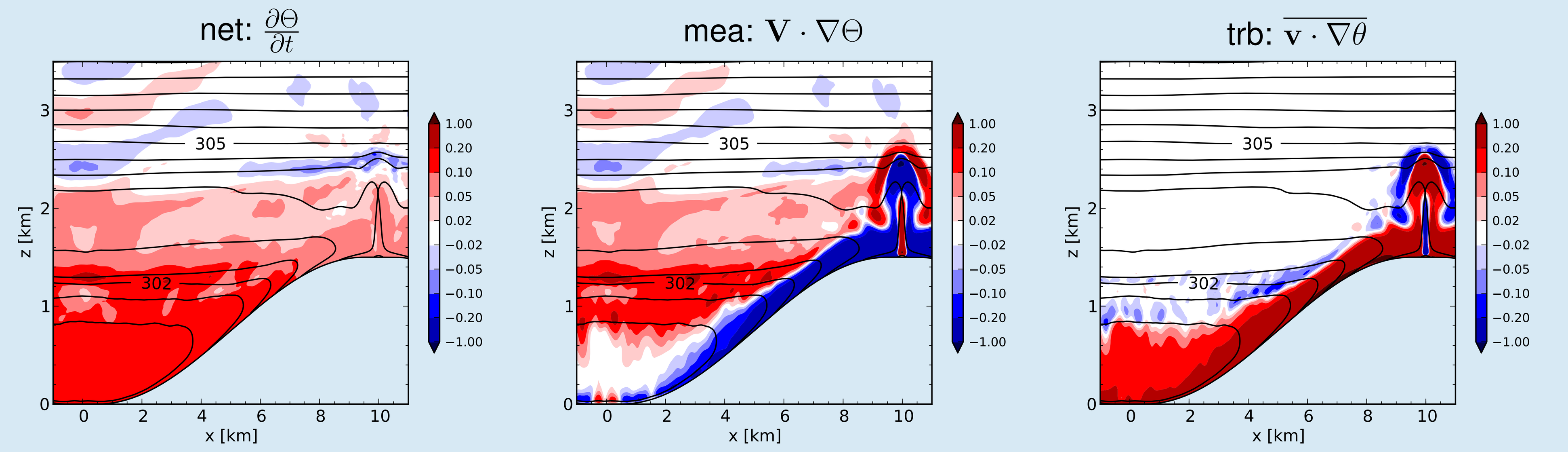


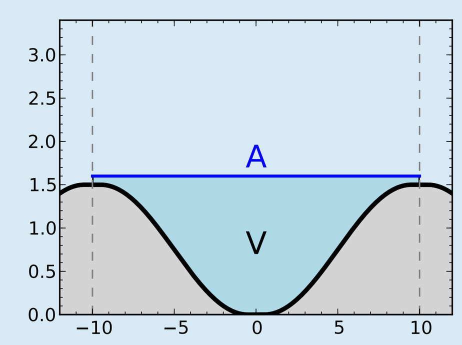
Figure 3: Cross sections of temperature tendencies (10^{-3} K/s).

⇒ Top-down warming by advection (in stable part) and bottom-up warming by turbulence (in mixed layers).

Bulk perspective on valley heating

Heat budget for valley control volume

$$\underbrace{\frac{1}{M}\int_V \rho \frac{\partial \Theta}{\partial t}\,dV}_{\text{net}} = \underbrace{-\frac{1}{M}\int_{\partial V} \rho \mathbf{V}\Theta \cdot \mathbf{n}\,dS}_{\text{mea}} \underbrace{-\frac{1}{M}\int_A \rho \overline{\mathbf{v}\theta}\cdot\mathbf{n}\,dS}_{\text{trb\_e}} + \underbrace{\frac{1}{M}\int_S \frac{H_0}{c_p}\,dS}_{\text{shf}}$$



Advective heat flux through top control surface using heat flux $\rho\mathbf{V}\hat{\Theta}$

$$\int_A \rho \mathbf{V}\hat{\Theta}\,dA = \int_A \rho \mathbf{V}\Theta\,dA$$

with perturbation temperature $\hat{\Theta} = \Theta - \theta_0$ where $\theta_0 = \frac{1}{A}\int_A \Theta\,dA$

⇒ Avoid large compensating fluxes!

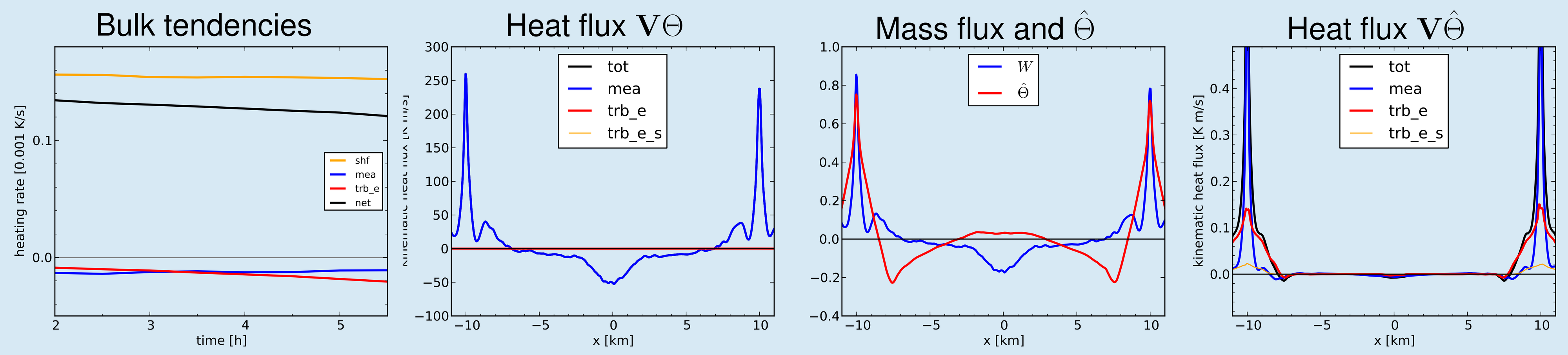


Figure 4: Time series of heat budget components averaged over valley volume (left) and cross-valley variation of corresponding heat fluxes through the valley top.

⇒ Downward heat flux associated with subsidence is **overcompensated** by upward heat flux over ridge.

Conclusions

- Volume effect is main cause of valley-plain temperature contrast — no additional warming due to subsidence
- Although slope winds induce *local* subsidence heating in valley core, their net *bulk* effect is to cool the valley atmosphere
- Heat transport in stratified fluids differs fundamentally from that of other quantities
  - → use perturbation temperature for budget considerations (compensating fluxes)
  - → budget analysis: always consider entire volume, not just one branch of flow ("remote effects")
- Clearly separate local and bulk perspectives — local concepts are not applicable to volume arguments

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