Quantifying horizontal and vertical tracer-mass fluxes of a developing daytime valley boundary layer

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① Motivation and Goals

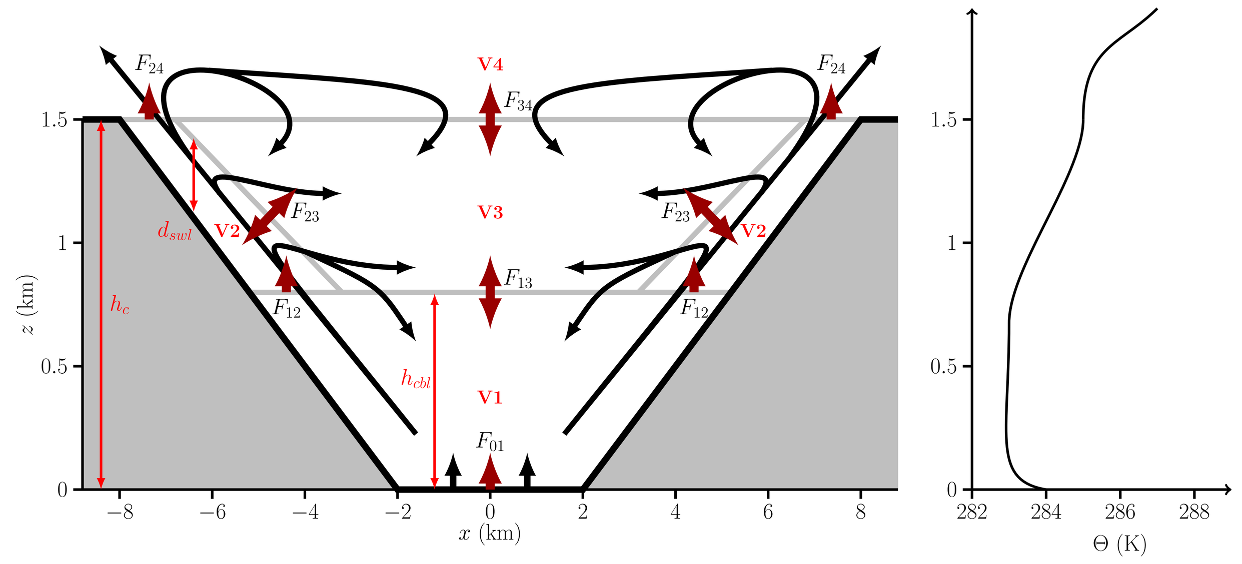
Slope winds provide a mechanism for the vertical exchange of air between the valley and the free atmosphere aloft. However, depending on strength of surface-layer heating (forcing) and atmospheric stability, one part of the up-slope flow may be redirected towards the valley center leading to a recirculation of pollutants within the valley (Vergeiner and Dreiseitl, 1987).

Main Questions:

- How much tracer mass is circulated within the valley; how much is exported out of it?
- How do these fluxes depend on stability and forcing strength?
- Is it possible to find a parameter describing the mutual effects of forcing and stability?

② Methods

- Large eddy simulations with the **WRF-ARW** model. $\Delta x = 50$ m, Δz increasing from 10 m to 75 m
- Terrain geometry: slopes with constant slope-angle, 4 km wide valley floor, homogeneous in y-direction, length: $L_y = 10$ km, valley width: $W = 17$ km, crest height: $h_c = 1500$ m
- The valley atmosphere is separated into three sub-volumes: the mixed layer (V_1), slope wind layer (V_2) and stable core (V_3). Above the valley is the free atmosphere (V_4).



Valley geometry and schematic representation of four sub-volumes with a typical profile of the potential temperature.

Periodic boundary conditions are used. No PBL scheme, and no land-surface scheme were used, but a three-dimensional 1.5 order TKE scheme and prescribed surface sensible heat flux. A **passive tracer** is released at the valley bottom ([-2,+2] km) with a **constant emission rate**.

Surface sensible heat flux and initial conditions

- Prescribed surface sensible heat flux:

$$H_s(t) = A_{shf} \sin\left(\frac{(t-6)\pi}{12}\right) \qquad t = 06...18 \text{ h}$$

- A_{shf} is varied between 62.5 and 375 W m^{-2} (called S0.5 to S3)
- H_s is homogeneous in x- and y-direction
- θ-Profiles: constant Brunt-Väisälä frequency N ranging from 0.006 to 0.020 s^{-1} (called N06 to N20)
- The initial atmosphere is at rest and has a relative humidity of 40 %

Flux calculation

A variable $\tilde{\psi}$ can be decomposed into mean, resolved turbulent, and subgrid scale turbulent parts:

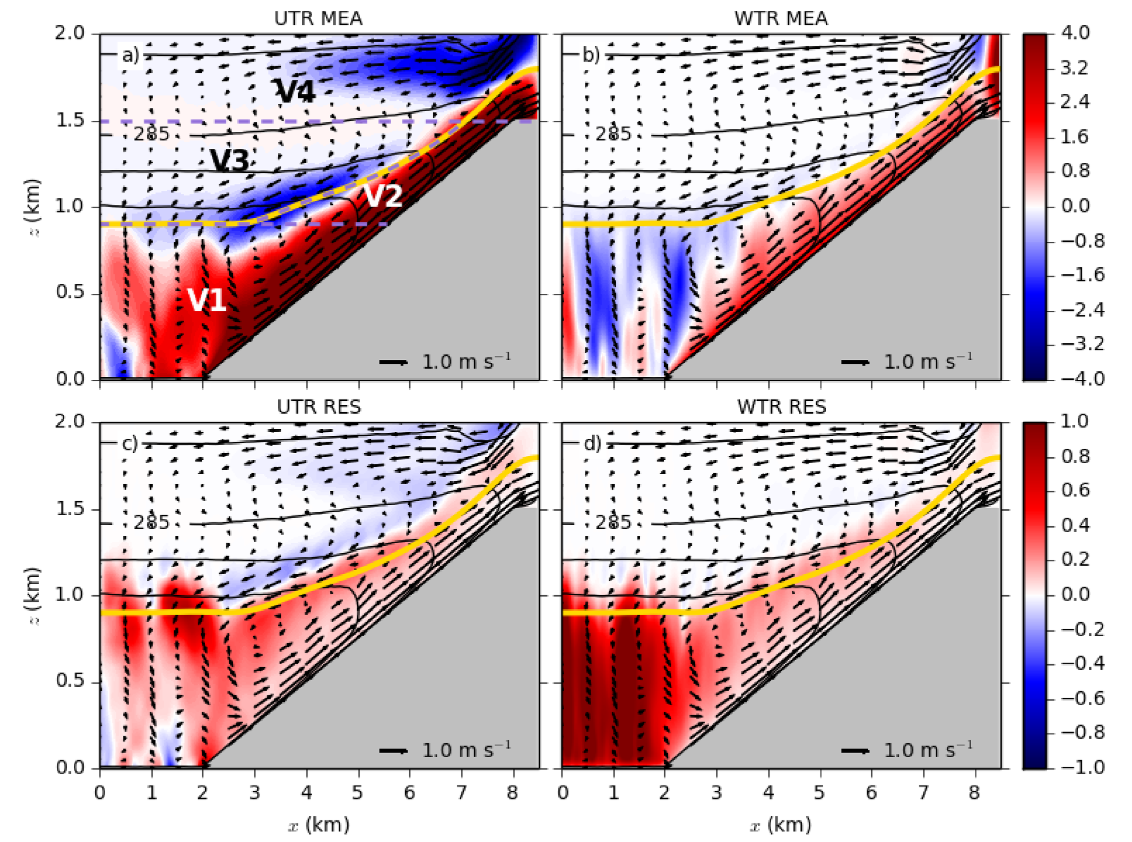
$$\tilde{\psi} = \underbrace{\langle\overline{\psi}\rangle}_{\text{MEA}} + \underbrace{\psi''}_{\text{RES}} + \underbrace{\psi'}_{\text{SGS}}$$

$\overline{\psi} = \langle\overline{\psi}\rangle + \psi''$ is the variable at the model grid point; $\langle\rangle$ an average along the valley and over 41 minutes.

This leads to the **vertical tracer mass flux**:

$$\underbrace{\langle \tilde{w}\,\tilde{\rho}_{tr} \rangle}_{\text{TOT}} = \underbrace{\langle\overline{w}\rangle\,\langle\overline{\rho}_{tr}\rangle}_{\text{MEA}} + \underbrace{\langle w''\rho''_{tr}\rangle}_{\text{RES}} + \underbrace{\langle w'\rho'_{tr}\rangle}_{\text{SGS}}$$

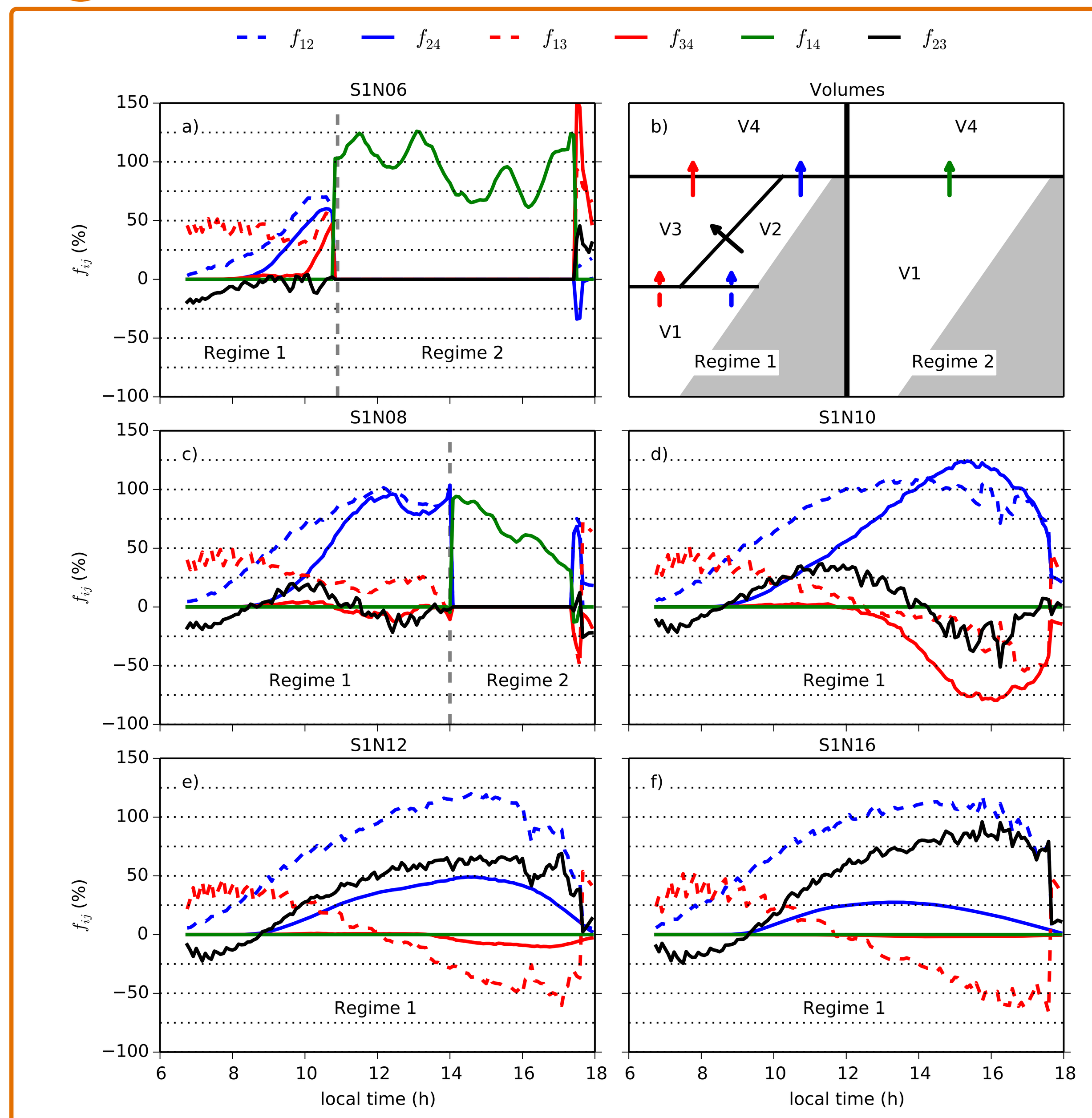
③ Tracer Fluxes



Tracer fluxes for $A_{shf} = 125$ W m^{-2} and $N = 0.01$ s^{-1} at 12 LT. Shown are a) horizontal mean, b) vertical mean, c) horizontal resolved turbulent, and d) vertical resolved turbulent tracer mass fluxes, normalized by the emission rate as colour contours. In addition, wind vectors and potential temperature (black contours) are shown for data averaged along the valley and over 41 minutes. The yellow line marks the convective boundary layer hight and slope wind layer depth, which defines the volumes V_1 to V_4 shown in a).

- Strong horizontal and vertical mean tracer fluxes
- Strong export of tracer mass at crest height
- Recirculation from V_1 over V_2 to V_3 and back to V_1
- Resolved turbulent fluxes generally much weaker than fluxes due to mean circulation
- At the top of the slope wind layer and at the valley center resolved turbulent fluxes are important

④ Bulk Flux Evolution



Normalized bulk fluxes at the interfaces between the four volumes V_1 to V_4 for $A_{shf} =$ 125 W m^{-2} and five different initial stabilities ($N = 0.006$ to 0.016 s^{-1}). The fluxes are normalized with the bulk tracer mass flux at the surface. A flux f_{ij} is positive when directed from volume V_i to V_j. Fluxes for $N = 0.014$, 0.018, and 0.020 s^{-1} are very similar to 0.016 s^{-1}.

- Weak stratification: inversion is eventually eroded (Regime change).
- Generally: strong flux from V_1 to V_2 (up to 100 %)
- Outflow f_{24} strongly dependent on N (magnitude from 25 % to >100 %)
- Flux f_{23} increases with increasing stability (up to 80 %)
- Significant recirculation of tracer mass from stable core to the mixed layer at higher stabilities

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⑤ Total Export of Tracer Mass

We seek a single parameter to combine the mutual effects of forcing strength and stability. The energy required to neutralize the initially stable stratification

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

and the total energy provided by the surface sensible heat flux

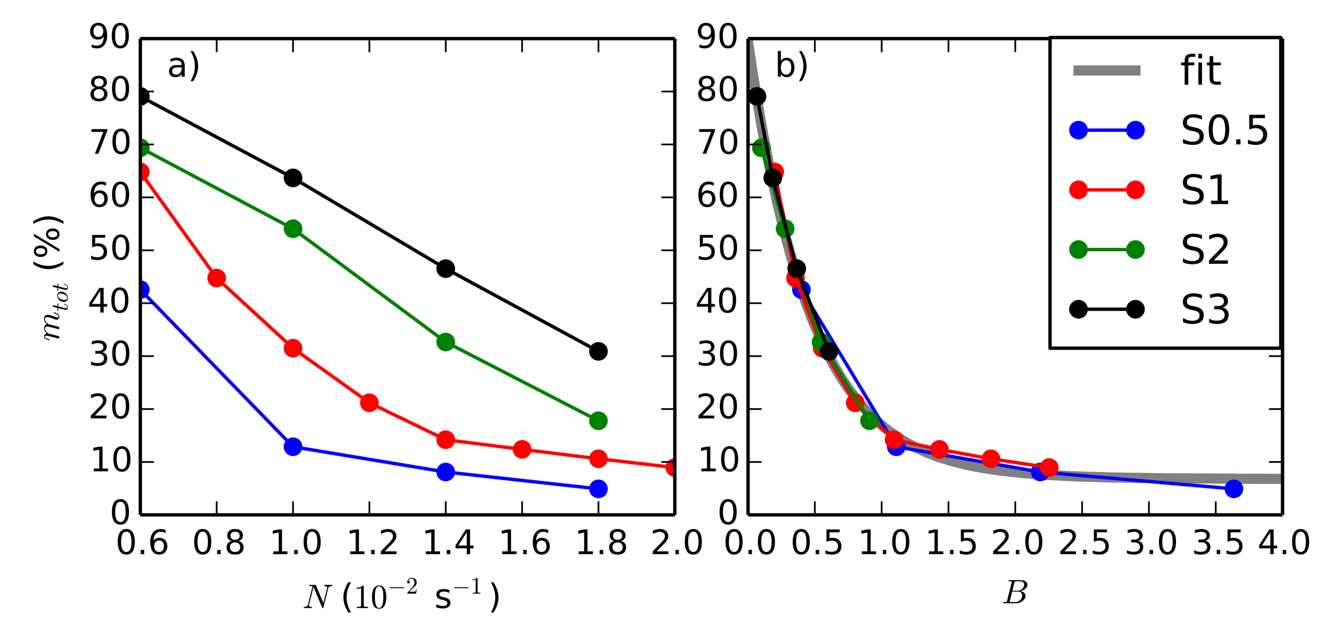
$$Q_{prov} = \int_{t_r}^{t_s} \int_A H_s(t,x,y)dxdydt.$$

Hereby, L_y is length of the valley, h_c the crest height, Θ_E the potential temperature at crest height, W the valley width, H_s the surface sensible heat flux, t_r the time of sunrise and t_s the time of sunset.

We define the **breakup parameter**:

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

For $B = 1$, just enough energy is provided to erode the initial inversion. $B > 1 \rightarrow$ no breakup; $B < 1 \rightarrow$ earlier breakup. However, heat is exported out of the valley, hence $B << 1.0$ is required for the breakup (Leukauf et.al 2015).



Total export of tracer mass at crest height, integrated from 06 to 18 LT as a function of a) N and b) the breakup parameter B. The fit corresponds to the analytic function below.

The total export of tracer mass at crest height is a function of the breakup parameter and can be described by the empirical fit:

$$m_{tot} = a\exp(-bB) + c,$$

where $a = 82.54$, $b = 2.098$, and $c = 6.79$.

⑥ Conclusion

- The tracer transport is dominated by mean fluxes resulting from the slope-flow circulation. Turbulent fluxes are weaker, but locally play an important role.
- Tracer transport into the slope wind layer is generally strong for all stabilities.
- With increasing stability or decreasing forcing, less tracer is exported at crest height.
- The flux from the slope wind layer towards the stable core increases accordingly.
- The total tracer export at crest height depends exponentially on the breakup parameter B. This parameter might be useful for a parametrization of the vertical exchange.
- More details can be found in Leukauf et.al 2016.

References

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