Understanding the effects of multi-scale flow interactions on convective boundary layer depth

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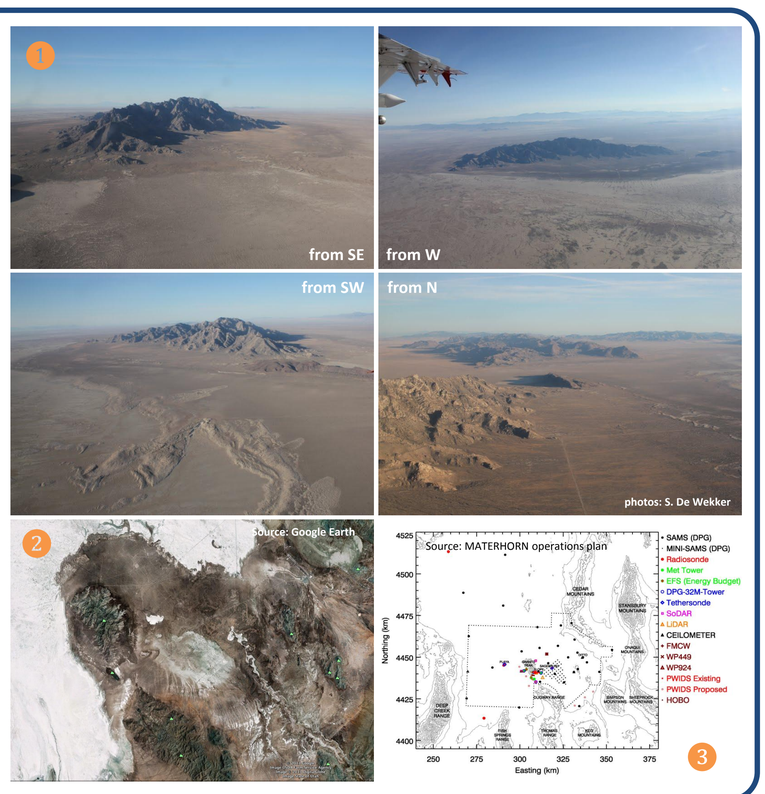
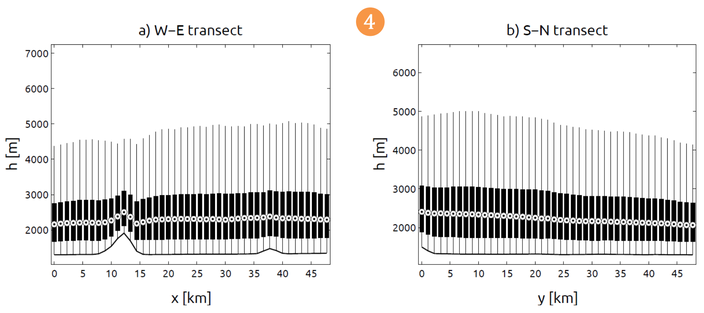
Introduction: Dugway Proving Ground, Granite Peak and the MATERHORN project

Granite Peak, located in the Dugway Proving Ground in western Utah, is an isolated mountain rising ~800 m above the surrounding terrain (1).
Granite Peak separates a salt flat (playa) to the W from a NW-sloping plain covered by herbaceous vegetation to the E (2).
During the day, thermally-driven flows induced both by topography and by land-surface heterogeneity are expected to occur in the area and to interfere with the CBL development.
During fall 2012 and spring 2013, DPG was the target area of the MATERHORN project. An existing meso-network of measurement stations (**SAMS**) was enhanced with an extensive set of special measurement platforms (3), including a Twin Otter aircraft with a Doppler Wind Lidar on board (TODWL).

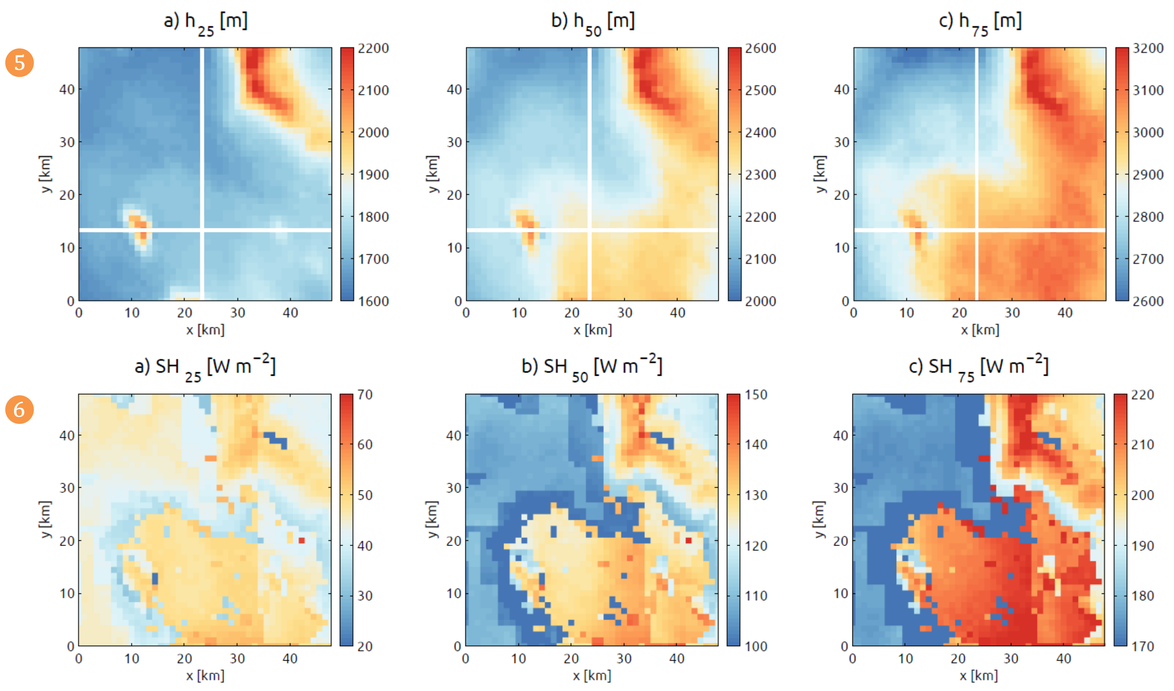


CBL depth variability at DPG

Since the early '90s, DPG has used a continuously operating meso-gamma-scale analysis and forecast system (4DWX) developed by the NCAR Research Applications Laboratory (RAL), currently based on WRF simulations with a maximum resolution of 1.1 km. "Final analysis" simulations are nudged towards SAMS measurements by means of Newtonian relaxation.



A statistical analysis of 4DWX output (three years of hourly data, 2009-2011) highlights a significant spatial variability of the CBL depth in the area, as demonstrated by transects (4) and quantile maps (5). The spatial variability of sensible heat fluxes (6), related to land-surface properties, explains the phenomenon only partially (Serafin et al. 2014).



Fact: The boundary layer structure around DPG has a marked spatial heterogeneity. The CBL is thicker on the east (sagebrush plain) than on the west (playa) side. This feature is consistently present in 4DWX simulations and was confirmed by TODWL flights at DPG.
Why?
Differential heat fluxes? (Sensible heat fluxes are weaker over the playa)
Topography? (Mountains around the sagebrush plain act as elevated heat sources and favour vertical mixing, making the CBL warmer and deeper)
Probably both factors matter. But what matters most?

Factor Separation

In this study, we explore the mechanisms for CBL depth variability at DPG using the factor separation method (FS). FS (Stein and Alpert, 1993) provides a useful formalism to design sensitivity studies. Consider one phenomenon modulated by two forcing factors. Four simulations: *0* (both forcings off), *1* (only forcing 1 on), *2* (only forcing 2 on), *12* (both forcings on). From each simulation one field of interest, s, is chosen (e.g., BL depth). Then four "factors" are computed:

$$\begin{aligned} f_0 &= s_0 \\ f_1 &= s_1 - s_0 \\ f_2 &= s_2 - s_0 \\ f_{12} &= s_{12} - s_1 - s_2 + s_0 \\ f_0 + f_1 + f_2 + f_{12} &= s_{12} \end{aligned}$$

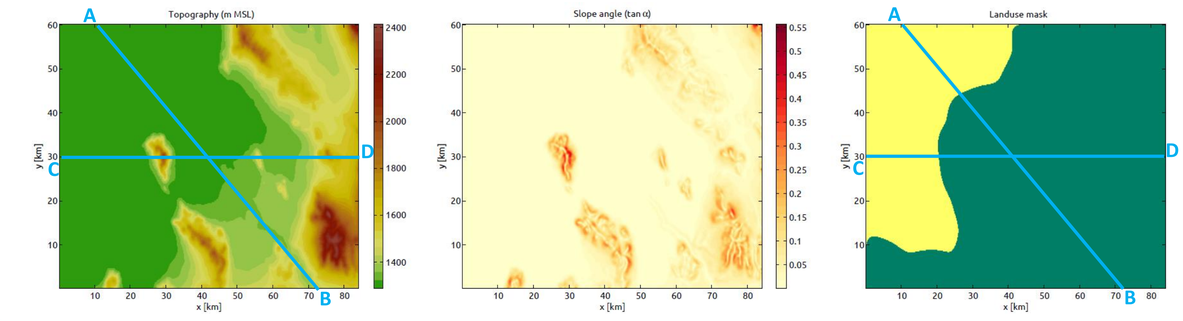
f_0 represents the undisturbed development of a phenomenon, f_1 and f_2 are the pure impacts of forcings 1 and 2, f_{12} is the impact of their interaction. f_{12} represents a nonlinear interaction, manifest in the fact that $s_{12} \neq f_0 + f_1 + f_2$. In our case, forcings 1 and 2 are respectively topography and differential heat flux.

	flat terrain	DPG topography
=HF	s_0, f_0 (uniform HF, no topography)	s_1, f_1 (uniform HF, with topography)
ΔHF	s_2, f_2 (differential HF, no topography)	s_{12}, f_{12} (differential HF, with topography)

CM1

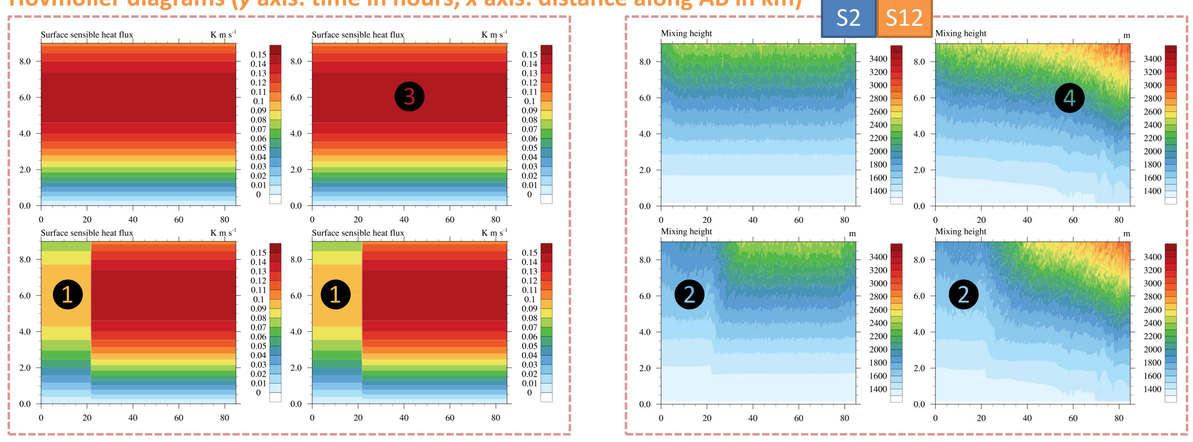
The idealized simulations presented in this study were performed using the CM1 model (Bryan and Fritsch, 2002).

- ❑ Topography from SRTM data at 1'' resolution, resampled and low-pass filtered on the model grid.
- ❑ Δx = 200 m, 84 x 60 km domain.
- ❑ Δz = 20 m near the ground, constant stretching factor of ~5%, 80 levels, model top at 16000 m MSL.
- ❑ Height-based terrain-following coordinate system.
- ❑ Deardorff (1980) TKE-based SGS turbulence closure. 5th-order horizontal and vertical advection.
- ❑ Surface sensible heat flux imposed with a sinusoidal variation in time (24-hour period).
- ❑ Initial conditions: quiescent atmosphere, thermal structure as on 10 October 2012 (MATERHORN IOP5), 14:15 MDT.
- ❑ Rayleigh damping within 10 km from the lateral boundaries, open lateral boundary conditions.
- ❑ Rigid-lid model top, Rayleigh damping in the upper 5 km.
- ❑ Passive tracer injected at the surface on the playa side, with constant mass flux.
- ❑ Nine-hour simulations.



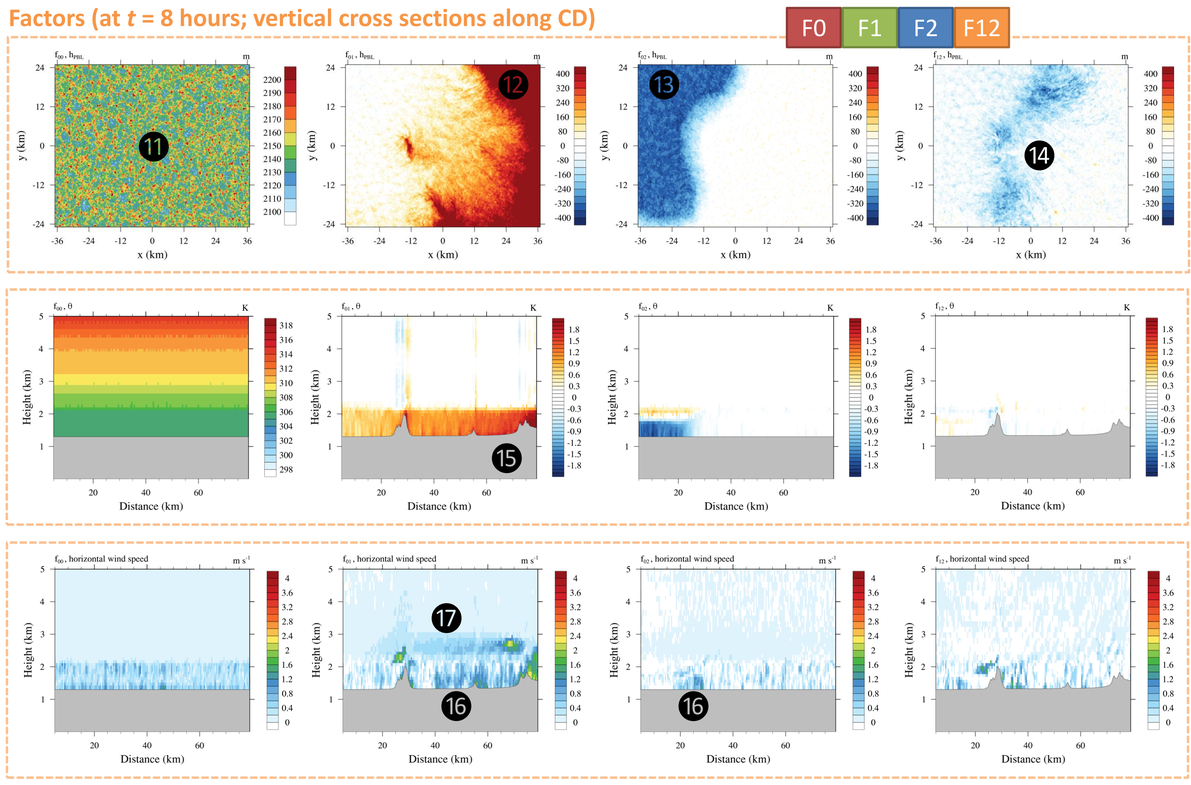
Hövmöller diagrams (*y* axis: time in hours, *x* axis: distance along AB in km)

S0 S1 S2 S12



Factors (at *t* = 8 hours; vertical cross sections along CD)

F0 F1 F2 F12



Conclusions

- ❑ Weaker heat fluxes over the playa (1) cause a locally thinner CBL (2).
- ❑ Even with spatially uniform heat fluxes (3), proximity to topography thickens the CBL (4).
- ❑ Horizontal ϑ variability is null in the s_0 simulation (5). Topography causes a larger temperature imbalance than differential heat fluxes (6). Orographically-induced horizontal temperature imbalances become weaker with time (7).
- ❑ Horizontal temperature differences generate mass advection (playa breeze, ~3 m s^{-1}) (8). The breeze front moves at ~1 m s^{-1} and is fastest in the s_{12} simulation (9).
- ❑ Weaker heat fluxes over the playa cause weaker mixing and hence higher near-surface pollutant concentration (10).
- ❑ The undisturbed CBL has uniform depth (parcel method) (11). Elevated heat input related to the topography causes mixing height differences of over 400 m (12). Weaker heat fluxes over the playa causes mixing height differences of around 200 m (13).
- ❑ The interaction between topographical forcing and differential heating causes a CBL depression along the playa breeze front (14).
- ❑ Due to deeper mixing, the CBL is warmer near topography (15).
- ❑ Circulation induced by topographical forcing is stronger and more extensive than the playa breeze (16), in particular above the CBL where a weak return flow is present over topography (17).
- ❑ What causes the largest impact on CBL depth variability? Probably, topography.

References

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