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Eulerian and Lagrangian perspectives on an Alpine Foehn event

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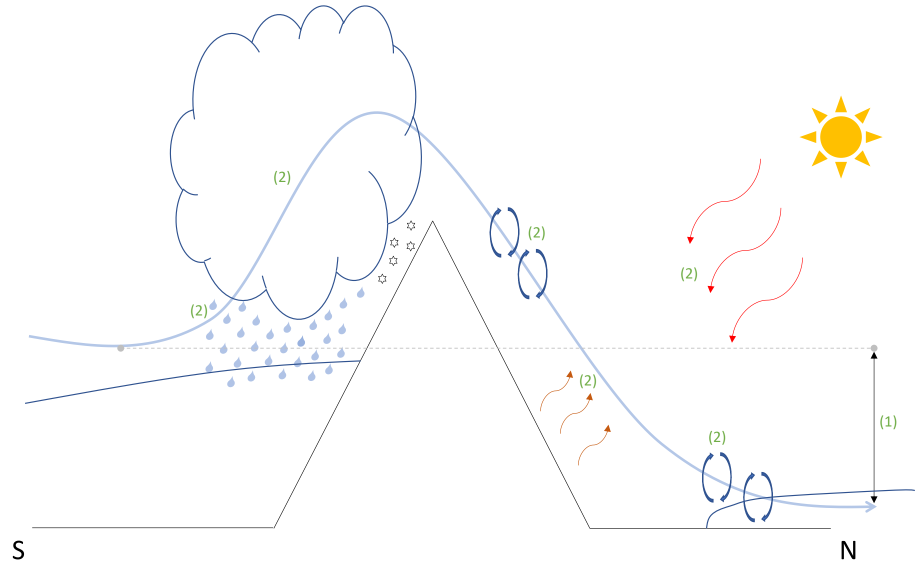
Link to Abstract: [here]

Main research questions

Research on the Alpine Foehn has a history that goes back more than one century. Among the first questions posed were the reason why the Foehn air is so warm. Recent publications (e.g. Miltenberger et al., 2013; Elvidge and Renfrew, 2016) show that the »classical» thermodynamic Foehn theory explaining the warming by latent heat release during condensation on the upstream side is an oversimplification.

Here we re-address the question of the Foehn air warming by combining high-resolution model simulations of the regional NWP model COSMO with the calculation of air parcel trajectories for a South Foehn case from 20 – 25 November 2016. In detail, we:

1) **Describe the synoptic- to mesoscale characteristics associated with the event**
2) **Present a Lagrangian analysis of the pathways and upstream properties of Foehn air masses bevore their arrival within different northern Alpine valleys**
3) **Quantify the Foehn air warming, separate adiabatic and diabatic contributions and address spatio-temporal variability**



Conceptual illustration of a cross-Alpine transect during a South Foehn event including the idealized pathway of an air parcel trajectory. Its temperature can be affected by:

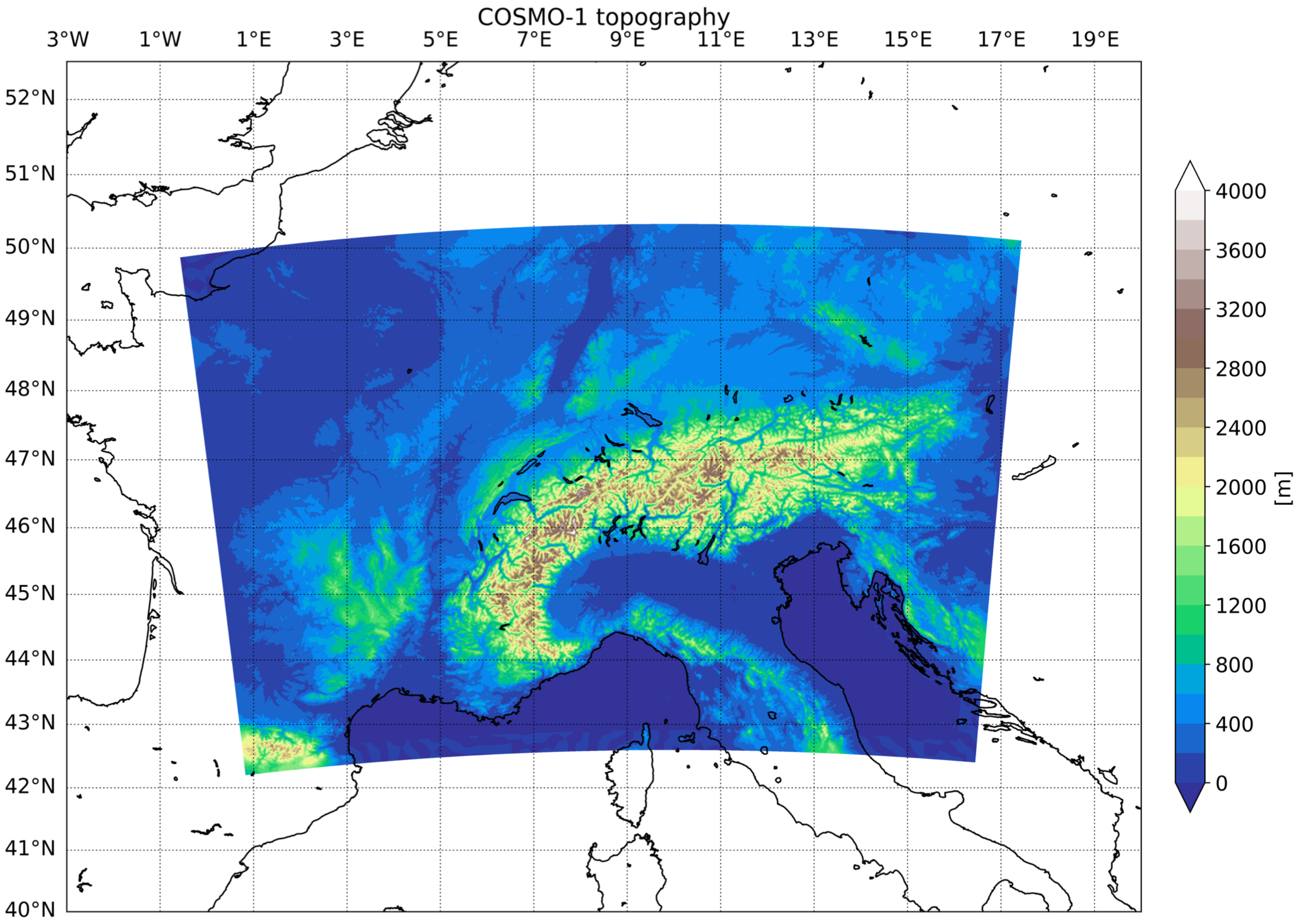
(1) Dry adiabatic desent (isentropic drawdown)
(2) Diabatic processes

Methods – COSMO

The COSMO model is a limited-area nonhydrostatic NWP model designed to run on a convection-resolving scale (Baldauf et al., 2011). It is used as such by several national weather services.

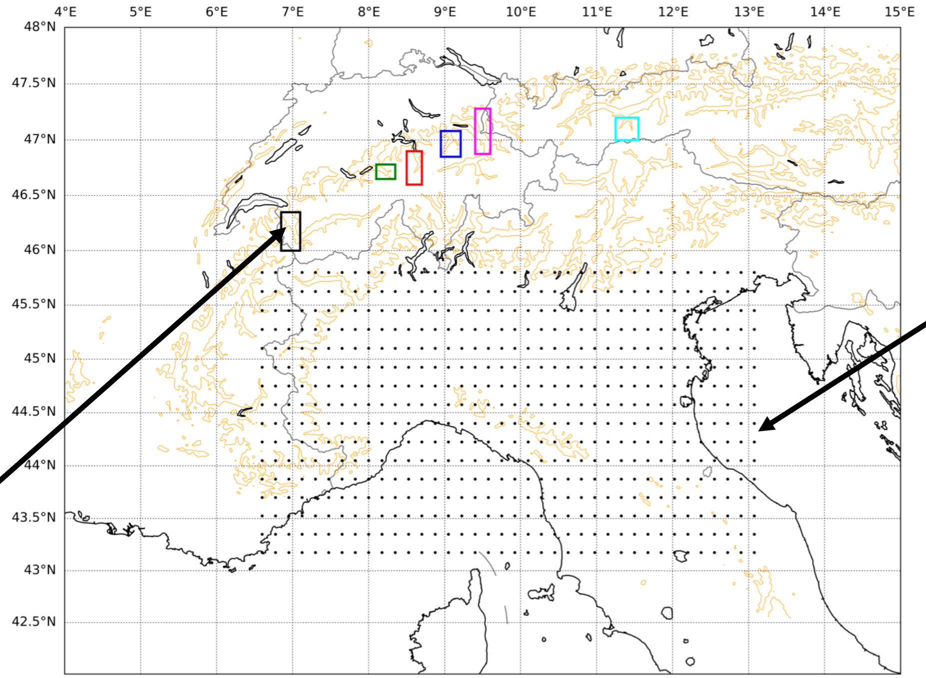
Model setup for the study:

- Integration time from 19 November 18 UTC – 25 November 18 UTC on a domain covering the greater Alpine region, output every 10 min
- Setup close to COSMO-1 of MeteoSwiss: Horizontal resolution of 1.1 km, 80 vertical levels, time step of 10 s
- Subgrid-scale processes are parametrized except for convection, which is assumed to be resolved explicitly
- Initial and boundary conditions from COSMO-1 analysis of MeteoSwiss (with the same spatial resolution)



Methods – Air parcel trajectories

Trajectories are an adequate tool to study mountain meteorological phenomena from a Lagrangian perspective. We calculate backward and forward air parcel trajectories with the Lagrangian analysis tool LAGRANTO (Wernli and Davies, 1997).



Six Foehn valleys are defined for further investigation. 36-hourly **backward trajectories** are started every 2 hours on a mesh with 0.125 ° x 0.125° x 100 m spacing from 20 m above surface up to 1200 m within the colored valley boxes.

36-hourly **forward trajectories** (offline and online) are started every 2 hours within a box extending from 20 m above ground to 8000 m (vertical spacing of 500 m) on the southern side of the Alps.

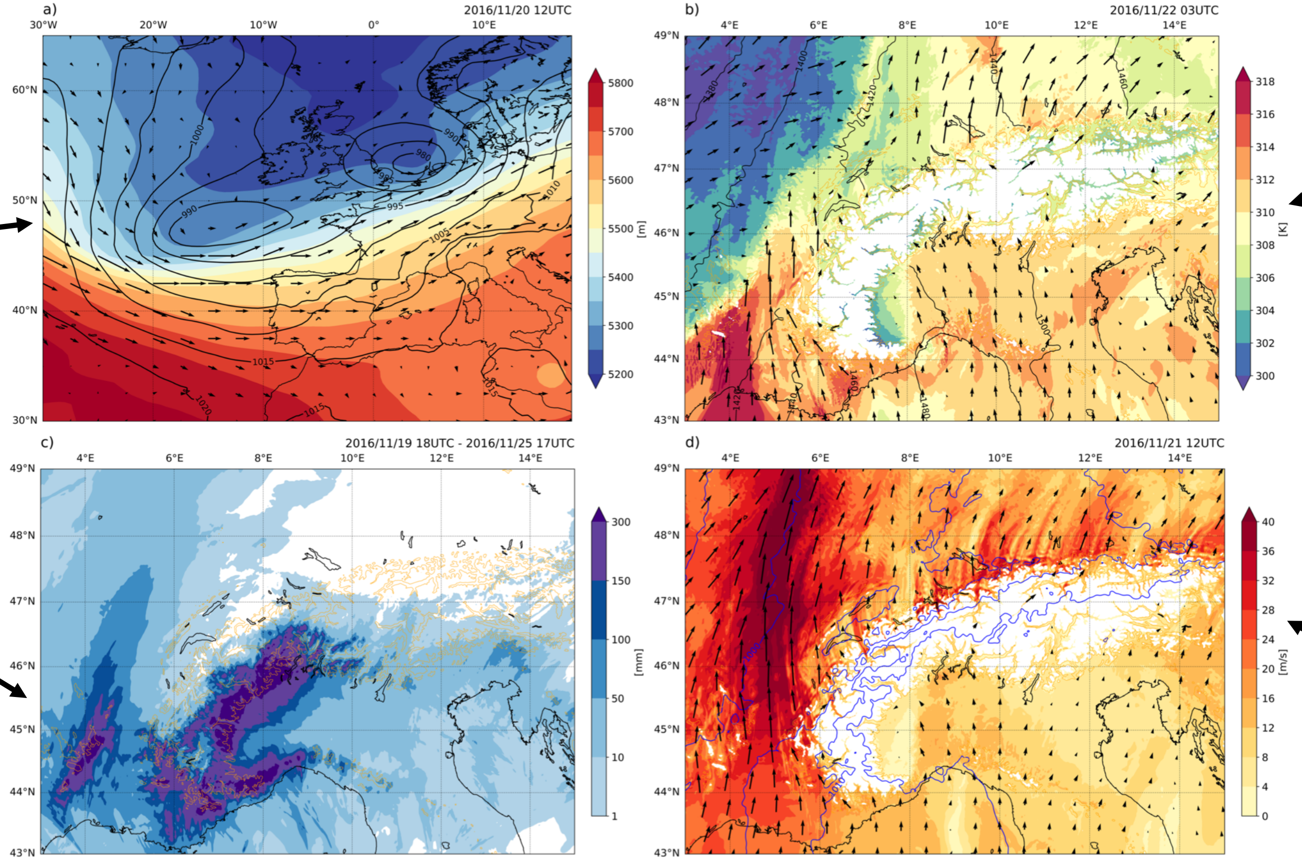
Synoptic overview

Geopotential height and wind barbs on 500 hPa, SLP (from [ERA-5](ERA-5)):

On the 20 November 2016 an upper-level trough and its associated surface cyclone approach Europe. Southwesterlies prevail over the Alpine region, supporting the development of a deep Foehn event. During the following days, the trough remains quasi-stationary and a cutoff forms over the Iberian Peninsula.

Θ_e and geopotential height on 850 hPa:

A cold front attending the cyclone approaches the Alps. But since the upper-level trough remains stationary, it dissolves before passing over Switzerland. This supports the exceptionally long duration of the event.



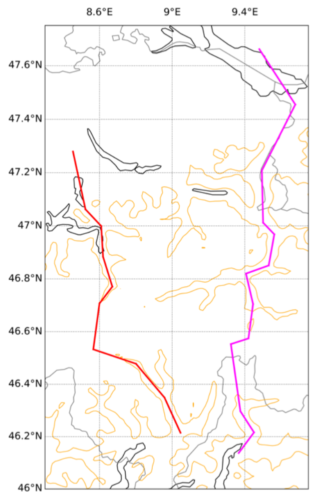
Accumulated precipitation from 20 November 18 UTC – 25 November 17 UTC:

The event is associated with intense orographic precipitation on the Alpine south side, locally exceeding 300 mm.

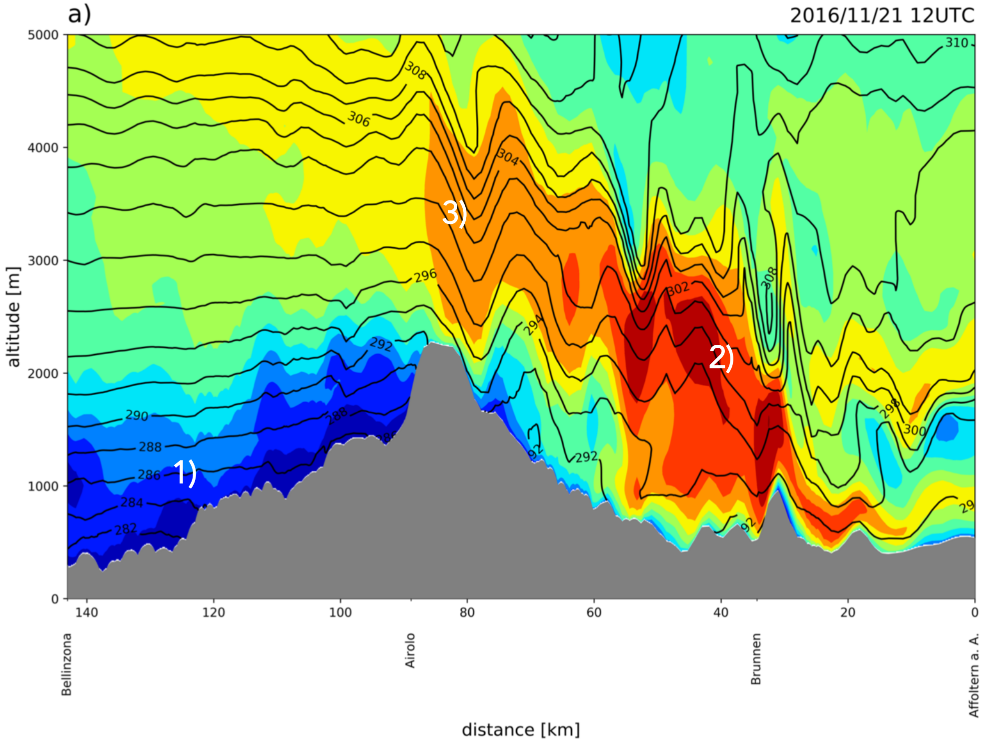
Wind velocity and vectors on 850 hPa, SLP:

The Foehn flow emerges as narrow jets emanating from the the valleys on the lee of the Alps. A striking feature is the strong low-level jet westward of the mountain chain.

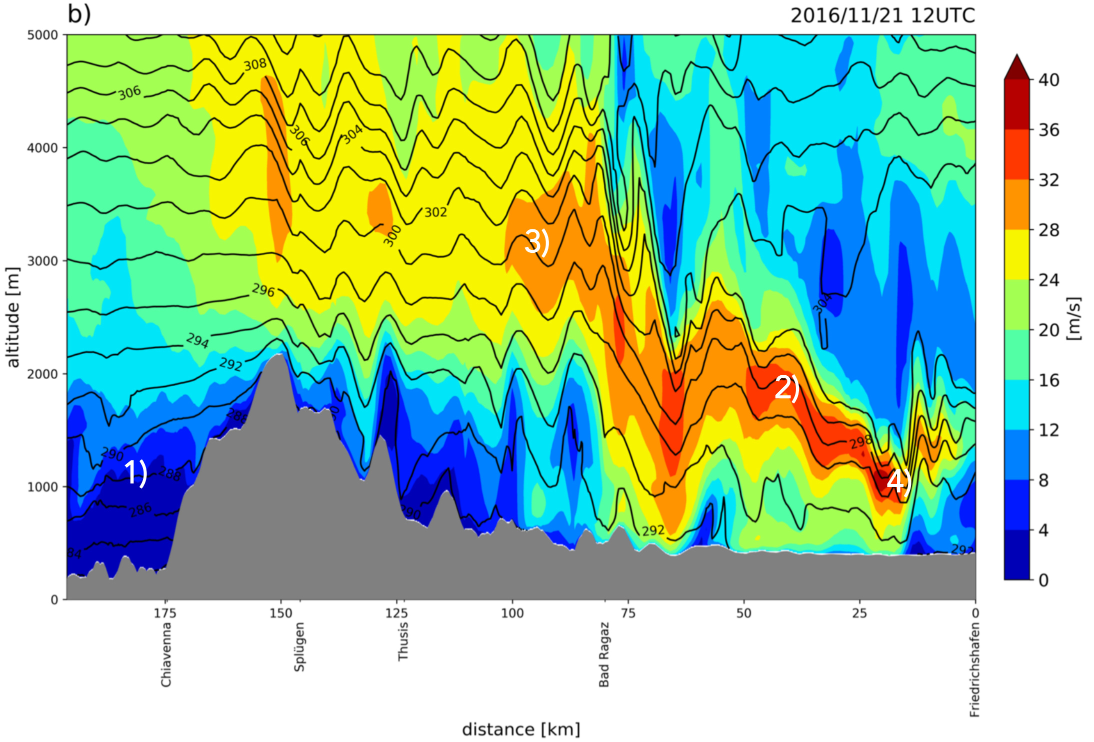
Mesoscale characteristics – Cross sections



Reuss valley (central Switzerland)

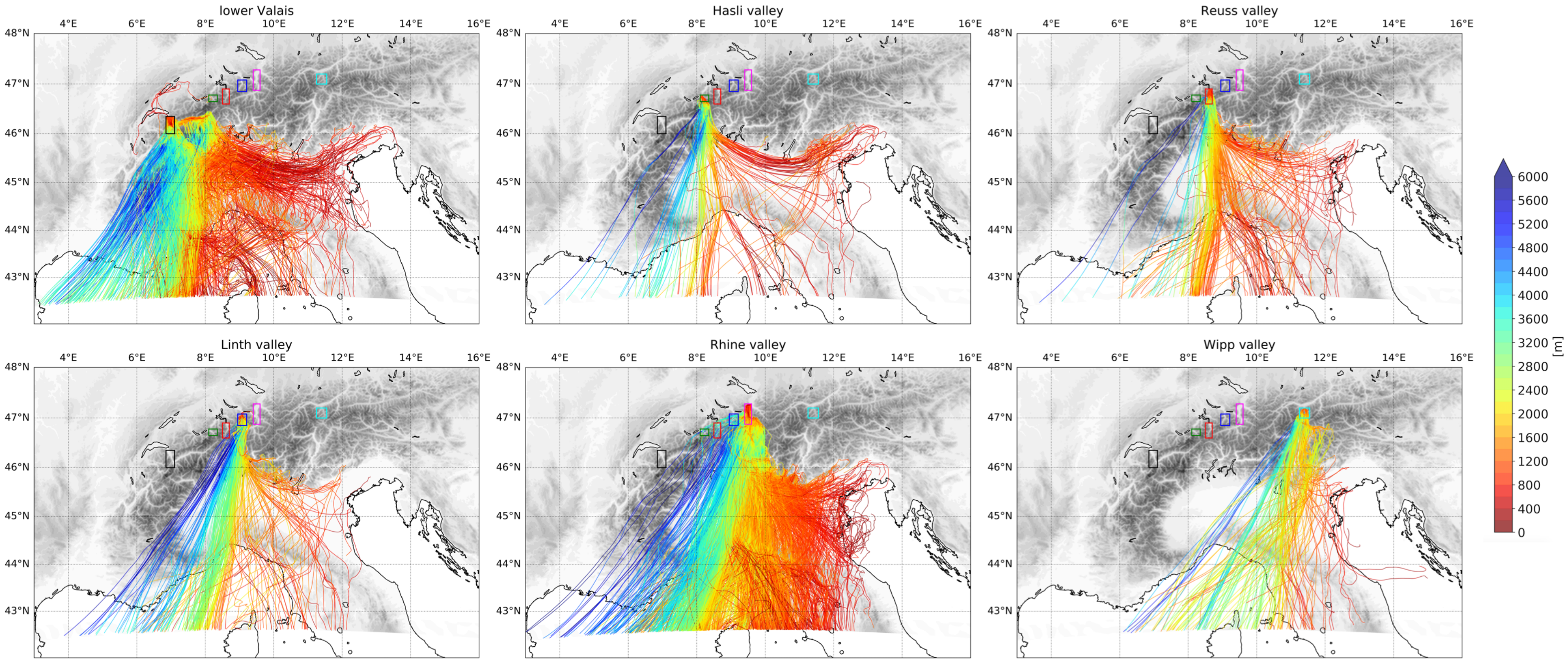


Rhine valley (eastern Switzerland)



1) Slightly enhanced stability (black contours: isentropes) in the Po valley and low velocity values (color: velocity) indicate a partially blocked air mass within the Po valley
2) The Foehn flow is apparent as a filament of enhanced wind velocities in the zone of narrowing and strongly downward bent isentropes
3) This region starts directly north of the crest for the Reuss valley, but is shifted downstream for the Rhine valley
4) A striking hydraulic jump-like feature is evident in the lower Rhine valley near the shore of Lake Constance

Lagrangian analysis – Pathways

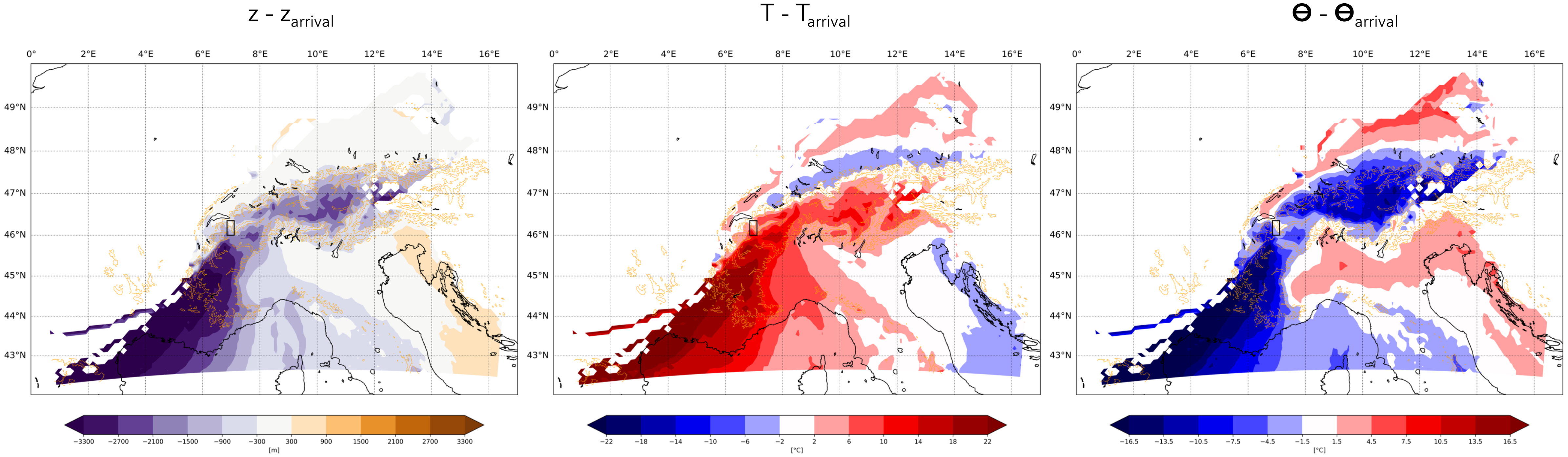


Backward trajectories arriving in the Foehn valleys at 21 November 12 UTC (colored by altitude) show that:

- Air parcels arriving within Foehn valleys spread over the entire Po valley, e.g. different air masses contribute to the Foehn flow
- Transition from West to East for each valley: Trajectories from the West stem from much higher altitudes than trajectories from the East
- A substantial amount of air parcels is captured within an easterly low-level jet in the Po valley before passing the Alpine crest

Lagrangian analysis – Footprint of the lower Valais

Gridded means of trajectory properties:



- Backward trajectories that pass over the French Alps descend very strongly before arriving within the valley, while those originating from the Po valley and the Adriatic Sea do not experience a noteworthy net vertical displacement
- Consequently, the descending trajectories experience intense warming; The net temperature increase is less pronounced in the Po valley
- But: The flow is not adiabatic, the descending trajectories experience strong diabatic cooling, the Po valley trajectories diabatic warming

A complex spatial pattern emerges… But what does that imply for the mean trajectory properties? And how do the different valleys compare?

Lagrangian analysis – Normalised mean properties

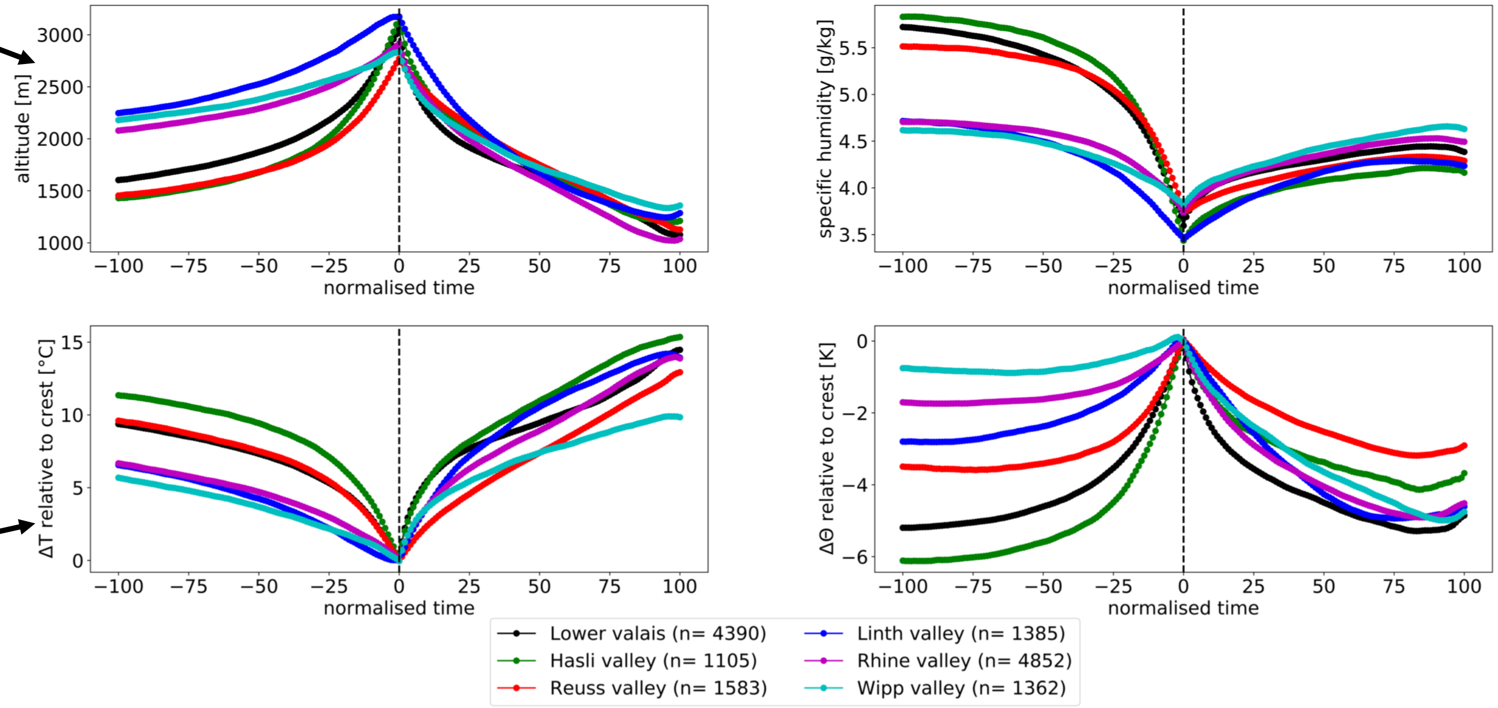
Method: Forward trajectories that descend below 1200 m within each valley box are selected to represent the Foehn flow. Each forward trajectory is normalised to the moment when it passes over the maximum surface altitude (i.e. the Alpine crest) by linear interpolation. Then, the mean is calculated for each valley.

altitude:

- Descent exceeds ascent for all valleys
- Two cluster on upstream side: Air parcels arriving in western valleys originate at ~1500 m and their ascent is more pronounced, those in eastern valleys originate from above 2000 m

specific humidity:

- The trajectories from the western valleys have higher humidity, but also loose more moisture during their ascent
- After the crest, a slight moisture uptake is apparent



ΔT:

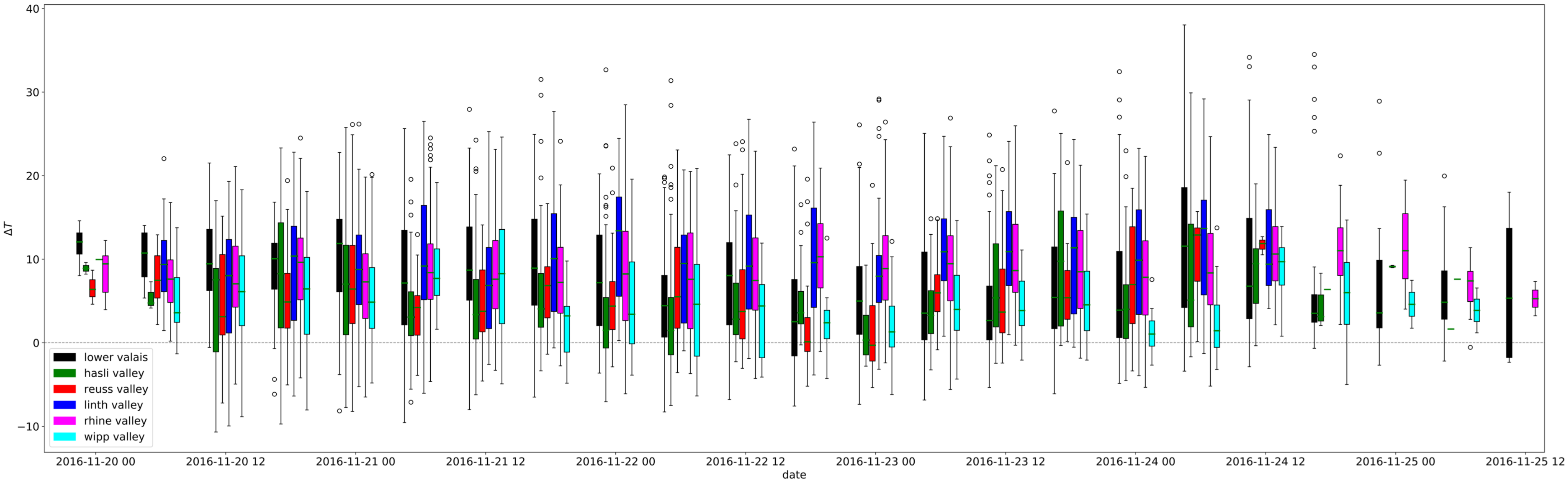
- Foehn air warming after crest exceeds cooling before crest
- The stronger ascending trajectories also experience stronger cooling

ΔΘ:

- Vast spread on upstream side with an east-west transition again, indicating that diabatic processes are more important for the western Alpine Foehn
- Diabatic cooling after the crest for all valleys

Foehn air warming – Temporal evolution

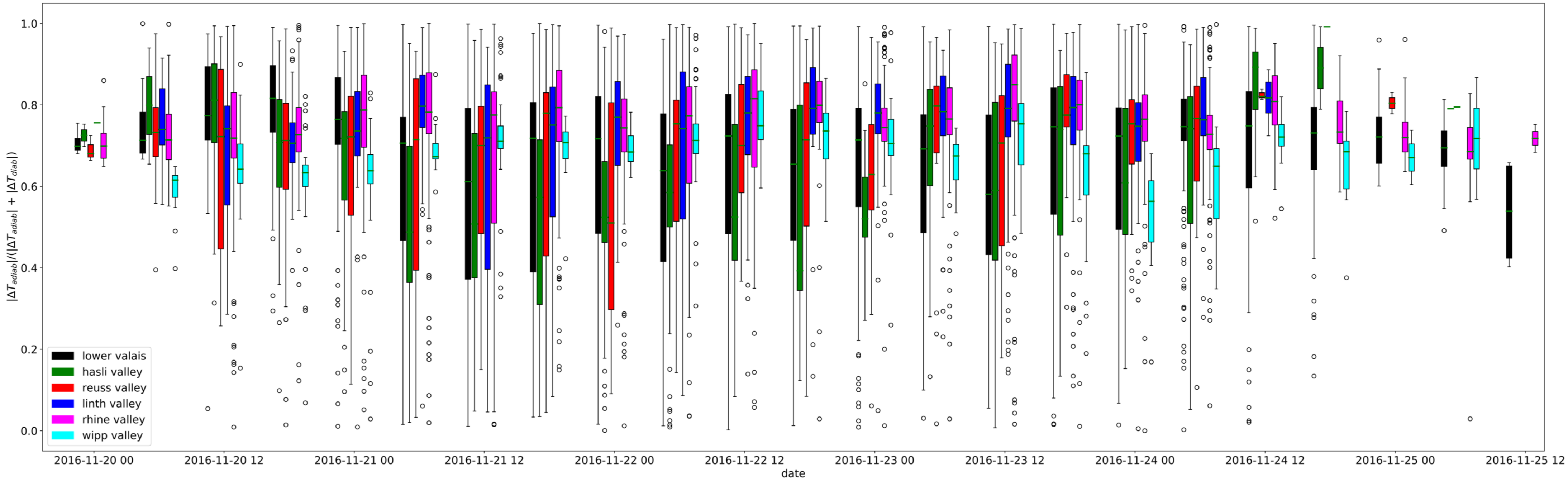
Method: Forward trajectories that cross a specific latitude within each valley below 1200 m are selected. Afterwards, the difference of their arrival temperature with respect to their initial temperature is shown in boxplots in six-hourly steps (similar to Miltenberger et al., 2013).



- Despite the large spread, the majority of air parcels experiences substantial warming while passing over the Alps
- No clear trend or maximum over the whole time period of the event, but slightly enhanced warming during first two days and on 24 November
- Warming tends to be stronges for Linth and Rhine valley and weakest for the Wipp valley
- Onset is synchronous (except for Wipp valley), but cessation differs by 24 hours

Foehn air warming – Adiabatic vs. diabatic contributions

Method: Same trajectory selection criterion as for the temperature difference; The fraction of adiabatic temperature change is quantified as follows: $f_{\Delta T_{adiab}} = \frac{|\Delta T_{adiab}|}{|\Delta T_{adiab} + \Delta T_{diab}|} = \frac{|\Delta T - \Delta\Theta|}{|\Delta T - \Delta\Theta| + |\Delta\Theta|}$



- Most of the net Foehn air warming (50 – 90%) is explicable by the isentropic drawdown mechanism
- The fraction of diabatic temperature change is larger for the western Alpine valleys
- But: Which diabatic processes are repsonsible for the remaining ~30%? And how does their temporal evolution look like?

→ **We will address this question in future studies using online trajectories and by tracing diabatic temperature tendencies along them**

Conclusions and Outlook

We used the regional NWP model COSMO in combination with air parcel trajectories to to analyze an Alpine Foehn event. Our main findings are:

- The synoptic situation supported the development of a strong and long-lasting Alpine South Foehn event from 20 – 25 November 2016
- This Foehn flow emerges as thin filaments of enhanced wind velocities along downward-bent isentropes emanating from northern Alpine valleys
- Backward trajectories reveal a complex flow pattern on the upstream side with trajectories contributing from various locations and altitudes
- The six investigated valleys can be separated into a western and an eastern group, different with respect to ascent behaviour and thermodynamical history on the southern side of the Alps
- Air parcels experience substantial warming while passing over the Alpine crest, whereby the main part can be attributed to isentropic drawdown

This analysis framework will be applied to online trajectories (Miltenberger et al., 2013) calculated during model integration and extended to several case studies. Thereby, we want to gain a more comprehensive understanding on Foehn air warming.

Questions and comments are very much appreciated and can be directed to: lukas.jansing@env.ethz.ch

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