FESSTVaL
Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Numerical modeling of the mountain boundary layer and application to pollution control

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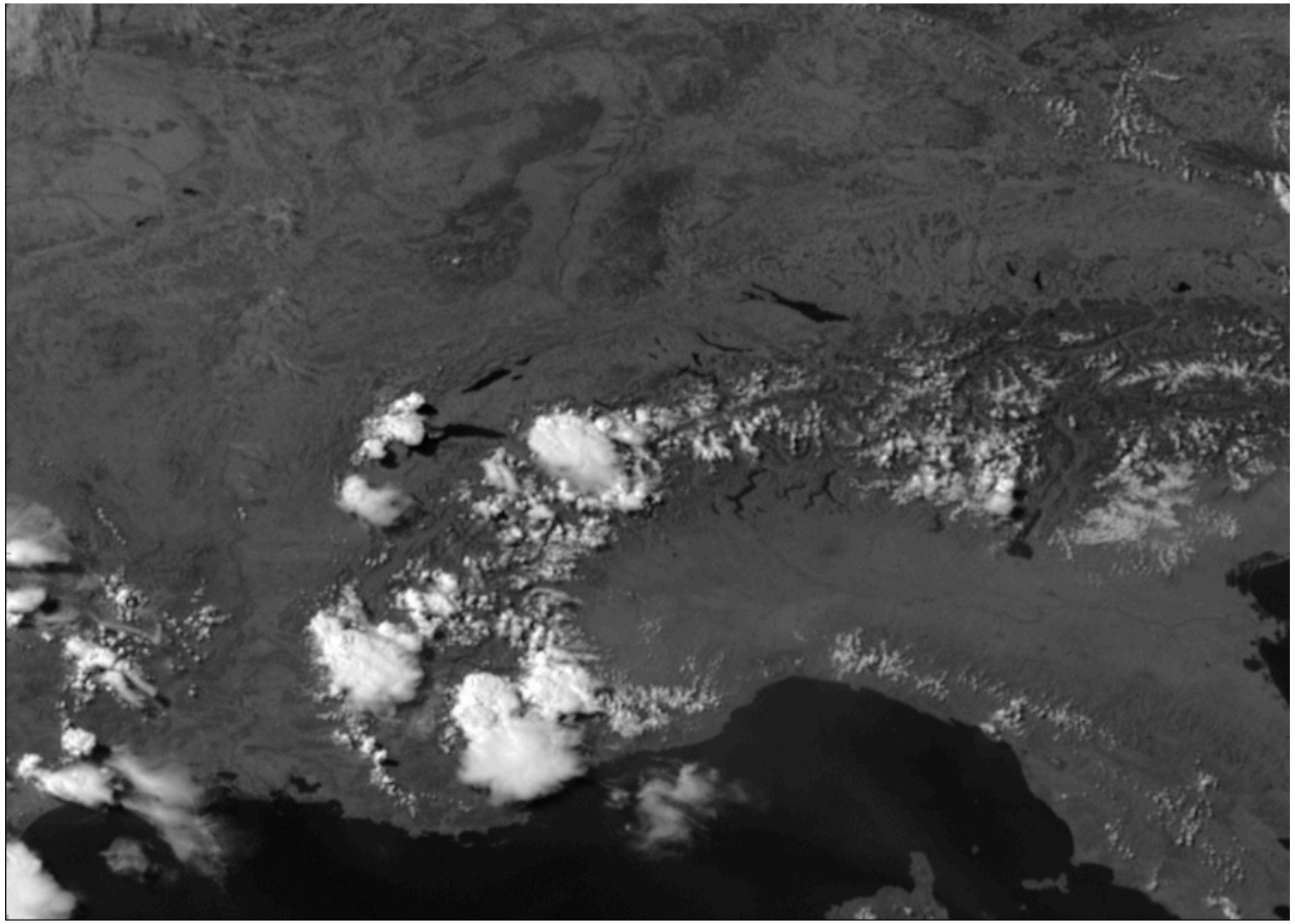
12 July 2021

FESSTVaL Summer School

Convection over the Alps

20.06.2005 15 UTC (17 LT)



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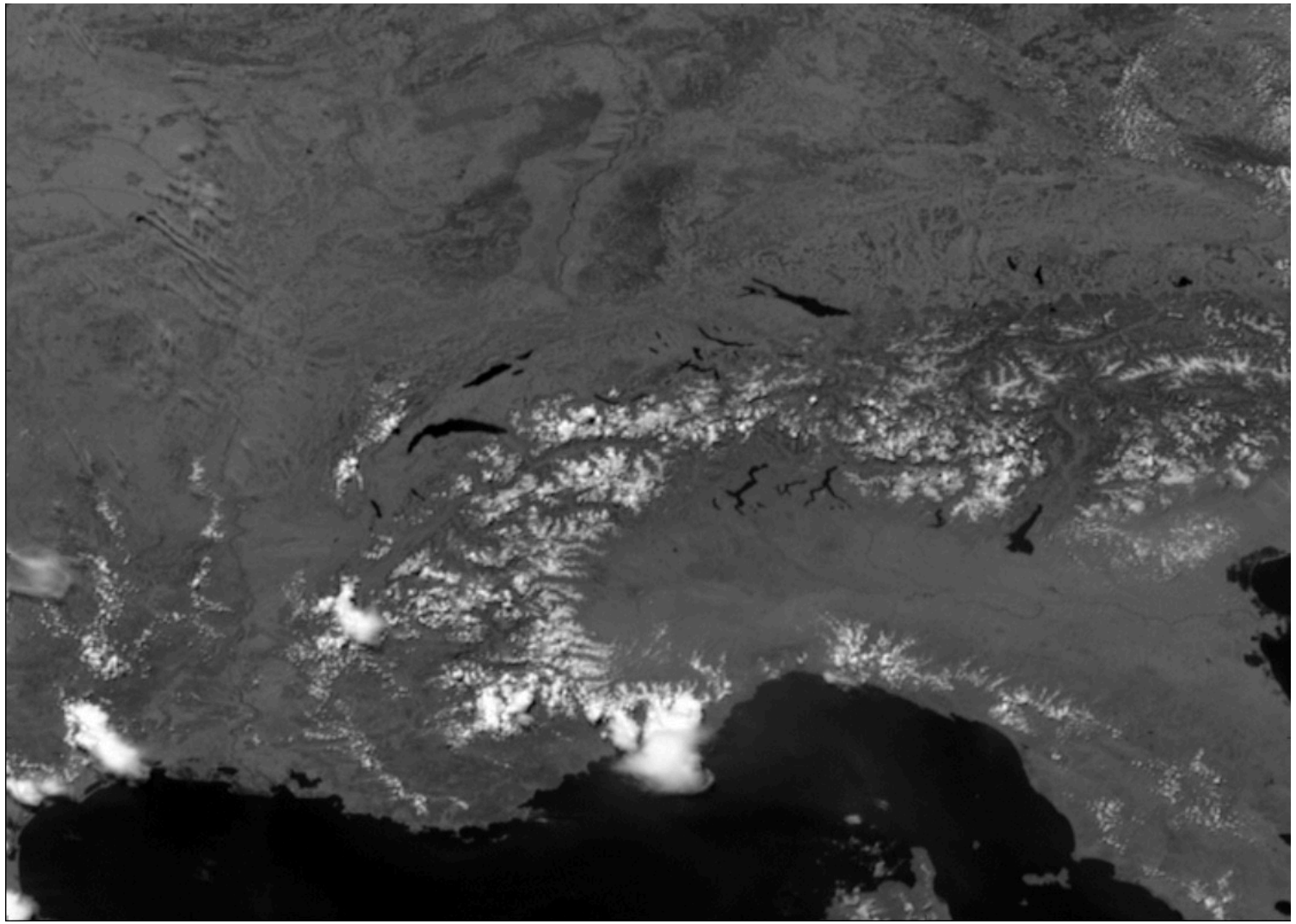


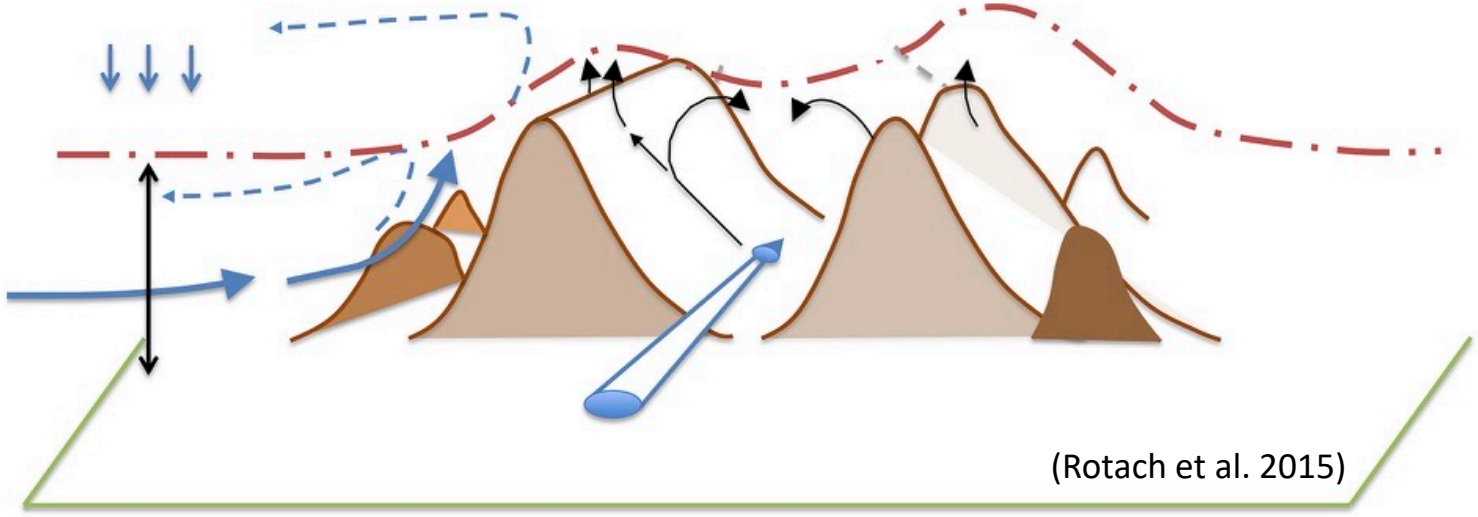
Why care about the mountain boundary layer (MoBL)?

- Impacts near-surface weather in mountainous regions (many settlements)
- Key role in triggering deep convection and producing extreme events
- Exchange of heat, momentum, moisture & pollutants between surface and atmosphere

Outline

- **Some basics on the mountain boundary layer (MoBL)**
- Modeling the MoBL
- Application to air pollution

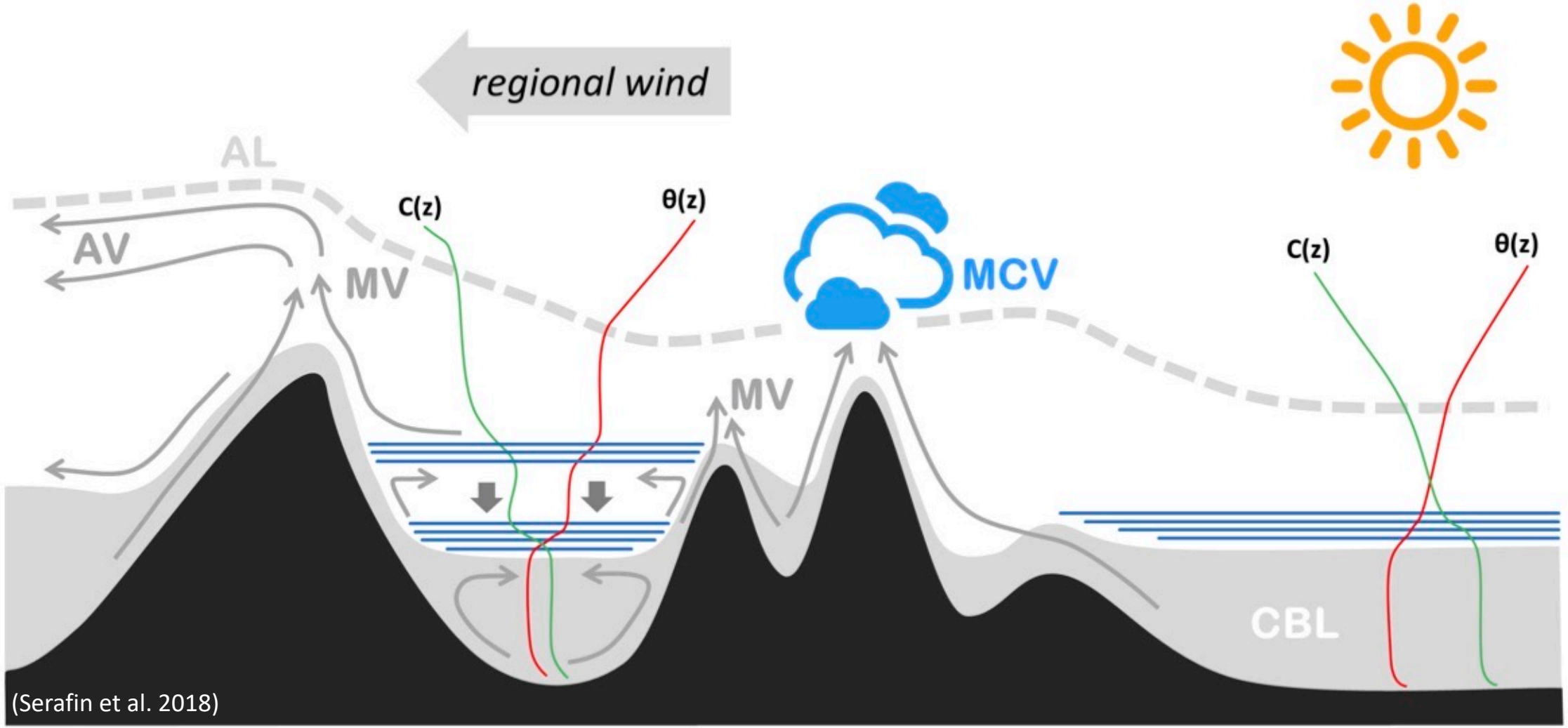
The mountain boundary layer (MoBL)



Diurnal mountain winds
→ slope winds
→ along-valley winds
→ plain-mountain circulation

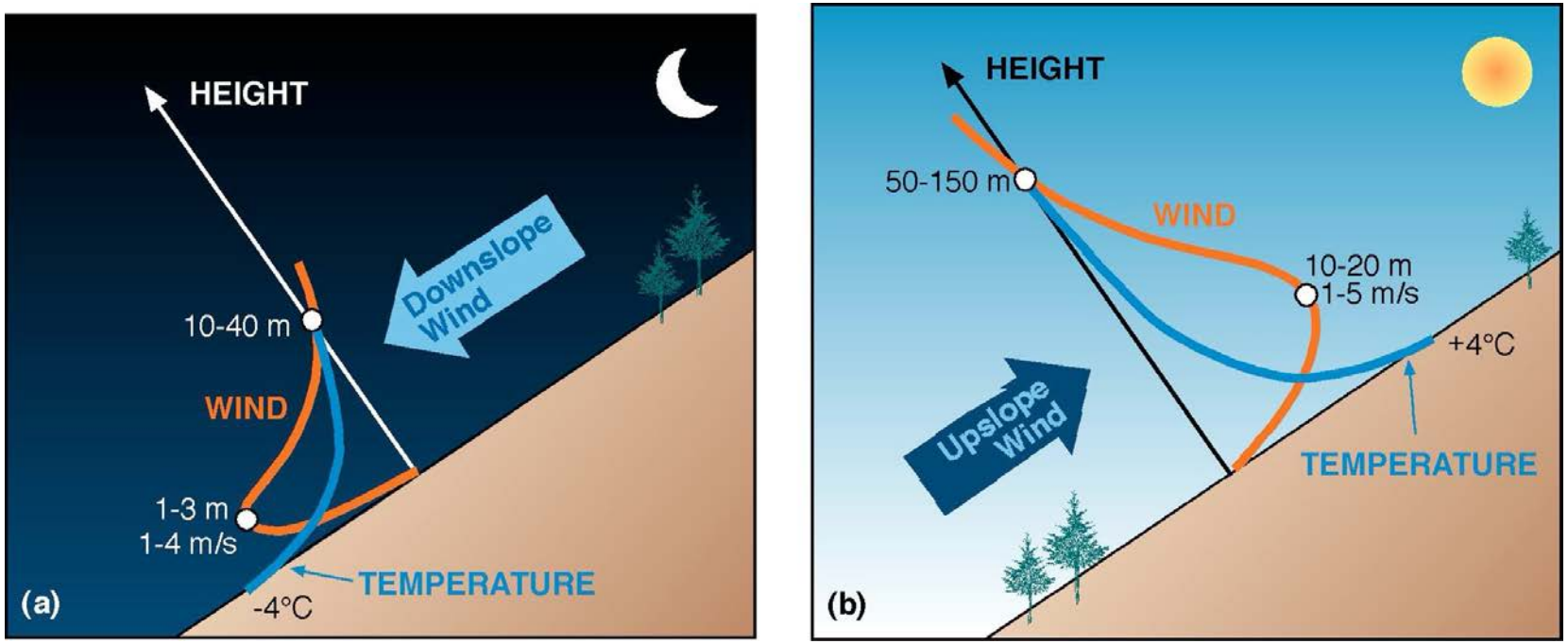
Definition of MoBL:
Lowest part of troposphere that is *directly influenced* by the mountainous terrain, responds to surface and terrain forcings with *time scales of about one to a few hours*, and is ***responsible for exchange of energy, mass, and momentum*** between mountainous terrain and free troposphere.
(Lehner and Rotach, 2018)

The mountain boundary layer (MoBL)



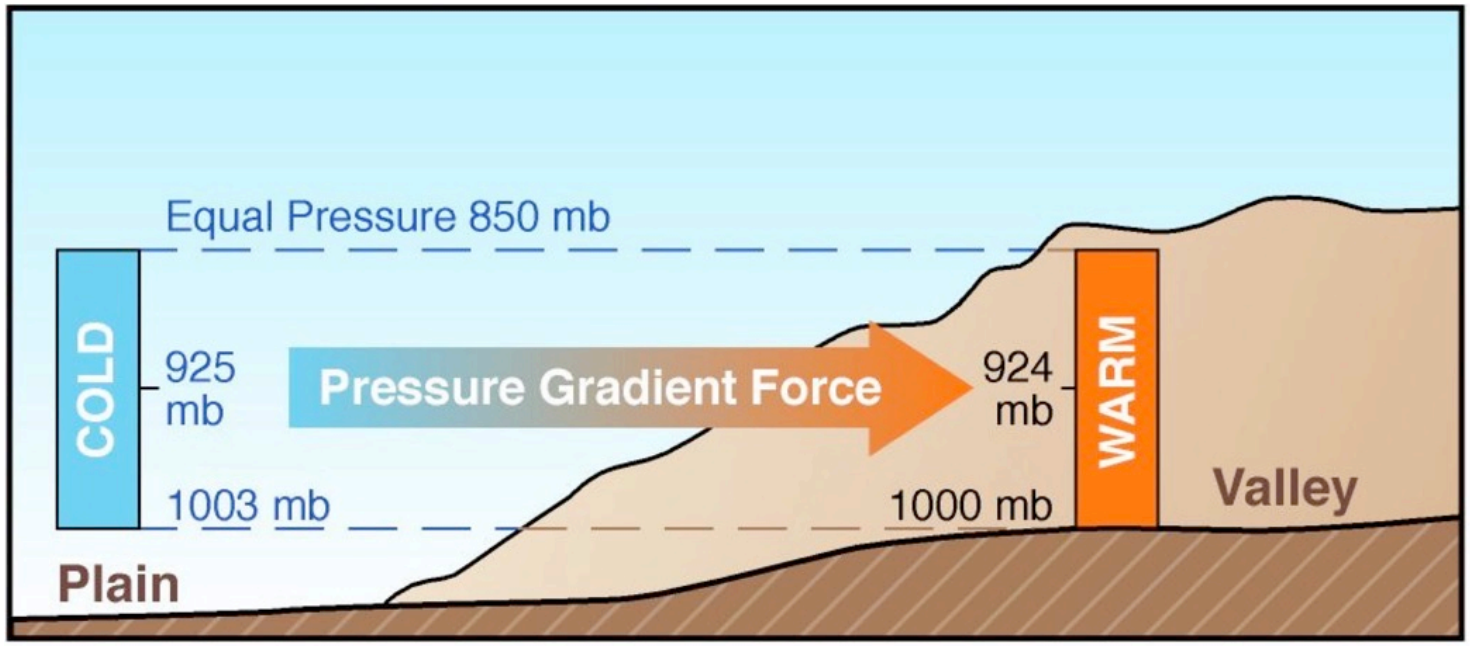
(Serafin et al. 2018)

Slope winds



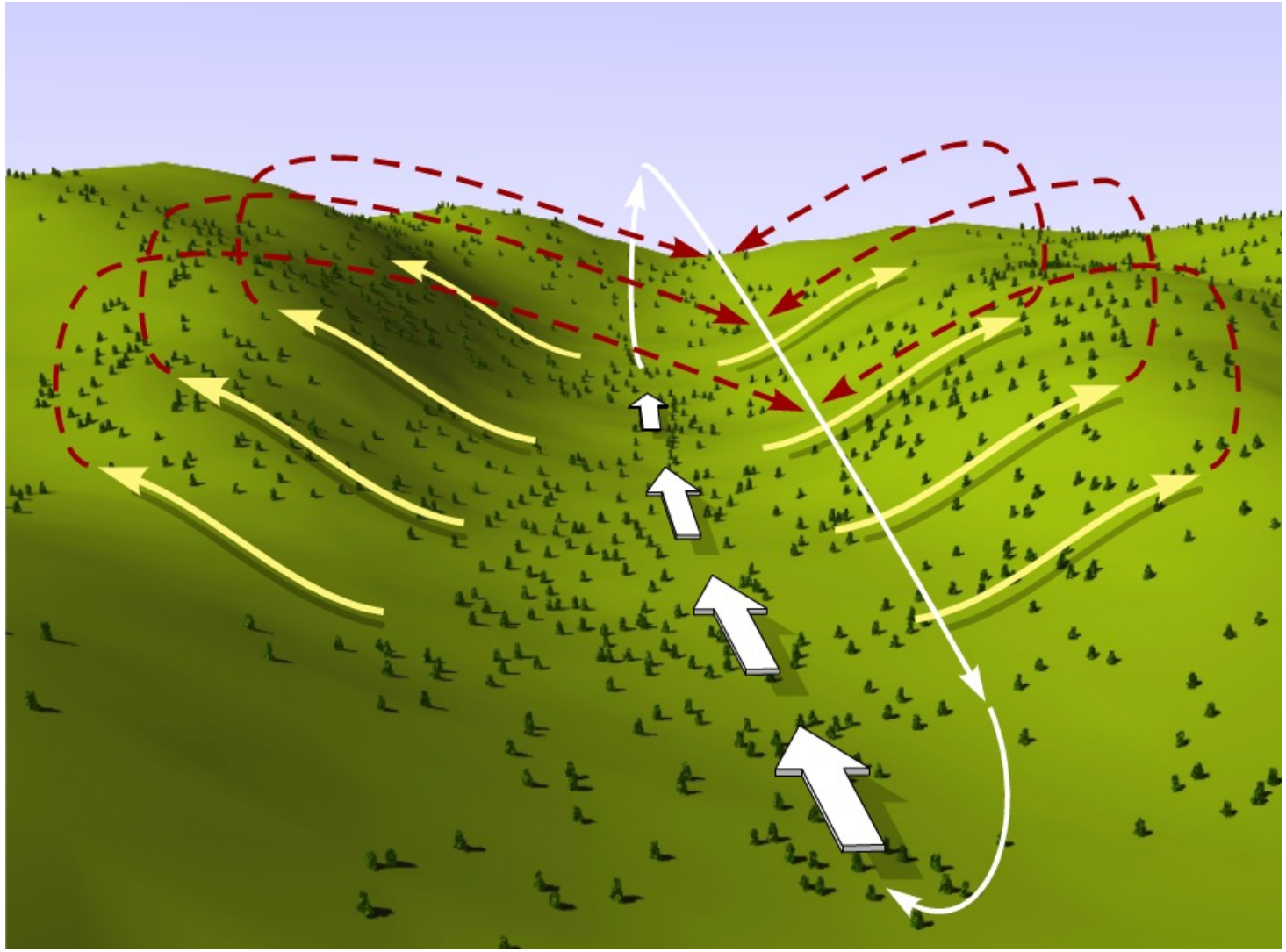
- **Mechanism:** Caused by differences in temperature between the air heated or cooled over the slopes and air at the same altitude over the valley center
- Daytime: Warm air is lighter and runs up the slope
- Nighttime: Cold air is heavier and runs down the slope

Along-valley winds

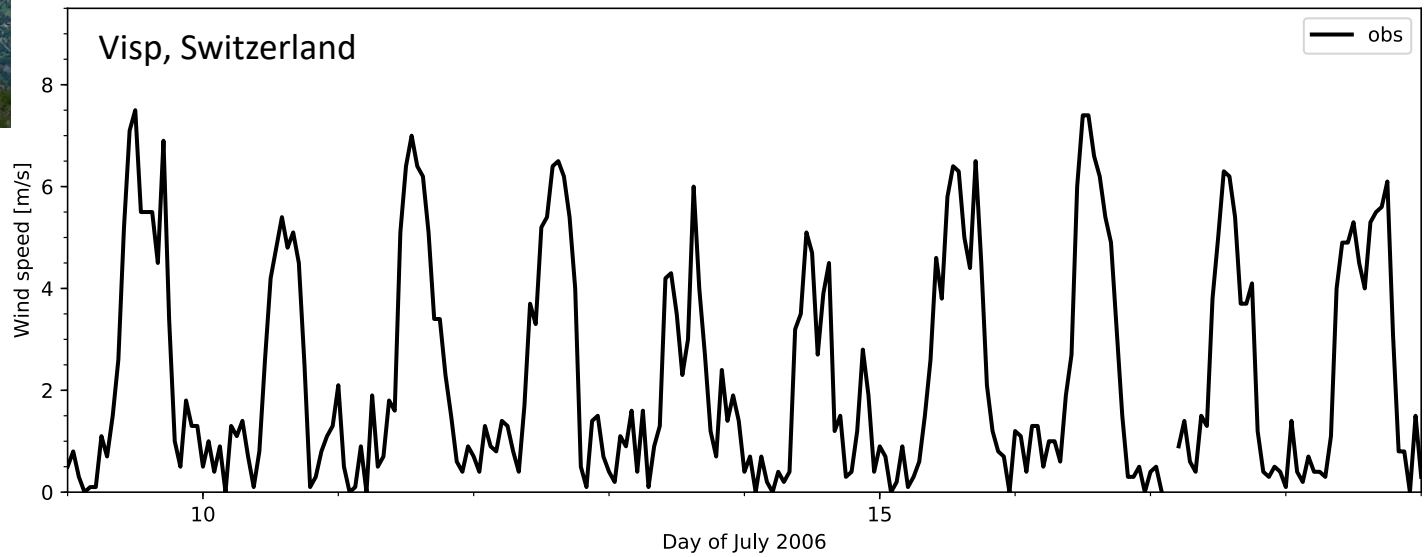


- **Mechanism:** Driven by along-valley pressure gradients due to temperature differences
- Daytime: Valley atmosphere heats more rapidly due to valley volume effect → up-valley winds
- Nighttime: Valley atmosphere cools more rapidly → down-valley winds
- Typical velocities: 3-10 m/s

The valley wind system



Wind speed in an Alpine valley



Outline

- Some basics on the mountain boundary layer (MoBL)
- **Modeling the MoBL**
- Application to air pollution

Question

How well do current numerical weather prediction (NWP) models represent the mountain boundary layer and the diurnal mountain winds?

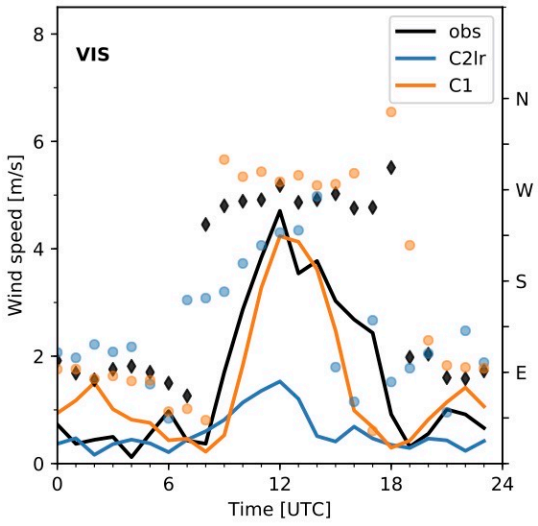
Previous research

Best operational NWP models have horizontal grid spacing of O(1km): **Is that enough?**

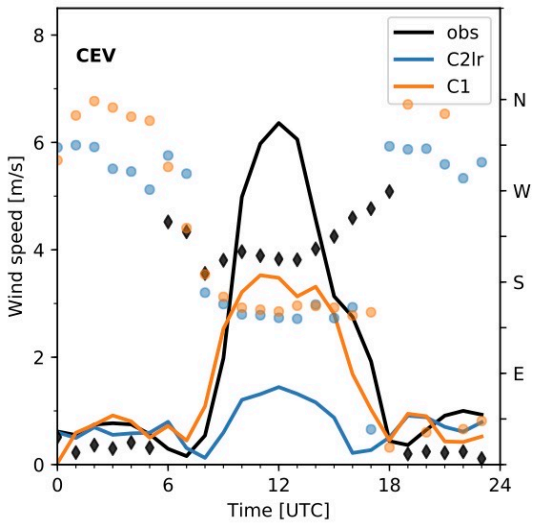
Study with COSMO model in quasi-operational setup (Schmidli et al., 2018)

- Valley winds well captured in **larger** Alpine valleys,
  if 1km grid spacing & **high-resolution land surface** datasets are used

large valley



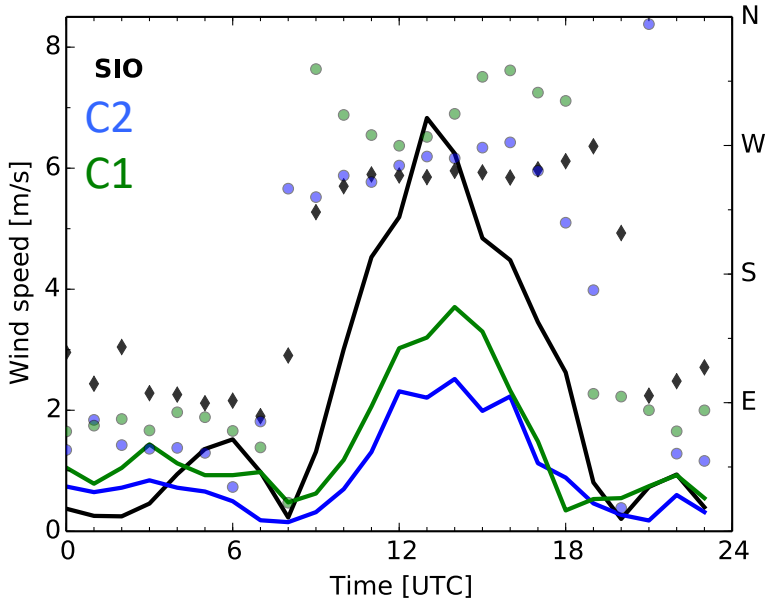
small valley



Mean diurnal cycle for July 2006

Previous research

...except for Sion

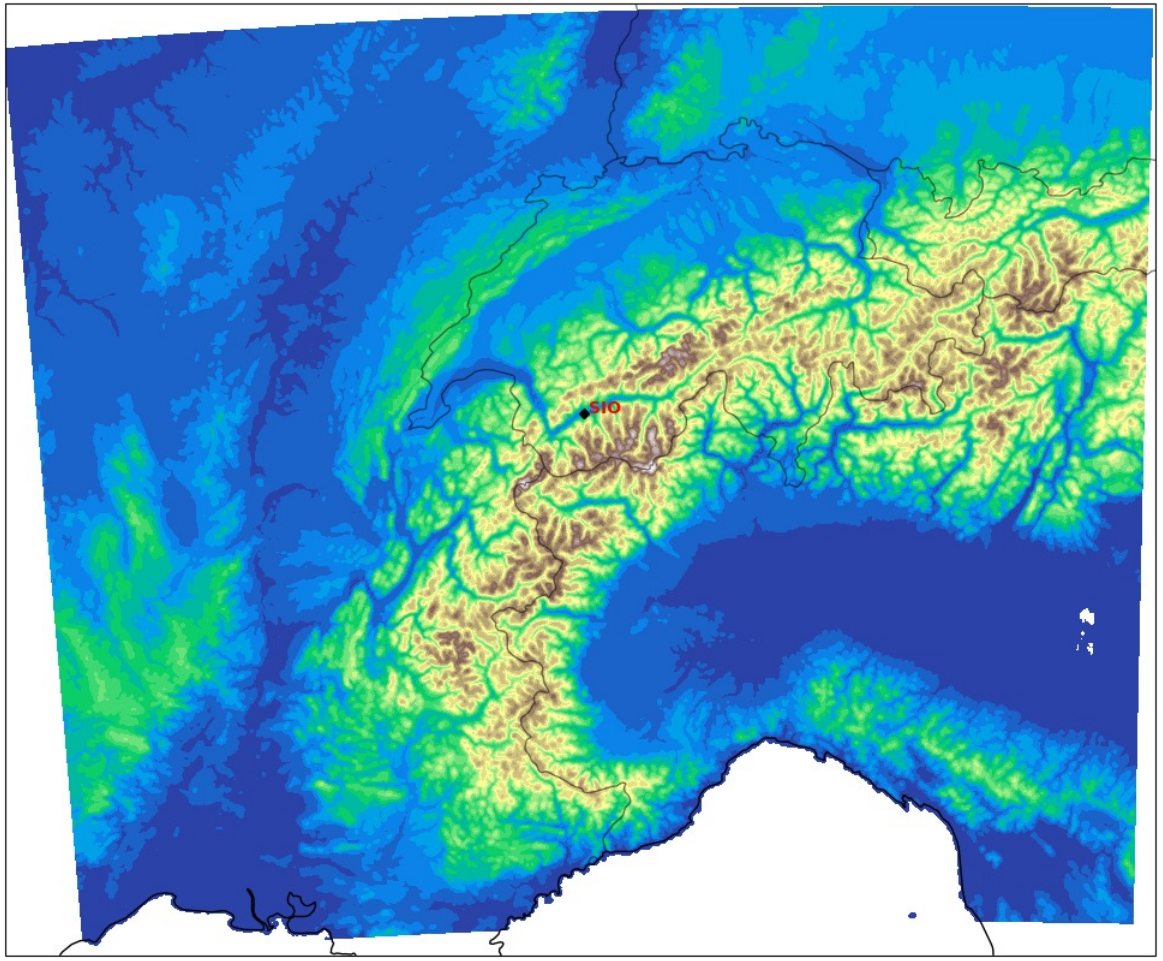


Questions

- What is the cause of the poor skill for Sion?
- Skill of simulated wind at higher elevations?

Experimental setup

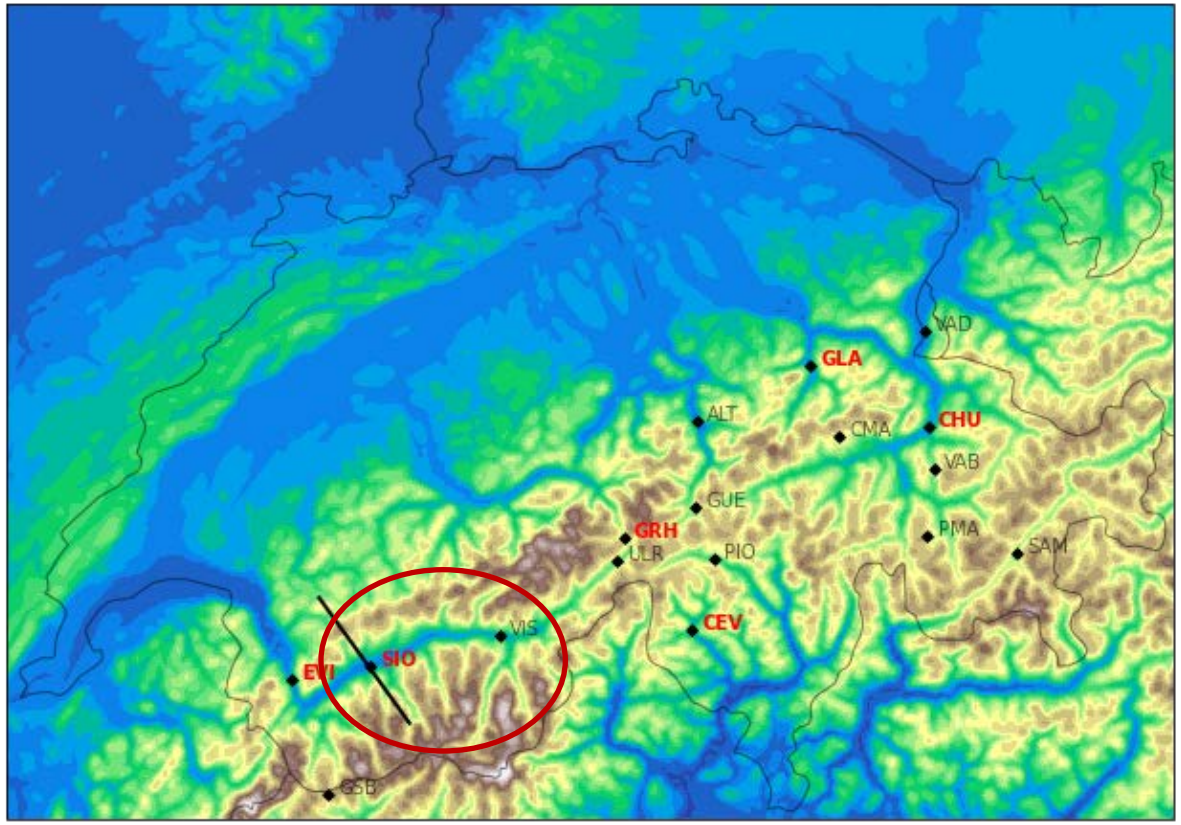
- Simulation period: **September 2016**
- COSMO model (as used by MeteoSwiss)
- **Grid spacing**: Δ=1 km, 80 levels
- Integration domain: ca 830x830 km
- Initial and BCs from COSMO-1 analysis (MeteoSwiss)
- Standard physics options, close to COSMO-1 operational setup at MeteoSwiss (no shconv; Kmin = 0.1)
- Land surface characteristics
  - ASTER topography (30 m)
  - GC2009 land cover (300 m)
  - HWSD soil (1 km)



Observations

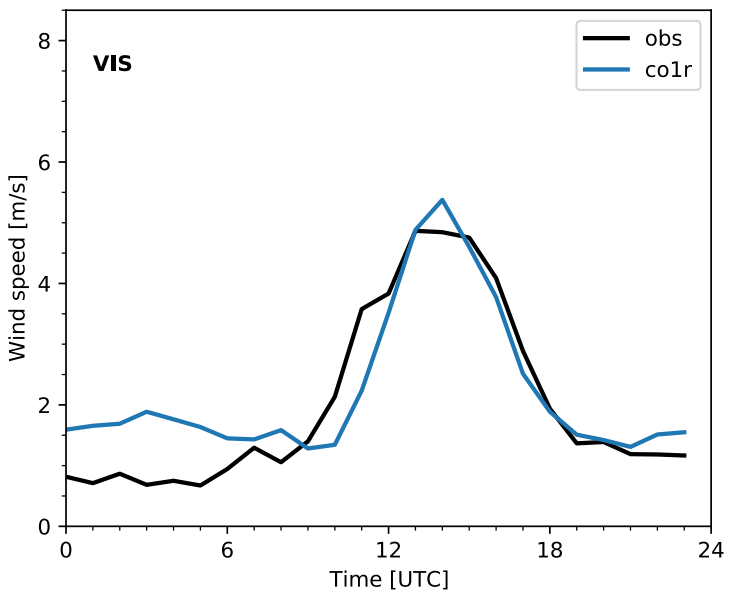
- Standard hourly observations (wind, T, …) from MeteoSwiss automatic station network
- Wind profiler located next to Sion station (Sep 2016 – Jul 2017)

(Photo: A. Haefele, MeteoSwiss)

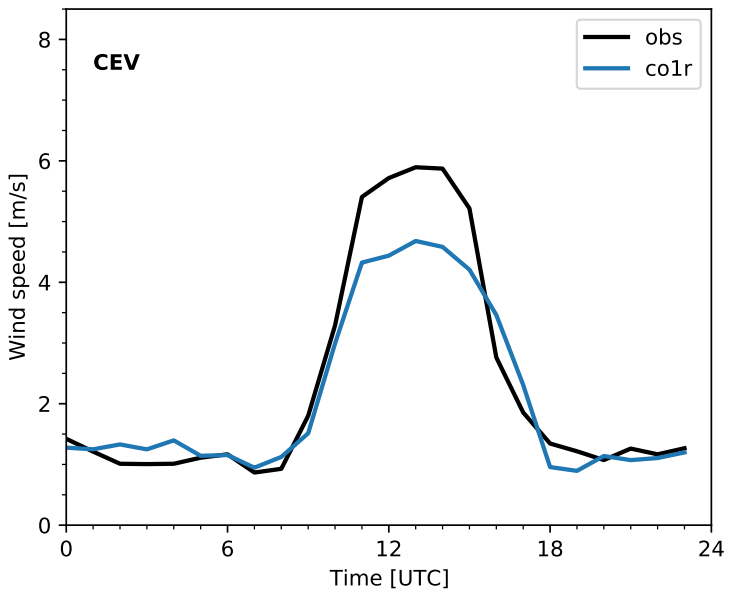


Mean diurnal cycle of along-valley wind for Sep 2016 (18 days)

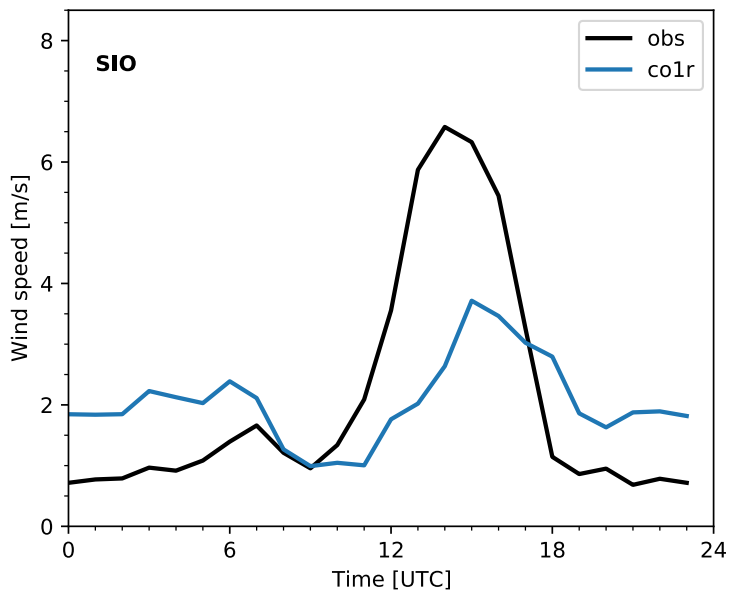
large valley



small valley



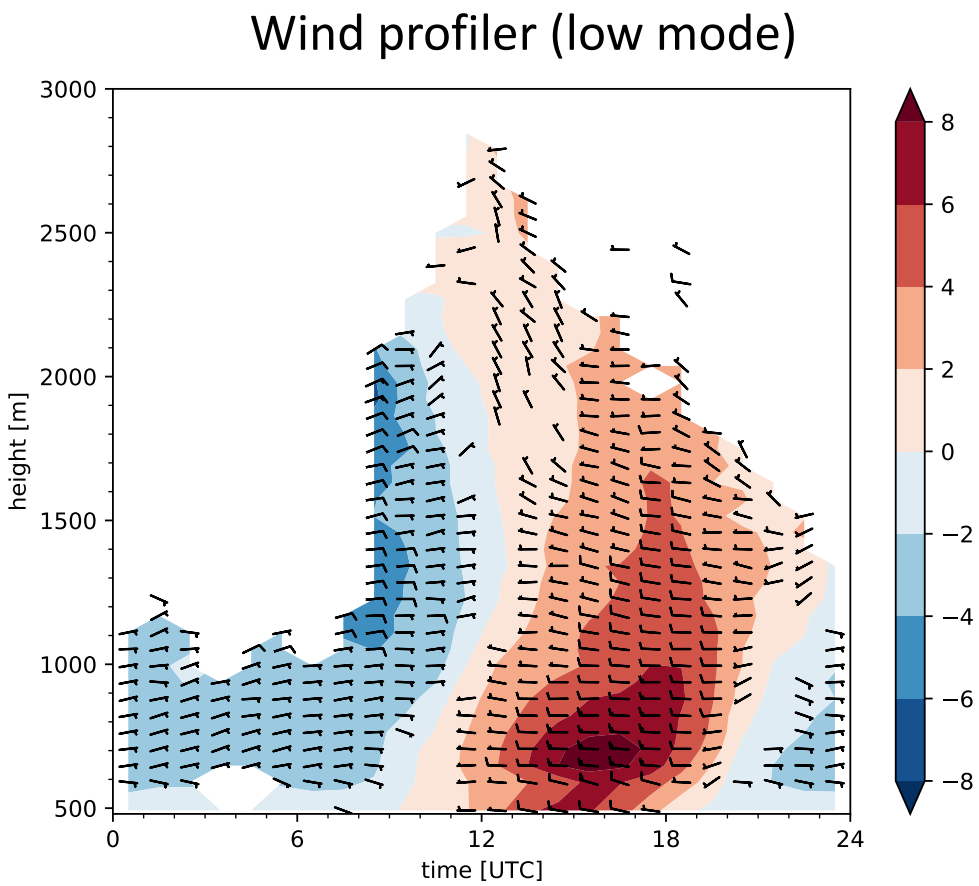
Sion

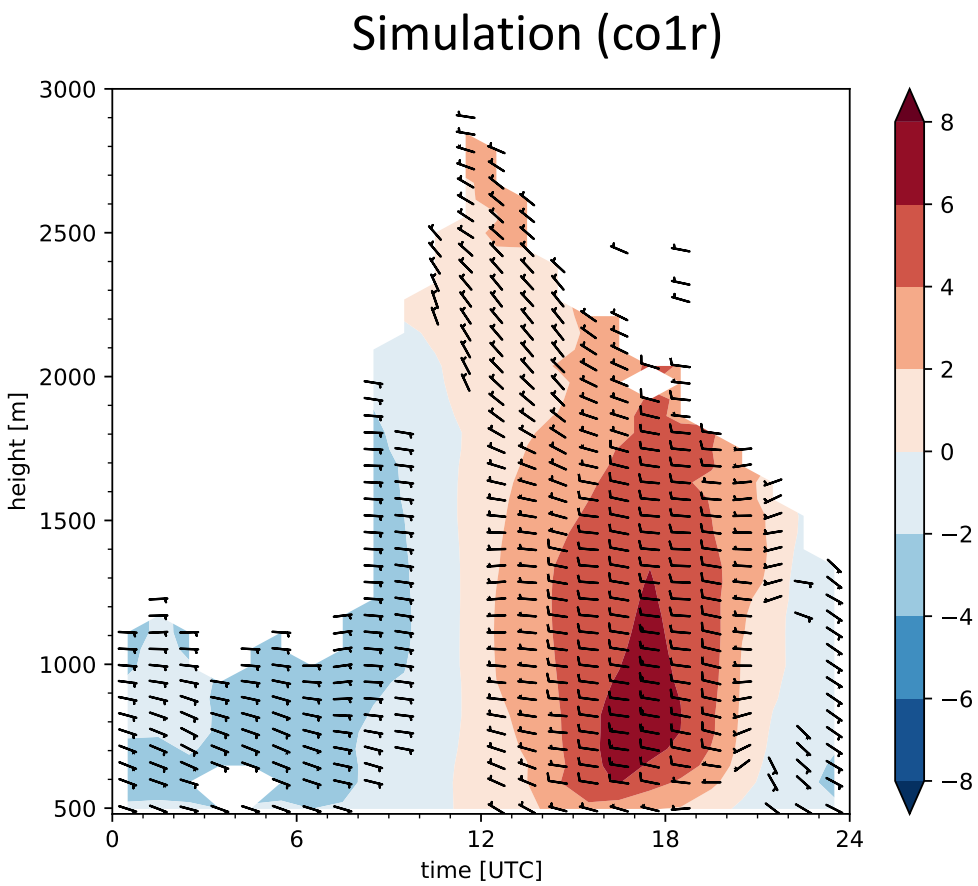


→ similar results to previous study (different period & different model version)
→ **still: underestimation** of **wind speed for Sion** (as in previous study)

→ Valley wind at Sion generally too weak, or just near the surface?
→ Investigate wind profile throughout valley depth!

Mean diurnal cycle of along-valley wind (18 days, fval=0.5)





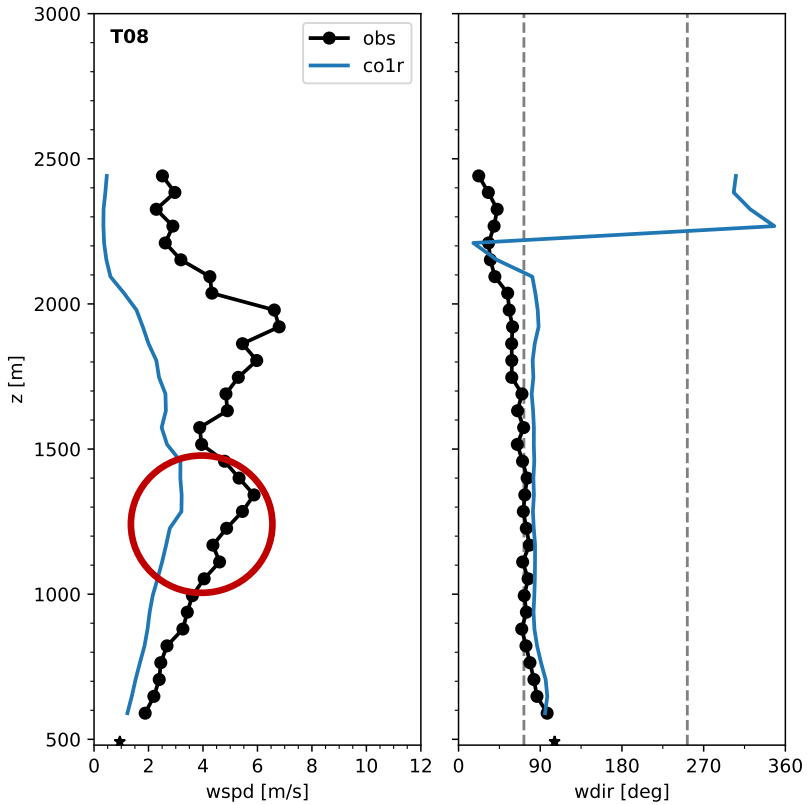
→ as expected: strong diurnal cycle throughout valley atmosphere

→ low-level up-valley jet

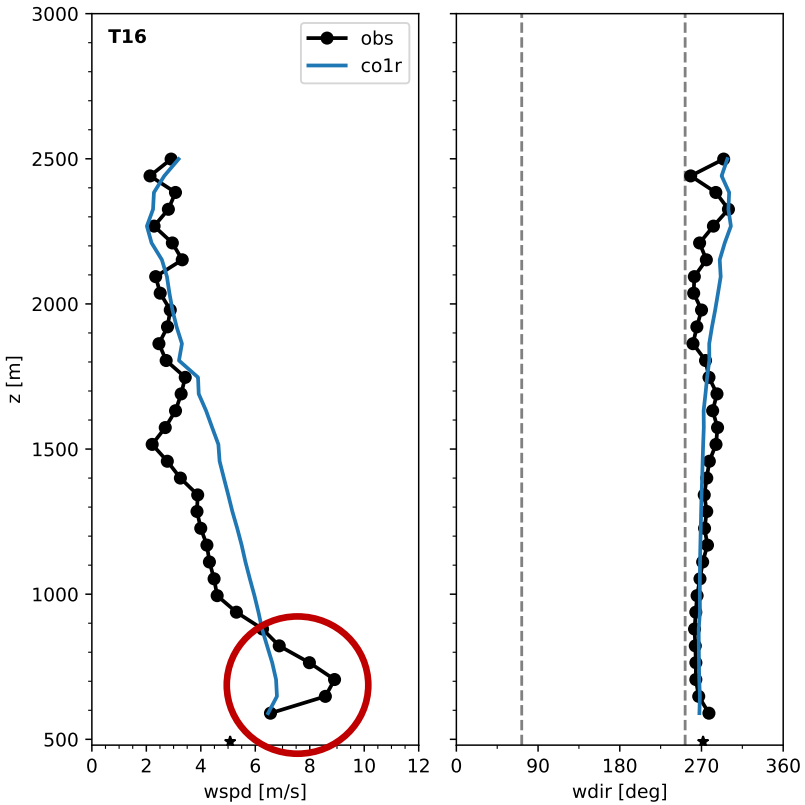
Evaluation of valley wind profile at Sion (18 days)

Low mode wind profiler data (dz = 58 m)

Mean down-valley wind (8 UTC)



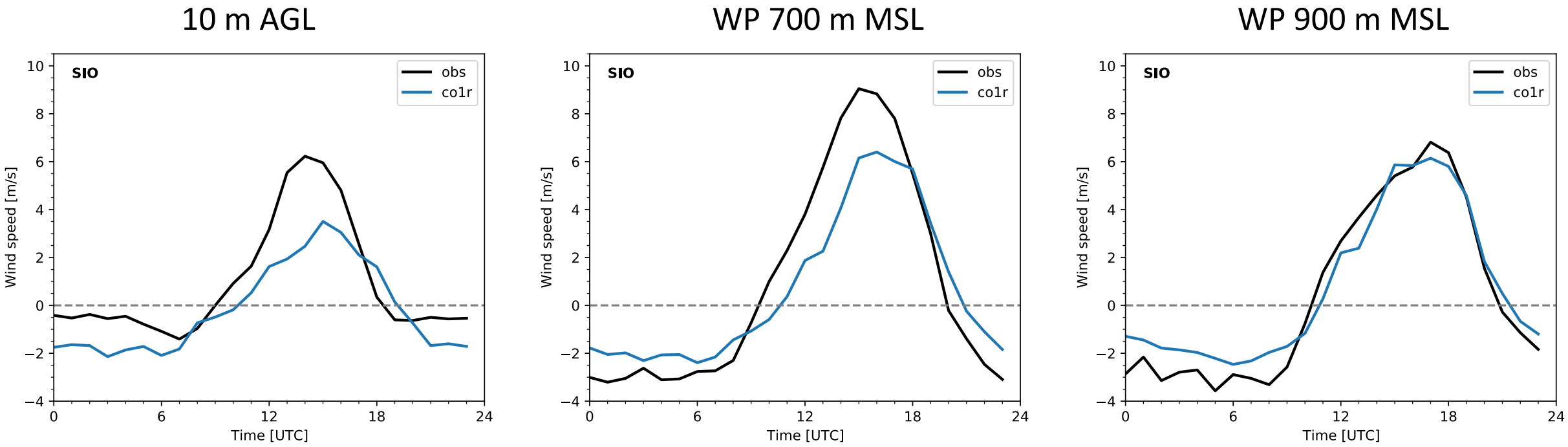
Mean up-valley wind (16 UTC)



→ too weak nighttime down-valley flow

→ too weak near-surface daytime up-valley flow

Mean diurnal cycle of along-valley wind at Sion

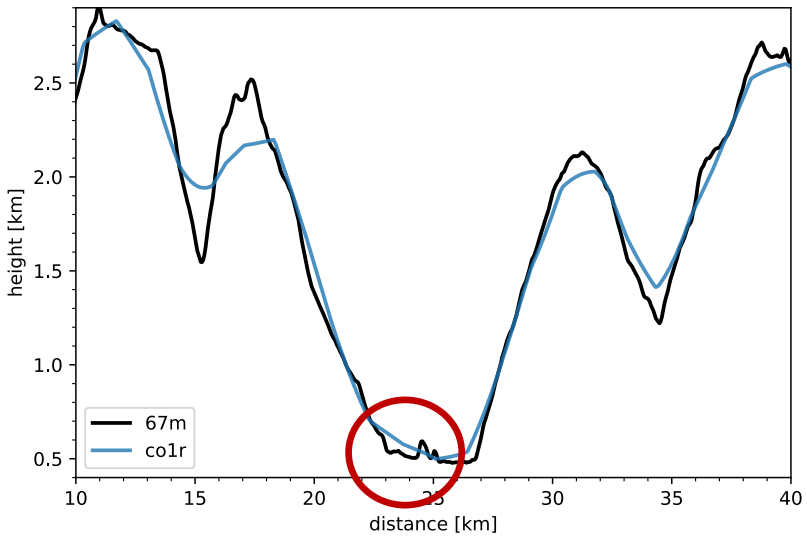


→ excellent agreement at 900 m MSL

→ COSMO-1 up-valley wind too weak **only** near the surface (lowest 200-300 m AGL)

Why large bias of near-surface wind speed at Sion?

Orography (cross section at Sion)

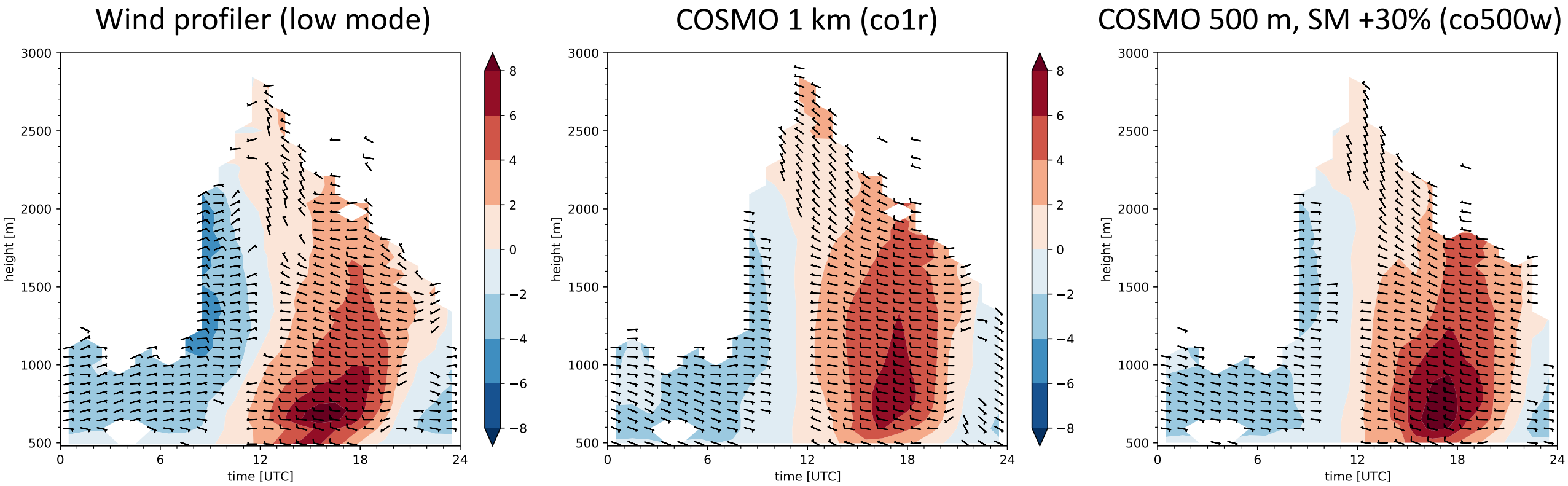


- local constriction of valley leads to flow acceleration in lowest 200-300 m AGL
  → the low-level up-valley jet seen in wind profiler data

Improvement possible?

→ New experiment: COSMO with $\Delta = 500$ m and increased soil moisture (SM +30%): co500w

Mean diurnal cycle of along-valley wind (18 days, fval=0.5)

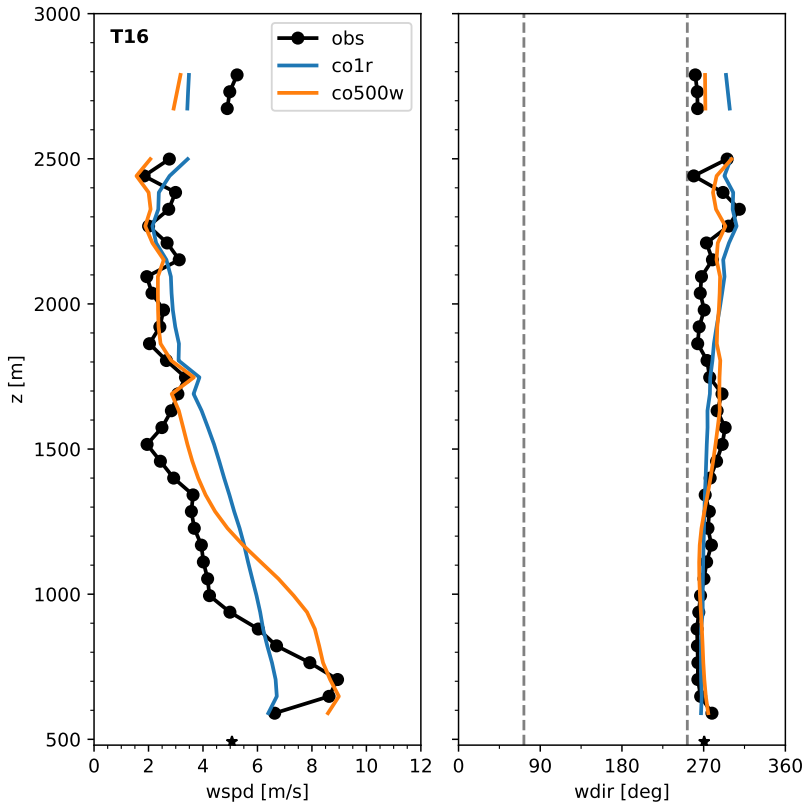


→ significant improvement for co500w (SM +30%, dx=500m)

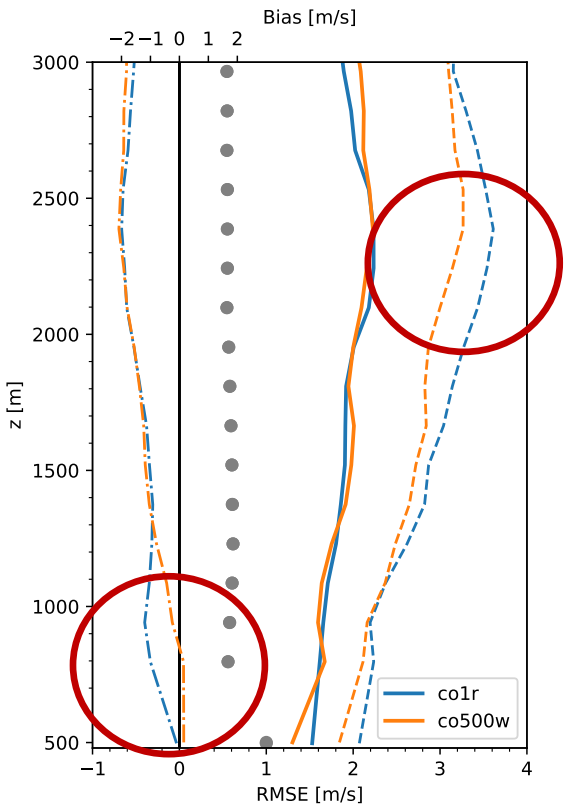
Evaluation of valley wind profile at Sion (16 days)

Mean up-valley wind (16 UTC) and RMSE

Low mode wind profiler



RMSE (all hours)



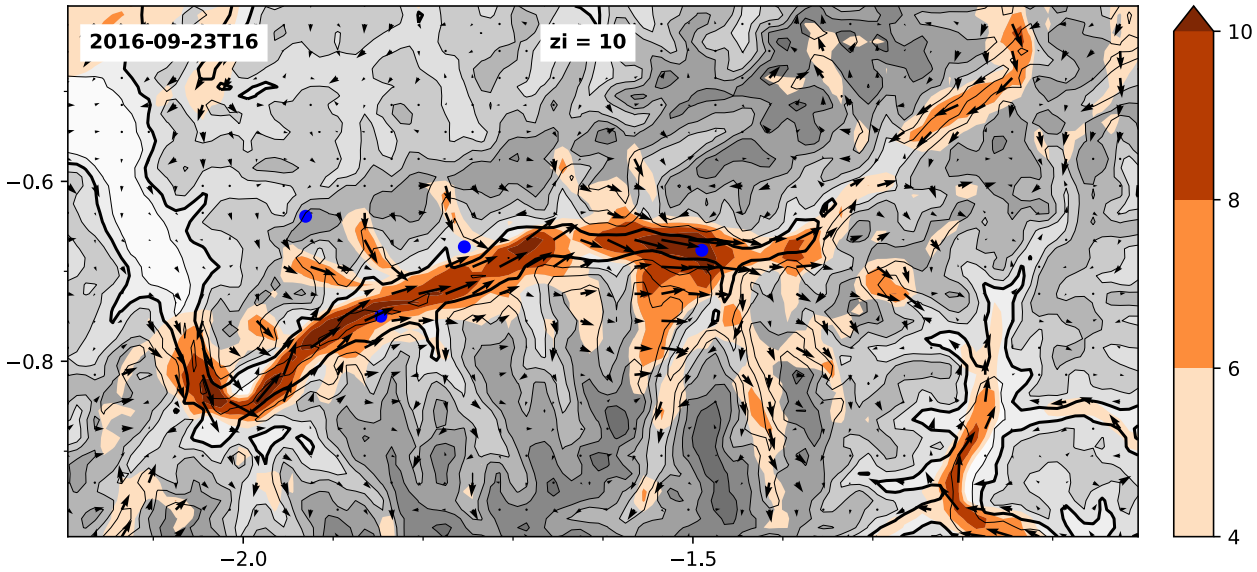
→ strength of low-level up-valley jet better captured by co500w

→ reduced bias in lowest 700 m AGL and reduced RMSE (velocity vector) at all levels for co500w

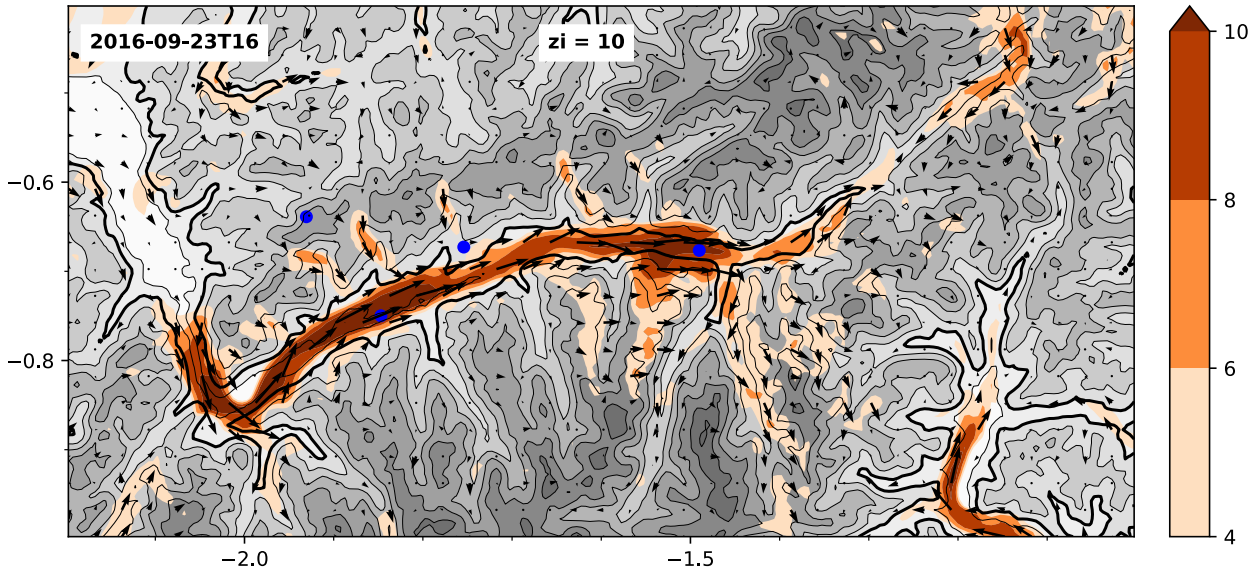
→ Implications for specific days?

Example 1: 23 Sep 2016 – 16 UTC
Wind at ca 200 m AGL

COSMO 1 km (co1r)



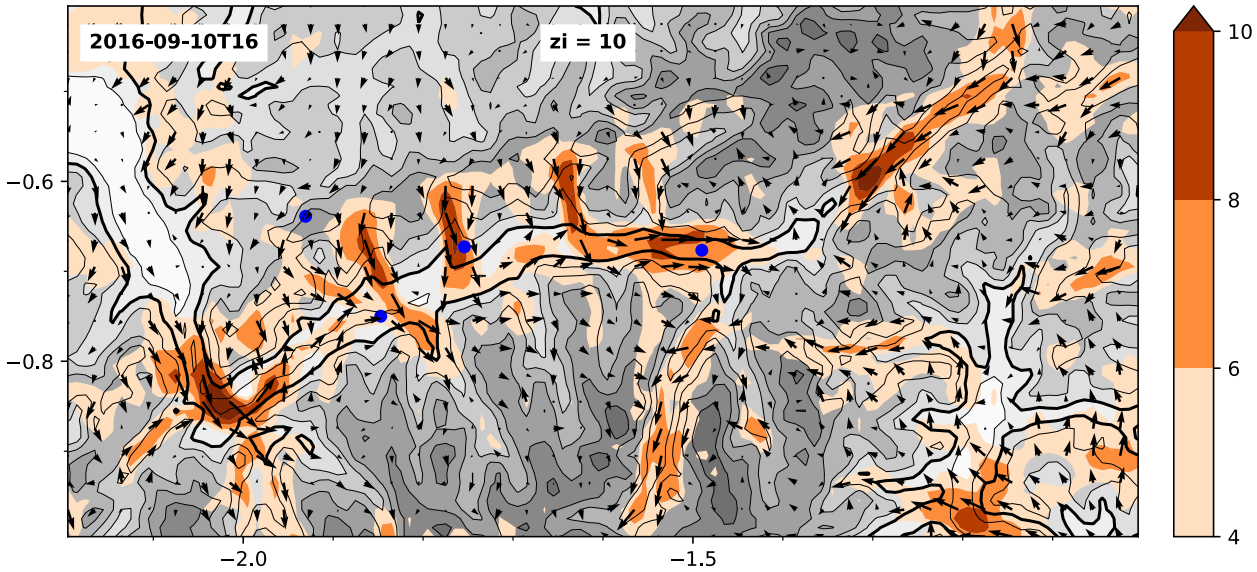
COSMO 500 m, SM+30 (co500w)



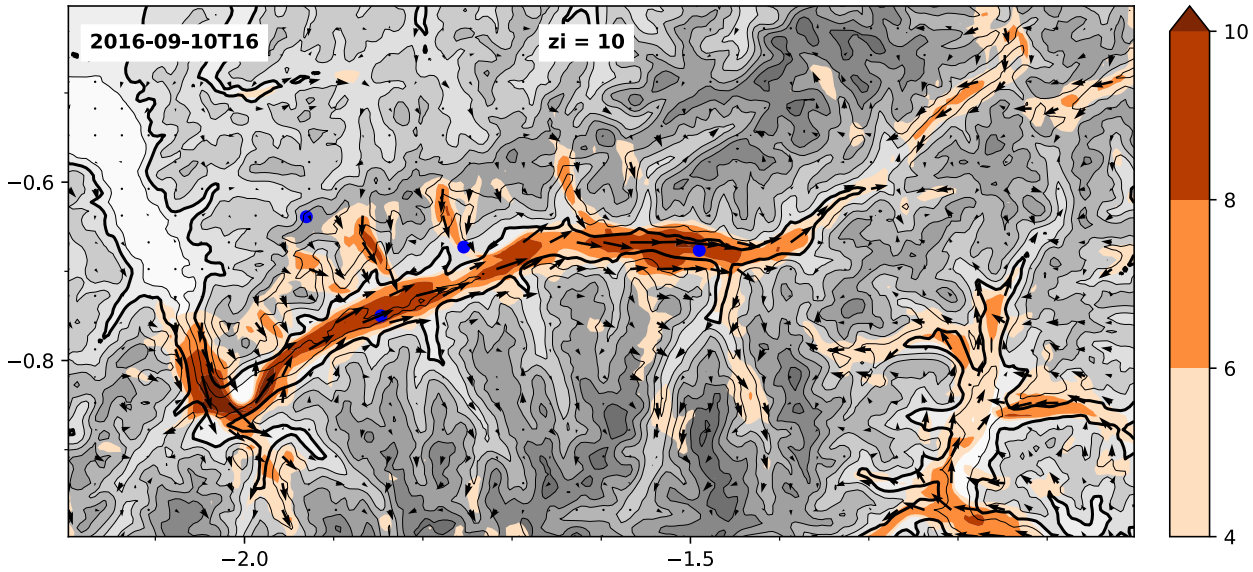
→ quite similar evolution of up-valley wind; somewhat stronger & more continuous for co500w

Example 2: 10 Sep 2016 – 16 UTC

COSMO 1 km (co1r)



COSMO 500 m, SM+30 (co500w)



→ co1r: **strong cross-ridge flow** disturbs development of up-valley wind

→ co500w: strong up-valley wind, consistent with observations

→ **large difference on some days, in particular for days with a northerly upper-level flow component**

→ **a story for another day**

Lessons learned

- Mountains and MoBL have strong impact on local weather & the larger scale weather and climate
- Accurate prediction of MoBL and mountain weather is challenging due to complex interactions of many different phenomena (e.g. turbulence & diurnal mountain winds)
- Example: Along-valley wind at Sion
  - Strong diurnal cycle with daytime up-valley jet of 9 m/s
  - COSMO 1km: good agreement with observations, except for lowest 200 m
  - Poor skill for lowest 200 m due to local valley geometry and general model biases (too well-mixed and too deep valley boundary layer)
- **There is a significant potential for improved forecasts**
  - Large improvement for COSMO 500m (and SM + 30%)

➢ **Achieving accurate simulations of valley weather** requires

  ➢ Detailed observations of boundary layer structure in Alpine valleys

  ➢ Improved model initialization (e.g. soil moisture) and physics parameterizations

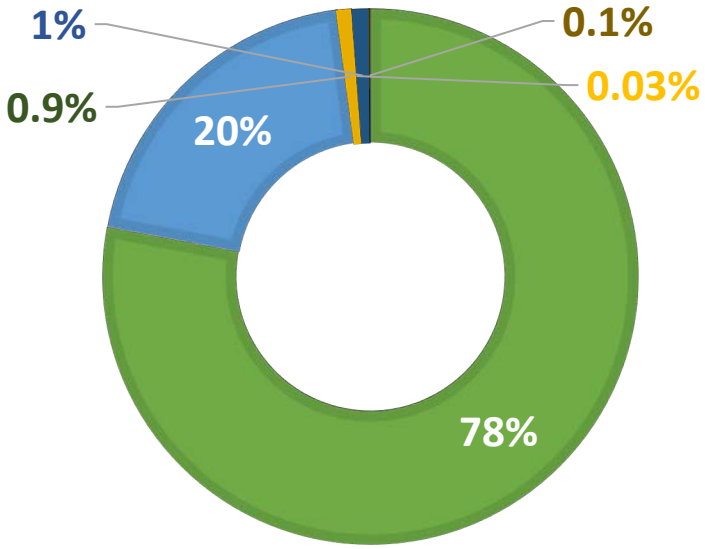
Motivation

http://www.mountain-spirit-guides.com
Chamonix 11th Feb 2012

- *What is that?*
- *How often does it happen?*
- *Where does this come from?*
- *Is it like this everywhere?*
- *Why such pollutant accumulation?*

What is that?

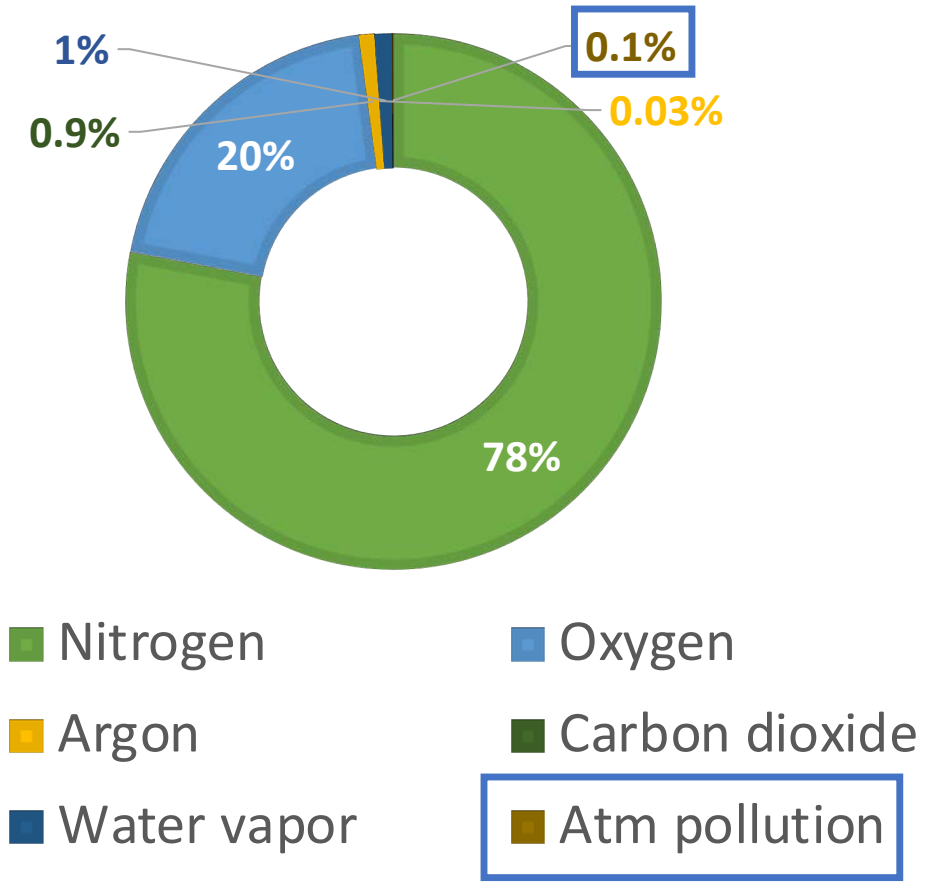
Low atmosphere composition:



- Nitrogen
- Oxygen
- Argon
- Carbon dioxide
- Water vapor
- Atm pollution

What is that?

What else is in there?



Main Pollutants in the Atmosphere

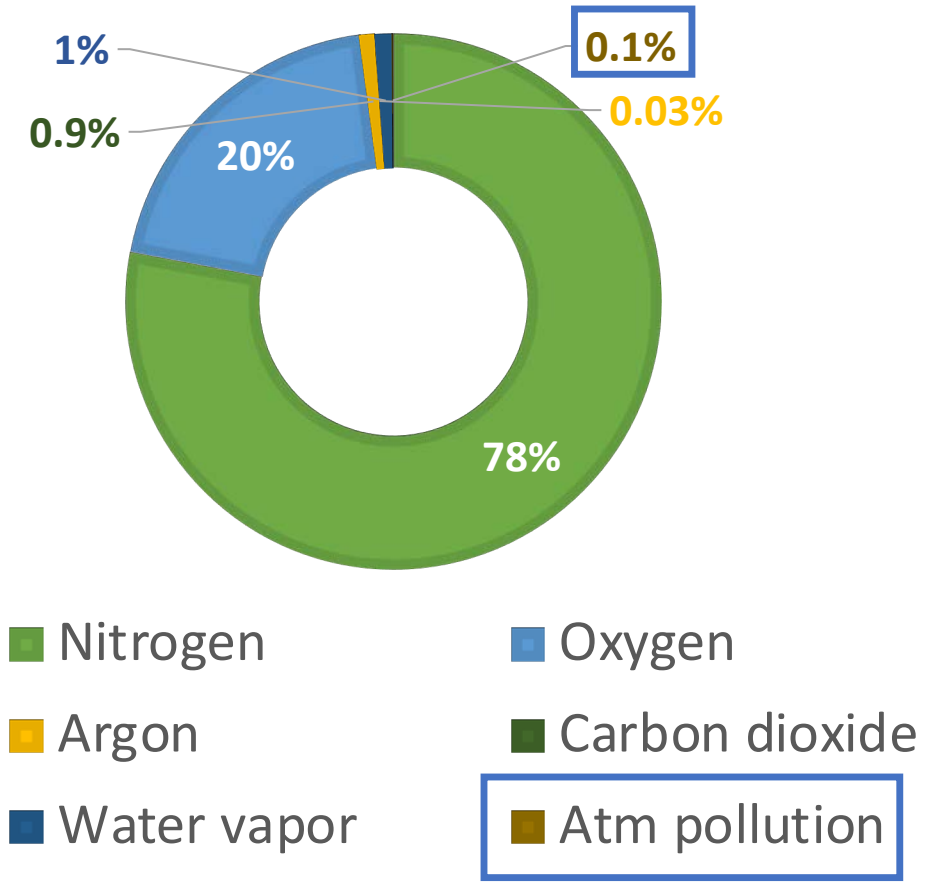
- Nitrogen oxides (NOx)
- Particulate matter ($PM_{2.5}$ and PM_{10})

Wintertime peaks

Jaffrezo et al. 2005a

What is that?

What else is in there?



Main Pollutants in the Atmosphere

- Particulate matter ($PM_{2.5}$ and PM_{10})

Wintertime peaks

Jaffrezo et al. 2005a

What is that?

Why is this a problem?

Impact on human's health
Impact on human's health
Particulate air pollution

- 4.2 million **premature deaths** worldwide for 2016 can be attributed to (outdoor) air pollution in both cities and rural areas. (WHO, 2018)
- 800,000 premature deaths worldwide each year can be attributed to particulate air pollution (Anderson et al., 2012a).

As a scale, Los Angeles has a population of 4 million.

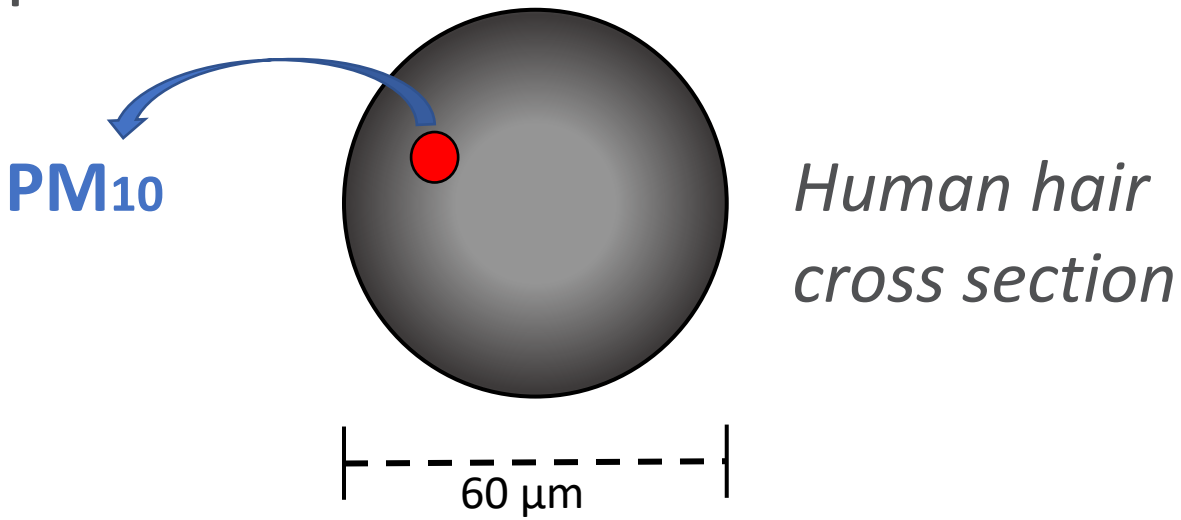
PM_{10}

*Common product of biomass combustion**

What is that?

What is PM_{10}?

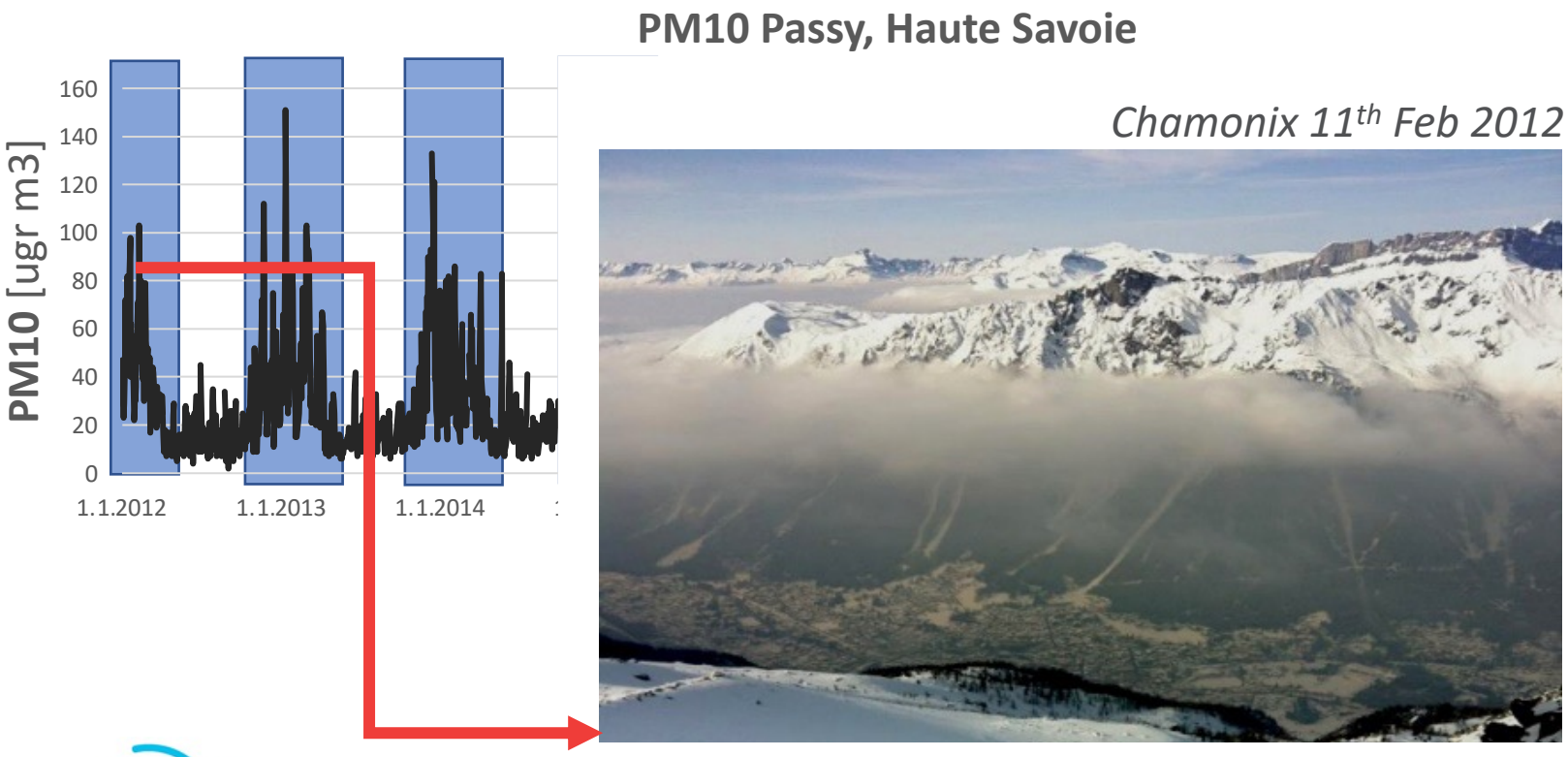
- Particles with an aerodynamic diameter of less than 10 µm.



- Particles emitted by anthropogenic sources.

How often does it happen?

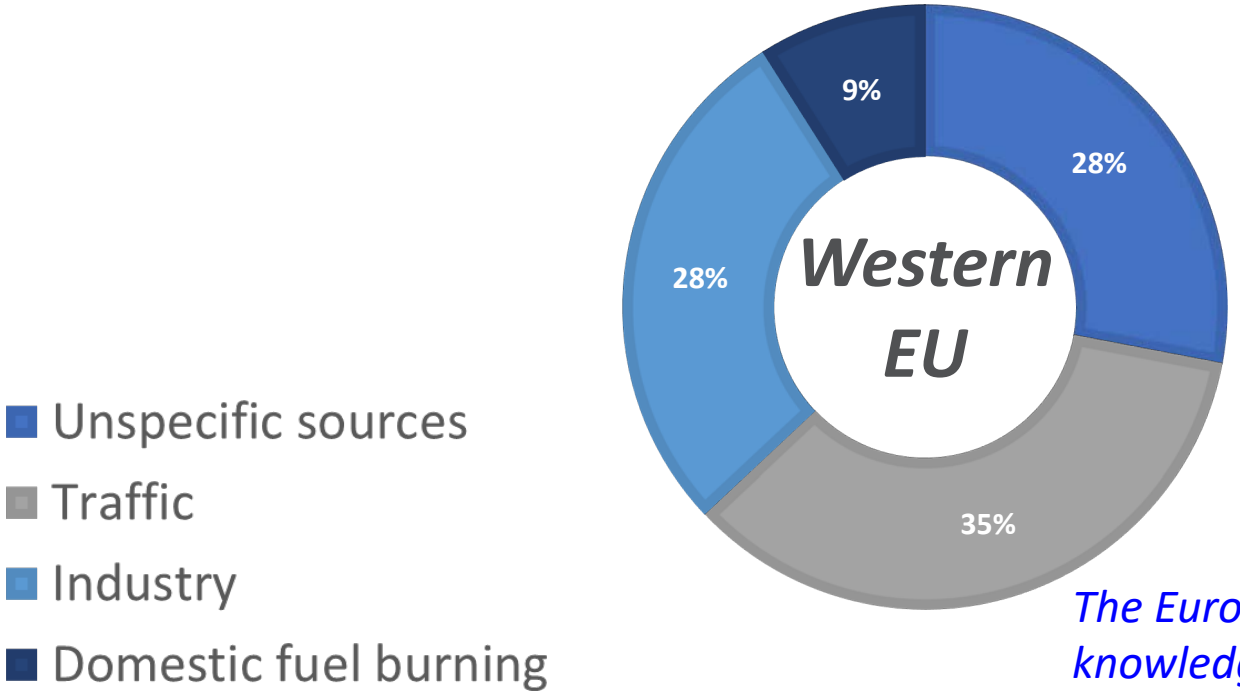
Seasonality



A Similar picture every winter

Where does this come from?

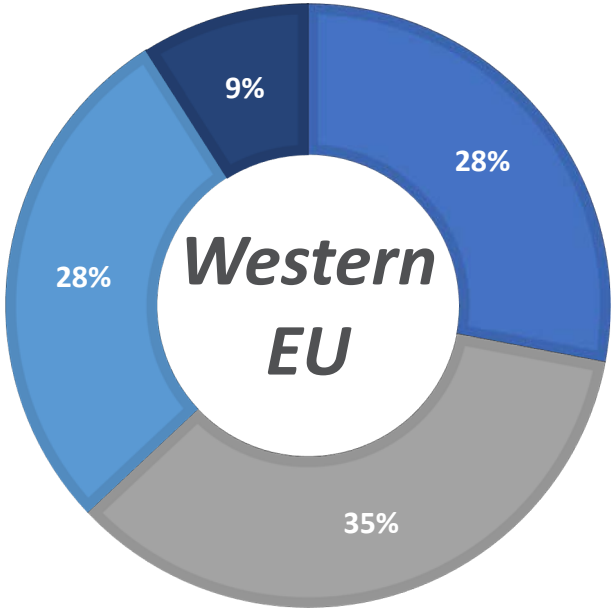
*Anthropogenic Source Contributions to **Total PM10** in urban sites*



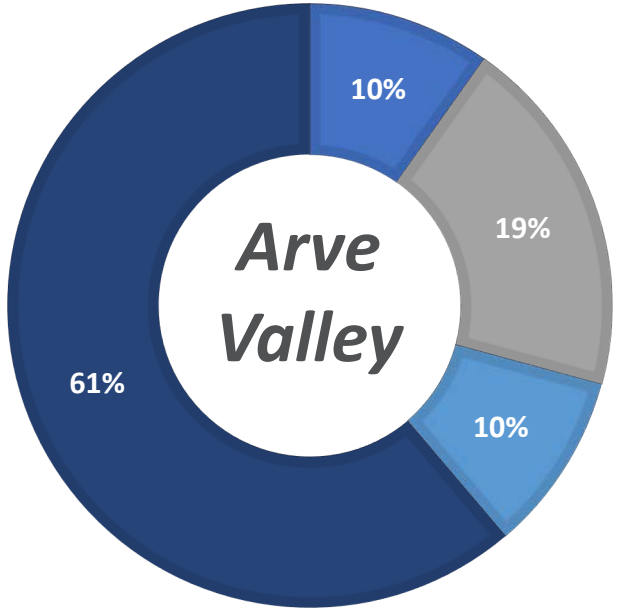
The European Commission's science and knowledge service, 2015

Where does this come from?

*Anthropogenic Source Contributions to **Total PM10** in urban sites*



The European Commission's science and knowledge service, 2015



Atmo Aura, 2017

- Unspecific sources
- Traffic
- Industry
- Domestic fuel burning

Is it like this everywhere?

Yes …

Santiago de Chile, Chile

Saide et al., 2011

Salt Lake City, Utah, US

Whiteman et al., 2014

Kathmandu Valley, Nepal

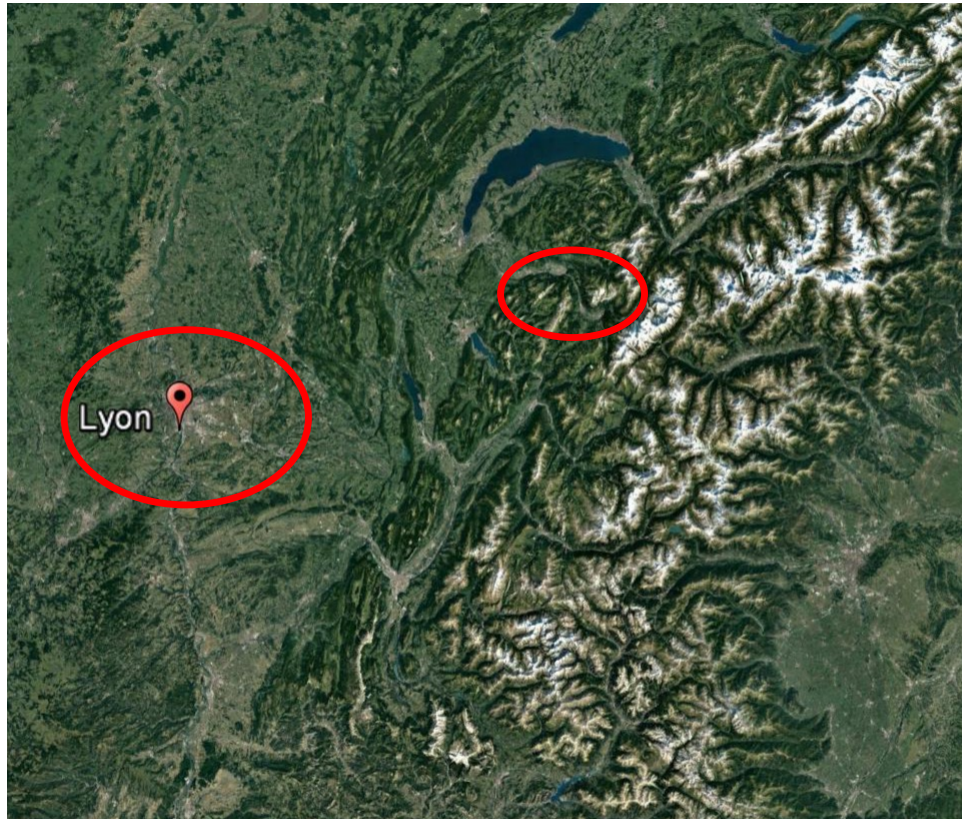
Regmi et al., 2003

- *Cold season*
- *Mountains*

Is it like this everywhere?

And no …

Mountainous vs. flat areas

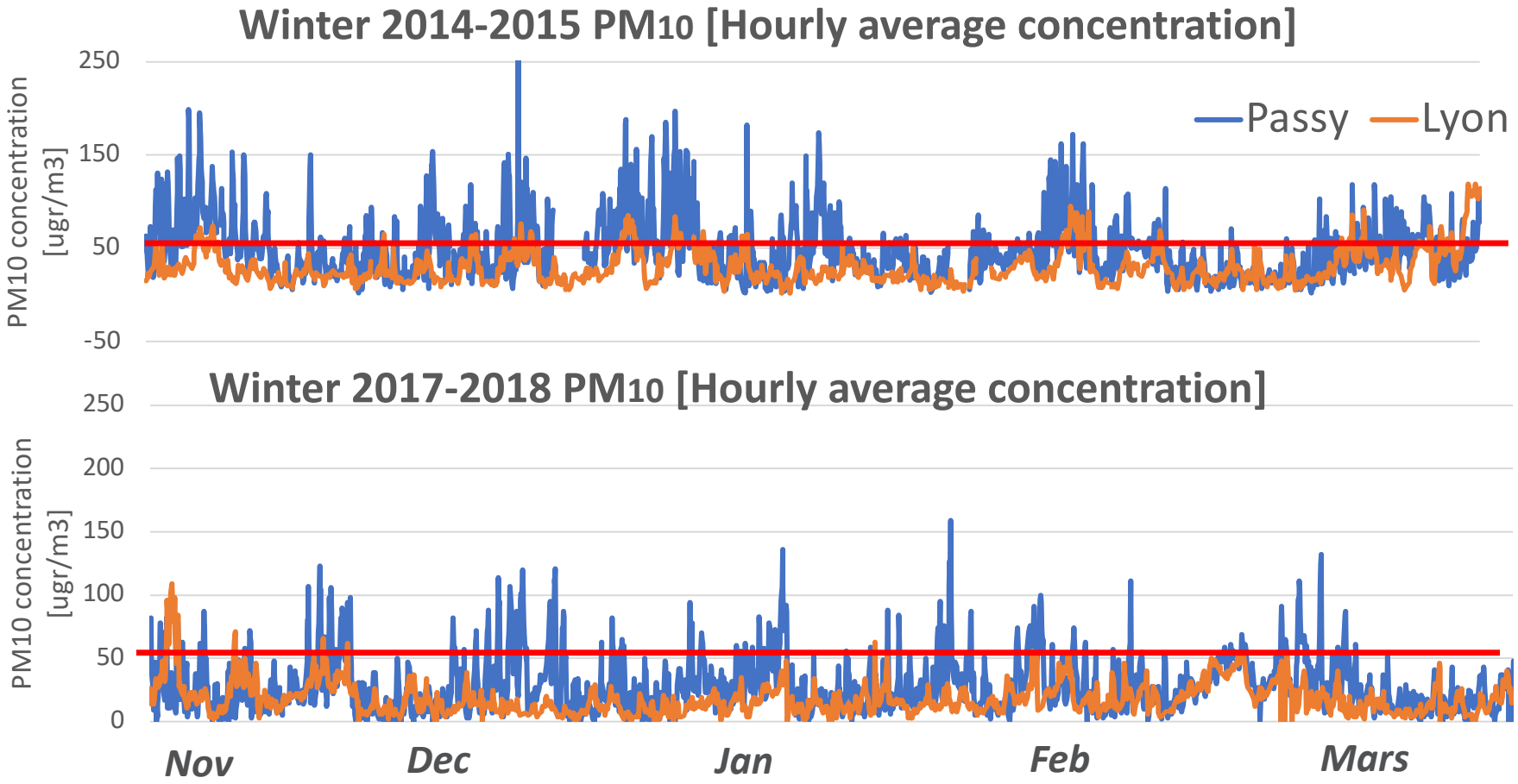


Is it like this everywhere?

- Inhabitants

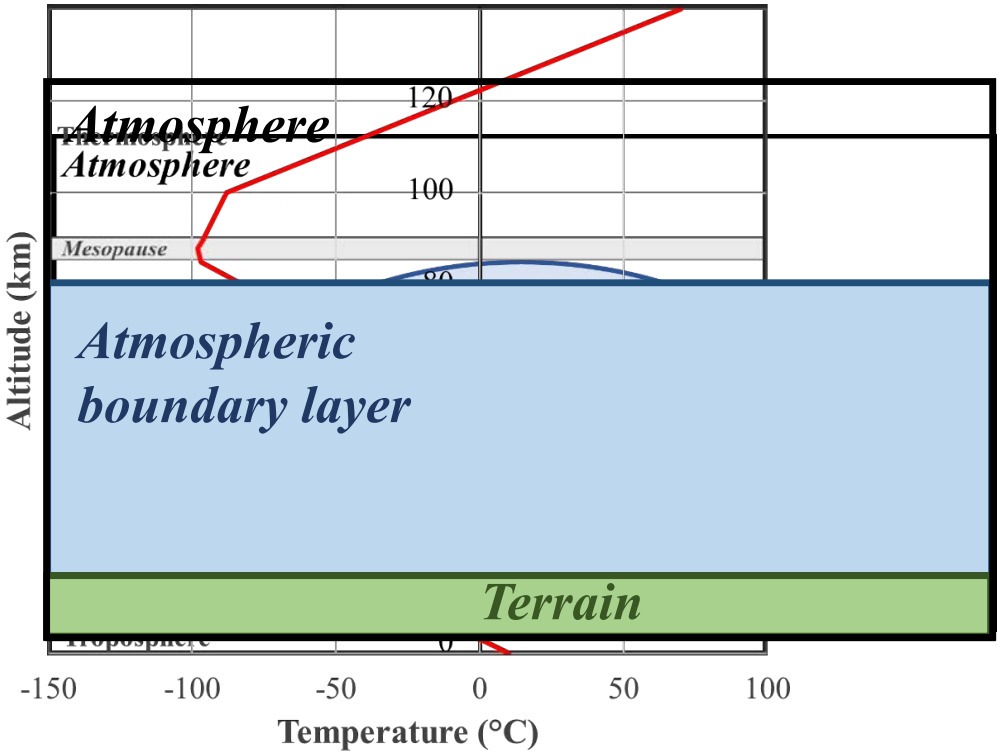
And no …

Lyon: 1’370.678 - Passy: 60.234



Why such pollutant accumulation in complex terrain?

The atmosphere → ***Pollution transport at local scales***



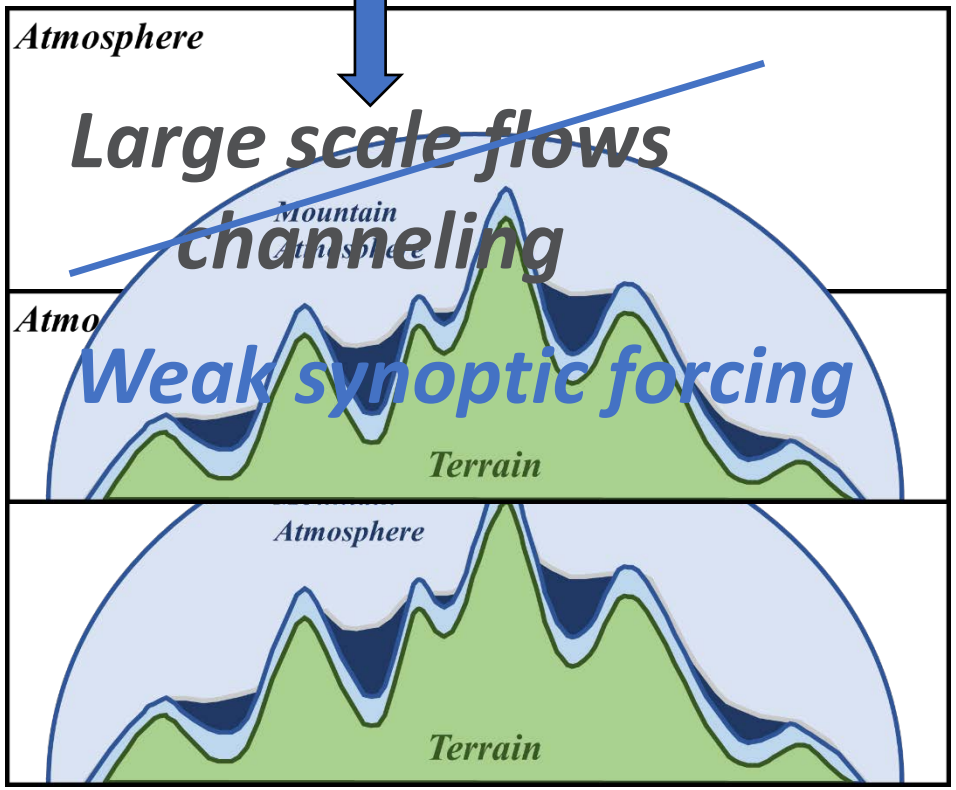
The Atmospheric boundary layer

Why such pollutant accumulation in complex terrain?

Wind Dynamics

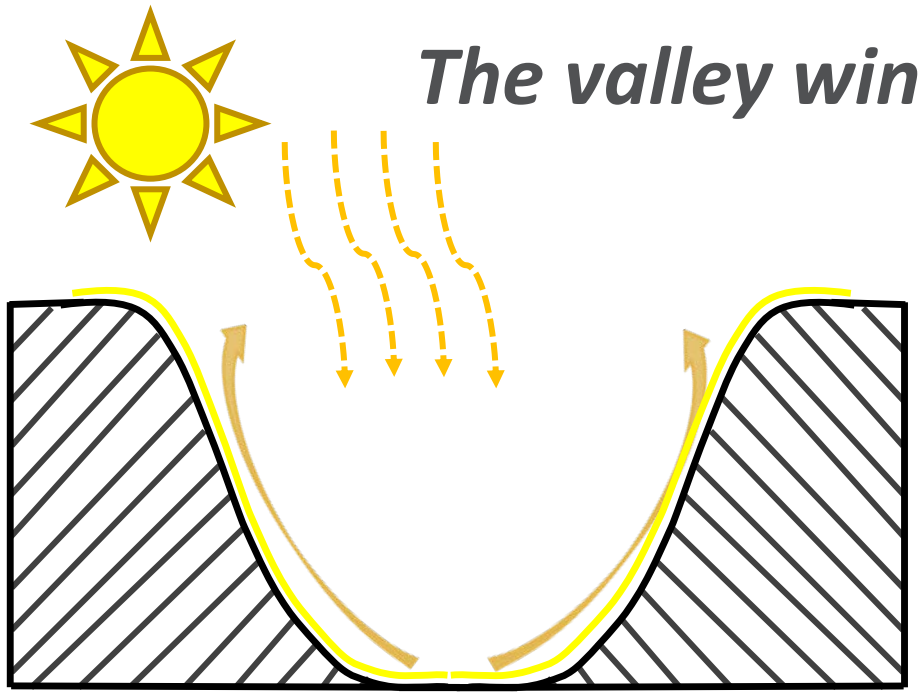
Terrain induced flows

Thermally driven flows



Valley wind System

Why such pollutant accumulation in complex terrain?



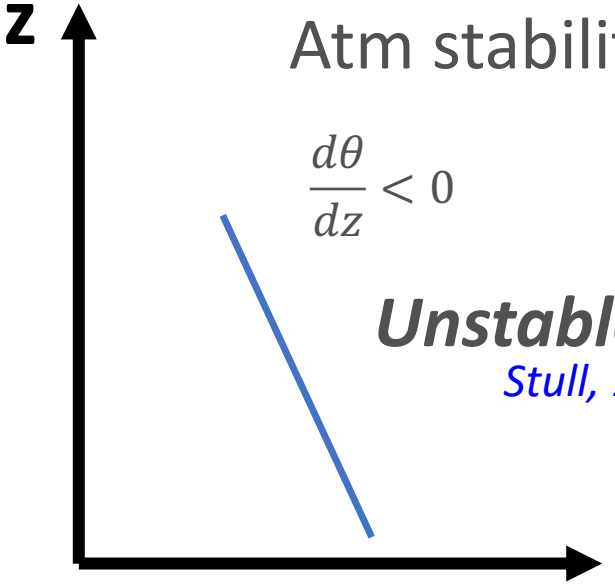
Slope flows

- Upslope during daytime

- Daytime: Positive surface radiative budget

Atm stability:

$$\frac{d\theta}{dz} < 0$$

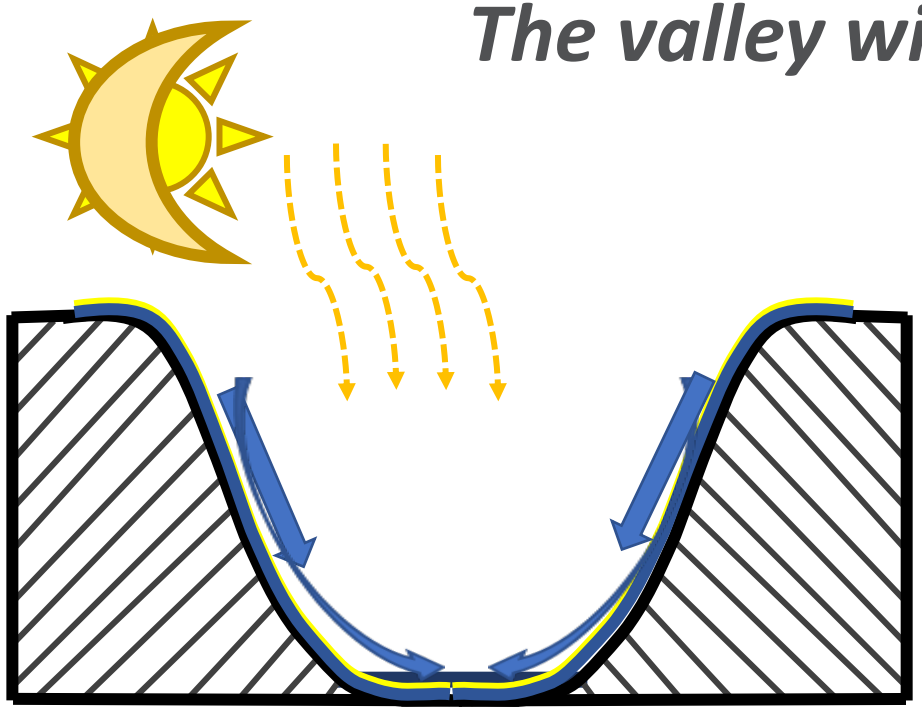


Unstable

Stull, 1988

Why such pollutant accumulation in complex terrain?

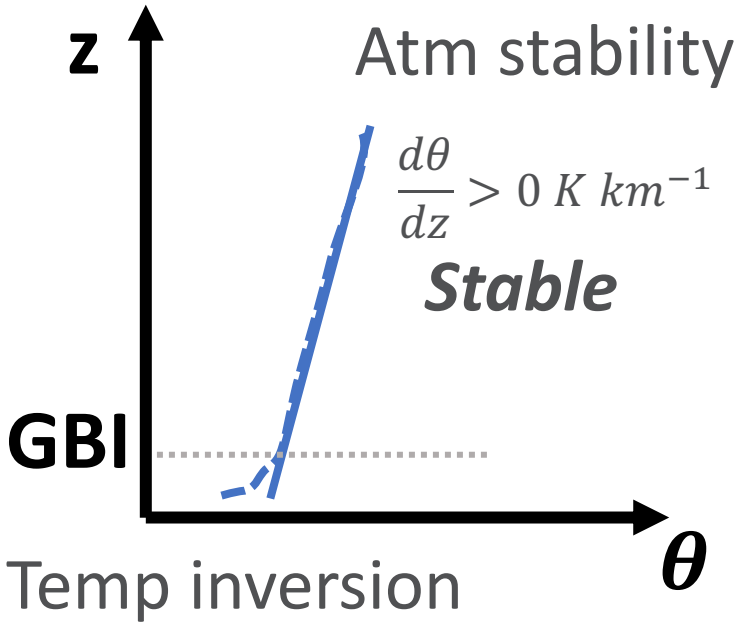
The valley wind system



Slope flows

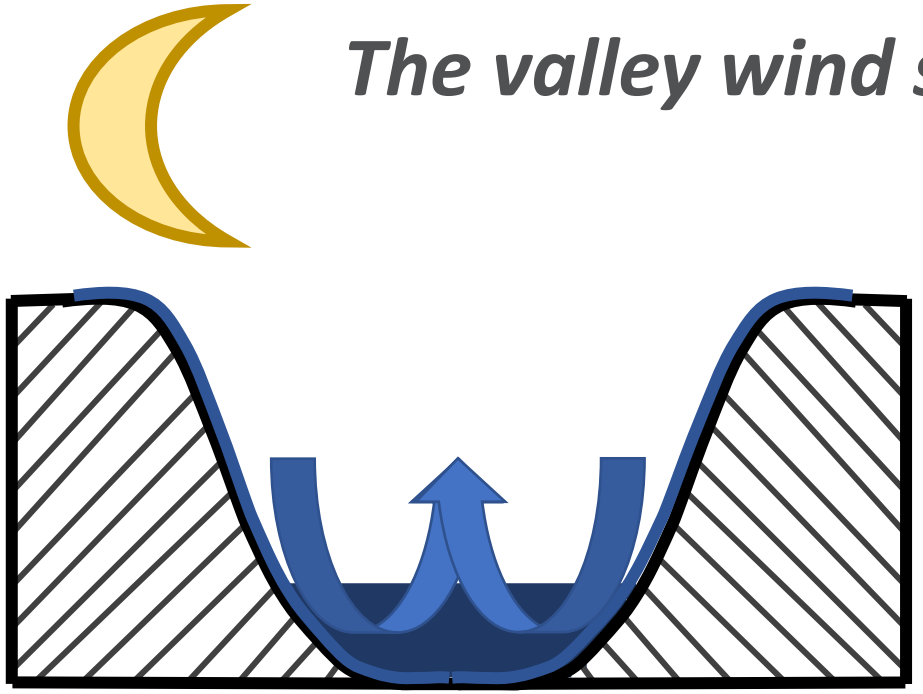
❖ Downslope during nighttime

❖ Daytime: Positive
Nighttime: Negative
surface radiative budget



Why such pollutant accumulation in complex terrain?

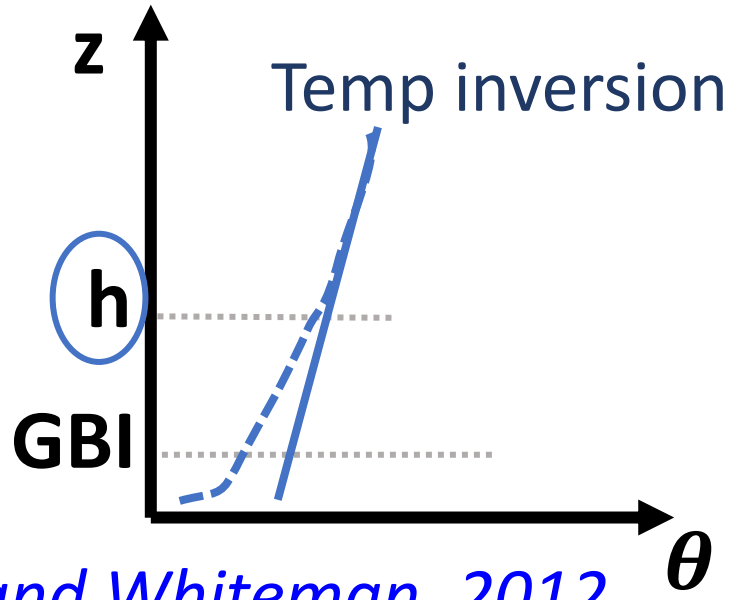
The valley wind system



- Creating a Cold air pool (CAP) at the valley bottom

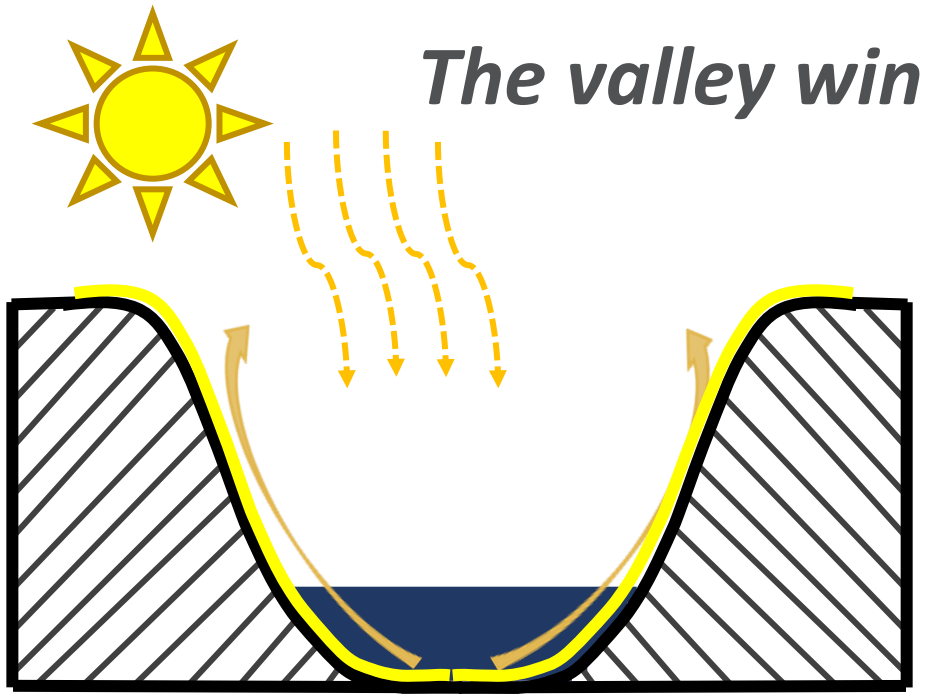
Slope flows

- Downslope during nighttime



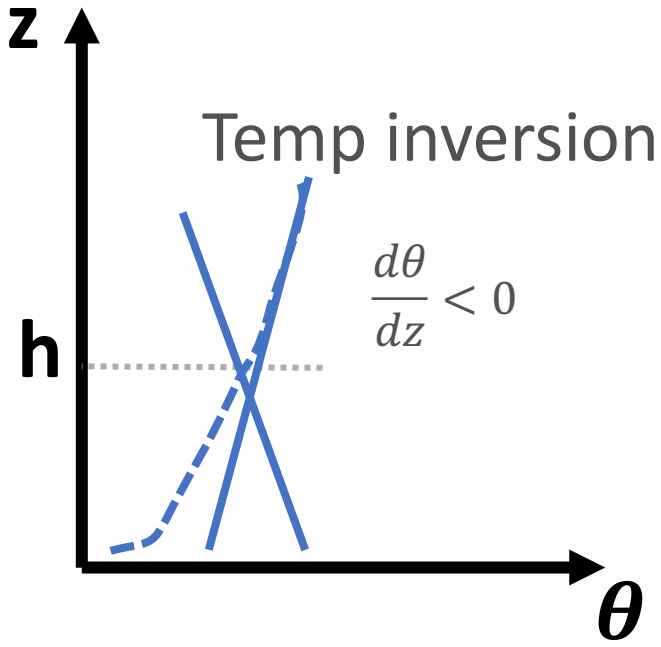
Zardi and Whiteman, 2012

Why such pollutant accumulation in complex terrain?



The valley wind system

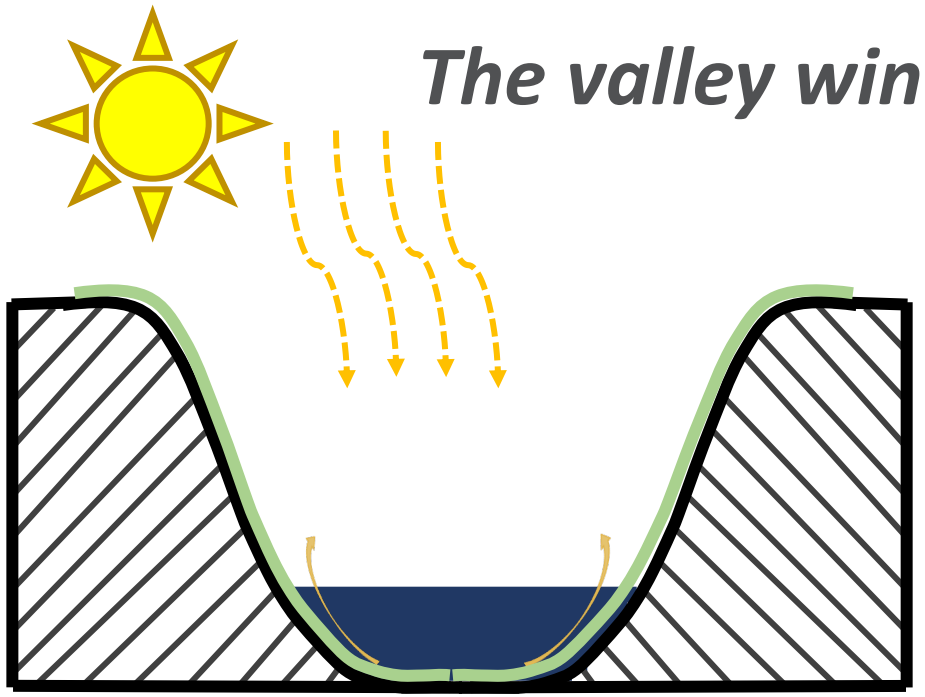
- Destroying the Cold air pool at the valley bottom



Slope flows

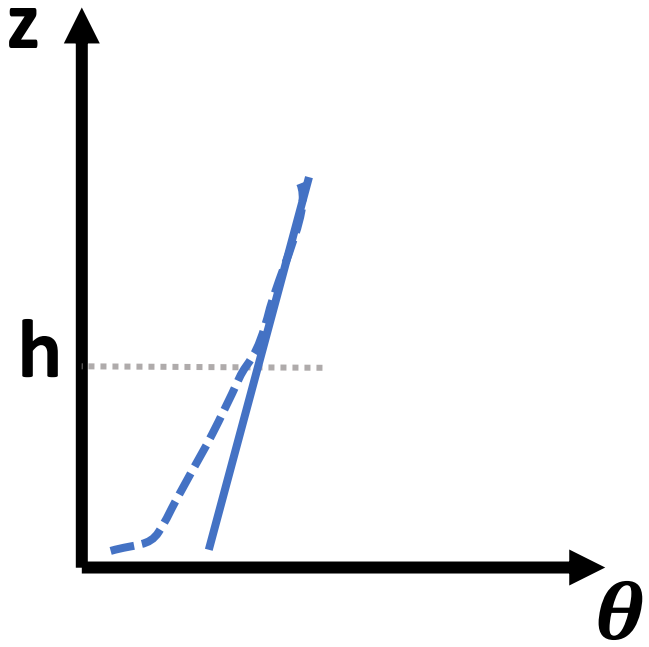
- Upslope during daytime

Why such pollutant accumulation in complex terrain?



The valley wind system

❖Cannot destroy the Cold air pool at the valley bottom



❖**Persistent CAP**

Suitable for pollutant accumulation (Lareau et al., 2013).

Motivation

http://www.mountain-spirit-guides.com
Chamonix 11th Feb 2012

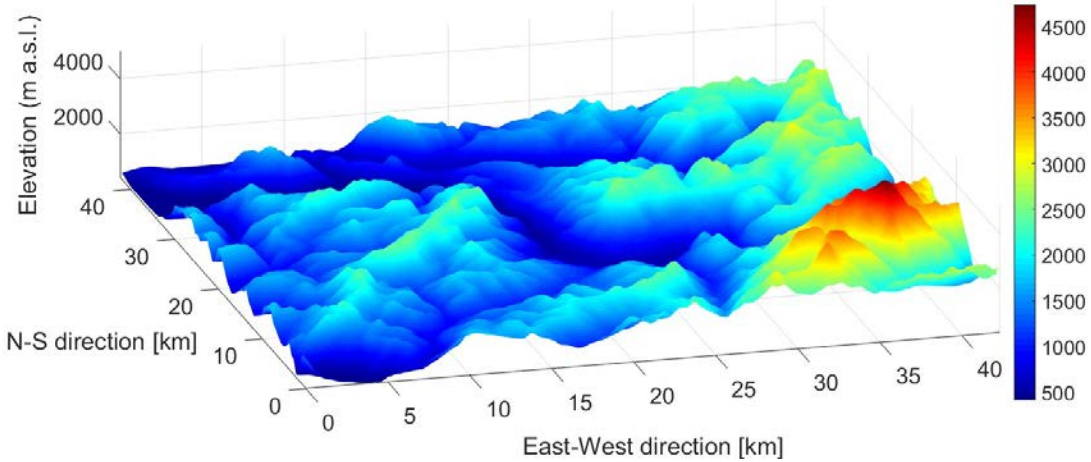
- *Why is it like this everywhere?*
- *Is it like this everywhere?*
- *Why is it like this in Europe?*
- *Actual pollution levels, topography, meteorology, etc. are not the same for the world but the influence of the very complex topography, meteorology and emissions must be considered to explain the problems in the area.*
- *Yes, similar processes can be seen around the world but the influence of the complexity in the area must be considered to explain the problems in the area.*
- *Why is it like this in Europe?*
- *Why is it like this everywhere?*

Atmospheric dynamics **Local sources** **Topography** **complexity in the area** **Meteorology** **Transport** **Transfer** **PM10**

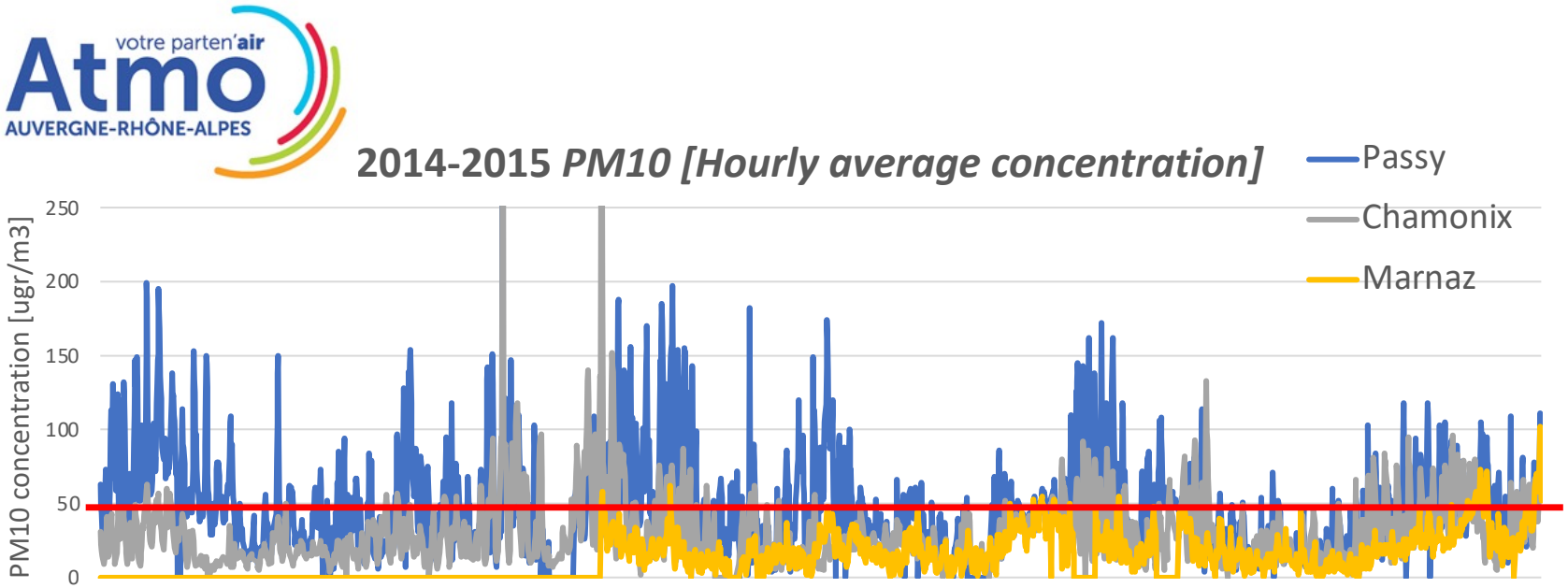
Case study: Arve river valley

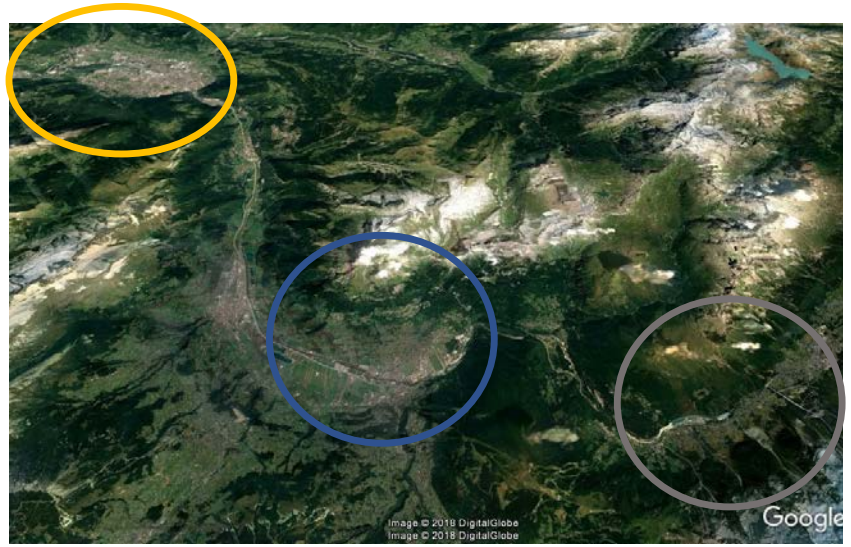
Real case simulation:

❖ Methodology:



Why the Arve river valley?





Background

❖ What have been done?

Passy field campaign Winter 2014-2015

Staquet et al. (2015), Sabatier et al. (2018)

A large set-up of instruments was deployed (wind, temperature and water vapor profilers, scanning lidars, instrumented towers…) with aim to link the meteorology to high pollution episodes at Passy during wintertime.

http://passy.sedoo.fr/

Full End of Nov 2014 – Beginning Mach 2015

IOP1 6th - 13th Feb 2015

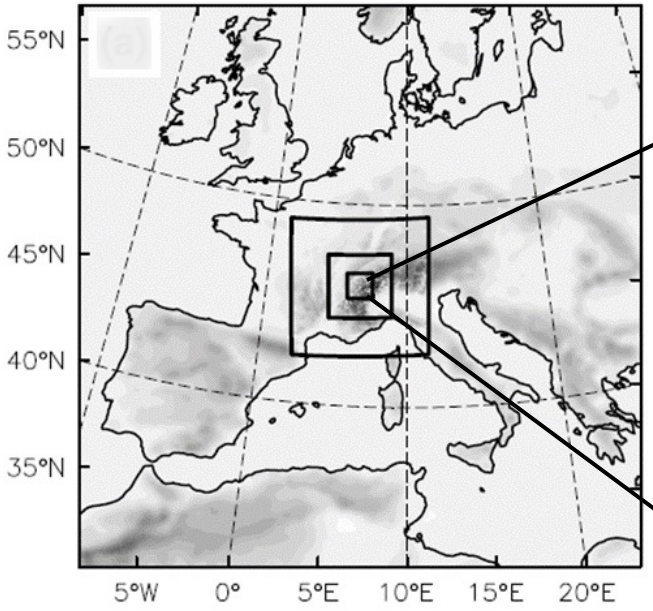
IOP2 17th – 20th Feb 2015

Methodology

Numerical simulation using WRF + Chem (Passive scalars).

* Five domains (One-way nesting) =>

Domains d01 – d04



d01: Covers continental scale.
d04: Main regional-scale orographic features.

Domain d05

d05: Area of interest.

Methodology

Numerical simulation using WRF + Chem (Passive scalars).

∗ Five domains (One-way nesting) =>

Dom	nx	ny	nz	$\Delta x = \Delta y$	1st mass Point
d01	202	202	46	15 km	21 m
d02	246	246	46	3 km	21 m
d03	340	340	46	1 km	21 m
d04	406	406	92	333 m	11 m
d05	178	286	92	111 m	4.6 m

Domain d05

d05: Area of interest.

- 17 grid points in the first 200 m above the ground.
- Initial conditions provided by ECMWF data.
- LES simulation for d04 and d05.
- Snow covering and albedo initialization from MODIS data.
- Emissions released only in d05

Methodology

Emission input

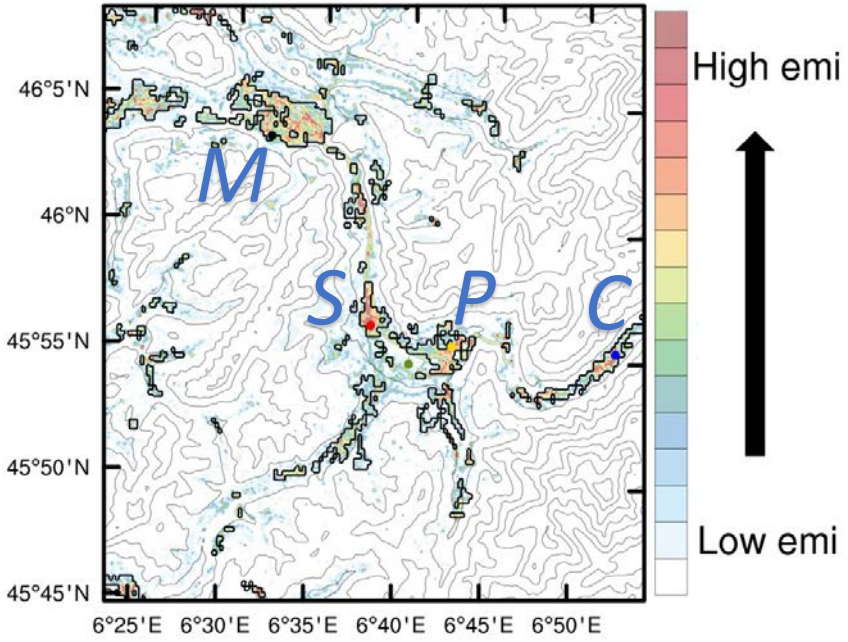
- Emission inventory for the year 2015 (Atmo Aura).
- 100 m grid resolution.
- The bottom-up methodology has been used as much as possible. When the data were not available at the fines scale, a top-down methodology through the disaggregation of regional scale data.
- The 11 snap sectors have been taken into account, being the major contributors:

  Snap 2 : Residential heating

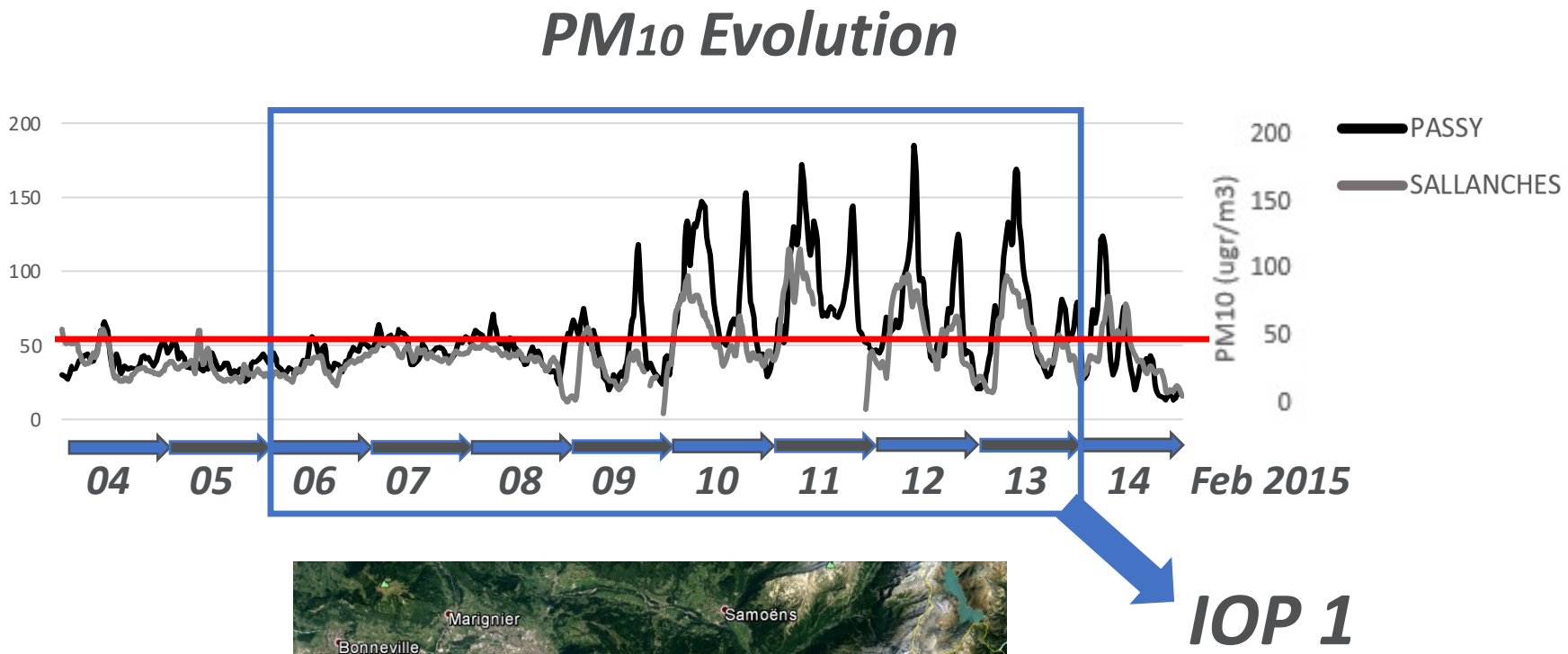
  Snap 4 : Industrial combustion

  Snap 7 : Route transport

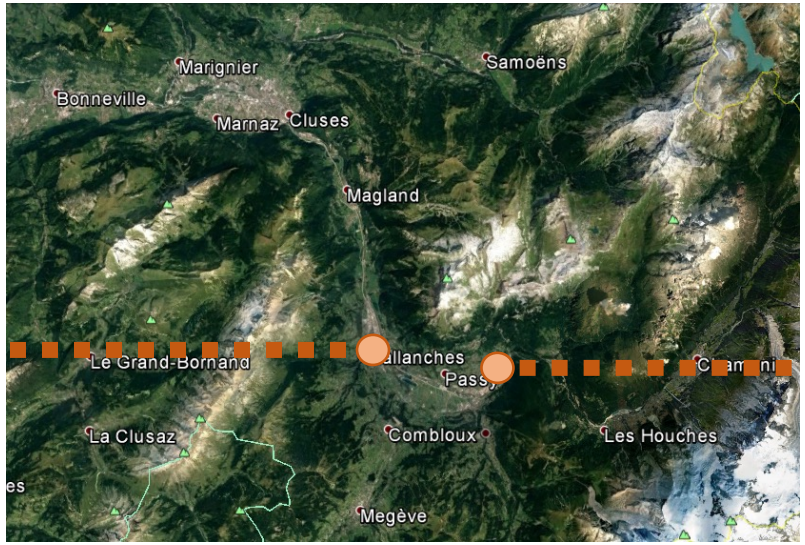
  accounting for the 93% of the emissions in the valley.



Results



Sallanches

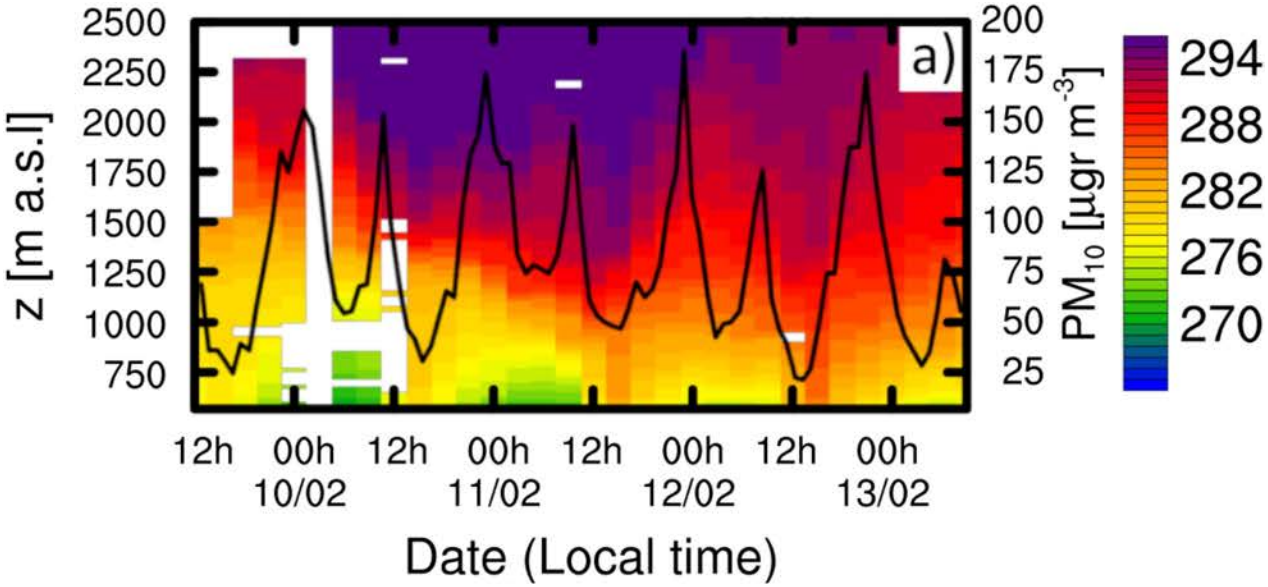


Passy

Results

PM10 + CAP's Evolution

Bias
MAE



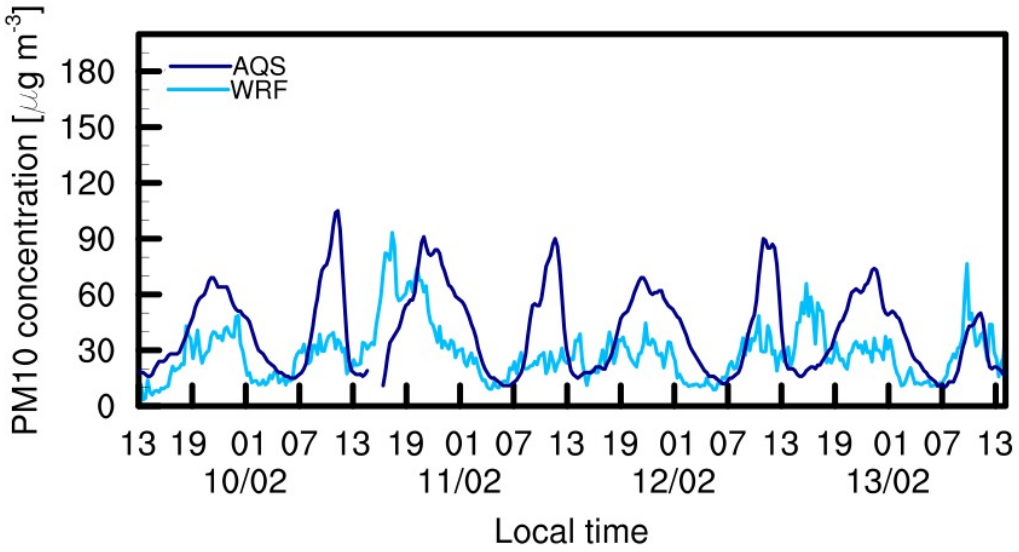
Observations: RS (ϴ) + PM10

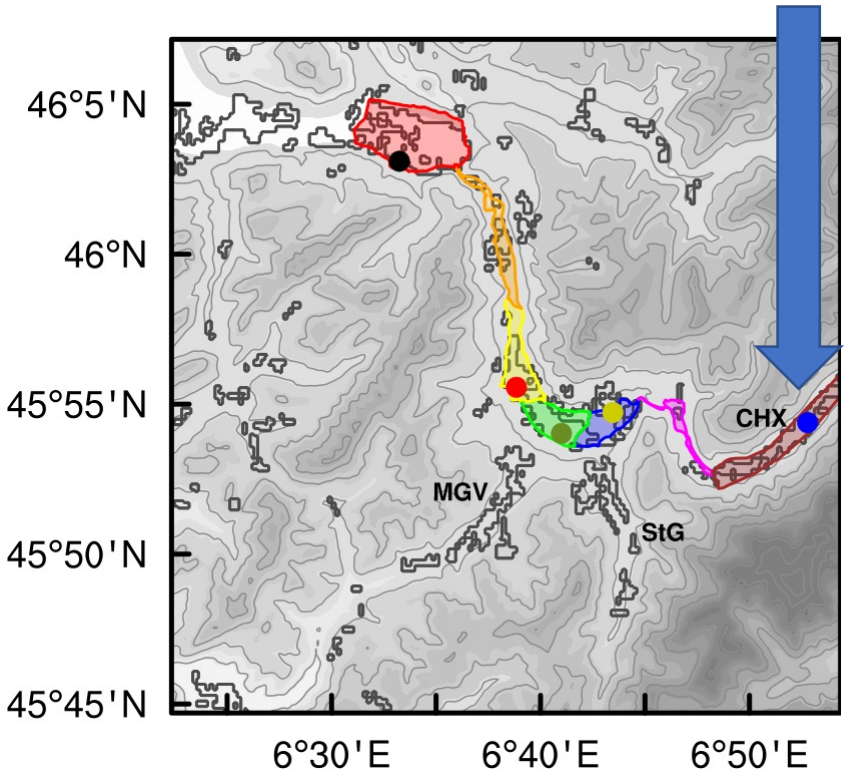
WRF d05: ϴ [k]

Results

WRF-Chem Vs AQ stations

Chamonix

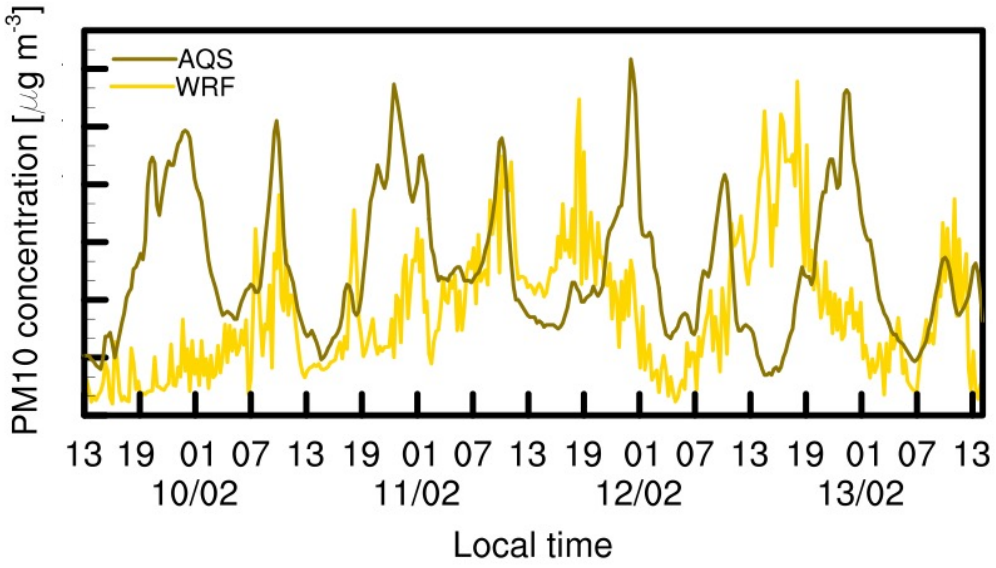


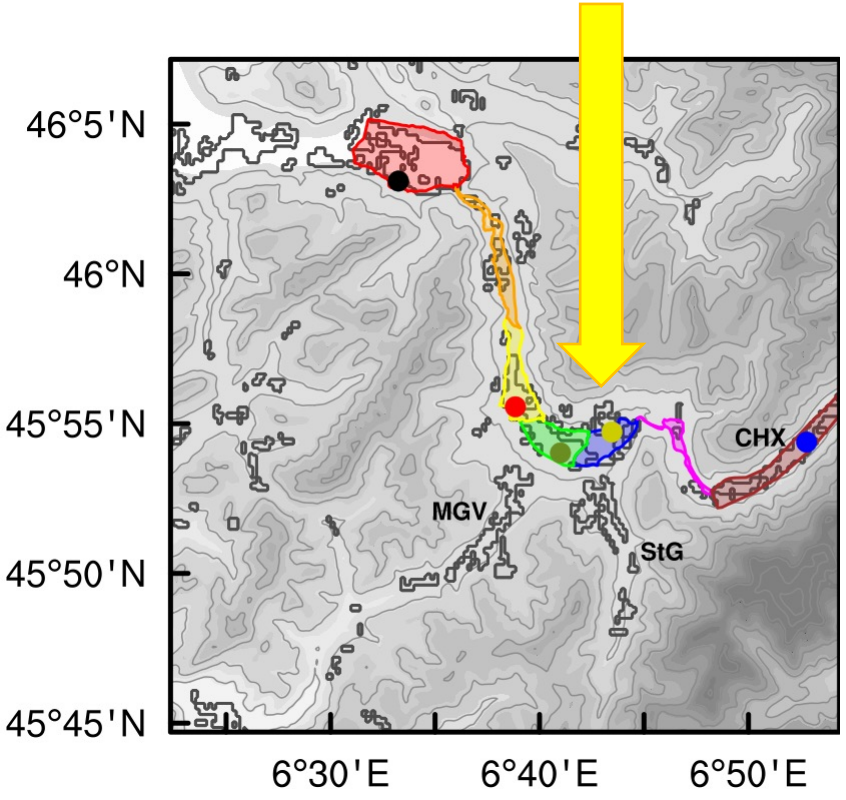


Results

WRF-Chem Vs AQ stations

Passy

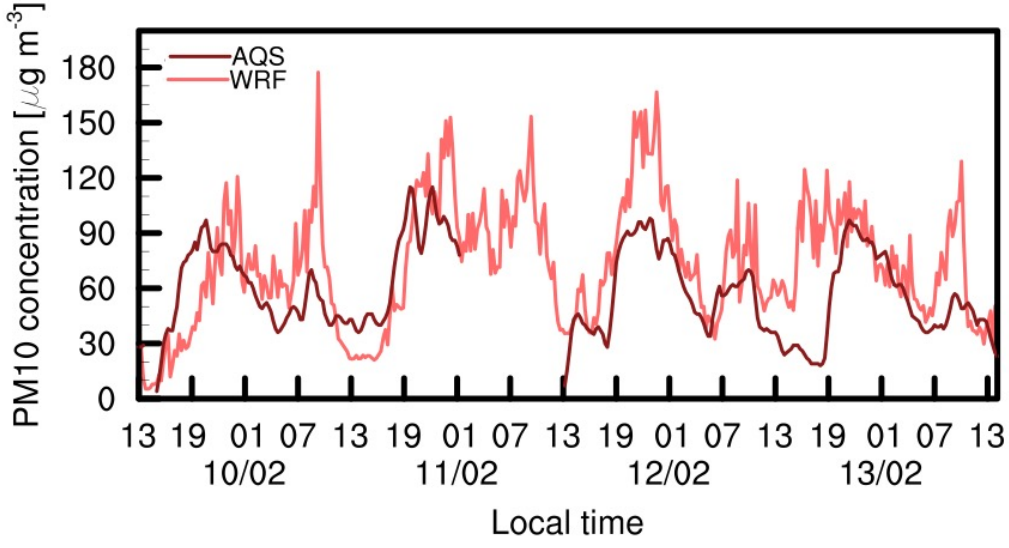


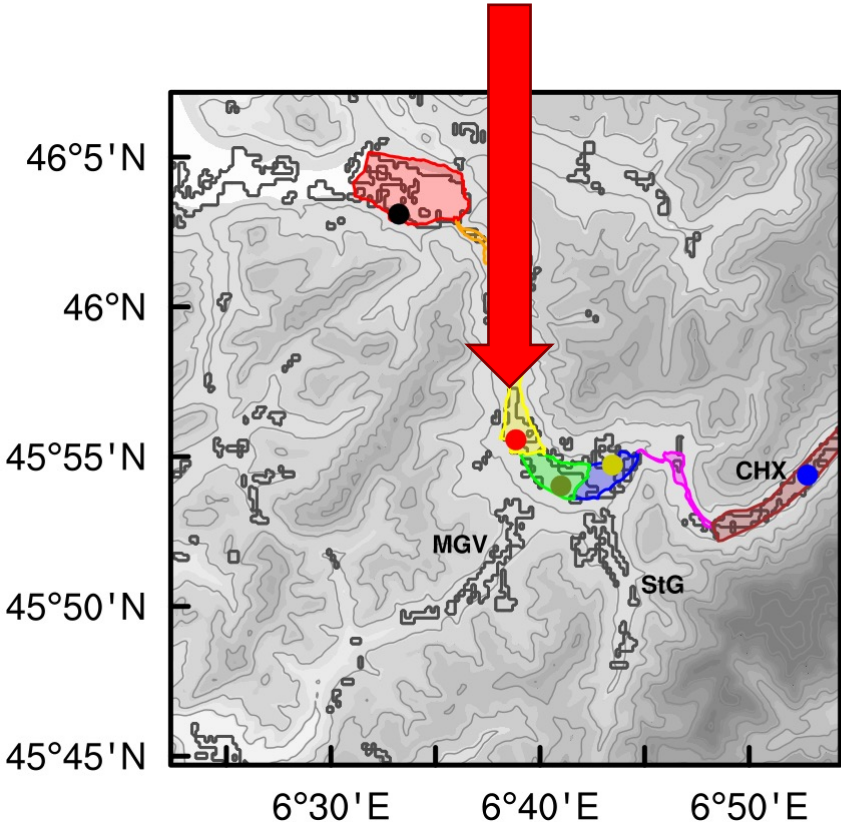


Results

WRF-Chem Vs AQ stations

Sallanches

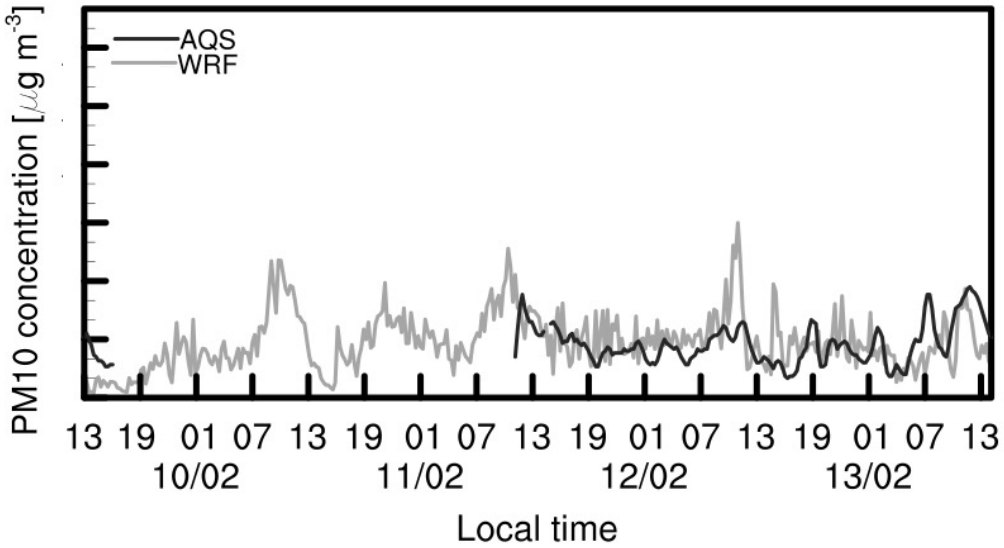


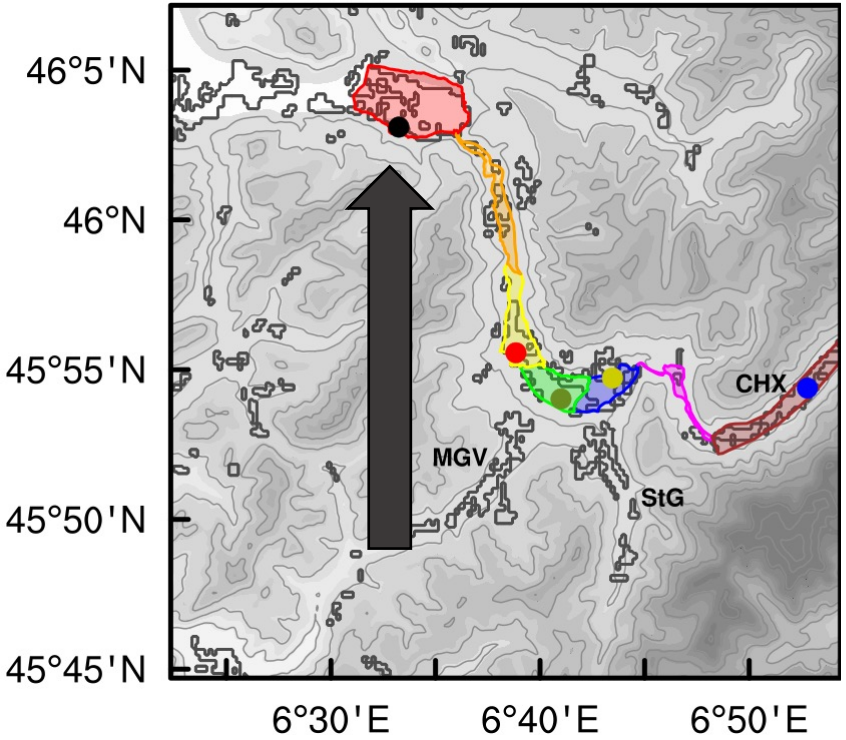


Results

WRF-Chem Vs AQ stations

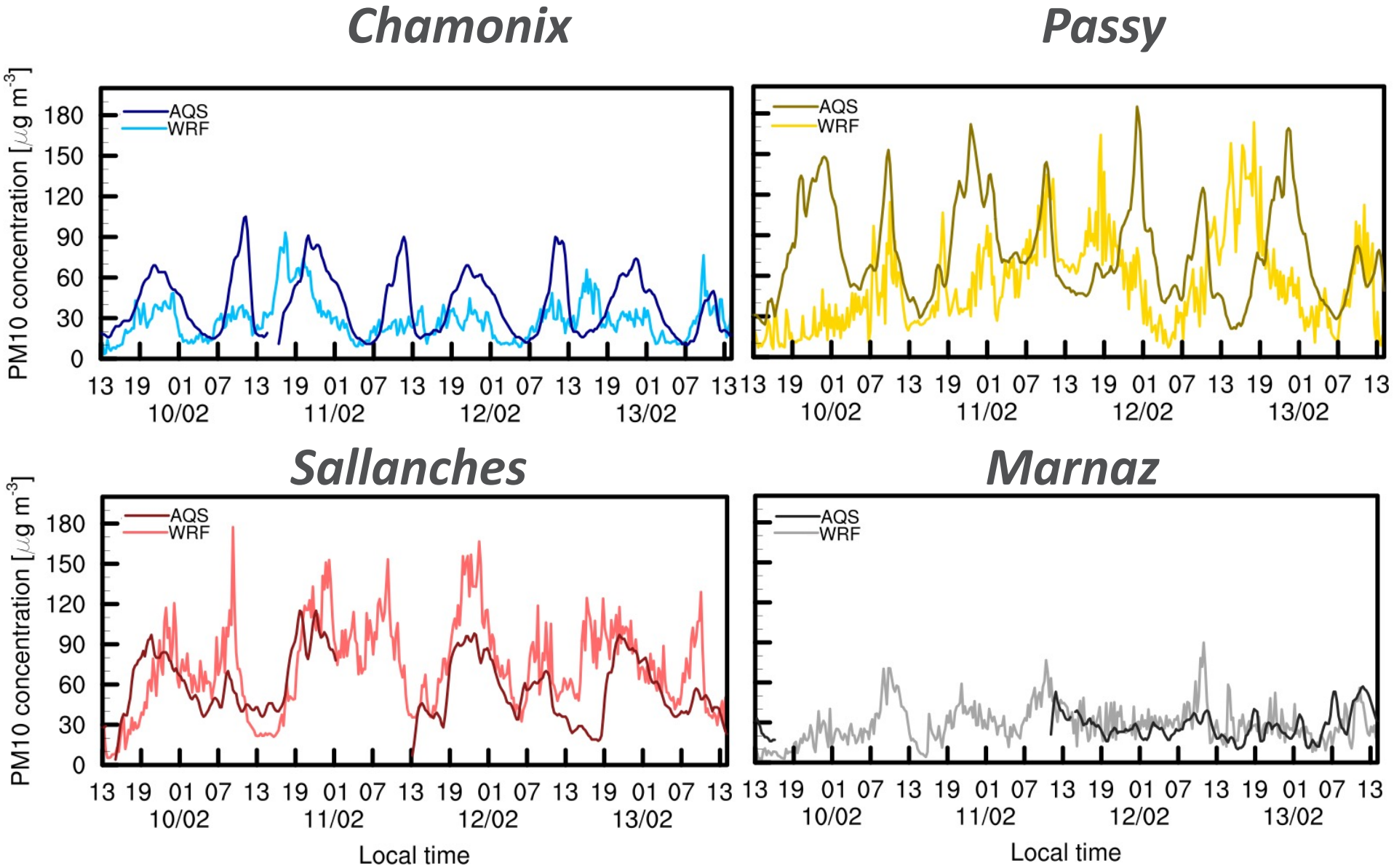
Marnaz





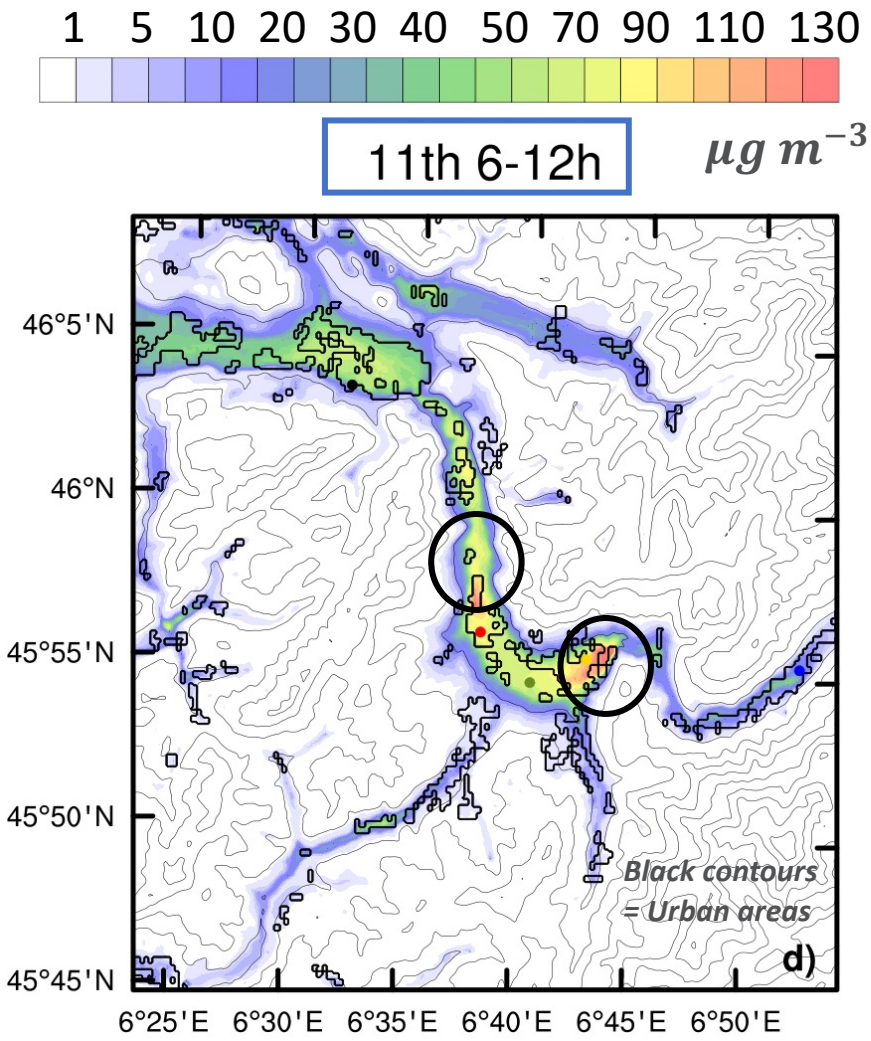
Results

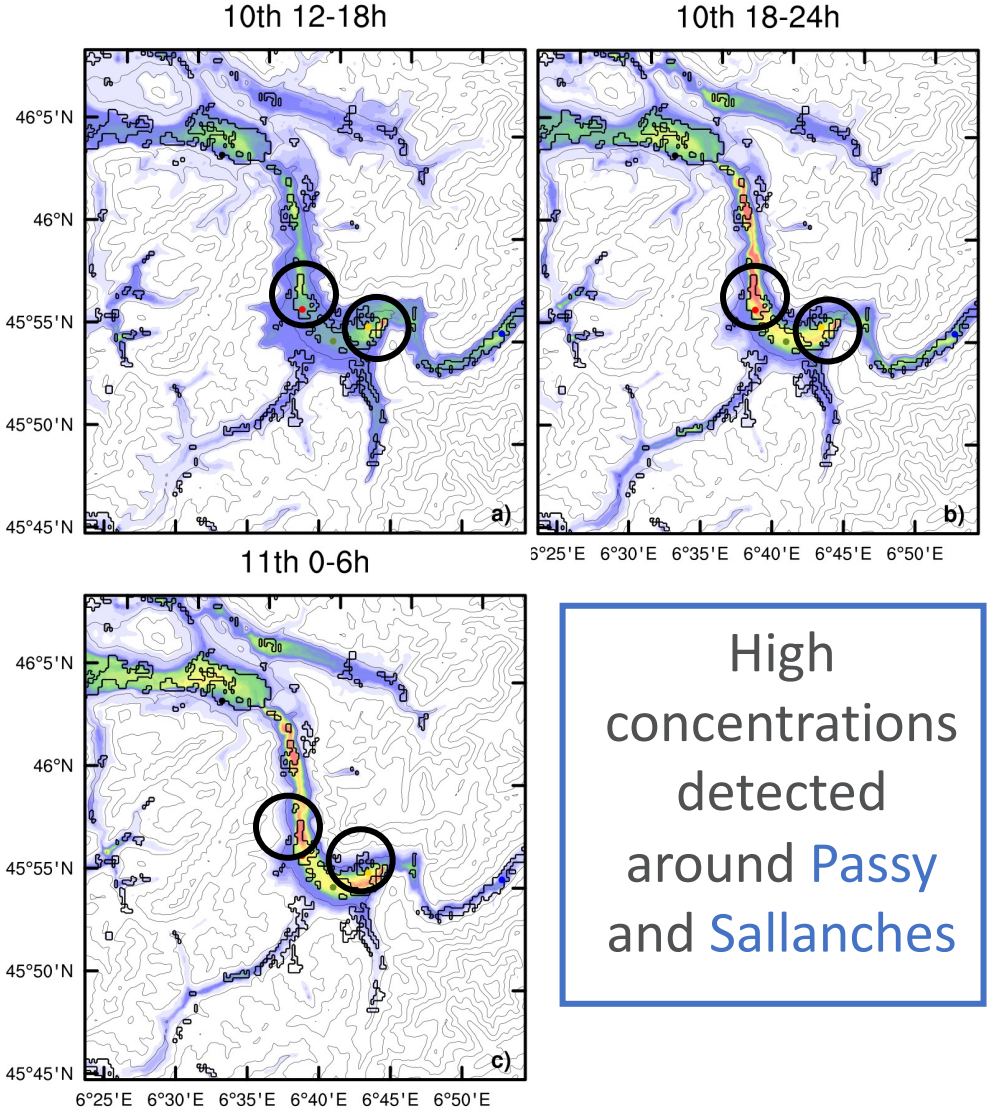
WRF-Chem Vs AQ stations



Results

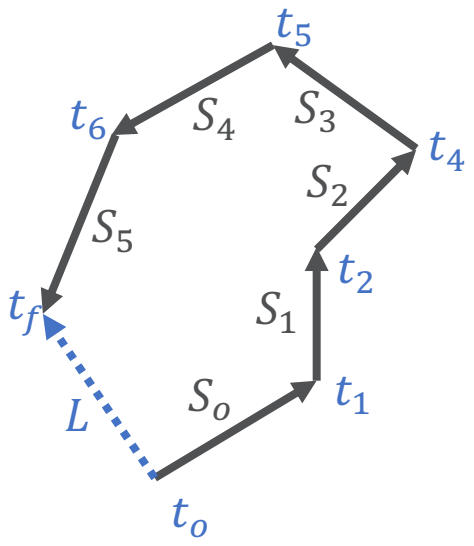
PM10 Horizontal distribution, *6 hr average.*





High concentrations detected around Passy and Sallanches

Recirculation, stagnation and ventilation zones



Defining the categories:

$Ventilation$: $S \geq S_c$ and $R \leq R_c$
Recirculation: $R \geq R_c$
Stagnation: $S \leq S_c$
Critical stagnation: $S \leq S_c$ and $R \geq R_c$

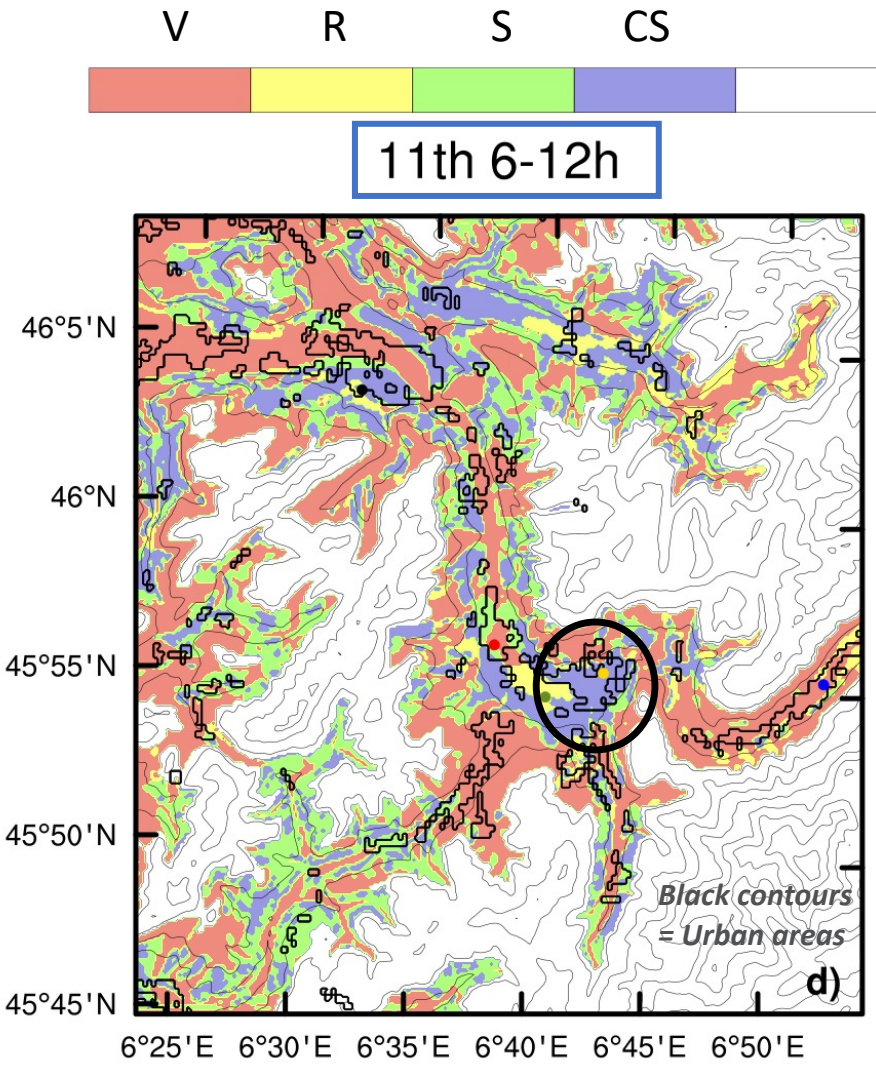
$$R_{index} = 1 - \cancelto{0}{\frac{L}{S}}$$

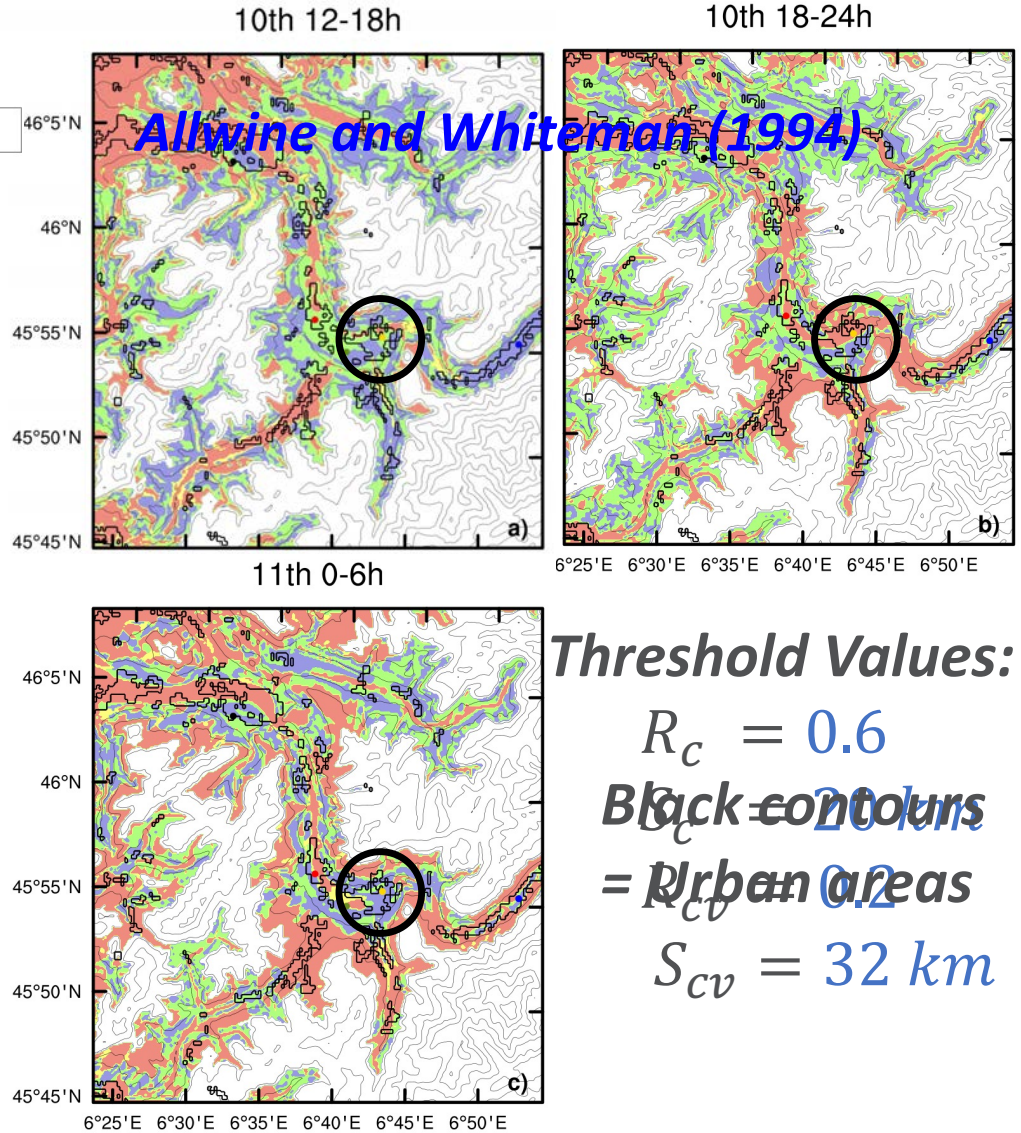
$$S_{wind\ run} = \sum_{t_o}^{t_f} S_i$$

$$\boxed{\begin{aligned} Recirculation&: R \rightarrow 1 \\ Ventilation&: \quad R \rightarrow 0 \end{aligned}}$$

Results

Stagnation and Ventilation zones, 6 hr average





Threshold Values:

$R_c = 0.6$

$S_c = 20\ km$

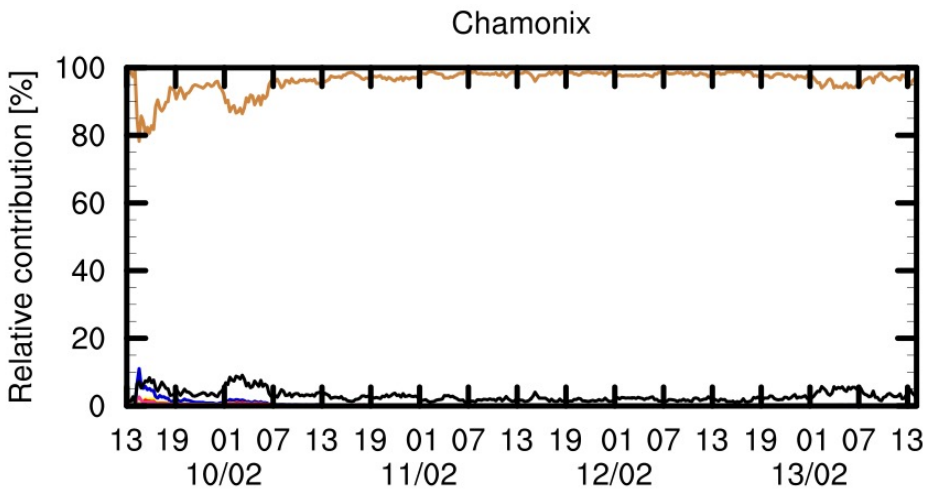
$R_{cv} = 0.2$

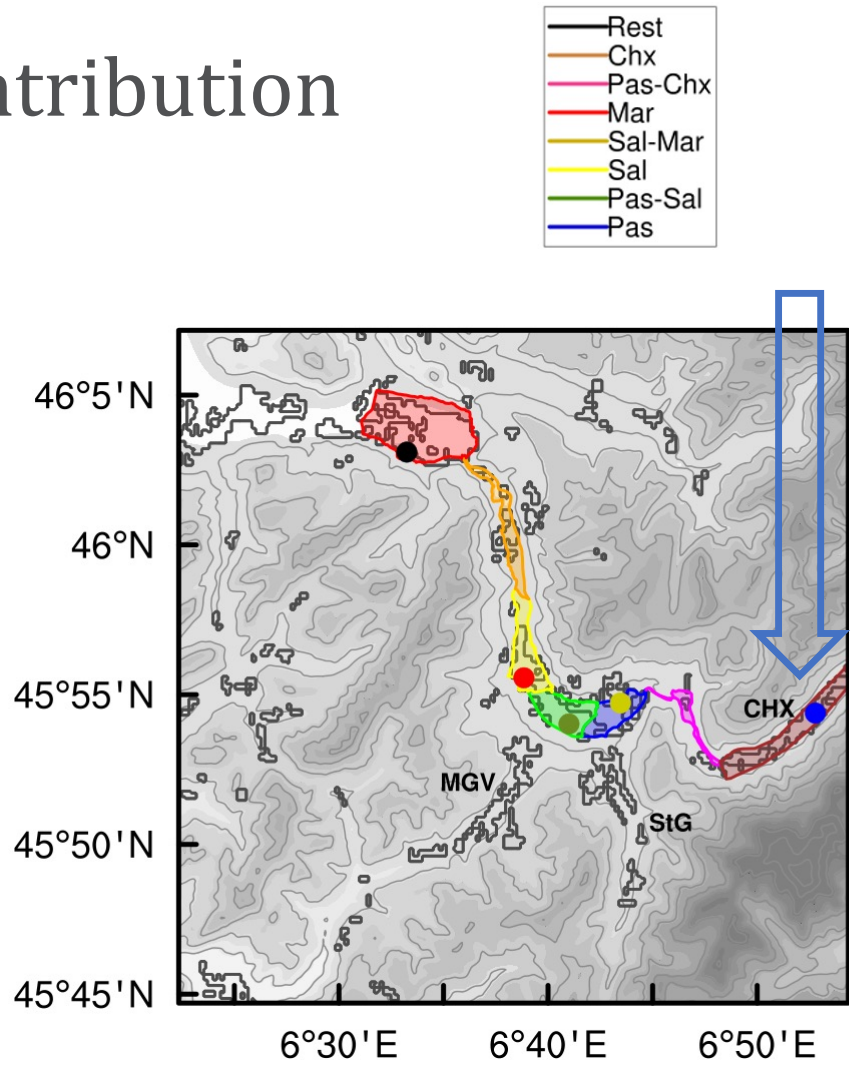
$S_{cv} = 32\ km$

Black contours = Urban areas

Results

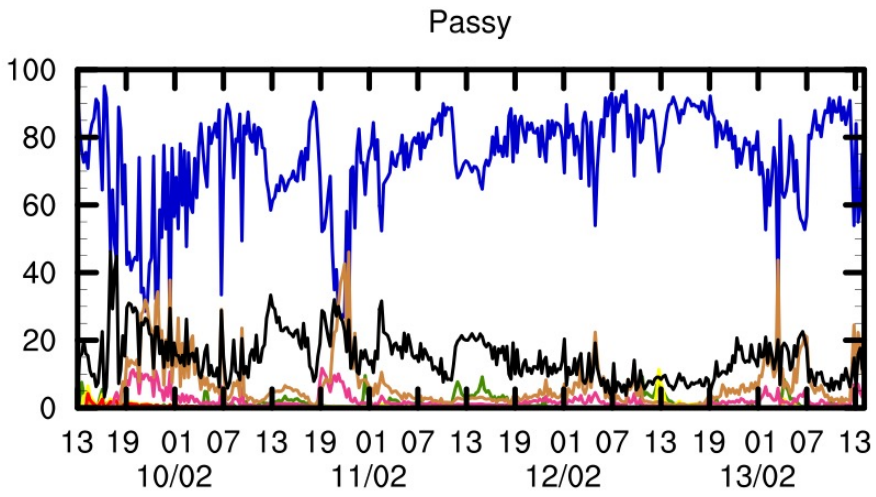
Local Vs Non – local contribution

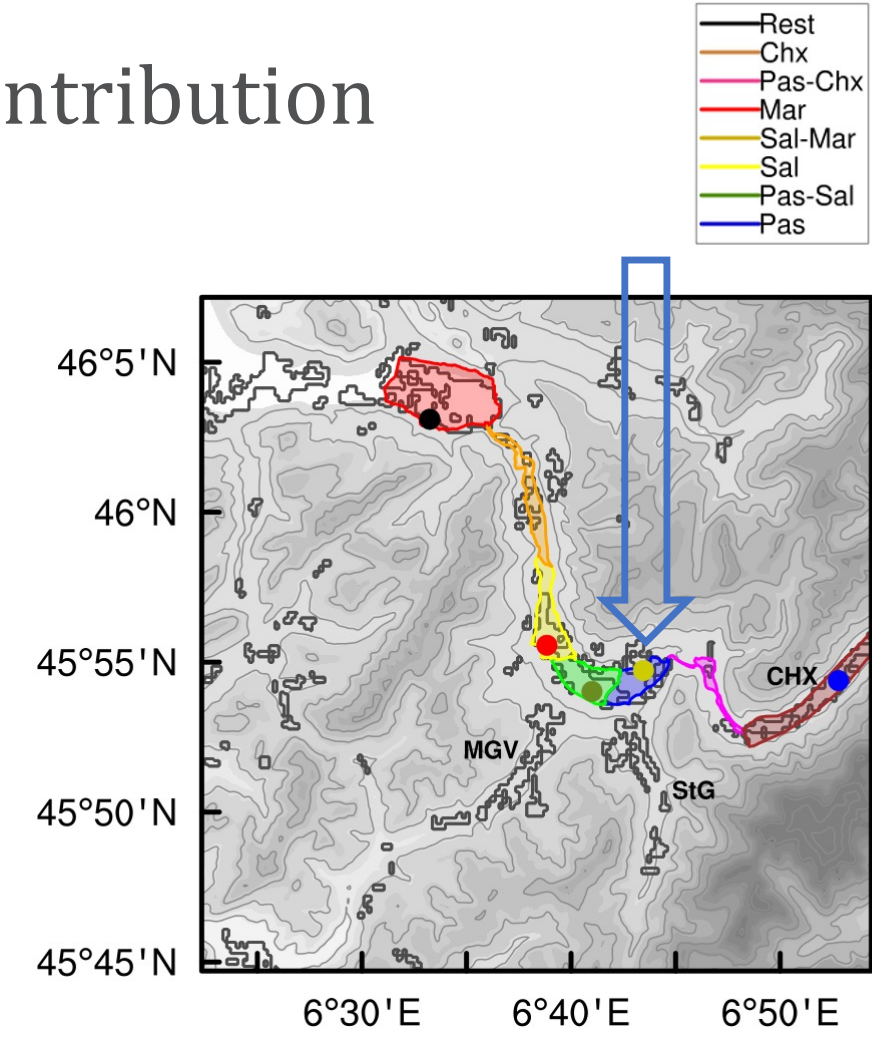




Results

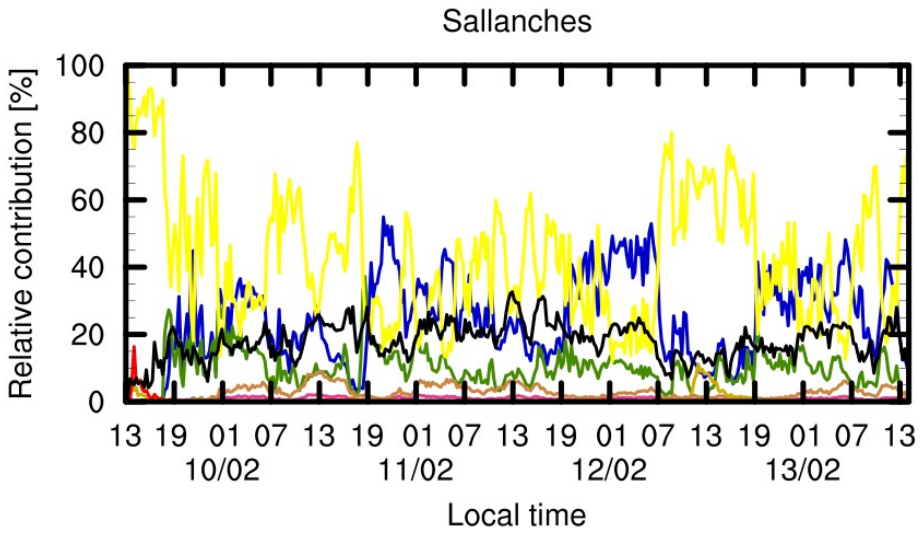
Local Vs Non – local contribution

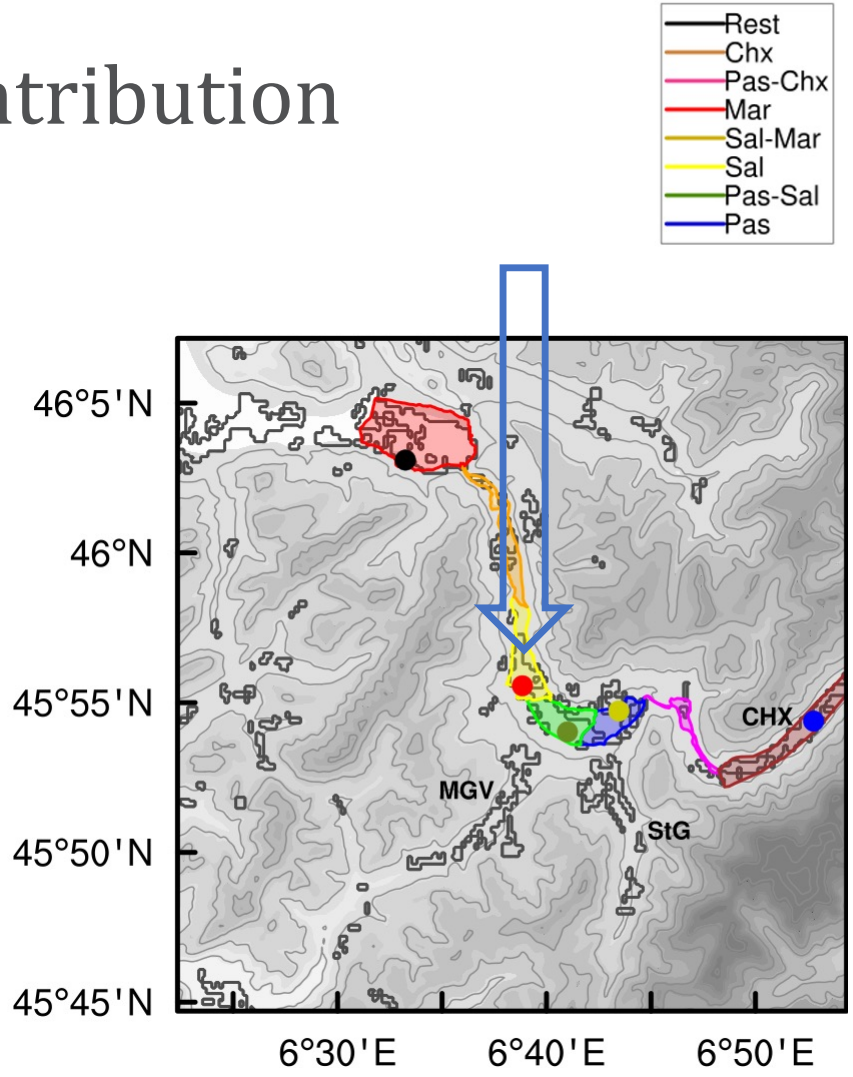




Results

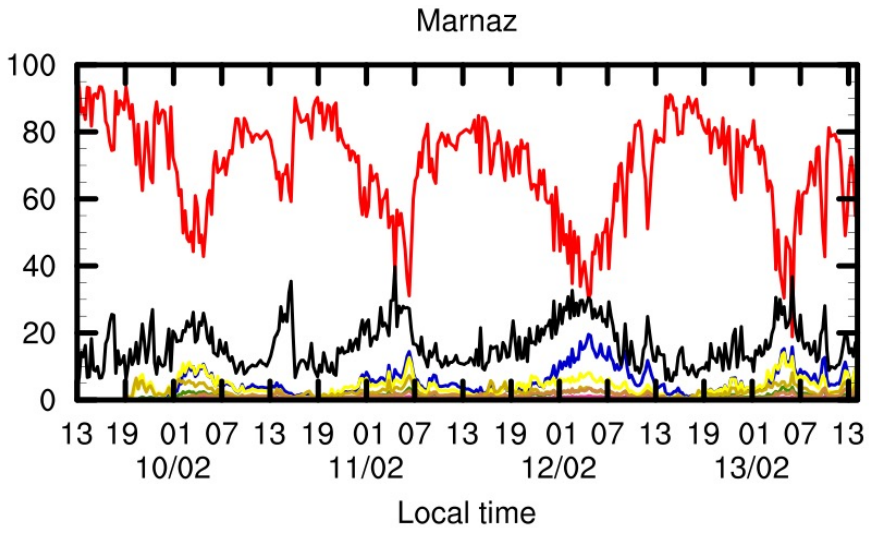
Local Vs Non – local contribution

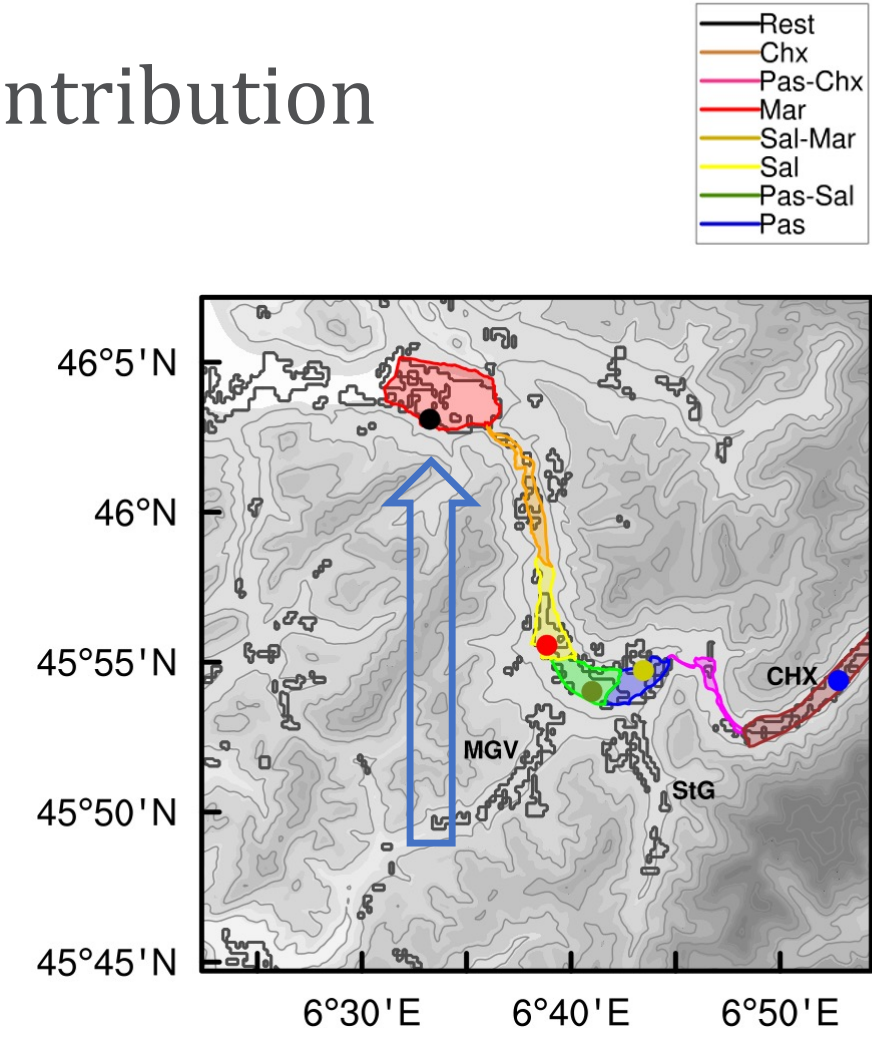




Results

Local Vs Non – local contribution





Conclusions

- The development of the persistent CAP due to warm air exported from the higher atmosphere triggers the high pollution episode registered during IOP 1.

- The bad combination between poor ventilation in the area, along with the location of the large pollution emission led to such localized high pollutant peaks recorded in Passy.

- The air pollution problems in the Arve river valley are mainly due to local sources, in fact, in Chamonix, Passy and Marnaz local emissions are almost entirely responsible for the high concentration recorded by the AQS.

Thank you!

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