# Investigating mountain-breeze characteristics and their effects on $CO_2$ concentration at three different sites

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## Characterization of mountain breezes

NIGHTTIME EVENTS — DAYTIME EVENTS

**HER - GUADARRAMA**
- 365 days analysed
- 177 nighttime events (local downslope)
- 136 daytime events (anabatic + upbasin winds)

SMALLER RANGE OF WIND DIRECTION VARIABILITY FOR NIGHTTIME BREEZES!

**CRA - PYRENEES**
- 365 days analysed
- 112 nighttime events (mountain-plain/downvalley winds)
- 56 daytime events (plain-mountain)

**SLV - SALT LAKE VALLEY**
- 210 days analysed
- 30 nighttime events (downvalley)
- 31 daytime events (upvalley + lake breeze!)

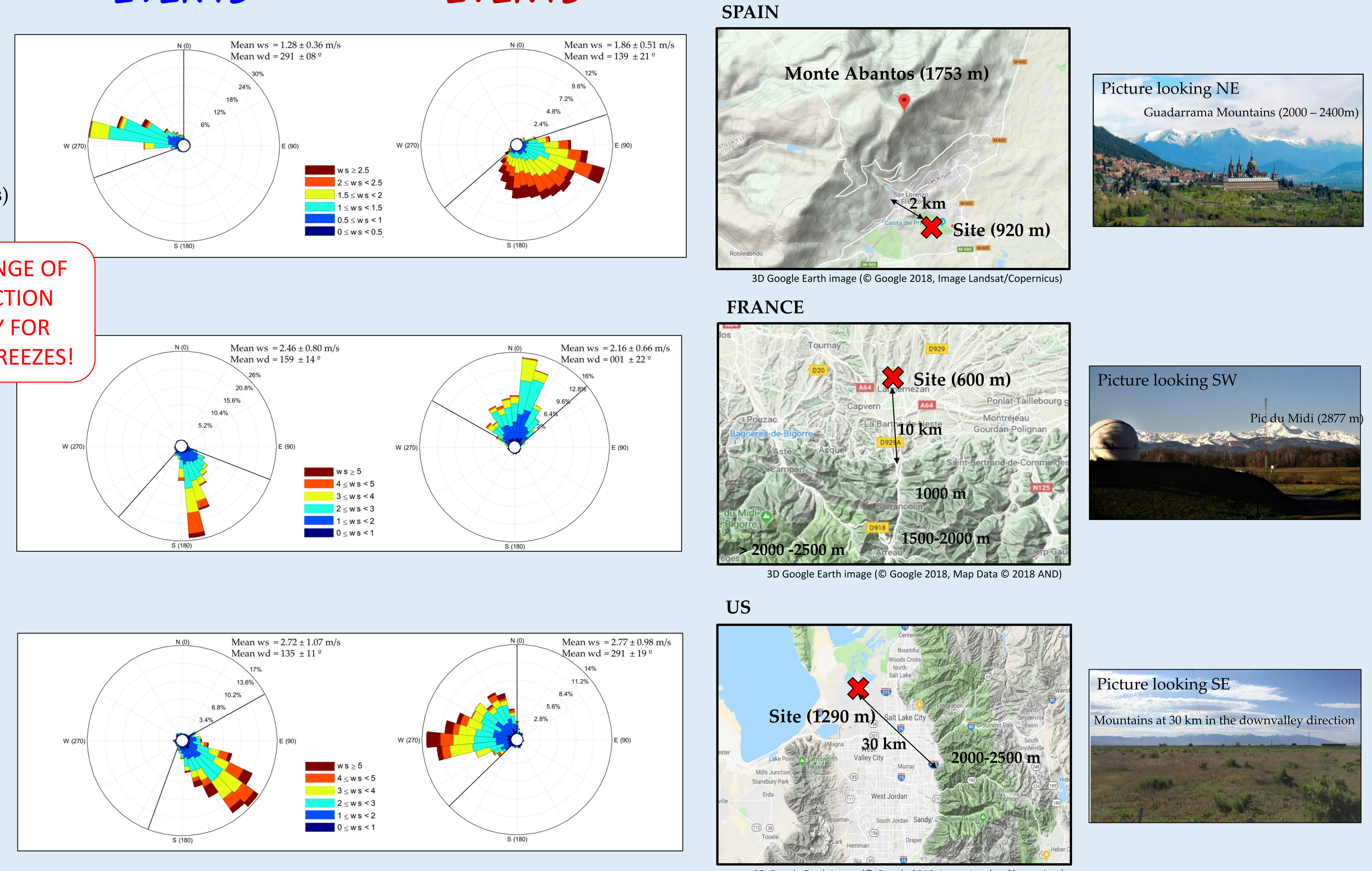
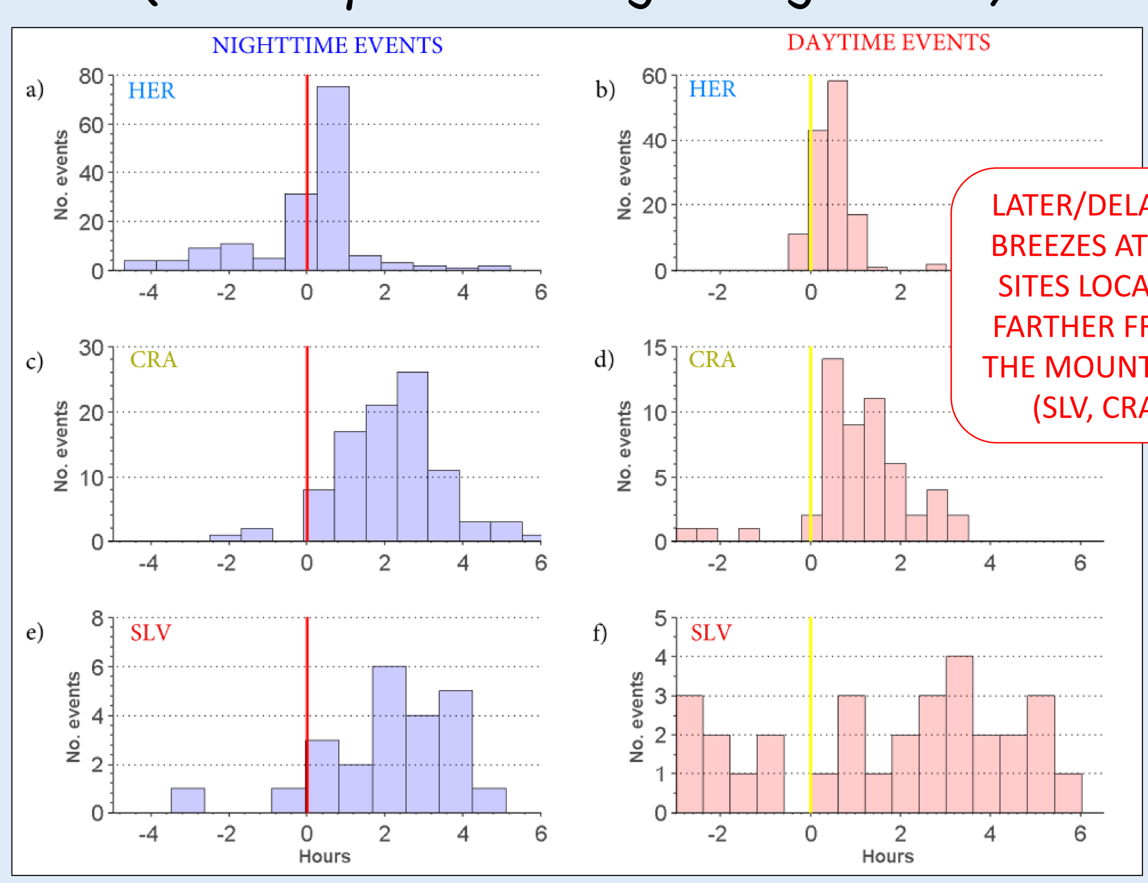



**Fig. 1.** Windroses for 10-m wind including all the detected nighttime and daytime events. All the thermally driven flows have been detected with an algorithm based on appropriate weather conditions (synoptic + local) for mountain breezes development (fair weather) and on appropriate wind directions for daytime and nighttime flows, based on criteria in Arrillaga et al. 2018 QJRMS. Maps (from Google Maps/Google Earth © 2018) and pictures show the areas of study: HER site (Guadarrama mountains) on top, CRA site (Pyrenees) in the middle and SLV site (Rocky Mountains) at the bottom. Note the greater complexity in the SLV site, also influenced by the lake breezes.

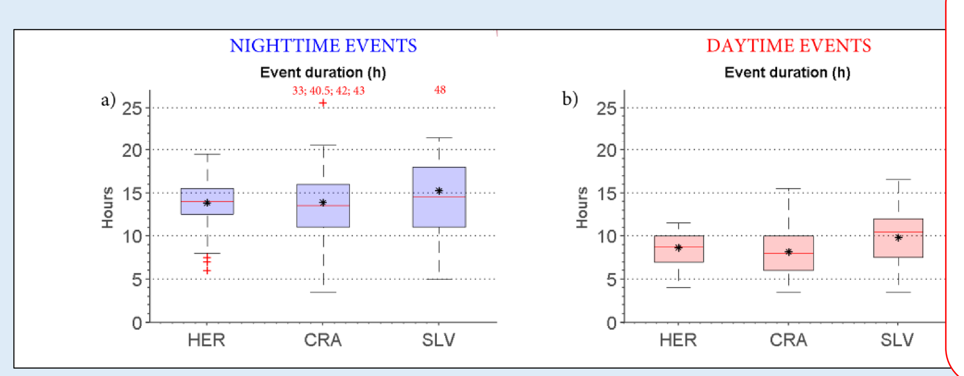
### Time of event arrival (with respect to change in sign of SH)




LATER/DELAYED BREEZES AT THE SITES LOCATED FARTHER FROM THE MOUNTAINS (SLV, CRA)

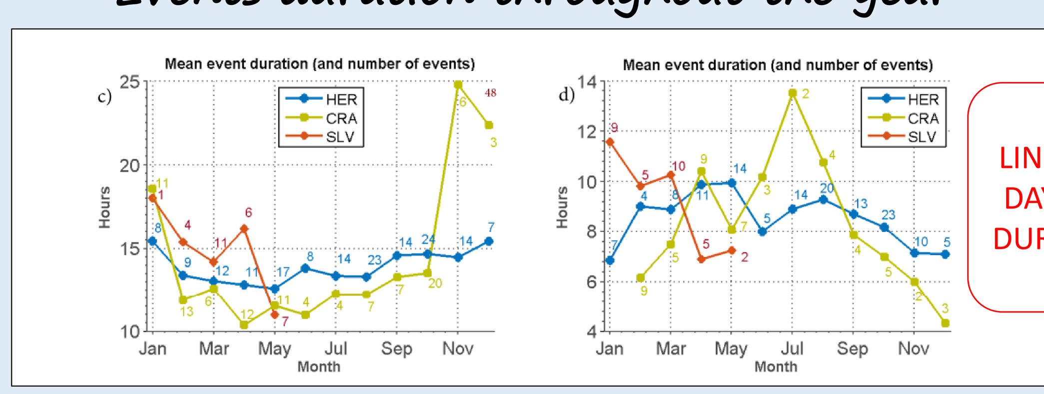
**Fig. 2.** Number of nighttime (left) and daytime (right) events regarding their arrival time with respect to the time when the sensible heat (SH) flux changes sign in the evening (left) and in the morning (right) at each site.

### Events duration




LONGER NIGHTTIME THAN DAYTIME BREEZES, SOME VERY PERSISTENT NIGHTTIME EVENTS IN CRA AND SLV

### Events duration throughout the year




LINKED TO DAYLIGHT DURATION!

**Fig. 3. UP** - Event-duration distribution (in h) for nighttime (a, in blue) and daytime (b, in red) events. Central boxes indicate the central 50% of the distribution and whiskers the remaining 25%. The median is indicated with red horizontal lines and the mean with black stars. Outliers are marked with red crosses and with numbers in red.

**DOWN** - Monthly evolution of nighttime (c) and daytime (d) events mean duration (in h) for HER (blue), CRA (green) and SLV (red). Small numbers indicate the number of mountain-breeze events used in each month at each site.

## Mountain breezes impacts on $CO_2$

### $CO_2$ mixing ratio daily anomaly (case, mean and sd)

NIGHTTIME EVENTS

DIURNAL CYCLES MARKED BY $CO_2$ "JUMP" IN THE EVENING AND DECREASE IN THE MORNING. BUT…

How do the mountain breezes influence the $CO_2$ mixing ratio?

→ SEE 3 FIGURES BELOW (analysis only for nighttime events)

DAYTIME EVENTS

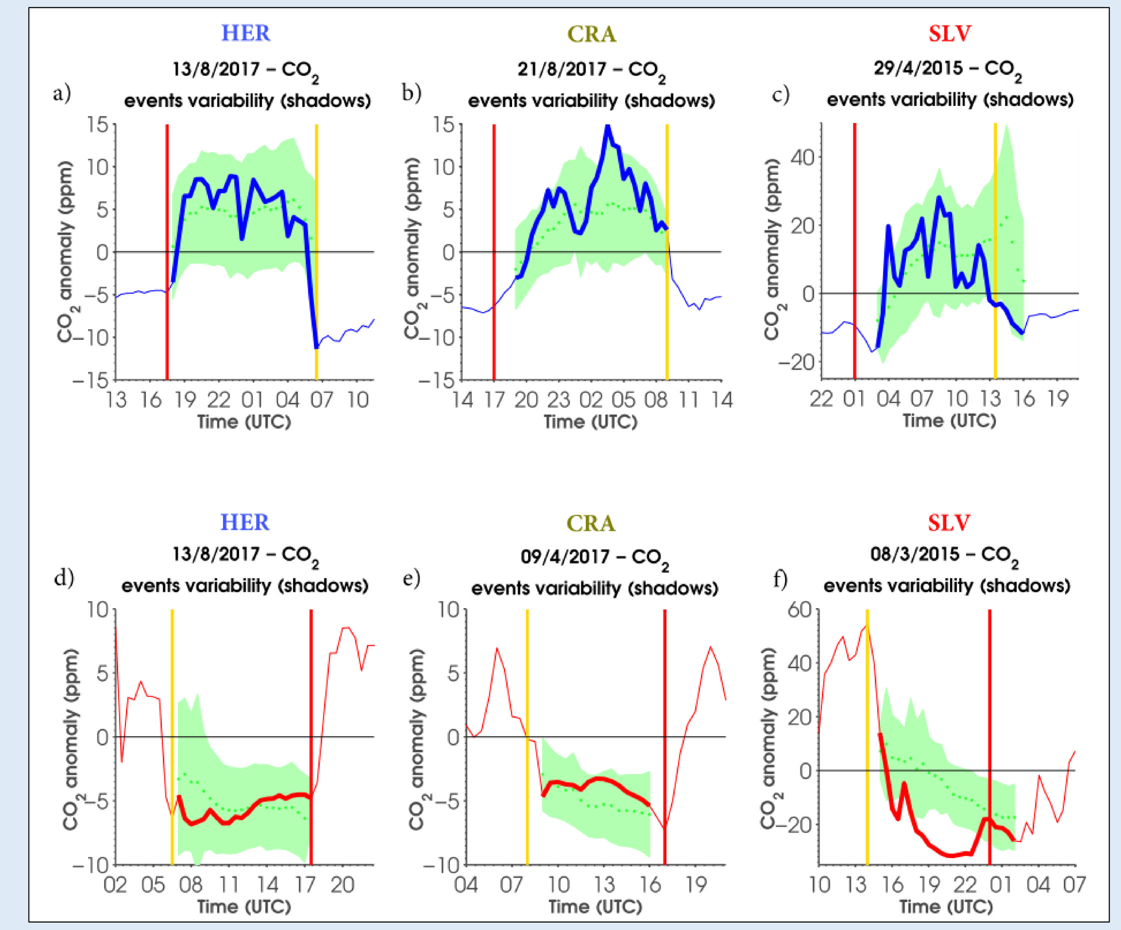



**Fig. 4.** $CO_2$ mixing ratio daily anomaly (in ppm) for some examples of nighttime (up) and daytime (below) events at each site.

Vertical yellow and red lines indicate the time when *H* changes sign.

The blue (red) thick lines show the $CO_2$ mixing ratio during each event.

Dotted-green lines show the mean $CO_2$ mixing ratio for all the events at each site.

The variability (sd) is shown with green shadows.

Note how the y-axis scale of SLV figures (c, f) is larger than for the other sites.

### Difference between time of maximum $CO_2$ increase (evening) and onset time of nighttime breezes

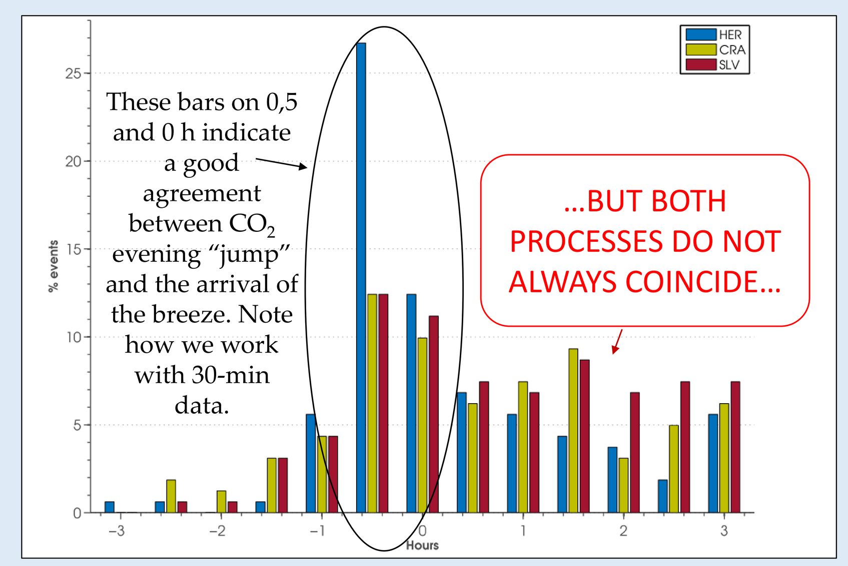



**Fig. 5.** Percentage of events from total ones (y-axis) with time difference (in h) between the initiation time of the maximum $CO_2$ increase (in 1 h) and the arrival time of the nighttime event (x-axis). Example: the 27% of blue bar at −0.5 h means that the initiation of the maximum $CO_2$ increase (in 1 h) is observed 0.5 h before the nighttime event arrival to the site in 27% of the total detected events at the HER site. Note how only maximum $CO_2$ evening increases larger than 5 ppm have been included.

### Mean $CO_2$ concentration anomaly for different ranges of TKE values during the nighttime breezes

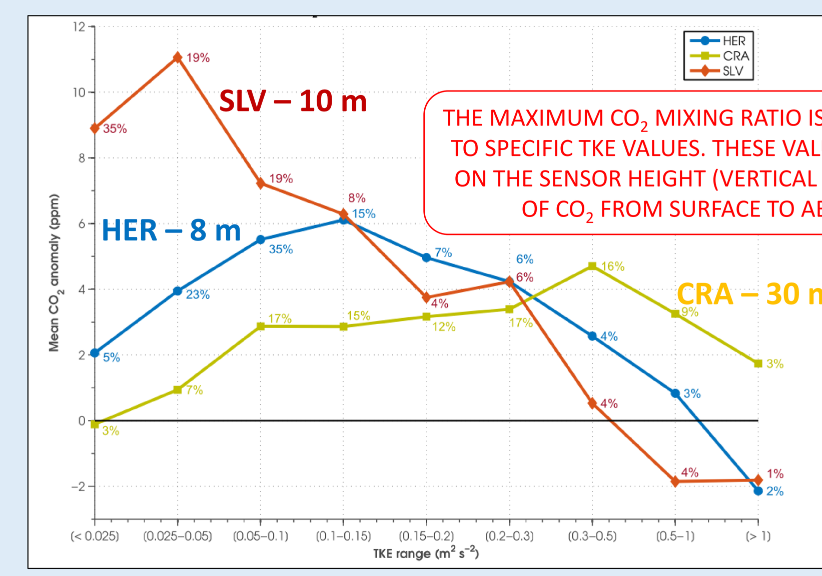
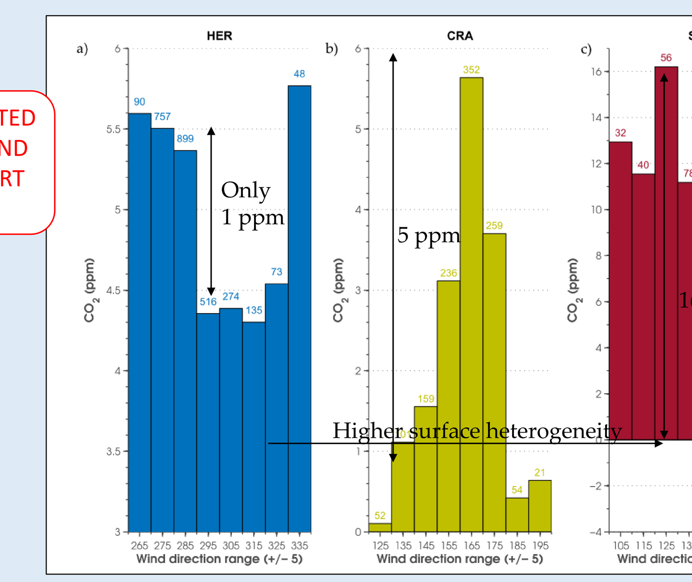



**Fig. 6.** Mean $CO_2$ mixing ratio (anomaly with respect to the daily mean) in ppm associated with different ranges of values of turbulent kinetic energy (TKE) ($m^2 s^{-2}$) during all nighttime events at the HER (blue), CRA (green) and SLV (red) sites. Only periods strictly during nighttime have been used. Percentages in numbers represent the percentage of time with those values of TKE for all nighttime events used; for example, the first number for the SLV line (35% in red) means that TKE has values lower than 0.025 $m^2 s^{-2}$ during 35% of all the nighttime-events time.

### Mean $CO_2$ concentration anomaly for different ranges of WIND DIRECTION during the nighttime breezes




WIND DIRECTION HAS A LARGER IMPACT ON $CO_2$ OVER HETEROGENEOUS SITES (SLV) WITH DIFFERENT EMISSION AREAS

**Fig. 7.** Mean $CO_2$ anomaly with respect to the daily mean in ppm (y-axis) observed for different ranges (of 10º) of wd (x-axis) for the HER (a), CRA (b) and SLV (c) sites. These ranges are around the main nighttime wd and are calculated strictly during nighttime moments (removing data during daytime) and for specific values of TKE: CRA from 0.025 to 0.2 $m^2 s^{-2}$; CRA from 0.05 to 0.3 $m^2 s^{-2}$ and SLC from 0 to 0.1 $m^2 s^{-2}$. Numbers above the bars indicate the number of 30-min data used for the mean computation.

## CONCLUSIONS

### MOUNTAIN BREEZES

- The features of the breezes depend on the type of phenomena (katabatic, mountain-plain, valley flows), distance to the mountains, tower location…
- Daytime breezes blow from a wider range of directions than nighttime ones.
- The breezes are later detected at the sites located farther.
- Nighttime breezes are normally more persistent and easier to form than daytime ones.
- The SLV site presents more complexity (lake + city) than the two other sites.

### IMPACTS ON $CO_2$

- The evening $CO_2$ jump does not always coincide with the nighttime breeze arrival (which somehow unlinks the advection effect).
- The $CO_2$ mixing ratio is controlled by the TKE values during the nights with nocturnal breezes.
- Maxima $CO_2$ mixing ratios depend on the measurements height (higher measurements "need more TKE" to see the maximum $CO_2$ values).
- The wind direction controls the $CO_2$ mixing ratio during the night over highly heterogeneous areas such as SLV, with a large lake and a big city.

## PUBLICATION, ACKNOWLEDGEMENTS AND AUTHORS AFFILIATIONS

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