Supplement

June 1, 2023

How to force WRF with MAR

Forcing WRF requires certain mandatory variables (Table S1) satisfying specific characteristics regarding, for example, vertical and temporal resolutions and map-projection. These variables are easily provided by reanalysis but can be unavailable among RCM outputs by default. In this work, MAR was re-run to generate the forcings for WRF for the selected PCAP episodes by using about one year of the long-term MAR simulations (see subsection 2.2.2) as spin-up time. Re-running MAR allowed to increase the vertical resolution of the model (from 24 to 36 vertical levels) and to store the variables specified in Table S1 with hourly frequency. These variables were then subject to a complex post-processing that aimed at making them suitable for the WPS-*metgrid*.

First of all, a change of the map projection was necessary. MAR uses an *oblique stereographic projection*. This projection is not supported by the WPS-metgrid, which instead accepts *polar stereographic projections* (besides other projections, like *Lambert* and *Mercator*). The conversion of the oblique stereographic projection to a polar stereographic projection was performed via the transformation equations for a North polar stereographic (J.P. Snyder, 1987):

$$
\begin{aligned}
x' &= 2R\, k_0 \tan(\pi/4 - \phi/2)\sin(\lambda - \lambda_0) \\
y' &= -2R\, k_0 \tan(\pi/4 - \phi/2)\cos(\lambda - \lambda_0)
\end{aligned}
$$

where $k_0 = 1$ = central scale factor, ϕ = latitude, λ = longitude, λ_0 = the standard longitude = $7.2°$ E, and R = the Earth radius = $6371,229$ km (where the values of λ_0 and R are the ones set in MAR).

After the transformation, all MAR variables (originally defined on a regular grid x-y of 7x7 km) were defined on a distorted grid on the plane of projection x'-y' tangent to the North pole. Since the WPS-metgrid requires that data have a regular grid spacing, all MAR variables were interpolated on a regular grid of 7x7 km in the x'-y' plane. A cubic spline interpolation was used for almost all variables, with the exception of "discontinuous" fields, such as snow height, for which the linear interpolation was used.

Then, those variables indicated as mandatory in Table S1 but not available by MAR were computed offline. The 3d-field of pressure was computed as $(SP - P_{top}) \cdot \sigma + P_{top}$, where $P_{top} = 0.1$ hPa and σ = sigma levels of MAR.

Temperature and moisture of soil layers (ST*tttbbb* and SM*tttbbb*) were derived as follows. By using $(k-1, k)$ to indicate a soil layer and (k) to indicate a soil depth (instead of *tttbbb* and *mmm*, respectively):

- $ST_{k-1,k} = \frac{1}{d_k}\left(SOILT_k \cdot \sum_{i=1}^{k} d_i - SOILT_{k-1} \cdot \sum_{i=1}^{k-1} d_i\right)$, assuming that SOILT at depth $k=1$ is equal to ST of the first layer; such equation is derived from the approximation of SOILT as weighted average of SM, where the weights are the layer thicknesses d_k.

- $SM_{k-1,k} = \frac{1}{\rho^{(water)}}\ \frac{1}{d_k}\left(SOILM_k \cdot \sum_{i=1}^{k} d_i - SOILM_{k-1} \cdot \sum_{i=1}^{k-1} d_i\right)$, assuming that SOILM at depth $k=1$ is equal to SM of the first layer multiplied by the density of water $\rho^{(water)} = 1000$ kg/m³; such equation is derived from $SM_{k-1,k} = \frac{m_{k-1,k}^{(water)}\ /\ \rho^{(water)}}{V_{k-1,k}^{(soil)}}$.

Finally, all the MAR variables, which were saved in NetCDF files, were converted into the intermediate file format readable for the WPS-metgrid. Usually, the intermediate-format meteorological data are prepared by the WPS-*ungrib,* but this is valid only if data are provided in GRIB-formatted files. In our case, a new python-routine was created to write the intermediate-format meteorological data starting from the NetCDF-formatted files, following the indications of the ARW Guide (chapter 3).

References

- J.P. Snyder. Map projections: A working manual. Report, Washington, D.C., 1987, URL http://pubs.er.usgs.gov/publication/pp1395 [pages 157-158]

- NCAR. ARW, Version 4 Modeling System User's Guide. Report, 2019, URL https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_v4/contents.html

Field	Unit	Description	Notes	MAR variables	
				Names	**Description**
3d fields					
TT	K	3-d air temperature		TT (time, atmlay, y, x)	Real Temperature ('C)
RH	%	3-d relative humidity	Not needed if SPECHUMD is available	/	Relative humidity (%)
SPECHUMD	kg kg⁻¹	3-d specific humidity	Not needed if RH is available	QQ	Specific humidity (g/kg)
UU	m s⁻¹	3-d wind u-component		UU	X-wind speed component (m/s)
VV	m s⁻¹	3-d wind v-component		VV	Y-wind speed component (m/s)
GHT	m	3-d geopotential height		ZZ	Model surface height (m)
PRESSURE	Pa	3-d pressure	Needed for non-isobaric datasets	/	
Surface level					
TT2	K	2-meter air temperature		TTz (ztqlev = 1)	2-m air temperature ('C)
RH2	%	2-meter relative humidity	Not needed if SPECHUMD2 is available	/	/
SPECHUMD2	kg kg⁻¹	2-meter specific humidity	Not needed if RH2 is available	QQz (ztqlev = 1)	2-m specific humidity (g/kg)
UU10	m s⁻¹	10-meter wind u-component		UUz (zuvqlev = 2)	10-m UU
VV10	m s⁻¹	10-meter wind v-component		VVz (zuvlev = 2)	10-m VV
PSFC	Pa	Surface pressure		SP	Surface pressure (hPa)
PMSL	Pa	Mean sea-level pressure	Not needed if *psfc_to_psfc = TRUE*	/	
SKINTEMP	K	Skin temperature		ST	Surface temperature ('C)
SOILHGT	m	Soil height		SH	Surface height (m)
LANDSEA	proprtn	Land-sea mask		SRF	Surface type (4=land, 1=sea)
Underground levels					
ST*tttbbb*	K	Soil temperature		/	
SM*tttbbb*	m³ m⁻³	Soil moisture		/	
SOILT*mmm*	K	Soil temperature	not needed if ST*tttbbb* available	SLT1, SLT2, SLT3	Soil temperature ('C)
SOILM*mmm*	kg m⁻³	Soil moisture	not needed if SM*ttttbbb* available	SLQ1, SLQ2, SLQ3	Soil Humidity Content (kg/m3)
Optional BUT desired fields					
SEAICE	proprtn	Ice flag		/	
LANDN	proprtn			/	
SNOW	kg m⁻²	Water equivalent snow depth		MB	
SNOWH	m	Physical snow depth		ZN3	Snow Pack Height Total (m)
SST	K	Sea surface temperature		ST2(sector=1)	SST ('C)

mmm is the level depth in cm

ttt is the layer top depth in cm, and *bbb* is the layer bottom depth in cm

In MAR:
zuvlev = 2, 10, 50, 100 m
ztqlev = 2, 10, 50, 100 m
sollay = 0.1, 1.5, 4, 12, 40, 120, 400 cm (underground)

Table S1: List of variables required to force WRF (the list is taken from ARW Guide, pag. 59). In green, the MAR variables used in this work to force WRF.

Additional Figures
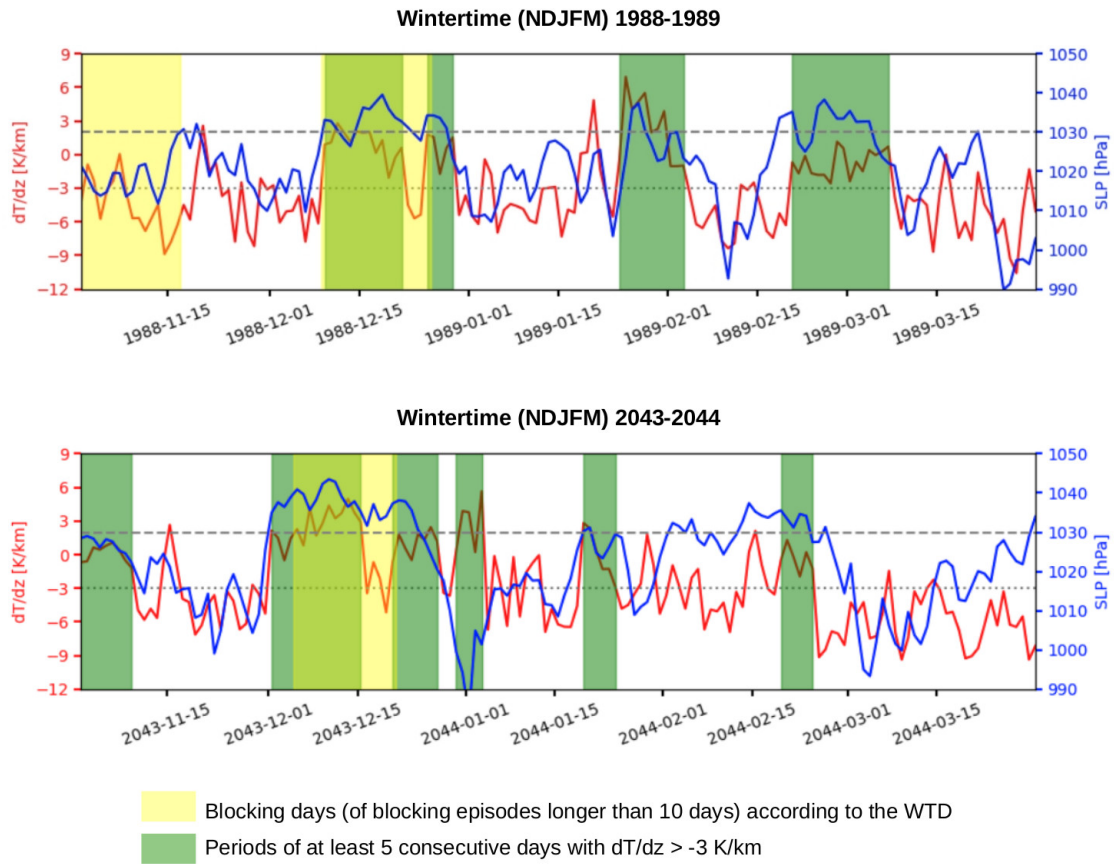
Figure S1: Temporal series of vertical temperature gradient (red) and sea level pressure (blue) for the two winter seasons including the selected PCAPs (14-21 December 1988 and 4-15 December 2043).
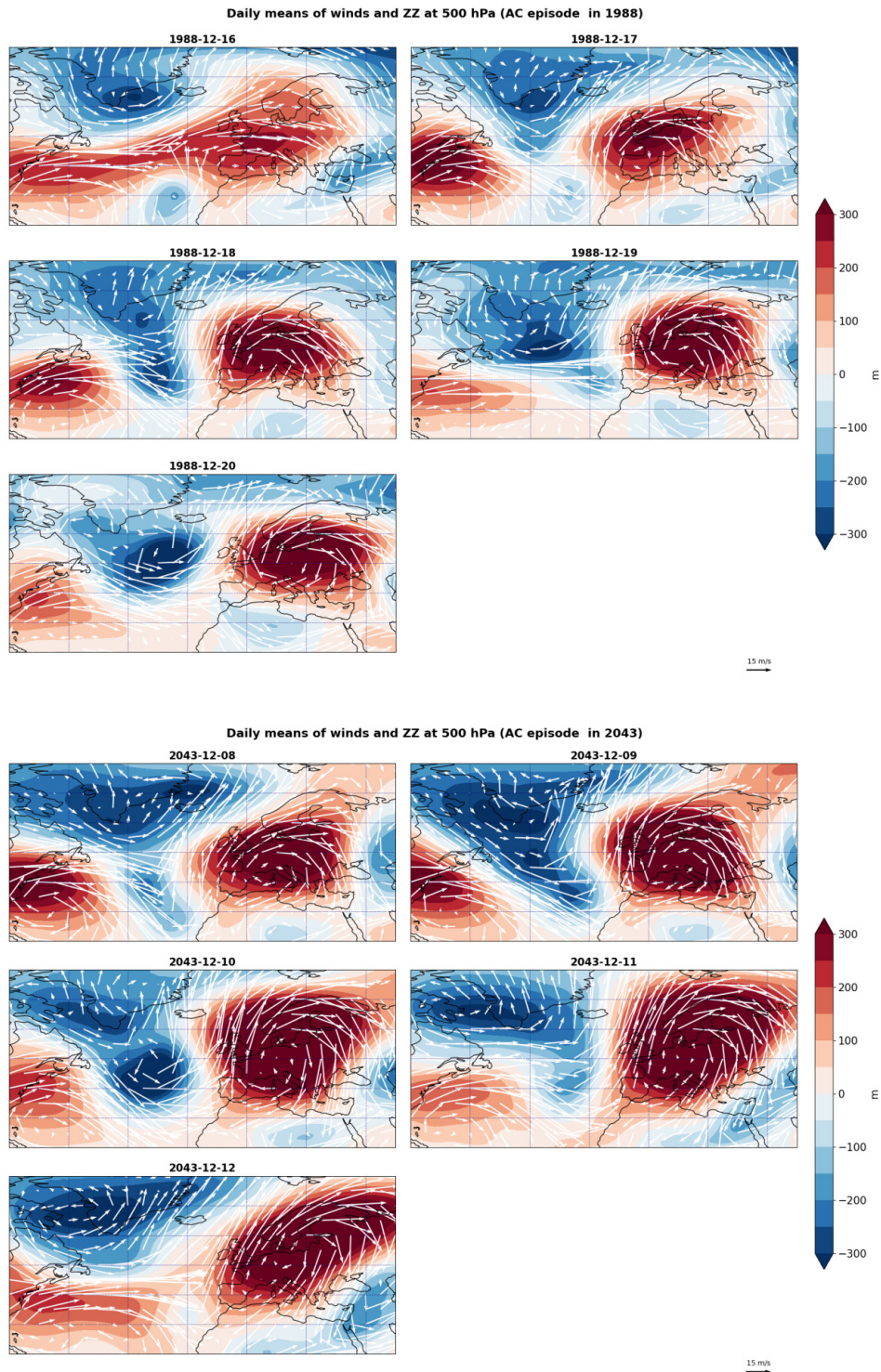
Figure S2: Daily means of geopotential height (ZZ) at 500 hPa and wind speed at 500 hPa of MPI_HIST and MPI_SSP5 for the five days of the selected PCAPs simulated with WRF
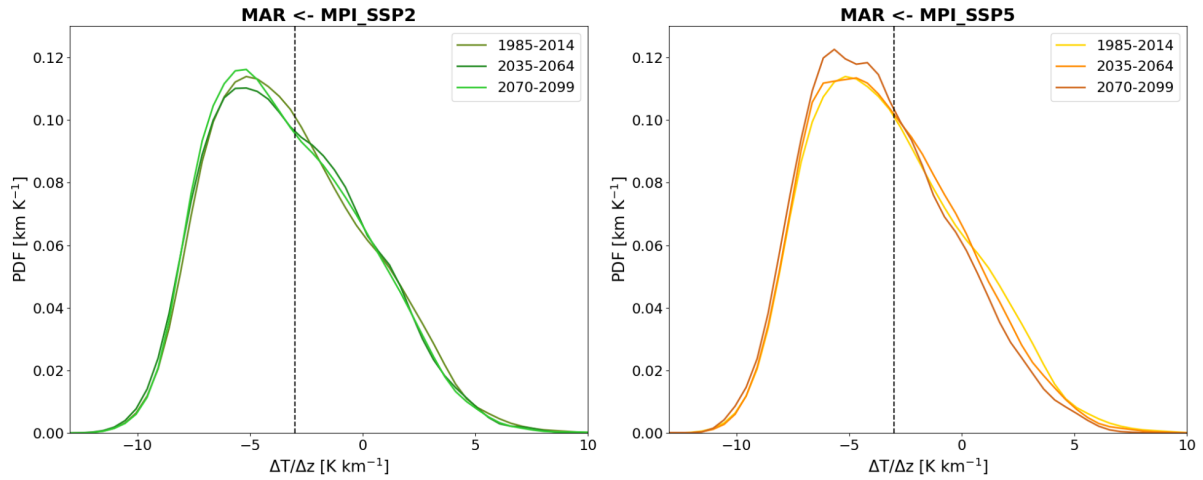
Figure S3: Normalized probability density functions (PDFs) of daily $\Delta T/\Delta z$ computed with MAR←MPI_SSP2 and MAR←MPI_SSP5 for 30 years around 2000, 2050, and 2085 during NDJFM. The vertical line is at $\Delta T/\Delta z = -3$ K km^{-1} (i.e. the threshold used to identify PCAP episodes).
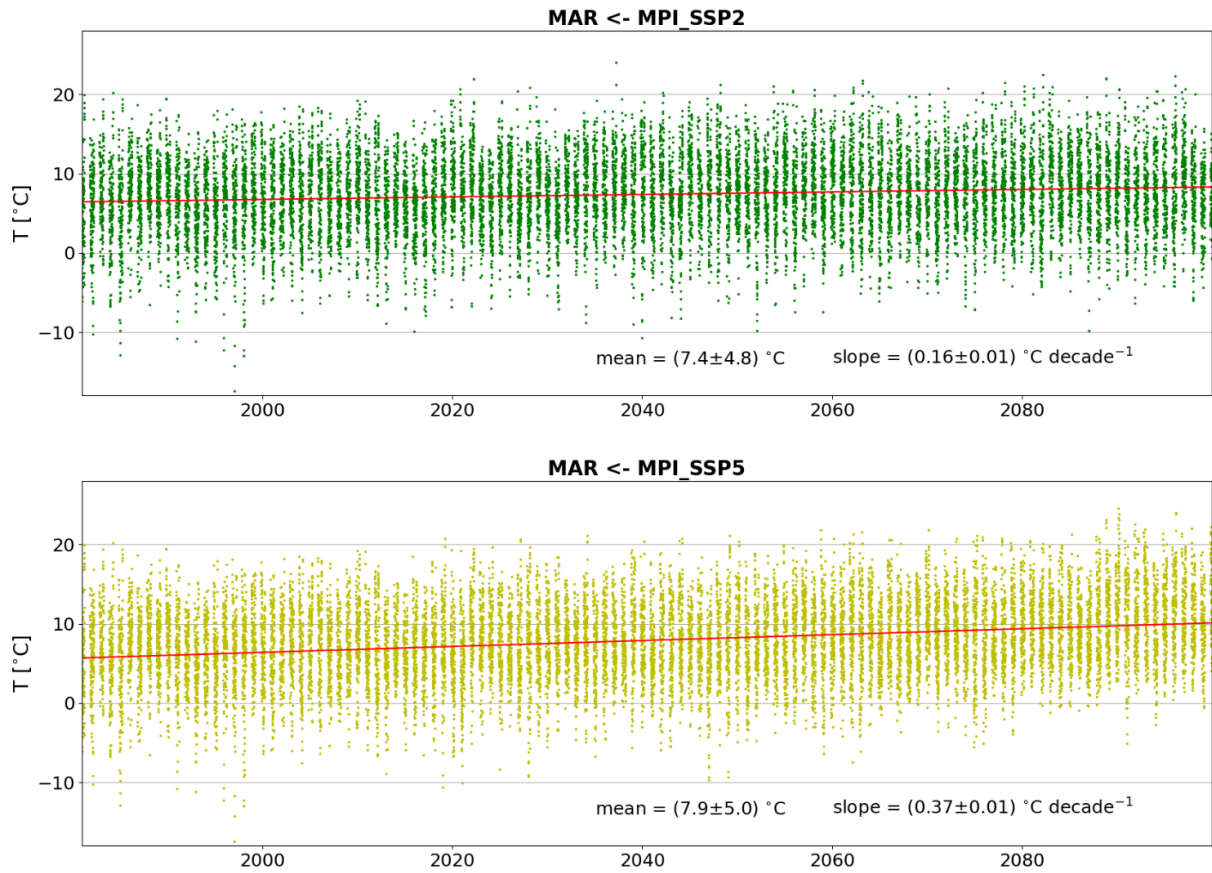
Figure S4: Temporal series of daily winter near-surface air temperature (T2) for MAR←MPI_SSP2 and MAR←MPI_SSP5. The red line is the trend (which is statistically significant at 95%). The mean and the slope of the trend refer to the entire time series (i.e. 120 winters).
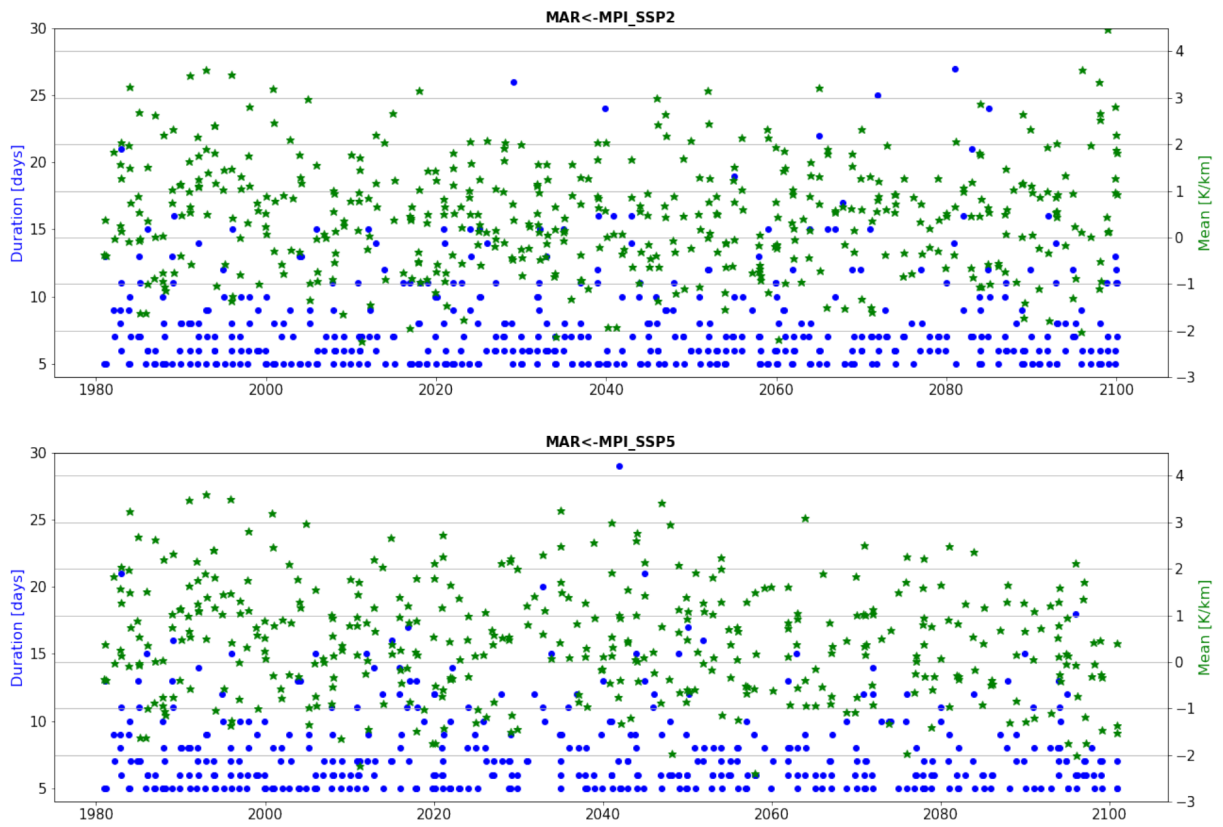
Figure S5: Duration (blue) and intensity (green) of all PCAP episodes identified in MAR←MPI_SSP2 and MAR←MPI_SSP5.
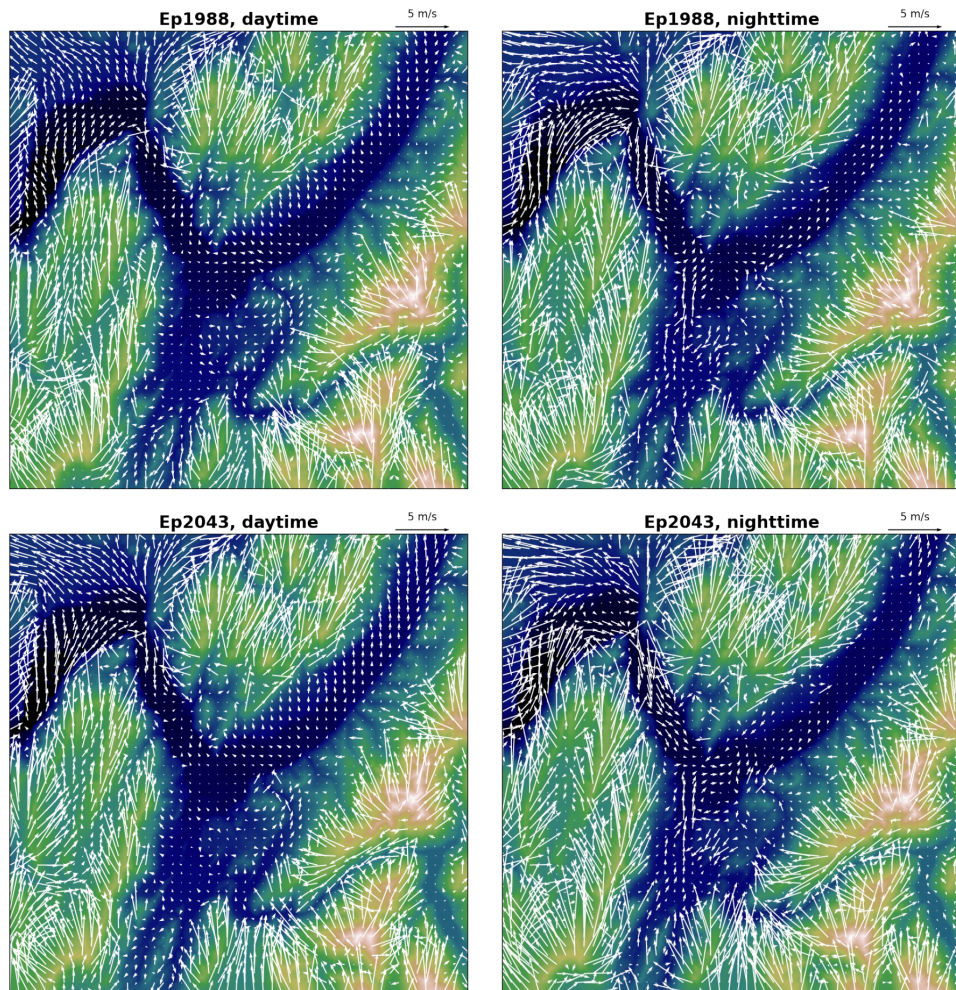
Figure S6: Horizontal wind at 10 m a.g.l. for daytime and nighttime of Ep1988 and Ep2043. The winds are temporally averaged for daytime (from 8:00 UTC to 18:00 UTC) and nighttime (from 18:00 UTC to 8:00 UTC) for the selected three days of the episodes.
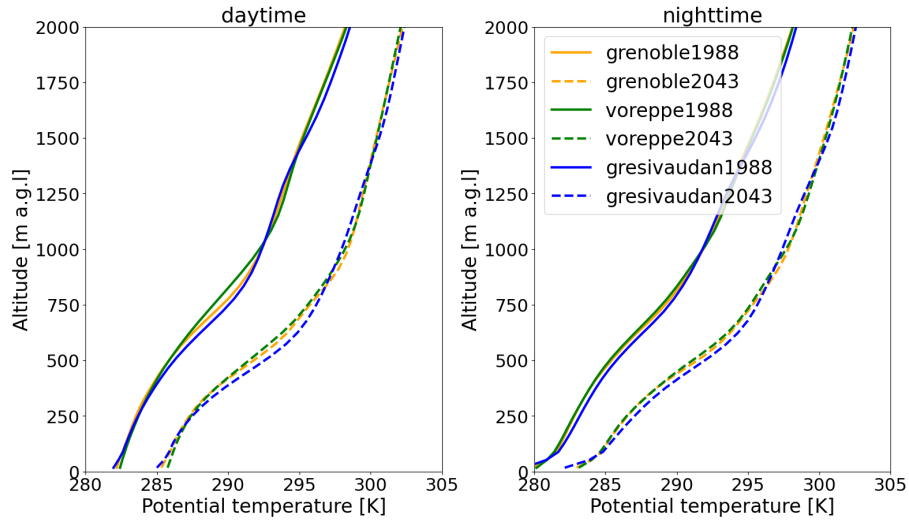
Figure S7:   Vertical profiles of the potential temperature during daytime (left) and nighttime (right) spatially averaged over the Grenoble basin (orange), Voreppe valley (green) and Grésivaudan valley (blue) for Ep1988 (continuous line) and Ep2043 (dashed line). The day (night) periods are defined between 7:00 UTC and 17:00 UTC (17:00 UTC and 7:00 UTC). Each profile is also averaged over the three selected days and nights of each episode.
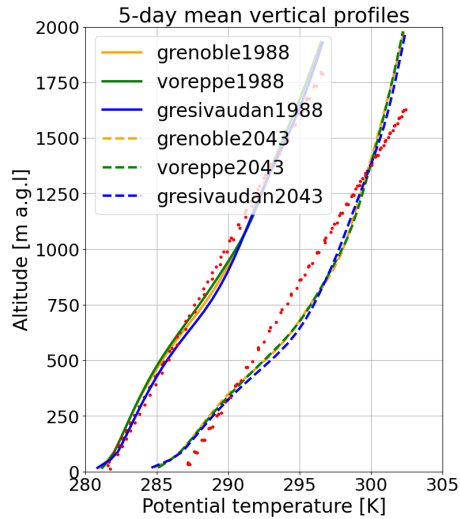
Figure S8:   Vertical profiles of the potential temperature spatially averaged over the Grenoble basin (orange), Voreppe valley (green) and Grésivaudan valley (blue) for Ep1988 (continuous line) and Ep2043 (dashed line). Each profile is averaged over all days of each episode. The red dotted lines are the linear regressions for each profile. The root-mean-square errors (between each profile and its linear regression) are equal to 59.12 m, 54.46 m and 58.74 m for Ep1988 and to 104.73 m, 105.41 m and 105.53 m for Ep2043.