Supplement of Atmos. Chem. Phys., 22, 3901–3909, 2022
https://doi.org/10.5194/acp-22-3901-2022-supplement

Atmospheric Chemistry and Physics
Open Access

Supplement of

Aerosol indirect effects in complex-orography areas: a numerical study over the Great Alpine Region

Anna Napoli et al.

Correspondence to: Anna Napoli (anna.napoli@cimafoundation.org)

Supplementary Material

S1 Control run (PRISTINE)

In this section, the climatological conditions of the PRISTINE run are shown.
Figure S2, and S3 show respectively the maps of the seasonal mean temperature, and of cloud frequency in winter (DJF) and in summer (JJA). Figures S4, and S5 show the daily cycle of the seasonal mean temperature and of the seasonal mean cloud frequency as a function of surface elevation. Figure S2 highlights seasonal temperature characteristics: during winter the land is warmer than the sea, while in summer the opposite happens: the sea has lots of stored heat from the summer, which takes time to dissipate. Due to the vertical gradient of temperature, mountains are always colder than lowlands. The daily cycle of the seasonal mean cloud frequency is shown in Figure S3: the altitudinal dependence of cloud is clearly visible, associated to the orographic lifting of air masses that favors condensation and cloud formation on the upslope of the mountains, favoring a corresponding increase in precipitation (Fig. S7).
Figure S8 represents the seasonal mean number of days with convective events (daily maximum vertical velocity greater than 3.5m/s) in the Summer season (JJA) as a function of surface elevation.
In Figure S6 we show the PBL height daily cycle as a function of altitude for winter (a) and summer (b): during cold (warm) months the atmospheric column is more (less) stable and the PBL is thin (thick).
Figure S9 and S10 represent respectively the daily cycle of short-wave and downward long-wave radiation in the Winter season (a) and in the Summer season (b) as function of surface elevation.

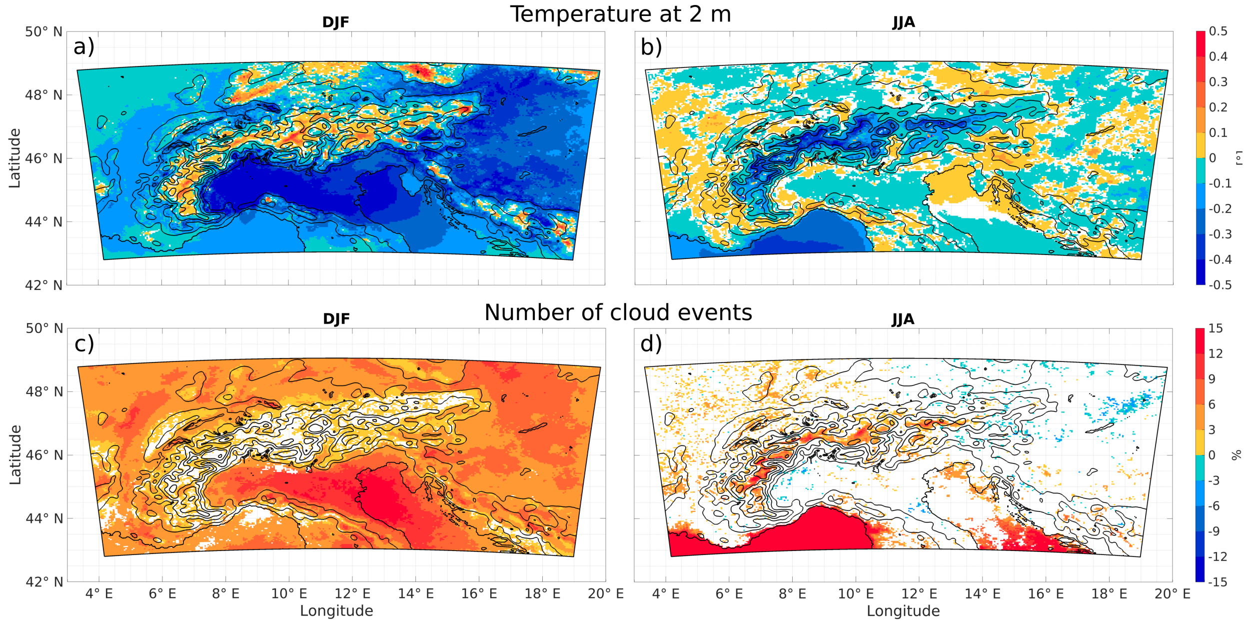

Figure S1: *Seasonal mean difference in 2 m temperature in DJF (a) and JJA (b). Relative variation of seasonal mean cloud frequency in DJF (c) and in JJA (d). Coloured pixels represent points that are significant at the 95% confidence level. Elevation contours are shown every 500 m.*

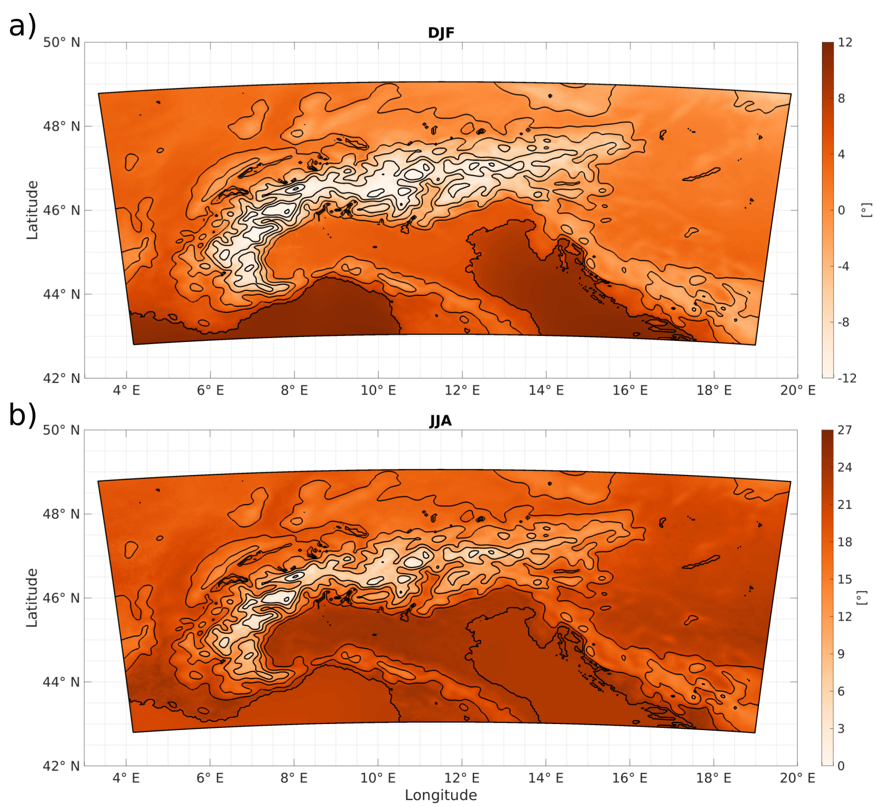

Figure S2: *Daily mean temperature in DJF (a) and JJA (b) of the PRISTINE run.*

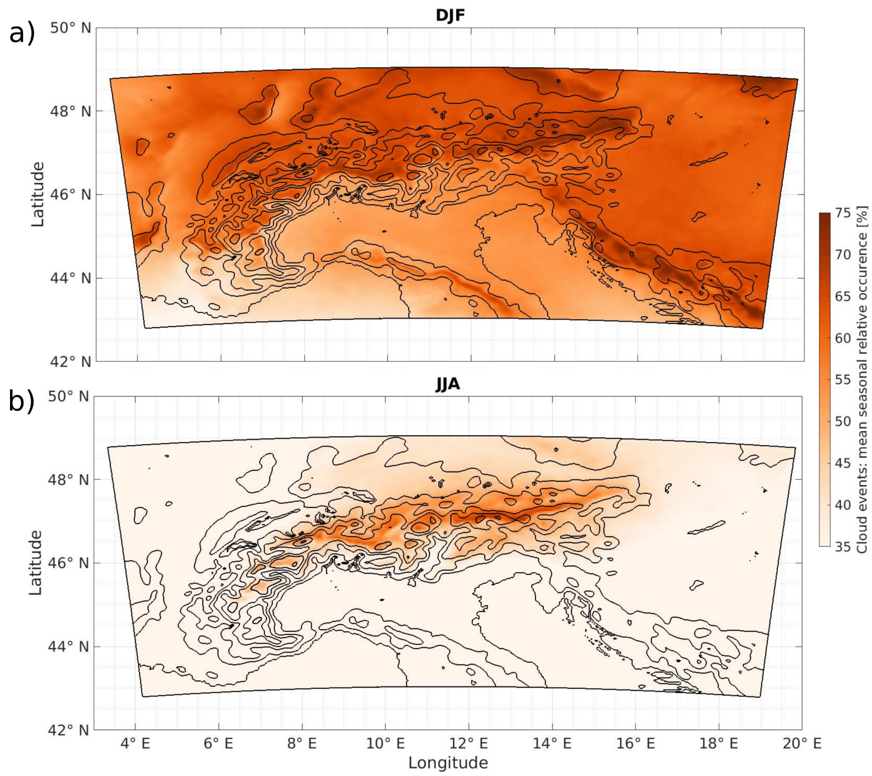

Figure S3: *Seasonal mean cloud frequency in the PRISTINE run in DJF (a) and JJA (b).*

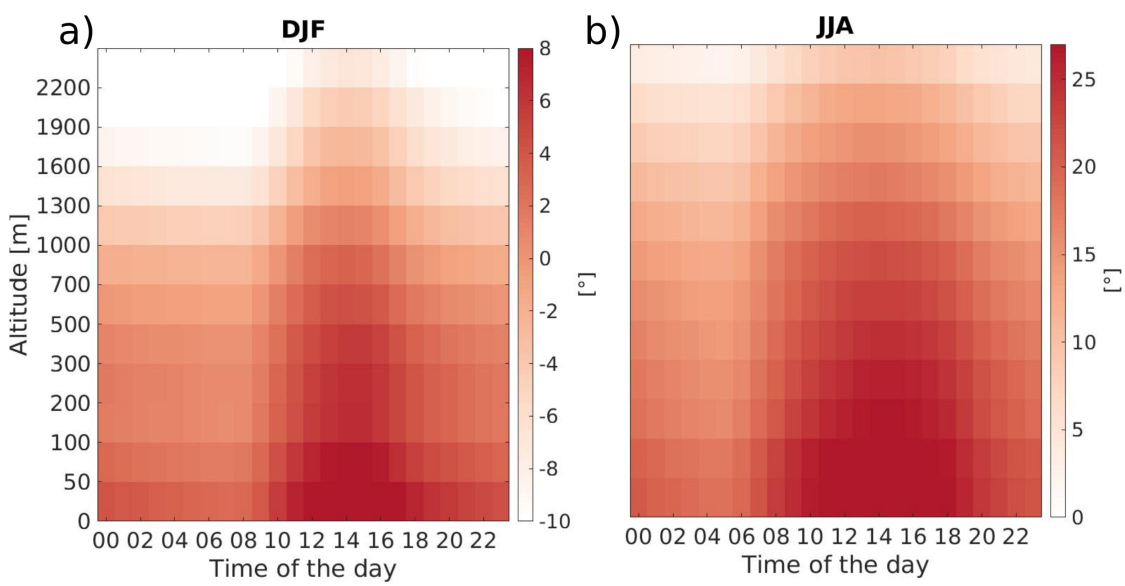

Figure S4: *Daily cycle of temperature at 2 m as a function of ground elevation in DJF (a) and JJA (b) for the PRISTINE run. Only land points have been taken into account to make this figure.*

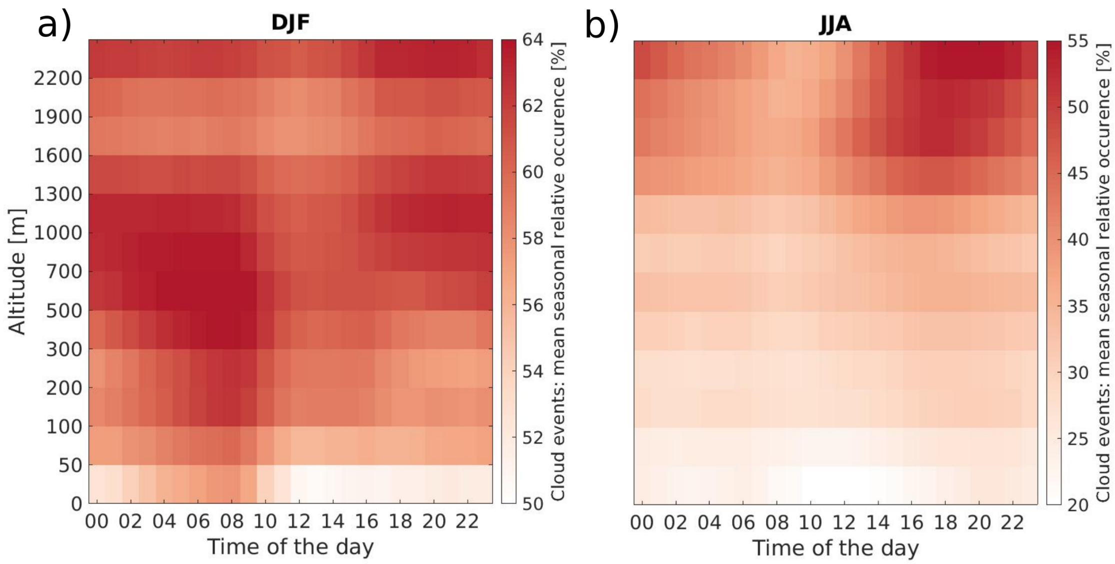

Figure S5: *Daily cycle of cloud frequency as a function of ground elevation in DJF (a) and JJA (b) for the PRISTINE run. Only land points have been taken into account to make this figure.*

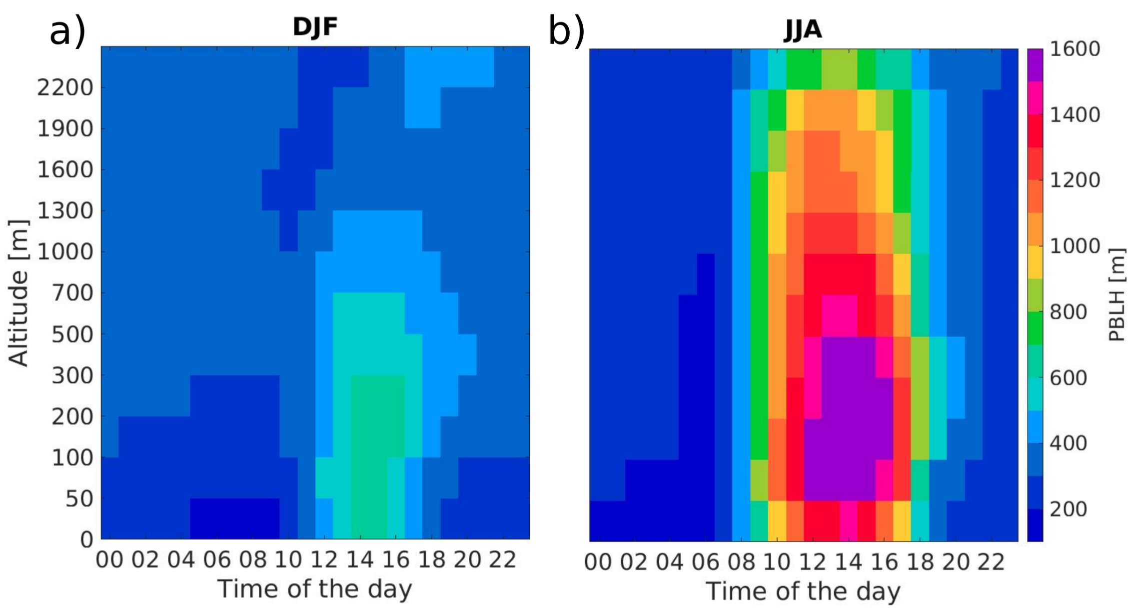

Figure S6: *Daily cycle of PBLH as a function of ground elevation in DJF (a) and JJA (b) for the PRISTINE run. Only land points have been taken into account to make this figure.*

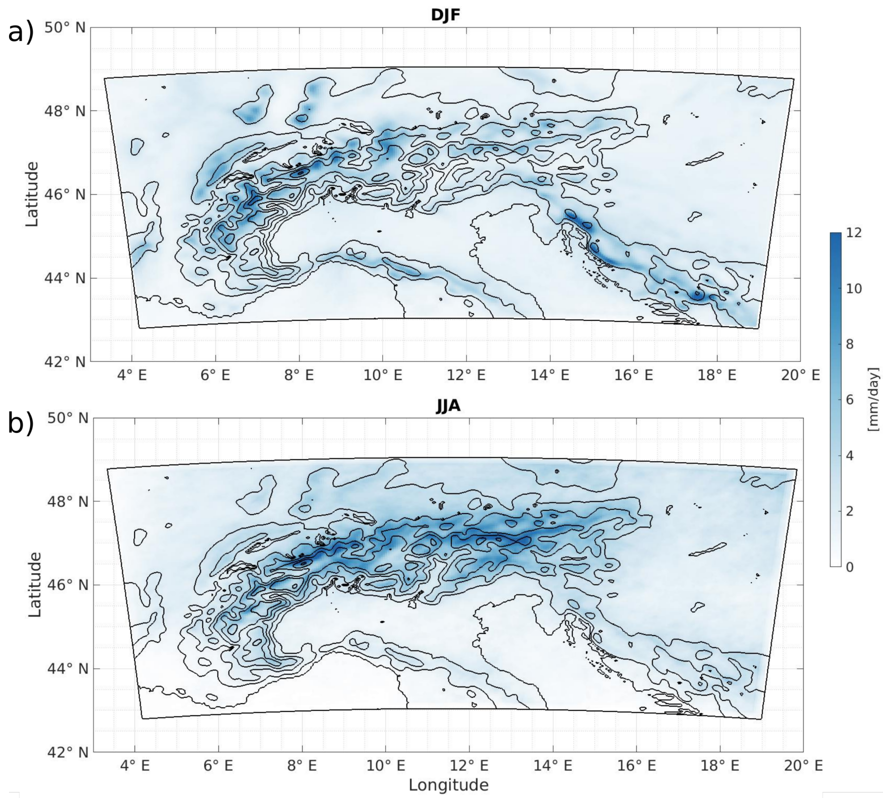

Figure S7: *Seasonal mean precipitation in DJF (a) and JJA (b) for the PRISTINE run.*

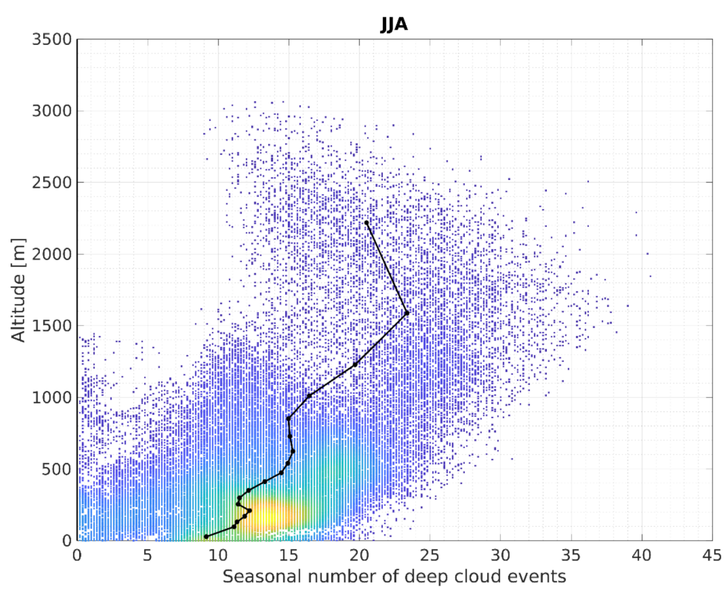

Figure S8: *Seasonal mean number of days with deep convective events (daily maximum vertical velocity greater than 3.5m/s) in Summer as function of surface elevation. Only land points have been taken into account to make this plot. Colors represent the density of the points in the GAR from yellow (high density) to blue (low density).*

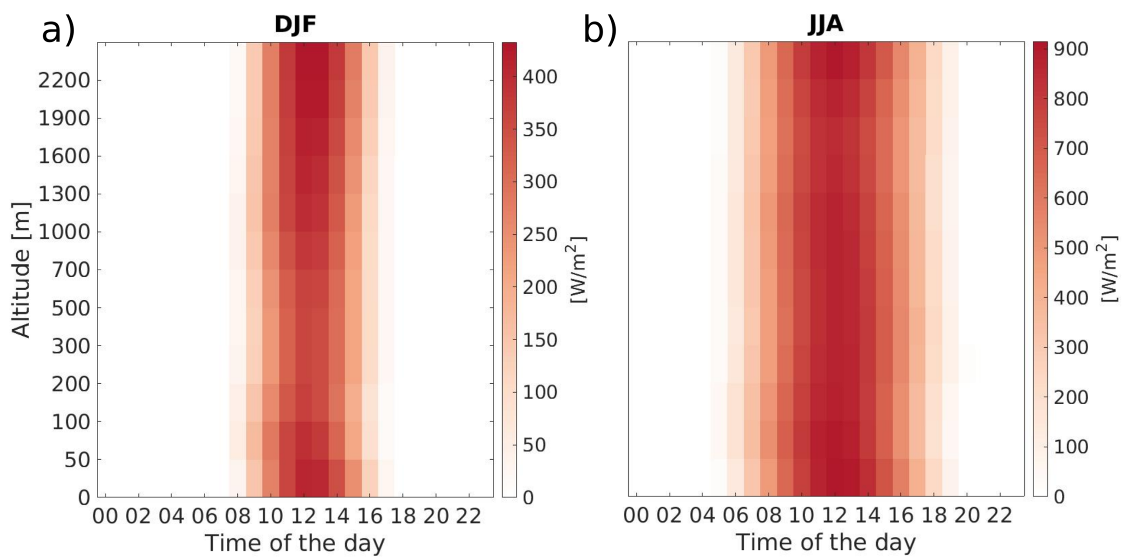

Figure S9: *Daily cycle of short-wave radiation reaching the surface as a function of ground elevation in DJF (a) and JJA (b) for the PRISTINE run. Only land points have been taken into account to make this figure.*

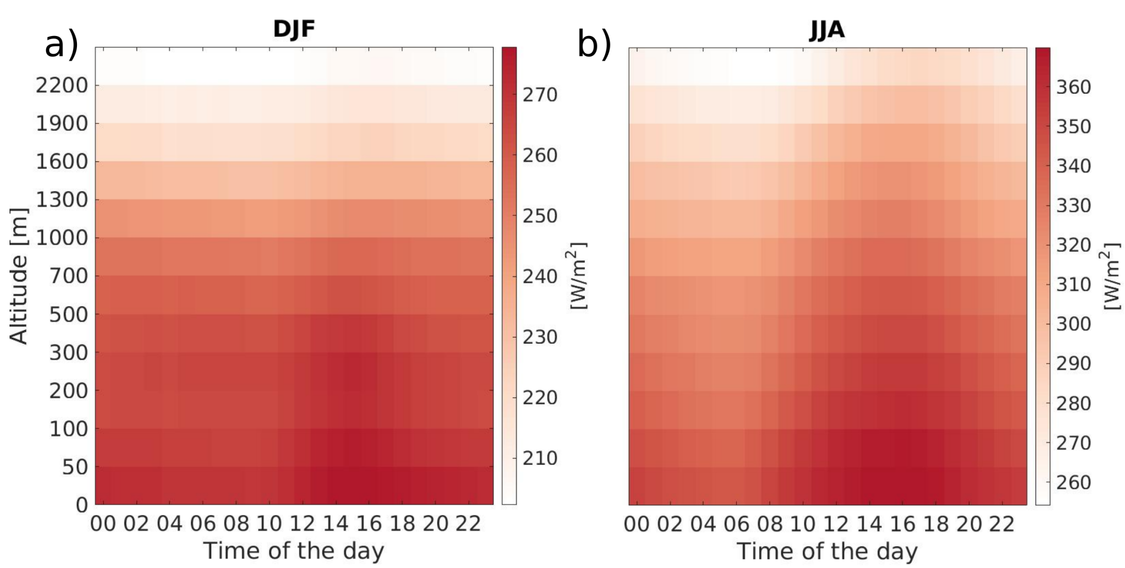

Figure S10: *Daily cycle of downward long-wave radiation at the surface as a function of ground elevation in DJF (a) and JJA (b) for the PRISTINE run. Only land points have been taken into account to make this figure.*

S2 Concentration of aerosols

The Thompson aerosol aware microphysic scheme computes a surface emission flux of aerosols starting from the initial vertical concentration profiles that are equal for all grid points at the same altitude. The definition of the vertical profiles is in module *module_mp_thompson.F*, *SUBROUTINE thompson_init*:

```
if (max_test .lt. eps) then
   write(mp_debug,*) ' Apparently there are no initial CCN aerosols.'
   CALL wrf_debug(100, mp_debug)
   write(mp_debug,*) '   checked column at point (i,j) = ', its,jts
   CALL wrf_debug(100, mp_debug)
   do j = jts, min(jde-1,jte)
   do i = its, min(ide-1,ite)
      if (hgt(i,1,j).le.600.0) then
         h_01 = 0.8
      elseif (hgt(i,1,j).ge.1500.0) then
         h_01 = 0.01
      else
         h_01 = 0.8*cos(hgt(i,1,j)/600.0 - 1.0)
      endif
      niCCN3 = -1.0*ALOG(naCCN1/naCCN0)/h_01
      nwfa(i,1,j) = naCCN1+naCCN0*exp(-((hgt(i,2,j)-hgt(i,1,j))/1000.)*niCCN3)
      do k = 2, kte
         nwfa(i,k,j) = naCCN1+naCCN0*exp(-((hgt(i,k,j)-hgt(i,1,j))/1000.)*niCCN3)
      enddo
   enddo
   enddo
else
   has_CCN   = .TRUE.
   write(mp_debug,*) ' Apparently initial CCN aerosols are present.'
   CALL wrf_debug(100, mp_debug)
   write(mp_debug,*) '   column sum at point (i,j) = ', its,jts, SUM(nwfa(its,:,jts))
   CALL wrf_debug(100, mp_debug)
endif
```

The vertical profile is a combination of naCCN0 (naIN0) and naCCN1 (naIN1) input variables, and it depends on surface elevation through the niCCN3 (niIN3) value for water-friendly (ice-friendly) aerosols. The input variable values are defined as follows, in POLLUTED and PRISTINE respectively:

- naCCN0: 10000 cm^{-3}, 10 cm^{-3}
- naCCN1: 10 cm^{-3}, 10 cm^{-3}
- naIN0: 10000 cm^{-3}, 0.005 cm^{-3}
- naIN1: 0.005 cm^{-3}, 0.005 cm^{-3}

The values correspond to those used in the paper by Da Silva et al. 2018, chosen to *"ensure that aerosol indirect effects emerge from the "natural noise"* [1]. It should be noted that 10,000 /cc is a realistic value measured in urban areas by counting particles larger than 0.01 μm [2].
The values highlighted in orange in the subroutine have been modified from original code to better represent the aerosol concentrations in the Great Alpine Region. Indeed, the initial vertical profile in the out-of-the-box microphysics-28 scheme has been designed to fit the Continental U.S. conditions, over which the near-surface value is found to exist within an idealized layer of approximately 200 to 1000 meters depending on starting elevation. In more details, the formulation tries to account for a very thin idealized layer ($\mathcal{O}(10m)$) in high terrain above 2500 meters and a thicker layer ($\mathcal{O}(1000m)$) for grid points at elevations lower than 1000m.

The proposed modifications for the Great Alpine Region admit a shallow layer of aerosols for elevations above 1500m (rather than 2500m) and a thicker layer for elevations lower than 600m. In Figure S11 the resulting surface input flux of water-friendly aerosols is shown for the POLLUTED run. In the PRISTINE experiment, the input of water-friendly aerosols is characterized by a single low flux value, and it is homogeneous over the whole domain.

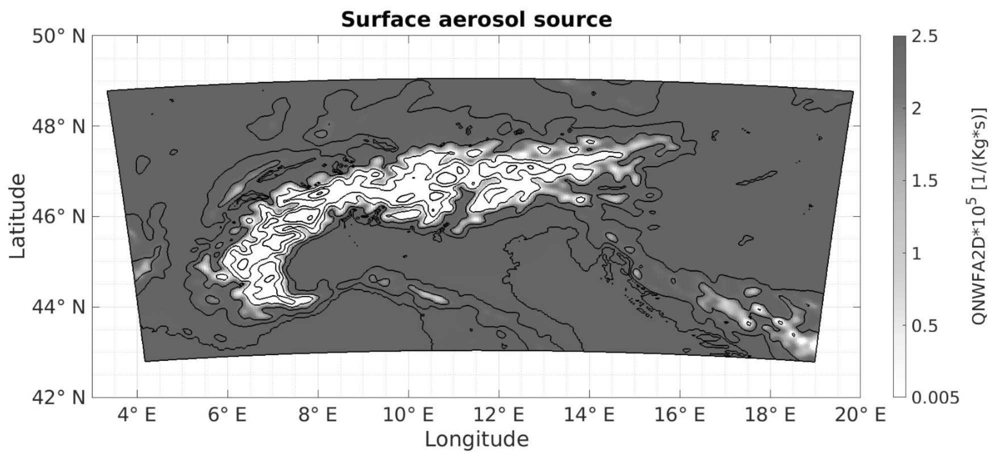

Figure S11: *QNWFA2D variable: surface input flux of water-friendly aerosols in POLLUTED simulation.*

The concentration of aerosols depends on the height of the Planetary Boundary Layer: during winter the PBLH is shallow (Fig. S6a) and thus more pollution is trapped, while during summer the greater instability in the lower troposphere favors thickening the PBL (Fig. S6b) and, consequently, aerosols are more dispersed in the air column. Figure S12 shows the mean concentration in the PBL of the water-friendly aerosols at 3a.m. in winter and in summer for both experiments. The Planetary Boundary Layer thickness seasonal dependence is also visible in Figure S13, that shows the mean vertical profile over the entire domain of QNWFA in POLLUTED and PRISTINE experiments for ranges of altitudes in DJF (a) and in JJA (b): at higher altitudes during the summer season higher concentrations are present compared to the winter season.

S3 Definition of cloud events

Sensitivity experiments on the definition of cloud events based on different thresholds for cloud fraction have been performed. Figure S14 shows the relative variation in cloud frequency between POLLUTED and PRISTINE experiments when a cloud event is defined at a given position if cloud fraction in at least one level is larger than 0.1, 0.5 and 0.9. The results presented in the main paper, which are not sensitive to the precise definition of cloud events, refer to the case with threshold value corresponding to 0.5.

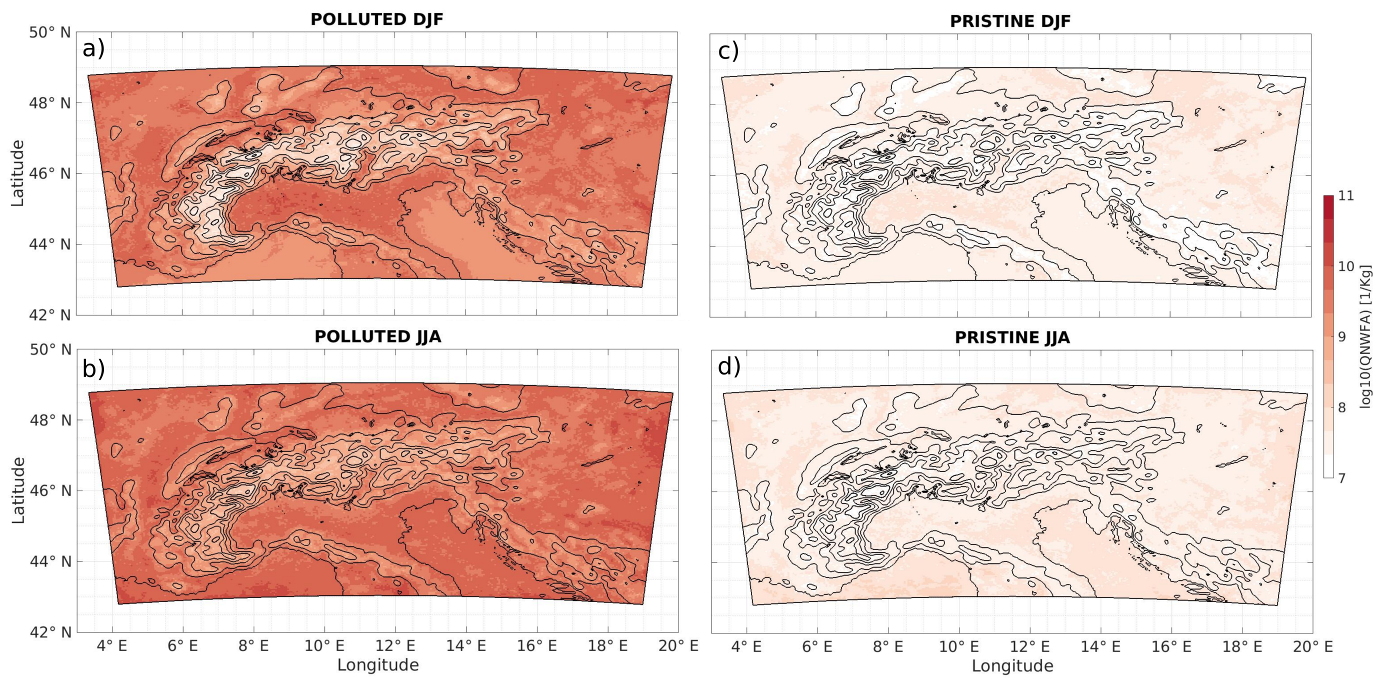

Figure S12: *Seasonal mean concentration of water-friendly aerosols over the PBL.*

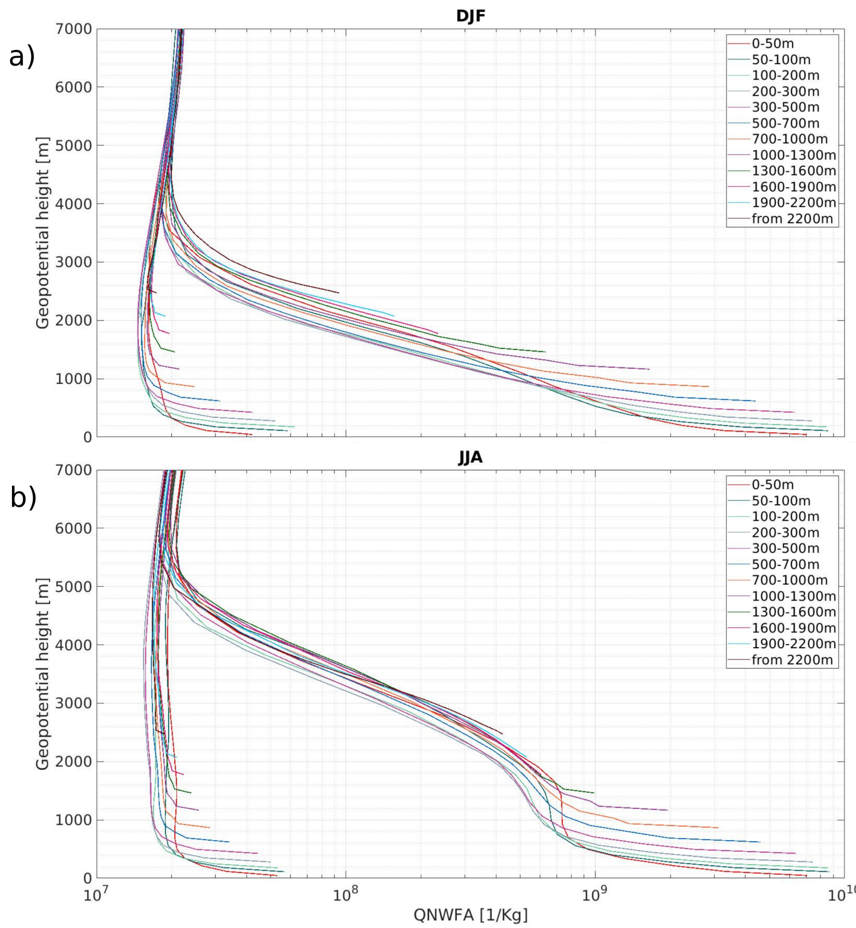

Figure S13: *Mean vertical profile of QNWFA concentration for ranges of altitudes in Winter (a) and Summer (b) for the POLLUTED (lines at the bottom right of the plots) and PRISTINE (lines at the bottom left of the plots) experiments.*

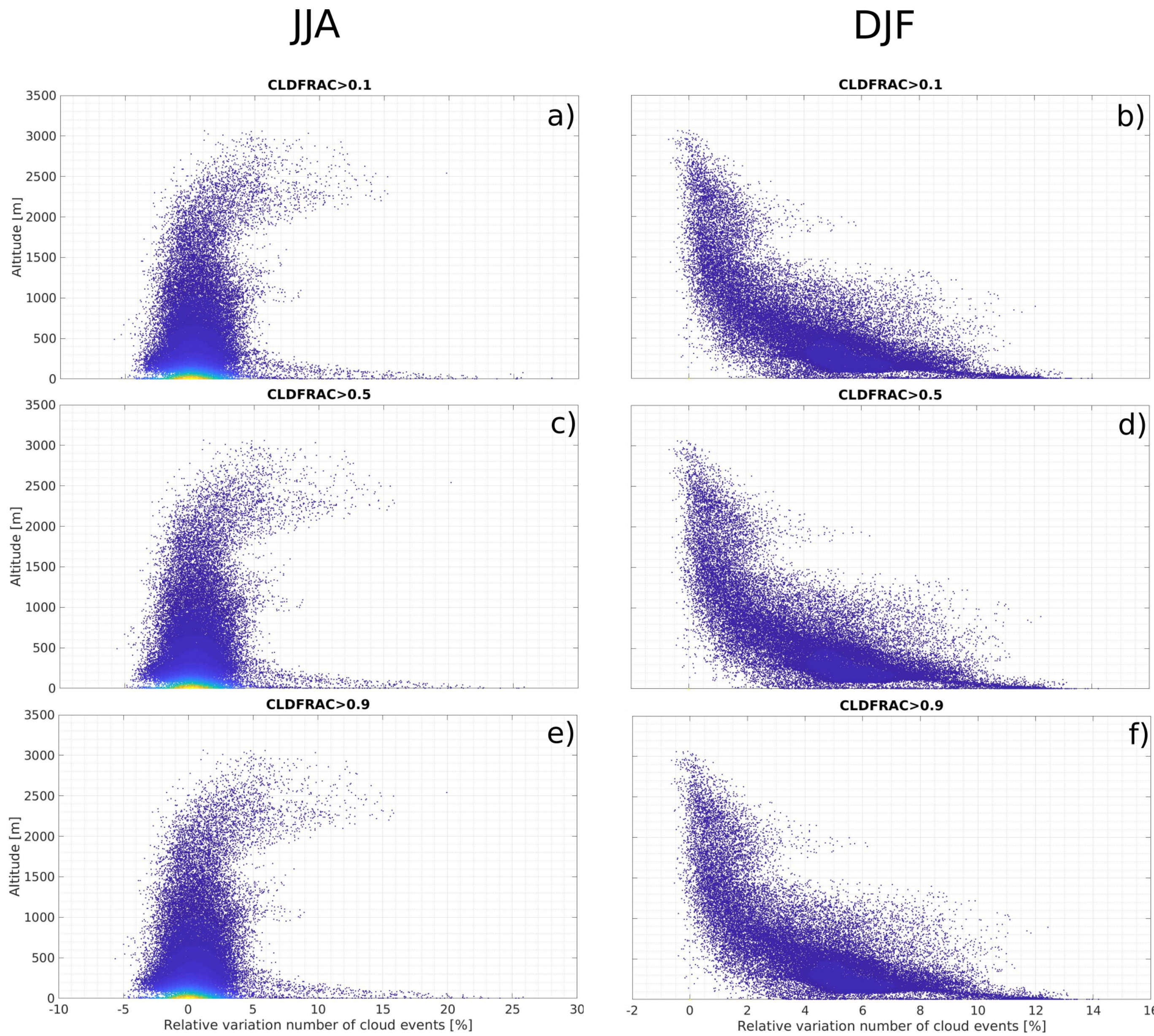

Figure S14: *Relative variation of the cloud frequency in JJA and in DJF: a), c) and d) show the relative variation of three different cloud fraction thresholds for the definition of cloud events during JJA, while b), d) and f) show the relative variations during DJF. Colors represent the density of the points from yellow (high density) to blue (low density).*

S4 Response to aerosols: other metrics

We here show how different metrics, not shown in the main paper, respond to aerosol loading.
In Figure S15 the map of the relative variation of daily seasonal precipitation is shown.
To investigate the response of convective events to changing aerosol loading, we computed the daily maximum vertical velocity in the air column for each grid point, in the summer season. We then made histograms of their occurrence and finally computed the relative variation in this occurrence between POLLUTED and PRISTINE runs. The results are shown in Figure S16. It can be seen that convective updrafts are inhibited in the POLLUTED run, which has a strong reduction of intense events (reduction of the order of 30-40% for updrafts of 20m/s and higher).
Finally, we show in Figure S17 the daily cycles of the difference of the hourly shortwave radiation reaching the ground (a, b) and downward longwave radiation at the surface (c, d) in the two different seasons.

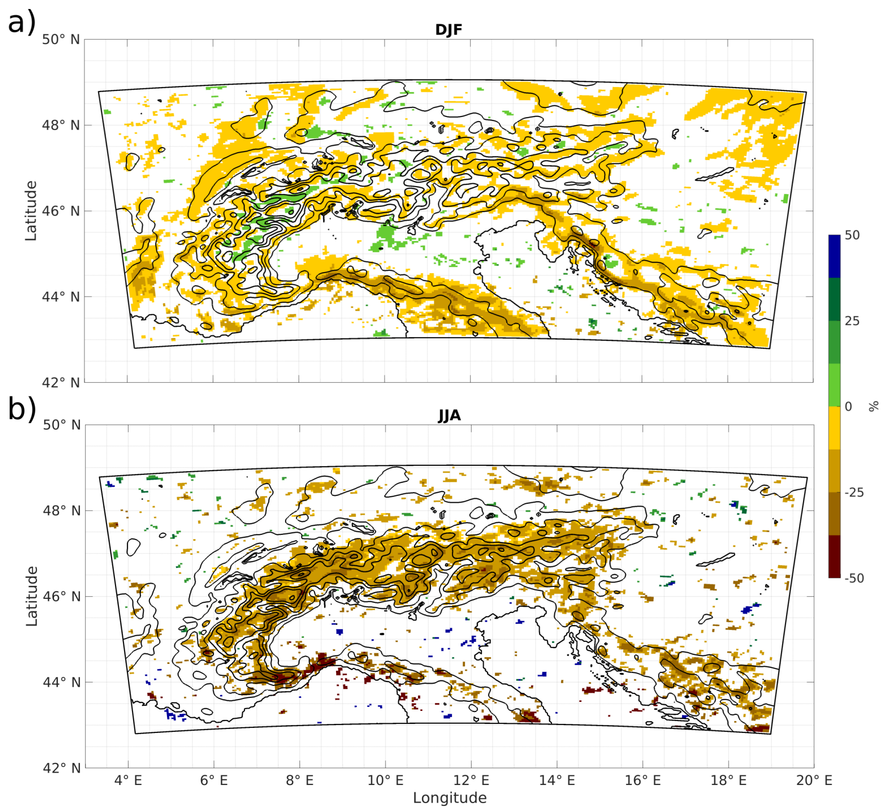

Figure S15: *Relative variation of the seasonal mean precipitation in DJF (a) and JJA (b) between the POLLUTED and the PRISTINE runs. Coloured pixels represent points that are significant at the 95% confidence level. Elevation contours are shown every 500 m.*

S5 Variations over the sea

In the main article we do not present any result over the sea, as the aerosol load in the POLLUTED experiment is highly irrealistic for marine areas, that typically have a very different concentration and distribution of cloud condensation nuclei than continental areas. We here report those results as, even being irrealistic, they provide interesting information: in Figure S1 we can notice that the Adriatic Sea and the Ligurian Sea are characterized by different behaviours. In particular, while the conditions in the Adratic Sea have a strong similarity with the Po Valley conditions, a sharp boundary separates the different conditions between the Gulf of Genoa and the coastal area nearby. These results can be rationalized in terms of the

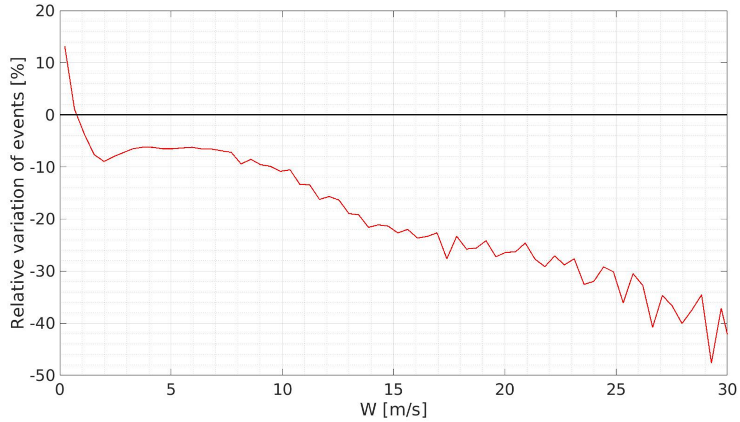

Figure S16: *Relative variation of the number of updrafts per each class of daily maximum vertical velocity in JJA, between POLLUTED and PRISTINE runs. Only land points have been taken into account.*

different depth of the two basins: the very shallow Adriatic Sea has much larger thermal seasonal excursions than the deep Ligurian Sea. A large difference exists between the thickness of the boundary layer over the two basins (thick over the Adratic and thin over the Ligurian Sea during summers and opposite during winter), resulting in very different concentrations of aerosols. Moreover, during summer, the warm waters in the Adriatic favor convection, while in the Ligurian Sea convective events are rare. For those reasons, over the Ligurian Sea summer clouds (mainly non convective clouds) are very sensitive to aerosol concentration.

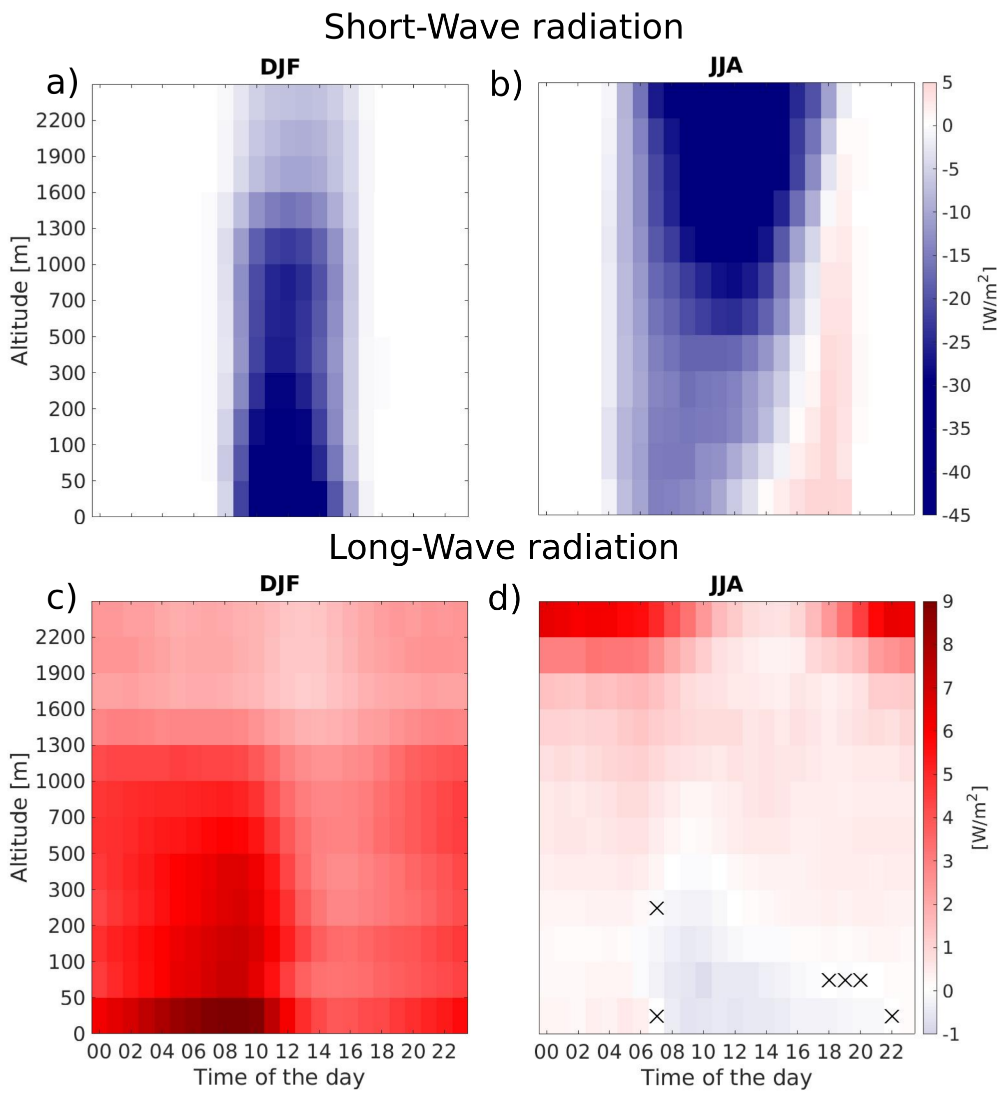

Figure S17: *Daily cycle at local time of the difference of the hourly short-wave radiation at the ground in DJF (a) and in JJA (b). Daily cycle at local time of the difference of the hourly downward long-wave radiation at the ground in Winter (c) and in Summer (d). Crosses represent points that are not significant at the 95% confidence level.*

References

[1] Da Silva, N., Mailler, S., and Drobinski, P. (2018). Aerosol indirect effects on summer precipitation in a regional climate model for the euro-mediterranean region. In *Annales Geophysicae*, volume 36, pages 321–335.

[2] Van Dingenen, R., Raes, F., Putaud, J.-P., Baltensperger, U., Charron, A., Facchini, M.-C., Decesari, S., Fuzzi, S., Gehrig, R., Hansson, H.-C., et al. (2004). A european aerosol phenomenology—1: physical characteristics of particulate matter at kerbside, urban, rural and background sites in europe. *Atmospheric Environment*, 38(16):2561–2577.