

Referee comments

RC1

General comment:

5 The paper by Castellanos et al., entitled “Projected elevation-dependent warming in the Alps
depicted with surface energy balance trends”, is a well-executed study that addresses a
research topic of growing interest using robust and appropriate methodological approaches.
The study investigates projected EDW in the European Alps using the MAR model,
10 highlighting different warming patterns as a function of elevation at the surface and altitude
in the free atmosphere. The results show an enhanced warming signal that progressively
shifts toward higher elevations throughout the seasons, in connection with the seasonal
migration of the snowline. The authors further investigate the physical processes underlying
this EDW pattern, showing that changes in net shortwave radiation and in the energy
15 available for snowmelt play a key role. One notable novelty of this work is the inclusion of an
analysis of the free atmosphere in addition to surface processes. I therefore suggest that the
authors consider explicitly reflecting this aspect in the title of the manuscript.

Overall, the paper is sound and suitable for publication; however, some major points need to
be reconsidered. In particular, some sections would benefit from a more technical and
specific treatment in order to strengthen the interpretation of the results and the robustness
20 of the conclusions.

Major comments:

- The abstract is not fully clear to me. In particular, sentences from 25 to 28: when reading
the abstract on its own, it is not clear what is meant by maximum. Moreover, the definition of
the EDW signal is not explicitly stated. Clarifying these aspects in the abstract would
25 substantially improve its clarity and allow readers to better grasp the main results at first
glance.

- Lines 165–169: it would be interesting to better explain why only these three variables were
selected to evaluate GCM skill. Did you analyse both means and trends? Additional
information would be valuable. I do not think this analysis needs to be included in the main
30 manuscript, but it could be very interesting in the supplementary material or Appendix, with a
brief mention in the main text.

- Lines 175–182: Why was this specific ensemble selected instead of considering all
possible combinations of GCMs, model versions, and realizations? Including a larger
number of members could provide additional insight into model variability. Or perhaps I
35 missed some important information?

- Lines 202–217: in addition to analysing spatial biases, it would be very useful to examine
the annual cycle of the three analysed variables. As stated by the authors, biases arise not
only from models but also from observational limitations at high elevations. Since the main
goal is to assess whether models capture the dominant climate features, including the

40 annual cycle would strengthen the analysis.

- Lines 252–255: did the authors perform a sensitivity analysis before selecting these threshold values? Why did you adopt such a strict rule for pixel selection? I suggest including in the Appendix or in the Supplementary:

1) a map showing all selected pixels;

45 2) a table with the number of pixels per elevation band.

In my opinion, these elements would be very helpful for understanding the results.

- Lines 301–304 and Figure 2: I suggest using elevation isolines instead of national borders. Since the analysis focuses on elevation, the current representation may be difficult to interpret without detailed regional knowledge.

50 - Figure 3: it is not clear which brown line corresponds to the dashed and which to the solid representation. I suggest considering an alternative visualization (e.g., shaded bands instead of error bars?), which could improve readability. In addition, it may be worth evaluating whether to include daily surface temperature in this figure to provide a more complete picture, even though it is already shown in Figure 4.

55 - Lines 478-491: This paragraph, in my opinion, needs to be reconsidered and clarified for several reasons. First, the description of the results related to the “spatially averaged” trends is unclear to me. The manuscript refers to spatially averaged trends of the snowmelt energy flux and net shortwave radiation, but then reports maximum and minimum values without clearly specifying the dimension over which these extrema are computed. This ambiguity
60 makes it difficult to properly interpret the magnitude and meaning of the reported trends, as well as the subsequent comparison between net shortwave radiation and snowmelt energy flux. The second comment mainly concerns the method used to infer the causes of the EDW pattern. The approach adopted to isolate the effect of the snowline by subtracting low-
65 elevation trends from the elevation-dependent signals is conceptually reasonable and provides useful insight into the role of snow-related processes. However, this method relies on the assumption that trends at low elevations represent a warming signal that is independent of elevation and unaffected by snow-related feedbacks. As a consequence, subtracting low-elevation trends may not fully isolate the snowline effect, but rather provide a first-order proxy of snow-related contributions. The authors are therefore encouraged to
70 clarify the assumptions underlying this approach and to explicitly discuss its limitations. Moreover, I would be very cautious in stating that these variables are the causes of the observed changes, as many other factors are not considered (as the authors describe in the discussion). Throughout the manuscript, it would be more appropriate to describe these variables as one of the possible contributors to the observed changes.

75 - Lines 598-606: In my opinion, these aspects should not be considered true limitations of the study, as the authors intentionally adopt a sort of idealized experimental framework that does not account for several additional environmental changes. These simulations appear to adequately represent the climate of the domain while deliberately focusing on a limited set of processes and changes. Such changes do have an impact; however, as the authors
80 themselves note, further work would be required to explicitly include these processes and assess their influence. I recommend that the authors reconsider and reformulate this

paragraph.

- Figure B1: I suggest using white for the sea instead of the current color, as it may otherwise be confused with the colorbar.

85 **Minor comments:**

- From the beginning of the manuscript, whenever referring to topography, it would be preferable to use “elevation” rather than “altitude”, which is more commonly used in atmospheric contexts (e.g., lines 409–410).

- Line 42: climate changes → climate change

90 - Line 49: Elevation-dependent warming → Elevation-Dependent Warming

- Line 98: please define the acronym ERA-20C and cite the reference <https://doi.org/10.1175/JCLI-D-15-0556.1>

- Line 103: instead of stronger, I would suggest strong, unless a direct comparison is being made.

95 - Lines 142: I would avoid breaking the sentence into a new line.

- Lines 272–276: if I understand correctly, the lowest 10% and the highest 0.3% of elevations are excluded in order to focus on maximum warming at intermediate elevations, consistent with the definition of EDW. However, this choice excludes possible monotonic elevation trends. To be precise, it should be clearly stated that this study only considers elevation-
100 dependent trends that exhibit intermediate-elevation maxima.

- Line 282: remove the extra space before “:”.

- Line 318: remove the extra space before “:”.

- Line 335: the temperature trend 2 meters → the temperature trend at 2 meters

- Line 579: remove the extra space before “:”.

105 - Line 616: remove the extra space before “:”.

- Figure A1: this figure needs to be cited in the manuscript.

- Figure B2: please specify clearly in the caption that one panel shows the relative change, while the other shows the absolute change.

Citation: <https://doi.org/10.5194/egusphere-2025-6211-RC1>

110

RC2

General comments

115 The paper by Castellanos et al. is very interesting both because it presents a study on EDW and its drivers using a high-resolution Regional Climate Model and because it compares surface warming rates with warming rates in the free atmosphere. The paper deserves

publication after some - mainly minor - points, listed below, are addressed.

Major comments:

120 One drawback of the study is the small model ensemble which is employed, in particular the limit of using only two GCMs to drive the (two versions of the) RCM. Though the GCM selection has been explained by the authors (and though the explanation provided at lines 590-596) the limit of using a small ensemble persists. Moreover, the analysis of the drivers (through the energy balance) is performed using only one MAR simulation (MARv3.14).

125 Another question that came to my mind is whether there is quantifiable added value of the 7-km MAR simulations compared to the Euro-CORDEX ones, considering only their resolution. These are, of course, very different experiments, but the difference of resolution is not that huge.

Minor comments:

- 130 • Line 17: The word topography here is used to indicate the overall shape and physical features of the land surface, including slope, aspect, roughness, together with elevation, correct?
- 135 • Line 39: Placing this sentence “Mountain regions are hotspots of biodiversity thanks to their often unique ecosystems which are vulnerable to rapid climate change (Rahbek et al., 2019)” at the very beginning of the paper seems to suggest that biodiversity will be a focus, whereas the focus is on something else. Of course, the sentence is correct; it just seems a bit unusual to begin this paper by emphasizing biodiversity, at least to me.
- 140 • Line 49: “Elevation-dependent warming” □ “Elevation-Dependent Warming”
- Line 60: EDW has been investigated in more mountainous areas than those reported in the list, such as in the Andes and in the Rockies. I suggest including studies on those key mountains too.
- 145 • Line 71: Change “points” with “point”
- Line 76: Some thoughts on the sentence “and model grid resolutions that are coarse with respect to the orography on the other hand.” I think that the model resolution can be coarse also with respect to the extent of the GAR, besides the complex orography.
- 150 • Line 85: “ensuring a better representation of the topography and the mountain climate.” Not only RCMs allow a greater detail of local forcings, such as topography, but also an explicit representation of a larger number of processes, given the higher resolution.
- Line 96: what does “comprehensive” mean in this sentence?
- Line 104: “associated with scenarios SSP2-4.5 and SSP5-8.5 from 1961 to 2100”: of course, the scenarios apply only to the period 2015-2100.
- 155 • Lines 195-201: There is a comment on a previous paper (Beaumont et al. 2021) which used MAR simulations and found biases in temperature and snow cover in the Alps when comparing to gridded observational datasets, reanalyses and in-situ observations. Are those MAR simulations similar to those employed in the present study? What is the magnitude of the cited biases?
- Lines 214-217: “The biases provided here are an estimation, since observational

- 160 datasets over the Alps also have large uncertainties, due in particular to the inherent
missing values in such products (Prein and Gobiet, 2017 ; Kotlarski et al., 2019 ;
Matiu et al., 2024) that are not discussed in this article.” □this is an issue shared by
most (maybe all) mountain areas
- Line 223: please replace “topography” with “orography” in the caption of Fig. 1
 - 165 • Line 254: Can you explain the choice of 360 m as the lower elevation limit for the
Alps selection?
 - Line 256-257: are the selected 200-m bins composed of a coherent/similar number of
pixels? Can you provide any indications about that?
 - Line 285: “The first criteria gives ... ” change with “The first criterion gives ...”; the
170 same at line 286
 - Line 300 (and caption of Fig. 2): are the yearly and seasonal warmings shown in the
Figure an average of the three v3.10 MAR simulations?
 - Line 318: Change “its” with “the”
 - Lines 340-343: Are there any hypotheses on the different behaviour between
175 historical profiles and projected profiles seen in in summer and autumn for the MAR-
MPI SSP2 simulation (Figs. 3g and 3h) compared to all other cases?
 - Line 554: in the sentence “both a historical and projection periods” remove the “a”
 - Line 555: the authors use the word “topography” here. Do they mean topography or
orography? Because the paper does not discuss all topographic elements, but just
180 elevation.
 - Line 641: please replace “elevated” with “high-elevation”
 - Line 662: please remove “present” from the sentence

In addition:

- There are many extra spaces before the sign “:”
- 185 • The figures presented in the Appendix are not mentioned in the main text and
probably they should be (Fig. A1 in particular)

190 **Citation:** <https://doi.org/10.5194/egusphere-2025-6211-RC2>

Author's response

Referee #1 comments

195

The authors would like to thank Referee #1 for their detailed and insightful comments, which have been helpful to improve the manuscript of the article.

200 Please find below their comments (in bold) with the authors' responses (AC for Author Comment).

General comment

205 **The paper by Castellanos et al., entitled “Projected elevation-dependent warming in the Alps depicted with surface energy balance trends”, is a well-executed study that addresses a research topic of growing interest using robust and appropriate methodological approaches. The study investigates projected EDW in the European Alps using the MAR model, highlighting different warming patterns as a function of elevation at the surface and altitude in the free atmosphere. The results show an enhanced warming signal that progressively shifts toward higher elevations throughout the seasons, in connection with the seasonal migration of the snowline. The authors further investigate the physical processes underlying this EDW pattern, showing that changes in net shortwave radiation and in the energy available for snowmelt play a key role. One notable novelty of this work is the inclusion of an analysis of the free atmosphere in addition to surface processes. I therefore suggest that the authors consider explicitly reflecting this aspect in the title of the manuscript.**

210 **Overall, the paper is sound and suitable for publication; however, some major points need to be reconsidered. In particular, some sections would benefit from a more technical and specific treatment in order to strengthen the interpretation of the results and the robustness of the conclusions.**

220 AC : Thank you for your feedback. The new working title of the manuscript is the following : “Projected elevation-dependent warming in the Alps : contrasting free-atmosphere and surface trends with surface energy balance drivers”.

Major comments

225 - **The abstract is not fully clear to me. In particular, sentences from 25 to 28: when reading the abstract on its own, it is not clear what is meant by maximum. Moreover, the definition of the EDW signal is not explicitly stated. Clarifying these aspects in the abstract would substantially improve its clarity and allow readers to better grasp the main results at first glance.**

230

AC : Thank you for your feedback on this issue. We are preparing a version to clarify these aspects in the abstract.

This version will replace the phrase :

235 “EDW signals are found to be different near the surface than in the free atmosphere, with a maximum signal in the former that is migrating to higher elevations through the seasons, linked to the snowline migration.”

by :

240 “EDW profiles are found to be different near the surface than in the free atmosphere. Near the surface, a maximum warming is found in spring at mid-elevations that is migrating to higher elevations in summer and autumn, a process that is not found in the free atmosphere. The elevation of the maximum warming is closely linked to the snowline migration.”

245 - **Lines 165–169: it would be interesting to better explain why only these three variables were selected to evaluate GCM skill. Did you analyse both means and trends? Additional information would be valuable. I do not think this analysis needs to be included in the main manuscript, but it could be very interesting in the supplementary material or Appendix, with a brief mention in the main text.**

250 AC : We did not consider a trend analysis in the GCM evaluation, as we deemed that trends can be right for the wrong reasons. Indeed, if we consider the nonlinearity of the climate response to greenhouse gas emissions superimposed to the internal variability of the climate, there is a chance that a model with low skill over the region can show a good trend, and vice-versa. Instead, we focus on finding GCMs with appropriate skill for reproducing the mean climatology. The assumption is that if they are able to represent processes correctly in
255 the historic period, then they will produce more realistic future projections, an assumption made by Sobolowski et al., 2025 as well.

The choice of these three variables was made to broadly take into account relevant large-scale climate indices that finally impact the atmospheric conditions over the Alps. That is, to
260 consider the Sea-Surface Temperature to make sure the oceanic forcing is well

represented ; the temperature at 700 hPa to verify that the model simulates correctly the warming in the mid-troposphere (as a GCM can simulate surface temperature adequately while having a significant bias in the atmosphere) ; and the geopotential height at 500 hPa to make sure that the atmospheric circulation affecting the Alps is well represented.

265

From the temperature at 700 hPa, we further made a selection on climate sensitivity. The first criterion being that it is realistic and doesn't depart too much from the multimodel mean, the second being to select a model with a large climate sensitivity (EC-Earth3) and one with a lower climate sensitivity (MPI-ESM1-2-HR), which is in accordance with Meehl et al., 2020 (see table 2 within).

270

With your suggestion in mind, we are adding an Appendix section to include this explanation and a table with the GCM scores from this evaluation. Thank you for your comment !

275 Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M.: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models, *Science Advances*, 6, eaba1981, <https://doi.org/10.1126/sciadv.aba1981>, 2020.

280 **- Lines 175–182: Why was this specific ensemble selected instead of considering all possible combinations of GCMs, model versions, and realizations? Including a larger number of members could provide additional insight into model variability. Or perhaps I missed some important information?**

285 AC : Resource and time limitations prevented us from exploring a larger ensemble or even all possible realizations of the ensemble that is used. In particular running three centennial future projections with our MAR RCM model was accessible whereas it would have been impossible for us to run a full ensemble using more GCMs as lateral conditions for our model. As mentioned in lines 590-596, we believe also that studying single experiments provides a clear story-line of the physical processes at play, which might be tricky when considering ensemble average and different models with contrasted physical processes. Anyway, further investigations based on multiple GCM-RCMs should be considered also to further dig into this research.

290

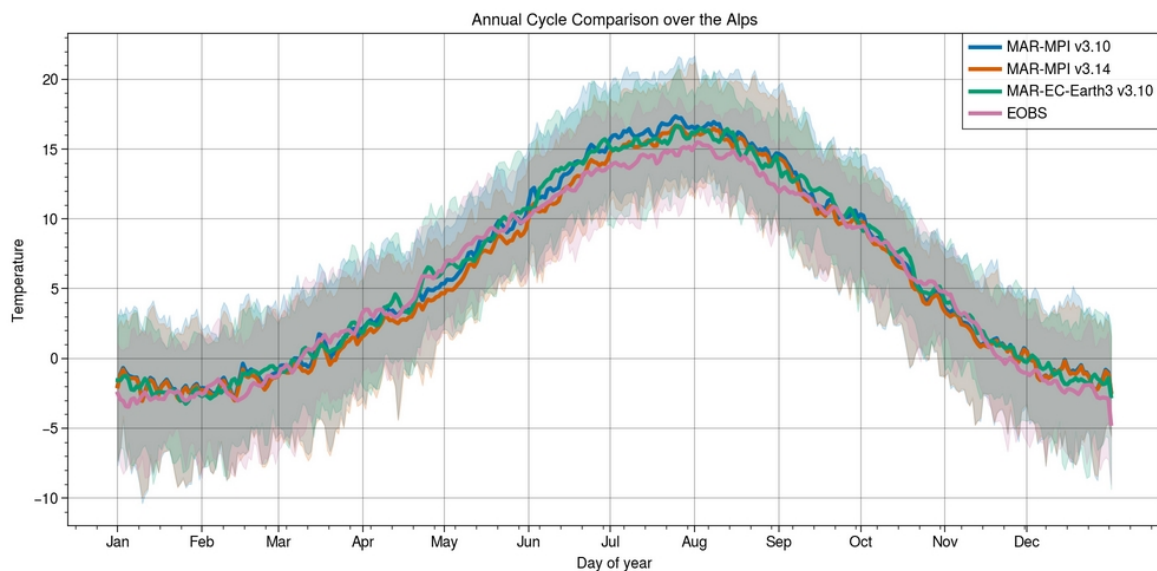
We are adding these details in the discussion part of the article.

295

- Lines 202–217: in addition to analysing spatial biases, it would be very useful to

300 examine the annual cycle of the three analysed variables. As stated by the authors, biases arise not only from models but also from observational limitations at high elevations. Since the main goal is to assess whether models capture the dominant climate features, including the annual cycle would strengthen the analysis.

AC : We will include in the appendices the annual cycle of the analysed variables. Here is the first one, for temperatures :



305 Figure C2 : Mean daily temperature at 2 m (T2m), averaged over 1961-2014 and over the Alps (coloured lines). The shaded bands represent the 10th and 90th percentile over 1961-2014.

310 - Lines 252–255: did the authors perform a sensitivity analysis before selecting these threshold values? Why did you adopt such a strict rule for pixel selection? I suggest including in the Appendix or in the Supplementary:

1) a map showing all selected pixels;

2) a table with the number of pixels per elevation band.

In my opinion, these elements would be very helpful for understanding the results.

315 AC : We tried out several threshold values to select the gridpoints belonging to the Alps in the MAR simulations. The goal was to accurately trace the contour of the Alps while excluding other mountain areas present in the simulated domain. The values presented and used in the paper were the most adequate in that regard.

Thank you for your suggestion, we agree that this would be helpful for understanding the

320 results. The contours in Figs. 1 and 2 show all selected gridpoints. We decided to add a
 histogram to figure 1 showing the number of gridpoints per elevation band. Here is the
 updated figure 1 :

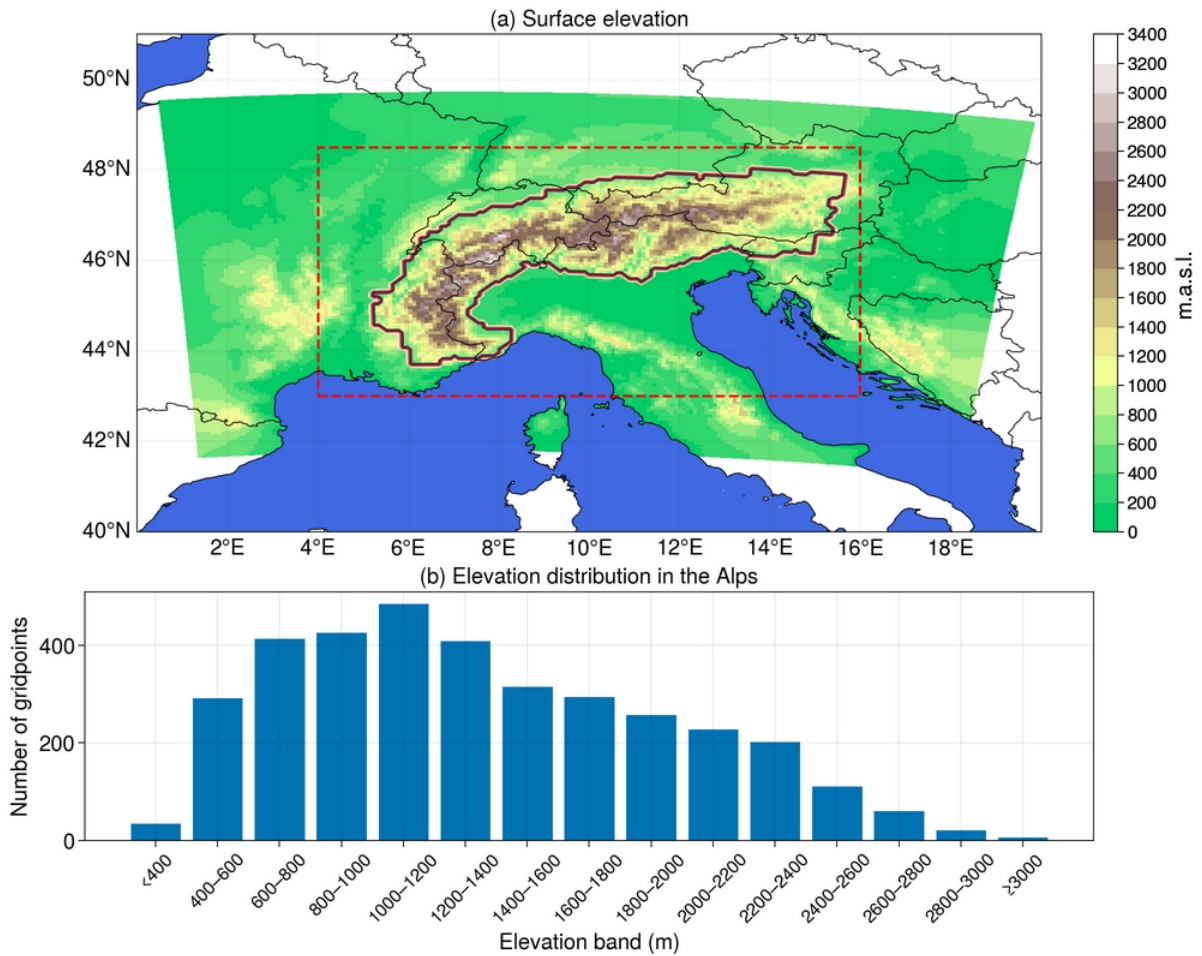


Figure 1 : (a) Domain and topography of MAR simulations. The contour defines the Alps
 325 (see Sect. II.2.2) and is used as a mask further on in this paper (e.g. whenever there is a
 value averaged over the Alps). The red box is the area shown in Fig. 2, corresponding to the
 domain considered after excluding the lateral parts affected by boundary conditions in the
 MAR experiments. (b) Elevation distribution in the contour, by elevation band.

330 There are six gridpoints above 3000 m with this topography.

- Lines 301–304 and Figure 2: I suggest using elevation isolines instead of national borders. Since the analysis focuses on elevation, the current representation may be difficult to interpret without detailed regional knowledge.

335

AC : Thank you for this suggestion ! We believed that national borders offered relevant and easy to identify landmarks. We have tried a version with isolines, and find that it

complements the spatial warming patterns well and helps with the interpretation. We will rely on Figure 1 for context regarding national borders (as having the national borders in addition to the isolines made the figure 2 too crowded). Here is the new version :

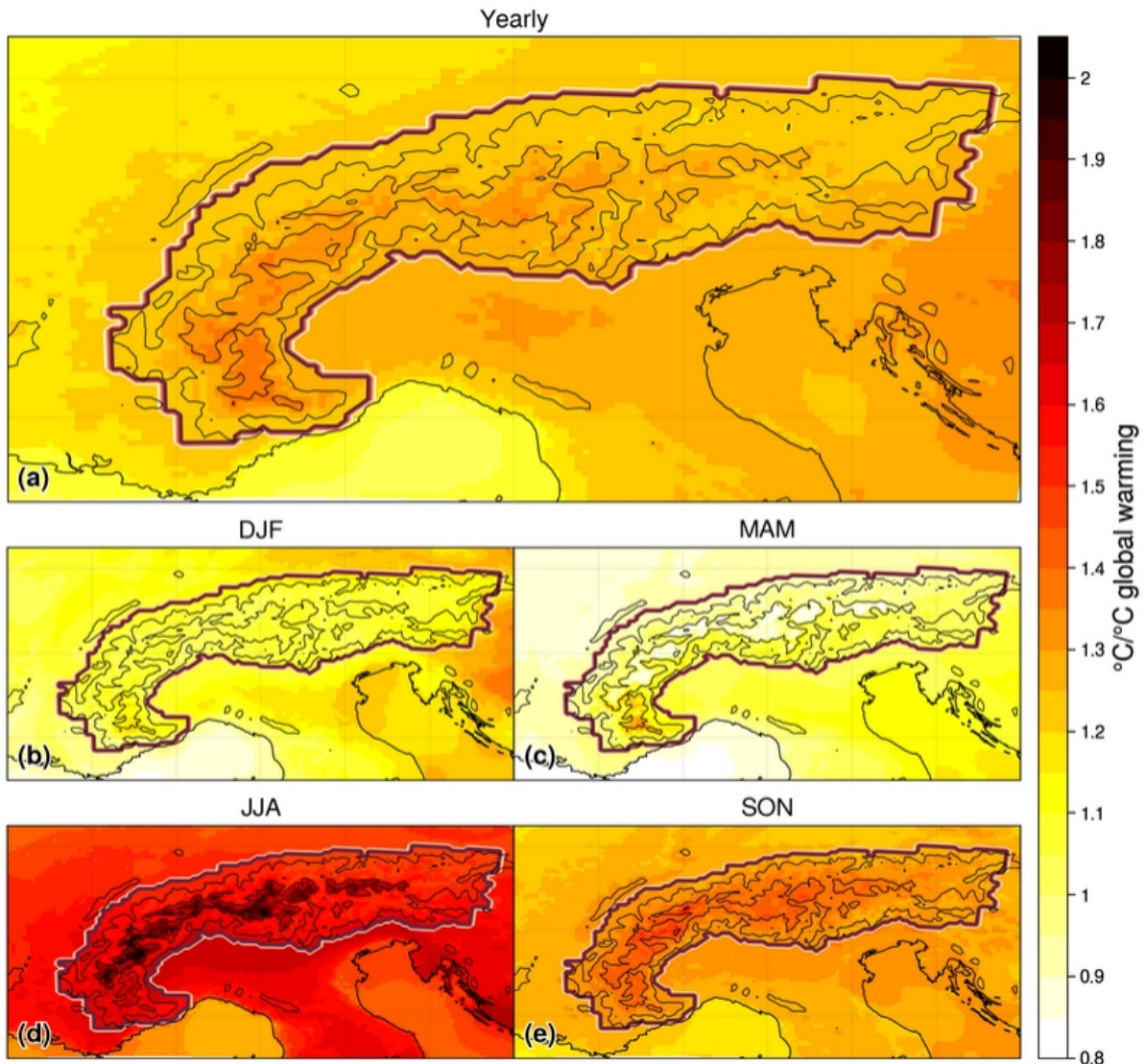


Figure 2 : (a) Yearly warming in the three v3.10 simulations scaled with respect to global warming level in the forcing GCM. (b), (c), (d), (e) : same as (a) at the seasonal timescale. See Figure 1 for the definition of the contour line. Isolines every 1000 m are shown.

- Figure 3: it is not clear which brown line corresponds to the dashed and which to the solid representation. I suggest considering an alternative visualization (e.g., shaded bands instead of error bars?), which could improve readability. In addition, it may be worth evaluating whether to include daily surface temperature in this figure to provide a more complete picture, even though it is already shown in Figure 4.

AC : Thank you for your feedback on this matter. We have implemented shaded bands to improve the visualization of this figure. However, we believe that adding daily surface temperature overburdens the figure and makes it more difficult to read. Below is the new version.

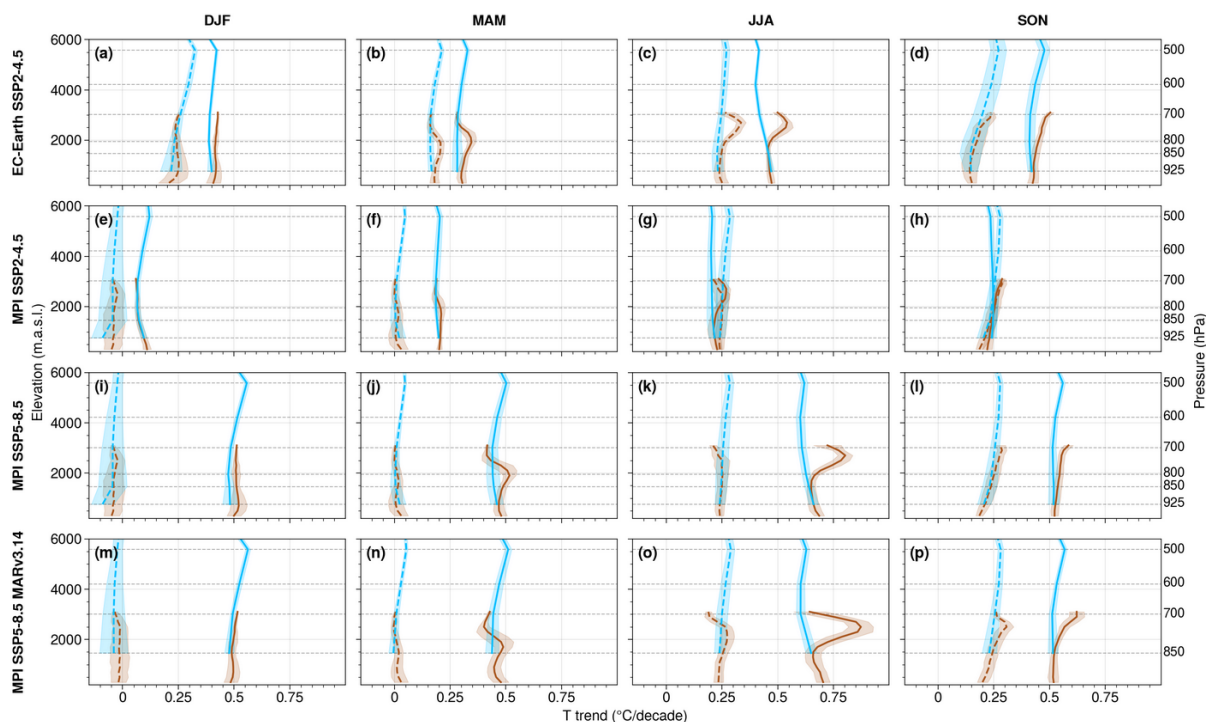


Figure 3 : Alpine temperature trends near the surface (along the slopes) averaged over 200 m-altitude bins (T2m, brown) and in the free atmosphere averaged over the available pressure levels (Tp, blue). The historical period (1961-2014) is in dashed lines, projection (2015-2100) is in full lines. Shaded bands represent the spatial standard deviation (1 sigma). The first three rows are the MAR v3.10 simulations. Columns are for each season.

365 - Lines 478-491: This paragraph, in my opinion, needs to be reconsidered and clarified for several reasons. First, the description of the results related to the “spatially averaged” trends is unclear to me. The manuscript refers to spatially averaged trends of the snowmelt energy flux and net shortwave radiation, but then reports maximum and minimum values without clearly specifying the dimension over which these
 370 extrema are computed. This ambiguity makes it difficult to properly interpret the magnitude and meaning of the reported trends, as well as the subsequent comparison between net shortwave radiation and snowmelt energy flux. The second comment mainly concerns the method used to infer the causes of the EDW pattern. The approach adopted to isolate the effect of the snowline by subtracting low-elevation

375 trends from the elevation-dependent signals is conceptually reasonable and provides
useful insight into the role of snow-related processes. However, this method relies on
the assumption that trends at low elevations represent a warming signal that is
independent of elevation and unaffected by snow-related feedbacks. As a
consequence, subtracting low-elevation trends may not fully isolate the snowline
380 effect, but rather provide a first-order proxy of snow-related contributions. The
authors are therefore encouraged to clarify the assumptions underlying this approach
and to explicitly discuss its limitations. Moreover, I would be very cautious in stating
that these variables are the causes of the observed changes, as many other factors
are not considered (as the authors describe in the discussion). Throughout the
385 manuscript, it would be more appropriate to describe these variables as one of the
possible contributors to the observed changes.

AC : Thank you very much for this feedback. We are reworking the text to make it more
explicit and clear.

390

Indeed, it is more correct to say that we compare the trends at low altitudes and at the
altitude of the snowline, and interpret the difference to be mainly due to snowline-related
effects, and not to any snow related effect. This is slightly different to actually “isolating” the
snowline, and we will change the text to reflect that.

395

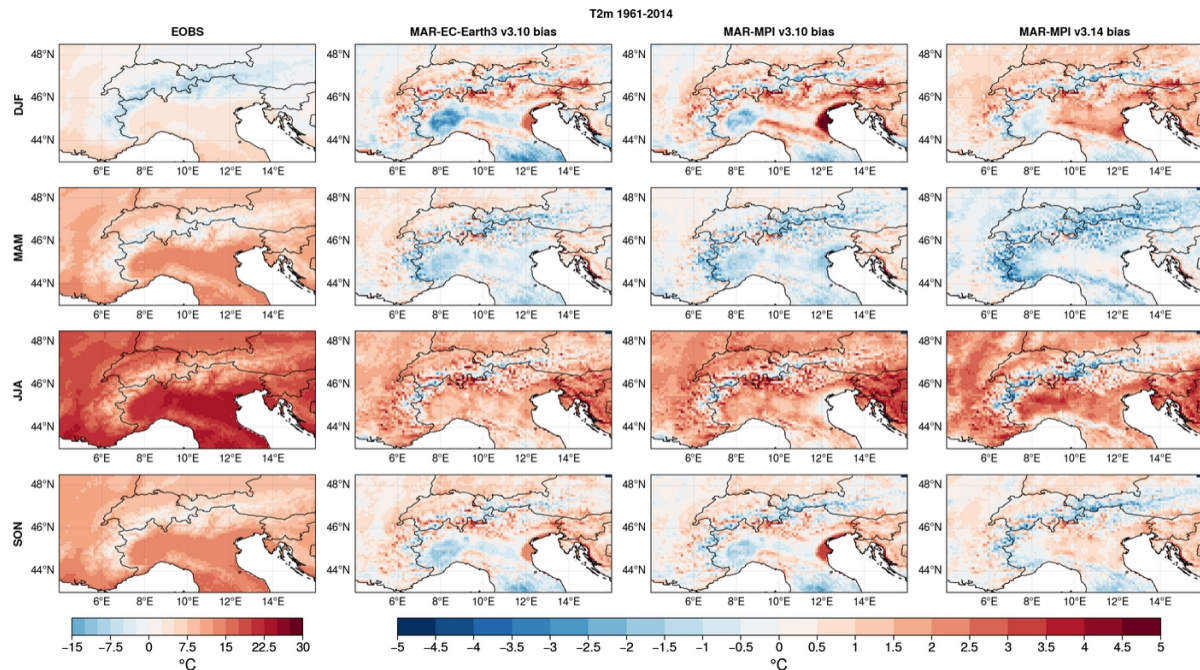
**- Lines 598-606: In my opinion, these aspects should not be considered true
limitations of the study, as the authors intentionally adopt a sort of idealized
experimental framework that does not account for several additional environmental
changes. These simulations appear to adequately represent the climate of the domain
400 while deliberately focusing on a limited set of processes and changes. Such changes
do have an impact; however, as the authors themselves note, further work would be
required to explicitly include these processes and assess their influence. I
recommend that the authors reconsider and reformulate this paragraph.**

405 AC : Thank you for the thoughtful analysis on what we presented as limitations of our work.
We are rewriting this paragraph to present these aspects as further investigation prospects
rather than limitations.

**- Figure B1: I suggest using white for the sea instead of the current color, as it may
410 otherwise be confused with the colorbar.**

AC : This is indeed a risk, we will modify the figures to correct that.

Here is one example of an updated figure, for T2m :



415

Minor comments

- From the beginning of the manuscript, whenever referring to topography, it would be preferable to use “elevation” rather than “altitude”, which is more commonly used in atmospheric contexts (e.g., lines 409–410).

420 - Line 42: climate changes → climate change

- Line 49: Elevation-dependent warming → Elevation-Dependent Warming

- Line 98: please define the acronym ERA-20C and cite the reference <https://doi.org/10.1175/JCLI-D-15-0556.1>

425 - Line 103: instead of stronger, I would suggest strong, unless a direct comparison is being made.

- Lines 142: I would avoid breaking the sentence into a new line.

- Lines 272–276: if I understand correctly, the lowest 10% and the highest 0.3% of elevations are excluded in order to focus on maximum warming at intermediate elevations, consistent with the definition of EDW. However, this choice excludes

430 **possible monotonic elevation trends. To be precise, it should be clearly stated that this study only considers elevation-dependent trends that exhibit intermediate-elevation maxima.**

- Line 282: remove the extra space before “:”.

- Line 318: remove the extra space before “:”.

435 - Line 335: the temperature trend 2 meters → the temperature trend at 2 meters

- Line 579: remove the extra space before “:”.

- Line 616: remove the extra space before “:”.

- Figure A1: this figure needs to be cited in the manuscript.

440 - Figure B2: please specify clearly in the caption that one panel shows the relative change, while the other shows the absolute change.

AC : Thank you for these detailed comments ! We are preparing a revised version of the manuscript which takes them into account.

445 Referee #2 comments

The authors would like to thank Referee #2 for their interesting and insightful comments, which have been helpful to improve the manuscript of the article.

450 Please find below their comments (in bold) with the authors' responses (AC for Author Comment).

General comment

455 **The paper by Castellanos et al. is very interesting both because it presents a study on EDW and its drivers using a high-resolution Regional Climate Model and because it compares surface warming rates with warming rates in the free atmosphere. The paper deserves publication after some - mainly minor - points, listed below, are addressed.**

460 AC : Thank you for this positive comment ! As mentioned in response to Referee #1's
comments, we have a new working title of the manuscript to further emphasise the
comparison between the surface warming and the warming in the free atmosphere :
"Projected elevation-dependent warming in the Alps : contrasting free-atmosphere and
surface trends with surface energy balance drivers".

465 Major comments

One drawback of the study is the small model ensemble which is employed, in particular the limit of using only two GCMs to drive the (two versions of the) RCM. Though the GCM selection has been explained by the authors (and though the explanation provided at lines 590-596) the limit of using a small ensemble persists.

470

AC : This is indeed a limitation of our study. It was also brought up by Referee #1, here is our response on the matter :

475 Resource and time limitations prevented us from exploring a larger ensemble or even all possible realizations of the ensemble that is used. In particular running three centennial future projections with our MAR RCM model was accessible whereas it would have been impossible for us to run a full ensemble using more GCMs as lateral conditions for our model. As mentioned in lines 590-596, we believe also that studying single experiments provides a clear story-line of the physical processes at play, which might be tricky when
480 considering ensemble average and different models with contrasted physical processes. Anyway, further investigations based on multiple GCM-RCMs should be considered also to further dig into this research.

We are adding these details in the discussion part of the article.

Moreover, the analysis of the drivers (through the energy balance) is performed using only one MAR simulation (MARv3.14).

485

AC : It is a limitation of our study to use only one limited area model, but it also allows us to focus our study on a particular model scheme and not mix different schemes that could override individual signals in an ensemble average.

490 The full analysis is only available for the MARv3.14 simulation in which we included the full list of variables required to have a full view on the surface energy balance (including the ground flux and the heat storage in soil and snow layers, some variables that are often missing in RCM outputs). Some variables were not available in the previous MARv3.10 simulations. But a partial analysis was still made with the latter (not shown in the article) that

495 is consistent with the former, showing similar signals and behaviours for the available
surface energy balance variables. We are adding these elements to the discussion, thank
you for your input !

500 **Another question that came to my mind is whether there is quantifiable added value
of the 7-km MAR simulations compared to the Euro-CORDEX ones, considering only
their resolution. These are, of course, very different experiments, but the difference of
resolution is not that huge.**

505 AC : The difference in topography going from the EURO-CORDEX resolution (~12.5 km) to
the MAR 7 km resolution presents the advantage of better representing the narrow alpine
valleys as mentioned in line 151 (which allows for better wind representation for instance).
Another advantage is in the representation of the spectrum of elevations, which reaches
close to 3400 m.a.s.l. at 7 km compared to less than 3000 m.a.s.l. in EURO-CORDEX. This
is a clear added value when studying snow in particular which is more present at high
510 elevations.

We compared gridpoint distribution as a function of elevation bands in the Alps between the
MAR, EURO-CORDEX (more specifically, the RCA4 regional climate model) and ETOPO1
topographies (ETOPO1 is a global relief model at 1-arcminute resolution, which is ~1.8 km
resolution in the Alps) :

515

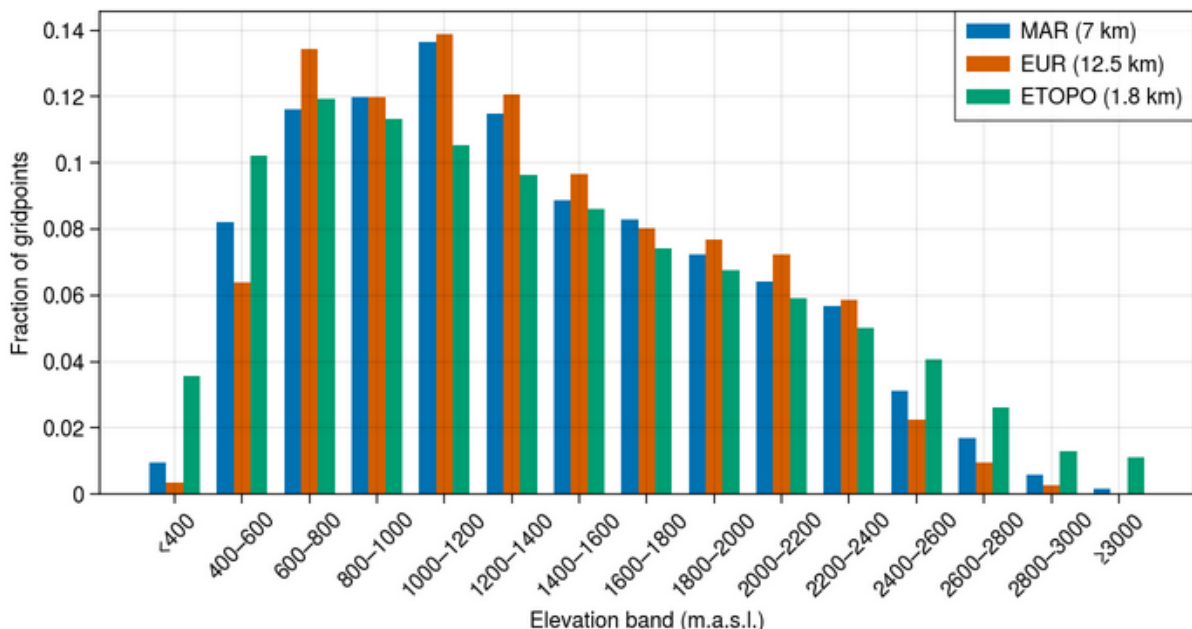


Figure 1 : Density of gridpoints for a range of elevation bands within the Alps contour defined in Sect. 2.2.2 in the article (in the case of EURO-CORDEX and ETOPO1, the contour was interpolated to their respective grids).

520

Figure 1 shows that the distribution of gridpoints at the MAR 7 km resolution is closer to the ETOPO distribution than the EURO-CORDEX distribution is, for almost all elevation bins and especially below 800 m and above 2200 m. This is consistent with our assumption that the MAR topography represents narrow valleys and high mountain ranges better than the EURO-CORDEX counterpart.

525

We are reworking the text in Section 2.1.2 to reflect these elements :

530

“This resolution was chosen to depict the alpine topography - with its narrow valleys - more accurately than the 12 km EUROCORDERX resolution while still being compatible with the hydrostatic approximation in middle latitudes configurations (which imposes a ~5-10 km resolution at the lowest). This resolution smoothes the Alps to a maximum elevation close to 3500 m.a.s.l. while the real maximum elevation is 4808 m.a.s.l. at the Mont Blanc.”

535

becomes :

540

“This resolution was chosen to depict the alpine topography - with its narrow valleys and high elevation snow - more accurately than the 12.5 km EUROCORDERX resolution while still being compatible with the hydrostatic approximation in middle latitudes configurations (which imposes a ~5-10 km resolution at the lowest). This resolution smoothes the Alps to a maximum elevation close to 3400 m.a.s.l. - compared to under 3000 m.a.s.l. in 12.5 km EURO-CORDEX simulations - while the real maximum elevation is 4808 m.a.s.l. at the Mont Blanc.”

545

We have also modified Figure 1 to include the gridpoint distribution for the given elevation bands :

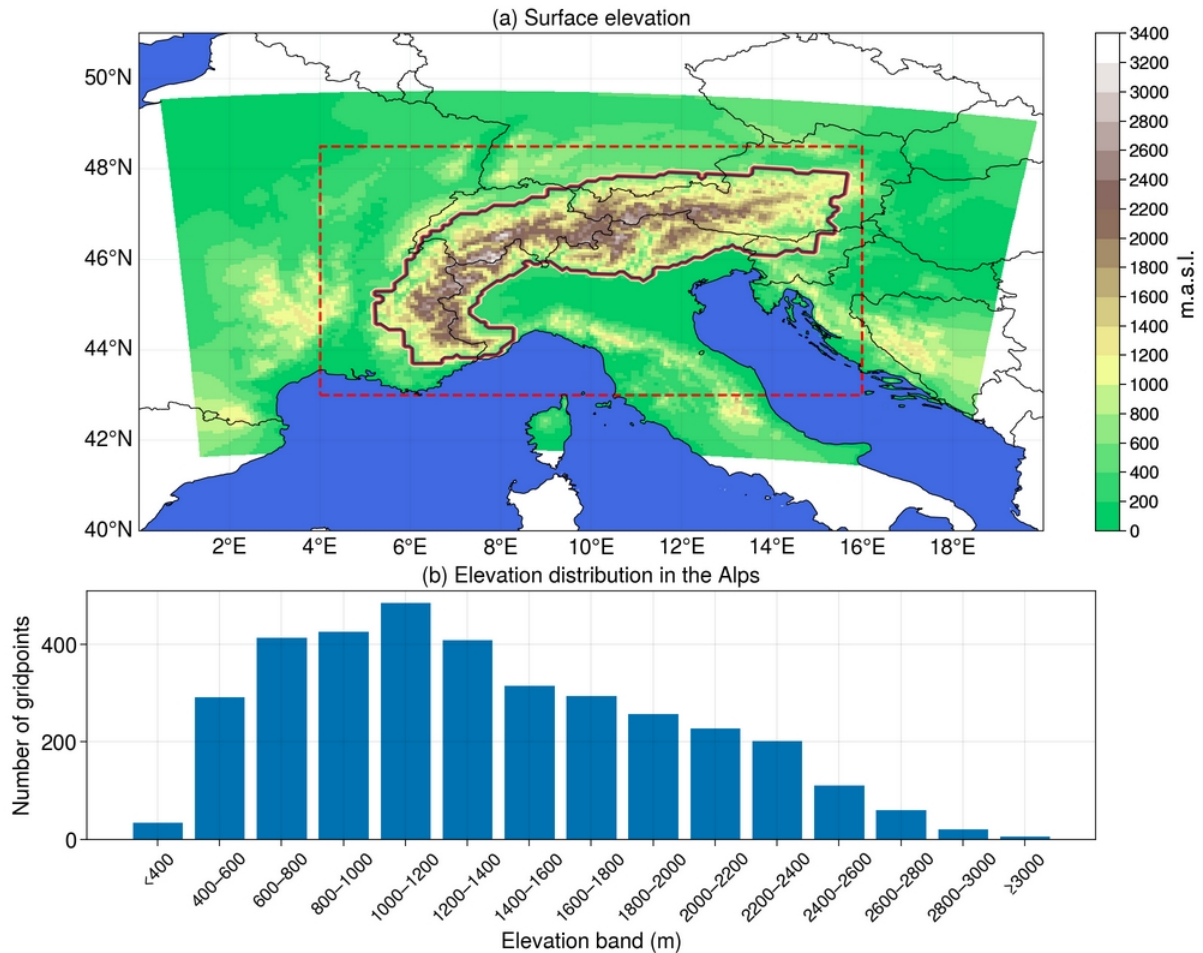


Figure 1 : (a) Domain and topography of MAR simulations. The contour defines the Alps (see Sect. II.2.2) and is used as a mask further on in this paper (e.g. whenever there is a value averaged over the Alps). The red box is the area shown in Fig. 2, corresponding to the domain considered after excluding the lateral parts affected by boundary conditions in the MAR experiments. (b) Elevation distribution in the contour, by elevation band.

550

There are six gridpoints above 3000 m with this topography.

555 Minor comments

- **Line 17:** The word topograhly here is used to indicate the overall shape and physical features of the land surface, including slope, aspect, roughness, together with elevation, correct?

AC : This is correct !

560

- **Line 39:** Placing this sentence “Mountain regions are hotspots of biodiversity thanks to their often unique ecosystems which are vulnerable to rapid climate

565 **change (Rahbek et al., 2019)” at the very beginning of the paper seems to suggest that biodiversity will be a focus, whereas the focus is on something else. Of course, the sentence is correct; it just seems a bit unusual to begin this paper by emphasizing biodiversity, at least to me.**

AC : Thank you for this feedback. The sentence was intended to give broader context for the interest in investigating climate change in these areas, but the placement and focus it brings can indeed be confusing. We are preparing a rework of this sentence.

- 570
- **Line 49: “Elevation-dependent warming” “Elevation-Dependent Warming”**
 - **Line 60: EDW has been investigated in more mountainous areas than those reported in the list, such as in the Andes and in the Rockies. I suggest including studies on those key mountains too.**

AC : Thank you for this feedback, we are preparing a new version to take this into account !

- 575
- **Line 71: Change “points” with “point”**
 - **Line 76: Some thoughts on the sentence “and model grid resolutions that are coarse with respect to the orography on the other hand.” I think that the model resolution can be coarse also with respect to the extent of the GAR, besides the complex orography.**
 - **Line 85: “ensuring a better representation of the topography and the mountain climate.” Not only RCMs allow a greater detail of local forcings, such as topography, but also an explicit representation of a larger number of processes, given the higher resolution.**
- 580

AC : This is indeed true and relevant, thank you for pointing this out ! We will include this point in the revised version of the manuscript.

- 585
- **Line 96: what does “comprehensive” mean in this sentence?**

AC : This term is later repeated in line 126, in which we refer to the paper by Brun et al. (1992). It refers to the fact that the snow cover scheme is comprised of several layers and takes into account laws of metamorphism in the snow, which allows it to simulate accurately the evolution of the snow cover stratigraphy.

590 We are adding these elements to the manuscript.

- **Line 104: “associated with scenarios SSP2-4.5 and SSP5-8.5 from 1961 to 2100”: of course, the scenarios apply only to the period 2015-2100.**

AC : Indeed, we will clarify this.

- 595
- **Lines 195-201: There is a comment on a previous paper (Beaumont et al. 2021) which used MAR simulations and found biases in temperature and snow cover in the Alps when comparing to gridded observational datasets, reanalyses and in-situ observations. Are those MAR simulations similar to those employed in the present study? What is the magnitude of the cited biases?**

600 AC : Yes, indeed, these simulations are similar to those employed in the present study : they use the same version of MAR (version 3.10 that is, as version 3.14 did not exist at the time), over the same domain and with the same resolution.

In Beaumont et al. 2021, they are compared to the S2M snow and climate reanalysis dataset and the SPAZM dataset. In winter, MAR-ERA-20C is 2.5°C warmer at low elevations and colder at high elevations, with good agreement at intermediate elevations. MAR-ERA5 is
605 generally 0.5 to 0.8°C warmer than MAR-ERA-20C. MAR simulations also systematically underestimate snow cover duration by 10 to 60% at low elevation (<1500 m.a.s.l.).

- **Lines 214-217: “The biases provided here are an estimation, since observational datasets over the Alps also have large uncertainties, due in particular to the inherent missing values in such products (Prein and Gobiet, 2017 ; Kotlarski et al., 2019 ; Matiu et al., 2024) that are not discussed in this article.” this is an issue shared by most (maybe all) mountain areas**
- 610

AC : This is true, we will modify this sentence to reflect this.

- **Line 223: please replace “topography” with “orography” in the caption of Fig. 1**
 - **Line 254: Can you explain the choice of 360 m as the lower elevation limit for the Alps selection?**
- 615

AC : This was also a question raised by Referee #1. Here is the response :

We tried out several threshold values to select the gridpoints belonging to the Alps in the MAR simulations. The goal was to accurately trace the contour of the Alps while excluding other mountain areas present in the simulated domain. The values presented and used in
620 the paper were the most adequate in that regard.

- **Line 256-257: are the selected 200-m bins composed of a coherent/similar number of pixels? Can you provide any indications about that?**

AC : No, the 200-m bins do not have a similar number of pixels. As said above, we modified

figure 1 to include the distribution of pixels per elevation band. Thank you for this comment !

- 625
- **Line 285: “The first criteria gives ... ” change with “The first criterion gives ...”; the same at line 286**
 - **Line 300 (and caption of Fig. 2): are the yearly and seasonal warmings shown in the Figure an average of the three v3.10 MAR simulations?**

AC : The method used in Fig. 2 is described in Sect. 2.2.1. To obtain these maps, we regressed at each gridpoint the three merged MAR v3.10 anomalies onto the global warming level. This allows us to get an estimation of the local warming as a function of global warming, combining the three v3.10 simulations.

630

- **Line 318: Change “its” with “the”**
 - **Lines 340-343: Are there any hypotheses on the different behaviour between historical profiles and projected profiles seen in in summer and autumn for the MAR-MPI SSP2 simulation (Figs. 3g and 3h) compared to all other cases?**
- 635

AC : Comparing the behaviour with the other simulations, this confirms that the MPI-ESM1-2-HR model has a relatively low climate sensitivity, as we expected from our GCM selection. However, comparing between seasons, we do not have any hypotheses on why the summer and autumn seasons do not simulate an increase in warming in the projection compared to the historical period, in contrast with all other cases.

640

An in-depth analysis would be required to explain this, which we leave for further investigations.

- **Line 554: in the sentence “both a historical and projection periods” remove the “a”**
 - **Line 555: the authors use the word “topography” here. Do they mean topography or orography? Because the paper does not discuss all topographic elements, but just elevation.**
- 645

AC : Thank you for this comment ! Indeed, orography is a more suitable term as the paper discusses only elevation. We will modify this.

650

- **Line 641: please replace “elevated” with “high-elevation”**
- **Line 662: please remove “present” from the sentence**

In addition:

- **There are many extra spaces before the sign “:”**

- 655
- **The figures presented in the Appendix are not mentioned in the main text and probably they should be (Fig. A1 in particular)**

AC : Thank you again for all the comments. We are preparing a revised version of the manuscript which takes them into account.

Revised version with author's changes

665 Projected elevation-dependent warming in the Alps: contrasting free-atmosphere and surface trends with surface energy balance drivers

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Abstract

680 Because of topography, climate change exhibits complex regional imprints in the Alps. This study aims at understanding the processes that link elevation-dependent warming (EDW) - i.e. the modulation of temperature trends with elevation - at seasonal scale in the Alps with the surface energy balance. We investigate projected EDW patterns in the Alps using 7-km resolution simulations spanning the period 1961-2100 made with the Modèle Atmosphérique Régional (MAR), exploring scenarios SSP2-4.5 and SSP5-8.5 and driven by two general circulation models, EC-Earth3 and MPI-ESM1-2-HR. We find a larger yearly warming signal at high elevations (1.2 to 1.5 °C/°C of global warming) than at low elevations (1.1 to 1.3 °C/°C of global warming), with contrasted seasonal patterns and intensities (up to 2 °C/°C of global warming at high elevations in summer). EDW profiles are found to be different near

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690 the surface than in the free atmosphere. Near the surface, a maximum warming is found in
spring at mid-elevations that is migrating to higher elevations in summer and autumn. This
signal is not found in the free atmosphere. The elevation of the maximum warming is moving
upward, consistently with the snowline migration over the years in a warming climate.
Investigating surface energy balance trends reveals a link between the profiles of EDW and
those of net shortwave radiation and energy used to melt snow. The snow-albedo feedback
695 linked to the net shortwave radiation trend is found to be responsible for two thirds of the
impact of the snowline on warming, while snow melt accounts for the last third. Melting limits
the warming at high elevation when snow is persisting. We suggest that snow melting is an
important driver of EDW that should be considered in any EDW-snow investigations.

1 Introduction

700 Mountain regions face singular challenges with climate change due to their topography.
They are hotspots of biodiversity thanks to their often unique ecosystems which are
vulnerable to rapid climate change (Rahbek et al., 2019). They host large water resources
for both local and remote inhabitants (Viviroli et al., 2020), in relation to both orographic
705 precipitation and snow and glacier melting, which can make downstream inhabitants
eventually vulnerable to climate change further up the slopes (e.g. Colombo et al., 2023).
Their orography influences the atmospheric circulation at the synoptic scale, through local
variation of the atmospheric flow and at the hemispheric scale through planetary waves
triggered by the mountains, extending their influence to the surrounding regions.

710 Climate change in the mountains shows specific features, in particular because of potential
Elevation-Dependent Warming (EDW). EDW is defined as the modulation with elevation of
near-surface atmospheric temperature trends, a warming “along the slopes”. Although it is
sometimes simplified as a linear regression of warming against elevation (e.g. Rangwala et
715 al., 2010 ; Tudoroiu et al., 2016 ; Palazzi et al., 2017 ; Palazzi et al., 2019 ; Toledo et al.,
2022), studies increasingly show nonlinearity in the dependency of warming with elevation
(e.g. Kotlarski et al., 2012, 2015, 2023 ; Palazzi et al., 2017 ; Minder et al., 2018 ; Beaumet
et al., 2021 ; Toledo et al., 2022 ; Napoli et al., 2023). Indeed, the drivers of EDW are
numerous, interconnected, and may be confined to certain elevations. Hence, EDW profiles
720 are highly variable depending on the area and the period considered (Ohmura, 2012, Pepin
et al., 2025). Pepin et al. (2015) give an overview of different processes that may impact
EDW (albedo, clouds, water vapour, blackbody emission and aerosols) and the shape of
their expected elevational dependency. EDW has been investigated in different mountainous
areas: in the Alps (see reviews by Gobiet et al., 2014 ; Kuhn et al., 2020) ; in High Mountain
725 Asia, where small EDW signals have been reported over the last decades (Li et al., 2020)
but are expected to intensify in future projections (Dimri et al., 2019). A strong EDW is
simulated in the Rocky Mountains and is linked to the snow-albedo feedback (Minder et al.,
2018). Contrasted EDWs are suggested for minimum and maximum daily temperature in the
Andes, in relation with shortwave and longwave radiation changes (Toledo et al., 2022) or
730 specifically reduced cloudiness and snow (Chimborazo et al., 2022). In places where it has a
strong seasonal cycle, snow is identified as one of the major drivers of EDW through the
snow-albedo feedback (Rangwala et al., 2010 ; Kotlarski et al., 2015, 2023 ; Minder et al.,

2018 ; Palazzi et al., 2019 ; Warscher et al., 2019 ; Beaumet et al., 2021 ; Byrne et al., 2024).

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The Greater Alpine Region (GAR) is one of the most studied mountain regions in the world. Observation data broadly point towards an enhanced warming at high elevations in this region (Pepin et al., 2022), but an opposite signal can be found depending on the area and the period of interest (Philippona, 2012 ; Tudoroiu et al., 2016 ; Rottler et al., 2019). Overall, EDW in the GAR is not yet fully characterized and understood. This is mainly due to limitations in the amount of high-elevation observations on the one hand, and model grid resolutions that are coarse with respect to the orography on the other hand.

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Simulations made with General Circulation Models (GCMs) are able to reach finer and finer resolutions as computational resources increase, but are still falling short of adequately representing the complex topography in mountain regions (Sandu et al., 2019) and in the Alps in particular when studying climate change and its drivers (Palazzi et al., 2019). The need arises then to downscale these products to more suitable resolutions. Regional Climate Models (RCMs) are a frequently-used method to dynamically downscale GCMs. They allow for simulations at ~10-km scale resolution, ensuring a better representation of the topography and the mountain climate, as well as explicitly representing several physical processes that have to be parameterised at coarser resolutions.

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As mentioned earlier, snow is a crucial driver of EDW, making it an important variable to represent correctly in simulations used to study climate change in mountain regions. A finer model resolution improves the representation of snow (Lüthi et al., 2019), but even the 12-km resolution of the EURO-CORDEX experiments yields significant biases (Terzago et al., 2017 ; Matiu et al., 2020), highlighting the need for even finer resolutions. Most RCMs also have a simple representation of the snowpack, using a single layer varying in thickness over time. In our study, we use 7 km resolution experiments made with the Modèle Atmosphérique Régional (MAR, Gallée and Schayes, 1994), a RCM further described in the next section, that uses a detailed multi-layer snow cover scheme.

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MAR simulations at 7 km forced by the ERA-20C reanalysis (ECMWF Reanalysis of the 20th century ; Poli et al., 2016) have been performed previously to investigate the past evolution of climate and EDW in the Alps (Beaumet et al., 2021). The results highlight seasonal contrasts in EDW over the period 1959-2010, with larger warming found at low elevations in winter (< 1000 m.a.s.l.), at high elevations in summer (> 2000 m.a.s.l.) and at intermediate elevations in spring (1500-1800 m.a.s.l.). In this study, we aim to investigate the simulated EDW in the Alps from 1961 to 2100, considering different future projections following the scenarios SSP2-4.5 and SSP5-8.5 (from 2015 to 2100). In order to investigate the processes driving EDW, we focus on all the components of the surface energy balance. To our knowledge, this is the first study where all these components are analysed, in addition to using 140-years-long simulations until the end of the century at a high resolution.

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First, the data and methods are described in Sect. 2. We delve into the results in Sect. 3 by: (i) exploring the warming footprints in the Alps in our simulations ; (ii) comparing EDW profiles near the surface and in the free atmosphere ; (iii) investigating trends in the surface

energy balance components and (iv) determining the elevation changes of the snowline and of the other drivers affecting the temperature trend. A discussion and a conclusion are offered in Sect. 4.

2 Data and methods

2.1 Model data

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2.1.1 The Modèle Atmosphérique Régional (MAR)

MAR is a hydrostatic, primitive equation, limited-area model with constant sigma coordinates on the vertical axis (Gallée and Schayes, 1994 ; Gallée et al., 2005). It has been developed for polar regions (e.g. Fettweis et al., 2017, Agosta et al., 2019, Amory et al., 2020) and mountainous environments (e.g. Ménégoz et al., 2013 over the Himalayas ; Ménégoz et al., 2020 and Beaumet et al., 2021 over the Alps ; Collao 2018 in Patagonia ; Fettweis et al., 2023 in the Vosges mountain region). This wide range of applications is supported by its comprehensive multi-layer snow cover scheme (Brun et al., 1992) which accounts for the laws of metamorphism in the snow, allowing to simulate accurately the evolution of the snow cover stratigraphy. It has also been used over western Africa (Kouassi et al., 2010, Chagnaud et al., 2020) to study the tropical hydrological cycle.

In the present work, data from simulations using two successive versions of MAR, 3.10 and 3.14, are analysed. Simulations made with version 3.10 were indeed missing some of the surface energy balance components as diagnostic variables (see Table 1). A new simulation using the latest version of MAR, version 3.14, was thus run in which all the variables of interest were saved. Using both versions' simulations allows us to increase the spread of investigated scenarios and climate sensitivities that we explore.

MAR version 3.10 uses a radiative transfer scheme developed by Morcrette (1991, 2002) and used in the ERA-40 reanalyses (Uppala et al., 2005). Owing to some identified issues within MAR of this scheme with downward radiation (e.g. Delhasse et al., 2020), and its lack of modularity, the Morcrette scheme has been replaced by the ecRad radiation scheme (Hogan and Bozzo, 2018) in version 3.14 of MAR (J.-F. Grailet, 2023). The second difference between the two versions of MAR for the present paper lies in the climatology of aerosols. In version 3.10 aerosols have a yearly climatology that evolves until 2005 - later years use the 2005 climatology. Version 3.14 by contrast uses the climatology provided by the European Center for Medium Range Weather Forecasts (ECMWF, cycle 43r3 - see Bozzo et al., 2020) which remains fixed throughout the whole simulation.

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2.1.2 The simulations over the Alps

MAR is applied over the Alps at a 7 km resolution. This resolution was chosen to depict the alpine topography - with its narrow valleys and snow-covered peaks - more accurately than

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825 the 12.5 km EUROCORDEX resolution while still being compatible with the hydrostatic approximation in middle latitudes configurations (which imposes a ~5-10 km resolution at the lowest). This resolution smoothes the Alps to a maximum elevation close to 3400 m.a.s.l. - compared to under 3000 m.a.s.l. in 12.5 km EUROCORDEX simulations - while the real maximum elevation is 4808 m.a.s.l. at Mont Blanc. Within the Alps, most elevations are around the 1000-1200 m.a.s.l. range at this resolution (Fig. 1b). The domain extends from 1.5 to 18.5° E and from 41.5 to 49.5° N (Fig. 1a).

Temperature (°C)	
T2m	Daily mean temperature at 2 meters above the surface
Tp	Daily mean temperature at different pressure levels
Tmin	Minimum daily temperature at the first atmosphere layer (sigma level)
Tmax	Maximum daily temperature at the first atmosphere layer (sigma level)
ST	Daily mean surface temperature
Surface energy balance, daily mean (W/m²)	
NSW	Net shortwave radiation (difference between downward and upward flux)
NLW	Net longwave radiation (difference between downward and upward flux)
LHF	Latent heat flux
SHF	Sensible heat flux
Melt top*	Snowmelt energy flux at the topmost layer
Freeze top*	Freeze energy flux at the topmost layer
GF*	Ground flux
HAcc*	Heat accumulation in the topmost layer
SWt*	Shortwave radiation transmitted to lower layers (only with snow, as soil layers are opaque in the model)

Table 1: MAR variables used in this study. Variables with a * are only available for the MAR version 3.14 simulation.

835 Due to human and computational constraints, a large ensemble approach exploring model and scenario variability was not pursued. Instead, a storyline-based approach was adopted, relying on a limited-area model that accurately simulates the relevant physical processes. From the CMIP6 database (Eyring et al., 2016), we retained for our study the two GCMs showing the best skill over the European-North-Atlantic area (80° W-45° E, 35° N-75° N):

840 EC-Earth3 and MPI-ESM1-2-HR. This choice is based on a comparison with the ERA5
reanalysis over 1971-2000, using the weighted mean square error of 3 variables: the
temperature at 700 hPa, the geopotential height at 500 hPa, and the sea surface
temperature weighted at half weight (see Eq. (1) in Appendix A). These variables were
845 selected to evaluate the skill of the GCMs to reproduce the large scale climate features, as
the RCM is expected to represent the smaller scale processes. Table A1 (Appendix A)
summarises the results of this evaluation. The selected criteria and forcing GCMs are
consistent with the recommendations detailed in Sobolowski et al., 2025: the geopotential
height at 500 hPa criterion ensures an appropriate large-scale atmospheric circulation, the
sea surface temperature a realistic oceanic forcing, and the temperature at 700 hPa allows
850 to discriminate GCMs that would provide too high biases in the middle troposphere. As
Sobolowski et al. (2025), we highlighted MPI-ESM1-2-HR and EC-Earth3 as two GCMs
exhibiting an appropriate level of skill for climate downscaling over Europe (see Table 2
therein).

CMIP6 simulations include a historical period available over 1850-2014 and future
855 projections over 2015-2100, based on different scenarios, including in particular the
intermediate greenhouse gas emissions (SSP2-4.5) and the high emission scenario SSP5-
8.5 (O'Neill et al., 2016). In this study, we use the following four 1961-2100 simulations
made with either version 3.10 or version 3.14 of MAR:

- 860 - MAR version 3.10 forced by EC-Earth3 (historical, 1961-2014 ; SSP2-4.5, 2015-
2100) ;
- MAR version 3.10 forced by MPI-ESM1-2-HR (historical, 1961-2014 ; SSP2-4.5,
2015-2100 ; SSP5-8.5, 2015-2100) ;
- MAR version 3.14 forced by MPI-ESM1-2-HR (historical, 1961-2014 ; SSP5-8.5,
2015-2100).

865 Hereafter, the simulations will be referred to as MAR-EC-Earth3 SSP2, MAR-MPI SSP2,
MAR-MPI SSP5, and MARv3.14-MPI SSP5 respectively.

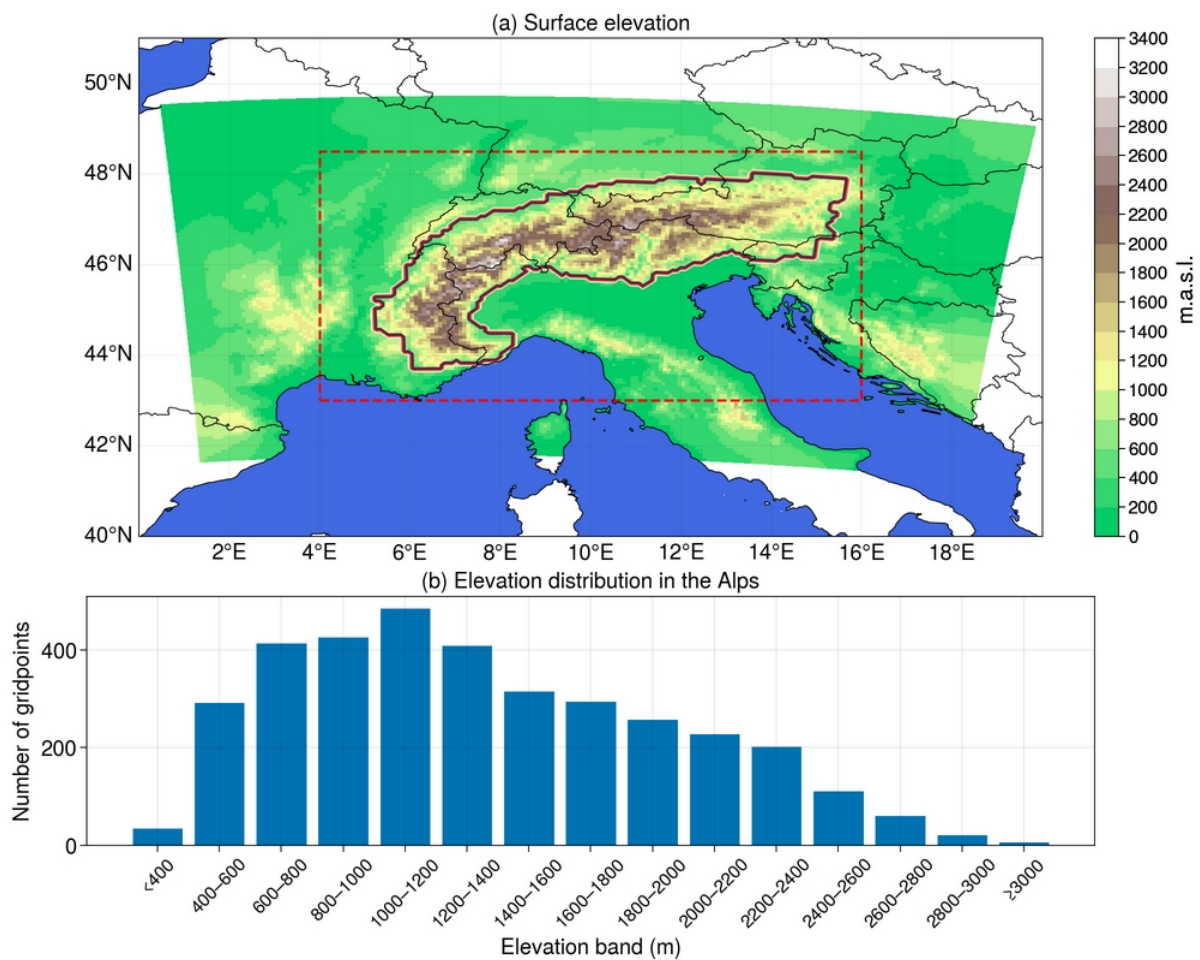
The v3.10 MPI simulations have previously been presented in Bacer et al. (2024). We
include here the v3.10 MAR-EC-Earth3 SSP2 and MARv3.14-MPI SSP5 simulations.

870 We present the variables (and associated acronyms) used in this study in Table 1.
The outputs of MAR are described in Appendix B, along with the surface energy balance in
the soil and snow routine in MAR (see Fig. B1 for an illustration of the routine).
A data set for a limited number of variables and levels is available online (see “Data
875 availability” at the end of this paper).

Beaumont et al. (2021) find biases in temperature and snow cover in the Alps in MAR
simulations forced by reanalyses (ERA-20C and ERA5) when comparing to gridded
observational datasets, reanalyses and in-situ observations. In their study, the MAR
880 experiments are found to slightly overestimate temperature at low elevations and
underestimate at high elevations, especially in winter. They also are found to underestimate
snow cover duration at low elevation (< 1500 m.a.s.l.). Nevertheless, the biases found are
typical of RCMs and are overall considered acceptable.

By comparing the MAR simulations used in the present study to gridded observational
885 datasets based on station interpolation (see Appendix C, Figs. C1-C4), these simulations

were found to have a cold bias reaching maximum values up to 3 °C at high elevations (above ~2000 m.a.s.l.) across the seasons and a generally warm bias at lower elevations (below 1000-1500 m.a.s.l. depending on the season), especially in summer for which it can reach maximum values of 4 °C. There is also a wet bias in precipitation at high elevation (above 1500 m.a.s.l., except in summer which has a dry bias) reaching around 7 mm per day in winter. Lower elevations (below ~1000 m.a.s.l.) tend to have a dry bias (~2 mm on average, up to 5 mm) in summer and autumn. Also, compared to satellite estimates (Appendix C, Fig. C5), MAR shows a too long snow cover duration at high elevations (above ~2000 m.a.s.l.) for all seasons (a bias reaching maximum values of 50 additional days of snow in spring and summer), and a too small amount of snow days at low elevations (below ~1000 m.a.s.l.) in winter (up to 40 fewer days of snow). The biases provided here are an estimation, since observational datasets over the Alps also have large uncertainties (a problem typically found in all mountain regions), due in particular to the inherent missing values in such products (Prein and Gobiet, 2017 ; Kotlarski et al., 2019 ; Matiu et al., 2024) that are not discussed in this article.



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Figure 1: (a) Domain and orography of MAR simulations. The contour defines the Alps (see

Sect. II.2.2) and is used as a mask further on in this paper (e.g. whenever there is a value averaged over the Alps). The red box is the area shown in Fig. 2, corresponding to the domain considered after excluding the lateral parts affected by boundary conditions in the MAR experiments. (b) Distribution of elevation inside the alpine contour discretized over 200m elevation bands. There are six gridpoints lying above 3000 m.a.s.l.

915 2.2 Methods

2.2.1 MAR warming as a function of global warming

As a preliminary step before studying EDW, we produce the maps of MAR warming as a function of global warming. For this, we combine all three v3.10 simulations (excluding the v3.14 simulation to avoid giving too much weight to the same model-scenario pair).

920 We first compute the global warming in each GCM forcing simulation by averaging yearly as well as spatially the global monthly 2-meter air temperature from 1850 to 2100. We then fit a 3rd degree B-spline using 4 knots through the resulting series of 251 yearly global temperature. This allows us to have a smooth correspondence between any given year and the global mean temperature in the forcing simulation (see Appendix D). We choose 1961-1990 as a reference period to compute the warming anomaly (subtracting the mean of the reference period to the global mean temperature spline). We regress at each gridpoint the three merged MAR v3.10 anomalies onto the global warming level given by the splines. This allows us to get an estimation of the local warming as a function of global warming. Finally, 930 we apply the same procedure at the seasonal scales.

2.2.2 Elevation-dependent trends in the Alps

In this study, we consider historical and projected trends for temperature and surface energy balance fluxes. The historical period spans 1961-2014 and the projection 2015-2100. For 935 each grid point, period and variable of Table 1, we compute the trend in the seasonal mean with a linear regression against the years.

In order to consider elevation-dependent trends at the scale of the Alps, we first apply a mask to our data to isolate the Alps, by selecting the grid points that satisfy the two 940 conditions of being at least 360 meters above sea level (m.a.s.l.) and having a neighbouring grid point at 1300 m.a.s.l. or more (see the contours in Figures 1 and 2). These criteria were tested and selected to accurately trace the contour of the Alps while excluding other mountain areas present in the simulated domain.

945 Then, we classify the grid points into 200 m-elevation bins and compute the mean and standard deviation of the trends for each bin, for any given variable. The temperature in the free atmosphere is the only variable that is not classified in bins, as it is available at seven different pressure levels in the MAR v3.10 outputs (five in version 3.14).

950 2.2.3 Elevation change of maximum trends

In order to track the evolution of the elevation of the maximum trend (defined below) at intermediate to high elevations in temperature and surface energy balance fluxes, we first smooth the seasonal data at each grid point by fitting a 3rd degree spline with the year as covariate (implemented with an adaptive smoothing parameter s used to choose the number of knots, $s = N \cdot v$ with N the number of years and v the variance of the yearly series), in order to remove the year-to-year noise. Then, we divide the 1961-2100 simulation into 90 overlapping 50-year windows (1961-2010, 1962-2011, ..., 2051-2100) and compute the difference between the first and last year of the estimated spline at each grid point and for each window. At this point we have one trend per grid point and window.

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960 Then, for each window, we fit another 3rd degree B-spline using 5 knots through the scatter plot of grid point trends versus the elevation. We take the elevation of the maximum warming after excluding the lowest 10 % and highest 0.3 % elevations of the spline to properly target the local maximum at intermediate elevations in windows that feature a global maximum at the bottom or the top of the elevation range (see Appendix E). For each variable, we end up

965 with an elevation of maximum trend for each window, and thus with a temporal evolution of the elevation of maximum trend.

2.2.4 Snowline elevation

970 The snowline elevation can be computed with different methods, and three of them are provided here: we compute over the Alps and for each day (i) the mean elevation of the 10 highest grid points having < 1 millimeter water-equivalent (mmWe) of snow, (ii) the mean elevation of the 10 lowest grid points having ≥ 1 mmWe of snow, and finally (iii) the average of these two criteria. The first criterion gives an estimate of the elevation above

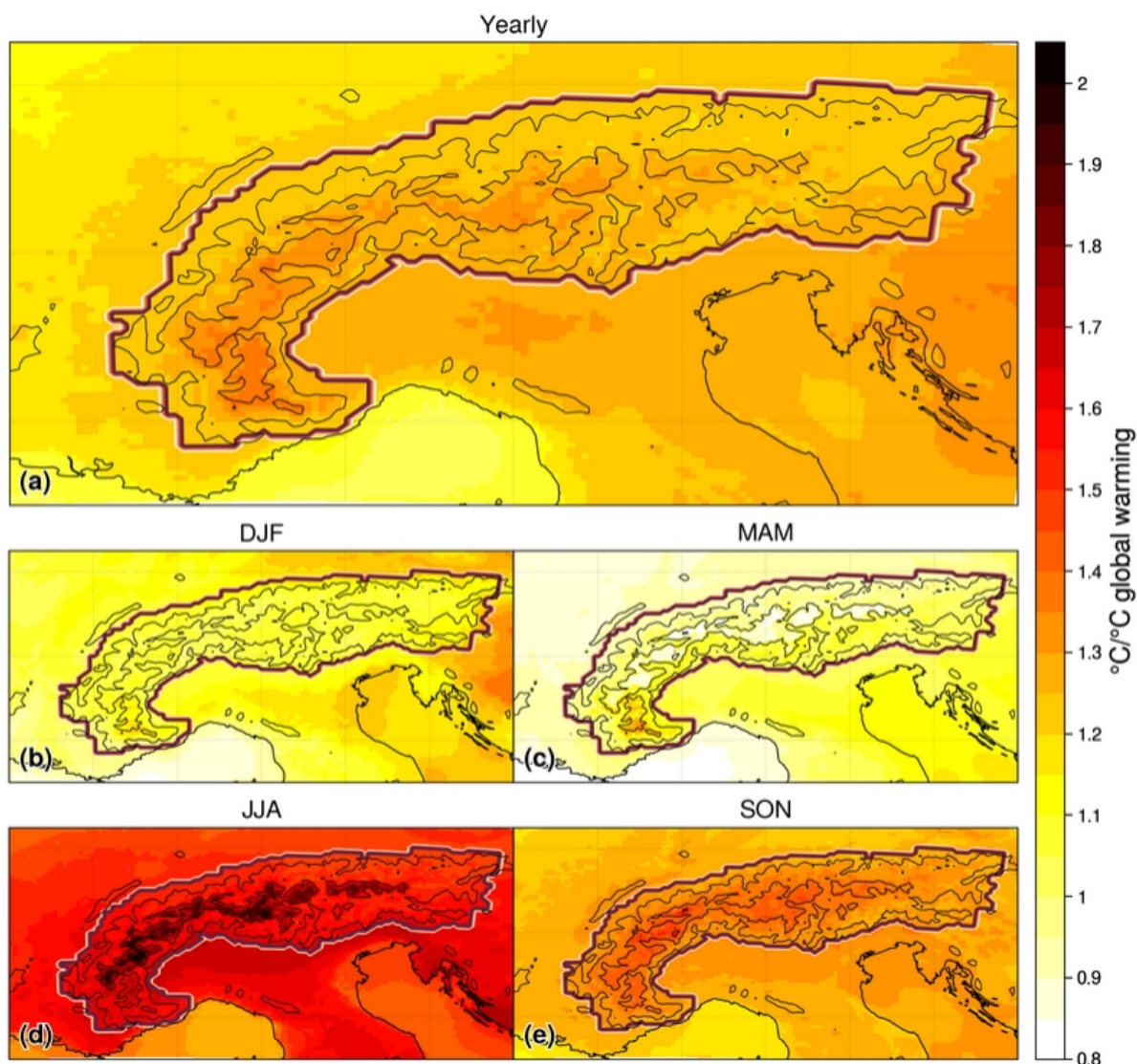
975 which all grid points have snow, the second criterion the elevation below which no grid points have snow. The two elevations define a snow transition band between them, in which some grid points have snow and some don't.

We then take the seasonal median of these daily values to get an average of the snow line

980 elevation over the whole period or window.

3 Results

3.1 Warming footprint in the Alps



985 Figure 2: (a) Yearly warming over 1961-2100 in the three v3.10 simulations scaled with
respect to global warming level in the forcing GCM. (b), (c), (d), (e): same as (a) at the
seasonal timescale.
See Figure 1 for the definition of the contour line. Isolines every 1000 m are shown.

990 Figure 2 shows the yearly and seasonal warmings in the three v3.10 MAR simulations with
respect to global warming (see Sect. II.2.1). As seen in Fig. 2a, yearly temperatures are
rising faster at higher elevations in the Alps (~ 1.2 to 1.5 °C/°C) than in the surrounding
lowlands, which are already warming at a faster rate than global warming (~ 1.1 to 1.3
°C/°C). There is also a strong longitudinal gradient in this area, the continental climate in the
Eastern part warming faster than the Western European climate that is under an oceanic
995 influence.

Overall, strong seasonal contrasts can be seen both in warming intensity and pattern over the Alps (Figs. 2b, c, d, e).

1000 The warming is particularly intense in summer (JJA) with values around 1.6 to 1.7 °C/°C
 global warming in the lowlands, and reaching twice the global warming at high elevations. In
 contrast, the domain warms at a similar rate to global warming (1-1.1 °C/°C) in spring (MAM)
 and at even lower rates (0.8-0.9 °C/°C) at high elevation, except in the southern Alps.
 1005 Autumn (SON) is similar but less extreme than summer, while winter (DJF) is similar to
 spring, albeit showing a slightly higher warming rate.

The pattern of warming is opposite between summer and spring: summer shows the highest
 rates of warming at high elevations, where spring shows its lowest rates of warming. The
 exception being in the southern Alps, where this pattern is reversed.

1010 It is therefore essential to consider seasonal timescales in order to understand the
 processes that are behind these contrasting patterns.

3.2 Elevation-dependent warming near the surface and in the free atmosphere

1015

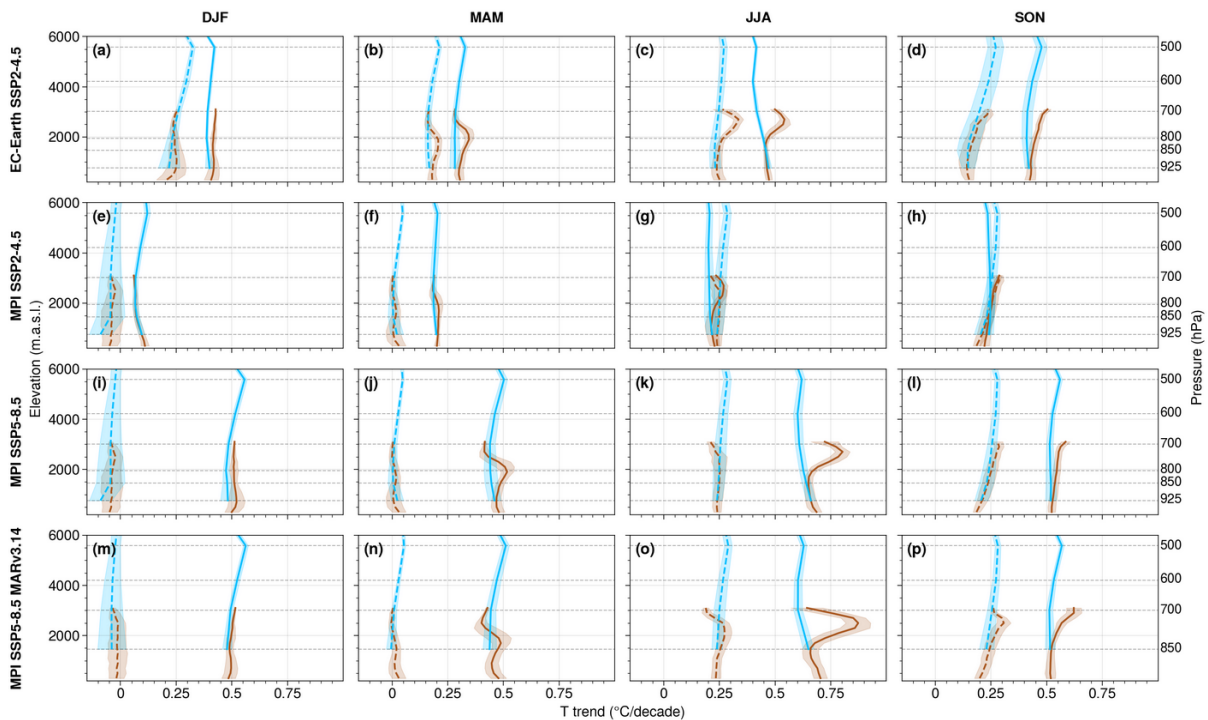


Figure 3: Alpine temperature trends near the surface (along the slopes) averaged over 200
 m-elevation bins (T2m, brown) and in the free atmosphere averaged over the available
 pressure levels (Tp, blue). The historical period (1961-2014) is in dashed lines, projection
 (2015-2100) is in full lines. Shaded bands represent the spatial standard deviation (1 sigma).
 1020 The first three rows are based on the MAR v3.10 simulations and the last one on the MAR
 v3.14 experiment. Columns are for each season.

1025 Figure 3 shows the temperature trend at 2 meters above the surface and in the free
atmosphere (at different pressure levels) at the scale of the Alps, for the four simulations
over the historical (1961-2014) and the projection (2015-2100) periods, using the method of
Sect. II.2.2.

1030 Overall, the warming is generally larger in the projection than in the historical period, both in
the free atmosphere and near the surface. The exception is in summer and autumn for the
MAR-MPI SSP2 simulation (Figs. 3g and 3h) where the two periods experience similar
warming. The lowest temperature trend is close to zero in winter in the historical period for
the MPI simulations (Figs. 3e, 3i and 3m). The largest warming is simulated in summer with
1035 the MARv3.14-MPI SSP5 simulation (Fig. 3o) and reaches 0.86 °C/decade on average at
2500 m.a.s.l., i.e. almost 7.4 °C of warming between 2015 and 2100.

Looking at their vertical profiles, the rates of warming in the free atmosphere and near the
surface have a similar altitudinal gradient in winter. The trend values are similar, with slightly
larger trends for the near-surface warming and a larger spatial standard deviation.
1040 In spring, the same can be generally said for the low and high elevations. However, we can
see higher rates of warming at mid-elevations near the surface than in the free atmosphere
for both periods in MAR-EC-Earth3 SSP2 (Fig. 3b), and for the projection periods of MAR-
MPI SSP5 (Figs. 3j and 3n).

For MAR-EC-Earth3 SSP2, in spring, the maximum of warming near the surface is found at
1045 a higher elevation in the projection than in the historical period, suggesting an upwards
migration of the underlying cause for this heightened near-surface warming.

In summer and autumn, the near surface maximum warming signal moves at higher
elevations, with the strongest signal seen in summer for MARv3.14-MPI SSP5 (Fig. 3o).

1050 This enhanced surface warming appearing at mid-elevations in spring, moving upwards and
increasing in summer, and continuing to move upwards with a lower intensity in autumn, is
investigated along with its link to surface processes in the next section.

1055 In some simulations and periods, we also see a rate of warming lower near the surface than
in the free troposphere that is located above the elevation of the maximum warming. This
can particularly be seen in the SSP5 simulations in spring for the projection (Figs. 3j, 3n) and
in summer for the historical period (Figs. 3k, 3o).

1060 In the free atmosphere, the warming is generally more skewed towards lower (925hPa) and
higher (500hPa) elevations in the projection period than in the historical period (see panels
a, c, d, e, i, j, k, l, m, o, p of Fig. 3). This leads to some altitudinal trends having a hook
shape, further discussed below (see Sect. IV). The warming in the free atmosphere in the
MAR experiment is following very closely the warming simulated in the forcing GCMs,
especially at high elevations (not shown). This highlights low atmosphere and surface
1065 feedbacks simulated with MAR that cannot be solved by the GCMs whereas the regional
climate is driven by large-scale features of the GCM projections.

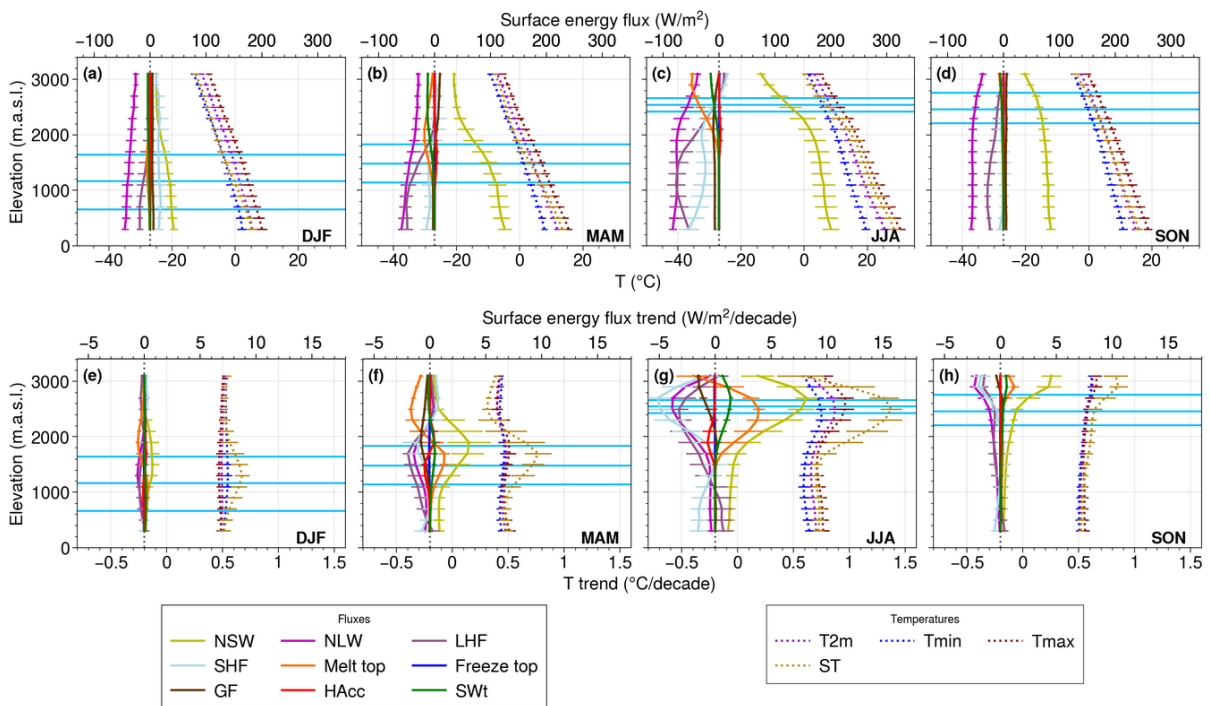
In the continuation of this study, we investigate this seasonal signal occurring near the
surface by analysing the surface energy balance fluxes and their respective trends.

1070 3.3 Projected temperature and energy flux trends

We define the surface energy balance in the model MAR as the sum of all fluxes occurring at the first surface layer of the ground and of the processes occurring within that layer - heat accumulation, snow melt and water refreezing. In this model, the first surface layer of the ground is 1-mm thick in the absence of snow and has the (variable) depth of the first snow layer in the presence of snow. The surface energy balance is expected to be closed, meaning that the sum of the fluxes is expected to be equal to zero.

1075 By identifying all the variables that are part of this balance (see Sect. II.1) and computing their trends, we ensure that we have a comprehensive view of what is happening at the surface and that we do not overlook any process contributing to increased surface warming. Only MARv3.14 results are used here as this version allows to display all the different energy fluxes. The two versions have similar EDW trends in the Alps as displayed by the last two rows in Fig. 3.

1085



1090 Figure 4: Profiles along the elevation of the projected (2015-2100) mean values (top) and trends (bottom) for temperatures (dotted) and fluxes (full lines) averaged over the Alps, in the MAR v3.14 simulation. For each panel, the temperature (trend) values are indicated on the lower axis and the surface energy flux (trend) values on the upper axis. Horizontal bars are the spatial dispersion (1 sigma). Blue horizontal lines refer to the elevation of the snowline computed in three different ways (cf. Methods/Sect. II.2.4). Fluxes are positive when directed towards the surface. Season is indicated in the bottom right corner.

1095

Figure 4 displays the profiles along the elevation of the projected mean values and trends for

1100 temperatures and surface energy fluxes. The blue horizontal lines indicate the mean
elevation of the snowline for each season using the method presented in Sect. II.2.4. The
top and bottom lines can be seen as a snow transition band including the snow line.

1105 The average values (top row) highlight the sign and the vertical distribution of the
temperature and surface energy fluxes. Fluxes are defined as positive when directed
towards the surface. The mean NSW flux is positive for all seasons with a seasonal cycle
that reaches its maximum in summer, as expected, and decays with height. A stronger
decay above the snowline showcases the impact of the presence of snow on the NSW flux.
1110 The mean NLW flux is the main component balancing the NSW flux, and as such has a
similar profile except that it is negative and follows a weaker seasonal cycle. The SWt flux is
negative in the presence of snow, since it is being transmitted to the lower layers from the
surface, and equal to zero in the absence of snow since the ground is opaque in the model.
1115 The mean LHF is negative (except at the top), meaning that evaporation is cooling down the
surface (humidity transfer from the surface to the atmosphere). It decreases with height as
well - which might be due to less available NSW flux at high elevations - except at the
bottom in summer (Fig. 4c), which might be due to less available humidity at low elevations.
1120 The mean SHF is positive in winter, indicating that the surface is being heated up by
turbulent fluxes in the surface boundary layer (ST is cooler than T2m). It is negative at low
elevations in spring, summer, and autumn, as ST is warmer than T2m, and switches sign at
higher elevations. Mean melt top is always negative by convention (energy is used by the
surface to melt snow) and largest in summer. It is larger at intermediate elevations in winter
and spring, because temperature is too low to induce melting at high elevation, and larger
near the top of the profile in summer and autumn. We do not delve into the other variables
because of their low amplitude.

1125 The bottom row of Fig. 4 shows that T2m, Tmin and Tmax exhibit similar trends, while ST
exhibits the largest trend, near the top of the snow band. This suggests again that the
maximum T2m trends are mainly driven by surface processes. The closer to the surface, the
stronger the temperature trend signal. The surface absorbs more energy over time which is
then redistributed to the near-surface atmosphere thanks to the longwave radiation and
1130 sensible and latent heat fluxes, explaining the temperature signal found close to the surface
that shows a similar shape but with a smaller intensity.
In spring and summer, ST also exhibits a minimum trend at higher elevations.

1135 Let us remember that a positive trend means an *increase* for a positive flux, but a *decrease*
for a negative flux. NSW and NLW fluxes both show a clear increase in their absolute values
over time and throughout the seasons, which is expected in a warming climate. By contrast,
SWt is decreasing, which is explained by the decrease in snow cover over time.
LHF and SHF have large trends that generally point to an absolute increase, but not for all
elevations, as both the mean values and the trends switch signs at different elevations and
1140 seasons. They might be in part a response to the perturbations in NSW flux and melting.
GF, HAcc and Freeze have small or non-existent trends.

1145 Melting flux shows large trends in spring and summer. For both seasons, the trend first
increases with elevation, then decreases until it ends as a negative trend near the top of the
elevational gradient. As seen with the temperature, the melt trend is larger and shifted to
higher elevations in summer compared to spring, as expected. The presence of both a
maximum trend, and then a minimum trend at higher elevations, is reminiscent of the surface
temperature trend and the lower rate of warming above the maximum signal discussed in the
previous section.

1150

Figure 4 shows evidence that the snow-albedo feedback is the main driver of the elevation-dependent warming signal. Indeed, the NSW variable shows the largest trend at the snow transition band elevations. The NLW, SHF and LHF trends compensate for this increase to maintain the surface energy balance with a maximum trend at similar elevations but negative in sign.

1155

Melting strongly impacts the surface energy balance and temperature as well, with a positive trend within the snow transition band, transitioning to a negative trend above. The snow melt energy flux is negative (top row of Fig. 4) which means that the snow melt increase (negative trend) is slowing down the warming at elevations where there are still significant amounts of snow, and the snow melt decrease (positive trend) is speeding up the warming where snow is becoming scarce. This is due to the phase transition from solid to liquid water. When the snowpack reaches 0 °C, additional energy provided by e.g. solar radiation is consumed to melt the snow without an increase in temperature in the system. Once the snowpack is no longer present, the energy which was used to melt the snow is back to increasing the surface temperature once again.

1160

1165

In spring, the mean trend of the snow melt energy flux reaches a maximum of 1.31 W/m²/decade and a minimum of -1.71 W/m²/decade along the elevation profile, while the mean NSW trend reaches a maximum of 3.50 W/m²/decade. Assuming that the difference between the warming at low elevations and at the snowline is mainly due to snow-related processes, we can subtract the former to the latter to get a first order approximation of the effect of the snowline on the two variables. This assumes that (i) snow-related processes are minimal or non-existent at low elevations, and (ii) that the signal is otherwise independent of elevation which is de facto the case for snow melt, and reasonable to assume for the NSW trend given that the treeline is fixed in the model. With this approximation, the NSW trend is closer to 2.63 W/m²/decade and the melt to 1.27 and -1.75 W/m²/decade.

1170

1175

In summer, the mean trend of the snowmelt energy flux reaches a maximum of 3.90 W/m²/decade and a minimum of -1.96 W/m²/decade, while the NSW trend reaches a maximum of 8.18 W/m²/decade. Subtracting the trend at low elevations to approximate at the first order the effect of the snowline alone, the NSW trend is closer to 7.12 W/m²/decade (melt is unchanged).

1180

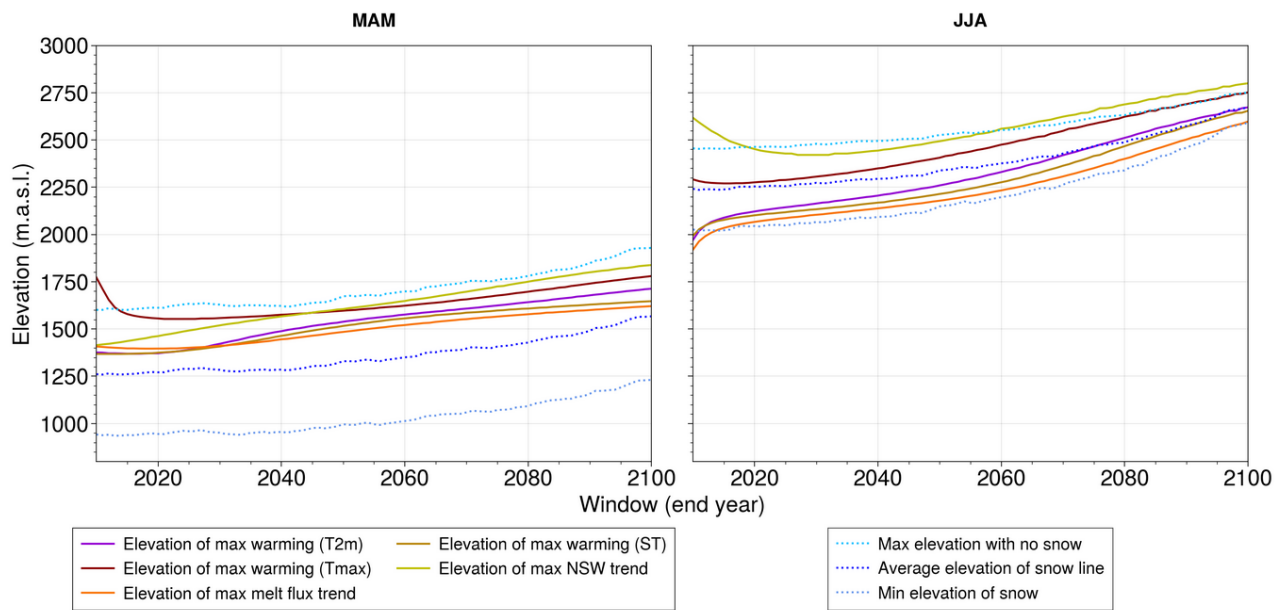
For both seasons, the NSW maximum trend is slightly more than twice the snow melt energy flux trend (either positive or negative). This means that while the snow-albedo feedback effect is the main cause behind the simulated elevation-dependent warming in both seasons, the snow melt change is also having a significant effect on the warming at and near the surface.

1185

The snowline is expected to migrate upwards with global warming. In the continuation of this study, we investigate if there is a similar migration in the elevations of the maximum trends.

1190

3.4 Snowline and elevation of maximum warming



1195 Figure 5: Elevation of snowline, maximum warming trends (T2m, Tmax, ST), melt flux trend and net shortwave trend in spring and summer over the course of rolling 50-year windows spanning 1961-2100 in the MAR v3.14 simulation over the Alps. The final year of each window is shown on the x axis.

1200 Figure 5 shows the evolution of the elevation of the maximum trend throughout the MARv3.14-MPI SSP5 simulation spanning 1961-2100 for T2m, ST, Tmax, NSW and the melt flux for rolling 50-year windows (see Sect. II.2.3). Superimposed is the elevation of the snowline using the criteria defined in Sect. II.2.4 for each 50-year window.

1205 In spring, the snow transition band migrates by approximately 300 meters to higher elevations between the first (1961-2010) and the last (2051-2100) windows. The elevations of the maximum trends are contained within this band and shift similarly, with shifts ranging from 200 meters to over 400 meters (not counting the first few windows for Tmax where the maximum trend is higher than expected).

1210 In summer, the snow transition band is narrowing and migrates to upper elevations. The top of the band increases in elevation by approximately 300 meters between the first and last windows, the bottom by approximately 550 meters. The elevations of the maximum trends are again mostly contained within this band. They migrate upwards by 450 to 650 meters, except for NSW which is unexpectedly high and decreasing in elevation for the first 10-15 windows.

1215 This suggests a correlation between the migration of the snow transition band and the elevation of maximum warming, the latter staying largely contained within the former in spring and summer in the span of the entire simulation.

4 Discussion and conclusion

1220

In this study, we analysed four MAR simulations over the Greater Alpine Region in order to investigate the physical drivers of EDW. We saw higher warming in the Alps compared to the global warming simulated in the forcing GCMs: 1.2 to 1.5 °C/°C at the yearly timescale. The warming reaches higher values in summer, with values around 1.7 °C/°C at low elevations and up to 2 °C/°C at the highest elevations. We found a reversed EDW in spring, with a warming at high elevation that reaches lower values than the global warming (0.8-0.9 °C/°C). The different warming patterns from season to season highlighted the need to investigate EDW at the seasonal timescale. Then, we compared the warming near the surface (along the slopes) and in the free atmosphere and highlighted a maximum signal along the slopes moving upwards from spring to summer to autumn. This local warming is explained by surface-atmosphere exchanges, since it does not happen in the free atmosphere. There is no clear EDW in winter, which could be explained by a lower available amount of solar radiation, making temperature trends less dependent on its variations at the surface. Among the different surface energy fluxes, NSW and melt energy fluxes have a maximum trend at a similar elevation than the maximum temperature trend, located near the top of the snow transition band (i.e. where the snow starts to disappear in a warming climate). Assuming the signal seen at the elevation of the snowline is mainly due to these two snow-related processes, almost two thirds of this maximum warming is explained by NSW changes (2.63 W/m²/decade in spring, 7.12 W/m²/decade in summer), whereas melting changes contribute over a third in our model experiments (-1.75 to 1.27 W/m²/decade in spring, -1.96 to 3.90 W/m²/decade in summer). Finally, we saw that the trends of T2m, Tmax, ST, NSW and melting fluxes show a maximum value at an elevation that moves upward over time. This happens at the elevation of the snow transition band, i.e. in the elevation band covering the areas where the snow cover starts to disappear and where the last snow patches are remaining.

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An added value of the simulations used in this study compared to previous studies on EDW in the Alps with model data (Kotlarski et al., 2012, 2015, 2023 ; Gobiet et al., 2014 ; Palazzi et al., 2019 ; Lüthi et al., 2019 ; Warscher et al., 2019 ; Beaumet et al., 2021 ; Napoli et al., 2023) is the combination of (i) a fine resolution at 7 km ; and (ii) a large timespan of 140 years covering both historical and projection periods. The 7 km resolution allows for a good compromise between the representation of the alpine orography (to reduce snow cover biases seen e.g. at 12 km in the EURO-CORDEX experiments ; see Terzago et al., 2017, Matiu et al., 2020) and the hydrostatic approximation required in MAR experiments. The large timespan allows for investigating trends in a context where natural variability induces small signal-to-noise ratios.

1250

1255

Pepin and Seidel (2005) find enhanced warming at the surface compared to the free atmosphere in global mountain regions by comparing surface temperature in observation data sets and free atmosphere temperature from an interpolated reanalysis product for the period 1948-1998. However, the weakest signal in absolute value is found for locations over Europe (see Table 4 within). In the Rocky Mountains, Minder et al. (2018) find stronger warming rates along the slopes than in the free troposphere in RCM experiments, highlighting the role of the snow-albedo feedback. To our knowledge, our study is the first one that is providing a similar finding in the Alps, with a complete view of all the surface processes at play.

1260

1265 The melting of snow consumes energy due to the phase transition of snow to liquid water. This
process limits the warming above the snowline at elevations where melt is increasing, and
enhances the warming below the snowline where melt is decreasing. As stressed above, with
the aforementioned assumptions in mind, we find that it is responsible for approximately a third
of the snowline's impact (positive or negative) on warming in the MAR version 3.14 simulation.
1270 We suggest that this process is a driver of EDW and should be considered in any EDW-snow
investigations.

The impact of snow on elevation-dependent warming is often simplified to the snow-albedo
feedback effect (e.g. Pepin et al. 2015, Palazzi et al., 2019, Warscher et al., 2019 ; Byrne et al.,
2024). Thornton et al. (2021) identify snow melt as an essential mountain climate variable, but
1275 from a hydrological standpoint only. Dimri et al. (2022) investigate snow melt trend as a
function of elevation in the Indian Himalayan region, seeing a similar signal to ours: the snow
melt trend transitions from positive (the melting process decreases over time) to negative (that
process increases) when going from low elevations to high elevations. The signs of the trends
are reversed in their study as they look at the snow melt in kg/m^2 , which is positive, while the
1280 present study looks at the melt contribution to the surface energy balance, which is negative.
However, they do not mention a possible contribution of the energy consumed by snow melt,
again only mentioning the effect on albedo. Minder et al. (2018) find, when removing the snow-
albedo feedback, similar EDW profiles between the free troposphere and near the surface.
However a small signal near the surface remains in their study. We may hypothesize this to be
1285 the melt energy flux in light of our study.

Our study is based on a small ensemble experiment (two configurations with two different
forcing GCMs, one of them with two scenarios) due to resource constraints preventing us from
producing and exploring a larger ensemble. We use a single RCM, which has its own climate
1290 sensitivity (Glaude et al., 2024). As seen in Appendix C (Fig. C5), the MAR simulations used in
this study tend to overestimate the duration of snowcover on the ground, mainly due to an
overestimation of precipitation at high elevations. This might exaggerate the impact of snow on
EDW. Larger ensemble experiments would help to diagnose the temperature and snow
changes, disentangling the forced signals versus those related to climate internal variability.
1295 Nevertheless, it is useful to identify the patterns and the physical drivers of EDW with single
experiments, since ensemble averaged signals might overwhelm the local enhanced trends
that might differ among GCM-RCM configurations.

This study utilized a simplified framework to isolate and study specific processes. Two main
1300 prospects for further characterization of EDW in the Alps appear in our model framework: (i)
we are considering a fixed aerosol climatology in our future projections (stationary forcing over
2005-2100 in version 3.10 and over the entire period in version 3.14), that is limited to the
aerosol direct effect (indirect effects are neglected). This prevents the possibility of
investigating the local cooling related to particle pollution that is mainly active at the bottom of
1305 the valley (Napoli et al., 2022) and that is currently decreasing in Europe with a significant
impact on surface temperature (Philipona, 2012 ; Tudoroiu et al., 2016 ; Nabat et al., 2025). (ii)
The model also uses a stationary land surface cover which excludes the possible effect of the
migration of the tree line on EDW. These two aspects should be investigated in future work.

1310 Further research could also investigate other processes acting as feedback on EDW. An
increase in humidity (i.e. atmospheric moisture) entails an increase in the downward longwave
radiation, and the Planck feedback entails an increase in the upward longwave radiation.
Moreover, seasonal contrasts may be reinforced due to these processes: in winter, humidity is
1315 higher than in summer and temperature is lower, potentially strengthening one process over
the other in winter and switching in summer. These two effects are implicitly resolved in our
modelling framework, but a detailed investigation should be done to properly quantify their
impact. We found the impact of atmospheric moisture challenging to assess in this study, for
two reasons: (i) it is hard to disentangle its trend with the temperature trend and to know which
1320 cause came first, as higher temperature often leads to higher humidity which in turn impacts
warming, in a feedback loop ; and (ii) it is not clear whether atmospheric moisture is expected
to have an increasing or decreasing impact on EDW. Several studies argue that it has an
increasing impact (Pepin et al., 2015 ; Ruckstuhl et al., 2007 and Rangwala et al., 2010), but
the effect on EDW has been found to be the opposite in Byrne et al. (2024) (opposing EDW
instead of increasing it) and to have no effect in Minder et al. (2018).

1325 Convection could explain the enhanced warming at 500hPa (upper part of the hook shape
seen in the free atmosphere trends) as more humidity is brought to high elevations and
condenses, releasing heat (as seen in the tropics in Romps, 2011 and Keil et al., 2023 ; in the
tropics and to a lesser extent at midlatitudes in Vallis et al., 2015 ; in the Tibetan Plateau in Wei
1330 et al., 2025). The Planck feedback could also explain this signal, since it is expected to induce
positive EDW (Pepin et al., 2015) which would favor higher warming at high elevations.
Explaining the slightly enhanced warming at 925hPa (lower part of the hook shape in the free
atmosphere trends, and to some degree near the surface) is more challenging. As mentioned
in the previous paragraph, atmospheric moisture has a negative EDW signal (favoring low
1335 elevations) according to Byrne et al. (2024) which could explain this signal, however other
studies also cited in the previous paragraph predict a positive EDW signal from atmospheric
moisture. Another possible explanation could be the enhanced warming during inversion layer
events of the lowest atmospheric layer (Ohmura, 2012).

1340 It is interesting to note that the hook shape can also be seen in the winter months in Minder et
al. (2018) in the Rocky Mountains for the free troposphere EDW, although they found no
impact of atmospheric moisture on EDW in general. Further investigation would be needed to
fully characterize the signals driving this hook shape warming in the troposphere.

1345 Overall, we highlight a decoupling between the free atmosphere and the high-elevation
surface areas, with a strong EDW along the slopes induced by surface feedbacks that is not
occurring in the free atmosphere.

Appendices

1350 A - General Circulation Model (GCM) selection for dynamical climate downscaling over the Alps

1355 In order to select the General Circulation Models for dynamical downscaling with MAR, we considered three relevant large-scale climate indices that impact the atmospheric conditions over the Alps: the temperature at 700 hPa (T700), the geopotential height at 500 hPa (Z500) and the Sea-Surface Temperature (SST). We compared each of them over 1971-2000, in the European-North-Atlantic area (80° W-45° E, 35° N-75° N), to the reanalysis product ERA5. We computed the spatial root-mean-square error (RMSE) for each model i and each variable χ , and normalised it with the multi-model median and interquartile range (IQR), using the method described in Barthel et al. (2020):

$$1360 \quad RMSE(\chi)_{i,norm} = \frac{RMSE(\chi)_i - \text{median}(RMSE(\chi))}{IQR(RMSE(\chi))} \quad (1)$$

The best-performing models are those with the lowest (i.e. most negative) values of $RMSE(\chi)_{i,norm}$. This normalisation allowed us to combine them into one score by computing the weighted mean of the three variables:

$$1365 \quad S_i = \frac{RMSE(T\ 700)_{i,norm} + RMSE(Z\ 500)_{i,norm} + \frac{1}{2} RMSE(SST)_{i,norm}}{3} \quad (2)$$

1370 We chose a half weight for the SST because it is less relevant than the other two variables for downscaling in the Alps. The scores are given in Table A1.

Model	DJF	MAM	JJA	SON	Year
EC-Earth3	-0.65	-1.06	-0.68	-0.90	-0.82
CESM2	-0.80	-0.70	-0.01	-0.24	-0.44
MPI-ESM1-2-HR	-0.47	-0.54	0.08	-0.62	-0.39
MRI-ESM2-0	-0.37	-0.10	-0.59	-0.05	-0.28
UKESM1-0-LL	-0.74	-0.06	0.19	-0.37	-0.25
BCC-CSM2-MR	-0.16	-0.16	-0.20	-0.21	-0.18
GFDL-ESM4	-0.02	-0.04	-0.33	-0.11	-0.12
MIROC6	0.24	-0.20	0.31	0.26	0.15
CAMS-CSM1-0	0.29	-0.13	0.01	0.53	0.17
GFDL-CM4	0.45	0.40	0.12	0.25	0.31
NESM3	0.92	0.76	0.10	-0.20	0.39
CanESM5	1.16	0.63	-0.41	0.47	0.46
CNRM-ESM2-1	-0.08	0.33	1.29	0.55	0.52
FGOALS-g3	0.68	0.10	0.73	1.16	0.67
CNRM-CM6-1	0.34	0.69	1.77	0.93	0.93
IPSL-CM6A-LR	0.65	1.10	1.31	0.85	0.98

1375 Table A1: Validation scores S_i (mean normalised RMSE with half less weight for SST) for CMIP6 ensemble compared to ERA5, for each season and for the whole year. The more negative the value, the closer the model is to ERA5. The shaded rows indicate the two models selected to be downscaled with MAR.

Although the CESM2 model shows the second lowest score, we did not select it as it has climate sensitivity close to EC-Earth3. To explore a larger range of climate sensitivities, we thus selected instead the third best, MPI-ESM1-2-HR.

1380 B - MAR output data and surface energy balance

The outputs of the version 3.10 experiments are available at different height and pressure levels (2, 10, 50, 100m and 925, 850, 800, 700, 600, 500, 200 hPa for the daily mean temperature), and the first 3 sigma levels (for Tmax and Tmin).

1385 The version 3.14 experiment is available at 2, 10, 100m and 850, 700, 600, 500, 200 hPa for the daily mean temperature, and the first 2 sigma levels for Tmax and Tmin. Its output also features the melt/freeze top, GF, HAcc, and SWt variables unlike version 3.10.

1390 Figure B1 describes the surface energy balance in the soil and snow routine in MAR. It is computed for the top layer, which is 1mm thick when there is no snow on the ground, and of variable thickness when there is snow (depending on the amount of recent snowfall and the evolution of the snowpack).

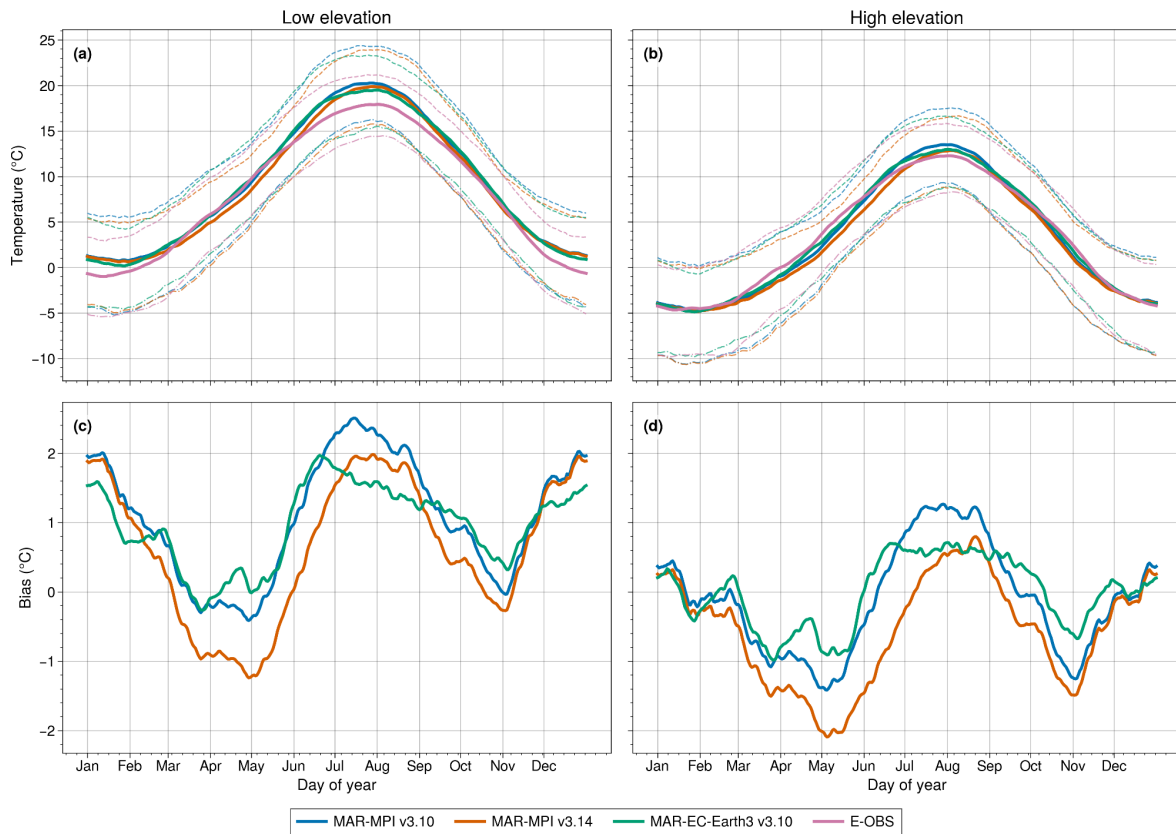


Figure C1: Top : Daily mean temperature at 2 m (T2m), averaged over 1961-2014 and over the Alps for low elevations (< 1200 m.a.s.l.) and high elevations (> 1200 m.a.s.l.), for the three MAR historical simulations and E-OBS (full lines). The dashed lines represent the 90th percentile and the dashed and dotted lines represent the 10th percentile, over 1961-2014. Bottom : Bias of the three MAR historical simulations compared to E-OBS over the same period. A 30-day rolling mean has been applied to the data, both in the top and bottom panels.

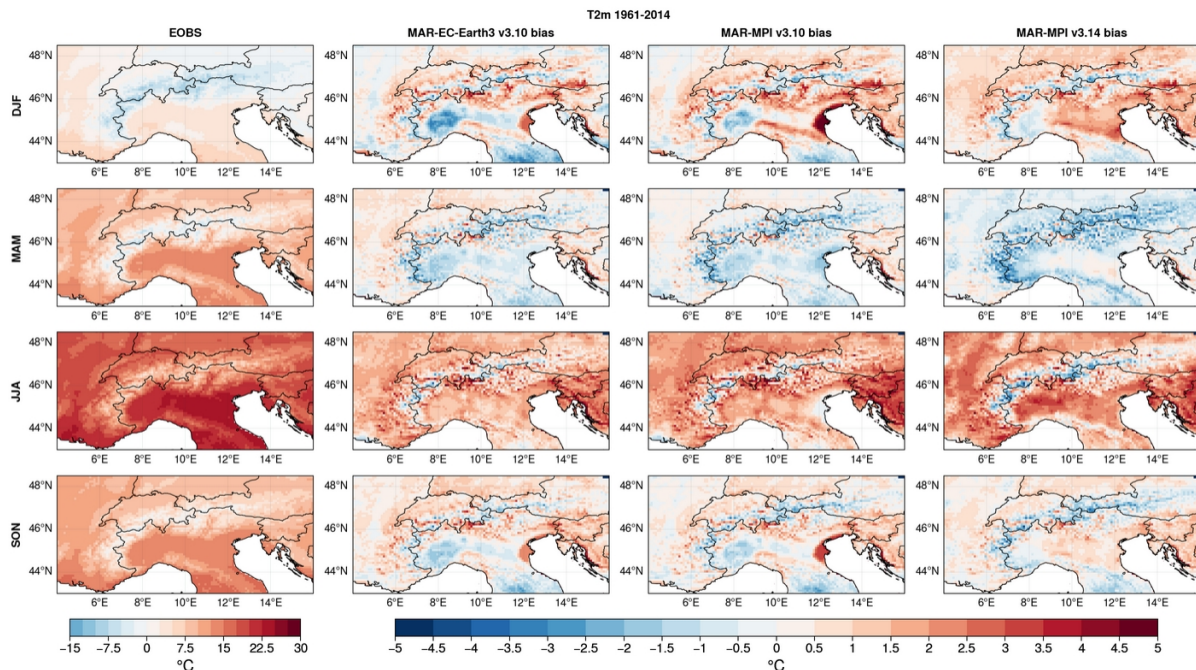
1415

We use E-OBS as a reference to validate MAR daily mean temperature at 2 m. E-OBS is a high resolution ($0.1^\circ \times 0.1^\circ$) gridded dataset over Europe based on daily station time series from the European Climate Assessment & Dataset (ECA&D). It uses an interpolation algorithm to produce an ensemble of reconstructions (Cornes et al., 2018). We use here the ensemble mean for daily mean air temperature in the version 29 of the dataset.

1420

Fig. C1 shows the annual cycle of the three historical simulations of MAR and E-OBS, together with the bias with respect to E-OBS. We can see that all three MAR simulations are in good agreement for the annual cycle of temperature in the Alps in the historical period, although the MAR-MPI v3.14 simulation tends to be a bit colder, especially in spring and early summer (by up to 1 degree) both at low (panels C1a and C1c) and high elevations (panels C1b and C1d). Comparing them to E-OBS for low elevations, they present a warm bias reaching over 2 °C in summer and winter and the MAR-MPI v3.14 presents a cold bias reaching 1 °C in spring (panel C1c). For high elevations, the bias is shifted by 1.5 °C towards lower temperatures (panel C1d).

1430

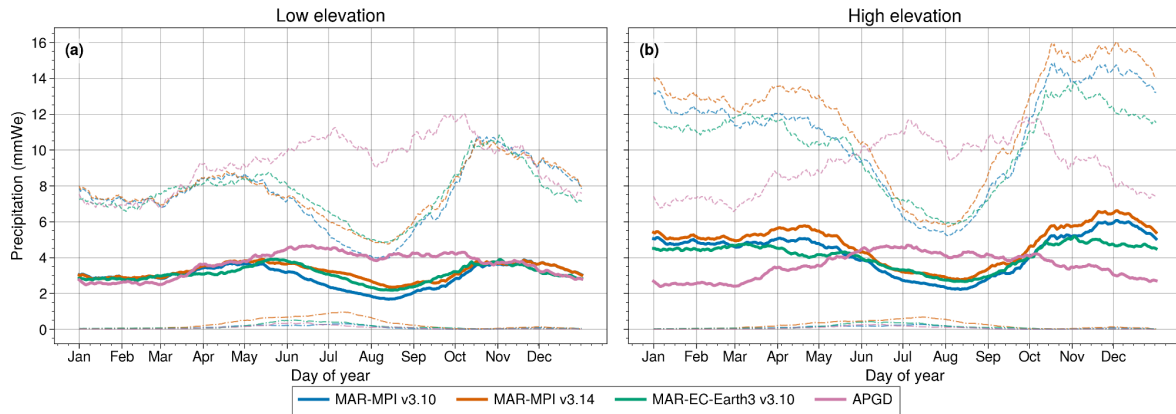


1435 Figure C2: First column: Mean daily temperature at 2m (T2m) for each season averaged over 1961-2014 for E-OBS. Next three columns: Difference between MAR simulations (forced by EC-Earth3 and MPI-ESM1-2-HR using version 3.10 of MAR, and by MPI-ESM1-2-HR using version 3.14 of MAR for the 2nd, 3rd and 4th columns respectively) and E-OBS over the same period.

1440 Figure C2 shows the maps of the temperature bias over the historical period for the MAR GCM-driven simulations compared to E-OBS.

1445 With some exceptions, all three simulations have similar biases compared to E-OBS. A cold bias at high elevations of about 3 °C stands out for all simulations and all seasons. In summer, the lowlands present a warm bias of around 2 °C for MAR-EC-Earth3 and 3 °C for both MAR-MPI simulations, reaching 4 °C in some locations. Autumn and winter show contrasted biases ranging generally from -2 to +2 °C for the former and -3 to +3 °C for the latter. In spring, all simulations show a cold bias to the south of the Alps but show different signs to the north - these also range generally from -2 to +2 °C.

1450 **Precipitation**

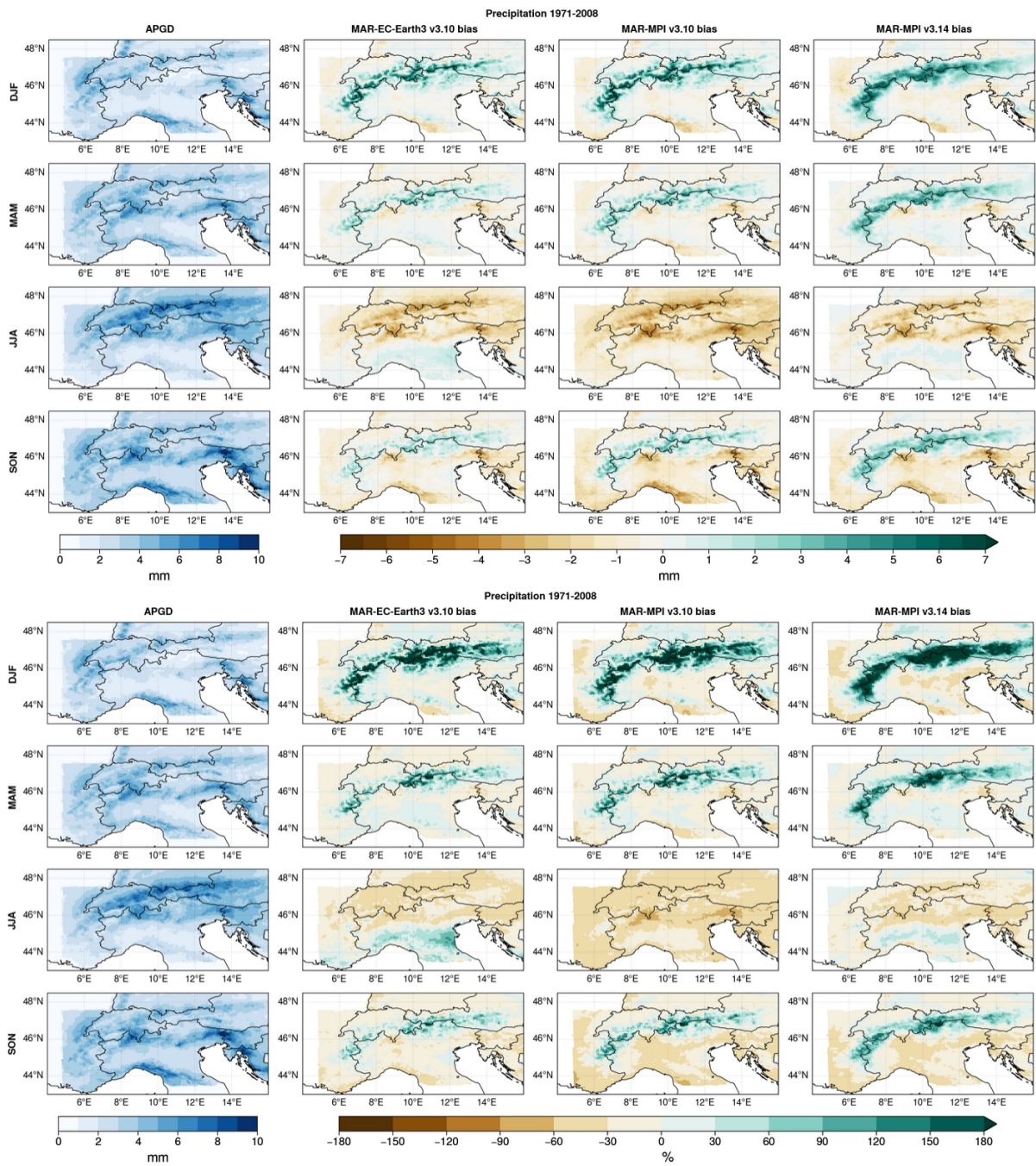


1455 Figure C3: Daily mean precipitation in mmWe, averaged over 1971-2008 and over the Alps
 1455 for low elevations (< 1200 m.a.s.l.) and high elevations (> 1200 m.a.s.l.), for the three MAR
 1455 historical simulations and APGD (full lines). The dashed lines represent the 90th percentile
 1455 and the dashed and dotted lines represent the 10th percentile, over 1971-2008.

1460 We use APGD as a reference to validate MAR daily mean precipitation. APGD is a pan-
 1460 Alpine grid dataset based on rain-gauge data using an interpolation method that integrates
 1460 climatological precipitation-topography relationships (Isotta et al., 2014).

1465 Fig. C3 shows the annual cycle of the three historical simulations of MAR and APGD. It
 1465 demonstrates a lower amount of precipitation in the Alps in MAR-EC-Earth3 than in the MPI
 1465 simulations near the end of the year at high elevations, and a slightly lower amount of
 1465 precipitation in MAR-MPI v3.10 during the summer than in the other two MAR simulations.
 1470 Otherwise, all three MAR simulations are in good agreement. Comparing them to APGD at
 1470 low elevations, they present a dry bias of up to 2 mmWe from June to October, and present
 1470 a similar climatology the rest of the year. At high elevations, the dry bias is from June to
 1470 September, and there is otherwise a clear wet bias reaching over 2 mmWe during the rest of
 1470 the year.

1475

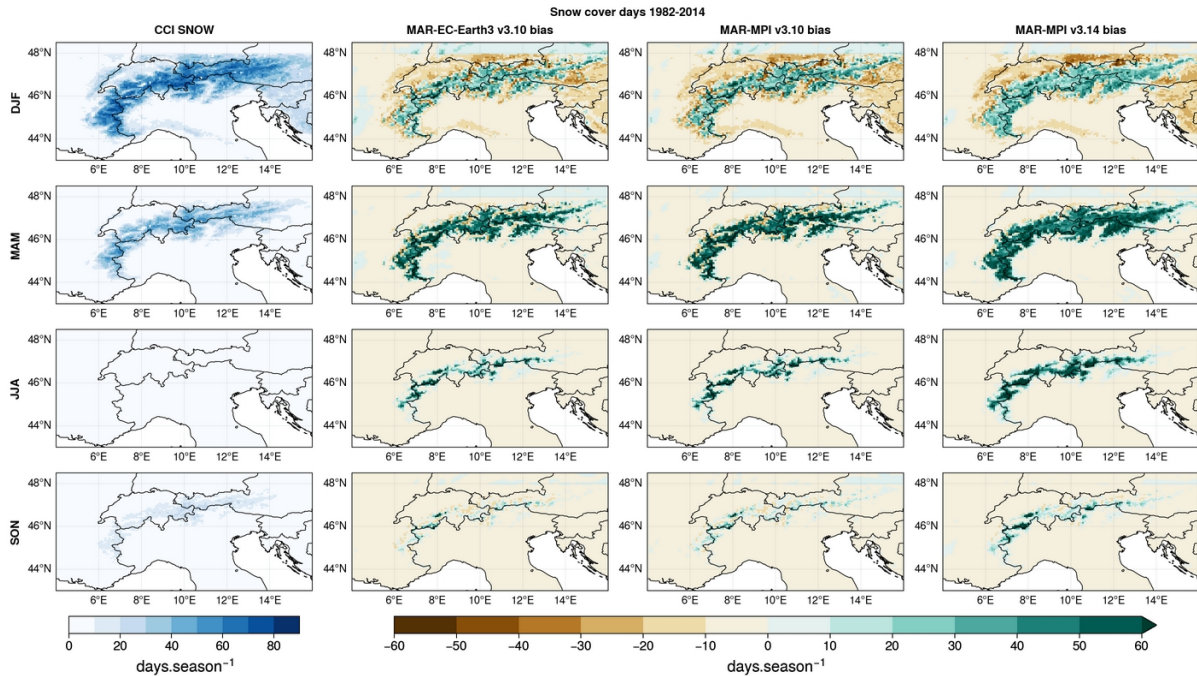


1480 Figure C4: Same as Fig. C2 but for daily mean precipitation, using APGD - top panel is the absolute bias (in mmWe), bottom panel is the relative bias (in percent).

Figure C4 shows the maps of the daily mean precipitation bias for the period 1971-2008 of the MAR simulations compared to APGD.

1485 All three simulations have once again similar biases. As seen in Fig. C3, there is a positive bias in the Alps, especially at high elevations in winter, spring and autumn. The bias is highest in winter with values reaching up to 7mm and over 180 % relative to APGD. In summer, the bias becomes negative in the Alps with values reaching 5mm for some locations, or over 60 % relative to APGD.

1490 **Snow cover duration**



1495 Figure C5: Same as Fig. C2 but for the number of days per season with snow on the ground, using SNOW-CCI. A grid point in MAR is considered to have snow if it has >50 mmWe of snow.

1500 We use the SNOW-CCI dataset (Naegeli et al., 2022) as a reference to validate the number of days with snow on the ground in MAR simulations. SNOW-CCI is a satellite observation product that has been gap-filled, using a linear interpolation of the data for windows of missing data with a maximum duration of 10 days (see Lalande et al., 2023). A second algorithm is used to count the number of snow days for each grid cell. A grid cell is considered to have snow if at least 50 % of the grid is covered with snow. To account for the remaining gaps not filled by the abovementioned interpolation, the number of days with snow is extrapolated at the monthly timescale (Derksen et al., 2025) - for X days covered with snow among Y available daily data per month, we define the snow cover duration SCD as:

1505 $SCD = X/Y * [\text{number of days in the month}]$

The extrapolation is performed only if there are at least 15 days of available data in the month.

1510 Figure C5 shows the bias for the mean number of days with snow on the ground per season for the MAR simulations compared to the SNOW-CCI dataset. The three simulations again show similar biases: there is a positive bias at high elevations in summer and autumn up to 60 days/season, and no bias at low elevations. The positive bias extends to the entire Alps in winter and spring, with winter having additionally a negative bias at low elevations surrounding the Alps of about 20-30 days/season.

1515

This is consistent with the cold temperature and high precipitation bias seen at high elevations (Figs. C2 and C4).

1520 D - GCM warming splines

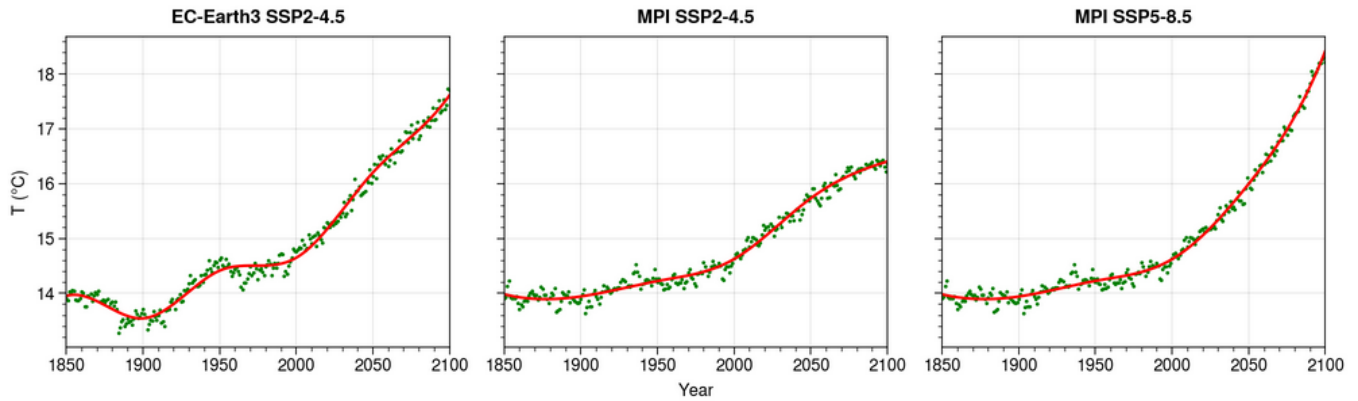
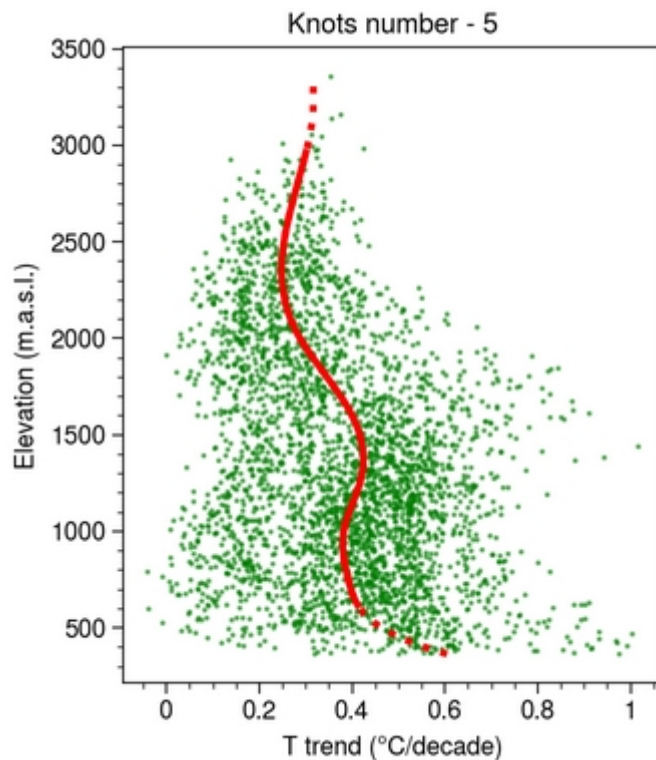


Figure D1: Spline fit (red) of yearly global warming at 2m average series (green) in the forcing GCM simulations. We used a 3rd degree B-spline with 4 knots.

1525 Figure D1 shows the smoothed warming in the GCMs used to force the MAR simulations used in this study. All three start at 14 °C global temperature and rise (from least to most) by 2.4 °C for MPI-ESM1-2-HR using the SSP2-4.5 scenario, 3.6 °C for EC-Earth3 with the same scenario, and 4.5 °C for MPI-ESM1-2-HR using the SSP5-8.5 scenario by the end of the 21st century.

1530 Using these three experiments to force MAR allows us to have a spread in the forcings at the simulations' boundaries.

E - Elevation of maximum trend



1535 Figure E1: Warming in the Alps during a given 50-year window, with a fit using a 3rd degree B-spline using 5 knots (red). Green dots are the warming for individual grid points. Dashed line: full spline. Full line: we cut off 10 % of the lower elevations and 0.3 % of the highest to ensure that we target the local maximum around 1500 meters.

1540 Figure E1 shows the method used to identify the elevation of the maximum warming, by smoothing the data with a spline.

Code and data availability

1545 All scripts to produce the figures are available at https://github.com/Ian-CD/PhD/tree/master/Article_EDW. The Python environment used is also included.

The MAR simulations are available on Zenodo repositories.

1550 Version 3.10: Beaumet et al., 2022a (<https://doi.org/10.5281/zenodo.5834221>), Beaumet et al., 2022b (<https://doi.org/10.5281/zenodo.5834376>), Beaumet et al., 2022c (<https://doi.org/10.5281/zenodo.5838345>)

Version 3.14: Castellanos et al., 2025a (<https://doi.org/10.5281/zenodo.17534365>), Castellanos et al., 2025b (<https://doi.org/10.5281/zenodo.17569252>)

1555

The E-OBS temperature dataset was downloaded from Copernicus servers. The APGD precipitation dataset (DOI: 10.18751/Climate/Griddata/APGD/1.0) was also retrieved from

Copernicus servers. The Snow CCI dataset was downloaded at <https://doi.org/10.5285/3f034f4a08854eb59d58e1fa92d207b6> (Naegeli et al., 2022).

1560

Author contributions

MM and JB¹ produced the MAR version 3.10 simulations, IC produced the MAR version 3.14 simulation. HG and XF developed MAR and provided helpful discussion and information on the model. EM-C provided the EC-Earth3 forcing files. MM and JB² contributed to the design and the direction of the study. IC produced the figures and wrote the article, and all authors contributed with suggested changes and helpful comments.

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Competing interests

The authors declare that they have no conflict of interest.

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