

Contrasting processes driving tropical and non-tropical winter warm spells

Corresponding Author: Professor Ming Luo

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Luo,

Your manuscript titled "Contrasting Processes Driving Tropical and Non-tropical Winter Heatwaves" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns. Specifically, a revised manuscript must:

1. Refine the cold season definition for tropical regions and focus on more regional analysis to improve the applicability of the findings.
2. Fully discuss the potential impacts of resolution on results and clarify how heatwaves are counted, particularly regarding event continuity and thresholds.
3. Provide more clarification on how advection and adiabatic heating are calculated, especially with respect to topography.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper shows contrasting mechanisms driving wintertime warm spells between tropical and non-tropical regions, present global distributions of warm spells' indices and their trends.

First of all, in my opinion, the term 'heatwaves', which is used thorough the manuscript is misleading. According to AMS glossary (and other surces), a heat wave is regarded as a period of abnormally and uncomfortably hot (and usually humid) weather. The 'uncomfortably hot' weather is the main feature of a heat wave. By contrast, authors define heat waves based on an exceedance of calendar 90th percentile Tmean values for at least three consecutive days within the cold season (Lines 364–366). The actual temperature during these events is far from the uncomfortably hot conditions in the large majority of worlds regions. Although off-season heat waves certainly occur as I vividly remember especially the untypical April 2023 heat wave in Spain (38.8°C in Córdoba), events defined in this manuscript should not be labelled as heat waves. I recommend using, for example, the term 'warm spells' (e.g. <https://climate.copernicus.eu/esotc/2020/heatwaves-and-warm-spells-during-2020>).

The use of the same definition to analyse warms spells worldwide is definitely challenging. Authors determine cold season as a coldest consecutive three-month period. This definition is straightforward and correct over the mid-latitudes and polar regions but it does not make much sense in the tropics, where temperature-based seasons are not defined and winter does not occur. Due to an absence of temperature-based season, diabatic drivers of winter warm spells in the tropics identified in this manuscript are analogous to their 'summertime equivalent' in Röthlisberger and Papritz (2023; <https://doi.org/10.1038/s41561-023-01126-1>) and therefore I cannot consider this finding as novel, which is a key criterion for this journal.

Authors highlight the contrast between tropical warms spells driven by excessive shortwave downwelling radiation (SWD) and non-tropical warms spells driven by downwelling longwave radiation (LWD). The absence of the SWD component during non-tropical wintertime warm spells is not surprising because it is given be astronomical factors – high solar zenith angles or even a presence of the polar night in winter. These factor are not mentioned or discussed in the manuscript. As authors define wintertime warm spells based on daily mean temperatures, cloudy skies prevent substantial night-time

cooling and thus contributes to positive temperature anomalies through LWD. In my opinion, this process is more important compared to discussed 'blocking of sunlight' (Lines 210–212).

Generally, I found the presented decomposition of temperature anomalies interesting and I acknowledge the effort the authors put in this process but I am afraid that the claims are not very convincing as they are based on questionable foundations – mainly problematic definition of winter season and individual events due to a usage of the global domain. In future submissions, I recommend focusing on more regional analyses (e.g. individual climatic zones).

Because I support a transparent review process, I sign this comments.

Ondrej Lhotka,
The Czech Academy of Sciences, Institute of Atmospheric Physics

Reviewer #2 (Remarks to the Author):

This manuscript provides a global assessment of winter heatwaves from 1979 to 2023 based on ERA5 reanalysis data, investigating their frequency, duration, and intensity. It offers new insights into the mechanisms and drivers behind these off-season temperature events, which are indeed much less studied than summer heatwaves but with potentially significant societal and ecological impacts as pointed out by the author. A key focus is given to contrasting physical processes in tropical versus non-tropical regions, a classical approach of decomposing the temperature anomalies into advection, adiabatic warming, and diabatic heating. The authors further explore other atmospheric variables such as cloud cover, relative humidity and its mean day-to-day evolution, to provide a comprehensive view of these winter heatwaves, with summarizing schematics to understand the mean mechanism of winter heatwaves over tropical and non-tropical regions. I believe the manuscript is timely with the emerging need to understand the impacts of a warming climate on winter temperature distribution.

While I don't feel fully equipped to critically examine the details of the methodology used, I hope other experts in those can provide further insights. Nonetheless, the core result of the paper is convincing and will be of great interest to the community. I recommend the paper for publication with some minor revisions and explanations.

However, a few points that could be clarified or expanded to improve the paper.

My first concern is regarding the resolution used (2.5°). While it is understandable that a global study can be computationally expensive at finer resolutions, conducting a short test at higher resolution for a smaller domain could help confirm the robustness of the results or at least discussing the potential impact of resolution would be valuable.

There were a few sections that were unclear to me. Please see my suggestions below for improvement:

The negative trend in mean and maximum intensity can seem counterintuitive given that many parts of the world are experiencing overall winter warming (such as in Europe: <https://climate.copernicus.eu/boreal-winter-season-1920-was-far-warmest-winter-season-ever-recorded-europe-0>). An additional explanation or analysis could help to show if this decrease is in fact due to more frequent and prolonged heatwave days (the commented inverse proportionality).

In the methods section (line 366), the authors identify winter as the coldest consecutive three-month period, since the text only briefly states that, Is it the standard winter months DJF for the Northern Hemisphere and JJA for the Southern Hemisphere? It would help to clarify.

In methods, several heatwave metrics are calculated per year. The description of how events are counted (frequency) could be clearer. For instance, how many days below the threshold are allowed before a new event starts? For example, if a temperature anomaly goes below the 90th percentile threshold for just one day within a generally continuous warm period, are they classified as two separate events or one continuous heatwave?

Lines ~407–414 mention that advection and adiabatic heating are calculated at one chosen pressure level based on surface pressure (950, 850, 750, or 650 hPa). Although the reasoning for this might be unfamiliar to some readers. A short explanation or reference to how this method accounts for topography and whether it might miss certain vertical structures in mountainous regions would provide helpful transparency. (For myself and the readers)

Finally, it might strengthen the discussion to briefly touch on how winter and summer heatwaves differ or are similar, (Such as the role of subsidence having more influence in summer heatwaves)

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Version 1:

Decision Letter:

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Dear Professor Luo,

Your revised manuscript titled "Contrasting Processes Driving Tropical and Non-tropical Winter Warm Spells" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewer 2. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for incorporating my comments and suggestions into the manuscript. I have no objections to publishing the manuscript but I will leave the final decision to the editor who can better assess the novelty of your findings in the context of the COMMSERV journal.

O. Lhotka

Reviewer #2 (Remarks to the Author):

Revision-2

The revisions from the authors were thorough and appropriate. In its current shape, this paper adds valuable insight into the winter warm spell for different global regions.

Including results based on a higher-resolution dataset makes the findings robust.

It is interesting to see the contribution from different physical processes for different regions from Reviewer 1's comment: Fig. S1. I would also recommend adding this figure to the main article, but this is up to the authors.

I have a couple of minor comments and suggestions, which should not require substantial revisions:

1) Trend maps by climate zones (related to Fig. 2):

The time series analysis in Figure 2 shows clear increasing trends in warm spell metrics at the global scale. I am curious if this is consistent with all the different climate zones (e.g. tropics, mid-latitudes, polar regions). Verifying this would confirm if the global trend is representative of all regions or if some zones exhibit a different trend from the global behaviour. If so, it would be useful to comment on it.

Tabulate the quantities of contributing physical processes:

In the section titled: The information and values are dispersed. Summarising these values into a table would improve clarity and allow readers to more easily compare the relative importance of each process for regions.

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Responses to Review Comments

Dear Editor,

We thank you and both reviewers very much for their careful review and valuable comments. We have addressed each of the comments carefully and revised the manuscript accordingly. Below please find our response to each review comment. Please note that the reviewer's remarks are in black, **our response** is highlighted in blue, and **extracts from the manuscript** are in red, with **new texts that have been added/edited** marked in bold. We hope that you and both reviewers find our responses and revised manuscript satisfactory. Thank you very much.

Kind regards,

Ming Luo, on behalf of all co-authors

A summary of the revision:

1. Refined definition of the cold season and enhanced regional analysis: We have replaced the term “heatwaves” with “warm spells” throughout the manuscript suggested by Reviewer #1. The definition of the cold season has been clarified, with clear explanations provided for tropical regions. We have also included an additional analysis by focusing on the regional decomposition of temperature anomalies within specific climate zones. This additional examination improves the understanding of the regional variations in warm spell mechanisms and enhance the applicability of our findings.

2. Incorporation of higher resolution analysis and event identifying clarification:

To address concerns about the potential impacts of resolution on our results, we have conducted an additional analysis using the ERA5 reanalysis dataset with a higher spatial resolution of $1^{\circ}\times 1^{\circ}$. The results show that the observed climatology and long-term changes of global winter warm spells at the $1^{\circ}\times 1^{\circ}$ resolution during 1979–2023 remains consistent with our previous results at the $2.5^{\circ}\times 2.5^{\circ}$ resolution. This additional analysis demonstrates the soundness and robustness of our findings of increasing and longer-lasting winter warm spells. Additionally, we have provided a detailed explanation of the criteria used for identifying warm spell events, including event continuity and threshold considerations.

3. Detailed explanation of advection and adiabatic heating calculations : We have

carefully explained the calculation of advection and adiabatic heating terms. The selection of pressure levels (i.e., 950 hPa, 850 hPa, 750 hPa, and 650 hPa) in our study is based on the surface pressure distribution during warm spell days and the influence of topography. This approach ensures that the advection and adiabatic heating calculations are representative of the lower (near the true topography surface) to mid-troposphere.

Reviewer #1 (Remarks to the Author):

The paper shows contrasting mechanisms driving wintertime warm spells between tropical and non-tropical regions, present global distributions of warm spells' indices and their trends.

1. First of all, in my opinion, the term 'heatwaves', which is used thorough the manuscript is misleading. According to AMS glossary (and other sources), a heat wave is regarded as a period of abnormally and uncomfortably hot (and usually humid) weather. The 'uncomfortably hot' weather is the main feature of a heat wave. By contrast, authors define heat waves based on an exceedance of calendar 90th percentile T_{mean} values for at least three consecutive days within the cold season (Lines 364–366). The actual temperature during these events is far from the uncomfortably hot conditions in the large majority of worlds regions. Although off-season heat waves certainly occur as I vividly remember especially the untypical April 2023 heat wave in Spain (38.8°C in Córdoba), events defined in this manuscript should not be labelled as heat waves. I recommend using, for example, the term 'warm spells' (e.g. <https://climate.copernicus.eu/esotc/2020/heatwaves-and-warm-spells-during-2020>).

Response:

Thank you for pointing out this. Following your suggestion, we have replaced the term “heatwaves” with “warm spells” throughout the manuscript. For example, in Lines 392–394 of the Methods section, we have revised the definition: “A winter **warm spell event is defined when daily T_{mean} exceeds its corresponding calendar 90th percentile values for at least three consecutive days^{41,64} within the cold season (Supplementary Fig. 7).**”

2. The use of the same definition to analyse warms spells worldwide is definitely challenging. Authors determine cold season as a coldest consecutive three-month

period. This definition is straightforward and correct over the mid-latitudes and polar regions but it does not make much sense in the tropics, where temperature-based seasons are not defined and winter does not occur. Due to an absence of temperature-based season, diabatic drivers of winter warm spells in the tropics identified in this manuscript are analogous to their ‘summertime equivalent’ in Röthlisberger and Papritz (2023; <https://doi.org/10.1038/s41561-023-01126-1>) and therefore I cannot consider this finding as novel, which is a key criterion for this journal.

Response:

Thank you very much for this comment. We appreciate your recognition that our definition of the cold season—as the coldest consecutive three-month period—is clear and appropriate for mid-latitudes and polar regions. We note that, although the seasonal temperature variations are relatively smaller in the tropics, our definition of the cold season can adaptively identify the coldest period relative to local climatology. This definition allows us to capture anomalous warm spell events in all regions worldwide, and enables a consistent comparison between tropical and non-tropical regions. Similar definition has also been used in previous studies (Hao et al., 2018; Liu et al., 2021; Nishant et al., 2019; Zscheischler et al., 2017).

We also thank you for introducing the research of Röthlisberger et al. (2023). We have carefully read this paper and notice that this study quantifies the physical processes leading to summer heatwaves by evaluating the contributions of advection, adiabatic warming, and diabatic heating to temperature anomalies during the hottest days of each year. Different from Röthlisberger et al. (2023), our research focuses on a distinct and unexplored phenomenon—warm spells in cold seasons where hot weather is typically known to not occur. These off-season events can challenge ecosystems and societies by triggering snowmelt-induced flooding and favoring wildfires, etc. (Administration, 2020; Mark, 2021), but are yet to be understood. In our current study, we have analyzed the behaviors and drivers of these off-season events globally, by revealing how advection, adiabatic warming, and diabatic heating drive temperature anomalies during winter warm spells. We have further decomposed diabatic heating into net shortwave radiation, downward longwave radiation, latent heat flux, sensible heat flux, and ground

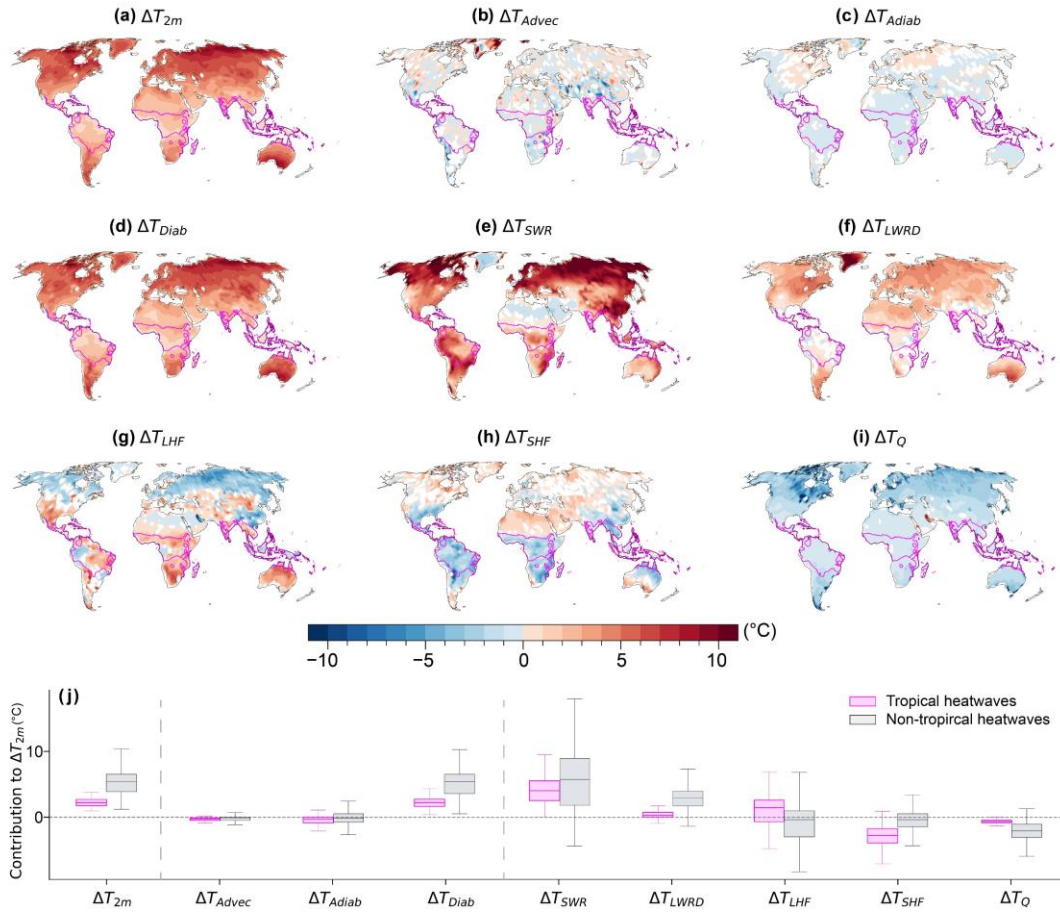
105 heat flux. Our results find that net shortwave and longwave radiations induced diabatic
106 heating predominantly contributes to temperature anomalies during winter warm spells,
107 but their contributions exhibit contrasts between tropics and non-tropics. This
108 distinction has not been reported in the literature, and it provides a novel perspective
109 on how regional climatic conditions modulate off-season extreme events. Additionally,
110 our study reveals that the frequency and duration of these off-season warm spells have
111 increased significantly during the period from 1979 to 2023. These increases highlight
112 the growing urgency to understand and address the impacts of intensifying warm spells,
113 as they occur outside the typical warm seasons and can disrupt natural and human
114 systems.

115 In this revision, we have extended our analysis by comparing the underlying
116 mechanisms of winter cold-season warm spells (Figs. 3–4 in the main text) and summer
117 hot-season heatwaves (Response Figs. R1–R2). Both winter warm spells and summer
118 heatwaves are accompanied by positive temperature anomalies predominantly driven
119 by net shortwave and longwave radiations induced diabatic heating (Fig.3 in the main
120 text and Response Fig. R1). However, the specific mechanisms and their relative
121 contributions differ significantly between the two types of events. During winter warm
122 spells, particularly in non-tropical regions, enhanced downwelling longwave radiation
123 under cloudier and wetter conditions plays a dominant role. In contrast, summer
124 heatwaves are more primarily induced by increased solar radiation, accompanied by
125 decreased cloud cover, dried soils and atmosphere in both tropical and non-tropical
126 regions, except for northern Africa, Greenland, and Saudi Arabia (Response Fig. R2).
127 The mechanisms associated with summer heatwaves are in line with Lhotka et al.
128 (2024), who reported that soil moisture is crucial for summer heatwave events,
129 particularly for near-surface atmospheric heatwaves.

130 In Lines 332–352 of the revised manuscript, we have included discussions of the
131 difference between winter warm spells and summer heatwaves: “**Contrasting physical**
132 **processes driving winter warm spells in tropical and non-tropical regions are**
133 **conceptualized in Fig. 6. Diabatic heating emerges as a dominant factor contributing to**
134 **positive temperature anomalies during winter warm spells across most global land**

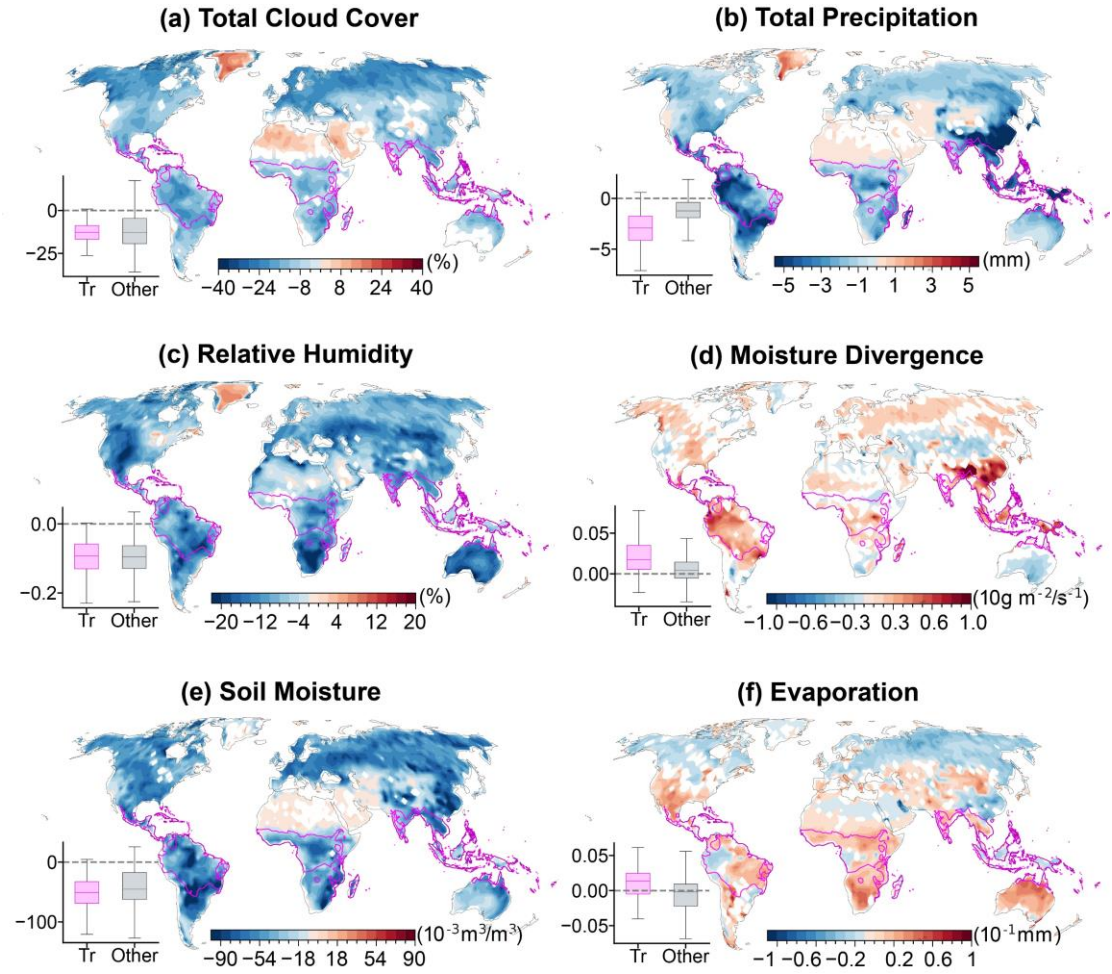
135 areas, with substantial contributions from net shortwave and downwelling longwave
136 radiations. The contributions of these processes are region-dependent, and exhibit
137 contrasting differences between the tropics and non-tropics. In the tropics, **surface**
138 **warming during winter warm spells is mainly attributed to increased clear-sky**
139 **incoming** solar radiation, accompanied by drying soil and atmosphere. By contrast,
140 non-tropical winter **warm spells** are primarily driven by increased downwelling
141 longwave radiation and sensible heat flux under a cloudier and wetter environment.

142 **We note that compared with winter warm spells, the distinction between**
143 **tropical and non-tropical mechanisms is much less pronounced in summer**
144 **heatwaves (Supplementary Figs. 3–4). During summer heatwaves, both tropical**
145 **and non-tropical regions experience amplification of diabatic heating, which is**
146 **generally driven by intensified solar radiation due to reduced cloud cover, along**
147 **with widespread soil and atmospheric drying—mechanisms well documented in**
148 **Röthlisberger and Papritz ⁵⁸. This finding is in line with Lhotka and Kysely ⁵⁹, who**
149 **reported that soil moisture is crucial for summer heatwave events, particularly for**
150 **near-surface atmospheric heatwaves. In contrast to winter warm spells, the role of**
151 **longwave radiation in summer heatwaves is relatively weak.”**



Response Fig. R1 (see also in Fig. S3 in the revised Supplementary Information). Decomposition of temperature anomalies during summer heatwaves. a, Temperature anomalies of summer heatwaves over global land areas during 1979–2023. **b–d,** The decomposition of temperature anomalies into the contributions of advection heating (b), adiabatic heating (c), diabatic heating (d). **e–g,** The decomposition of diabatic heating term into the contributions of net surface shortwave radiation (e), surface downward longwave radiation (f), surface latent heat flux (g), surface sensible heat flux (h), and ground heat flux (i). Regions with the composite mean not passing the 0.1 significance level by the Student's *t*-test are masked out. **j,** Boxplot showing the regional mean of the temperature anomalies and its decomposition into the contribution of different heating terms to summer heatwaves in the tropics (pink bar) and non-tropics (grey bar). The centerline indicates the median value, the box bounds depict the 25th and 75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5

times the interquartile range of the decomposition of temperature anomalies.



Response Fig. R2 (see also in Fig. S4 in the revised Supplementary Information). **Composite anomalies of key variables associated with summer heatwaves.** a–f, The composite mean anomalies of total cloud cover (a), total precipitation (b), relative humidity (c), moisture divergence (d), soil moisture (e), and evaporation (f) associated with summer heatwaves. Regions with the composite mean not passing the 0.1 significance level by the Student's *t*-test are masked out. The embedded boxplot chart shows the regional mean of the anomalies of corresponding variables associated with heatwaves in the tropics (pink bar) and non-tropics (grey bar). The centerline indicates the median value, the box bounds depict the 25th and 75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5 times the interquartile range of the composite mean anomalies.

3. Authors highlight the contrast between tropical warm spells driven by excessive shortwave downwelling radiation (SWD) and non-tropical warm spells driven by downwelling longwave radiation (LWD). The absence of the SWD component during

non-tropical wintertime warm spells is not surprising because it is given by astronomical factors – high solar zenith angles or even a presence of the polar night in winter. These factors are not mentioned or discussed in the manuscript. As authors define wintertime warm spells based on daily mean temperatures, cloudy skies prevent substantial night-time cooling and thus contribute to positive temperature anomalies through LWD. In my opinion, this process is more important compared to discussed ‘blocking of sunlight’ (Lines 210–212).

Response:

Thank you very much for reminding us the roles of astronomical factors. We agree with you that the absence of net shortwave radiation during non-tropical winter warm spells is largely due to astronomical factors such as high solar zenith angles and the polar night, and the process of increased cloud cover preventing nighttime cooling and enhancing downwelling longwave radiation is more important than the blocking of sunlight.

Following your suggestion, we have revised the manuscript accordingly by including the possible role of astronomical factors (Lines 221–230): “In the tropics, reduced cloud cover during warm spells allows more solar radiation to reach the surface, directly intensifying surface heating. In contrast, non-tropical warm spells are associated with decreased solar radiation, which is largely due to high solar zenith angles in the cold season and even a presence of the polar night in high-latitudes (e.g., polar regions). Over these non-tropical regions, increased cloud cover further reduces incoming solar radiation at the surface. Simultaneously, cloudier skies reduce nighttime cooling by trapping more atmospheric heat, thus enhancing downward longwave radiation⁵⁰. The added heat from increased downward longwave radiation in non-tropical regions helps elevate surface warming despite reductions in direct solar radiation (recall Fig. 3f).”

4. Generally, I found the presented decomposition of temperature anomalies interesting and I acknowledge the effort the authors put in this process but I am afraid that the

claims are not very convincing as they are based on questionable foundations – mainly problematic definition of winter season and individual events due to a usage of the global domain. In future submissions, I recommend focusing on more regional analyses (e.g. individual climatic zones).

Response:

Thank you for your comment and concern about the definition of cold season and individual events in a global domain. As responded to your comment #2, our definition of the cold season (i.e., the coldest three months of the year) aligns with previous studies (Hao et al., 2018; Liu et al., 2021; Nishant et al., 2019; Zscheischler et al., 2017), and this definition can adaptively identify the coldest period relative to local climatology, thus allowing us to capture anomalous warm spell events in all regions worldwide and enabling a consistent comparison between tropical and non-tropical regions. Also, we would like to clarify that our study focuses on the local mechanisms associated with winter warm spells at the grid-point level across the global land areas. This grid-based approach allows us to capture regional variability of these events and provides a comprehensive view of the physical processes driving temperature anomalies during winter warm spells across different climate zones.

Following your suggestion of more regional analyses, we have included an additional analysis by focusing on the decomposition of temperature anomalies within specific climate zones (Response Fig. R3). As shown in Response Fig. R3a, the temperature anomalies are consistently positive during winter warm spells in all climate zones, with a predominant contribution from diabatic heating. However, this contribution varies significantly across different climate regions. In polar and cold zones, diabatic heating contributes largely to positive temperature anomalies during winter warm spells, whereas the contribution of diabatic heating is relatively weaker in the arid and temperate zones. In contrast, in the tropical zone, the contributions of both diabatic and adiabatic heating to temperature anomalies are weaker than other climate zones.

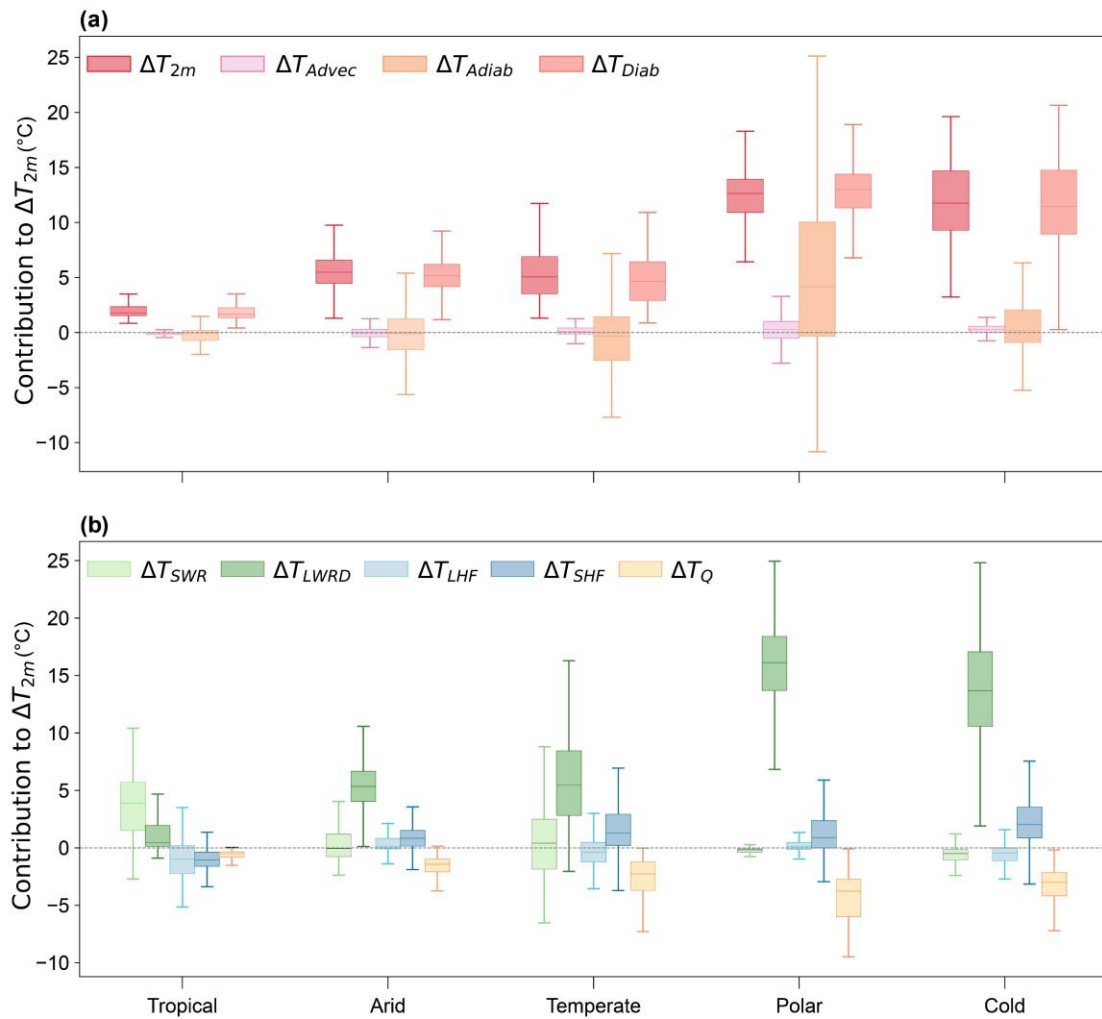
We have further decomposed the diabatic heating term into net shortwave radiation, downward longwave radiation, latent heat flux, sensible heat flux, and ground heat flux

in specific climate zones (Response Fig. R3b). It is noted that downward longwave radiation plays a predominant role in elevating temperatures during winter warm spells in most climate zones, particularly in polar and cold zones (except the tropics). In these regions, high solar zenith angles in the cold season largely reduce solar radiation, and a presence of the polar night can even cause the absence of solar radiation in high-latitudes, which contributes marginally to the temperature increases in polar and cold zones (Response Fig. R3b). Increased cloud cover further reduces incoming solar radiation at the surface, and moisture convergence (i.e., negative divergence) creates a more humid atmosphere (See Fig.4 in the main text). Simultaneously, cloudier and wetter skies reduce nighttime cooling by trapping more atmospheric heat, which enhances downward longwave radiation (Christy et al., 2006), thus increasing air temperatures near the surface (Wu et al., 2023). In comparison, solar radiation plays a larger role in temperature increases in the tropical, arid, and temperate zones, where the role of cloud cover is less significant. Sensible heat flux is generally a warming factor across all climate zones except the tropical zone, while latent heat flux has a notable warming effect in arid and polar zones. Ground heat flux typically has a cooling effect on winter warm spells in all climate zones, with the strongest cooling effect observed in polar regions.

In Lines 166–181 of the current revision, we have added the follow description of regional analyses: “In the non-tropics, winter **warm spells** experience considerable warming partially due to the advection of warm air masses from the tropics to mid-to-high latitudes (0.122 °C), which was also observed during the Antarctic **warm spell** of March 2022⁴⁵. **Across different non-tropical regions, the contribution of advection heating varies significantly. Specifically, advection heating contributes positively to temperature anomalies in cold (+0.281°C), temperate (+0.120 °C), and polar zones (+0.056 °C), whereas it has a negative contribution to warm spells in arid zones (-0.058 °C) (Supplementary Fig. 1a).** Adiabatic heating, resulting from the compression and warming of descending air masses, is also a key contributor to temperature anomalies in high-latitude and high-altitude regions (Fig. 3c), which is consistent with the findings of Kim, et al.³⁶. **The contribution of adiabatic heating is**

275 **particularly pronounced in polar (+5.984 °C) and cold zones (+1.236 °C), for**
276 **instance, in regions** including Greenland, the west coasts of North America, and
277 elevated terrains including the Rocky Mountains, Tibetan Plateau, and Andes, where
278 sinking air masses warm significantly, thereby amplifying temperature increases.”

279 In Lines 192–211 of the current revision, we have also added the follow description
280 of regional analyses: “We notice that the contributions of surface heating are contrasting
281 between tropical and non-tropical regions. Net shortwave radiation plays a dominant
282 role in elevating temperatures (+3.424 °C) during winter **warm spells** in the tropics
283 (Fig. 3e), whereas it generally exerts a cooling effect in non-tropics except for
284 southwestern North America and parts of western and southern Eurasia. **This cooling**
285 **effect is particularly pronounced in polar (-0.211 °C) and cold zones (-0.365 °C).**
286 Downwelling longwave radiation predominantly drives increases in temperature in
287 non-tropical regions (+10.263 °C), particularly in polar zone (+15.794 °C) (Fig. 3f and
288 **Supplementary Fig. 1b**), aligning with previous studies⁴⁷. By contrast, the contribution
289 of downward longwave radiation to temperature anomalies during tropical winter
290 **warm spells** is relatively weaker (1.246 °C). Latent and sensible heat flux anomalies
291 (Fig. 3g and 3h) also play roles in modulating temperature changes. Both latent and
292 sensible heat fluxes generally have cooling effects in tropical regions (-1.029 °C and -
293 1.037 °C), while the latter contributes significantly to **warming in non-tropics**
294 **(+1.696 °C), especially in the cold zone (+2.437 °C).** Ground heat flux typically has a
295 cooling effect on winter warm spells in all climate zones (Fig. 3i), **with the strongest**
296 **cooling effect observed in polar regions (Supplementary Fig. 1b).** Overall, the
297 temperature anomalies during winter **warm spells** in the tropics are primarily driven by
298 net solar radiation, while regions outside the tropics experience stronger contributions
299 from downwelling longwave radiation (Fig. 3j).”



Response Fig. R3 (see also in Fig. S1 in the revised Supplementary Information). Decomposition of temperature anomalies during winter warm spells across different climate zones. Boxplot showing the regional mean of the temperature anomalies and its decomposition into the contribution of different heating terms to winter warm spells in the global land areas and different climate zones. The centerline indicates the median value, the box bounds depict the 25th and 75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5 times the interquartile range of the decomposition of temperature anomalies.

Because I support a transparent review process, I sign this comments.

Ondrej Lhotka,

The Czech Academy of Sciences, Institute of Atmospheric Physics

Reviewer #2 (Remarks to the Author):

This manuscript provides a global assessment of winter heatwaves from 1979 to 2023 based on ERA5 reanalysis data, investigating their frequency, duration, and intensity. It offers new insights into the mechanisms and drivers behind these off-season temperature events, which are indeed much less studied than summer heatwaves but with potentially significant societal and ecological impacts as pointed out by the author. A key focus is given to contrasting physical processes in tropical versus non-tropical regions, a classical approach of decomposing the temperature anomalies into advection, adiabatic warming, and diabatic heating. The authors further explore other atmospheric variables such as cloud cover, relative humidity and its mean day-to-day evolution, to provide a comprehensive view of these winter heatwaves, with summarizing schematics to understand the mean mechanism of winter heatwaves over tropical and non-tropical regions. I believe the manuscript is timely with the emerging need to understand the impacts of a warming climate on winter temperature distribution.

While I don't feel fully equipped to critically examine the details of the methodology used, I hope other experts in those can provide further insights. Nonetheless, the core result of the paper is convincing and will be of great interest to the community. I recommend the paper for publication with some minor revisions and explanations.

However, a few points that could be clarified or expanded to improve the paper.

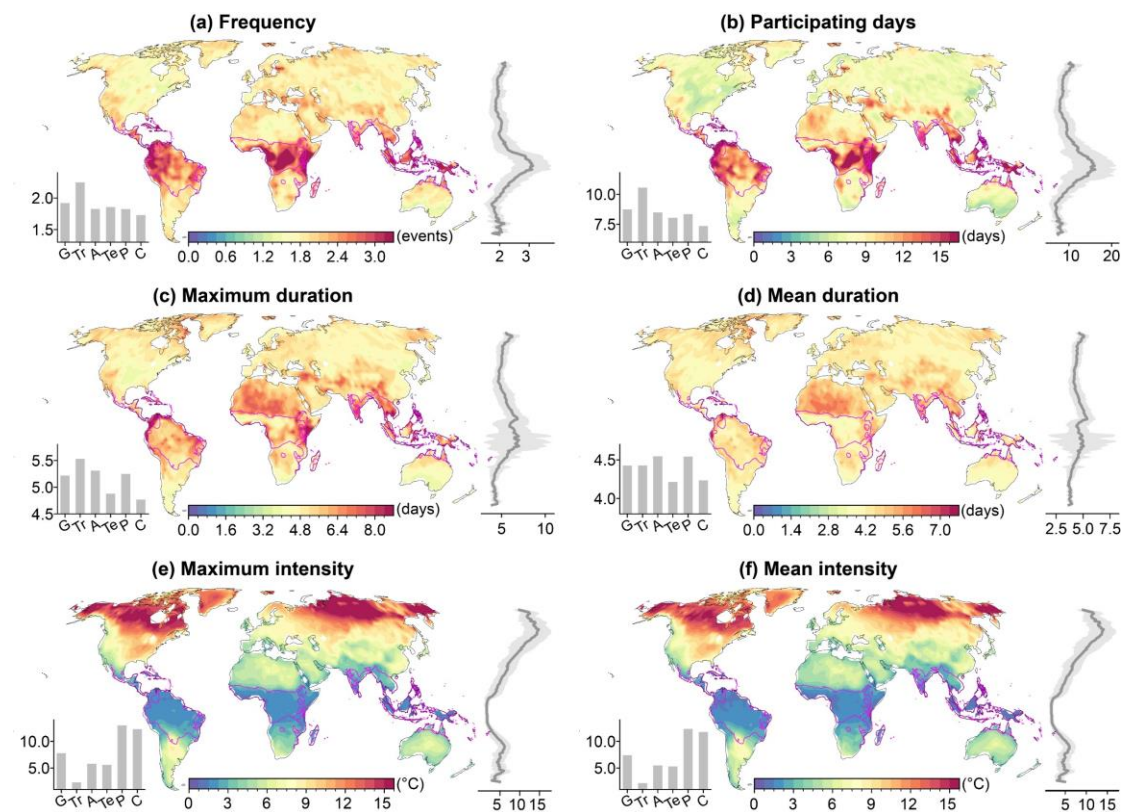
Response: We gratefully appreciate for your positive comment and valuable suggestions. We have accordingly revised our manuscript and prepared a list of point-to-point responses.

1. My first concern is regarding the resolution used (2.5°). While it is understandable that a global study can be computationally expensive at finer resolutions, conducting a short test at higher resolution for a smaller domain could help confirm the robustness of the results or at least discussing the potential impact of resolution would be valuable.

Response:

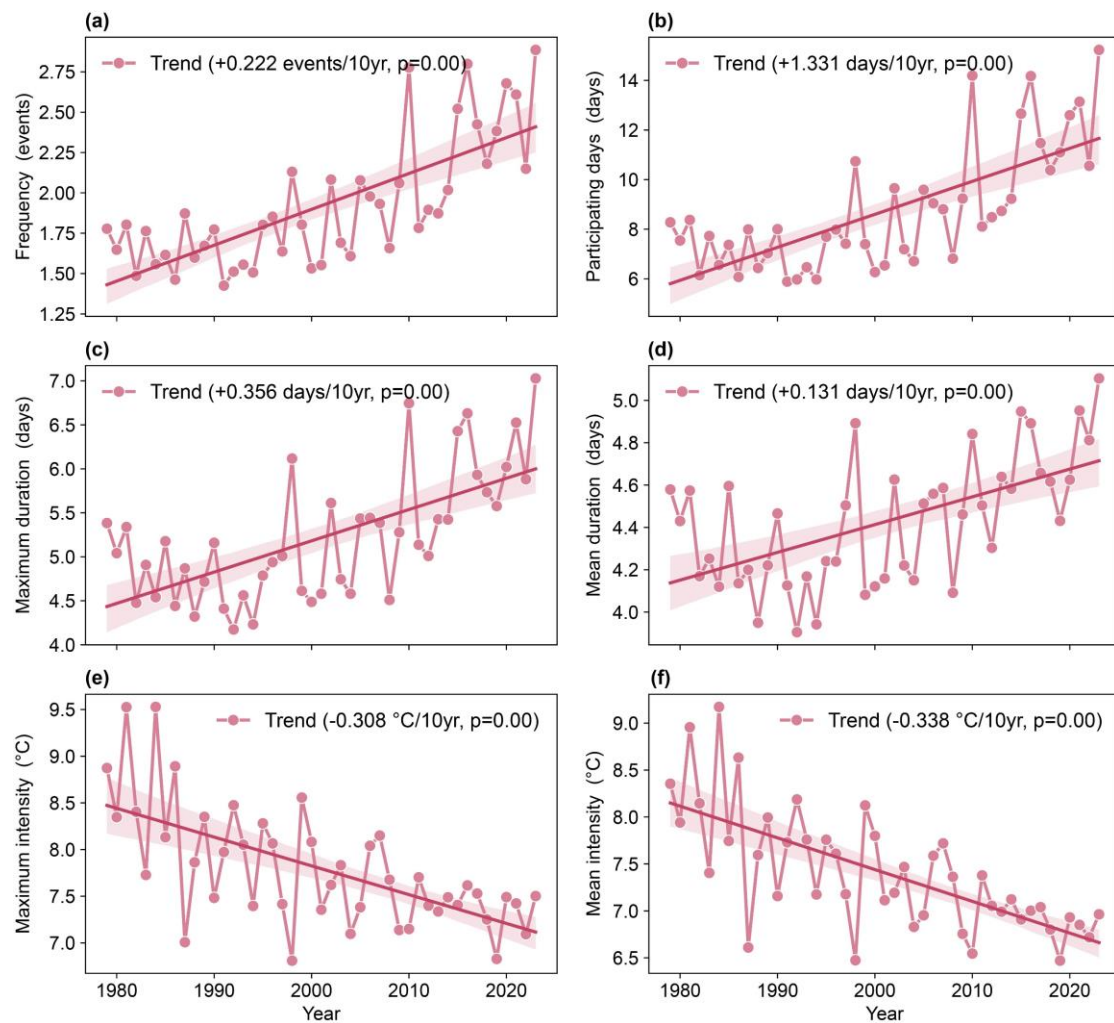
Thank you very much for your suggestion. In the current revision, by following your suggestion we have conducted an additionally analysis using dataset with a higher spatial resolution of $1^\circ \times 1^\circ$. As shown in Response Figs. R4–R5 below, the observed climatology and long-term changes of global winter warm spells at the $1^\circ \times 1^\circ$ resolution during 1979–2023 remains consistent with our previous results at the $2.5^\circ \times 2.5^\circ$ resolution, although the magnitude of some features slightly differs between the two resolutions (compare Response Figs. R4–R5 and Figs. 1–2 in the main text). These additional analyses suggest that the higher spatial resolution do not alter the main conclusions.

In Lines 387–389 and Supplementary Figs. S5 and S6, we have included the results based on the ERA5 dataset at the $1^\circ \times 1^\circ$ resolution to demonstrate the robustness of our results: **“We note that using different spatial resolutions (e.g., $1^\circ \times 1^\circ$ and $2.5^\circ \times 2.5^\circ$) yield a consistent result of the climatological patterns and long-term trends (Supplementary Figs. 5–6).”**



Response Fig. R4 (see also in Fig. S5 in the revised Supplementary Information). Observed climatology of global winter warm spells at the $1^\circ \times 1^\circ$ resolution. a–f,

Maps showing the climatological mean of annual mean frequency (a), participating days (b), maximum duration (c), mean duration (d), maximum intensity (e), and mean intensity (f) of winter warm spells over global land areas during 1979–2023. The embedded bar chart shows the climatology of the corresponding characteristics in different climate zones (G: global, A: arid zone, Te: temperate zone, Tr: tropical zone, P: polar zone, and C: cold zone). The latitudinal curves accompanying the maps show the zonal means of the climatology of the corresponding characteristics, and the shading indicates the spread of zonal mean values (mean $\pm$ s.d.).



Response Fig. R5 (see also in Fig. S6 in the revised Supplementary Information). Long-term changes of global warm spells at the $1^{\circ}\times 1^{\circ}$ resolution. a–f, Time series of the spatially-averaged annual mean of frequency (a), participating days (b), maximum duration (c), mean duration (d), maximum intensity (e), and mean intensity (f) of warm spells over global land areas from 1979 to 2023. The straight line indicates the linear trend, and the shading indicates the corresponding 90% confidence interval. Slope and p -value estimates for the trend per decade are given in parentheses.

2. There were a few sections that were unclear to me. Please see my suggestions below for improvement:

The negative trend in mean and maximum intensity can seem counterintuitive given that many parts of the world are experiencing overall winter warming (such as in Europe: <https://climate.copernicus.eu/boreal-winter-season-1920-was-far-warmest-winter-season-ever-recorded-europe-0>). An additional explanation or analysis could help to show if this decrease is in fact due to more frequent and prolonged heatwave days (the commented inverse proportionality).

Response:

Thank you very much for your concern. The negative trend in the intensity, despite overall winter warming, can be explained by the inverse relationship between the intensity and frequency (or duration) of winter warm spells. For each warm spell event, the intensity is defined as mean temperature exceedance relative to the threshold by averaging all days during the event, and the yearly metric of maximum (mean) intensity is derived from the intensities of all events occurring in the same year. In this sense (i.e., the intensity is the sum of temperature exceedance divided by duration of the event), the intensity is inversely proportional to the number of warm spell days. Therefore, as the number of warm spell days increase, a decrease in the intensity can be expected.

In Lines 139–147 of this revision, we have included the following explanations: **“The annual maximum and mean intensity exhibit significant decreasing trends of 0.305 °C and 0.334 °C per decade, respectively (Fig. 2e and 2f). The decrease in the intensity, despite overall winter warming, can be explained by the inverse relationship between warm spell intensity and their frequency (or duration)⁴¹. For each warm spell event, intensity is defined as mean temperature exceedance relative to the threshold by averaging all days during the event, and the annual maximum (mean) intensity is derived from the intensities of all events occurring in the same year. Thus, as the number of warm spell days increases, a decrease in**

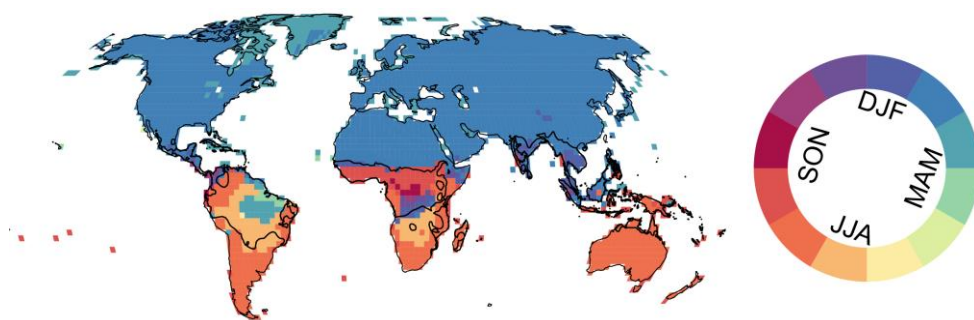
the intensity can be expected.”

3. In the methods section (line 366), the authors identify winter as the coldest consecutive three-month period, since the text only briefly states that, Is it the standard winter months DJF for the Northern Hemisphere and JJA for the Southern Hemisphere? It would help to clarify.

Response:

Thank you for this question. Yes, we define cold season as the coldest consecutive three-month period in each grid cell, and such cold season may not always align with the standard winter months (i.e., December-January-February (DJF) for the Northern Hemisphere and June-July-August (JJA) for the Southern Hemisphere) in certain regions. Specifically, for each calendar month, we first calculate its multi-year climatological mean temperature, then calculate the three-month mean of the local climatology of temperature (i.e., October-November-December [OND], November-December-January [NDJ], December-January-February [DJF], January-February-March [JFM], and so forth). We then determine the three-month period with the lowest temperature as the cold season for each grid cell (Response Fig. R6).

In Lines 392–400 of the Methods section, we have clarified this approach defining the cold season: “A winter **warm spell** event is defined when daily T_{mean} exceeds its corresponding calendar 90th percentile values for at least three consecutive days^{41,64} within the cold season (Supplementary Fig. 7). The **cold season** is determined as the coldest consecutive three-month period in each grid cell. Specifically, for each calendar month, we first calculate its multi-year climatological mean temperature, then calculate the three-month mean of the local climatology of temperature (i.e., October-November-December [OND], November-December-January [NDJ], December-January-February [DJF], January-February-March [JFM], and so forth). We then determine the three-month period with the lowest temperature as the cold season for each grid cell.”



**Response Fig. R6 (see also in Fig. S7 in the revised Supplementary Information).
Spatial distribution of the cold season.**

4. In methods, several heatwave metrics are calculated per year. The description of how events are counted (frequency) could be clearer. For instance, how many days below the threshold are allowed before a new event starts? For example, if a temperature anomaly goes below the 90th percentile threshold for just one day within a generally continuous warm period, are they classified as two separate events or one continuous heatwave?

Response:

Thank you for this concern. In our study, a warm spell event is defined as a period during which the daily mean temperature exceeds its calendar-specific 90th percentile for at least three consecutive days. This definition strictly requires at least three continuous days exceeding the threshold, and we do not merge the events that are separated by one- or two-day gap, which is consistent with many previous climate change studies (Perkins-Kirkpatrick et al., 2020; Rantanen et al., 2024; Wu et al., 2023). Therefore, if there is even a single day within an otherwise prolonged warm period where the temperature falls below the 90th percentile, the continuity is broken, and we treat such condition as two events—given that each event independently satisfies the criterion of the minimum duration of three consecutive days.

In Lines 400–405, we have revised the methods section to clarify this event-counting process: “The calendar-specific percentile is calculated based on a 15-day moving window of daily T_{mean} centered on each calendar day (i.e., seven days before and after) over the reference period of 1981–2010 (i.e., a set of 15 days $\times$ 30 years =

450 days). This definition strictly requires three consecutive days with temperature exceeding the threshold, and we do not merge the events that are separated by one- or two-day gap.”.

5. Lines ~407–414 mention that advection and adiabatic heating are calculated at one chosen pressure level based on surface pressure (950, 850, 750, or 650 hPa). Although the reasoning for this might be unfamiliar to some readers. A short explanation or reference to how this method accounts for topography and whether it might miss certain vertical structures in mountainous regions would provide helpful transparency. (For myself and the readers)

Response:

Thank you very much for your suggestion. The selection of pressure levels (i.e., 950 hPa, 850 hPa, 750 hPa, and 650 hPa) in our study is based on the surface pressure distribution during warm spell days and the influence of topography. Specifically, for the majority of warm spell days (i.e., 82.04%) occurring in lowland areas with surface pressure between 900–1100 hPa, we use the 950 hPa level to represent surface advection heating and adiabatic heating. For regions with surface pressure between 800–900 hPa (11.96%), 700–800 hPa (3.48%), and below 700 hPa (2.52%), we select 850 hPa, 750 hPa, and 650 hPa, respectively. This approach ensures that the advection and adiabatic heating are representative of the lower (near the true topography surface) to mid-troposphere. While this approach accounts for topography, it may not fully resolve vertical structures in complex mountainous regions at local scale. However, given that most warm spell events occur in lowland areas, this approach offers a balance between simplicity and applicability. Future studies should explore more spatially-detailed vertical analyses to address potential limitations in complex terrain.

In Lines 444–452 of the revised manuscript, we have added the reason for selecting these pressure levels to calculate advection and adiabatic heating: “Following the study of Tian, et al. ³⁴, the calculations of advection heating and adiabatic heating are performed at four pressure levels (i.e., 950 hPa, 850 hPa, 750 hPa, and 650 hPa),

covering the lower and mid-troposphere. The selection of pressure level (i.e., p_l) depends on the surface pressure of the location where winter **warm spell** events occur, **which is influenced by topography**. Specifically, for **warm spell days** with surface pressure exceeding 900 hPa (**82.04% of cases**), the 950 hPa level is selected. In cases where surface pressures range from 800–900 hPa (**11.96% of cases**), 700–800 hPa (**3.48% of cases**), and below 700 hPa (**2.52% of cases**), the corresponding pressure levels are set as 850 hPa, 750 hPa, and 650 hPa, respectively.”

6. Finally, it might strengthen the discussion to briefly touch on how winter and summer heatwaves differ or are similar, (Such as the role of subsidence having more influence in summer heatwaves)

Response:

Thank you for this suggestion of strengthening the discussion of the mechanisms of winter cold-season warm spells and summer hot-season heatwaves. In Lines 332–352, we have made the following edits to strengthen the discussion: “Contrasting physical processes driving winter **warm spells** in tropical and non-tropical regions are conceptualized in Fig. 6. Diabatic heating emerges as a dominant factor contributing to positive temperature anomalies during winter **warm spells across** most global land areas, with substantial contributions from net shortwave and downwelling longwave radiations. The contributions of these processes are region-dependent, and exhibit contrasting differences between the tropics and non-tropics. In the tropics, **surface warming during winter warm spells is mainly attributed to increased clear-sky incoming** solar radiation, accompanied by drying soil and atmosphere. By contrast, non-tropical winter **warm spells** are primarily driven by increased downwelling longwave radiation and sensible heat flux under a cloudier and wetter environment.

We note that compared with winter warm spells, the distinction between tropical and non-tropical mechanisms is much less pronounced in summer heatwaves (Supplementary Figs. 3–4). During summer heatwaves, both tropical and non-tropical regions experience amplification of diabatic heating, which is

generally driven by intensified solar radiation due to reduced cloud cover, along with widespread soil and atmospheric drying—mechanisms well documented in Röthlisberger and Papritz⁵⁸. This finding is in line with Lhotka and Kysely⁵⁹, who reported that soil moisture is crucial for summer heatwave events, particularly for near-surface atmospheric heatwaves. In contrast to winter warm spells, the role of longwave radiation in summer heatwaves is relatively weak.”

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570

Responses to Review Comments

Dear Editor,

We thank you and both reviewers very much for their careful review and positive comments on our previously revised manuscript. In the second-round revision, we have addressed each of the comments carefully and revised the manuscript accordingly. Below please find our point-by-point responses to all review comments. Please note that the reviewer's remarks are in black, **our response** is highlighted in blue, and **extracts from the manuscript** are in red, with **new texts that have been added/edited** marked in bold. We hope that you and both reviewers find our responses and revised manuscript satisfactory. Thank you very much.

Kind regards,

Ming Luo, on behalf of all co-authors

17 **Reviewer #1** (Remarks to the Author):

18 Thank you for incorporating my comments and suggestions into the manuscript. I have
19 no objections to publishing the manuscript but I will leave the final decision to the
20 editor who can better assess the novelty of your findings in the context of the
21 COMMSENV journal.

22 *Response:* Thank you very much for your positive comments on how we addressed the
23 comments that you raised in the first round of review.

24

25

Reviewer #2 (Remarks to the Author):

The revisions from the authors were thorough and appropriate. In its current shape, this paper adds valuable insight into the winter warm spell for different global regions.

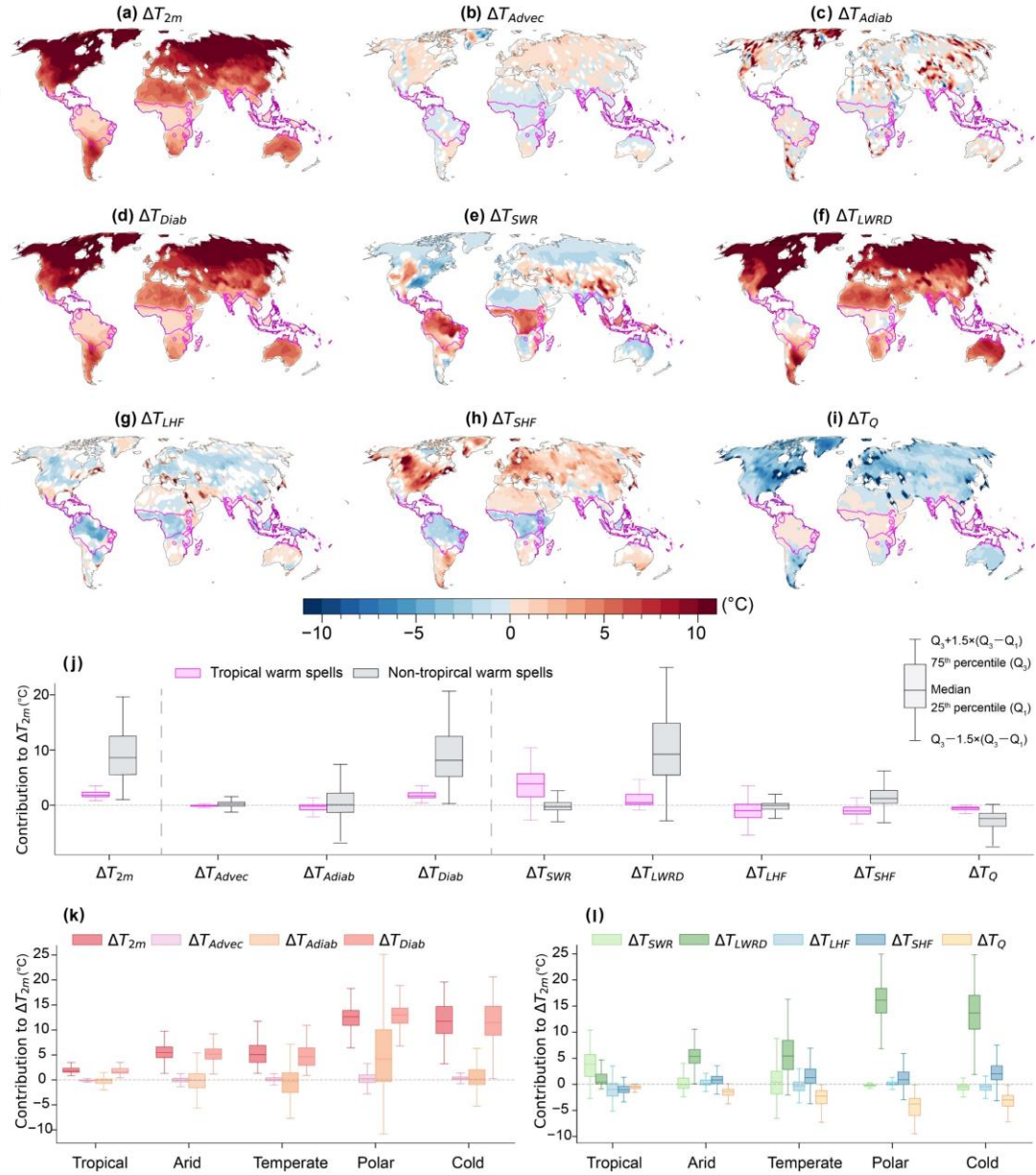
Including results based on a higher-resolution dataset makes the findings robust.

Response: Thank you for your positive comments on how we addressed the comments raised in the first round of review and for your valuable suggestion in this round of review. We have carefully and accordingly revised our manuscript and prepared a list of point-to-point responses.

1. It is interesting to see the contribution from different physical processes for different regions from Reviewer 1's comment: Fig. S1. I would also recommend adding this figure to the main article, but this is up to the authors.

Response:

We greatly appreciate your recognition on our investigation of the contribution from different physical processes for different regions. Per your suggestion, we have incorporated the previously Fig. S1 into the revised main text as Fig.3k – l.



Response Fig. R1 (see also in Fig. 3 in the revised manuscript) Decomposition of temperature anomalies during winter warm spells. **a**, Temperature anomalies of winter warm spells over global land areas during 1979–2023. **b–d**, The decomposition of temperature anomalies into the contributions of advection heating (**b**), adiabatic heating (**c**), diabatic heating (**d**). **e–g**, The decomposition of diabatic heating term into the contributions of net surface shortwave radiation (**e**), surface downward longwave radiation (**f**), surface latent heat flux (**g**), surface sensible heat flux (**h**), and ground heat flux (**i**). Regions with the composite mean not passing the 0.1 significance level by the Student's *t*-test are masked out. **j**, Boxplot showing the regional mean of the temperature anomalies and its decomposition into the contribution of different heating terms to winter warm spells in the tropics (pink bar) and non-tropics (grey bar). **k–l**, Boxplot showing the regional mean of the temperature anomalies and its decomposition into the contribution of different heating terms to winter warm spells across different climate zones. The centerline indicates the median value, the box bounds depict the 25th and

75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5 times the interquartile range of the decomposition of temperature anomalies.

I have a couple of minor comments and suggestions, which should not require substantial revisions:

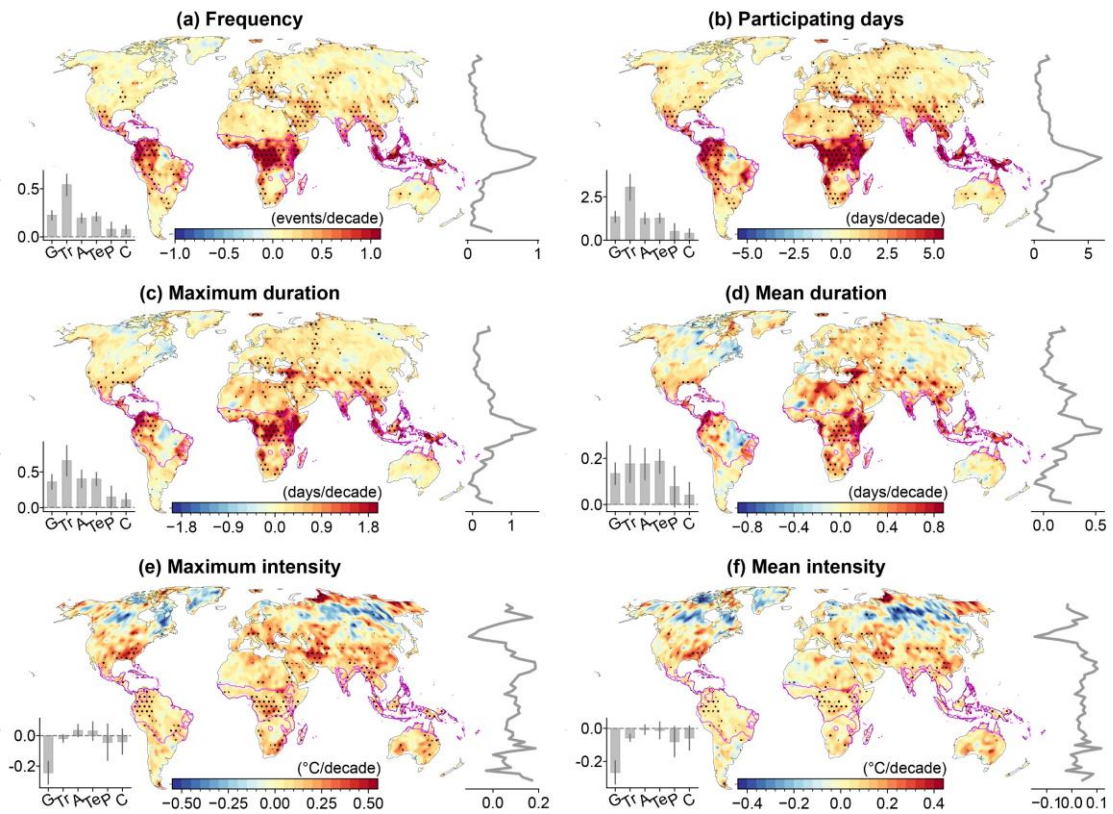
2. Trend maps by climate zones (related to Fig. 2): The time series analysis in Figure 2 shows clear increasing trends in warm spell metrics at the global scale. I am curious if this is consistent with all the different climate zones (e.g. tropics, mid-latitudes, polar regions). Verifying this would confirm if the global trend is representative of all regions or if some zones exhibit a different trend from the global behaviour. If so, it would be useful to comment on it.

Response:

We appreciate your suggestion to examine trends by climate zone. Accordingly, we have added Fig. S1 (see Response Fig. R2 below) in the revised supplementary information to show the spatial distribution of the long-term trends of winter warm spells over global land areas and the magnitude of trends in different climate zones. As the figure shows, all climate zones exhibit increasing trends in the frequency, participating days, maximum duration, and mean duration of winter warm spells. Notably, tropical warm spells exhibit the strongest upward trends in the frequency (0.541 events per decade), participating days (3.056 days per decade), and maximum duration (0.656 days per decade), which are 2.41 times, 2.27 times, 1.82 times the corresponding magnitudes of global mean trends, respectively. The greatest increases in mean duration of warm spells are seen in temperate zone (0.187 days per decade), followed closely by the tropics (0.176 days per decade).

In Lines 135–142 of the current revision, we have also added the follow description of long-term trends in different climate zones: “As shown in Fig. 2, all metrics except for intensity exhibit significant increasing trends at the 0.05 level, indicating a notable intensification of winter warm spell events since the 1980s. Specifically, the global mean annual frequency of winter warm spells has risen by 0.224 events per decade (Fig. 2a), accompanied by an increase in the annual participating days by 1.347 days per

decade (Fig. 2b). The duration of these warm spells has also lengthened, with both maximum and mean durations prolonging by 0.360 and 0.134 days per decade, respectively (Fig. 2c and 2d). These intensifying trends are also seen in all climate zones (Supplementary Figure 1). Notably, tropical warm spells exhibit the strongest upward trends in the frequency (0.541 events per decade), participating days (3.056 days per decade), and maximum duration (0.656 days per decade), which are 2.41 times, 2.27 times, 1.82 times the corresponding magnitudes of global mean trends, respectively. The greatest increases in mean duration of warm spells are seen in temperate zone (0.187 days per decade), followed closely by that in the tropics (0.176 days per decade).”



Response Fig. R2 (see also in Fig. S1 in the revised supplementary information). Spatial distribution of the long-term trends of global winter warm spells. a–f, Maps showing the long-term trends of the frequency (a), participating days (b), maximum duration (c), mean duration (d), maximum intensity (e), and mean intensity (f) of winter warm spells over global land areas during 1979–2023. The embedded bar chart shows the magnitude of the long-term trends of the corresponding characteristics with the black line encompassing its 90% confidence interval in different climate zones (G: global, Tr: tropical zone, A: arid zone, Te: temperate zone, P: polar zone, and C: cold zone). The latitudinal curves accompanying the maps show the zonal means of the

trends of the corresponding characteristics.

3. Tabulate the quantities of contributing physical processes:

In the section titled: The information and values are dispersed. Summarising these values into a table would improve clarity and allow readers to more easily compare the relative importance of each process for regions.

Response:

Following your suggestion, we have summarized the values of the contributions of different heating terms to winter warm spells across globe and different climate zones (see Response Table R1 below) to improve clarity of the relative importance of each process for regions.

Response Table R1 (see also in Table S1 in the revised supplementary information). Contributions of different heating terms to winter warm spells across globe and different climate zones

Contributions	Global	Tropical	Non-tropical	Arid	Temperate	Polar	Cold
Advection heating	0.09	-0.13	0.12	-0.06	0.12	0.06	0.28
Adiabatic heating	1.09	-0.41	1.34	0.19	0.01	5.98	1.24
Diabatic heating	7.80	1.90	8.82	5.29	4.90	12.62	11.72
Net surface shortwave radiation	0.54	3.42	0.05	0.46	0.52	-0.21	-0.37
Surface downward longwave radiation	8.94	1.25	10.26	5.41	5.92	15.79	13.79
Surface latent heat flux	-0.26	-1.03	-0.13	0.37	-0.33	0.10	-0.51
Surface sensible heat flux	1.30	-1.04	1.70	0.90	1.60	1.39	2.44
Ground heat flux	-2.72	-0.70	-3.06	-1.86	-2.81	-4.46	-3.63