Review for

Future Changes in Severe Frontal Precipitation Events over Europe and Their Drivers

by

Schaffer et al.

Summary: In their study, the authors consider heavy and severe frontal precipitation events over Europe, based on CMIP6 and EURO-CORDEX ensembles. To this aim, the precipitation of the simulations is objectively attributed to cold and warm fronts. The future changes in the frontal precipitation is decomposed into frequency changes of frontal systems and thermodynamic/dynamic changes of the frontal circulations and thermodynamic properties. It is claimed that most changes are due to thermodynamic effects, specifically the higher moisture loading in a warming climate and the enhanced horizontal and vertical (atmospheric stability) gradients. Certainly, the topic is of high scientific interest, however the discussion of thermodynamic/dynamic drivers of frontal precipitation seems not convincing enough to me in its present form. Furthermore, I think that a more careful distinction between larger-scale dynamic drivers, e.g., warm-conveyor belts (WCB), and small-scale dynamic drivers, e.g., ageostrophic frontal circulations, would be needed. These deficiencies will be further detailed in the major concerns below. In this sense, some of the statements of the manuscript are, in my opinion, too strong given the too weak support by the analysis presented. Therefore, I cannot recommend the manuscript's publication in its present form but would recommend some major revisions, as outlined below.

Major concerns:

1**) Thermodynamic vs dynamic drivers:** A key statement of the study is that thermodynamic drivers are more important than dynamic drivers. However, the distinction between the thermodynamic and dynamic drivers is not clear-cut, and the authors are not able to make this convincingly clear. In section 2.4, equation 4, the first term in the decomposition is attributed to thermodynamics, and the second one to dynamics (frequency of fronts). Hence, the change in p, as the conditional probability of a front to producing a frontal extreme precipitation event (EPE), is purely attributed to thermodynamics. This, in my view, is misleading as it contains both, thermodynamic and dynamic effects. Thermodynamically, the higher temperature allows for higher moisture loading of the air, which in turn lead to enhanced gradients in humidity (relative and specific) and equivalent -potential temperature across the front. In addition to this moisture effect, the ageostrophic frontal circulation might change because of changed vertical stability profiles and/or because of changed local forcings of the ageostrophic circulation (see, e.g., Sawyer-Eliasson equation to quantify it). This second effect can also have a substantial effect on EPE formation, but I would argue that it is not pure thermodynamics. I think the authors must more carefully discuss what is thermodynamics and what is dynamics, and the should also very clearly distinguish between small-scale changes in the frontal circulation and the large-scale drivers affecting the frequency of fronts (see point 2).

2) Large-scale WCB drivers: At the end of section 3.3., very briefly WCBs are introduced as key synoptic-scale drivers for frontal precipitation variability. I fully agree that WCBs are essential to understand mid-latitude precipitation, but the discussion in L225-232 is not detailed enough to make strong statement about their influence on future EPE. The WCB referred to in 228-229 does not fit the airstream definition that is typically applied: moist air masses ascending from low levels to the upper troposphere within about 1-2 days. In this sense, the discussion about the WCB's influence on EPE in a future, warming climate lacks some depth. Note also that some relevant literature on the WCB/precipitation link and on the changes of WCBs in a warming climate are missing. The following two papers might be a starting point for a more thorough literature review:

> *Joos, H., Sprenger, M., Binder, H., Beyerle, U., and Wernli, H.: Warm conveyor belts in present-day and future climate simulations – Part 1: Climatology and impacts, Weather Clim. Dynam., 4, 133–155, https://doi.org/10.5194/wcd-4-133-2023, 2023.*
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> *Pfahl, S., E. Madonna, M. Boettcher, H. Joos, and H. Wernli, 2014: Warm Conveyor Belts in the ERA-Interim Dataset (1979–2010). Part II: Moisture Origin and Relevance for Precipitation. J. Climate, 27, 27–40, https://doi.org/10.1175/JCLI-D-13-00223.1.*

In short, I think that the authors will have to deepen their analysis on the large-scale drivers for EPE. A few lines (L225-232) is not enough.

3) Quantification of frontal circulation: The study makes rather strong statements about the role of thermodynamic vs. dynamic drivers on EPE, essentially claiming that the changes are 'completely' due to thermodynamics. To make such strong statements, however, I would expect a more quantitative analysis of the frontal circulation (dynamics, not thermodynamics!) in the historic and future climate. Currently, the conclusion is either based on rather indirect arguments (the stability is increasing because of a stronger warming at higher altitudes), or based on diagnostics (mesoscale convergence and vorticity; Figure 6-9) that are also not easily linked to the strength of the frontal circulation. It would be 'cleaner' to quantify this circulation strength by a more direct measure, as, e.g., derived from the Sawyer-Eliasson equation. As a side remark: I wonder whether the patterns in , for example, Figure 6 are affected by cancellation if the average is taken. Specifically, convergent and divergent structures might be nearby along the frontal line, and compensate in the averaging. The authors might want to briefly discuss whether this is potentially the case or not.

4) Indirect (sometimes weak/speculative) statements: At several places I had the impression that the statements drawn based on the analysis are too strong. I will list a few examples here:

*- L211-213: “ highlighting a general increase in static stability. As a consequence, convection within the frontal zone could be dampened, reducing the potential for heavy and extreme precipitation.” Yes, in the mean the static stability is somewhat increased, but I think to link this *directly* to the intensity of convection at the frontal zone is challenging, at least. There are many other factors that determine the intensity (and triggering) of convection!*

- L246 & L252: “Our analysis shows that the strong increase in frontal EPEs is primarily driven by thermodynamic changes.” & “These results identify thermodynamic mechanisms as the primary driver of future increases in the frequency of severe frontal precipitation events.” This is a very strong statement, but it remains somewhat unclear what exactly ‘thermodynamic forcing’ includes, and whether it is really only thermodynamic’.

-L271: “In conclusion, our results underscore the importance of thermodynamic amplification in shaping future frontal precipitation.” The term ‘thermodynamic amplification’ is not clearly defined.

- L268-269: “Larger-scale air streams, like the warm conveyor belt, remain stable, suggesting that the observed intensification of frontal precipitation is primarily thermodynamically driven rather than dynamically forced” What does ‘remain stable’ exactly mean? Does it refer to the frequency of these airstreams, or does it mean that the ‘internal structure’ of this weather feature remains the same in a warming climate? Note also the afore-mentioned literature that points to actual changes in WCB frequencies and charactersitsics.

Specific/minor comments:

- L27: Catto and Pfahl (2013) is referred to for the relationship between fronts and (extreme) precipitation. Two other studies linking the two are:

Rüdisühli, S., Sprenger, M., Leutwyler, D., Schär, C., and Wernli, H.: Attribution of precipitation to cyclones and fronts over Europe in a kilometer-scale regional climate simulation, Weather Clim. Dynam., 1, 675–699, https://doi.org/10.5194/wcd-1-675-2020, 2020.

Prein, A. F., Mooney, P. A., & Done, J. M. (2023). The multi-scale interactions of atmospheric phenomenon in mean and extreme precipitation. Earth's Future, 11, e2023EF003534. https://doi.org/10.1029/2023EF003534

The authors might check whether these newer studies complements the one from 2013 by Catto and Pfahl.

- L73-74: “To account for model-dependent variability and climate change effects, the $\nabla\theta e$ threshold is computed separately for each model and period (historical and future)... “ I see that some kind of normalisation is needed to make the different models comparable. If I understand correctly, for each model different threshold for equivalent-potential temperature are used for the historical and the future simulation. This seems not intuitive to me, as the model resolution (and physics) remains the same and therefore I would expect to see how fronts, as defined today, become more (or less) frequent in a future climate. In short, the authors might explain in greater detail this climate-regime dependent choice.

- L82: Stationary fronts, with front-normal velocity below 1.5 m/s, are neglected. This is okay, but is also not immediately clear why the stationarity of a front should be taken as a filter criterion. Please discuss briefly the role (or not) of stationary fronts.

- L86: “For warm fronts, we require a positive potential temperature difference between points 300 km ahead and behind the front to eliminate false detections associated with strong humidity gradients near warm conveyor belts (Schaffer et al., 2025).” I am not sure whether the difference must be positive, or negative! Please check, and take the following ‘convention’ into account: Ahead of the warm front (in the direction it's moving, i.e., the cold side it hasn't reached yet); Behind the warm front (where it's already passed), i.e., the warm air side.

- L89: “A circular area of 300 km” Does this mean that the radius of the circle is 300 km? Not completely clear.

- L96: “the differences between the historical and future period are normalized...” Which difference? It becomes clear later in the text, but is not clear here.

- L121-122: “Fronts causing HPEs are more likely to be able to cause EPEs, quantifying the frequency change in a more meaningful way” What does “meaningful way” exactly mean? Rephrase in clearer way.

- L123: “This term...” Far-reaching reference?! What does ‘this term’ refer to?

- L127-131: In this paragraph, the method to get the front composites is described. From the text alone, however, I think it is difficult to get all the details. The description would benefit potentially from a small schematic figure where the front, frontals segments, most active segments... is visualized and the reader more easily can connect all aspects to the text. For example, I am not sure whether ‘frontal segments’ were clearly defined, in addition to frontal objects, frontal points,...

- Figure 1 (caption) and correspondingly for other figures: “Areas are shaded gray if the fraction of frontal events relative to total events is below 10 % in the historical period or if they lie outside the EURO-CORDEX domain”. In this okay to shade areas according to a historic 10% threshold. What, however, happens if in the historic simulation the frequency is below 10%, but in the future simulation the frequency becomes much larger (higher than 10%). This would be an important change, but according to the proposed methodology it would be gray-shaded and thus not be discernible in the figure. Possibly, I get this point wrong?

- L154-155: “The weaker signal in CORDEX is consistent with the lower storm track sensitivity of the driving CMIP5 compared to CMIP6” Please explain what ‘storm track sensitivity” means in this context.

- L164-165: “In most regions and seasons, the higher percentile increases more strongly, indicating that nonlinear effects contribute to the increase in frontal EPEs” Okay, but it would be better to be more precise: What kind of nonlinear effects?

.-L173: “..consistent with large-scale dynamical weakening of frontal activity.” What is ‘large-scale dynamical weakening’? The term is not well defined, and I also wonder why it is ‘large’scale’?