Idealised framework to prescribe sea surface temperatures to investigate the atmospheric circulation response

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Manuscript ID: egusphere-2026-1762, submitted to *Geoscientific Model Development*

Response to Reviewers

We thank the Editor and the Reviewers for their careful reading of our manuscript and for their constructive comments. We have addressed all comments below. Reviewer comments are reproduced in grey boxes, with our responses shown below.

Response to Reviewer 1

General comments

This paper presents an interesting approach by proposing an idealized framework for prescribing mid-latitude SST front in aquaplanet experiments. While the underlying concept and proposed framework are valuable, the manuscript requires major revisions before it can be considered for publication. Specifically, there are errors in the unit notation within the equations and figures. Furthermore, the physical interpretations of the sensitivity experiments are insufficient, as is the discussion regarding the differences and advantages of this approach compared to existing sensitivity experiments based on observational data.

We thank Akira for having agreed to review our work, and for providing constructive feedback, to which we respond below line by line.

Specific comments

Page 4, Line 110: Incorrect unit for α: Please check if it should be °C (100 km)$^{-1}$

Since α represents the linear rate of change in the meridional gradient of SST, its units are those of the gradient (°C (100 km)$^{-1}$) further divided by distance, hence the units are correct (°C (100 km)$^{-2}$). The product between α and latitude should still have the units of a meridional gradient of temperature.

Page 4, Line 113: Since α is given in °C (100 km)$^{-1}$ and Φ_T represents latitude, unit conversion is required.

The Reviewer raises a fair point regarding the units of α, which according to Equation 1 should be given in terms of degrees of latitude rather than per 100 km. The unit of °C (100 km)$^{-1}$ is widely used in previous literature and, to facilitate comparison between different studies, we decided to retain the same convention. Of course, one needs to convert °C (100 km)$^{-2}$ to °C (deg latitude)$^{-2}$ before multiplying by latitude. To clarify this point, we have rephrased lines 110-112 of the original manuscript as follows: "We point out that unit conversion from °C $(100\text{km})^{-2}$ to °C $(^\circ\text{lat})^{-2}$ is required before multiplying α with latitude."

Page 6, Figure 1: Is the y-axis for d/dy SST defined as positive northward (from the equator to the pole)? If so, the values in the graph should be negative.

Apologies for the confusion. The meridional gradient is indeed defined positive northwards. For visualisation purposes, Figure 1 was supposed to show either its absolute value or its opposite value such that d/dy SST (red) and SST (black) would never cross. To avoid confusion, we have changed the label in the figure to indicate the absolute value of the gradient, i.e. "|d/dy SST|", and adapted the caption accordingly. We have further modified colours so that red highlights the four parameters that we modulate in the various experiments. The updated figure and caption are included here in Fig. AR1.

Page 8, Section 4.2: Could you please clarify the sensitivity of the sensible heat flux? Also, it would be beneficial to present the vertical changes in temperature and water vapor structure, and to provide further discussion regarding their sensitivity and underlying physical mechanisms.

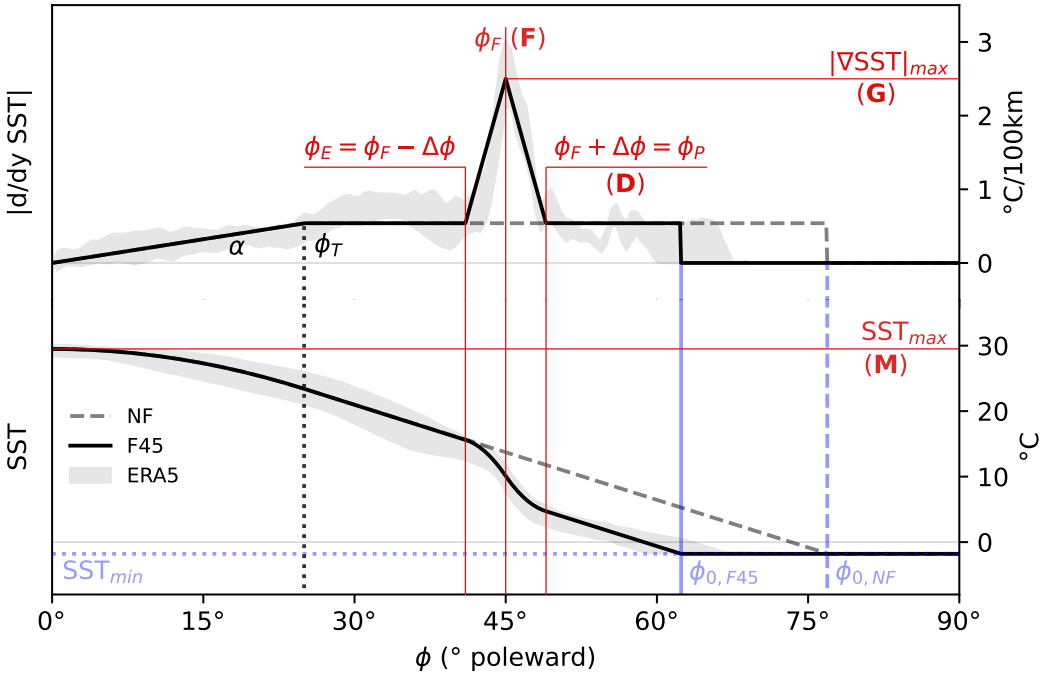

Fig. AR1. Idealised profiles of meridional SST gradient (above) and corresponding SST (below) for the control experiment (F45), superimposed over ERA5 climatology over the Southern Indian Ocean (MAMSON 1979-2022, 60°-80°E). SST gradient increases linearly at rate α until ϕ_T and then stays constant ($\alpha\phi_T$). An SST front is prescribed as a triangular peak in the gradient. The front is centred at ϕ_F (F), has a half-width of $\Delta\phi$ (D), and a set maximum gradient (G). Latitudes $\phi_E = \phi_F - \Delta\phi$ and $\phi_P = \phi_F + \Delta\phi$ represent, respectively, the equatorward and poleward extent of the SST front. The SST profile is obtained by integrating the SST gradient from the equator, where the maximum temperature (M) is set to 29.5°C. The SST reaches the minimum temperature $SST_{\text{min}} = -1.79°C$ at ϕ_0, and is set to constant polewards. Also shown are the profiles for the NF experiment (dashed), where no SST front is prescribed. Red labels (and corresponding capitalised letters) indicate the parameters that are modulated in the different experiments in Figs. 3-7.

We thank the Reviewer for this helpful suggestion. We examined the sensitivity of the sensible heat flux, as well as the associated temperature and water-vapour responses, across the experiments. The corresponding diagnostics are shown in Figs. AR2–AR6.

The time- and zonal-mean sensible heat flux (SHF) shows enhanced extrema near the SST front, with positive fluxes (ocean to atmosphere) on the warm flank and negative fluxes on the cold flank. Its meridional structure broadly follows the SST-T_{2m} difference, indicating that the surface air–sea temperature contrast is the primary control on the flux response. We also find local minima near the freezing latitude ϕ_0, poleward of which SST is held constant. The temperature tendency from vertical diffusion at 1000hPa indicates that vertical mixing plays an important role in producing these features. They likely arise because the relatively warm, constant SSTs contrast with colder air aloft, which is additionally cooled radiatively. However, the vertical-diffusion signal is substantially weaker in the model levels immediately above (e.g., 950hPa, not shown), suggesting that this response is largely confined to the near-surface layer.

To assess the vertical temperature response, we calculated the meridional gradient of vertically averaged temperature in the lower (900–800hPa) and upper (300–200hPa) troposphere. The response is strongest in the lower troposphere, where the atmospheric meridional temperature gradient closely reflects the imposed SST gradient. In the upper troposphere, the response is generally weaker. The main exceptions are the F35 experiment, which also exhibits the strongest zonal-mean jet response (Fig. 5a of the main manuscript), and the M/F45$\pm$5 experiments, in which the upper-level signal predominantly reflects vertical shifts in tropopause height under warmer and colder conditions.

We further assessed changes in atmospheric moisture using total column water vapour (TCWV), obtained by vertically integrating specific humidity across all model levels. The TCWV changes are consistent with the prescribed SST distributions and with the evaporation responses shown in Figs. 3d–7d of the main manuscript: warmer SST regions and enhanced evaporation are associated with increased column moisture, whereas colder regions and reduced evaporation correspond to lower TCWV.

These additional diagnostics support the interpretation that the near-surface thermal and moisture responses are primarily controlled by the imposed SST gradients and their influence on air–sea temperature contrast, surface turbulent fluxes, and evaporation. Their effects on the free troposphere are more limited and depend on the experiment, with upper-level responses likely mediated by changes in baroclinicity, circulation, and tropopause height.

We have included these analyses in our response for completeness. However, because they do not alter the central conclusions of the manuscript, and because a detailed investigation of the distinct lower- and upper-tropospheric baroclinic responses is the subject of ongoing work, we have decided not to include them in the revised manuscript in the interest of conciseness. The present paper is intended primarily to introduce and document the experimental framework.

Page 10, Figure 3: Since the precipitation and evaporation plots are strongly dominated by the climatology, showing them as anomalies from the control experiment would make the results much clearer.

We appreciate the Reviewer's suggestion that anomalies could facilitate comparison across experiments. We initially explored this approach and include here evaporation (Figs. AR2g-AR6g) and precipitation (Figs. AR2h-AR6h) anomalies relative to the control experiment (F45).

However, we point out that selecting an appropriate reference state is not straightforward. Although the control experiment is a natural candidate, the no-front experiment could be equally justified. Moreover, while F45 has an SST profile closest to the ERA5 Southern Indian Ocean climatology, all experiments remain substantially idealised. Using F45 as the reference could therefore unintentionally imply that it represents a realistic baseline.

For these reasons, we found that anomaly plots did not substantially clarify the atmospheric water cycle response and chose not to include them in the revised manuscript. A more detailed analysis

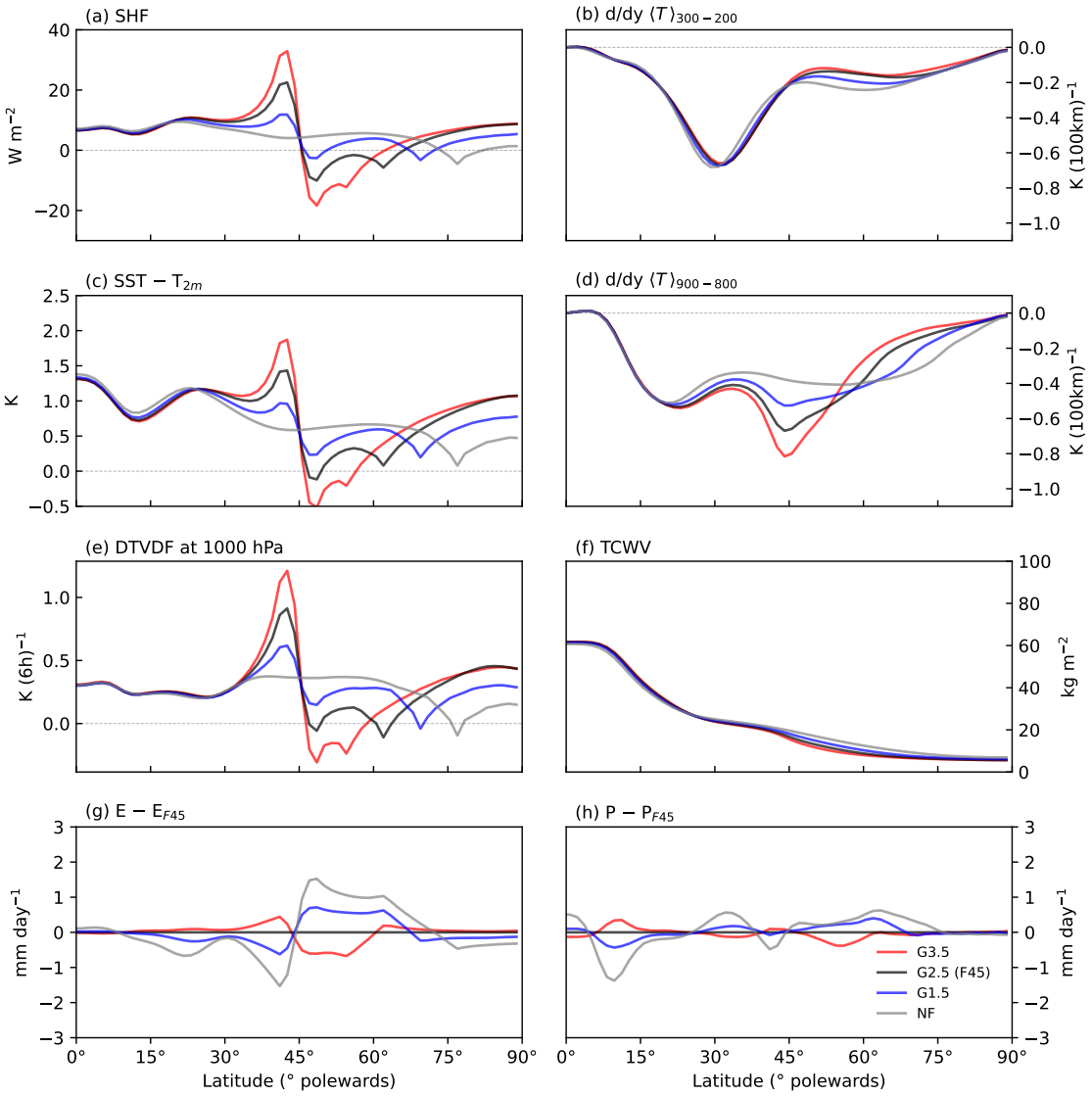

Fig. AR2. Climatological zonal means based on G3.5 (red), G2.5 (corresponding to F45; black), G1.5 (blue), and NF (grey). (a) Surface sensible heat flux SHF. (b) Meridional gradient of upper tropospheric (300-200 hPa) vertically averaged T. (c) Difference between SST and T at 2-metres. (d) As in b, here for lower-tropospheric (900-800 hPa) vertically averaged T. (f) Model temperature tendency due to the vertical diffusion scheme at 1000 hPa. (g) Zonally-averaged evaporation (E) minus the corresponding profile of the control experiment (F45). (h) Same as in g, here for precipitation (P).

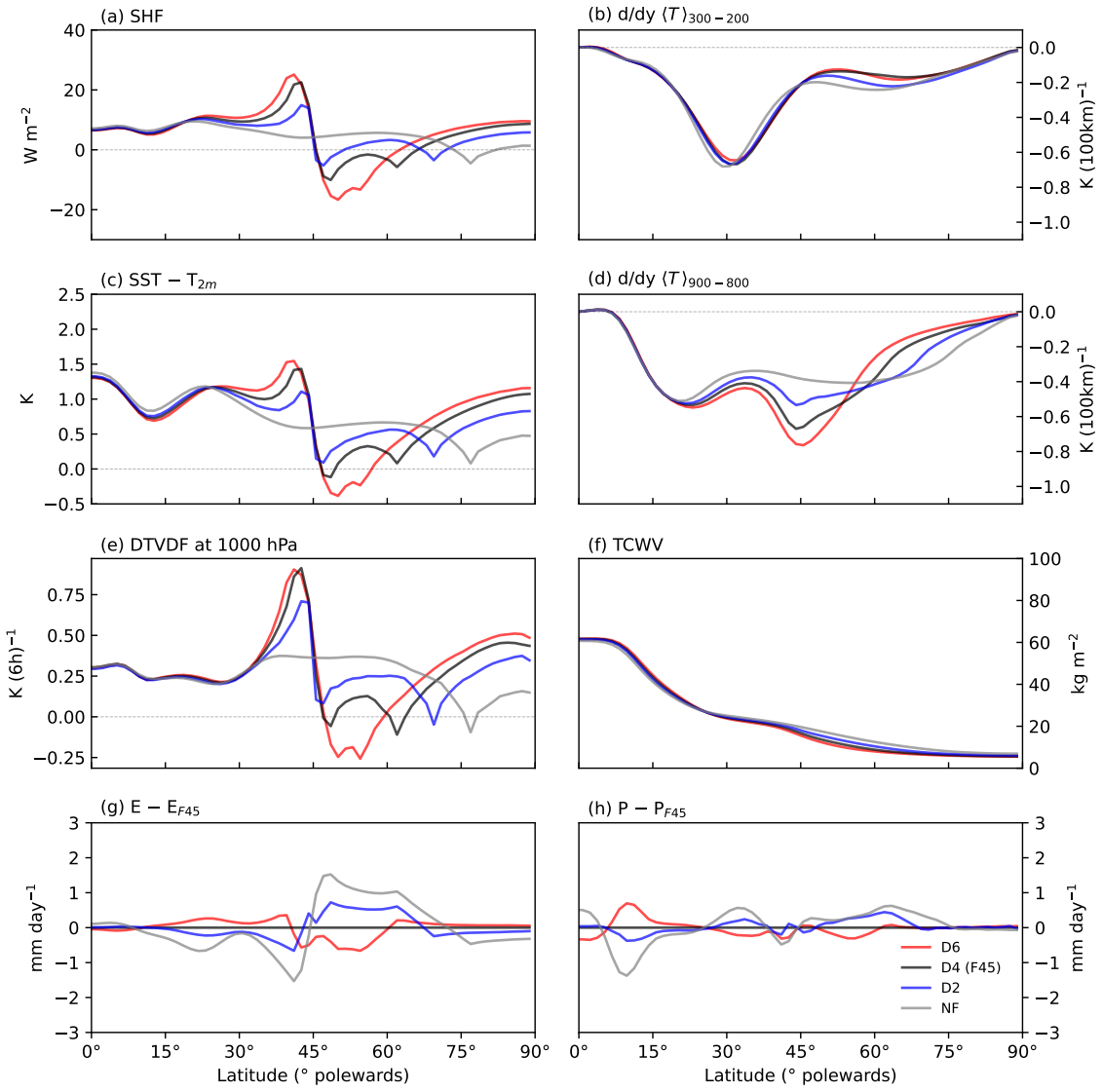

Fig. AR3. As in Fig. AR2, but for D6 (red), D4 (corresponding to F45; black), D2 (blue), and NF (grey).

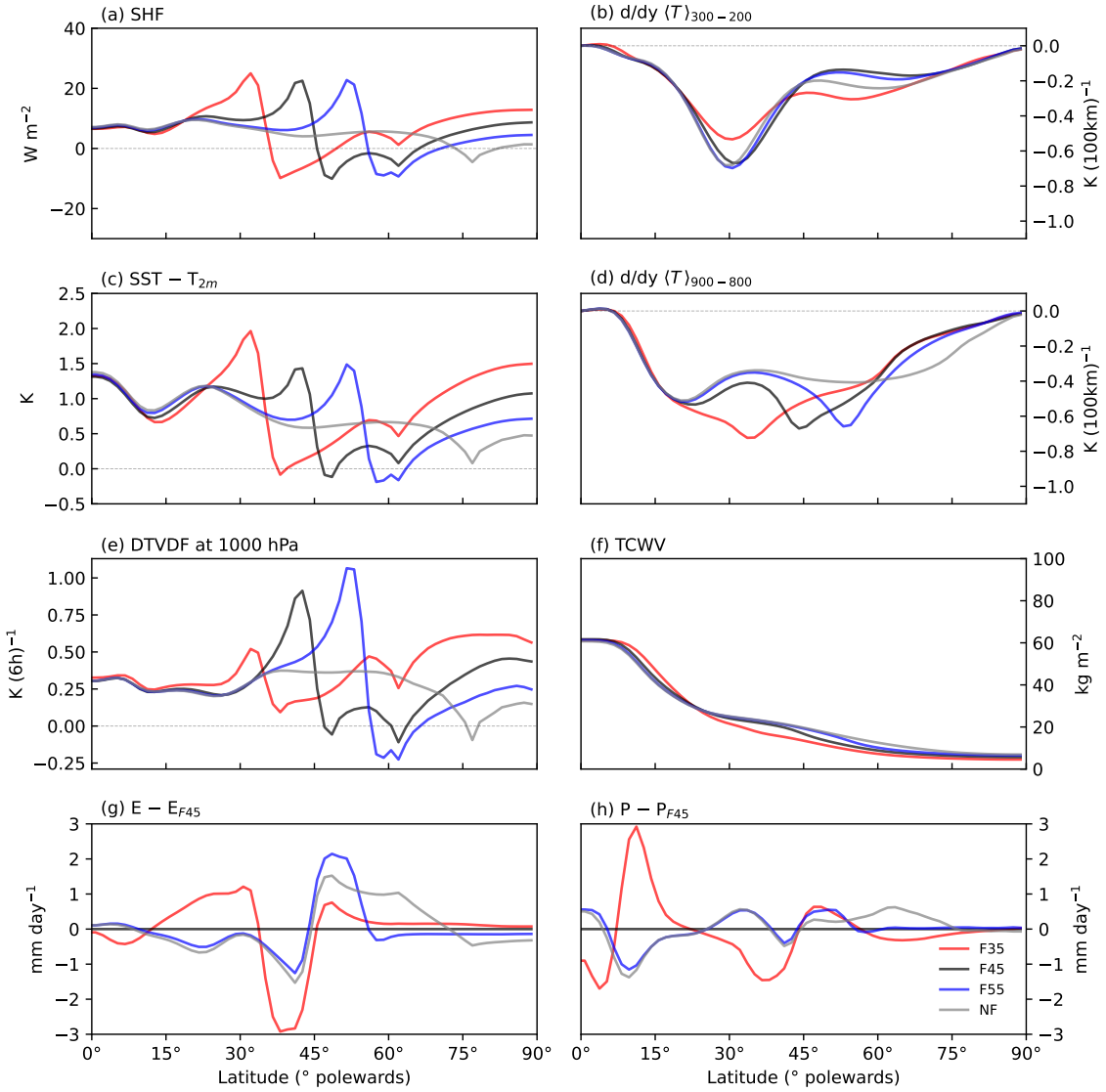

Fig. AR4. As in Fig. AR2, but here for F35 (red), F45 (black), F55 (blue), and NF (grey).

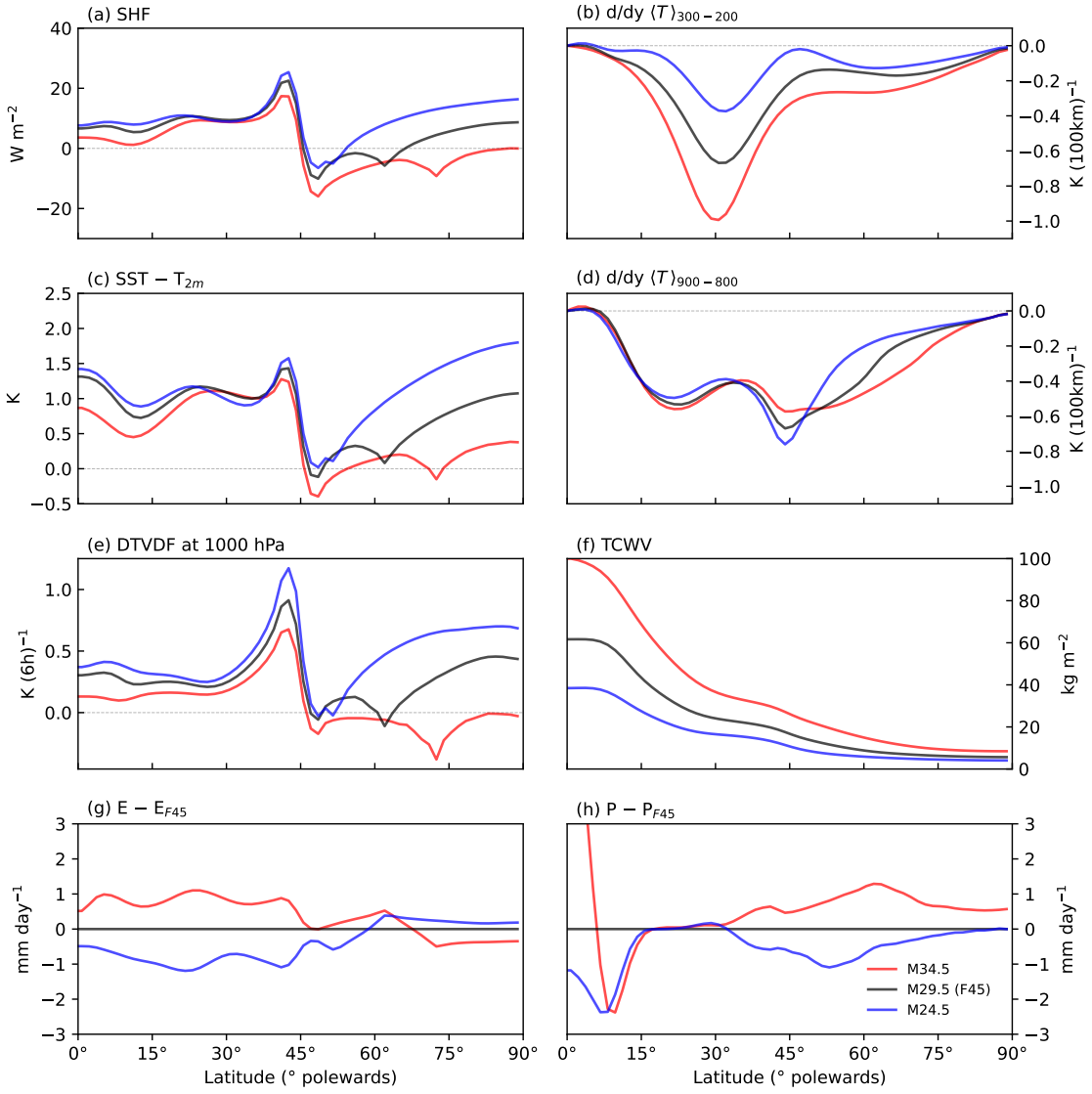

Fig. AR5. As in Fig. AR2, but here for M34.5 (red), M29.5 (corresponding to F45; black), and M24.5 (blue).

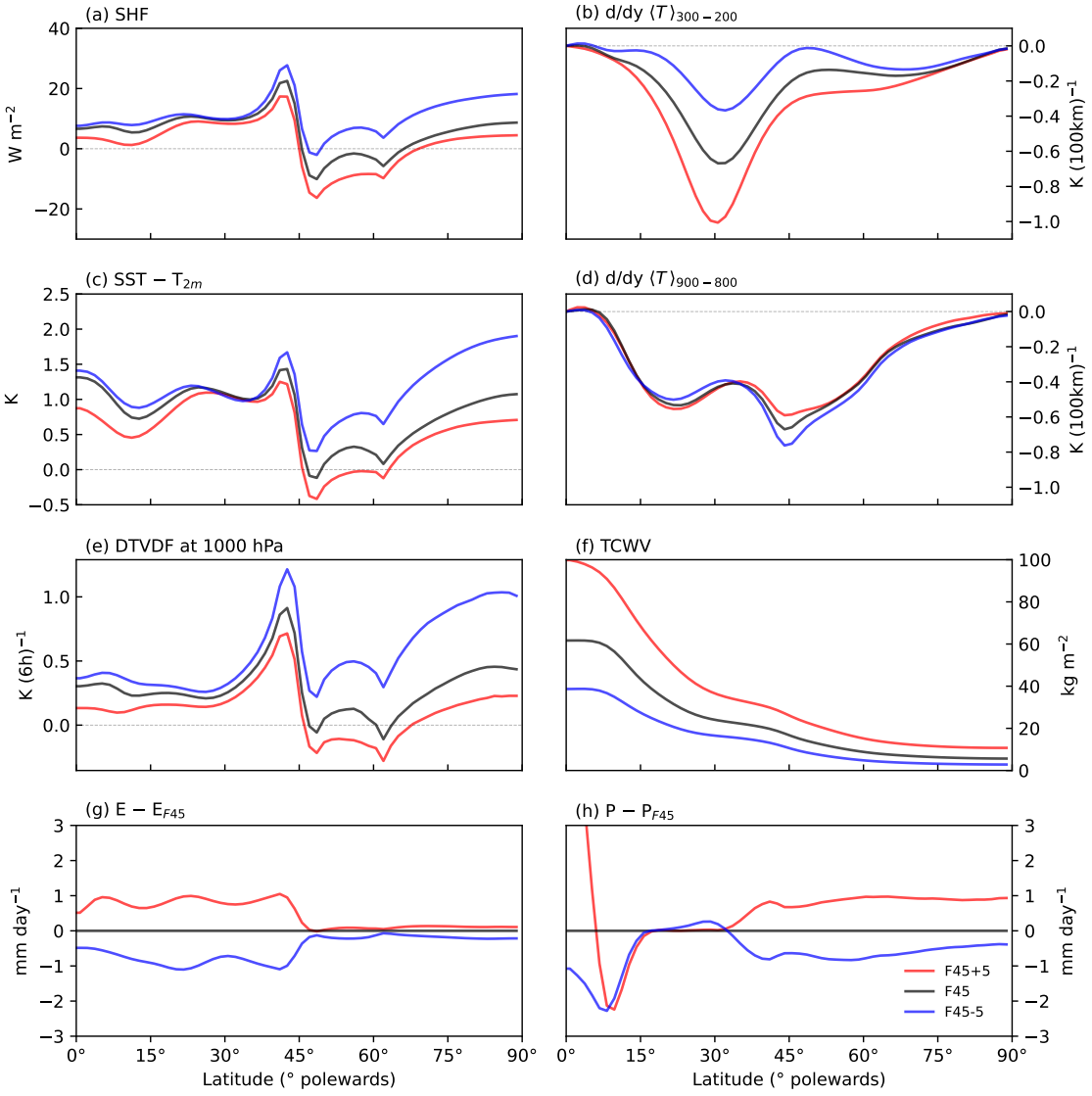

Fig. AR6. As in Fig. AR2, but here for F45+5 (red), F45 (black), and F45-5 (blue).

of evaporation and precipitation anomalies, and more generally of the response of the atmospheric water cycle, is the subject of ongoing work. The present paper is intended as a concise, technical description of the experimental framework, and an extended discussion of water cycle anomalies would be beyond its scope.

Page 11, Section 4.4: To improve readability and flow, please consider adding a brief introductory statement at the start of each subsection to outline its objective.

We have added a brief introductory paragraph at the beginning of Section 4 to explain how results from the different experiments are presented.

"In order to identify the response of the atmospheric circulation to different SST frontal characteristics, we modify the different frontal parameters (G, D, F, M) and modulate them one at a time. In the following subsections, we focus on the response to each parameter individually compared to the control experiment presented in the previous section."

We consider the subsection titles sufficiently descriptive of their respective objectives and therefore chose not to add potentially redundant introductory statements to each subsection.

Page 14, Section 5: The manuscript lacks results and discussion demonstrating how the issues associated with using observational SSTs as boundary conditions – as raised in the Introduction – are addressed by the proposed SST profile. Furthermore, the authors should discuss whether this approach yields new insights that could not be obtained from existing studies.

We thank the Reviewer for this comment. We have clarified in the Introduction and Conclusions how the proposed SST-profile framework addresses the limitations of experiments forced with observational or climatological SSTs. In particular, observational SST boundary conditions impose a fixed and geographically complex combination of frontal characteristics, which limits the ability to vary individual properties independently. Our idealised SST profiles instead allow the frontal location, strength, width, and meridional background gradient to be modified systematically and independently.

The results presented in Section 4 demonstrate that the framework enables controlled examination of the response of the atmospheric circulation, energy cycle, and water cycle to changes in these frontal parameters. This flexibility is the main advantage of the proposed setup relative to existing approaches based on prescribed observational SSTs: it allows causal attribution of the atmospheric response to specific aspects of the SST front, rather than to the combined effects of multiple, co-varying features in an observed SST field.

The purpose of the present paper is to introduce and document this experimental framework, rather than to provide a comprehensive investigation of the associated synoptic-scale dynamics. Ongoing work uses the framework to examine, for example, the tropospheric baroclinicity response, cyclone and instantaneous jet activity, and the detailed responses of the water and energy cycles. We therefore consider a more extensive discussion of the novel physical insights enabled by the framework to be beyond the scope of this technical paper.

Nevertheless, we decided to expand the Conclusions (lines 321-341 in the revised manuscript) to more clearly highlight the types of questions that can be addressed with the framework and its possible extensions. These include introducing asymmetries in the SST profile to represent solstitial conditions, zonal variations in frontal properties to emulate front meanders or the narrowing and broadening associated with western boundary currents, and temporal variability in the imposed SST structure.

Response to Reviewer 2

This manuscript introduces an analytically defined framework for prescribing zonally symmetric SST distributions in aquaplanet AGCM experiments. The framework is demonstrated using AFES through a series of sensitivity experiments examining storm tracks, jets, diabatic energetics, and the hydrological cycle. The approach is conceptually simple, reproducible, and potentially useful for systematic inter-comparison and process studies, and I believe it is within the scope of GMD. As such, I recommend prompt publication.

We are thankful to the Reviewer for the very positive remarks. We hope to address all the remaining concerns as outlined below.

Line 313: it is great to be able to isolate properties of SST fronts, but do these properties correlate? If so, does it make sense to figure out a way to change properties in sync as a group to keep everything in balance?

The Reviewer raises a fair point: the different values that we chose to present here for the maximum gradient (G) and front width (D) yield similar SST profiles, which might suggest these two frontal properties need not be entirely independent in reality. However, as we point out at the end of section 4.3 on lines 216-220, allowing for a wider range of values would further distinguish the response of the atmospheric circulation to these parameters. Ongoing work is aimed at answering these questions more thoroughly, while for this GMD paper we believed these results to be sufficient to showcase the applicability of our framework. It is indeed also a possibility, within our framework, to analytically impose additional constraints when modulating frontal parameters, such that, for instance, the cross-frontal temperature difference remains constant. For the sake of conciseness, we eventually decided not to include these in the final manuscript and instead employ them in a future, less technical paper. In the revised manuscript, we expanded the conclusions to better outline the potential of the proposed framework as discussed here.

Relatedly regarding F45+5 and F45-5, would it make sense to perturb the SST by a zonally varying amount?

It is indeed a possibility, within our framework, to introduce zonal variability in the SST profiles, including the F45$\pm$5 experiments. As a matter of fact, we have already tested the atmospheric response to zonal variations in the SST front, though we did not include the results in this paper. All of the frontal parameters (G, D, F, M) can be modulated depending on longitude. For instance, it is possible to prescribe a narrow front that transitions into a broader front, thus introducing zonal frontal parameters like the zonal widths of the narrow and broad fronts, as well as the width of the transition zone. This opens a manifold of possible experiments that answer different research questions, thus we limited the focus of this paper on the basic frontal parameters. In line with our response to the previous comment, we expanded the conclusion to better outline the potential of the proposed framework, including this discussion (lines 333-341 in the revised manuscript).

What's needed for this framework to be useful/usable for full-complexity atmosphere models?

As an atmospheric general circulation model, AFES used in this study already fully represents atmospheric dynamics and thermodynamics numerically. Thus, applying our framework to a full-complexity atmospheric model does not require a fundamental modification of the framework itself.

Rather, the main step toward more realistic applications would be to introduce more complex lower-boundary conditions. All of the experiments are run in an aquaplanet configuration, so quite idealised but still appropriate to test the atmospheric response to different SST profiles. It would

be relatively straight-forward to introduce land masses to account also for land-sea contrast effects to modify the responses to the prescribed SST profiles with the controlled frontal properties. We therefore expect our framework to be easily adapted for such experimental configurations.

However, the framework would not suit atmosphere-ocean coupled simulations where the initially specified SST front properties cannot be maintained throughout the simulation, obfuscating the link between atmospheric response and SST frontal parameters. Application of our framework to air-sea coupled models would therefore require technical approaches to constrain or restore the SST field. This topic is beyond the scope of this study and left for future studies.