

This paper investigates factors influencing the hemispheric asymmetry of storminess, defined as the extratropical eddy kinetic energy, using the MSE budget. The authors use the transient eddy MSE flux as a proxy for the EKE, and explain the former using other terms in the MSE budget. The authors then perform model experiments to test the causality of the MSE diagnostics. The authors then use this framework to interpret the recent observed trend in storminess.

This is a well-developed study with theory backed by numerical experiments and observational analysis. It answered a fundamental question in the Earth's climate and offered an explanation for an aspect of the observed climate change. I recommend acceptance after addressing the following minor comments and suggestions.

**We thank the reviewer for their feedback. We have thoroughly revised the manuscript to address the comments from the reviewer.**

General comments:

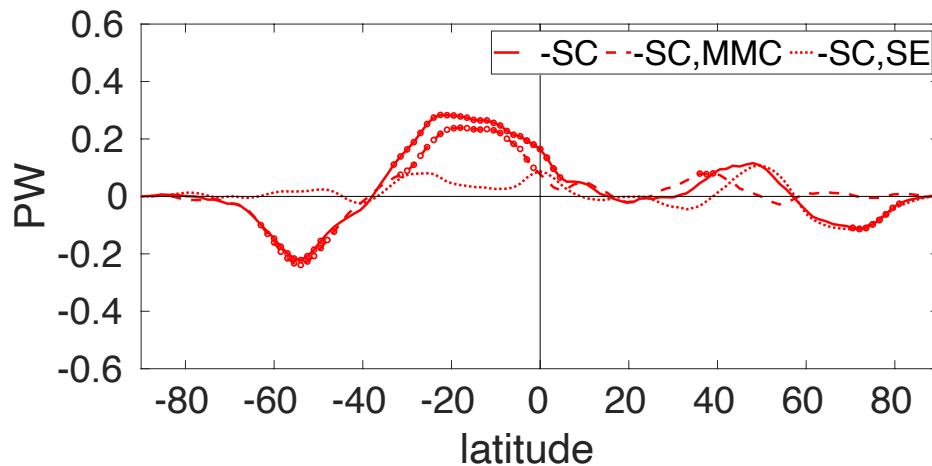
1. The TOA flux is an important term in the trend of asymmetry (Fig. 3). Why isn't there a model experiment to test it? A new experiment is not required for acceptance, but it would help to clarify why the TOA flux is so important in the trend but not in the climatology.

**We added text to clarify why the TOA flux is more important for the trend than the climatology (see lines 72-74, 194-218). As noted on lines 72-74, the TOA radiation makes a negligible contribution to the climatological storminess asymmetry because the net TOA radiation is nearly symmetric about the equator. The TOA radiative flux trend is consistent with enhanced absorption of shortwave radiation in the NH extratropics due to Arctic sea ice loss and snow melt over the Northern Hemisphere continents (Fig. S5 and S6), which weakens the TOA contribution to Northern Hemisphere storminess and, thus, results in a positive storminess asymmetry trend (orange bar, Fig. 3 b,c). The hemispheric asymmetry of TOA radiative flux trend is consistent with the transient climate response to increased CO<sub>2</sub>, which differs between the hemispheres. In climate models the transient response to increased CO<sub>2</sub> involves Arctic Sea ice loss, Arctic amplification of surface temperature, snow melt over Northern Hemisphere continents, and land warming more than ocean. In contrast the transient response involves negligible changes in Antarctic Sea ice and no Antarctic amplification of surface temperature. Instead, transient cooling occurs over the Southern Ocean. Consistently climate models simulate a larger hemispheric asymmetry of radiative changes for the transient response than the quasi-equilibrium response, which involves Antarctic Sea ice loss and Antarctic amplification of surface temperature.**

2. There is no discussion on the trend of the stationary circulation term in Fig. 3. Is it related to the trend of the surface flux?

**The SC trend reflects an asymmetry of the stationary circulation energy flux trend. In particular, the trend is larger in the Southern hemisphere, reflecting a significant increase in stationary circulation energy flux from ~20-40S (Fig. S5). The strengthening in the Southern Hemisphere is dominated by the mean meridional circulation (Hadley and Ferrel cell) contribution to the stationary circulation energy flux (Fig. R1 below). The connection between documented trends in the Hadley cell and the stationary circulation energy flux is currently unclear. Our diagnostic analysis cannot rule out the possibility that the stationary circulation trend is related to the surface energy flux trend. We added**

discussion of the SC trend see lines 219-231 and added Fig. R1 below as supplementary Fig. S7.



**Figure R1: Trend of ERA5 stationary atmospheric circulation energy flux (SC) decomposed into contributions from the mean meridional circulation (MMC, dashed) and stationary eddies (SE, dotted). Trends that are statistically significant ( $p$  values lower than 0.05) are marked with a circle.**

3. The motivation for doing the flat topography experiment is weak. I suggest adding a version of equation [2] to the main text. The stationary circulation term is a good motivation for altering the topography.

We added more motivation for the possible role of topography. In particular, the asymmetry of eddy kinetic energy in Fig. 1c suggests a role for topography (the orange contours coincide with regions of large topography over Eurasia and North America) as we now note on lines 19-22.

Furthermore, even though their model was biased the results of Manabe & Terpstra (1974) pointed to a significant impact of flattening topography on Northern Hemisphere storminess. We added more discussion of the Manabe & Terpstra (1974) results to provide additional motivation for revisiting the role of topography (see lines 37-41).

We agree with the reviewer that the stationary circulation term in equation (2) is a good motivation for flattening topography. We added equation (2) to the main text (see new equation 1) when discussing the model response to flattened topography (see lines 55-89).

4. Fig. 2e vs. 2f: EKE is larger in FLAT than SYMS, but STM is larger in SYMS than FLAT. To what extent is STM a good proxy for EKE? Please also explain the factor of 0.5 in Line 338.

Eddy kinetic energy is significantly correlated with energetic storminess defined by transient eddy MSE flux across the reanalysis data and ECHAM6 simulations ( $R^2 = 0.98$ , see Fig. R2 below). A significant correlation between eddy kinetic energy and energetic storminess was also noted in previous work looking at the seasonal cycle, response to CO<sub>2</sub> and response to Arctic Sea ice loss (Barpanda & Shaw 2020, Shaw et al. 2018, Shaw

& Smith 2022). Thus, energetic storminess is a good proxy for EKE. We added a discussion of this point to the methods section (see lines 397-399) and Fig. R2 below as supplementary Fig. S10. We also added an explanation of the rescaling factor, which allows us to quantitatively compare the climatological storminess asymmetry using the two metrics and follows previous work (see lines 408-415). Note there was a typo such that 0.5 should have been 0.65.

In Fig. 2e and 2f the EKE is larger in FLAT than SYMS but STM is larger in SYMS than FLAT in part because there is a different impact of FLAT and SYMS on transient eddy dry static energy (DSE) versus latent energy flux. Transient eddy dry static energy decreases monotonically across the simulations like EKE but transient eddy latent energy decreases in FLAT and then increases in SYMS (see Fig. R3 below). Nevertheless, it is crucial to use MSE and not DSE to interpret the results because it is only MSE that connects to the surface energy fluxes (implied ocean energy transport). We cannot test the energetic mechanism with the DSE budget. We mention the role of dry static energy versus latent energy on lines 400-402. We also added Fig. R3 below to the supplementary material (see Fig. S11).

Importantly the fact that EKE is larger in FLAT than SYMS but STM is larger in SYMS than FLAT does not affect our overall conclusion that topography and ocean circulation contribute roughly equally to the storminess asymmetry. In particular, the role of each can only be attributed to within the nonlinearity, which is 3% (Fig. 2e, F+S), or the accuracy of closing of the MSE budget, which is 5%. We added a discussion of this on lines 402-407.

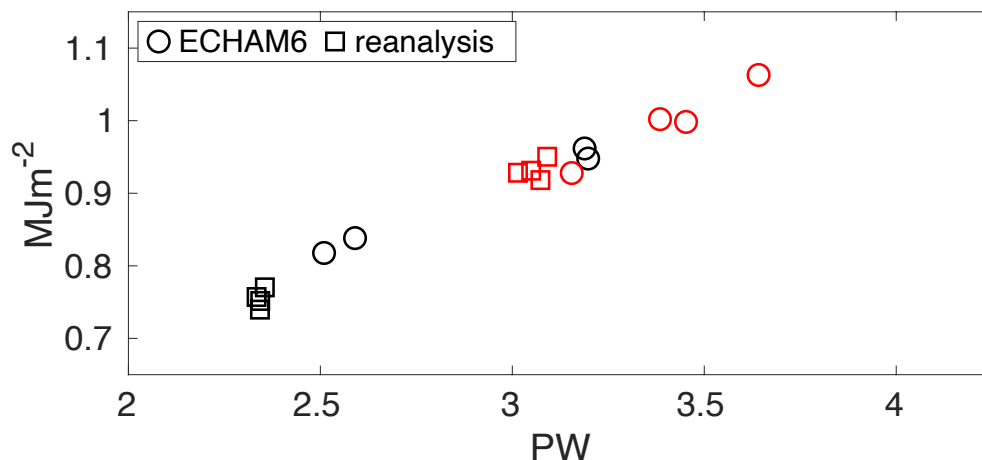
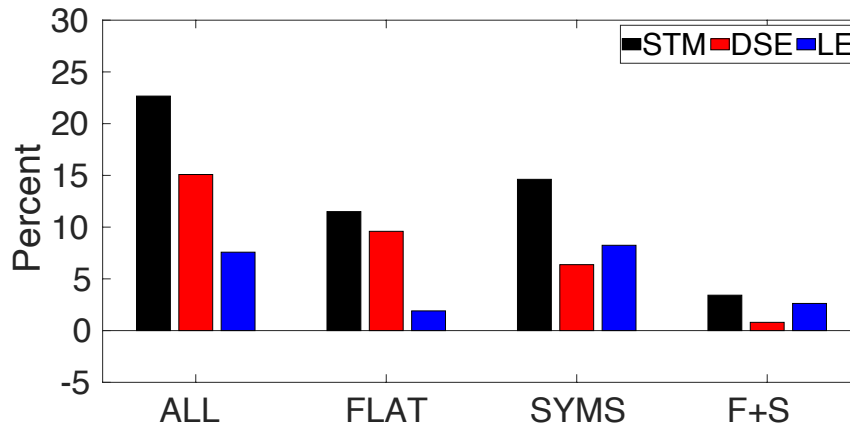


Figure R2: Eddy kinetic energy ( $\text{MJm}^{-2}$ ) versus transient eddy MSE flux (PW) for ECHAM6 simulations (circle) and reanalysis data (square) averaged over the extratropics (20-90 degrees) of the Northern Hemisphere (black) and Southern Hemisphere (red).



**Figure R3: Decomposition of the hemispheric asymmetry of energetic storminess (STM) into dry static energy (DSE) and latent energy (LE) contributions for the ECHAM6 simulations.**

5. Please discuss how well the MSE budget is closed in Fig. 2f and 3b and 3c.

**In Fig. 2f, the MSE budget in ECHAM6 is closed to within 5%. More specifically, the hemispheric asymmetry of atmospheric energy flux calculated using the difference of top of atmosphere radiation and surface energy fluxes differs from the hemispheric asymmetry of atmospheric energy flux calculated using 6 hourly winds and MSE by 5%. We added text discussing this point on lines 388-393.**

**In Fig. 3b the budget is closed by construction because the surface energy flux is inferred as a residual of the atmospheric energy flux divergence from reanalysis data and the TOA flux from ERA5 following previous work for the climatology as discussed in the methods section (see lines 311-343, 393-394).**

**In Fig. 3c the budget is closed by defining the SC term as a residual because it cannot be accurately calculated using the CMIP5 data because the coarse vertical pressure grid makes the computation of SC inaccurate. We added text discussing this point on lines 394-396.**

Specific comments:

Line 183: do you mean "yellow" bar?

**We changed the yellow bars in Fig. 3 to orange so that they are consistent with Fig. 2f.**

Methods: description of the FLAT experiment is missing.

**We added a description of the FLAT experiment to the methods section (see lines 350-352).**

Ref 33 is missing.

**Ref. 33 was fixed. There was a typo in the bibtex file.**