Can Arctic sea ice melting lead to more summer heat extremes?

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Abstract

September Arctic sea ice cover has halved since the 1970s, and this trend projects to continue. Climate models predict that a high-emission scenario could lead to a fully ice-free summertime Arctic ocean before 2100. Arctic sea ice plays a central role in our climate system; in this study, we aim to identify the effects that this projected melting will have on global summertime temperatures, and to understand the mechanisms by which these effects take place. We analyze data on 2-meter temperature, 850-hPa temperature, and 500-hPa zonal wind speed from experiments ran on two different climate model configurations: an atmosphere-only configuration using CESM1-WACCM, and an atmosphere-ocean coupled configuration using the same atmospheric component coupled to CESM1's ocean component. We find that the majority of the globe sees significant increases to average temperature in the coupled configuration, with particular amplification in the Arctic; while most average temperature changes in the uncoupled configuration are insignificant. We also find that wind speeds change significantly in both configurations, but with more amplification in the coupled. In particular, in the coupled experiments, the equatorward shift of the northern hemisphere's polar jet is associated with an unusually strong rise in temperature where the jet is shifting away from, and a fall in temperature in the place the jet is shifting towards. Finally, we find that the frequency of extreme temperatures increases almost all around the globe in the coupled experiments, with many locations seeing at least twice as many heat extremes, and some seeing over 90% extremes. Our broad takeaways are that melting Arctic sea ice projects to increase both average summertime temperature and frequency of extremes globally, and that ocean-atmosphere coupling and shifting jet streams both play a role.

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1 Introduction

September Arctic sea ice cover has halved since the 1970s (Screen et al., 2018), and this trend is likely to continue, with models projecting that a high-emissions scenario will lead to a fully ice-free summertime Arctic Ocean before the year 2100 (Notz & Community, 2020). This is already impacting components of the Arctic, but sea ice is a key part of the climate system, and research indicates that it is likely also capable of affecting the rest of the globe. Kang et al. (2023) finds that the melting of Arctic sea ice projects to contribute to the weakening of summertime storminess by the late 21st century. Screen et al. (2015) finds that with an atmospheric model, extreme weather (hot, cold, wet, and dry) projects to change more strongly over central and eastern North America than other mid-latitude regions. England et al. (2020) finds with a fully coupled model that *Antarctic* sea ice loss projects to contribute to warming and precipitation changes in the tropics. In this study, we seek to identify the effects that melting Arctic sea ice will have on global temperatures, specifically summertime extremes. We also seek to discern the driving mechanism behind these effects, by comparing atmosphere-only model experiments with atmosphere-ocean-coupled model experiments. Deser et al. (2014) finds that ocean coupling plays a role in the atmosphere's response to melting Arctic sea ice; we investigate this relationship further.

2 Models and experimental design

We use CESM1-WACCM for the atmosphere-only model configuration. This model has a horizontal resolution of 1.9° latitude by 2.5° longitude, giving us 94x144 horizontal grid boxes. It extends from the surface to 5.1×10^{-6} hPa, or about 140 km, with 66 vertical levels. It is detailed further in Marsh et al. (2013).

For the atmosphere-ocean model configuration, we couple CESM1-WACCM with CESM1's ocean component, which has nominal 1° horizontal resolution and 60 vertical levels, which are spaced at 10m in the upper 160m, then grow farther apart until reaching 250m spacing below about 3500m. More details can be found in Danabasoglu et al. (2012).

a) Uncoupled experiments

We make use of the model experiments performed by Dr. Lantao Sun. A pair of 300-year-long experiments were conducted on the uncoupled model configuration to investigate the impact of projected Arctic sea ice loss. In the control experiment, a repeating seasonal cycle of sea ice concentration (SIC) and sea surface temperature (SST) is set, given by the daily average values from 1980-1999 of the average of three twentieth-century simulations on the coupled model configuration. So this experiment is meant to show a world with what we might call "unperturbed" SIC and SST values, i.e. those we'd expect to see between 1980 and 1999.

In the perturbation experiment, a repeating seasonal SIC cycle in the Arctic is set, given by the daily average values from 2080-2099 of a twenty-first-century simulation on the coupled model forced by Representative Concentration Pathway 8.5. RCP8.5 corresponds to a radiative forcing level of 8.5 W/m^2 by 2100; this simulates future sea ice levels under a high-emissions scenario. Additionally, in each grid box where the perturbation SIC is less than the control SIC, the perturbation SST is set to the 2080-2099 average, to account for the local warming of the sea surface. All other locations have SST set to the 1980-1999 average. When we subtract the control experiment data from the perturbation experiment data, we see the impact of projected Arctic sea ice loss and associated sea surface warming. Sun et al. (2015) details the same set of experiments run for less time (161 years).

b) Coupled experiments

An analogous pair of 300-year-long experiments on the coupled configuration were conducted, performed again by Dr. Lantao Sun. In coupled models, because sea ice is inside of the model, it can't just be explicitly set like it was in the uncoupled model, where it's just a boundary condition. Instead, SIC values are manipulated with the ghost flux method used in Deser et al. (2015), in which a longwave radiative flux is applied to the ice model. Kang et al. (2023) details a similar set of experiments.

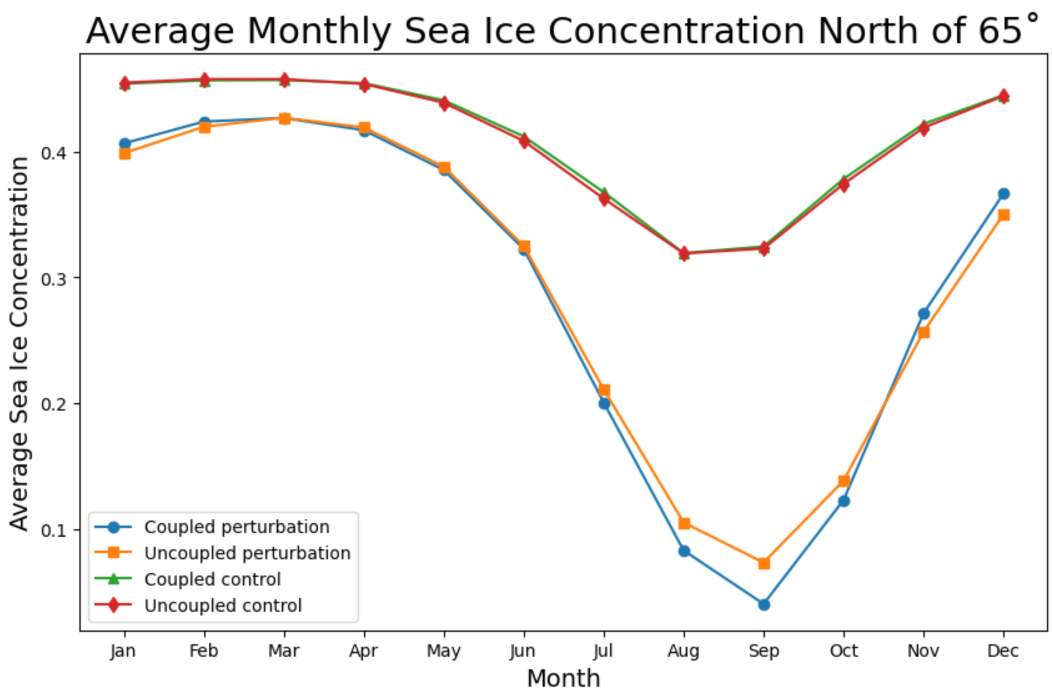

Figure 1: Corresponding pairs of experiments have similar, but not identical, average monthly SIC values. The percent differences, calculated as (difference in uncoupled - difference in coupled) / (average of difference in uncoupled and coupled), are as follows, in order of month: [16.53%, 14.42%, 1.74%, -7.79%, -8.42%, -6.97%, -9.79%, -9.96%, -12.92%, -7.88%, 7.50%, 18.36%]. We judge that this demonstrates sufficient similarity for comparison.

Because the method of setting SIC differs between the two models, SIC values are not necessarily identical between the corresponding pairs of experiments. The experiments were designed such that SIC values would be similar, allowing us to take the difference between coupled and uncoupled results to find the impact of ocean coupling; but we don't know *a priori* that they are the same.

Before comparing coupled and uncoupled results, we verify that their SIC values are sufficiently similar (Fig. 1). We have monthly SIC data for all 300 years of the experiment; we only consider the last 200 years, once the sea ice has reached a new equilibrium after reacting to the forcing. For each experiment, we check the monthly values averaged across 200 years.

In addition to monthly SIC data, we have the following: daily-average 2-meter air temperature data in the coupled experiments, and daily-average 850-hPa (or about 1.5 km) air temperature data in the uncoupled experiments. Because we do not have the same variable recorded in both sets of experiments, we are forced to compare 2m temperature with 850-hPa temperature, making the assumption that temperatures change at the same rate in different levels of the atmosphere when exposed to the same stimulus. We also have daily-average 500-hPa (or about 5.5 km) zonal wind speed data in all experiments; zonal wind is the eastward/westward component of wind. Finally, we have daily-maximum 2m temperature data, but only in the coupled experiments. For all this data, we focus on the summer months of June, July, and August.

3 Results

3.1 Summertime temperature averages

The coupled model predicts significant temperature increases across most of the globe (Fig. 3). In particular, it sees greater rises in temperature in the upper and lower 30°, with the strongest signal coming from the southern tip of Greenland. It also sees significant cooling in the midlatitudes over the Atlantic, just south of Greenland (Fig. 2).

The uncoupled model predicts mostly insignificant changes (Fig. 3), with a mix of increases and decreases (Fig. 2). The main chunks of significant change are over the higher latitudes of North America/Greenland and Asia, along with some splotches in the tropics. Most significant changes are increases.

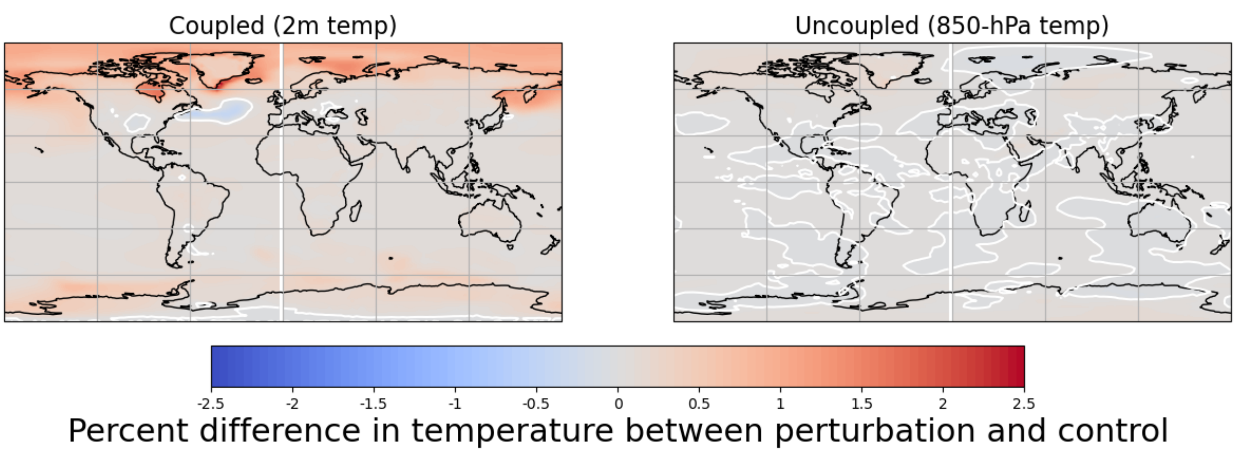

Figure 2: Percent change in temperature when Arctic sea ice melts. 2-meter temperature in the coupled model and 850-hPa temperature in the uncoupled model. Because many values are close to 0, white contour lines represent values of 0 to allow us to distinguish between positives and negatives. We see that most values on the coupled map are positive.

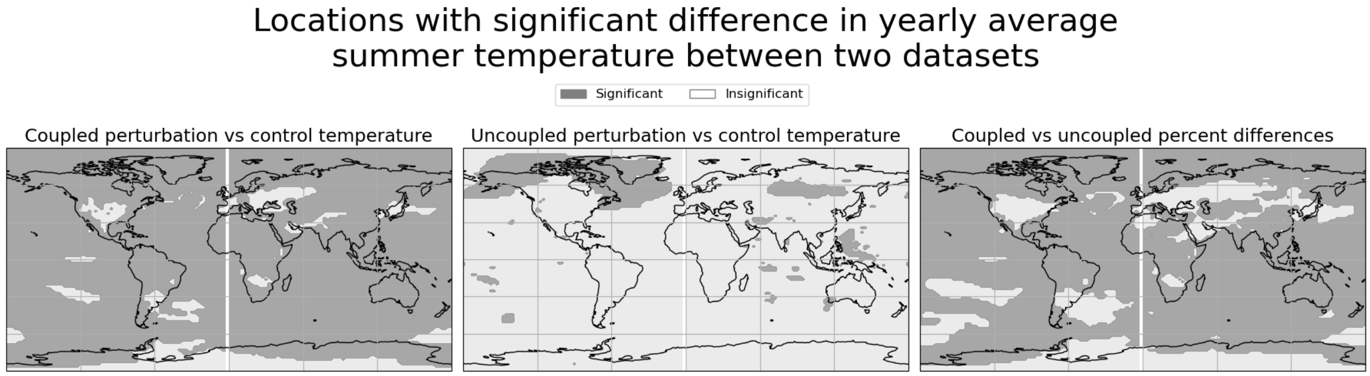

Figure 3: Significant changes in the coupled experiments when Arctic sea ice melts; then in the uncoupled; then significant differences in the changes between the two. We see large continuous chunks of significance/insignificance. 92.4% of the Earth's surface sees significant change in the coupled experiments, compared to 7.6% in the uncoupled. 83.6% of Earth sees a significant difference between the two.

3.2 Summertime wind speed averages

Both models predict significant changes to wind speeds distributed pretty evenly across the globe (Fig. 5). We see more amplified changes in the coupled model (Fig. 4). In particular, the coupled model sees an equatorward shift of the northern hemisphere's polar jet, and amplified wind speeds in the upper 20°. Impacts on other jet streams, in either model, are not as clear.

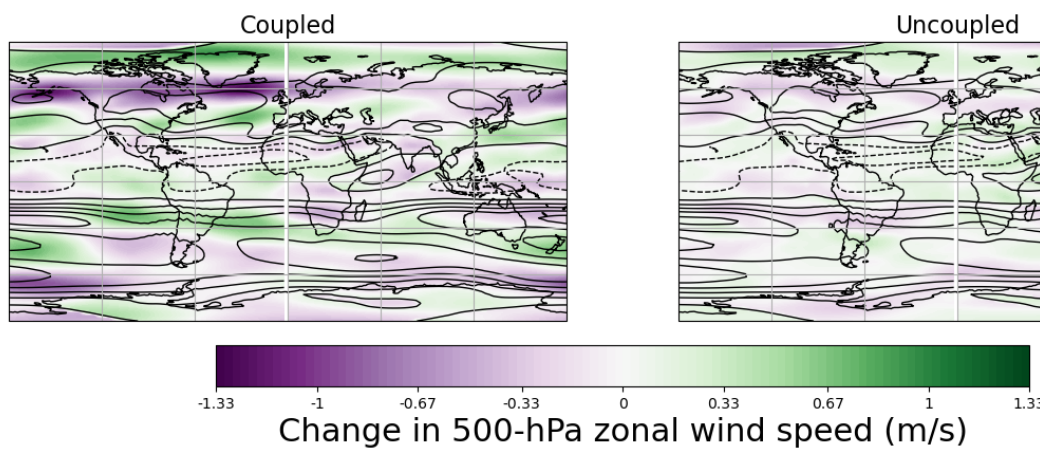

Figure 4: Change in wind speeds when Arctic sea ice melts. The contour lines give the climatology, i.e. the wind velocities of the control runs. Solid lines show westerly (west-to-east) winds, and dotted lines show easterly winds. Regions of 0 wind are somewhere between the dotted and solid lines, so the regions of maximum wind speed are inside the closed curves. When wind slows down on one side of a peak and speeds up on the other side, it indicates that the peak is moving towards where the wind is speeding up, i.e. that the jet stream is shifting.

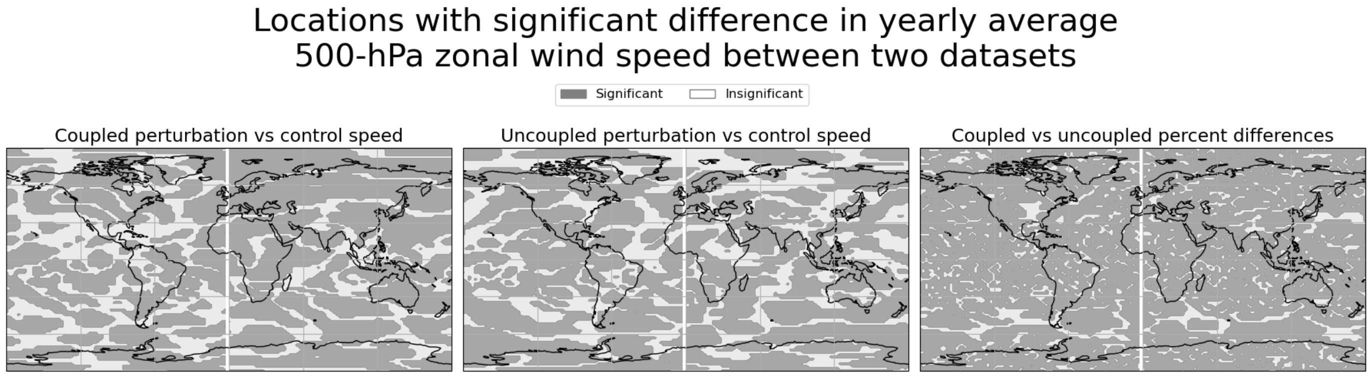

Figure 5: Significant changes in the coupled experiments when Arctic sea ice melts; then in the uncoupled; then significant differences in the changes between the two. 66.5% of the Earth's surface sees significant change in the coupled experiments, compared to 66.2% in the uncoupled. 78.7% of Earth sees a significant difference between the two. Regions of significance and insignificance are mixed in with each other.

3.3 Summertime temperature extremes

We define a temperature extreme as a temperature that is at the 95th percentile or higher of control temperatures on that date. For example, on June 1, the 95th percentile might be 30°C, so all June 1 measurements $\geq$ 30°C would be extreme; while on August 31, the 95th percentile might be 32°C instead. Tautologically, 5% of temperature observations in the control runs are extreme. Here, we compute how many temperature observations in the perturbation runs exceed the 95th percentile of the *control* runs, thus qualifying as extremes. We then divide by 5% to find the ratio of frequencies of extremes. For example, if 10% of perturbation temperatures qualify as extremes, then we have a ratio of 2: there are twice as many heat extremes in the perturbation run.

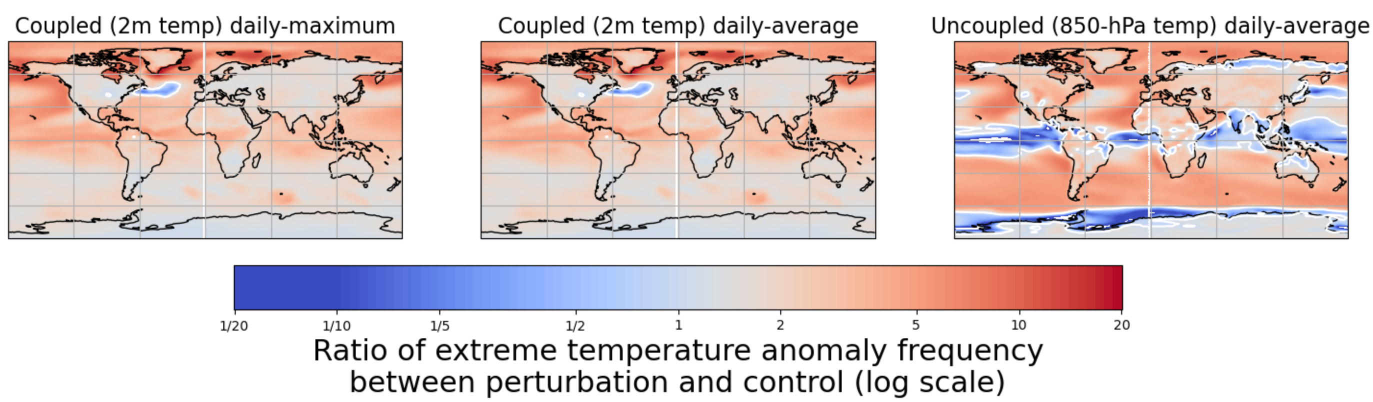

Figure 6: Data displayed on a log scale, so that the full extent of the rise in frequency of extremes is visible. In the Arctic in the coupled experiments, some locations see increases by factors of over 10, even up to 18. Because many values are close to 0, white contour lines represent values of 0 to allow us to distinguish between positives and negatives. We see that most values on the coupled map are positive.

In the coupled experiments, frequencies rise across almost all parts of the map (Fig. 6). In some locations, like the southern tip of Greenland, over 90% of temperature observations

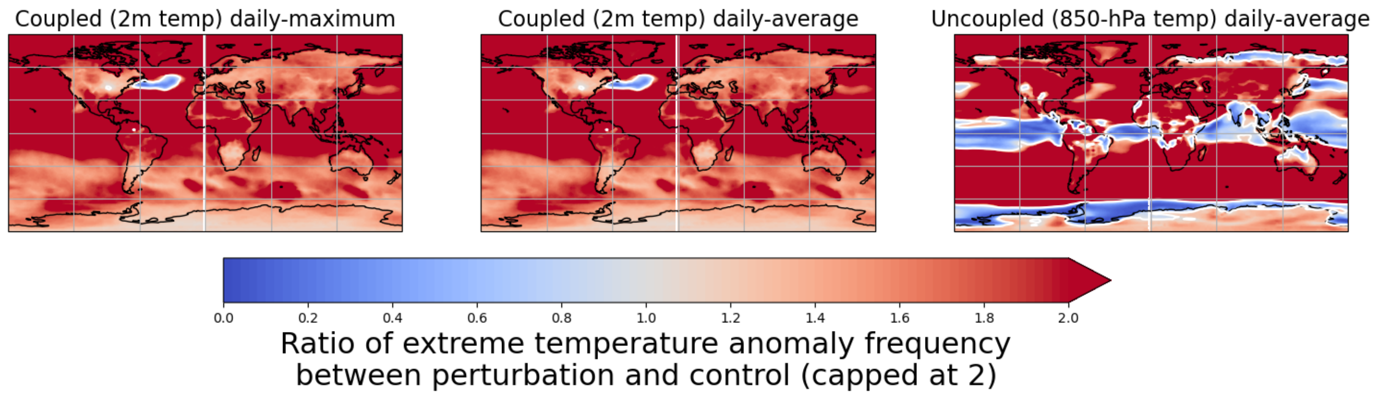

Figure 7: Data displayed on a linear scale from 0 to 2, where every value greater than 2 is colored the same as 2. This allows the details of the areas where frequencies increase by a factor less than 2 to become visible. We see smaller rises in the midlatitude regions in the coupled experiments.

qualify as extreme, for ratios of 18 or higher. Frequencies generally increase more over the ocean, often by factors of 5 or more; over the continents, the factor is often between 1 and 2 (Fig. 7). Land regions that see particularly strong increases – with factors mostly between 2 and 4 – include Central/South America, Africa, and Southeast Asia. In the uncoupled experiments, responses are more varied, with strong cooling patterns throughout the tropics and over the Southern Ocean. The difference between the daily-maximum map and the daily-average map are visually indistinguishable.

3.4 Summertime temperature spread

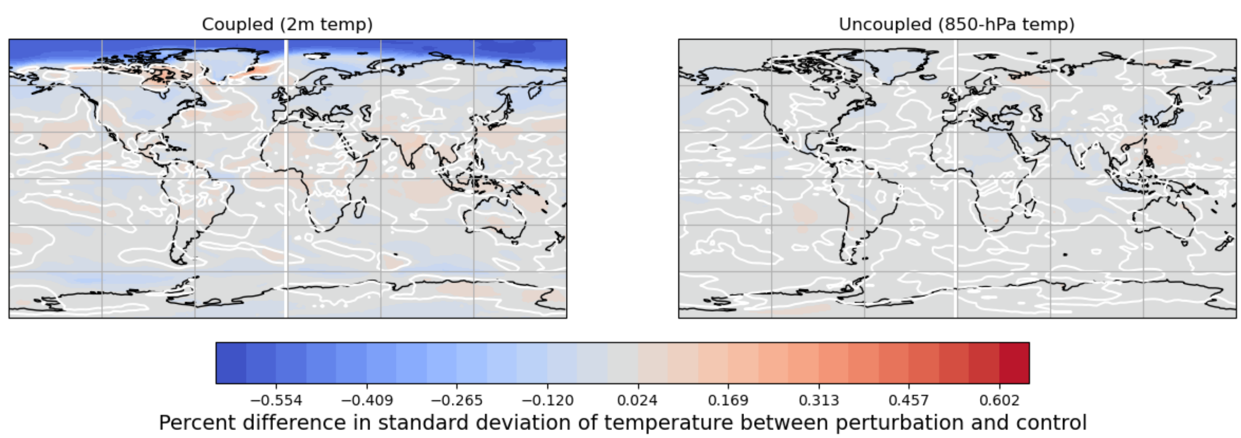

Figure 8: Standard deviations decrease in the Arctic of the coupled experiments, and don't change with any discernible pattern anywhere else.

We compute the standard deviations of temperature values in all four experiments, and the percent differences. This offers insights into the changes in frequencies of extremes – rising standard deviations would be associated with more increases in extremes. We find small changes in standard deviations across both maps except in the Arctic of the coupled experiments, where there's a strong decrease (Fig. 8).

4 Discussion

Broadly, we find that temperatures – both averages and extremes – project to increase significantly as a result of projected melting Arctic sea ice, and that ocean coupling is key to see this increase. When we compare daily-average temperatures between the perturbation and control runs, over 90% of the world sees a significant difference with ocean coupling, compared to less than 10% of the world without ocean coupling. This indicates that when we only consider atmospheric mechanisms, the global temperature response to melting Arctic sea ice is rather small, but when we also consider ocean mechanisms, the response is widespread.

However, we also see that ocean coupling itself has an impact on conditions in the atmosphere, which in turn seem to contribute to changes in temperature. In the coupled experiments, the northern hemisphere's polar jet shifts equatorward: wind speeds drop by over 1 m/s near the southern tip of Greenland, and pick up about 15° south of that. The motivation for looking at wind speed data in the first place is for its inverse association with temperatures: when wind slows down, weather patterns can stagnate, allowing hot areas to get hotter; and when it speeds up, it can blow through and relieve a place of some of its heat. This shift of the jet aligns quite well with the strongest signals from the temperature change data. Where wind slows down most strongly, we see the most radical increase in temperature, near the Southern tip of Greenland; and where it speeds up the most, we see the largest region of significant temperature drop. This indicates that atmospheric circulation has some explanatory power for the observed changes in temperature. However, note that these new circulation patterns were themselves a result of ocean coupling – we don't see such a clear shifting of the jet in the uncoupled experiments.

With temperature extremes, we also see largely global increase only in the coupled experiments. It is unclear what causes the tropical cooling patterns in the uncoupled experiments. In the coupled, we see the same amplification in the regions associated with the slowing jet – over 90% of temperatures qualify as extreme where the wind slows down, whereas extremes get cut in half under the jet stream's new peak. Frequencies increase more over the ocean than on land; on land, they increase more in the tropics than the midlatitude regions. In many land-based parts of the tropics, they double or more.

We also see that the difference between changes in daily-average extremes and daily-maximum extremes is small enough to not be visible on the maps, at least in the case of the coupled model, which is the only model for which we have daily-maximum data. This indicates that using daily-average data for this analysis is likely good enough even though daily-maximum data aligns better with the question we're actually asking.

While frequency of extremes increases globally, the spread of the temperature distribution does not change much outside of the Arctic, indicating that a rightward shift of the distribution is primarily responsible for this increase in number of extremes. If we were to measure temperature anomalies with respect to mean values in the perturbation run, rather than the control run, we would expect to not see very much change in frequency of extremes. In the Arctic, the distribution appears to be narrowing, with standard deviation values dropping substantially. This tells us that here, the increase in extremes is also caused by the rightward shift of the distribution, and that it would be even higher if the spread had stayed the same. Arctic temperatures collapse towards the mean value a bit, but the increase in mean is such that there's still an overall increase in the number of extreme temperatures observed.x

5 Conclusions

Globally, average and extreme summertime temperatures significantly rise as a result of melting Arctic sea ice. Ocean coupling is necessary to see this significance, which indicates that the driving mechanism is ocean-related. However, we also see strong association between changes in wind speed and changes in temperature in the ocean-coupled experiments, indicating that the ocean-related mechanism also has an impact on atmospheric circulation, which in turn is a driver behind this rise in temperature.

6 Recommendations

The results of this paper open up a number of paths for further research. Most trivially, it would be good to look at 2-meter temperature in both the coupled and uncoupled models, to ensure that the differences we see are not simply due to some property not shared between 2-meter temperature and 850-hPa temperature. It would also be ideal to have daily-maximum temperature values recorded in both pairs of experiments in addition to daily-average temperature values; in particular, we don't know for certain that there wouldn't be a difference between changes in daily-average extremes and daily-maximum extremes under the uncoupled model (though it seems likely that they would be the same).

Beyond data collection, there are a number of questions raised by this paper. One idea is that it would be interesting to analyze the relationship between wind changes and temperature changes more rigorously. Our analysis is limited to the visual observation that the strongest changes in both variables happen on the same parts of the map, with the relationship we'd expect them to have. Putting these variables in statistical conversation with each other would allow us to see whether changing wind has an affect on temperatures globally.

It is also unclear what's going on in the uncoupled extremes data. There is a large section across the tropics, and a smaller one across the Southern Ocean, where we see fewer extremes than before. Further research could investigate the cause of this unexpected behavior.

Further research could also look into the drop in standard deviation of temperature in the Arctic. The stark contrast with the seemingly negligible changes across the rest of the world is interesting; why would it be that temperatures in the Arctic collapse towards their mean, while temperatures elsewhere do not? And why is ocean coupling necessary to see this?

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