Substantial Weakening of Indian Summer Monsoon Synoptic Activity in Response to Polar Sea Ice Melt

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Abstract

The effect of polar sea ice melt on low latitude climate is little known. In order to understand the response of Indian summer monsoon (ISM) to the sea ice melt, we have run a suite of coupled and uncoupled climate model simulations. In one set of simulations, the albedo of sea ice is changed in such a way that it would melt as a result of increased absorption of solar radiation. We find a substantial weakening of ISM in sea ice melt experiments. Further, the genesis frequency of monsoon low-pressure systems (LPS) declines by about 40% in the sea ice melt simulations. A weakening and equatorward shift of ITCZ causes the decline in LPS genesis. Overall, the response of ISM to the sea ice melt resembles the response to greenhouse gas induced warming.

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Key Points:

- Mean monsoon and synoptic activity weaken in response to the Arctic and Antarctic sea ice melt in climate model simulations
- The genesis of monsoon low-pressure systems declines by 40%
- Decline in LPS genesis is linked to an equatorward shift in ITCZ over the Indian Ocean

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Abstract

The effect of polar sea ice melt on low latitude climate is little known. In order to understand the response of Indian summer monsoon (ISM) to the sea ice melt, we have run a suite of coupled and uncoupled climate model simulations. In one set of simulations, the albedo of sea ice is changed in such a way that it would melt as a result of increased absorption of solar radiation. We find a substantial weakening of ISM in sea ice melt experiments. Further, the genesis frequency of monsoon low-pressure systems (LPS) declines by about 40% in the sea ice melt simulations. A weakening and equatorward shift of ITCZ causes the decline in LPS genesis. Overall, the response of ISM to the sea ice melt resembles the response to greenhouse gas induced warming.

Plain Language Summary

The Arctic and Antarctic sea ice are melting rapidly which can have feedback effects on climate system. However, the effect of sea ice melt on low latitude climate is not adequately understood. The Indian summer monsoon, known as the lifeline of Southeast Asia, is important to the water security of more than 1.5 billion people. We examined the response of Indian summer monsoon to the polar sea ice melt using a suite of global climate model experiments. Our simulations show that the monsoon circulation and rainfall weakens substantially in response to the sea ice melt. Further, the propagating precipitating vortices embedded in the monsoon circulation declined by about 40% in the sea ice melt experiments. Our results suggest that the Arctic and Antarctic sea ice melt can have serious implications on the water security of Southeast Asia.

1 Introduction

The effect of Arctic and Antarctic sea ice melt on tropical climate is little known until recently. However, the recent evidences suggest that the polar sea ice melt can affect the deep tropics. The sea ice melt can have far reaching effects on global climate system through surface energy imbalance and the response of ocean dynamics (Screen & Simmonds, 2010; Serreze & Barry, 2011). Due to the thermal inertia of the oceans, the effect of sea ice melt can persist for multiple seasons (Francis et al., 2009). Experiments using atmospheric general circulation models (AGCM) have shown that the Arctic sea ice depletion explains most of the seasonal pattern of high latitude climate response to enhanced green house gas (GHG) warming (Deser et al., 2010).

The effects of sea ice melt and the Arctic amplification on mid-latitude climate are clear through the changes in storm tracks, jetstream, and the Rossby wave activity (Rinke et al., 2017; Francis & Vavrus, 2012). These changes cause an increased frequency of extreme weather events, such as floods, heatwaves, and severe cyclonic storms in the mid and high latitude regions (Cohen et al., 2014; Budikova, 2009). The effects of sea ice melt on low latitude weather have only recently started receiving attention from the research community. One possible channel for the changes in the Arctic to influence the tropics is through the response of oceanic heat transport (Tomas et al., 2016). It is well known that the Atlantic meridional overturning cell, which plays a key role in oceanic heat transport, would weaken in response the Arctic sea ice melt (Sevellec et al., 2017; Liu & Fedorov, 2019). The effect of Arctic amplification on the atmospheric thickness and subsequent changes in the equatorward Rossby wave propagation can be another channel for Arctic to tropics teleconnection (Francis & Vavrus, 2012). However, the low latitude impact of the Arctic sea ice melt was not clear in terms of response of the extreme weather events(Barnes et al., 2014; Wallace et al., 2014). Possible teleconnection between the Arctic sea ice variability and the Asian summer monsoon has been suggested on intraseasonal scales (Guo et al., 2014; Krishnamurti et al., 2015; Chatterjee et al., 2021).

In climate model simulations, in the absence of ocean dynamics, the effect of Arctic sea ice melt is largely confined to regions poleward of 30°N while the addition of ocean dynamics resulted in an equatorward shift of the inter-tropical convergence zone (ITCZ) (Deser et al., 2015; Liu & Fedorov, 2019). When only the thermodynamic coupling is retained by suppressing dynamic coupling, the ITCZ and Hadley cell shifted poleward in response to the Arctic sea ice melt (Tomas et al., 2016). The changes in the mean position of ITCZ can affect the tropical cyclone (TC) genesis (Molinari & Vollaro, 2013; Berry & Reeder, 2014). Aquaplanet simulations suggest that poleward shift in ITCZ would result in an increased frequency of TC like synoptic scale weather systems (Ballinger et al., 2015). Deng et al. (2018) argued that the variability in the Arctic sea ice might influence the mid-Pacific trough which in turn can affect the TC genesis over the Northwest Pacific. The response of ocean dynamics to the sea ice melt can induce a global oceanic response (Deser et al., 2010; Liu & Fedorov, 2019). Such an oceanic response can have far reaching effects on earth's climate system, including tropical cyclones and monsoons.

One of the reasons for a lack of understanding of the effect of sea ice melt on the genesis of high impact tropical weather systems is that the coarse-resolution simulations using coupled models do not resolve TCs and monsoon low-pressure systems (LPS). One way to overcome this issue is to run high-resolution AGCM simulations forced with the sea surface temperatures (SST) and sea ice concentrations (SIC) from coupled model experiments (Murakami et al., 2011; Sandeep et al., 2018). The effect of global sea ice melt on mean and synoptic scale features of ISM is not understood. The synoptic scale vortices embedded in the monsoon circulation, known as LPS, contribute more than half of the total precipitation over the continental India (Praveen et al., 2015; Hunt et al., 2016). Here we investigate the response of monsoon LPS to the global sea ice melt using a series of coarse-resolution coupled and high-resolution uncoupled climate model simulations.

2 Data and methods

A control experiment (CTRL) is performed by running the community earth system model (CESM) version 1.2.2 (Hurrell et al., 2013) in a fully coupled mode, with preindustrial (B1850_CAM5) forcing, for 350 years. The atmosphere and land are configured with a 0.9x1.25 degree horizontal resolution while the ocean and sea ice share a variable resolution gx1v6 displaced pole grid. In another experiment, the CESM model is restarted from the 300$^{\mathrm{th}}$ year of CTRL experiment and run for 50 years. In the latter experiment, we decreased the albedo of bare and ponded sea ice and snow cover on ice over the Arctic and Antarctic Oceans in the sea ice component of CESM. Specifically, we changed the parameters R_{ice} and R_{pnd} from 0 to -2. Also, we reduced the single scattering albedo of snow by 10% for all spectral bands. These settings are similar to Liu and Fedorov (2019). The changes in albedo will result in the melting of sea ice due to an increased absorption of solar radiation. We designate this simulation as sea ice melt experiment (SIME).

TCs and monsoon LPS are not adequately resolved in the coarse resolution coupled model simulations. In order to save computational resources, we have designed a set of high-resolution AGCM simulations using the community atmospheric model (CAM5). The CAM5 model is run at 50 km horizontal resolution and forced with the annual cycles of sea surface temperatures (SST) and sea ice concentrations (SIC) from the CTRL and SIME simulations. The annual cycles of monthly climatology of SST and SIC are constructed using the last 10 years of the CTRL and SIME simulations. The other forcing of CAM5 are fixed at year 2000 conditions for both the experiments. An ensemble of four runs of CAM5 have been done by slightly perturbing the SST boundary condition for both the experiments. Each annual cycle experiment span four years and first year is discarded in the analysis to avoid spin up. Similar high-resolution AGCM experiments forced with SST and SIC annual cycles from coupled models have been done by

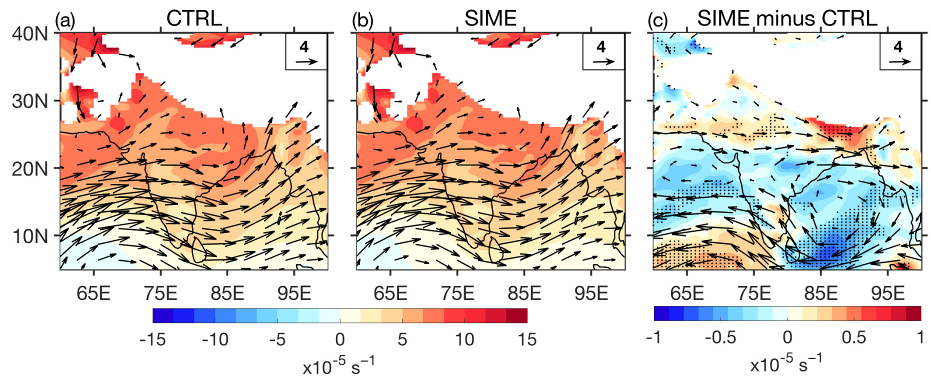

Figure 1. JJAS mean, ensemble mean wind vectors and absolute vorticity at 850 hPa for (a) CTRL and (b) SIME simulations, and (c) ensemble mean SIME minus CTRL wind vectors and absolute vorticity at 850 hPa. Stippling in (c) denote the statistically significant (at 95% confidence level) difference between SIME and CTRL absolute vorticity, as revealed by a t-test

Sandeep et al. (2018) to investigate the changes in LPS activity in a warming scenario. The results presented here pertain to the CAM5 ensemble mean, unless otherwise mentioned.

The trajectories of LPS in the CAM5 simulations are tracked using Praveen et al. (2015) tracking algorithm. This algorithm detects and track LPS from gridded daily sea level pressure (SLP) data by identifying closed isobars at every 1 hPa interval. This algorithm also classifies the LPS according to their intensity category based on the pressure depth (ΔSLP). The categorization of monsoon LPS over the Indian region is shown in Table S1. Further, we have used the LPS data extracted by Praveen et al. (2015) from the daily gridded SLP of European Centre Interim Reanalysis (ERAI). This data is also reported by Meera et al. (2019).

3 Results and Discussion

The ensemble mean June - September (JJAS) mean wind vectors and the absolute vorticity at 850 hPa resemble the typical Indian summer monsoon (ISM) low-level flow pattern (Fig. 1 a). The maximum low-level vorticity is seen over the monsoon trough region, extending from northwest India to the head Bay of Bengal. The head Bay of Bengal is the core genesis region of monsoon LPS (Sikka, 1977). The wind vectors and absolute vorticity climatology from SIME simulations also show a similar pattern as in the CTRL runs (Fig. 1b). In order to understand the difference between the two experiments, the difference in the wind vectors and absolute vorticity climatology between the two experiments is computed (Fig. 1c). The difference plot shows a weakening of low-level circulation and the absolute vorticity over the Indian region, with the maximum weakening seen over the Bay of Bengal. These results suggest that the ISM circulation would weaken in response to the melting of the Arctic and Antarctic sea ice. Recent studies suggest that the polar sea ice melt in climate model simulations produces climate system response patterns reminiscent of global warming induced by greenhouse gas emissions (Liu & Fedorov, 2019; England et al., 2020). The annual climatology and seasonal cycle of the SIC from coupled model simulations show a substantial melting of the sea ice in both polar regions in SIME experiment (Fig. S1, S2). The SST climatology shows a warming over the tropical oceans (Fig. S3). It is interesting to note that the pattern of decline in SIC closely resembles that in the end of 21st century projections under RCP8.5 scenario (Fig. S2). The ISM is known to weaken in a warming scenario and hence the

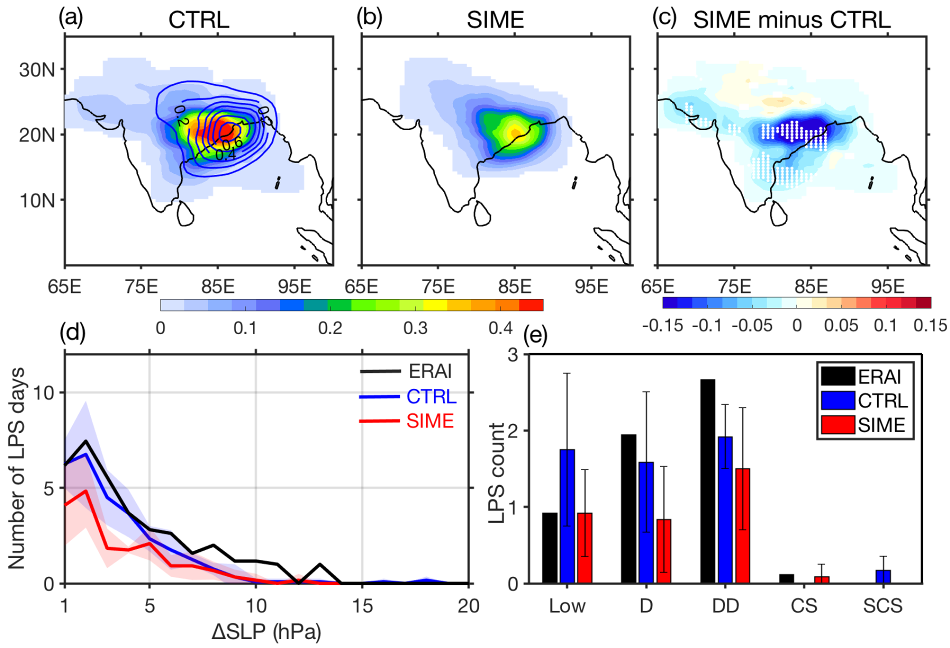

Figure 2. JJAS mean, ensemble mean LPS track density (unit: number of LPS per grid per season) for (a) CTRL and (b) SIME simulations; (c) ensemble mean difference between SIME and CTRL track density, (d) JJAS mean distributions of LPS days as a function of pressure depth (Δ SLP) of LPS, and (e) category-wise distribution of JJAS mean LPS counts in observations and model simulations. Stippling in (c) denote the statistically significant ($p<0.05$) difference between SIME and CTRL LPS track density, as revealed by a t-test. The blue (red) shading in (d) shows the ensemble spread in CTRL (SIME) experiments. The error bars in (e) also show ensemble spread (± 1 *std*) in CTRL and SIME runs. The calculations using ERAI are done for the period 1979-2014.

weakening seen in response to the global sea ice melt is not entirely surprising (Krishnan et al., 2013).

Ditchek et al. (2016) found a relationship between the monthly mean fields of monsoon and the monthly LPS genesis. A weakening in the mean low-level circulation and the associated vorticity in a warming climate was attributed to a significant decrease in the monsoon LPS activity simulated by an AGCM (Sandeep et al., 2018). In this wake, we explore the changes in LPS activity over India in response to the polar sea ice melt. The ensemble mean track density of LPS in CTRL runs of CAM5 shows a maximum in the LPS genesis over the head Bay of Bengal and the adjoining continental India (Fig. 2a). Further, the climatological LPS track density pattern in CTRL ensemble has a close match with the observations and the earlier high-resolution AGCM simulations (Krishnamurthy & Ajayamohan, 2010; Hurley & Boos, 2015; Sandeep et al., 2018; Thomas et al., 2021). The LPS track density shows about 32% weakening in the SIME ensembles in comparison to the CTRL runs (Fig. 2b). The difference plot between the CTRL and SIME track density shows a significant decrease in the LPS track density over the entire monsoon domain in the latter experiment. The weakening of LPS activity in response to the polar sea ice melt is closely comparable to that in global warming projections, except for a lack of northward shift in the storm genesis (Sandeep et al., 2018). The poleward shift in the low-level monsoon circulation and the LPS genesis in global warming simulations

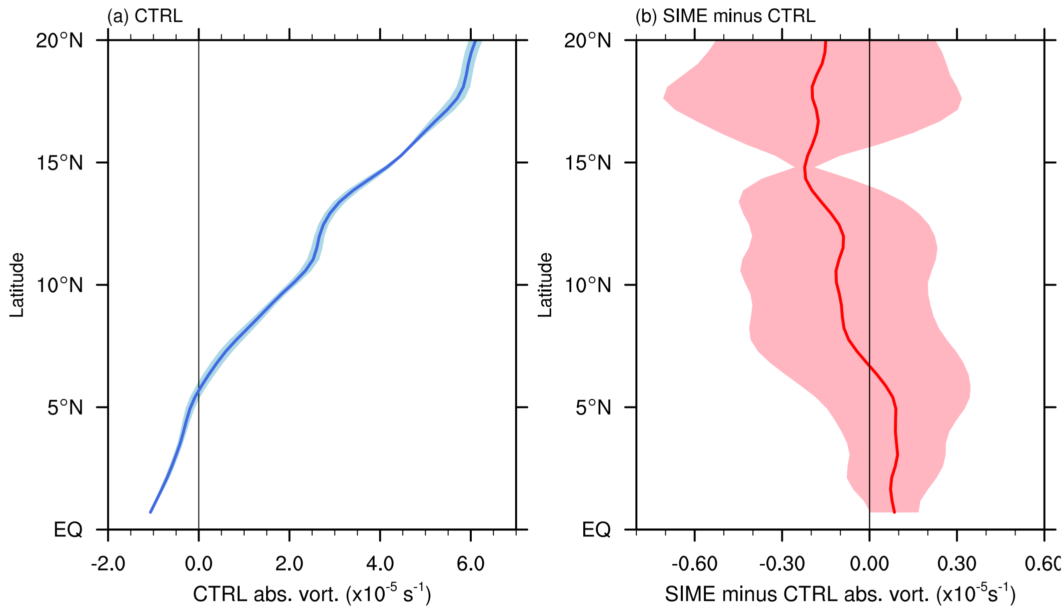

Figure 3. July-August mean zonal mean (50°E - 100°E) absolute vorticity at 850 hPa from (a) CTRL simulations and (b) difference in July - August mean absolute vorticity between SIME and CTRL simulations. The solid line shows ensemble mean and the shading ensemble spread

might be caused by an increase in the land-ocean temperature contrast over the Southeast Asian region (Sandeep & Ajayamohan, 2015).

The decline in the LPS activity can be due to a decrease in the intensity of the storms or a decrease in the storm genesis frequency or a combination of the two. The distribution of ΔSLP of LPS indicate the intensity of the storms during their life cycle (Fig. 2d). The model simulates the observed distribution of ΔSLP during the lifecycle of the storms, except for less number of high intensity storm days. The distribution of JJAS mean LPS counts in each intensity category shows that the CTRL ensembles have simulated more number of weaker LPS and less number of stronger LPS compared to the observations (Fig. 2e). Also, the SIME simulations show a decrease in the LPS numbers in all intensity categories, with about 40% decline across all categories. This suggest that the decline in the LPS activity is due to a decrease in the number as well as intensity of storms in the sea ice melt experiments.

Recent evidences suggest an equatorward shift in the ITCZ in response to the Arctic sea ice melt (Deser et al., 2015; Liu & Fedorov, 2019). Such a shift in ITCZ can result in a weakening of the cyclogenesis (Merlis et al., 2013; Ballinger et al., 2015). We examine the changes in the regional ITCZ over the Indian monsoon region that may explain the decline in LPS activity. The ITCZ can be identified as the centroid of maximum precipitation or the latitude of low-level zero absolute vorticity (Tomas & Webster, 1997; Liu & Fedorov, 2019). The zonal mean ensemble mean July-August absolute vorticity at 850 hPa from the CTRL experiments show a change of sign at around 6°N and a maximum around 20°N (Fig. 3a). We choose July-August as it is the peak LPS genesis period. The ensemble mean difference in the July-August zonal mean absolute vorticity shows a weakening north of about 7°N and a relative strengthening in the equatorward region (Fig. 3b). This is an indication of a decrease in the convergence over the core LPS genesis region and an equatorward shift in the ITCZ. A similar analysis using zonal mean July-August precipitation over the region shows consistent result. One difference in the zonal mean profile of the precipitation is the presence of a bimodal peak,

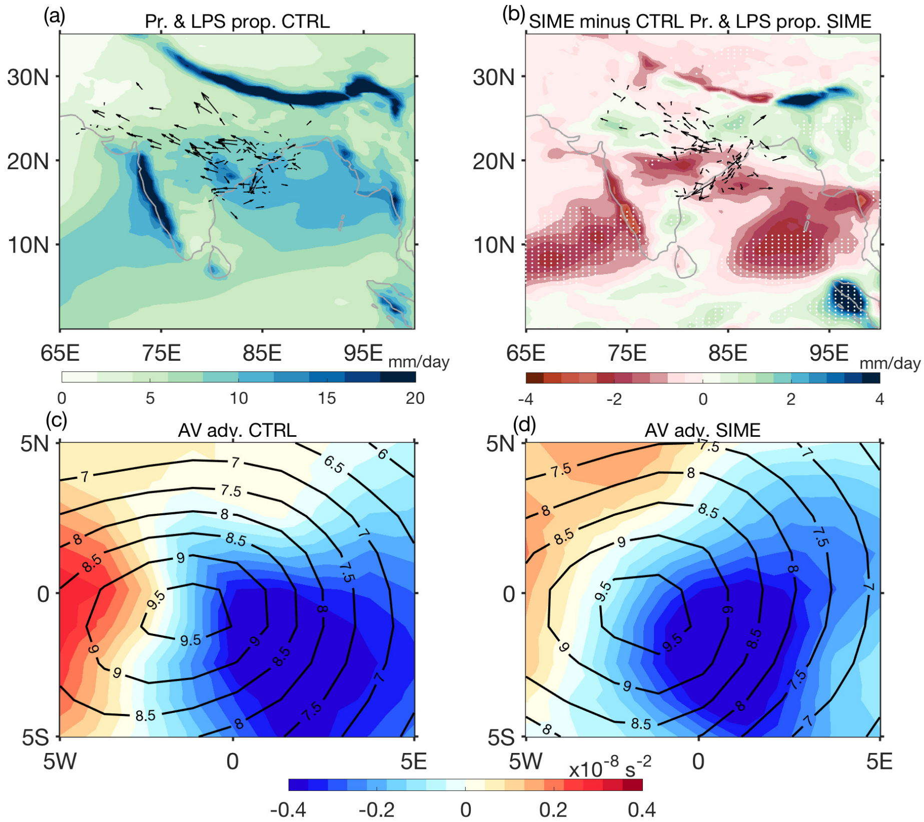

Figure 4. Top panel: (a) Ensemble mean JJAS mean precipitation (shading) LPS propagation vectors from CTRL and (b) difference in precipitation (shading) between SIME and CTRL, and LPS propagation vectors in SIME. Stippling shows statistically significant (at 95% confidence level) change in precipitation as revealed by a *t*-test. Bottom panel: Storm centered composites of 500 - 250 hPa averaged absolute vorticity (contours; units: x10^{-5} s^{-1}) and absolute vorticity advection (shading; units: x10^{-8} s^{-2}) for (c) CTRL and (d) SIME simulations.

with one between equator and 5°N and a larger peak around 18°N (Fig. S4). The difference in the zonal mean precipitation between SIME and CTRL shows a weakening (strengthening) north (south) of 5°N, consistent with the changes in absolute vorticity.

The propagation of LPS to the deep interior parts of the Indian landmass plays a crucial role in the distribution of precipitation during summer monsoon season. The ensemble mean propagation vectors of LPS from the CTRL simulations show a north-westward propagation (Fig. 4a) that is closely comparable with the observed horizontal advection of LPS (Krishnamurthy & Ajayamohan, 2010; Hurley & Boos, 2015; Srujan et al., 2021). The LPS propagation in SIME ensemble is weak and not penetrating to the northwestern India (Fig. 4b). The seasonal mean precipitation climatology in CTRL ensemble shows a band of non-orographic precipitation maxima aligned with the LPS propagation vectors. A widespread weakening of ISM precipitation can be seen in SIME ensemble, a part of which might be contributed by the weaker LPS activity. One of the suggested mechanisms of the LPS propagation is vorticity advection. The storm-centered composite of 500 - 250 hPa averaged absolute vorticity shows a maximum in the southwest quadrant of the storm in the CTRL ensemble (Fig. 4c) as observed (Sikka, 1977; Hurley & Boos, 2015). The advection of absolute vorticity shows a westward propagation that explains to a larger extent the simulated LPS propagation. In the SIME ensemble, the absolute vorticity and the advection of the absolute vorticity associated with the simulated LPS weaken (Fig. 4d). This explains the weaker LPS propagation in the SIME simulations.

4 Conclusions

The Arctic and Antarctic sea ice are projected to have ice free summers towards the end of the 21st century in simulations of high emission scenarios. The global sea ice melting is shown to affect tropical climate, primarily through ocean dynamics. However, the effect of sea ice melt on major tropical climate systems such as Indian summer monsoon is not understood. We have performed a suite of coupled and uncoupled climate model simulations to understand the impact of global sea ice melt on the Indian summer monsoon. Our results show that the ISM circulation would weaken significantly in response to the global sea ice melt. Further, the monsoon LPS that are responsible for more than half of the continental Indian rainfall weakens in the sea ice melt simulations. The weakening and an equatorward shift of the ITCZ over the Indian monsoon region cause a reduction in the LPS activity over the Bay of Bengal in the sea ice melt scenario. Our analysis show that about 40% decrease in the number of LPS occurs in response to the global sea ice melt. The horizontal advection of LPS also weakens in the sea ice melt simulations. These results suggest that the polar sea ice melt can have a substantial impact on the Indian summer monsoon through a weakening of the synoptic activity that is crucial for rainfall distribution over land.

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Open Research

The CESM-CAM5 model simulations and LPS tracks data (Chandra, 2021) can be accessed from `https://osf.io/bhqgd`.

References

Ballinger, A. P., Merlis, T. M., Held, I. M., & Zhao, M. (2015). The sensitivity of tropical cyclone activity to off-equatorial thermal forcing in aquaplanet simulations. *Journal of the Atmospheric Sciences*, *72*(6), 2286-2302. doi: 10.1175/JAS-D-14-0284.1

Barnes, E. A., Dunn-Sigouin, E., Masato, G., & Woollings, T. (2014). Exploring recent trends in northern hemisphere blocking. *Geophysical Research Letters*, *41*(2), 638-644. doi: 10.1002/2013GL058745

Berry, G., & Reeder, M. J. (2014). Objective identification of the intertropical convergence zone: Climatology and trends from the era-interim. *Journal of Climate*, *27*(5), 1894 - 1909. doi: 10.1175/JCLI-D-13-00339.1

Budikova, D. (2009). Role of arctic sea ice in global atmospheric circulation: A review. *Global and Planetary Change*, *68*(3), 149 - 163. doi: 10.1016/j.gloplacha.2009.04.001

Chandra, V. (2021). *Substantial weakening of indian summer monsoon synoptic activity in response to polar sea ice melt.* Retrieved from `https://osf.io/bhqgd`

Chatterjee, S., Ravichandran, M., Murukesh, N., Raj, R. P., & Johannessen, O. M. (2021). A possible relation between arctic sea ice and late season indian summer monsoon rainfall extremes. *npj Clim Atmos Sci*, *4*. doi: 10.1038/s41612-021-00191-w

Cohen, J., Screen, J., Furtado, J., Barlow, M., Whittleston, D., Coumou, D., ... Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geosci*, *7*, 627–637. doi: 10.1038/ngeo2234

Deng, K., Yang, S., Ting, M., Hu, C., & Lu, M. (2018). Variations of the mid-Pacific trough and their relations to the Asian–Pacific–North American climate: Roles of tropical sea surface temperature and Arctic sea ice. *Journal of Climate*, *31*(6), 2233-2252. doi: 10.1175/JCLI-D-17-0064.1

Deser, C., Tomas, R., Alexander, M., & Lawrence, D. (2010). The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century. *Journal of Climate*, *23*(2), 333-351. doi: 10.1175/2009JCLI3053.1

Deser, C., Tomas, R. A., & Sun, L. (2015). The role of ocean–atmosphere coupling in the zonal-mean atmospheric response to arctic sea ice loss. *Journal of Climate*, *28*(6), 2168-2186. doi: 10.1175/JCLI-D-14-00325.1

Ditchek, S. D., Boos, W. R., Camargo, S. J., & Tippett, M. K. (2016). A genesis index for monsoon disturbances. *Journal of Climate*, *29*(14), 5189 - 5203. doi: 10.1175/JCLI-D-15-0704.1

England, M., Polvani, L., Sun, L., & Deser, C. (2020). Tropical climate responses to projected Arctic and Antarctic sea-ice loss. *Nature Geoscience*, *13*, 275-281. doi: 10.1038/s41561-020-0546-9

Francis, J. A., Chan, W., Leathers, D. J., Miller, J. R., & Veron, D. E. (2009). Winter northern hemisphere weather patterns remember summer Arctic sea-ice extent. *Geophysical Research Letters*, *36*(7), L07503. doi: 10.1029/2009GL037274

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*(6). doi: 10.1029/2012GL051000

Guo, D., Gao, Y., Bethke, I., Gong, D., Johannessen, O. M., & Wang, H. (2014). Mechanism on how the spring arctic sea ice impacts the east asian summer monsoon. *Theor Appl Climatol*, *115*, 107-119.

Hunt, K. M. R., Turner, A. G., & Parker, D. E. (2016). The spatiotemporal structure of precipitation in Indian monsoon depressions. *Quart. J. Roy. Meteor. Soc.*, *142*, 3195–3210.

Hurley, J. V., & Boos, W. R. (2015). A global climatology of monsoon low-pressure systems. *Quarterly Journal of the Royal Meteorological Society*, *141*(689), 1049-1064. doi: 10.1002/qj.2447

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., … Marshall, S. (2013). The community earth system model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, *94*(9), 1339 - 1360. doi: 10.1175/BAMS-D-12-00121.1

Krishnamurthy, V., & Ajayamohan, R. S. (2010). Composite structure of monsoon low pressure systems and its relation to indian rainfall. *Journal of Climate*, *23*(16), 4285-4305. doi: 10.1175/2010JCLI2953.1

Krishnamurti, T. N., Krishnamurti, R., Das, S., Kumar, V., Jayakumar, A., & Simon, A. (2015). A pathway connecting the monsoonal heating to the rapid arctic ice melt. *Journal of the Atmospheric Sciences*, *72*(1), 5 - 34. doi: 10.1175/JAS-D-14-0004.1

Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., … Rajendran, K. (2013). Will the South Asian monsoon overturning circulation stabilize any further? *Clim Dyn*, *40*, 187–211. doi: 10.1007/s00382-012-1317-0

Liu, W., & Fedorov, A. V. (2019). Global impacts of arctic sea ice loss mediated by the atlantic meridional overturning circulation. *Geophysical Research Letters*, *46*(2), 944-952. doi: 10.1029/2018GL080602

Meera, M., Suhas, E., & Sandeep, S. (2019). Downstream and in situ: Two perspectives on the initiation of monsoon low-pressure systems over the bay of bengal. *Geophysical Research Letters*, *46*(21), 12303-12310. doi: 10.1029/2019GL084555

Merlis, T. M., Zhao, M., & Held, I. M. (2013). The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations. *Geophysical Research Letters*, *40*(15), 4109-4114. doi: https://doi.org/10.1002/grl.50680

Molinari, J., & Vollaro, D. (2013). What percentage of western north pacific tropical cyclones form within the monsoon trough? *Monthly Weather Review*, *141*(2), 499 - 505. doi: 10.1175/MWR-D-12-00165.1

Murakami, H., Wang, B., & Kitoh, A. (2011). Future change of western north pacific typhoons: Projections by a 20-km-mesh global atmospheric model. *Journal of Climate*, *24*(4), 1154 - 1169. doi: 10.1175/2010JCLI3723.1

Praveen, V., Sandeep, S., & Ajayamohan, R. S. (2015). On the relationship between mean monsoon precipitation and low pressure systems in climate model simulations. *Journal of Climate*, *28*(13), 5305-5324. doi: 10.1175/JCLI-D-14-00415.1

Rinke, A., Maturilli, M., Graham, R. M., Matthes, H., Handorf, D., Cohen, L., … Moore, J. C. (2017). Extreme cyclone events in the Arctic: Wintertime variability and trends. *Environmental Research Letters*, *12*(9), 094006. doi: 10.1088/1748-9326/aa7def

Sandeep, S., & Ajayamohan, R. S. (2015). Poleward shift in indian summer monsoon low level jetstream under global warming. *Clim Dyn*, *45*, 337–351. doi: 10.1007/s00382-014-2261-y

Sandeep, S., Ajayamohan, R. S., Boos, W. R., Sabin, T. P., & Praveen, V. (2018). Decline and poleward shift in indian summer monsoon synoptic activity in a warming climate. *Proc. Natl. Acad. Sci. USA*, *115*(11), 2681–2686. doi: 10.1073/pnas.1709031115

Screen, J. A., & Simmonds, I. (2010). Increasing fall-winter energy loss from the Arctic ocean and its role in Arctic temperature amplification. *Geophysical Research Letters*, *37*(16). doi: 10.1029/2010GL044136

Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, *77*(1), 85 - 96. doi: 10.1016/j.gloplacha.2011.03.004

Sevellec, F., Fedorov, A., & Liu, W. (2017). Arctic sea-ice decline weakens the Atlantic meridional overturning circulation. *Nature Clim Change*, *7*, 604–610. doi: 10.1038/nclimate3353

Sikka, D. R. (1977). Some aspects of the life history, structure and movement of monsoon depressions. *PAGEOPH*, *115*, 1501–1529. doi: 10.1007/BF00874421

Srujan, K. S. S. S., Sandeep, S., & Suhas, E. (2021). Downstream and in situ genesis of monsoon low-pressure systems in climate models. *Earth and Space Science*, *8*(9), e2021EA001741. doi: https://doi.org/10.1029/2021EA001741

Thomas, T., Bala, G., & Srinivas, V. (2021). Characteristics of the monsoon low pressure systems in the indian subcontinent and the associated extreme precipitation events. *Clim Dyn*, *56*, 1859–1878. doi: 10.1007/s00382-020-05562-2

Tomas, R. A., Deser, C., & Sun, L. (2016). The role of ocean heat transport in the global climate response to projected Arctic sea ice loss. *Journal of Climate*, *29*(19), 6841-6859. doi: 10.1175/JCLI-D-15-0651.1

Tomas, R. A., & Webster, P. J. (1997). The role of inertial instability in determining the location and strength of near-equatorial convection. *Quarterly Journal of the Royal Meteorological Society*, *123*(542), 1445-1482. doi: https://doi.org/10.1002/qj.49712354202

Wallace, J. M., Held, I. M., Thompson, D. W. J., Trenberth, K. E., & Walsh, J. E. (2014). Global warming and winter weather. *Science*, *343*(6172), 729–730. doi: 10.1126/science.343.6172.729

Supporting Information for "Substantial Weakening of Indian Summer Monsoon Synoptic Activity in Response to Polar Sea Ice Melt"

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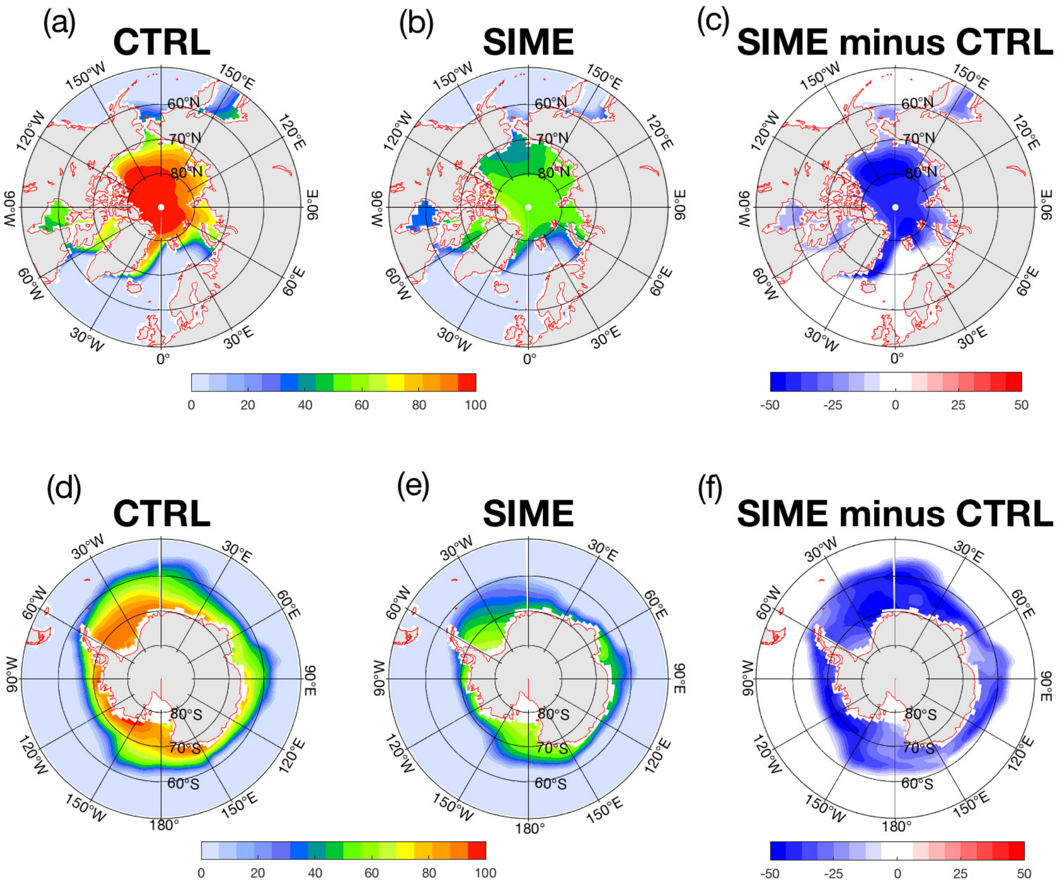

Figure S1. Annual mean climatology of sea ice concentration (%) over the Arctic in (a) CTRL and (b) SIME experiments, and (c) the difference in annual mean climatology of sea ice concentration over the Arctic between SIME and CTRL. (d) - (f) Same as (a) - (c), except for the Antarctic sea ice concentration.

Table S1. Categorization of monsoon LPS based on pressure depth (ΔSLP)

Δ SLP (hPa)	LPS category
≤ 2	Low
> 2 and ≤ 4	Depression
> 4 and ≤ 10	Deep depression
> 10 and ≤ 16	Cyclonic storm
> 16	Severe cyclonic storm

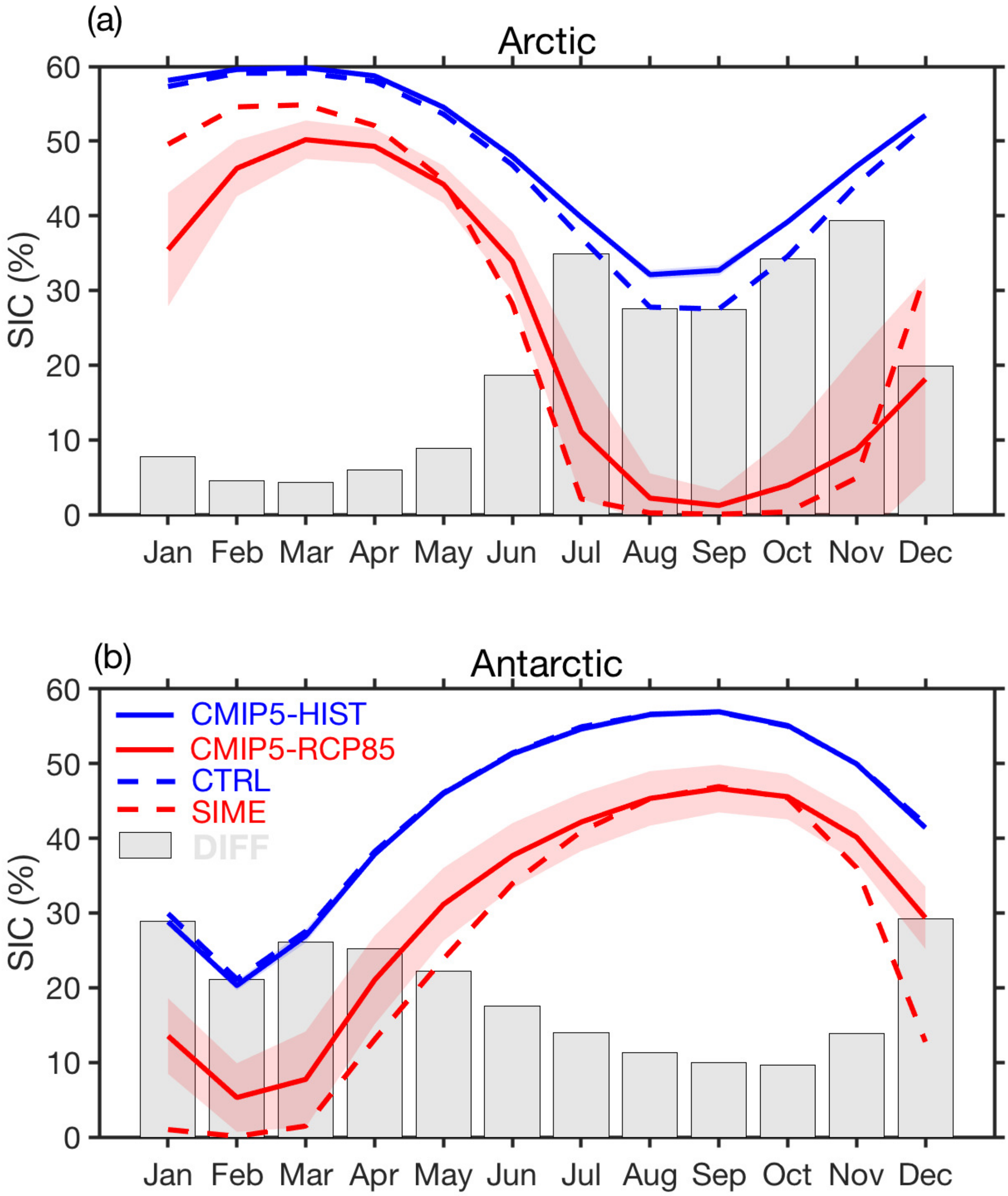

Figure S2. Seasonal cycle of sea ice concentration over the (a) Arctic and (b) Antarctic from the CTRL, SIME, historical, and RCP8.5 simulations. The historical (RCP8.5) simulations of CESM1.1 for 1981 - 2000 (2081 - 2100) period are considered. The bars show the difference in SIC between CTRL and SIME experiments.

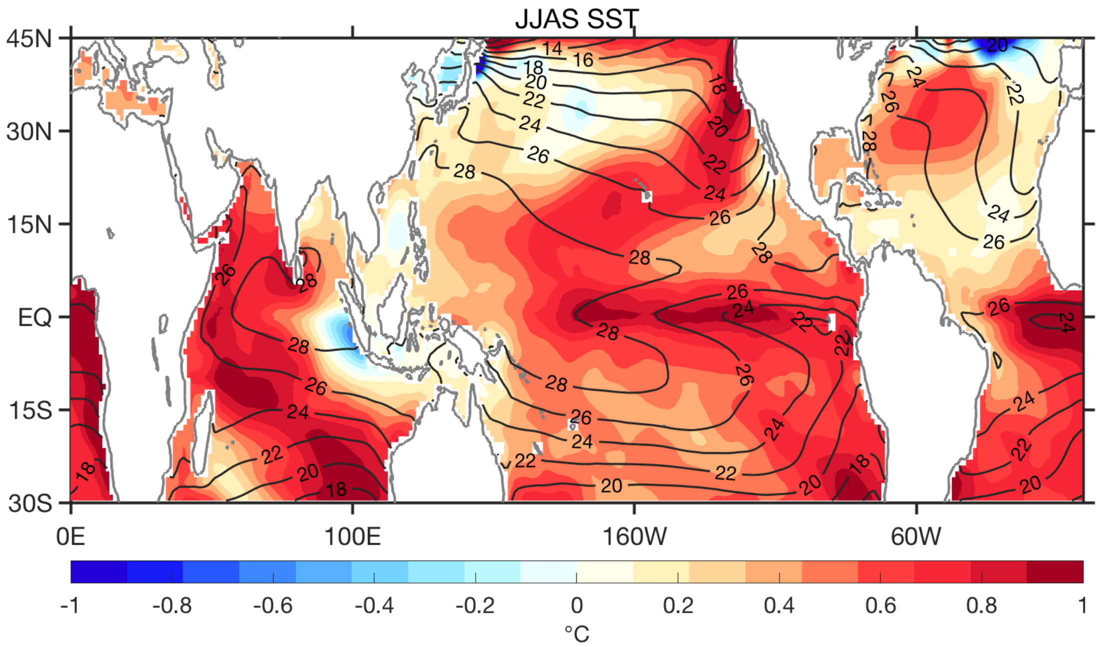

Figure S3. June - September mean climatology of sea surface temperature from CTRL simulation (contours; unit: °C) and the difference between SIME and CTRL simulations (shading). The calculations are based on the last 10 years of simulations.

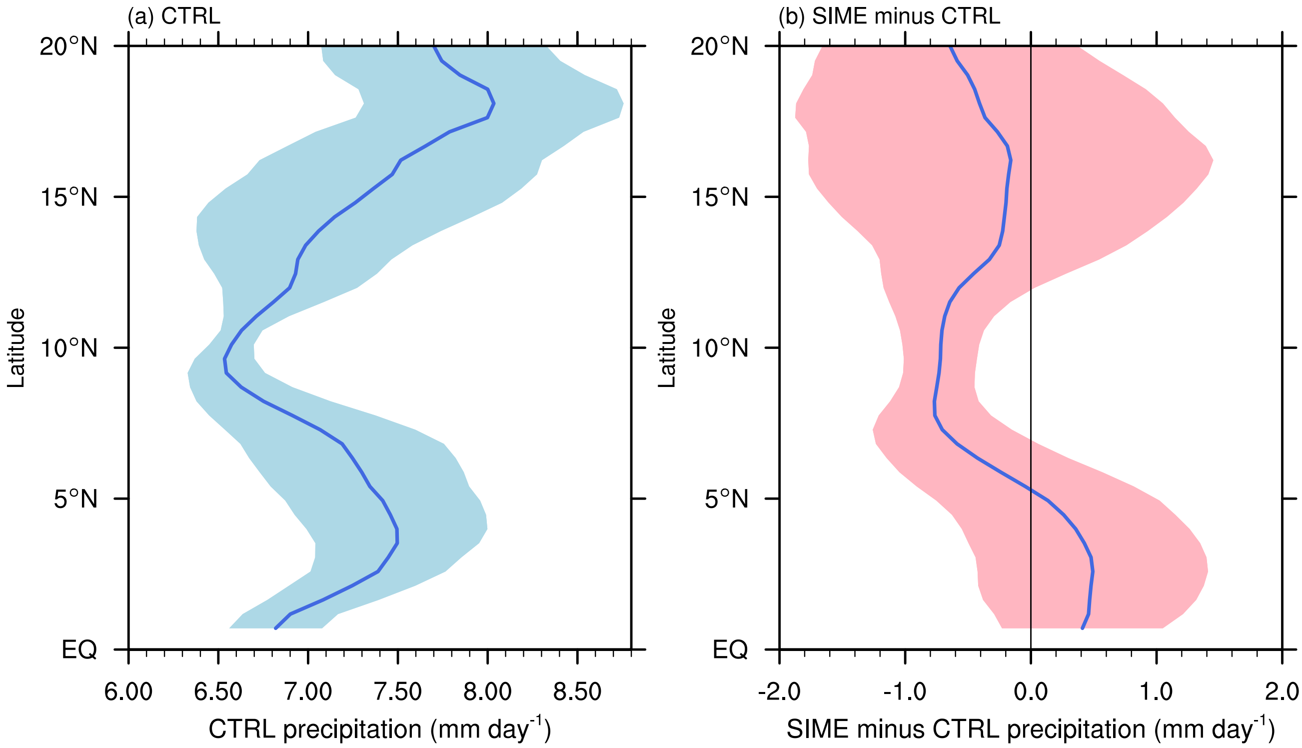

Figure S4. July-August mean zonal mean (50°E - 100°E) precipitation from (a) CTRL simulations and (b) difference in July - August mean precipitation between SIME and CTRL simulations. The solid line shows ensemble mean and the shading ensemble spread