Influence of mid-latitude sea surface temperature fronts on the atmospheric water cycle and storm track activity

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1. Introduction

The global atmospheric water cycle is governed by the balance between evaporation, precipitation, and the convergence of vertically integrated moisture fluxes [1]. This relationship suggests that regions with strong sea surface temperature (SST) gradients, such as midlatitude SST fronts, play a crucial role in shaping these interactions. In the extra-tropics, precipitation and evaporation often maximize near SST fronts, where warm and cool ocean currents converge. While the response of the mid-latitude atmospheric circulation to SST fronts has been well studied [2,3,4], their impact on the atmospheric water cycle and storm tracks remains largely unknown. This study investigates how the position and strength of midlatitude SST fronts affect the global atmospheric water cycle and storm track activity.

2. Aqua-Planet Experiments

We analyzed the outputs obtained from a series of idealized aqua-planet experiments conducted using the AGCM for the Earth Simulator (AFES) [5]. The experiments feature zonally symmetric SST profile, with single midlatitude SST fronts centered at a latitude of either 35°, 45°, or 55°, denoted as F35, F45, and F55, respectively (Fig. 1). An additional reference case (REF) was included, in which the SST front was smoothed out to eliminate its distinct gradient. The experiments used a horizontal resolution of T79 (about a grid interval of 150km) with 56 vertical levels up to 0.09hPa. The model was integrated over 120 months under perpetual austral winter solstice conditions, with the first six months disregarded as spin-up. Additional simulations were also performed by uniformly increasing or decreasing the global SST by 5 K for F45 and REF, respectively.

3. Results

a). Vertically Integrated Water Cycle

The tropical atmospheric water cycle showed minimal sensitivity to changes in the position or existence of midlatitude SST fronts (Fig. 2). Evaporation from warm ocean surfaces dominated the subtropical latitudes, supplying moisture that was

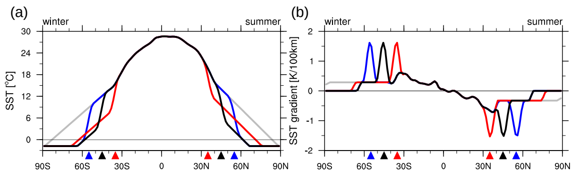

Fig. 1. (a) Meridional profiles of the prescribed zonally symmetric sea surface temperature [°C] and (b) their meridional gradient [K 10^2 km^{-1}]. Colors (red, black, blue) indicate the latitude of the SST front (35, 45, and 55°) as indicated by the triangles. The grey line corresponds to the non-front reference (REF) experiment. Adopted from [6].

transported upward by convection and removed by precipitation within the inter-tropical convergence zones (ITCZ). These processes were largely governed by the Hadley circulation, whose characteristics remained stable across the experiments (Fig. 3c-d).

In the midlatitudes, in contrast, the atmospheric water cycle exhibited pronounced sensitivity to the presence and position of SST fronts. Evaporation increased on the equatorward flank of the SST front, while large-scale precipitation and eddy-driven moisture flux convergence peaked on the poleward flank (Fig. 2a-c). The contrast in evaporation across the SST front was primarily due to the Clausius-Clapeyron relationship, which links surface saturation-specific humidity to SST. When the SST front was absent, as in the REF case, these sharp features disappeared (Fig. 2a-d), resulting in weaker moisture flux convergence and weaker storm track activity (not shown).

b). Storm Track Dynamics

The anchoring effect of SST front [2,3] also appeared as the organized diabatic heating from moisture flux convergence and precipitation along the SST front (Fig. 3a-b). This relationship was consistent across experiments, with the latitude of the storm track shifting in concert with the SST front. In addition, higher SSTs amplified storm track intensity, as seen in experiments with uniformly increased SSTs (not shown). The findings highlight the dual role of SST fronts: their position controls where storm track activity enhances, while the underlying SST modulates the strength of the associated processes.

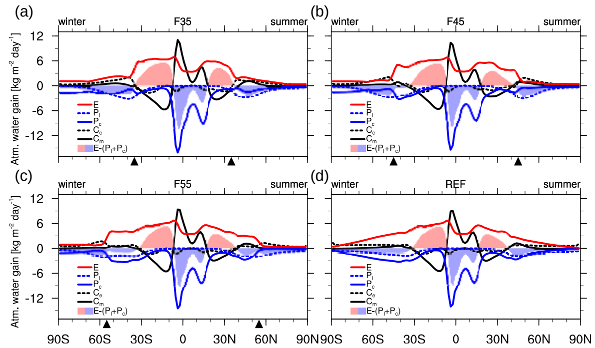

Fig. 2. Meridional diagram of the simulated zonal mean evaporation (red line), large-scale precipitation (dashed blue line), cumulus precipitation (blue solid line), vertically integrated convergence of northward eddy moisture flux (dashed black line), vertically integrated convergence of northward mean-flow moisture flux (solid black line), evaporation minus precipitation (shading, red colour is for positive values and blue colour is for negative values) for (a) F35, (b) F45, (c) F55, and (d) REF experiments. Unit is [kg m^{-2} day^{-1}]. Adopted from [6].

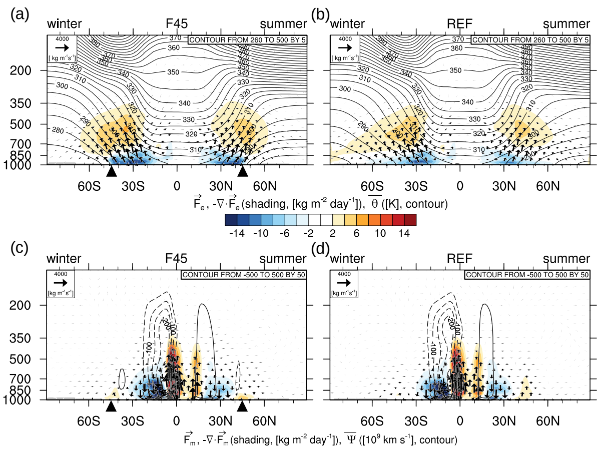

Fig. 3. (a) Simulated zonally averaged mean eddy moisture flux (vector, [kg m−2 d−1]), its convergence (shading, [kg m^{-3} day^{-1}]), and potential temperature (contour, [K]) for F45. (c) Zonally averaged mean-flow moisture flux (vector), its convergence (shading), and mass stream function (contour, [10^{9} kg s^{-1}]) for F45. (b, d) Same as (a, c), but for REF. Adopted from [6].

4. Conclusions

The experiments conducted in this study demonstrates that midlatitude SST fronts exert a significant influence on the atmospheric water cycle and storm track dynamics. In the tropics, the water cycle is primarily governed by time-mean circulation and remains largely unaffected by changes in SST front position. However, in the midlatitudes, SST fronts are critical for driving evaporation, moisture flux convergence, and precipitation patterns, all of which are tightly coupled to storm track activity.

The results also suggest that storm tracks are maintained through diabatic heating associated with eddy-driven moisture flux convergence and precipitation. The presence of a distinct SST front enhances these processes, leading to stronger storm tracks and the global water cycle. Conversely, the absence of an SST front results in a smoothed atmospheric response, with weaker eddy activity and reduced precipitation. The experiments also reveal that higher SSTs amplify the intensity of both the water cycle and storm tracks, underscoring the importance of accurately representing SST distributions in climate models.

By systematically exploring the sensitivity of atmospheric processes to SST fronts, this study highlights their central role in shaping midlatitude climate dynamics. Understanding these interactions is crucial for improving the representation of atmospheric water cycles and storm tracks in both observational and modeling frameworks. More detailed discussions on this report are found in [6].

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