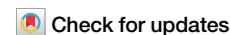


<https://doi.org/10.1038/s41612-025-00898-0>

Amplification of Northern Hemisphere winter stationary waves in a warming world



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This study leverages the Global/Regional Integrated Model system (GRIMs) version 4.0 climate model to examine the mechanisms behind the recent intensification of winter stationary waves over western North America. Prescribed sea surface temperature warming forces a strengthening of westerly winds, amplifying the ridge that characterizes the stationary waves in western North America. The streamfunction budget analysis reveals relative vorticity advection is mainly associated with this process. We further show that ocean warming is the primary driver of changes in westerly winds and stationary waves in the Northern Hemisphere. Sea ice losses exert a considerable effect through a different mechanism, complementing the dominant influence of ocean warming on these atmospheric changes. Our results thus reveal the crucial role tropical oceans play in modulating global warming's effect on the stationary waves in the Northern Hemisphere and add a more quantitative perspective to the previously reported influence of Arctic amplification.

The intensification of winter stationary waves across western North America presents a critical problem in climate dynamics, given its profound implications for regional hydroclimate changes. Recent observations have highlighted the formation of a persistent upper-tropospheric ridge as a key component of the North America Winter Dipole (NAWD)^{1–4}. This atmospheric phenomenon, manifested as winter stationary waves, has garnered increasing attention because of its role in driving extreme weather events, such as extreme droughts in the western U.S., and its potential exacerbation due to global warming^{5–8}. Despite the growing body of research on this topic, a comprehensive understanding of the dynamics behind the changes in stationary waves remains elusive. Recent analyses indicate that warming climate conditions may be strengthening large-scale stationary waves at higher latitudes through mechanisms that are not yet fully understood.

The maintenance and intensification of stationary waves involves a delicate balance of various atmospheric processes, primarily governed by vorticity dynamics. Previous studies have suggested that future projected zonal wind strengthening in the subtropical upper troposphere contributes to forming the intermediate-scale stationary waves affecting western North America⁹. The relative contributions of different forcing mechanisms, particularly ocean warming and sea ice loss, to these stationary waves' changes, remain a subject of active debate^{10–13}. Understanding the warming

impacts on the maintenance dynamics is crucial for predicting future changes in atmospheric circulation patterns and their regional climate modulations.

To address these knowledge gaps, this study employs the Global/Regional Integrated Model system (GRIMs) version 4.0¹⁴ and examines the streamfunction budget of the stationary waves in the Northern Hemisphere. This approach allows us to dissect the vorticity dynamics of amplified stationary waves, providing insights into the physical processes underlying their intensification. By leveraging incrementally forced experiments under warming conditions, we aim to identify the dominant dynamic processes contributing to the amplifying stationary waves that lead to wetter conditions along the Alaskan coast and drier conditions in the Pacific Northwest.

Results

Dynamical processes driving the amplification of stationary waves

To investigate atmospheric responses under forced warming conditions, we employed the GRIMs atmospheric general circulation model. In addition to the control simulation in which the observed sea surface temperature (SST) and sea ice concentration (SIC) were prescribed as the boundary conditions, a set of forced warming experiments were performed with varying degrees of

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warming by adjusting SST and SIC fraction to represent 1-, 2-, and 3-degree temperature increases compared to the 1920–1949 base period. This base period was chosen to align with the starting date of the CESM1 Large Ensemble datasets, reflecting a time before global warming progression. The SST and SIC conditions, corresponding to global mean surface air temperature increases of 1, 2, and 3 degrees, were derived from the ensemble mean of CESM1 40 members. Only zonal mean profiles are imposed to reduce the discrepancy and uncertainty in zonally asymmetric SST and SIC changes from observations and model projections (see Methods for detailed model setting).

The results averaged over 100 winters, created from an ensemble of 10 different initial conditions for each of the 10 winter seasons (December–January–February), revealed a consistent amplification of the western North American upper troposphere ridge as global warming intensifies (Fig. 1a). This finding aligns with recent diagnostic analyses¹⁵ and has significant implications on regional hydroclimate. Notably, the strengthened winter ridge is associated with wetter conditions along the Alaskan coast and drier conditions in the Pacific Northwest (Supplementary Fig. 1). These distinct wet-dry patterns near western North America, clearly replicated in the model results, validate the simulation and have continually prompted questions about the mechanisms driving atmospheric circulation evolution.

Significant amplification of the North Pacific ridge coincides with changes in the winter stationary waves (Fig. 1a). This change is likely caused by mean flow change in the subtropics and/or wave source change in the tropics. Our analysis indeed reveals a strengthening in the subtropical westerly wind (Fig. 1b, contour), similar to the observation^{9,16}. With a 1° temperature increase, westerly winds intensify near the climatological jet core latitude (dashed line). Further warming enhances the strength and northward reach of these winds. Consequently, the amplification of large-scale stationary waves occurs concurrently with the strengthening of the zonal mean westerly wind. Note that these strengthened winds are accompanied by strong warming in the tropical upper troposphere (Fig. 1b, shading). The resulting meridional temperature gradient, varying with altitude, regulates tropospheric wind shear through thermal wind balance^{17–20}.

To investigate the mechanisms of how westerly wind change contributes to the evolution of large-scale stationary waves, we employed the streamfunction budget equation²¹. This approach, derived from the inverse Laplacian of the vorticity budget equation, provides a low spatial variance formulation, favorable for interpreting broad-scale atmospheric structures. Equation (1) presents the streamfunction (Ψ) budget, where $\mathbf{V}_\phi$ represents the rotational wind and $\mathbf{V}_\chi$ is the divergent wind vector. The overbar denotes the seasonal mean, the prime indicates the deviation from the seasonal mean, and the subscript 'E' signifies the eddy component which

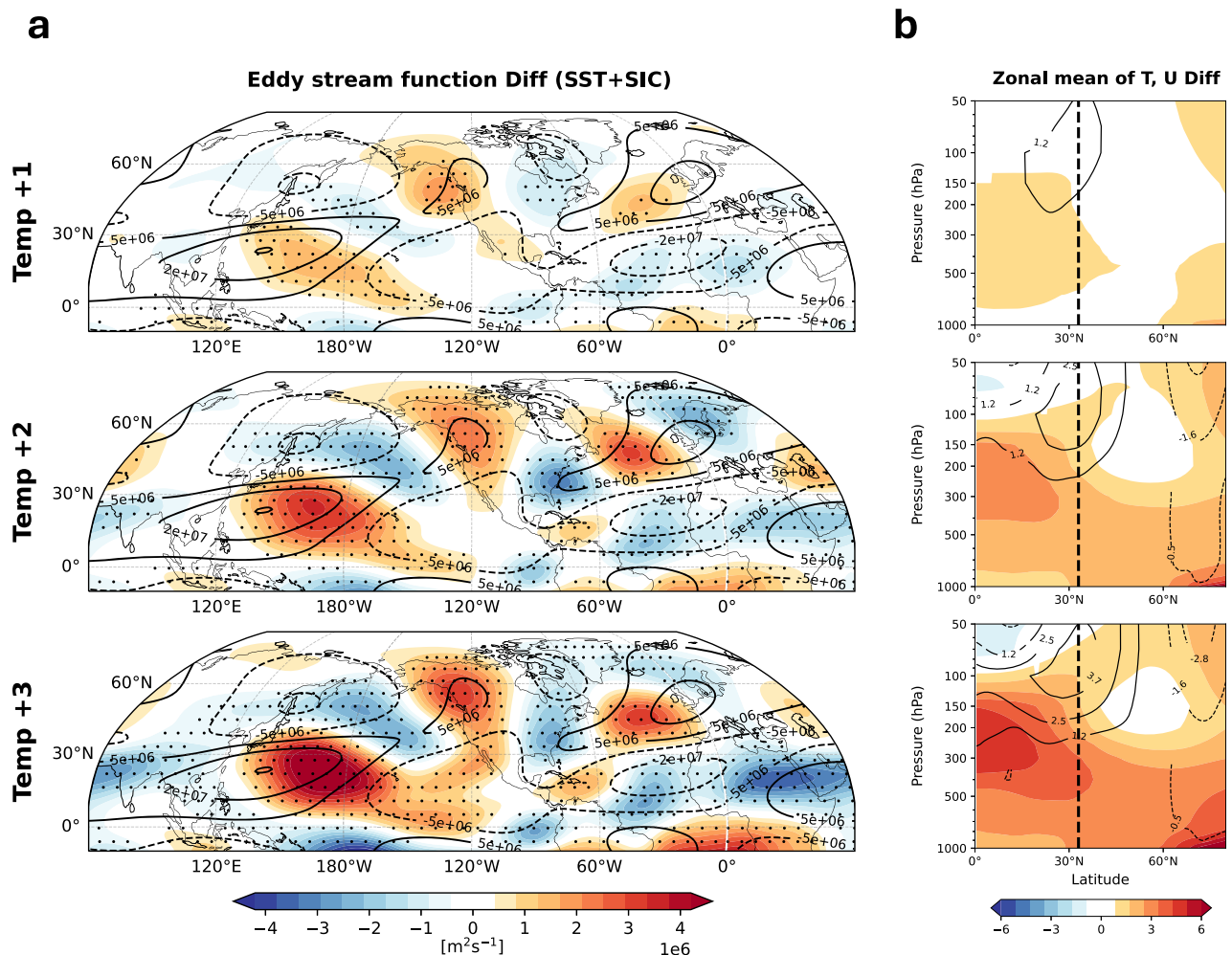


Fig. 1 | Amplified large-scale winter (DJF) stationary wave and strengthening westerly wind in the Northern Hemisphere. **a** The 200-hPa eddy streamfunction anomaly arising from the control and combined SST with SIC fraction warming forcing experiment (shading) juxtaposed with the climatology (units : m^2s^{-1}). Areas of

significance are dotted ($p < 0.05$ based on the Student's t -test). **b** Latitudinal anomaly in zonal mean air temperature (shading, units: K) and zonal wind (contour, units: ms^{-1}), with the climatological latitude of the midlatitude westerly jet core represented by the dashed line. Areas of significance are plotted ($p < 0.05$ based on the Student's t -test).

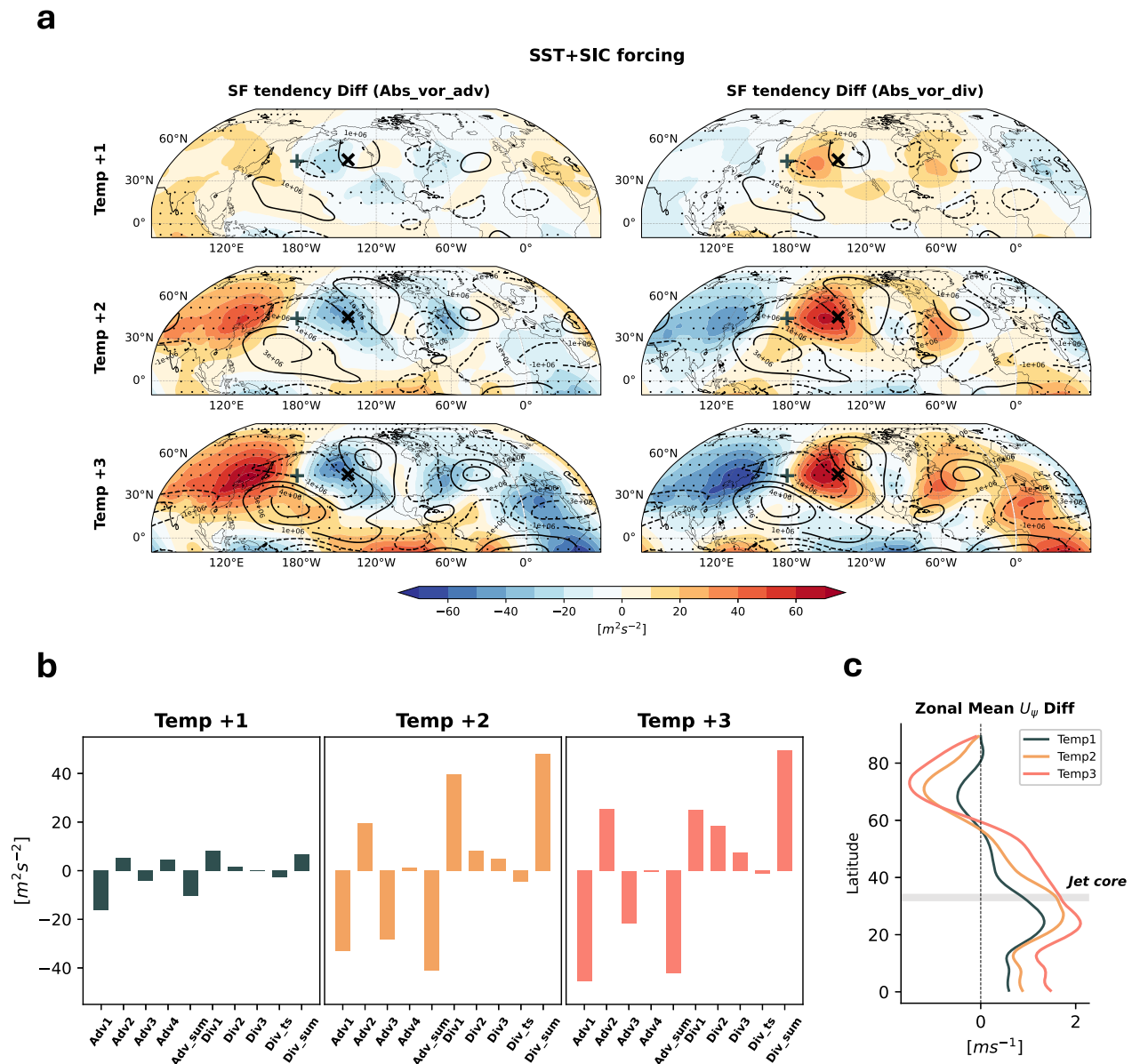


Fig. 2 | Diagnose the amplified stationary wave by streamfunction budget analysis. a Contours represent the 200-hPa eddy streamfunction (units: m^2s^{-1}), while shading is the streamfunction tendency by absolute vorticity advection (left, $\nabla^{-2}[-\bar{V}_\phi \cdot \nabla(f + \bar{\zeta})]_E$) and divergence (right, $\nabla^{-2}\{-\nabla \cdot [\bar{V}_\chi(f + \bar{\zeta})]_E\}$) under warming forcings (units: m^2s^{-2}). Areas with significant areas are dotted

($p < 0.05$ based on the Student's t -test). **b** The decomposed terms of Eq. (1) are compared by calculating a $10^\circ \times 10^\circ$ weighted area average over $145^\circ W$, $45^\circ N$ (marked 'x' in Fig. 2a, units: m^2s^{-2}). And the summation of the all of advection and divergence terms are represented in 'Adv_sum' and 'Div_sum' respectively. **c** The difference in the rotational wind (u_ψ , units: ms^{-1}) across each warming forcing.

represents the deviation from the zonal mean.

$$\begin{aligned} \frac{\partial \bar{\Psi}}{\partial t} = & \nabla^{-2} \left[-\bar{V}_\phi \cdot \nabla(f + \bar{\zeta}) \right]_E + \nabla^{-2} \left\{ -\nabla \cdot \left[\bar{V}_\chi(f + \bar{\zeta}) \right]_E \right\} \\ & + \nabla^{-2} \left[-\nabla \cdot \left(\bar{V}'\zeta' \right) \right]_E \approx 0 \end{aligned} \quad (1)$$

Among the three terms on the right-hand side, the first term is induced by the seasonal-mean absolute vorticity advection due to the rotational wind, while the second term arises from the divergence of seasonal-mean absolute vorticity flux caused by the divergent wind and the last term is for transient vorticity flux. The last two terms are treated as vorticity source-related terms, combining the horizontal advection of vorticity by divergent flow and vortex stretching²². The other terms that arise from vertical

advection, twisting, and dissipation of vorticity are much smaller than others. Thus, they can be ignored in the streamfunction tendency^{21,23}. For the large-scale winter stationary wave, the seasonal-mean streamfunction tendency approaches nearly zero.

Given that the magnitude of the streamfunction tendency due to transient vorticity flux is very small, we only compare the former two terms. In the warming forcing experiments, streamfunction tendencies display a quadrature relationship to the eddy streamfunction (Fig. 2a). Based on the trough in the central Pacific (marked '+' in Fig. 2a), the progression of rotational winds from west to east manifests through the depletion and accumulation of positive vorticity advection, resulting in respective positive and negative streamfunction tendencies (Fig. 2a left-hand side, $\nabla^{-2}[-\bar{V}_\phi \cdot \nabla(f + \bar{\zeta})]_E$). Conversely, positive vorticity diverging from the source region to the left of the trough induces a negative streamfunction

tendency, while convergence to the east leads to a positive streamfunction tendency (Fig. 2a right-hand side, $\nabla^{-2}\left\{-\nabla \cdot \left[\bar{\mathbf{v}}_{\chi}\left(f+\bar{\zeta}\right)\right]_E\right\}$). This relationship highlights opposing spatial structures among the terms, illustrating their counterbalancing interactions in maintaining large-scale stationary eddies. Notably, as global warming intensifies, both the amplitudes of large-scale stationary waves and the differences in streamfunction tendencies increase, sustaining the amplified stationary eddies.

To gain deeper insight into the physical processes at mid to high latitudes and to delineate the role of westerly winds, we decomposed variables into their zonal (represented by Z) and eddy components in Eq. (2). This decomposition allows us to examine how Rossby wave dynamics perpetuate the maintenance of large-scale stationary waves at these latitudes^{21,23–25}. Then, we computed each term based on model results and quantitatively compared their strengths by performing a $10^{\circ} \times 10^{\circ}$ weighted area average from the center (marked 'x' in Fig. 2a) west of the amplified ridge over western North America (Fig. 2b). This specific location was chosen to directly assess each tendency term's contribution to the ridge amplification, a key component of the stationary wave pattern. Analyzing the area west of the ridge captures immediate influences on this critical atmospheric feature.

$$\begin{aligned} & \underbrace{\nabla^{-2}\left(\bar{u}_{\varphi Z} \frac{\partial \bar{\zeta}_E}{\partial x}\right)}_{\text{Adv1}} + \underbrace{\nabla^{-2}\left(-\beta \bar{v}_{\varphi E}\right)}_{\text{Adv2}} + \underbrace{\nabla^{-2}\left(-\bar{v}_{\varphi E} \frac{\partial \bar{\zeta}_E}{\partial y}\right)}_{\text{Adv3}} + \underbrace{\nabla^{-2}\left(-\bar{v}_{\varphi E} \cdot \nabla \bar{\zeta}_E\right)}_{\text{Adv4}} \\ & + \underbrace{\nabla^{-2}\left(-f \nabla \cdot \bar{\mathbf{v}}_{\chi E}\right)}_{\text{Div1}} + \underbrace{\nabla^{-2}\left(-\bar{v}_{\chi E} \beta\right)}_{\text{Div2}} + \underbrace{\nabla^{-2}\left[-\nabla \cdot \left(\bar{\mathbf{v}}_{\chi E} \bar{\zeta}_E + \bar{v}_{\chi E} \bar{\zeta}_E\right)\right]}_{\text{Div3}} + \underbrace{\nabla^{-2}\left[-\nabla \cdot \left(\bar{\mathbf{v}}_{\chi E}\right)\right]}_{\text{Div4}} \approx 0 \end{aligned} \quad (2)$$

The first four advection terms are denoted as Adv1, Adv2, Adv3, and Adv4, while the subsequent three divergence terms are referred to as Div1, Div2, and Div3, with the final term being designated as Div_{ts}. The magnitude of streamfunction tendency by advection is predominantly governed by terms Adv1, Adv2, and Adv3, while divergence is mainly controlled by Div1 and Div2 (Fig. 2b). The sum of these terms (Adv_sum and Div_sum) have nearly equal magnitudes but opposite signs, indicating a closed state that achieves balance within the system. These results not only reflect the overall formation of the stationary wave but also demonstrate which terms predominantly contribute at a specific point near the western North America ridge that directly influences the amplified ridge.

Each decomposed term forms a quadrature relationship with the eddy streamfunction, and the difference across all terms becomes stronger as global warming intensifies (Supplementary Fig. 2). Moreover, the dominant terms that contribute to the difference in magnitude west of the ridge are statistically significant, indicating that the dominant terms highlighted in Fig. 2b are meaningfully influential. The sum of Adv1, Adv2, and Adv3, as well as Div1 and Div2, exhibit patterns similar to those in Fig. 2a and possess opposite signs, suggesting that the balance of these terms is apt for explaining the spatially overall maintenance of the amplified eddy streamfunction.

Focusing on the region west of the western North American ridge (marked 'x' in Fig. 2a), we find that the streamfunction tendency induced by relative vorticity advection (Adv1) has the strongest impact on the maintenance process (Fig. 2b). As global temperatures rise, this term becomes increasingly influential, suggesting a significant change in westerly winds. Correspondingly, we observe an intensification of the zonal mean westerly rotational wind associated with relative vorticity advection in all latitudes except the subpolar region as a result of global warming (Fig. 2c). Therefore, it can be concluded that under global warming with combined ocean and sea ice loss forcing, the strengthened upper-troposphere westerly winds contribute more prominently to the amplified large-scale stationary waves than other maintenance terms.

It is worth noting that these changes in zonal mean westerly may not be the sole factor that directly causes stationary wave amplification. Fundamentally, eddies contribute to westerly wind changes through eddy-mean

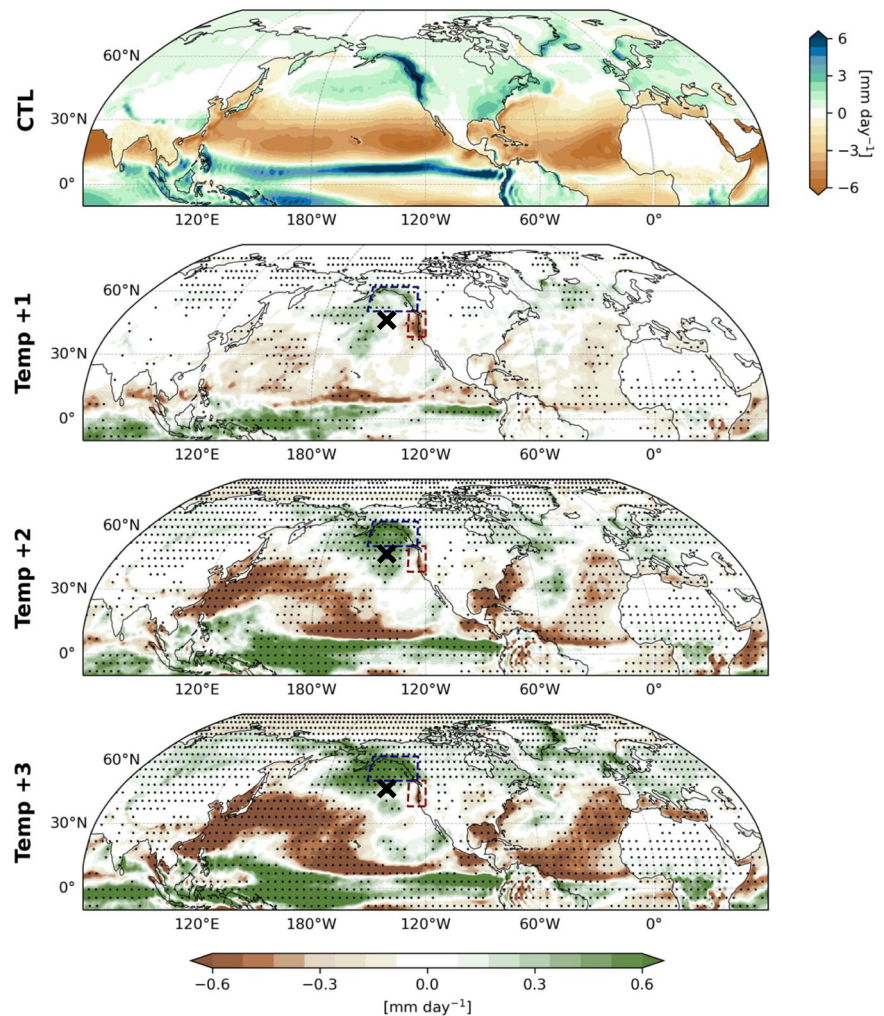
flow interaction. In particular, differences and fluctuations in the mid-latitude zonal mean westerlies are predominantly influenced by eddy momentum flux and buoyancy flux convergence^{26,27}. In this study, we focused on diagnosing the relative contributions of terms involved in maintaining the amplified stationary wave by analyzing their respective roles. Thus, further investigation into the causal role of eddies on mean zonal flow is required in terms of eddy-mean flow feedback. For instance, quantifying the contribution of eddy momentum flux convergence to the zonal mean flow changes could reveal how it strengthens the westerly wind, and it returns to streamfunction changes.

Ocean forcing plays a dominant role

The primary wave source appears to be tropical ocean warming, as indicated by strong convection and intensified surface water flux (precipitation minus evaporation) in the near-tropical areas (Fig. 3). Enhanced vertical motion in response to western tropical warming leads to increased upper troposphere divergence. This divergent flow interacts with areas of pronounced absolute vorticity gradients, commonly observed near the upper troposphere subtropical jets. Such interaction amplifies the wave source in the subtropics, the region where Rossby waves are typically initiated. Simultaneously, the wave advection term intensifies. These changes lead to a new balanced state that maintains the amplified stationary waves. This reconfiguration results in a sustained amplification of the stationary wave pattern. This amplification process prompts a re-examination of our streamfunction budget at the key nodal point ('x' in Fig. 2a). As the subtropical wave source strengthens, it sets the stage for positive vorticity convergence to the nodal point 'x'. This nodal point can be viewed as part of the established wave train, where the Rossby wave source exerts secondary effects in the evolving system. We observe that both advection and divergent terms at the nodal point grow at a similar rate in magnitude but with opposite signs. This balanced growth maintains the wave's nodal structure while allowing increased amplitude by subtropical wave source. This behavior demonstrates how local budget terms capture the broader wave dynamics, through a spatially quadrature relation with amplified ridge-trough systems. It shows that as the overall forcing increases, the amplified stationary wave maintains its fixed position. This insight encourages us to interpret the nodal point not in isolation but as a crucial indicator of how the initial subtropical forcing propagates through and amplifies the entire stationary wave.

Building on these processes, we further investigated the complex interplay between mid-latitude ocean warming and the Arctic sea ice reduction, which is crucial in determining the characteristics of the mid-latitude jet and a key factor in storm track dynamics^{10,28,29}. Departing from previous methods using combined SST and SIC forcings, we examined the independent effects of these factors on stationary waves and westerly winds. As shown in Fig. 4, the SST-only forcing experiments demonstrated similar tendencies to the All-forcing (SST + SIC) experiments in terms of stationary wave patterns (Fig. 1a). To quantify the spatial relationship between SST and SIC forcings, we employed a multi-linear regression analysis, focusing on the 200-hPa eddy streamfunction at mid-to-high latitudes (40° – 70° N). Differences between All forcing and control experiments were set as the dependent variable, with SST and SIC-only forcing experiments assumed as independent variables. This analysis reveals that combining SST and SIC forcings substantially explains the variance in the All forcing experiment outcomes, with R^2 values increasing from 0.55 to 0.81 as warming intensified from 1 to 3 degrees (Supplementary Table 1). Notably, SST's relative contribution increased markedly with temperature rise, while SIC's contribution remained modest, about 20% of SST forcing up to a 2° increase. Beyond this point, SST forcing becomes increasingly dominant, further diminishing SIC's relative influence (Supplementary Table 1, Temp +3). Visual inspection of the wave patterns corroborates this trend, with SST-induced stationary waves amplifying noticeably as temperatures rise, while SIC-forced stationary waves maintain relatively small and constant magnitudes across warming scenarios (Fig. 4). Streamfunction budget calculations (Supplementary Fig. 3) and decomposed term differences from SST-only forcing experiments (Supplementary Fig. 4) mirrored patterns

Fig. 3 | Intensified surface water flux over the Northern Hemisphere during the northern winter season (DJF). The winter precipitation minus evaporation flux derived from GRIMs as a control (CTL) run, and the anomalous pattern for 1-, 2-, 3-degree temperature increments (units: mm day^{-1}). The significant areas are dotted ($p < 0.05$ based on the Student's t -test). Positive values over Alaska and negative values over the Pacific Northwest are indicated by blue and brown boxes, respectively.



observed in All forcing results. This suggests that ocean warming, more than Arctic sea ice loss (Supplementary Fig. 5), primarily determines the level of intensification manifest in stationary waves.

Our analysis also reveals notable findings regarding the contributions of energy sources to westerly winds. The SST-only forcing experiments mirrored the All forcing experiments, showing intensified westerly winds around the subtropical jet core latitude. Conversely, the SIC-only forcing experiments exhibited a muted response near the northern part of the eddy-driven jet core (Fig. 6, contour). Despite the absence of lower tropospheric warming near the Arctic compared to All forcing results, the SST-only experiments still effectively capture the changes in the upper-troposphere westerly winds (Figs. 1b and 6, zonal mean of air temperature). These suggest that ocean warming contributes significantly to westerly winds and amplifying stationary waves, primarily through enhanced tropical convection acting as a subtropical wave source. This process initiates a chain of mechanisms, including altered vorticity balance, consistent with the All forcing results and driving these large-scale circulation changes. Conversely, sea ice loss on its own does not fully replicate these phenomena, indicating a more limited independent impact on these atmospheric patterns (Supplementary Fig. 6).

We note that CESM1 projections exhibit an El Niño-like warming pattern (Supplementary Fig. 9a), which is often found in multi-model projections^{30–33}. However, observational results show less pronounced changes in past El Niño-like SST patterns³⁴. This discrepancy between models and observations is mitigated in this study by prescribing the zonally mean profile of the CESM1 SST pattern. While the zonally asymmetric SST

changes may play a role in driving stationary waves in a warming climate, our zonally averaged approach captures the essence of the warming pattern while avoiding overemphasis on specific regional features.

While our diagnoses indicate a more consistent influence of ocean warming on westerly winds and corresponding stationary waves compared to sea ice loss, the impact of Arctic sea ice loss cannot be dismissed entirely. Despite potential climate model dependencies, our ensemble mean results over 100 winters show in-phase amplification of the stationary waves under sea ice loss (Fig. 4, SIC). This provides notable evidence for Arctic amplification's impact on mid-latitude waviness, even though the response is weaker compared to ocean warming. To address the ongoing debate about Arctic influences on mid-latitude atmospheric circulation, we further analyze how ocean warming and sea ice loss may operate through different mechanisms.

Wave activity flux difference revealed distinct energy propagation patterns in SST- and SIC-only forcing experiments (Fig. 5). All forcing and SST-only forcing shows energy propagation from lower latitudes toward the western ridge, while SIC-only forcing exhibited more horizontal propagation within mid- to high-latitude pathway as a waveguide. These come from the changes in background flow that significantly influence the changing wave propagation patterns. Furthermore, zonal mean wind differences showed that Arctic sea ice melting generates an anomalous easterly wind in the high-latitude upper troposphere, contrasting with westerly flow strengthening in SST warming (Fig. 6, SIC). This phenomenon could result from Arctic amplification, manifesting as a high-pressure anomaly over polar regions. This can be characterized as a process occurring

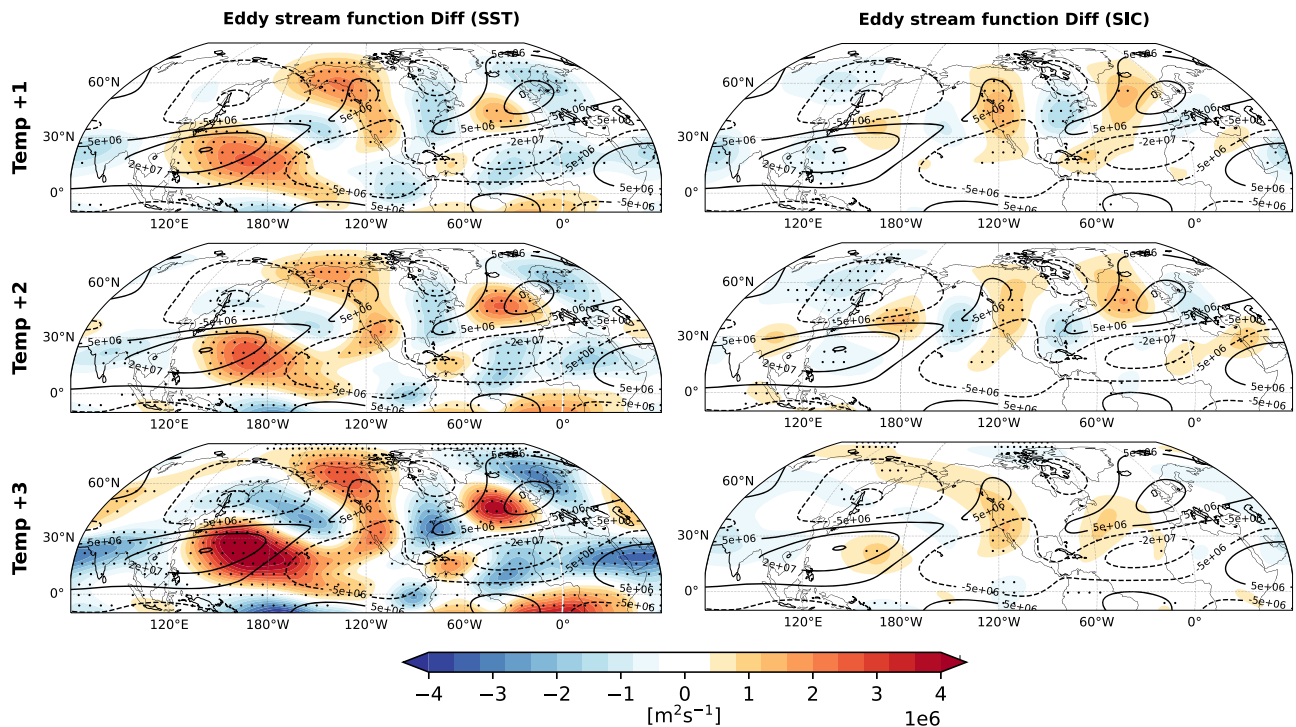


Fig. 4 | Northern Hemisphere winter stationary wave response to SST/SIC-only warming forcing. The 200-hPa eddy streamfunction anomaly induced by SST-only and SIC-only forcing experiment (units: $\text{m}^2 \text{s}^{-1}$). The significant areas are dotted ($p < 0.05$ based on the Student's t -test).

independently at higher latitudes, in contrast to the influences originating from the tropics. This process also can play a role in creating differences in the pathways through which wave activity flux changes propagate (Fig. 5).

Collectively, the processes by which these two main drivers operate through different mechanisms to influence atmospheric circulation. Ocean warming plays a dominant role in intensifying the jet and maintaining amplified stationary waves, primarily through tropical convection. However, Arctic sea ice loss independently contributes to mid-latitude circulation waviness, and its impacts remain non-negligible in the near future (Supplementary Table 1, up to temp+2).

Discussions

Our study uncovers the significant impact of global warming on the amplification of the winter stationary ridge in western North America. The intensification of the ridge leads to a marked increase in moisture along the Alaskan coast, while simultaneously driving drier conditions in the Pacific Northwest. Central to these changes is the behavior of the zonal mean westerly winds. As global temperatures rise, the westerly winds not only strengthen but also extend their influence northward. This shift is driven by an intensified wave source originating from the tropical western Pacific. The enhanced tropical heating induces upper troposphere divergence, which strengthens the Rossby wave source in the subtropical regions at the edge of the heating area (Supplementary Fig. 7). Concurrently, the strengthening of westerly winds contributes to enhanced wave advection. The balance between the intensified wave source and the enhanced wave advection allows for the sustained amplification of the stationary wave pattern. While our findings provide insights into these dynamic processes, the complex interactions between eddies and mean flow in this process warrant further investigation. Attributing stationary wave simplification solely to changes in the zonal mean jet may oversimplify the underlying dynamics.

We also find that ocean warming plays a far more significant role in driving these changes compared to the influence of Arctic sea ice loss. The warming of the ocean surface appears to be the main catalyst for the observed alterations in atmospheric circulation, highlighting the critical importance of ocean-atmosphere interactions in shaping the response of

regional stationary waves and global hydroclimate. Notwithstanding the divergent views in other studies and varying responses depending on the climate model, there is compelling evidence that Arctic sea ice loss and ocean warming independently affect mid-latitude atmospheric circulations. It should be noted, however, that this study did not incorporate interactive ocean-sea ice feedback, which recent research suggests can influence atmospheric responses³⁵. Despite this limitation, our findings may provide valuable insights into these altered atmospheric patterns. Specifically, the changes we observed in the background state of the jet could offer important clues to one of the key issues addressed in the “traffic jam theory” regarding the origins of blocking formations³⁶, furthering their implicated sources of atmospheric blocking in the warmer climate³⁷.

The findings of our study have significant implications for climate prediction and emphasize the need for further research. By shedding light on the complex interplay between warming oceans, melting Arctic sea ice, shifting atmospheric circulation patterns, and regional hydroclimate impacts, our work underscores the importance of considering these interactions in efforts to improve regional climate projections. As global temperatures continue to rise, understanding and accurately predicting the consequences for specific regions will be crucial for developing effective adaptation and mitigation strategies. Thus, this research not only contributes to the theoretical understanding of atmospheric dynamics but also has significant practical implications for predicting and mitigating the impacts of climate change on regional hydroclimates in western North America. Future research should explore how the climate responses and atmospheric roles identified in this study contribute to the mechanisms underlying previously observed non-linear hydroclimate responses in the western U.S.^{38,39}. Such studies could clarify how thermodynamic and dynamic processes contribute to these complex climate patterns, linking large-scale atmospheric changes to regional hydroclimate effects.

Methods

Observational dataset and CESM1

To calculate the impact of the upper-troposphere ridge over western North America on the surface net water flux (precipitation minus evaporation) for

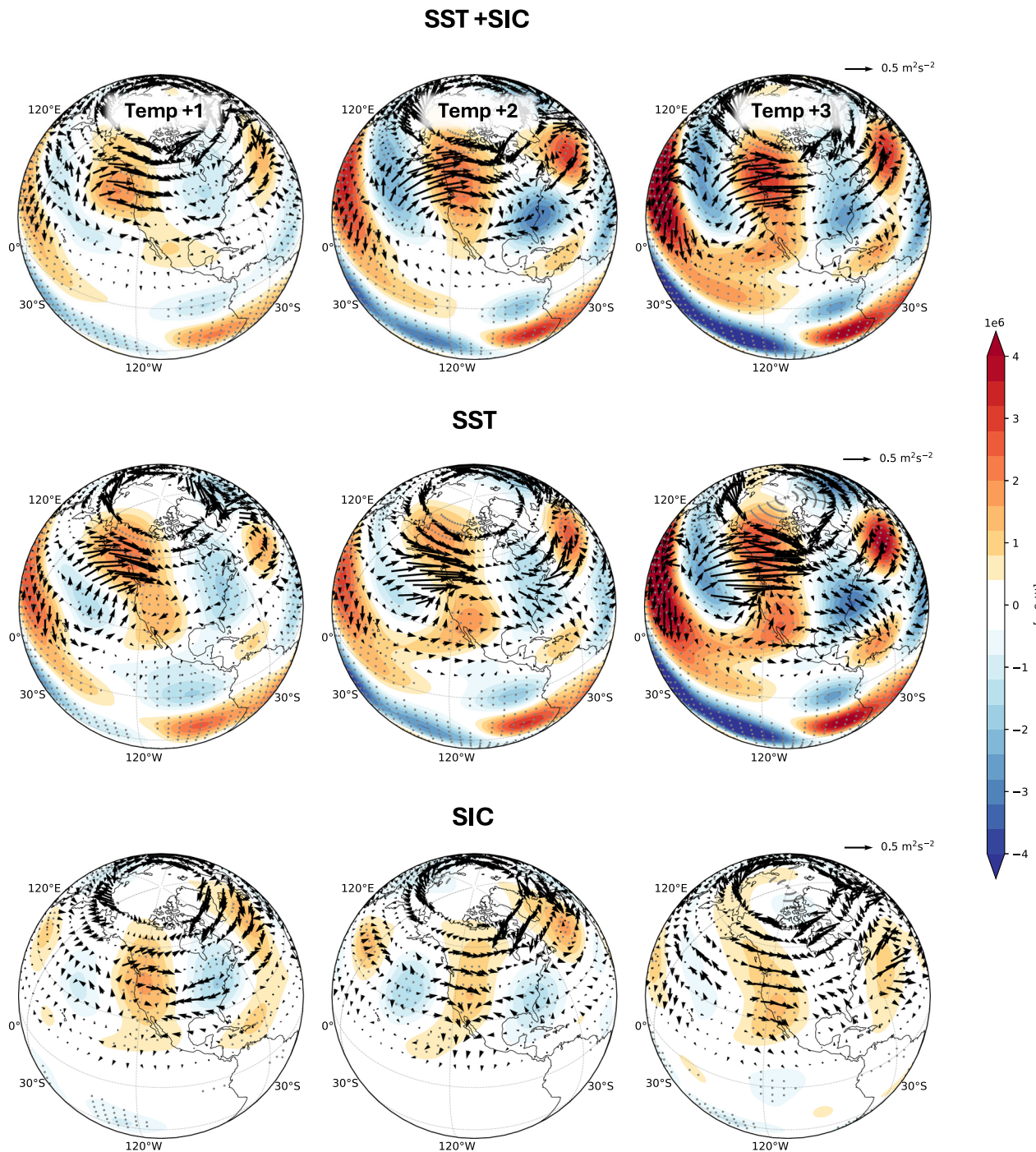


Fig. 5 | Wave activity propagation response to SST/SIC-only warming forcing. The 200-hPa wave activity flux (vector, units: m^2s^{-2}) and eddy streamfunction (shading, units: m^2s^{-1}) anomaly induced by combined SST and SIC, SST-only, and

SIC-only forcing experiment. The significant areas in shadings are dotted ($p < 0.05$ based on the Student's t -test).

the past 80 years (1941–2020), we obtained geopotential height, total precipitation, and evaporation data from the ECMWF Reanalysis v5 (ERA5)⁴⁰ data. For historical increments of 1-, 2-, and 3-degrees over the 30-year period from 1920 to 1949, we calculated the differences in SST and ice fraction to supplement the GRIMs boundary conditions using averaged data from the Community Earth System Model 1 Large Ensemble Community Project (CESM1 LENS)⁴¹ 40 members. The aim was to capture a general climate signal rather than specific period effects, and the ensemble average helped to reduce internal variability. The CESM1 LENS is a fully coupled

configuration for the period 1920–2100, with each member initialized using historical climate forcings (twentieth century) up to the year 2005, followed by projections based on the RCP8.5 scenario.

GRIMs experiment setting

This study utilized the Global/Regional Integrated Model system (GRIMs) version 4.0^{14,42} to simulate climate responses to prescribed boundary conditions (SST, SIC) at 1°, 2°, and 3° increments of warming. GRIMs have been developed for global and regional weather forecasting, climate research, and

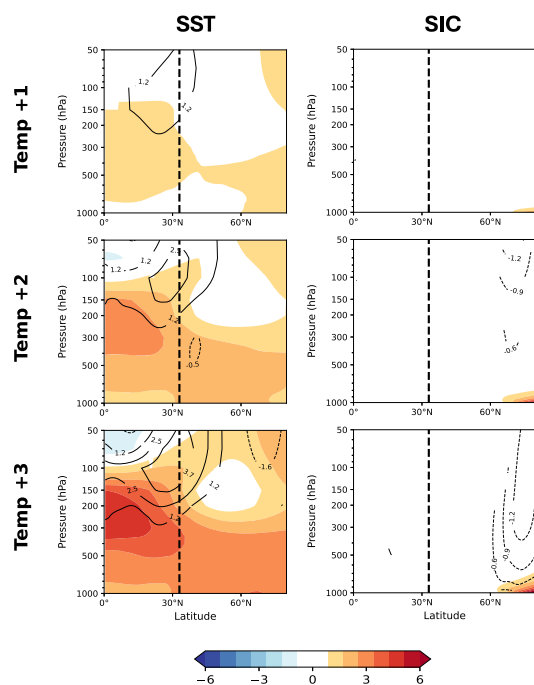


Fig. 6 | The zonal mean zonal wind, air temperature response to SST/SIC-only warming forcing. Similar plot with Fig. 1a but for the zonal mean of zonal wind (contour, units: ms^{-1}) and air temperature anomaly (units: K). Only significant changes in the area are plotted ($p < 0.05$ based on the Student's t -test).

seasonal prediction purposes^{43–46}, with version 3.1 being utilized as a reference model for the development of physical parameterizations for the Korean Integrated Model (KIM) at the Korean Institute of Atmospheric Prediction Systems (KIAPS)⁴⁷. The majority of its physical packages have been processed in ways employed by the Weather Research and Forecasting (WRF) model version 4.0¹⁴.

In our experiments, we set a horizontal resolution of T126, vertical layers at L28, and a model top at 3-hPa. Initial conditions were drawn from the NCEP/DOE reanalysis 2⁴⁸ sigma level and surface data, and boundary conditions were prescribed daily using NOAA OI SST v2⁴⁹ data for SST and SIC.

The integration period was deliberately aligned with the inception of a high-resolution OI SST dataset in the winter of 1981/82, chosen to reflect a timeframe before the extensive progression of global warming. The total integration spanned 12 years, from 1981/82 to 1992/93. After excluding the initial year for spin-up and the winter of 1987/88, which lacks OI SST data, our analysis focused on the remaining 10 winters. The initial conditions for the integration, starting in the winter of 1981, coincided with a weakly positive but largely neutral phase of the Pacific Decadal Oscillation (PDO). This study focused on boreal wintertime, and we ensure that the evolved SST boundary conditions used in our study cover periods of both positive and negative winter PDO phases, thereby presenting results that are not biased toward a single ocean state (Supplementary Fig. 8a). Meanwhile, this study prioritizes the analysis of differences resulting from the delta warming forcings applied to the boundary conditions, as detailed in the following sections. Consequently, the specific characteristics of the actual model integration period are of lesser importance for our analysis. We established 10 different ensemble members by selecting initial conditions at 10 distinct times with a 6-h interval, thereby obtaining data from 100 winter seasons.

A control experiment was conducted with no additional forcing, using boundary conditions appropriate for the integration period. Following the control experiment, we assessed the atmospheric response sensitivity in the GRIMs model. The upper-troposphere circulation patterns closely resemble those of CESM1, with a notable alignment in the location of the eddy component's center of action. This similarity underscores the GRIMs

model's capability to simulate large-scale atmospheric dynamics in line with CESM1. For the warming forcing experiments, global reference temperatures from the mean of CESM1-LE 40 ensembles were area-averaged to create a global temperature time series (Supplementary Fig. 8b). Each of its 40 ensemble members covers from 1920 to 2100 and starts with historical forcings until 2005, then projections based on the RCP8.5 scenario. The monthly anomalies for each 30-year period after 1949 were then calculated relative to the 30-year mean from 1920 to 1949. Increments of 1°, 2°, and 3° were superimposed on the 30-year mean SST and ice fraction values, and the zonal mean of these incremental changes was then added to the prescribed GRIMs boundary conditions (Supplementary Fig. 9a). For all experiments with increased temperature, the mean spatial pattern of prescribed reduced SIC boundary conditions, as shown in Supplementary Fig. 9b, ensures that a finite amount of sea ice is still factored into the warming model experiments. In our experiments, sea ice does not dynamically interact with the atmosphere but is rather treated as a prescribed condition. This approach allows us to isolate and examine the specific atmospheric responses to changes in SIC.

The warming forcing experiments are divided into three detailed scenarios: an experiment with both SST and SIC prescribed (All forcing), an experiment with only SST forcing (SST-only forcing), and an experiment with only SIC forcing (SIC-only forcing). The differences between these three experiments and the control were analyzed to assess the impacts of warming and to compare the individual effects of SST and SIC.

Data availability

All meteorological data used in this study are available for download. The ECMWF Reanalysis v5 (ERA5) data can be accessed at <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>. The Community Earth System Model 1 Large Ensemble Community Project (CESM1 LENS) data sets are available at <https://www.cesm.ucar.edu/community-projects/lens/data-sets>. Any requests regarding the GRIMs simulation for warming-forcing experiments should be addressed to cowndms123@gm.gist.ac.kr.

Code availability

The analyses in this study were conducted using python, NCAR Command Language (NCL), and Climate Data Operators (CDO). The source code is available from the corresponding author upon reasonable request.

Received: 13 August 2024; Accepted: 2 January 2025;

Published online: 17 January 2025

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Acknowledgements

This research is funded by the National Research Foundation of Korea (NRF-2021R1A2C1011827, NRF-2020M1A5A1110578, and RS-2023-00283239) and by the Korea Environment Industry & Technology Institute (KEITI) through “Climate Change R&D Project for New Climate Regime.”, funded by Korea Ministry of Environment (MOE) (RS-2022-KE002160). And the S.-Y.S.W. acknowledges fundings from the U.S. Department of Energy Award Number DE-686 SC0016605, SERDP Project RC20-3056, and NSF P2C2 award number 1903721. And D.K. was funded by the New Faculty Startup Fund and Creative-Pioneering Researchers Program from Seoul National University and the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2024-00336160).

Author contributions

J.L.: conducted research, created visualizations, analyzed the data, authored the initial draft, and reviewed and edited the manuscript. S.-Y.S.W. developed the study concept, contributed to writing, reviewed and edited the manuscript, and provided oversight. S.-W.S.: developed study concept, contributed to writing, and reviewed and edited the manuscript. D.K.: developed study concept, contributed to writing, and reviewed and edited manuscript. J.-H.J.: contributed to writing and reviewed and edited the manuscript. H.K.: contributed to writing and reviewed and edited the manuscript. J.-H.Y.: formulated study concept, conducted research, contributed to writing, reviewed and edited manuscript, and provided oversight.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41612-025-00898-0>.

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