Origins of Uncertainty in Projections of Summer North Pacific Subtropical High

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Key Points:

- Model variability in the future projection of summer NPSH originates from both SST and non-SST driven model uncertainty in the tropics
- Model spread in tropical SST changes modulates the NPSH by influencing tropical precipitation
- Model spread in tropical precipitation changes that are independent of SST also contributes to the uncertainty of the NPSH projections

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Abstract

The variability of summer North Pacific Subtropical High (NPSH) has substantial socioeconomic impacts. However, state-of-the-art climate models significantly disagree on the response of the NPSH to anthropogenic warming. Inter-model spread in NPSH projections originates from models' inconsistency in simulating tropical precipitation changes. This inconsistency in precipitation changes is partly due to inter-model variability in tropical sea surface temperature (SST) changes, but it can also occur independently of SST uncertainty. Here, we show that both types of precipitation uncertainty influence the NPSH via the Matsuno-Gill wave response, but their relative impact varies by region. Through the modulation of low cloud fraction, inter-model spread of the NPSH can have a further impact on extra-tropical land surface temperature. The teleconnection between tropical precipitation and the NPSH is examined through a series of numerical experiments.

Plain Language Summary

The North Pacific Subtropical High (NPSH) is a semi-permanent high-pressure system located in the subtropical North Pacific. The variability in the summer NPSH has a significant impact on the monsoon and typhoons over East Asia and the hydroclimate of California. However, future projections of the NPSH using state-of-the-art climate models remain highly uncertain. By evaluating how much individual models deviate from the multi-model mean at different locations, we find four hot spots of high uncertainty in NPSH projections. Our analysis further reveals that the primary source of model variance in changes in the NPSH is tropical precipitation, which can be attributed to both SST and non-SST driven factors. Through numerical experiments, we demonstrate that the teleconnection between tropical precipitation and the NPSH is achieved through wave propagation.

1 Introduction

The North Pacific Subtropical High (NPSH) plays a crucial role in shaping the hydroclimate in the North Pacific, East Asia and North America. As part of the subtropical stationary wave system, the NPSH reaches its peak magnitude in the boreal summer ranging from $15°N$ to $45°N$ with its western branch extending to East Asia and eastern branch bordering North America (Wills et al., 2019). The western flank of the NPSH (WNPSH) transports moisture from the ocean to East Asia and the Indochina Peninsula, strengthening the Meiyu-Baiu rainfall and causing typhoons and floods (B. Wang et al., 2013; S. Zhou et al., 2019; Y. Wang et al., 2022). Meanwhile, the west coast of North America experiences warm and dry summers under the influence of the eastern flank of the NPSH (Burls et al., 2017; Seager et al., 2019). The response of the NPSH to anthropogenic warming is expected to significantly impact regional climates (Wills et al., 2019; Seager et al., 2019; J. Choi et al., 2016; W. Choi & Kim, 2019); therefore, reliable future projections of the NPSH are crucial for preparing adaptation plans.

State-of-the-art climate models participating in the fifth and sixth phases of the Coupled Model Intercomparison Project (CMIP5 and CMIP6) exhibit diverging responses of the summer NPSH under global warming (Li et al., 2012; Sigmond et al., 2007; C. He & Zhou, 2015; X. Chen et al., 2020; D. Huang et al., 2022; Park & Lee, 2021). The explanations for models' poor agreement on the summer NPSH projections can be broadly categorized into local and remote processes. Local contributors include subtropical land-sea moist static energy (MSE) contrast and subtropical sea surface temperature (SST) (Lindzen & Nigam, 1987). For example, Shaw and Voigt (2015) and Baker et al. (2019) proposed that the opposing effects of CO_2 induced land-sea MSE contrast and subtropical SST warming result in a weak and insignificant NPSH response. In addition, model differences in the NPSH response are also attributed to the inter-model spread in the pattern of SST changes over the subtropical oceans (P. Huang et al., 2013; Levine & Boos, 2019). Furthermore, previous studies have demonstrated that the model differences in simulating East Asian summer monsoons (Rodwell & Hoskins, 2001; S. Zhou et al., 2019), the surface sensible heating over the Tibetan Plateau (Duan et al., 2017), and subgrid-scale topography (Boos & Hurley, 2013) also impact the NPSH projections.

Of all the remote factors contributing to uncertainties in the projections of the NPSH, model differences in the response of tropical precipitation is suggested to play a significant role (Baker et al., 2019; X. Chen et al., 2020; M. Chen et al., 2019; Park & Lee, 2021). Based on stationary wave theory, the summer subtropical highs are maintained by tropical and continental monsoon heating (e.g., Gill (1980); Ting et al. (2001); Rodwell and Hoskins (2001)). Therefore, model uncertainties in tropical diabatic heating could potentially propagate into the NPSH region as planetary Rossby waves and interact with the NPSH. The inter-model spread of tropical precipitation is shown to be connected to the tropical SST through convection processes (Xie et al., 2010a). For example, X. Chen et al. (2020) demonstrated that the model uncertainty in projecting the WNPSH is linked to inter-model spread of tropical SST, which involves a negative shortwave-convection-SST feedback. Specifically, a positive SST anomaly in the equatorial Pacific amplifies local convection, causing an increase in convective clouds. Consequently, incoming shortwave radiation is attenuated, leading to a decrease in the initial SST warming and the local convection. The restrained convection subsequently diminishes the intensity and the westward extension of the WNPSH. However, it is challenging to disentangle the relative impact of the tropical SST and precipitation on the inter-model spread of the NPSH projections in a coupled atmosphere-ocean system, given the complexity of their relationship (e.g., Xie et al. (2010b); P. Huang et al. (2013); J. He et al. (2014)). As a result, how model variability in tropical precipitation, both driven by SST and otherwise, influences the NPSH remains largely unexplored. Furthermore, the impacts of diabatic heating on subtropical highs have been examined primarily through idealized baroclinic wave models with a simplified atmosphere (Ting et al., 2001; Rodwell & Hoskins, 2001; Duan et al., 2017; Park & Lee, 2021). Therefore, the potential influences of diabatic heating on other factors such as land surface temperature (TS), which could potentially modulate the NPSH, have yet to be explored.

In this study, we utilize output from the coupled and atmosphere-only simulations from the Coupled Model Intercomparison Project (CMIP and AMIP) to identify the leading modes of inter-model spread in summer NPSH projections. We further explore the mechanisms underlying such uncertainties by prescribing diabatic heating in a comprehensive atmospheric general circulation model (AGCM). The relative roles of model differences in tropical precipitation independent of tropical SST and tropical precipitation driven by tropical SST are explored in detail. The connection between the inter-model spread of the NPSH projections and inter-model spread of extra-tropical land TS projections is also discussed.

2 Data and Method

2.1 CMIP and AMIP data

We use monthly mean data from fully coupled abrupt4$\times CO_2$ and pre-industrial control simulations of 46 models (Table S1) from both CMIP5 and CMIP6 (Taylor et al., 2012; O'Neill et al., 2016). Only one ensemble member (r1i1p1 or r1i1p1f1) is selected from each model. All data are interpolated to horizontal grids with $1^\circ \times 1^\circ$ spacing and 17 pressure levels. To investigate the inter-model uncertainties that are independent of inter-model differences in SST changes, we analyze 15 AMIP models (Table S1) from both CMIP5 and CMIP6. We consider all three AMIP scenarios: (1) AMIPControl, the control simulation forced by monthly mean SST and sea ice concentration; (2) AMIP4$\times CO_2$, same as AMIPControl but with CO_2 concentration quadrupled; (3) AMIPFuture, same as AMIPControl except adding the SST anomalies taken from CMIP3 experiments when

CO_2 concentration is quadrupled (Webb et al., 2017). We take the last 30-year June to August mean (JJAm) from the 150-year abrupt4×CO_2, and 30-year JJAm from AMIP-Future and AMIP4×CO_2 as equilibrium responses. We represent the total response to direct effect of CO_2 and CO_2 induced SST change as the summation of AMIPFuture and AMIP4×CO_2 (AMIP4×CO_2+Future) (J. He & Soden, 2015; Chadwick et al., 2017).

We use eddy streamfunction at 850 hPa to represent the NPSH (Ψ_{850}) (Wills et al., 2019; Shaw & Voigt, 2015). The NPSH response (ΔNPSH or $\Delta\Psi_{850}$) is calculated as the difference between the forced simulation and the control. Because diabatic heating is not a standard output from CMIP/AMIP, it is calculated as a residual from the time-mean thermodynamic energy equation (Rodwell & Hoskins, 2001):

$$\frac{\overline{Q}}{c_p} = \frac{\overline{\partial T}}{\partial t} + (\frac{p}{p_0})^{\frac{R}{c_p}}\overline{\omega}\frac{\overline{\partial\theta}}{\partial p} + \overline{\mathbf{v}} \cdot \nabla_{\mathbf{p}}\overline{T} + (\frac{p}{p_0})^{\frac{R}{c_p}}\frac{\partial}{\partial p}\overline{(\omega'\theta')} + \nabla_{\mathbf{p}} \cdot \overline{(\mathbf{v}'T')} \tag{1}$$

where Q is the diabatic heating or cooling, T is the temperature, c_p is the specific heat of dry air at constant pressure, R is the gas constant for dry air, p is the pressure, θ is the potential temperature, ω is the pressure velocity, and $\mathbf{v}$ are the horizontal wind velocities. The overbar represents the climatological June to August mean and prime is the deviation from that mean. Over the tropical ocean, the pattern of vertically integrated diabatic heating resembles the pattern of precipitation as the diabatic heating is dominated by condensational heating (Hagos et al., 2010).

2.2 Inter-model Uncertainty Analysis

We refer to the inter-model uncertainty (or spread) as the deviation of equilibrium response of each individual model from the multi-model mean (MMM) (Figure S1 and S2). The regions with large inter-model spread are first identified via inter-model standard deviations (Figure 1a). The leading modes of inter-model variability are further analyzed by the inter-model empirical orthogonal function (IEOF) (Figure 1b to 1d):

$$\delta\Delta X(m,s) = \sum_{i=1}^{n} PC_{m,i} \cdot IEOF_{i,s} \tag{2}$$

where ΔX denotes the projected changes of variable X (e.g., Ψ_{850}, precipitation), δ is the deviation from the MMM, s is the number of spatial grid points, m is the number of models, and n is the number of modes. The principal components (PCs) are normalized. To quantify the connection between the spread in two variables (e.g., X and Y), we calculate the relationship between the inter-model variability in Y and the ith mode of IEOF of variable X, through two approaches: (1) by regressing Y onto the corresponding ith Principal Component (PC_i) of X, or (2) by selecting where PC_i values of X are statistically significant, i.e., exceeding one standard deviation, and composing Y using models with positive PC_i values and models with negative PC_i values.

With a limited number of models, the inter-model spread may be more sensitive to specific outliers. Here, we conduct a robustness analysis by calculating the inter-model standard deviations of ΔNPSH using randomly selected subsets of 15, 20, and 30 models from the total of 46 CMIP models. The similarity between Figure 1a and Figures S3a to S3c suggests that a subset of 15 models is sufficient to capture the spatial structures of ΔNPSH inter-model spread.

2.3 Model Simulations

To investigate the physical mechanisms underlying the inter-model uncertainty of ΔNPSH, we use both the Community Atmosphere Model, version 5 (CAM5) within the framework of the Community Earth System Model, version 1 (CESM1) (Hurrell et al., 2013), and a baroclinic stationary wave model (SWmodel) (Ting & Yu, 1998; Held et al., 2002) to perform the sensitivity experiments. A comprehensive description of both models is provided in Table S2. Both CAM5 and the SWmodel are adequate for simulating the response of large-scale atmospheric circulation to prescribed forcing. However, CAM5 is more representative of the real atmosphere as it incorporates a much wider range of processes and is not subject to the relaxation toward a basic state or the idealized dampings that the SWmodel is. Specifically with CAM5, we are able to explore the associated response of land surface temperature, cloud cover and precipitation to prescribed forcing. In contrast, the SWmodel only focuses on the atmospheric stationary wave response which helps us to understand the dynamics and interactions of waves without confounding effects of other climate feedbacks, but it is an idealized model in which interactions, such as eddy-feedbacks, must be prescribed, and it is kept stable through relaxation toward a specified basic state and the addition of idealized damping. The control simulation in CAM5 is forced with the climatological SSTs and sea ice concentrations taken from the pre-industrial simulation of the CESM1 Large Ensemble Project (LENS) (Kay et al., 2015). The basic state in the SWmodel is the three-dimensional boreal summer climatology including temperature and horizontal winds, derived from the same LENS pre-industrial simulation mentioned above.

We explore the tropical ($30°S$-$30°N$) influence on the NPSH via a series of diabatic heating sensitivity experiments. Specifically, we consider two types of inter-model spreads of the tropical diabatic heating: the diabatic heating anomaly that is independent of tropical SST inter-model spread, and the diabatic heating anomaly that is induced by the tropical SST inter-model spread. The non-SST related diabatic heating inter-model spread is derived from the IEOF analysis on AMIP4$\times CO_2$+Future simulations, where SST and changes in SST are the same among models. The pattern of vertically integrated diabatic heating resembles Figure 2c. To quantify the diabatic heating anomaly attributed to the inter-model SST spread, we begin by imposing the tropical SST anomalies associated with the inter-model differences of ΔNPSH on the CAM5 control simulation. The SST anomalies are determined through the inter-model composite analysis of the output from the CMIP abrupt4$\times$CO$_2$ scenario ("Data and Method 2.2", Figure 2d and S4). The resulting total diabatic heating (Figure S5a) over the deep tropics ($15°S$-$15°N$) is then calculated as the sum of condensational heating, longwave heating, solar heating and vertical diffusion of temperature. The diabatic heating anomaly is added to both CAM5 and SWmodel as a constant temperature tendency term. For each SWmodel experiment, the model is integrated for 50 days, and the time average of the last 20 days is taken as the equilibrium response. For each CAM5 experiment, five ensembles of three-month simulations are branched off on the first day of June of different years. The equilibrium responses are calculated as the three-month mean of the differences between the forced and control runs averaged across all ensembles. Since CAM5 would non-linearly amplify the diabatic heating perturbation due to its moisture process and other feedbacks, we determine the diabatic heating perturbation to impose with an "iterative approach" as detailed in R. Chen et al. (2022).

To compare the relative importance of inter-model spread in extra-tropical SST changes to the tropical influence, we prescribe the SST inter-model uncertainty associated with inter-model spread of ΔNPSH over the North Pacific ($27-70°N$) to CAM5. The North Pacific SST inter-model spread is calculated through the same inter-model composite analysis from the abrupt4$\times CO_2$ output mentioned earlier.

3 Results

3.1 Overview of Inter-model Uncertainty in Summer NPSH Projection

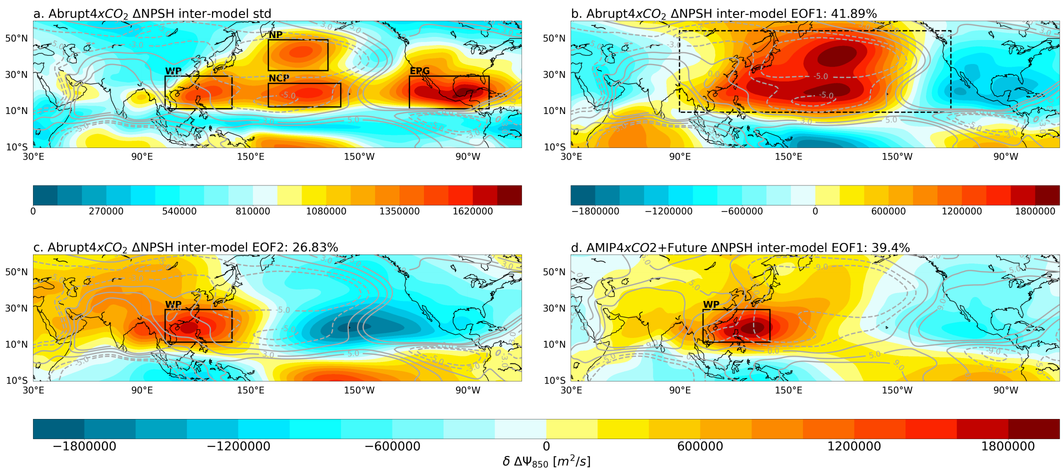

Figure 1. Inter-model spread of summer NPSH future projections. **a** The inter-model standard deviation of $\Delta\Psi_{850}$ under the abrupt4xCO_2 scenario. Four regions with high inter-model variability are marked with black rectangles. **b,c** The first two leading modes (IEOF1 and IEOF2) derived from IEOF analysis on $\Delta\Psi_{850}$ over the domain (10-50$^\circ N$, 90-240$^\circ E$; regions outlined with dashed line in **b**) under abrupt4xCO_2 scenario. **d** Same as **b** but for AMIP4xCO_2+Future scenario. The grey contours denote the ΔNPSH MMM (unit: $10^6 m^2 s^{-1}$) under abrupt4xCO_2 (**a** to **c**) and AMIP4xCO_2+Future scenarios (**d**), respectively. The percentage of inter-model variance explained by each mode is included in the subtitle.

The overall strength of summer NPSH weakens under the abrupt4xCO_2 scenario as indicated by the MMM response of Ψ_{850} (grey contours in Figure 1a) across 46 CMIP models. However, the inter-model standard deviation of ΔNPSH is comparable or even larger than the MMM response in most of the regions (compare color shadings and contours in Figure 1a). We find four zones of high ΔNPSH inter-model variability: the western Pacific (WP), the eastern Pacific and Gulf of Mexico (EPG), the North Pacific (NP) and the central North Pacific (NCP). These four hot spots are well captured by the first two leading IEOF modes which account for nearly 70% of the inter-model variance (Figure 1b and 1c). Here we pick the sign of the eigenvectors that feature a strengthening of the NPSH as the positive direction and all subsequent analyses follow this choice. The shape of the IEOF patterns, the amount of inter-model variance explained, and the underlying physical mechanisms remain the same regardless of our choice (Weare et al., 1976). The first IEOF features an overall strengthening of the NPSH with two centers of maximum variance located at the NP and the NCP respectively. The cyclones over the Asian continent and the EPG are also partially captured (Figure 1b). The second IEOF mode presents a dipole structure representing a strengthening and westward extension of the WNPSH, and a weakening of the NPSH over the eastern Pacific (Figure 1c). Since IEOF modes are orthogonal to each other, the inter-model spreads over the WP and the NP-NCP likely have independent underlying causes. Mechanisms of the two EOF modes will be examined in the rest of this paper.

To exclude the influence from inter-model variability in SST changes, we evaluate the inter-model spread of the NPSH response among 15 models under the AMIP4×CO_2+Future scenario, where all models are driven by the same SST changes ("Data and Method 2.1" and Table S1). Note that these 15 models are also included in the coupled abrupt4×CO_2 experiments and can capture the overall spatial patterns of ΔNPSH inter-model spread (Figure S6). As depicted in Figure S3d, the WP region demonstrates a notable inter-model standard deviation among 15 AMIP 4×CO_2+Future models. The leading inter-model variance pattern (Figure 1d) features a dipole structure with an anticyclone anomaly over the WP that resembles Figure 1c, suggesting that the inter-model spread of ΔWNPSH over the WP has non-SST related causes. On the other hand, the high inter-model variances over the NP and NCP (Figure 1b) are either absent or underrepresented in Figure 1d and Figure S3d, indicating that the inter-model uncertainties of ΔNPSH over the NP and the NCP might be related to SST.

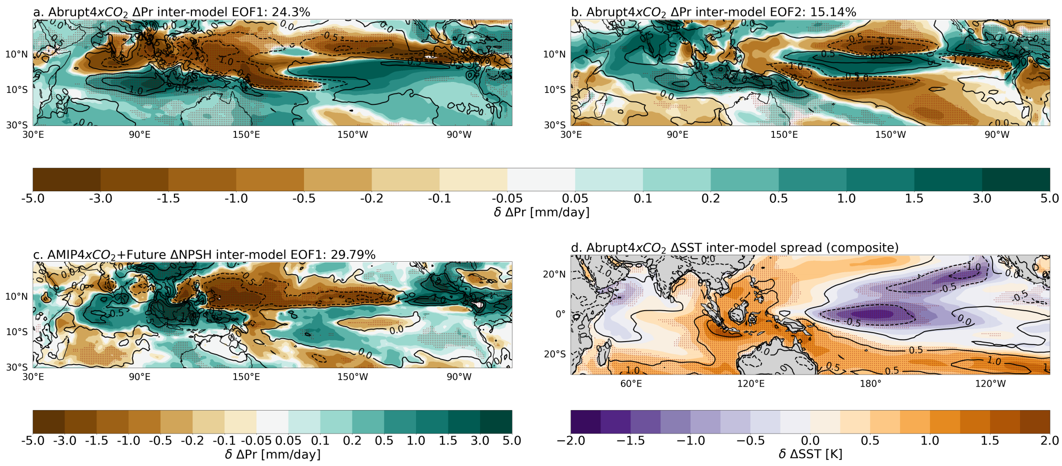

Figure 2. Tropical precipitation and SST anomalies associated with ΔNPSH inter-model spread. **a** The IEOF1 of precipitation (shadings; mm/day) and associated precipitation anomalies regressed onto PC2 of $\Delta\Psi_{850}$ (contours; mm/day) under the abrupt4xCO_2 scenario. **b** Similar to **a** but with IEOF2 of precipitation and associated precipitation anomalies regressed onto PC1 of $\Delta\Psi_{850}$. **c** Similar to **a** and **b** but with IEOF1 of precipitation and associated precipitation anomalies regressed onto PC1 of $\Delta\Psi_{850}$ under the AMIP4xCO_2+Future scenario. **d** Inter-model uncertainty of ΔSST by composite analysis (shadings; K) and SST anomalies associated with inter-model PC2 of precipitation changes (contours; K). Regions with statistically significant correlations are marked with stipples.

3.2 Tropical Origins of the Inter-model Uncertainty

As a key driver of the tropical circulation and the tropical-extratropical teleconnections, (Gill, 1980; Emanuel et al., 1994; Fereday et al., 2020), the tropical precipitation remains one of the most challenging components in climate projections. We examine the inter-model variability in the equilibrium response of tropical precipitation under the abrupt4×CO_2 scenarios via the IEOF method and evaluate their relationships with ΔNPSH. The IEOF1 of the tropical precipitation response displays a dry-north and wet-south dipole located in the Indo-West Pacific (shadings in Figure 2a). The second leading mode of the tropical precipitation inter-model spread exhibits a meridional alternating negative and positive anomaly structure spanning from the Indian Ocean to the subtropical Pacific (shadings in Figure 2b). The first two leading IEOF modes account for around 40% of the inter-model variance of the tropical precipitation response. When regressing the precipitation response onto the inter-model PCs of ΔNPSH, we find that the first mode of ΔNPSH inter-model spread is highly correlated with the second mode of tropical precipitation inter-model spread, while the second mode of ΔNPSH inter-model spread is highly correlated with the first mode of tropical precipitation inter-model spread (comparing contours to shadings in Figure 2a and 2b).

3.2.1 Contribution of SST Independent Precipitation Uncertainty

Given the resemblance between Figure 1c and 1d, and the significant correlation between tropical precipitation and the NPSH, as suggested in Figure 2a, we initiate our investigation by focusing on non-SST related precipitation inter-model spread. Under the AMIP4×CO_2+Future scenario (Figure 2c), the spatial pattern of IEOF1 of tropical precipitation response also exhibits a dry-north and wet-south dipole pattern over the Indo-West Pacific similar to Figure 2a. This precipitation dipole is related to an asymmetric diabatic heating with respect to the equator and this diabatic heating pattern will trigger a low-level anticyclone (cyclone) to the north (south) of the equator, as described by the Matsuno-Gill response (Gill, 1980; Matsuno, 1966). Indeed, the low-level anticyclone at the WP, and the cyclone at the Maritime Continent (MC) in Figure 1c and 1d appear to align with the Matsuno-Gill response to the Indo-West Pacific precipitation anomalies demonstrated in Figures 2a and 2c. This consistency leads us to hypothesize that the high inter-model ΔNPSH variance at the WP results from the inter-model tropical precipitation spread that is unrelated to SST.

To confirm our hypothesis, we conduct a set of sensitivity experiments in CAM5 and the SWmodel where the inter-model tropical diabatic heating anomaly obtained from the AMIP4×CO_2+Future output is prescribed ("Data and Method 2.3"). As demonstrated in Figure 3e and 3g, a quadrupole low-level circulation pattern with a strong anticyclone centered at the WP and a strong cyclone centered at the EPG appears as a primary response to the tropical diabatic heating. In the case of CAM5, the anomalous northeasterlies on the eastern flank of the anticyclone transport the off-equatorial dry (low moist enthalpy) air into the western Pacific, further suppressing the convection over the WP (Wu et al., 2017; Y. Wang et al., 2022). Moreover, the elevated land surface temperature over the extra-tropical Eurasian continent (Figure 4c) acts to reinforce the strengthening of the NPSH through the land-sea thermal contrast (Portal et al., 2022; Shaw & Voigt, 2015). The similar response of ΔΨ850 between CAM5 (Figure 3e) and the SWmodel (Figure 3g) suggests that the strengthening of the NPSH over the WP can be primarily attributed to the Matsuno-Gill response triggered by the anomalous tropical diabatic heating. The upper-level circulation presents a similar quadrupole pattern but with a cyclone over the western Pacific and anticyclone over North America and the EPG, suggesting a baroclinic wave structure between 15-20°N (Figure 3a and 3c) (Wills et al., 2019; Ting & Yu, 1998). As shown by the Takaya-Nakamura wave activity flux (Figure 3a), a northeastward propagating Rossby wave train emanates from the tropical western Pacific and extends to North America over the upper troposphere (Ding et al., 2018; Takaya & Nakamura, 1997). The weaker and eastward displaced upper-level cyclone center in the SWmodel (Figure 3c), when compared to CAM5, may be attributed to factors such as the absence of land and topography, as well as a lack of response of feedbacks involving transient eddies and extra-tropical diabatic heating.

3.2.2 Contribution of SST Driven Precipitation Uncertainty

The interaction between tropical SST and subtropical atmospheric circulation is often discussed in the context of the El Niño-Southern Oscillation teleconnection, such as the Pacific-North American pattern (e.g., Franzke et al. (2011); Dai et al. (2017)), Kelvin wave-induced Ekman divergence resulting from Indian Ocean (IO) warming (C. He & Zhou, 2014; Xie et al., 2009), local convection over a warm MC (Sui et al., 2007), moist enthalpy advection (Wu et al., 2017), and the ocean-atmosphere coupling between the IO SST and the Pacific-Japan pattern (Kosaka et al., 2013). In particular, by modifying the local convection, tropical SST can modulate the influence of tropical precipita-

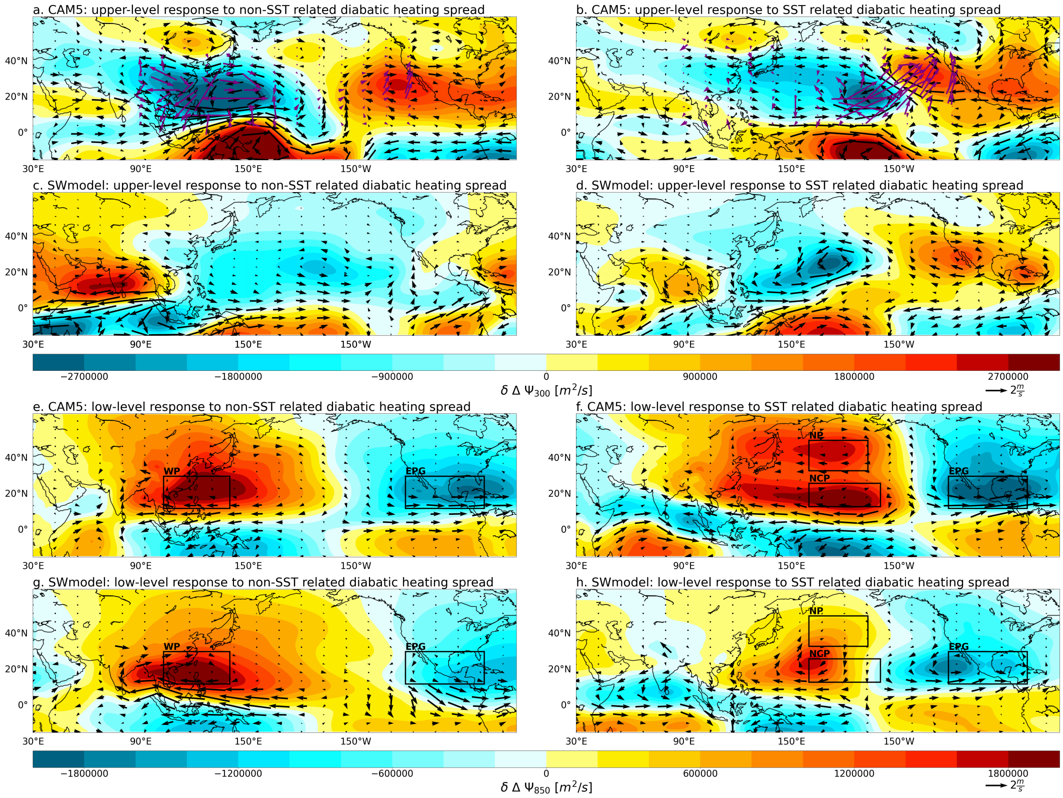

Figure 3. Response of subtropical circulation to prescribed tropical diabatic heating anomalies in CAM5 and SWmodel. The left column shows the response of eddy streamfunction (shadings; m^2/s) and horizontal winds (black vectors; m/s) to SST independent inter-model tropical diabatic heating spread. The right column is similar to the left one but with the ciculation response to tropical SST induced diabatic heating spread. **a-d** describe the results at 350 hPa and **e-h** describe the results at 850 hPa. The stationary Rossby wave propagation is shown as the Takaya-Nakamura Flux (purple vectors; normalized) in **a** and **b**. The CAM5 results are **a, b, e** and **f** and the SWmodel results are **c, d, g** and **h**.

tion on atmospheric circulation via wave generation and propagation. Therefore, it is plausible to speculate that the inter-model spread of tropical SST affects the NPSH by generating anomalous tropical precipitation. The tropical inter-model uncertainty in ΔSST features a La Niña-like pattern with cooling over the western Indian Ocean and central Pacific and a K-shaped warming anomaly covering the MC and the western subtropical Pacific (shadings in Figure 2d). This SST inter-model spread pattern is spatially correlated with the IEOF2 of precipitation (comparing contours to shadings in Figure 2d). In the meantime, the tropical precipitation anomaly regressed onto the inter-model PC1 of ΔNPSH (contours in Figure 2b) perfectly lines up with the IEOF2 pattern of precipitation, implying that the high inter-model ΔNPSH variance at the NP and the NCP are connected to the tropical precipitation anomalies that are linked to the inter-model SST uncertainty.

The role of the tropical SST-driven precipitation inter-model spread is further explored through numerical experiments ("Data and Method 2.3"). To focus on the impact of inter-model precipitation uncertainty in the deep tropics, we only prescribe diabatic heating anomalies between $15°S$-$15°N$ generated from the tropical inter-model SST spread experiment to CAM5 and the SWmodel. As shown in both Figure 3f and

Figure 3h, a Matsuno-Gill type circulation response appears in the lower troposphere in both CAM5 and the SWmodel. However, the two high-pressure centers located at the NP and the NCP are only captured by CAM5. The IEOF1 pattern of ΔNPSH (Figure 1b) is well replicated in CAM5 except that the anomaly over the NP is smaller compared to that of the NCP. The weak response in the NP could result from neglecting the inter-model uncertainty in representing other extra-tropical process such as the transient eddy feedbacks (Hurrell et al., 2013; White, 1982). The NPSH response in the SWmodel displays only one high-pressure center located in-between the NP and the NCP. The circulation response in the upper troposphere in both CAM5 and the SWmodel exhibits a northeastward propagating Rossby wave train, a baroclinic wave structure between 15-20$^{\circ}N$ and a barotropic wave structure between 45-55$^{\circ}N$ (Figure 3b and 3d). It is worth mentioning that the influence of the tropical inter-model SST spread extends beyond local convection to include precipitation changes in remote areas (contours in Figure S5b). The secondary convection produced over the extra-tropics also exerts an impact on the NPSH along with the tropical convection. For instance, the positive precipitation anomaly over East China Sea triggers a local cyclonic circulation anomaly, restricting the westward extension of the NPSH (shadings in Figure S5b).

3.3 Relationship with the Extra-tropics

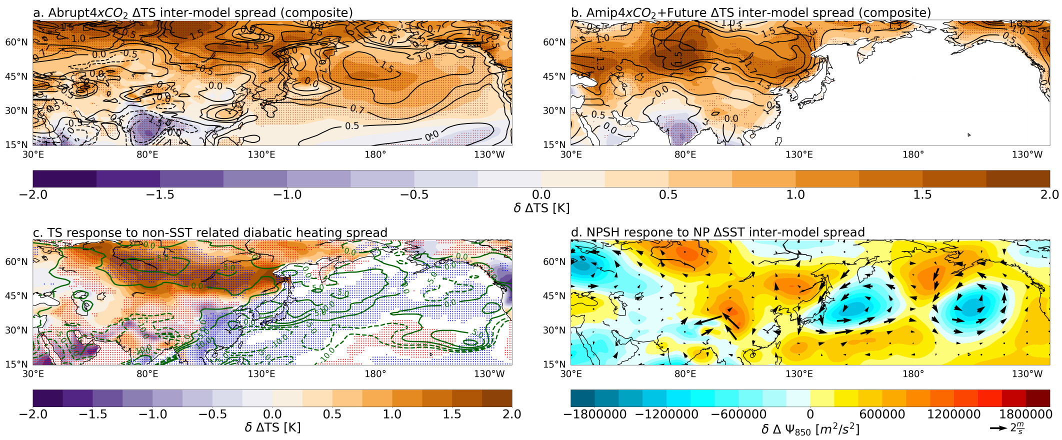

Figure 4. Relationship between inter-model uncertainty of ΔNPSH and extra-tropical land ΔTS and the North Pacific ΔSST. **a** Inter-model uncertainty of ΔTS by composite analysis (shadings; K) and TS anomalies associated with inter-model PC2 of $\Delta\Psi_{850}$ (contours; K). **b** Similar to **a** but with IEOF1 of land TS and associated land TS anomalies regressed onto PC1 of $\Delta\Psi_{850}$ under the AMIP4xCO_2+Future scenario. Regions with statistically significant correlations are marked with stipples in **a** and **b**. **c** Response of land TS (shadings; K), net surface shortwave radiation (thick green contours; W/m^2), and low cloud fraction (blue and red scatters where blue indicates a significant low cloud reduction and vice versa) to SST independent inter-model tropical diabatic heating spread in CAM5. **d** Response of eddy streamfunction at 850 hPa(shadings; m^2/s) and horizontal winds (vectors; m/s) to inter-model spread of ΔSST over North Pacific.

While we have determined that the primary sources of model uncertainty in ΔNPSH are related to both SST and non-SST driven tropical precipitation inter-model spread, it is also important to consider the potential connections to of extra-tropical SST and land TS. As illustrated in Figure 4a, the inter-model spread of land TS changes features an overall warming in northern Eurasia between 45-65$^{\circ}N$ and a cooling in South Asia and the Middle East. The high inter-model variability of ΔNPSH over the WP is statistically associated with this warming pattern over the extra-tropical Eurasia, while the other three hot spots do not exhibit any significant correlations (contours in Figure 4a , Figure S7 and S8). When examining the inter-model spread of extra-tropical land TS response under the AMIP4xCO_2+Future scenario, we find a similar warming pattern between 45-65$°N$ and this pattern is also significantly correlated with the inter-model PC1 of ΔNPSH.

The conventional perspective believes that the strengthening of the NPSH is driven by an enhanced land-sea thermal contrast (Li et al., 2012; Shaw & Voigt, 2015; Levine & Boos, 2019; Wills et al., 2019; Portal et al., 2022). However, we find that a substantial portion of the inter-model spread of extra-tropical land warming over northern Eurasia (Figure 4a and 4b) can also be produced by prescribing CAM5 with the non-SST driven diabatic heating anomalies (shadings in Figure 4c). The westward extension of the anomalous low-level anticyclone induced by the tropical diabatic heating inter-model spread is evident over Eurasia (Figure 3e and 3g). This extension intensifies the subsidence of dry air and leads to a reduction in cloud fractions, particularly for low clouds (blue scatters in Figure 4c). The reduction of the low clouds further promotes the absorption of solar radiation by the land, leading to a net increase of the downwelling shortwave radiation at the land surface (thick green contours in Figure 4c). In addition, the anomalous low-level southerly winds contribute to the extra-tropical land warming by advecting warmer air from the tropics (Figure 3e and 3g). On the other hand, the extra-tropical Eurasian warming is also expected to reinforce the intensification of the NPSH.

By regressing the inter-model ΔSST pattern over the North Pacific onto the inter-model PC2 of ΔNPSH, we find a warm anomaly stretching from the Kuroshio Extension to the west coast of Canada (Figure 4a). This warm SST anomaly along the Kuroshio Extension is also correlated with an enhancement of local precipitation and a reduction of precipitation to the north and south (Figure S9a) (Gan & Wu, 2012). When prescribing the inter-model spread of ΔSST over the North Pacific to CAM5, a very weak strengthening of the low-level circulation is seen over the NP, and two cyclonic circulations are shown in the western and eastern North Pacific as local responses to the enhancement of precipitation (Figure S9b). Nevertheless, the overall structure of the NPSH response is quite different from IEOF2 of ΔNPSH (Figure 1c). Conversely, the strengthening of the NPSH triggered by tropical precipitation inter-model spread leads to an overall reduction of low cloud fraction and intensification of downwelling surface shortwave radiation, which could partially explain the warming over the North Pacific (Figure 4c).

4 Summary and Discussion

We have confirmed that the model uncertainties in projections of the NPSH originate from both SST and non-SST driven tropical inter-model precipitation spread. Specifically, the large model variance of ΔNPSH over the WP is caused by inter-model precipitation uncertainty that is independent of SST. This inter-model ΔNPSH spread further influences changes in extra-tropical Eurasian TS and the North Pacific SST through the modulation of low cloud fraction. On the other hand, the inter-model spread in the changes of tropical SST can affect the NPSH over the NP and the NCP through the production of anomalous precipitation.

Our study highlights the importance of accurately projecting the tropical precipitation. When the model variance is absent in SST, the two plausible causes of inter-model precipitation spread could be models' diversity in cloud parameterization (Su et al., 2017; Mauritsen & Stevens, 2015) and tropical land albedo simulation (Levine & Boos, 2017; W. Zhou & Xie, 2017). In addition, other processes such as the subtropical transient eddy feedback (e.g., Hurrell et al. (2013)), the subtropical and mid-latitude cloud albedo feedback (Burls et al., 2017), and the Arctic amplification (e.g., Coumou et al. (2018)) might also contribute to the model uncertainty in projections of the NPSH and are worth deeper explorations.

Open Research Section

The CMIP5 data can be downloaded at: https://esgf-node.llnl.gov/projects/cmip5/, and the CMIP6 data can be downloaded at: https://esgf-node.llnl.gov/projects/cmip6/. The numerical experiment data can be downloaded at: https://doi.org/10.5281/zenodo.8048355

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