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## RESEARCH LETTER

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### Key Points:
- The El Niño-Southern Oscillation (ENSO)-Ningaloo Niño/Niña teleconnection is projected to weaken under greenhouse warming.
- A weakened atmospheric teleconnection from La Niña to Ningaloo Niño contributes to this weakened ENSO-Ningaloo Niño/Niña teleconnection.
- The weakened ENSO-Ningaloo Niño/Niña teleconnection is caused by the tropical Pacific mean state changes in the future.

### Supporting Information:
- Supporting Information S1

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**Weakened ENSO-Ningaloo Niño/Niña Teleconnection Under Greenhouse Warming**

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### Abstract
Ningaloo Niño/Niña is a mode of climate variability in the southeastern Indian Ocean with huge impacts on Australian climate. El Niño-Southern Oscillation (ENSO), as the dominant remote forcing, triggers Ningaloo Niño/Niña. However, how this teleconnection will respond to greenhouse warming is unclear. Using Coupled Model Intercomparison Project phase 5 (CMIP5) multimodel simulations, we find a weakened ENSO-Ningaloo Niño/Niña teleconnection under greenhouse warming, which manifests as weakened atmospheric teleconnection from La Niña to Ningaloo Niño. Such weakened teleconnection can be linked to the tropical Pacific mean state changes including an El Niño-like warming pattern and more stable atmosphere in the future climate, both suppressing the atmospheric convection in the western tropical Pacific, leading to a weaker Matsuno-Gill response in the southeastern Indian Ocean. Our results suggest that Ningaloo Niño/Niña becomes more challenging to predict as greenhouse warming continues.

### Plain Language Summary
Ningaloo Niño/Niña refers to an extreme ocean warming/cooling event off Western Australia with huge biological and climate impacts. El Niño-Southern Oscillation (ENSO) is able to trigger Ningaloo Niño/Niña through atmospheric and oceanic processes, but this teleconnection is projected to weaken in the future climate. As greenhouse warming continues, the eastern tropical Pacific warms faster than the west, and the tropical atmosphere becomes more stable. These changes induce a suppressed atmospheric convection over the western tropical Pacific, the key region of teleconnection processes, and hence weaken the teleconnection. This study suggests a more challenging prediction of Ningaloo Niño/Niña by ENSO in a warmer climate.

## 1. Introduction

Ningaloo Niño/Niña is a newly discovered climate variability mode in the southeastern Indian Ocean (SEIO). A Ningaloo Niño (Niña) event is characterized by anomalously warm (cold) sea surface temperatures (SSTs) off Western Australia (Kataoka et al., 2014). Ningaloo Niño events can provide a background favorable for the development of strong synoptic marine heatwaves along the west coast of Australia, leading to massive ecological loss for Australia. Specially, an unprecedented Ningaloo Niño event occurred in 2010–2011 caused irreversible coral bleaching and huge damage on local marine ecosystems (Pearce & Feng, 2013; Wernberg et al., 2013). Therefore, it is important to understand and predict Ningaloo Niño/Niña.

The generation and development mechanisms of Ningaloo Niño/Niña have been investigated in recent years. El Niño-Southern Oscillation (ENSO) is considered as the dominated remote forcing for triggering Ningaloo Niño/Niña, as more than half of the observed Ningaloo Niño (Niña) events are generated following La Niña (El Niño) (Feng et al., 2013; Kataoka et al., 2014; Tozuka et al., 2014). The ENSO-Ningaloo Niño/Niña teleconnection works in two ways through atmospheric and oceanic teleconnection, respectively. Here, we take Ningaloo Niño as a brief illustration, with the opposite processes operate for Ningaloo Niña. In terms of atmospheric teleconnection, warm SSTs associated with La Niña in the western tropical Pacific (WTP) induce diabatic heating which generates negative sea level pressure (SLP) anomalies in the SEIO through Matsuno-Gill response (Matsuno, 1966; Gill, 1980; Tozuka et al., 2014). This low SLP induces alongshore northerly wind anomalies, which weaken the background southerly winds off Western
Australia, bring the warm and moist air from the Maritime Continent, then reduce the local evaporation and strengthen the Leeuwin Current (Benthuysen et al., 2014; Marshall et al., 2015; Guo et al., 2020), hence warm SSTs. In terms of oceanic teleconnection, positive sea surface height (SSH) anomalies associated with La Niña in the WTP generate coastal downwelling Kelvin waves (Clarke, 1991; Clarke & Liu, 1994; Meyers, 1996; Feng et al., 2008). These waves propagate poleward along the coast of Western Australia which suppress the climatological coastal upwelling and strengthen the Leeuwin Current (Benthuysen et al., 2014; Marshall et al., 2015), and warm SSTs. In either way, the initial positive SST anomalies induced by La Niña may be amplified into a Ningaloo Niño event through local air-sea interactions involving wind-evaporation-SST feedback (Xie & Philander, 1994), coastal Bjerknes feedback (Bjerknes, 1969) and cloud-radiation-SST feedback (Tozuka & Oettli, 2018; L. Zhang et al., 2018).

Many previous studies have suggested that the characteristics of Ningaloo Niño/Niña events, such as frequency, amplitude, and predictability, are modulated by interdecadal variations in the tropical mean state changes associated with climate modes on the interdecadal timescale (Doi et al., 2015; Feng et al., 2015; Li et al., 2017, 2019; Tanuma & Tozuka, 2020). Based on their conclusions, it is supposed that the features of Ningaloo Niño/Niña will respond to changes in the tropical mean state on longer than interdecadal timescales. Under greenhouse warming, the mean state of the tropical Pacific is expected to show an El Niño-like warming pattern and more stable atmosphere (Allen & Sherwood, 2008; Collins et al., 2010; Johnson & Xie, 2010; Vecchi & Soden, 2007; Vecchi et al., 2006). These changes in the mean state will modify the characteristics of ENSO in many respects (Cai et al., 2015a, 2015b, 2018). Whether the ENSO-Ningaloo Niño/Niña teleconnection will change under greenhouse warming is unknown. If so, how do these changes in the mean state of the tropical Pacific influence the ENSO-Ningaloo Niño/Niña teleconnection? Here, we show that the ENSO-Ningaloo Niño/Niña teleconnection weakens under greenhouse warming, and the weakening can be linked to changes in the mean state of the tropical Pacific. Since ENSO provides a precursory memory for Ningaloo Niño/Niña’s predictability (Doi et al., 2013), our result suggests the Ningaloo Niño/Niña will be less predictable, making it more challenging to mitigate its climate and ecological impacts in the future.

2. Data and Methods

The observed monthly SST data are obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) data set (Huang et al., 2017). We use monthly SLP from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay et al., 1996). For the monthly sea surface height (SSH), an operational ocean analysis/reanalysis system (ORAS4; Balmaseda et al., 2013) is used. SST and SLP data cover the period of 1950–1999 while SSH data covers 1960–1999 due to its limited sample. In order to investigate the changes under greenhouse warming, we concatenate the historical and the Representative Concentration Pathway 8.5 (RCP8.5) simulations from 35 Coupled Model Intercomparison Project phase 5 (CMIP5) models (Table S1). The historical runs are forced by anthropogenic and natural radiative forcing from 1850 to 2005, and the RCP8.5 simulation starts from 2006 and forced by an increasing radiative forcing reaching about 8.5 W m⁻² at the end of the 21st century (Taylor et al., 2012). Here, we define 20th century (1900–1999) as present-day climate and 21st century (2000–2099) as future climate. All variables are quadratically detrended to isolate the greenhouse warming effect.

There are two commonly used methods to define the index of Ningaloo Niño/Niña in previous studies (Feng et al., 2015; Kataoka et al., 2014, 2017; Kido et al., 2016; Marshall et al., 2015; L. Zhang et al., 2018). One index, named Ningaloo Niño index (NNI), is derived from regional average of SST anomalies over 108°E-Australian western coast and 32°S–20°S, which is the core position of Ningaloo Niño/Niña. Another index is obtained from the first principle component (PC1) extracted from empirical orthogonal function analysis (EOF) on SST anomalies off the Western Australia (104°E–118°E, 34°S–16°S). Given that Ningaloo Niño events simulated in CMIP5 historical outputs are different among models in terms of core position and amplitude (Figure S1), we use these two indices together to select CMIP5 models of good performance. The NNI can capture the magnitude of SST over the core position and EOF-based index can capture the amplitude of Ningaloo Niño/Niña. The EOF-based amplitude of Ningaloo Niño is described as the standard deviation of PC1, with the total variance of EOF1 spatial pattern being scaled to unity. If both NNI amplitude and EOF-based amplitude in one model are close to that of the observation, that model can be regarded as...
reasonably simulating both the core position and amplitude of Ningaloo Niño/Niña. Then, we choose a box benchmarked with observation as the center, ±0.2 times standard deviation of models’ NNI and PC1 as the range to select models (Figure S2). In this way, we select 21 out of total 35 models for our study. We use Niño 3.4 index (120°W–170°W, 5°S–5°N) to measure ENSO, and different definitions of ENSO produce consistent results. Because the seasonality of ENSO and Ningaloo Niño/Niña are phase locked (Figure S3; Ham & Kug, 2014; Kataoka et al., 2014), we focus on their peak phase as December to February (DJF) for ENSO and January to March (JFM) for Ningaloo Niño/Niña. In this paper, Ningaloo Niño (Niña) events are defined as NNI above +1.0 SD (below −1.0 SD) and El Niño (La Niña) events are defined as Niño 3.4 index above +1.0 SD (below −1.0 SD) (Ham & Kug, 2015; Kataoka et al., 2014).

3. Results

3.1. Observed and CMIP5-Simulated ENSO-Ningaloo Niño/Niña Teleconnection

To depict both atmospheric and oceanic teleconnection processes, we calculate correlation coefficient map between JFM-averaged NNI and gridded DJF-averaged SST anomalies, DJF-averaged SLP anomalies, DJF-averaged SSH anomalies over the Indo-Pacific region in observations and multimodel ensemble mean (MMEM) of the 21 selected models (Figure 1). In observations, there is an ENSO-like spatial pattern over the tropical Pacific (Figure 1a), that is, negative correlations over the central and eastern and positive correlations over the western Pacific, confirming that the Ningaloo Niño (Niña) tends to occur following La Niña (El Niño). The CMIP5 MMEM realistically reproduce that in observations (Figure 1b), in spite

Figure 1. Spatial patterns of correlation coefficients between JFM NNI and (a) DJF SST anomalies over the 1950–1999 period; (c) DJF SLP anomalies over the 1950–1999 period in observations, respectively. (b), (c) and (d) are same as (a), (b) and (c), but for MMEM from CMIP5 present-day climate (1900–1999). Stippled regions denote the grid-point where the correlation is statistically significant above the 95% confidence level in (a, c, e) and where more than 80% models have the same sign with the MMEM in (b, d, f). CMIP5, Coupled Model Intercomparison Project phase 5; DJF, December to February; JFM, January to March; MMEM, multimodel ensemble mean; NNI, Ningaloo Niño index; SLP, sea level pressure; SSH, sea surface height; SST, sea surface temperature.
of the well-recognized model bias of ENSO's excessive westward extension (Cai et al., 2015a; Chowdary et al., 2014; Collins et al., 2010; Kim & Yu, 2012). As in previous papers on the generation and mechanism of Ningaloo Niño (Feng et al., 2013; Kataoka et al., 2014; Tozuka et al., 2014; Zinke et al., 2015), the WTP (120°E–150°E, 10°S–10°N, black box in Figure 1a) can be regarded as the key region bridging ENSO and Ningaloo Niño/Niña through the atmospheric and oceanic teleconnection. For the atmospheric teleconnection, Figures 1c and 1d show the correlation map between SLP and NNI. The observation and MMEM show a consistent center of negative correlation over the SEIO, which is attributed to the Matsuno-Gill response to an ENSO-induced diabatic heating over the WTP. For the oceanic teleconnection, both observation and MMEM show a positive correlation between NNI and SSH over the WTP and along the Western Australian coast, indicating the propagation by coastal Kelvin waves (Figures 1e and 1f; Figure S4).

The ENSO amplitude asymmetry refers to a stronger El Niño than La Niña (Burgers & Stephenson, 1999). Considering ENSO as the dominant remote forcing, Ningaloo Niño/Niña's amplitude should have negative skewness. However, NNI is positive skewed in the observation, implying that Ningaloo Niño is typically stronger than Ningaloo Niña (Marshall et al., 2015; Tozuka & Oettli, 2018). The unexpected skewness may mean that an asymmetric impact on Ningaloo Niño/Niña from ENSO may exist (Kusunoki et al., 2020). Here, we examine this asymmetric impact in the observation and the selected CMIP5 models. During Ningaloo Niño years, the tropical Pacific shows a distinct La Niña-like pattern (Figures 2a and 2b). But for Ningaloo Niña years, there’s no well-defined El Niño-like pattern (Figures 2c and 2d). This asymmetry has been verified from the asymmetric response of Leeuwin Current to ENSO (Feng et al., 2003) and distinct pattern of marine heatwaves to ENSO (N. Zhang et al., 2017). For that reason, the ENSO-Ningaloo Niño/Niña teleconnection manifested as a strong La Niña-Ningaloo Niño connection and a weak El Niño-Ningaloo Niña connection, which will be a focus in the following analysis. Overall, the high consistency in ENSO-Ningaloo Niño/Niña teleconnection processes and the asymmetry between observation and CMIP5 models gives confidence to use these models to investigate the ENSO-Ningaloo Niño/Niña teleconnection under greenhouse warming.

### 3.2. Weakened ENSO-Ningaloo Niño/Niña Teleconnection under Greenhouse Warming

In this section, we examine the changes in the ENSO-Ningaloo Niño/Niña teleconnection under greenhouse warming. We use the ratio of event coincidence to measure the relationship between Ningaloo Niño/Niña and El Niño/La Niña events. As shown in Figure 3, models above (below) the diagonal line indicate higher (lower) occurrence ratio of Ningaloo Niño/Niña following La Niña/El Niño in the future. A total of 15
models (71%) show a decreased occurrence ratio of Ningaloo Niño following La Niña in the future climate, with nearly no change in the occurrence ratio of Ningaloo Niña following El Niño (10 of 21 models show the decreased occurrence ratio). Because of the asymmetry in ENSO-Ningaloo Niño/Niña teleconnection, the weakened ENSO-Ningaloo Niño/Niña teleconnection should be attributed to the weakened relationship between Ningaloo Niño and La Niña (Figure S5).

To further investigate the role of atmospheric and oceanic teleconnection under greenhouse warming, we adopt the correlation coefficient between NNI and SST over the key region (WTP:120°E−150°E, 10°S–10°N) to measure the atmospheric teleconnection and correlation coefficient between NNI and SSH over the WTP to measure the oceanic teleconnection in present-day and future climate. A total of 16 models (76%) below the diagonal line suggesting that there is a consistent weakening of atmospheric teleconnection under greenhouse warming (Figure 4a). By contrast, there's nearly no change in relationship between NNI and SSH (models are evenly distributed on both side of the diagonal), indicating that oceanic teleconnection changes little under greenhouse warming (Figure 4b). We further calculate correlation coefficient between NNI and SLP anomalies in the SEIO (95°E−115°E, 25°S–15°S) and between NNI and SSH anomalies along the northern Australian coast (116°E−126°E, 20°S–14°S), which can also be used to quantify the atmospheric and oceanic teleconnections, and we get the same result. A total of 14 models (67%) produce a weaker negative NNI-SLP correlation with nearly no change (11 of 21 models) in the NNI-SSH correlation, which reconfirms that the atmospheric teleconnections instead of oceanic teleconnections are weakened under future climate (Figures 4c and 4d). Besides, we additionally adopt regression coefficients to measure those atmospheric and oceanic teleconnections, and we can get the same results (Figure S6). Hence, the weakened ENSO-Ningaloo Niño/Niña teleconnection results from the weakening of atmospheric teleconnection under greenhouse warming.

3.3. Changes in the Mean State of Tropical Pacific Induce This Weakened Teleconnection

Under greenhouse warming, the tropical Pacific shows two features of mean state changes in the coupled ocean-atmosphere system. One is the El Niño-like warming pattern, manifested as the eastern tropical Pacific (ETP) warms faster than the WTP (Cai et al., 2015a; Collins et al., 2010). This warming pattern will weaken the trade wind, suppressing convection over the WTP but strengthening over the ETP. Another is a more stable atmosphere, induced by faster warming mid-troposphere than the surface, which intensifying the atmospheric stability for the negative vertical temperature gradient (Allen & Sherwood, 2008; Johnson & Xie, 2010). Such changes in the tropical mean state can affect the tropical-extratropical teleconnections (Yeh et al., 2018). Here, we identify that these mean state changes may weaken the ENSO-Ningaloo Niño/Niña teleconnection in the future climate.
Considering an asymmetric ENSO-Ningaloo Niño/Niña relationship, which has been discussed in previous section (Figure 2), we further investigate the Matsuno-Gill response to the SST-induced diabatic heating/cooling over the WTP during Ningaloo Niño and Ningaloo Niña years, separately. A multimodel-based histogram is applied to depict the changes in SEIO-SLP response, and there's a weaker response of negative SLP during Ningaloo Niño years in the future (Figure 5a), with the multimodel climatological mean shifted from $-0.86$ to $-0.20$ hPa. By contrast, a minor change is detected during Ningaloo Niña years (Figure 5b), with the multimodel climatological mean shifted slightly from 0.68 to 0.78 hPa. The larger change in SEIO-SLP during the Ningaloo Niño years than the Ningaloo Niña years, together with the asymmetric impact from ENSO, indicate that the weakened ENSO-Ningaloo Niño/Niña teleconnection is driven by the weakened Matsuno-Gill response to La Niña-induced warm SST anomalies over the WTP during Ningaloo Niño years.

The asymmetric SLP response to ENSO under greenhouse warming is attributed to the mean state changes in the tropical Pacific. The El Niño-like warming pattern plays a key role in weakening the La Niña-induced diabatic heating over the WTP through the intensified westerlies, and weakening the La Niña-Ningaloo Niño relationship. Although it can strengthen the El Niño-induced diabatic cooling over the WTP, the El Niño-Ningaloo Niña relationship keeps nearly no change due to the asymmetric impact from ENSO. Further, models with a stronger El Niño-like warming pattern, defined by the SST warming trend difference between ETP and WTP (Figure 5c), tend to produce a weaker ENSO-Ningaloo Niño/Niña teleconnection in the future climate, and the tendency is statistically significant above the 99% confidence level (Figure 5d).
Besides, a more stable tropical atmosphere can weaken the ENSO-induced diabatic heating/cooling, help to further suppress the WTP convection for La Niña-Ningaloo Niño relationship, and cancel the enhancement effect for El Niño-Ningaloo Niña relationship based on the El Niño-like warming pattern (Figure S7). Thus, we conclude that the weakened ENSO-Ningaloo Niño/Niña teleconnection is attributed to the tropical Pacific mean state changes, which refer to the joint effect from the El Niño-like warming pattern and a more stable atmosphere under greenhouse warming.

4. Conclusion and Discussion

We identified a weakened ENSO-Ningaloo Niño/Niña teleconnection under greenhouse warming, which is attributed to the weakened La Niña-Ningaloo Niño relationship, rather than the unchanged El Niño-Ningaloo Niña relationship. The weakened teleconnection is caused by the weakened atmospheric teleconnection, as the majority of CMIP5 models consistently show that the correlation coefficient between NNI and WTP-SST decreases in the future climate compared to present-day climate. And there is no signifi-
cant change in the oceanic teleconnection. This weakened atmospheric teleconnection is resulted from the greenhouse warming-induced mean state changes in the tropical Pacific. The El Niño-like warming pattern tends to weaken the warm SST-induced diabatic heating over the WTP associated with La Niña, leading to a weaker Matsuno-Gill response over the SEIO, hence a weakened teleconnection to Ningaloo Niño.

Although the Matsuno-Gill response will slightly strengthen for the stronger cold SST-induced diabatic cooling under such warming pattern, there's no increase in El Niño-Ningaloo Niña relationship considering the weaker El Niño impact on Ningaloo Niña. A more stable tropical atmosphere can also help to weaken this teleconnection. Considering ENSO as the dominant predictability source of Ningaloo Niño/Niña, our result suggests that Ningaloo Niño/Niña may be less influenced by ENSO in the future climate as greenhouse warming continues, making it less predictable by ENSO.

Based on our research, the weakening of ENSO-Ningaloo Niño/Niña teleconnection mainly depends on the El Niño-like warming pattern in the future. Although most state-of-the-art climate models project such warming pattern, they do not capture the observed warming trend with a strengthening of west-minus-east SST gradient in the tropical Pacific over the past 50 years (Cane et al., 1997). Moreover, the consensus El Niño-like warming pattern may be a consequence of systematic model bias in the cold tongue (Seager et al., 2019). Therefore, we expect that further improvements of state-of-the-art climate models will improve projection of future change in the ENSO-Ningaloo Niño/Niña teleconnection.

Data Availability Statement
For observations, SST data were obtained from the NOAA Extended Reconstruc ted Sea Surface Temperature version 5 (ERSSTv5) data set (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html), SLP data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html), SSH data from the operational ocean analysis/reanalysis system (ORAS4) available at Asia-Pacific Data Research Center (http://apdrc.soest.hawaii.edu/).

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