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Roles of the Indo-Pacific subsurface Kelvin waves and volume transport in prolonging the triple-dip 2020–2023 La Niña

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Supplementary material for this article is available online

Abstract

The rare triple-dip 2020–2023 La Niña event has resulted in a series of extreme climate events across the globe. Here, we reveal the role of tropical Indo-Pacific oceanic interactions in driving the first triple-dip La Niña of the twenty-first century. Specifically, we found that the eastern Indian Ocean subsurface warming anomalies were associated with the re-intensification of the subsequent La Niña event. The subsurface warming anomaly signals were propagated eastward by equatorial and coastal subsurface Kelvin waves from the eastern Indian Ocean to the western Pacific Ocean through the Indo-Pacific oceanic pathway, which contributes to the accumulation of heat content and deepens the thermocline in the western tropical Pacific. The westward Indonesian Throughflow (ITF) transported more heat during multi-year La Niña events from the western Pacific Ocean to the eastern Indian Ocean than during single-year events, resulting in the injection of more warm water into the eastern Indian Ocean. The combination of subsurface Kelvin wave propagation and increased ITF volume transport in the Indo-Pacific region acted to prolong the heat content in the western Pacific during the decay phase of La Niña, ultimately leading to the rare triple-dip 2020–2023 La Niña event.

1. Introduction

During the winter of 2022/2023, the tropical Pacific experienced the first 'triple-dip' La Niña event of the twenty-first century, which began in late 2020 and lasted for three consecutive years. The prolonged persistence of this event has exacerbated La Niña's global climate impact. For instance, in China, North America, and Eurasia, extreme cold occurred during the winters of 2020/2021 and 2022/2023. Furthermore, persistent droughts were experienced in the United States and East Africa, severe floods in Southeast Asia, and increased hurricanes and cyclones in the Pacific and Atlantic Oceans (Jones 2022, Zheng *et al* 2022, 2023, Yao *et al* 2023). Similar events occurred in 1998–2001 and 1973–1976, both following extreme El Niño events on account of recharge oscillator dynamics (DiNezio *et al* 2017, Geng *et al* 2019, 2023). Multi-year La Niña events tend to recover a significant heat deficit over the equatorial band of the upper ocean that is discharged by extreme El Niño events (Jin *et al* 1994, Wu *et al* 2019, Iwakiri and Watanabe 2021). Compared to single-year El Niño–Southern Oscillation (ENSO) events, multi-year ENSO events tend to induce much more extreme climate events, such as prolonged droughts, severe floods, heatwaves, and extreme cold events (Archer *et al* 2017, Okumura *et al* 2017). Therefore, predicting multi-year ENSO events remains essential but challenging due to the asymmetry or diversity of the ENSO phenomenon in spatial-temporal evolution.

The asymmetry between the ENSO warm phase (El Niño) and cold phase (La Niña) is apparent in their amplitude, spatial pattern, and temporal evolution (Hoerling et al 1997, An 2004, Okumura and Deser 2010, DiNezio and Deser 2014, An and Kim 2018, Timmermann et al 2018). El Niño events typically dissipate quickly, whereas some La Niña events persist for the following year and even intensify in boreal winter, resulting in multi-year events (Kessler 2002, Choi et al 2013, Timmermann et al 2018). This asymmetry is due to the stronger discharge during El Niño compared to the recharge during La Niña, as well as tropical and extra-tropical climate interactions (Bejarano and Jin 2008, Choi et al 2013, Hu et al 2014, Fang and Yu 2020, Ding et al 2022, Kim and Yu 2022). The strength of the multi-year La Niña pattern, due to the thermocline feedback mechanism (coupling between thermocline and sea-surface temperature anomalies), depends on the depth of the mean thermocline and trade winds (Jin et al 1994, Jiang et al 1995, DiNezio et al 2014), whereas the typical single-year La Niña pattern is associated with a shallower thermocline and zonal advective feedback (Timmermann et al 2018, Xie and Jin 2018). Hu et al (2014) suggested that the cold water reflected from previous La Niña events could propagate westward Rossby waves and interrupt the oceanic heat recharge process, leading to a second-year La Niña. Recent research highlights the role of wind anomalies over the equatorial Pacific in triggering the 2020–2023 La Niña (Fang et al 2023).

Beyond internal variability within the tropical Pacific, studies have also focused on the inter-basin climate interactions during ENSO evolution (Cai et al 2019, Wang 2019). The Atlantic Niño (Niña) during boreal summer can induce an eastern Pacific-type La Niña (El Niño) in the following winter by modulating the Walker circulation (Rodríguez-Fonseca et al 2009, Ham et al 2013, Ding et al 2022). The Indian Ocean could affect the tropical Pacific Ocean via atmospheric connections and oceanic pathways. Many studies have investigated the impact of Indian Ocean basin-wide warming (cooling) on the duration of ENSO events (Wu and Kirtman 2004, Annamalai et al 2005, Du et al 2009, Ohba and Ueda 2009, Wu et al 2009, Xie et al 2009, 2016, Okumura and Deser 2010, Okumura et al 2011, Li et al 2017). The negative (positive) phase of the Indian Ocean Dipole (IOD) can also influence El Niño (La Niña) through modulation of the Walker circulation and the oceanic pathway via the Indonesian Throughflow (ITF) (Izumo et al 2010, 2014, Yuan et al 2013, Mayer et al 2018, Wang 2019).

Located in the Indo-Pacific warm pool, the ITF transfers approximately 15 Sv (1 Sv = 10^6 m^3 s^{-1}) of water from the tropical Pacific Ocean to the Indian Ocean via complicated straits in the Maritime Continent. It plays a crucial role in heat and freshwater exchanges as well as ocean–atmosphere interactions between the two oceans (Gordon 1986, 2001, Gordon et al 2003, Sprintall et al 2014, Hu et al 2015, Lee et al 2015, Gruenburg and Gordon 2018). Analysis of observational data has shown that the volume transport variability of the ITF is strongly influenced by ENSO (Li et al 2018, 2020), while the IOD can also affect the ITF by changing the sea level of the eastern Indian Ocean (Gordon et al 2019, Pujiana et al 2019). Conversely, the volume transport through the ITF can contribute to the evolution of ENSO and IOD (Santoso et al 2011, Yuan et al 2013, Wang 2019). Mayer et al (2018) indicated that an abnormal decrease in ITF volume and heat transport played a crucial role in the extreme El Niño event of 2015/2016. Recent research also suggests that subsurface connection through ITF has a longer memory and may contribute to the development of multi-year ENSO events (Wang et al 2023). However, the specific mechanisms by which Indo-Pacific subsurface interactions prolong the triple-dip La Niña events require further investigation.

In this study, we utilize observed and reanalyzed atmospheric and oceanic data to analyze the inter-basin connections during the 2020–2023 triple-dip La Niña, and comprehensively compare inter-basin connections between multi-year and single-year events. The differences in atmospheric and oceanic changes between these two types of events may help us identify the reasons behind the extended triple-dip La Niña, and clarify how Indo-Pacific oceanic connections contribute to this phenomenon.

2. Data and methods

Our analysis is primarily based on observational and satellite-derived data of the ocean and atmosphere, as well as reanalysis products. The monthly sea surface temperature (SST) data (from 1871 to present) with a 1° × 1° resolution are from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) (Rayner 2003). To investigate inter-basin correlations, we used monthly 10 m winds from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kalnay et al 1996) and monthly precipitation data from the NOAA Precipitation Reconstruction dataset (Chen et al 2002). The 0–100 m and 0–300 m monthly global ocean heat content (OHC) data, with 1° × 1° horizontal resolution from 1960 to present, is from the Institute of Atmospheric Physics (IAP, Cheng et al 2017). We also used Ocean Reanalysis System 5 (ORAS5) global ocean reanalysis data from 1958 to 2023 (Zuo et al 2019), with a 0.25° × 0.25° resolution and 75 vertical levels, to investigate subsurface temperature, current, and thermocline changes.

To identify single-year and multi-year La Niña events that exhibit seasonal evolution, the Season-reliant Empirical Orthogonal Function (S-EOF) analysis (Wang and An 2005) is applied on monthly SST anomalies (SSTa) from 1871 to 2022 in the tropical Pacific. The first two leading modes of S-EOF explain 38.7% and 22.7% of the total variance (figure S1).

The S-EOF1 is characterized by an unremitting cold SST pattern in the eastern Pacific Ocean throughout its evolution, which represents the multi-year La Niña mode with a 4–6-year period (figure S2). The S-EOF2, representing single-year La Niña mode with a 2–3-year period, is distinguished by periodic seasonal changes of SSTa, with a phase transition occurring during boreal spring and summer.

For consistency, the period used for computing composite anomalies and partial correlation is from 1960 to 2022. We calculated the Niño 3.4 index using 3-month running mean SSTa in the Niño 3.4 region (5° S–5° N, 170°–120° W). The El Niño and La Niña periods of ENSO events were determined using the Nino 3.4 index threshold of $\pm$ 0.5 °C for three consecutive months during the boreal winter. In the following, year (0) and (1) refer to the developing and decaying years of La Niña. The multi-year events were considered as the Niño 3.4 index remains below -0.5 °C during the boreal winter in year (1).

3. Tropical inter-basin interactions during 2020–2023 triple-dip La Niña

Figure 1 illustrates the evolving spatial distributions of SSTa, 10 m wind anomalies, and precipitation anomalies during the 2020–2023 triple-dip La Niña event. In this event, the tropical eastern Pacific SSTa remained in a cold state from JJA 2020 to DJF 2022/2023, accompanied by prolonged and sustained easterly wind anomalies, thus confirming the occurrence of a triple-dip La Niña event. It is noteworthy that during the summers of 2020 and 2021, the tropical Atlantic Ocean experienced significant SST warming, which might have contributed to the prolonged life cycle of the La Niña event from 2020 to 2022. As Ham *et al* (2013) pointed out, the warming in the tropical Atlantic can trigger a La Niña event the following winter by inducing a low-level cyclonic atmospheric flow over the eastern Pacific Ocean and generating easterly winds over the western equatorial Pacific. Additionally, we conducted a partial correlation analysis between S-EOF time series and SSTa, winds, precipitation, and OHC anomalies (OHCa) to identify factors that influenced the temporal evolution of multi-year La Niña events (see figure S3). Compared to single-year La Niña events, there was significant warming in the tropical Atlantic during JJA (0) and SON (0) in the multi-year La Niña event evolution. The tropical Atlantic can impact the Pacific directly through the atmospheric Rossby waves, or indirectly through atmospheric Kelvin waves by affecting the Indian Ocean. Both processes contribute to the intensification of La Niña events in winter, with the latter having a longer lag time and the potential to promote a recurrence of La Niña in the following year (Jiang and Li 2021).

SSTa in the eastern Indian Ocean were predominantly cold during the period of 2020–2023, with occasional minor warm anomalies (figure 1). This indicates that atmospheric influences on the persistence of La Niña may be weak. Meanwhile, the Maritime Continent and eastern Indian Ocean regions show significant positive precipitation anomalies with anomalous easterly winds persisting. Although the intensity of these anomalies weakened during JJA 2021, the pattern remained stable. The correlations between precipitation (winds) and S-EOF time series show significant differences in the Maritime Continent region between multi-year and single-year events (figure S3). In contrast to multi-year events, the single-year La Niña events exhibited a distinct phase transition occurring in JJA (1), with anomalies associated with La Niña virtually disappearing. Furthermore, the the SST conditions in the Indian Ocean did not vary significantly between the two types of La Niña events, implying that the eastern Indian Ocean may impact the La Niña event duration through the Indo-Pacific oceanic pathway instead of air–sea interactions.

Partial correlations between the time series of the upper 100 m OHCa and the two S-EOF modes show differences in the western Pacific warm pool and the eastern Indian Ocean (figure 2). During single-year La Niña events, the warm OHC in the western Pacific and eastern Indian Ocean dissipated rapidly after DJF (1), resulting in an insignificant correlation with its eastern counterpart (figures 2(a)–(c)). Conversely, during multi-year La Niña events, the eastern Indian Ocean still experiences significant warm OHCa in MAM (1), which moderately weaken in JJA (1) (figures 2(e) and (f)). In the meantime, warm OHCa in the western Pacific persisted, sustaining the La Niña phenomenon. Notably, throughout the entire 2020–2023 triple-dip La Niña event, the eastern Indian Ocean experienced warm ocean heat anomalies (figure 3). These changes suggest that warm water in the eastern Indian Ocean may contribute to the development of multi-year La Niña events, whereas similar signals are absent during single-year events (see figure S4). The connection between the eastern Indian Ocean and the western Pacific via the Indo-Pacific oceanic pathway may have played a significant role in prolonging the 2020–2023 triple-dip La Niña.

4. Contrasting Indo-Pacific subsurface Kelvin wave propagation during multi-year and single-year La Niña

To gain further insight into how warm OHCa in the eastern Indian Ocean contribute to multi-year La Niña events, we analyzed Hovmöller diagrams of equatorial upper 100 m OHCa, 26 °C isotherm depth, and 20 °C isotherm depth anomalies from the eastern

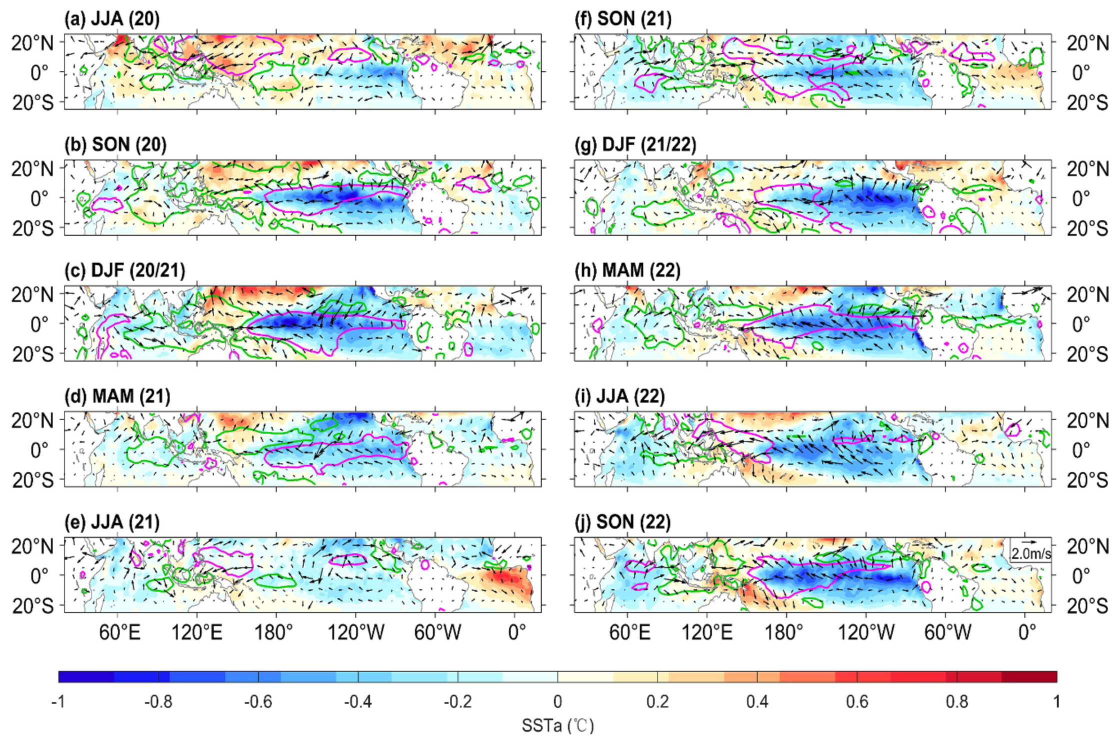

Figure 1. Spatial distribution of SSTa (°C), 10 m wind anomalies (m s^{-1}), and precipitation anomalies (mm d^{-1}) from JJA 2020 (a) to SON 2022 (h). The green contours represent areas with precipitation of more than 1 mm d^{-1}, while the purple contours show areas with precipitation of less than −1 mm d^{-1}.

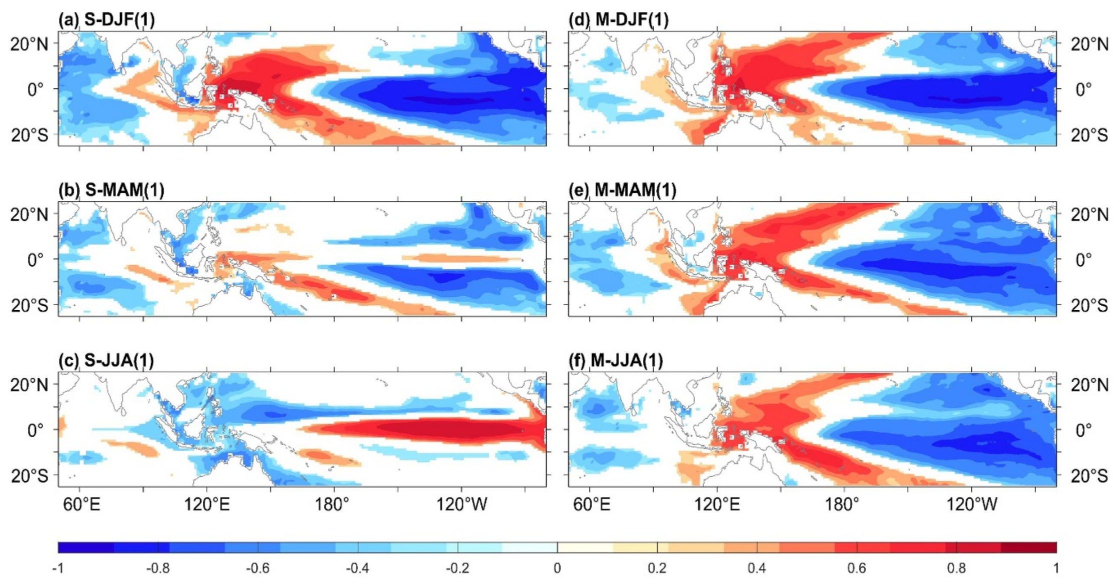

Figure 2. Partial correlations of upper 100 m OHCa (shading) with S-EOF PCs from 1960 to 2022, with effect of another mode removed. Panels (a)–(f) display partial correlation of PC2 (single-year mode) with OHCa, while panels (g)–(l) show partial correlation of PC1 (multi-year model) with OHCa. Only values above 95% confidence level are shown.

Indian Ocean to the central-eastern Pacific via the Indo-Pacific oceanic pathway (figure 4). During SON 2020, the developing phase of the first triple-dip La Niña event, there were prominent warm OHCa in the upper 100 m and deeper thermocline anomalies (20 °C isotherms) in the eastern Indian Ocean that were opposite to SSTa. The warm OHCa in the eastern Indian Ocean gradually extended and increased from the eastern Indian Ocean to the exit of the ITF along Sumatra as the La Niña events developed, reaching their maximum in DJF 2020/2021. After the initial peak of the multi-year La Niña events in winter 2020, we observed that the warm water anomaly signal in the eastern Indian Ocean could be transmitted to the western Pacific via the Indo-Pacific oceanic pathway. This warm anomaly transmission was associated with

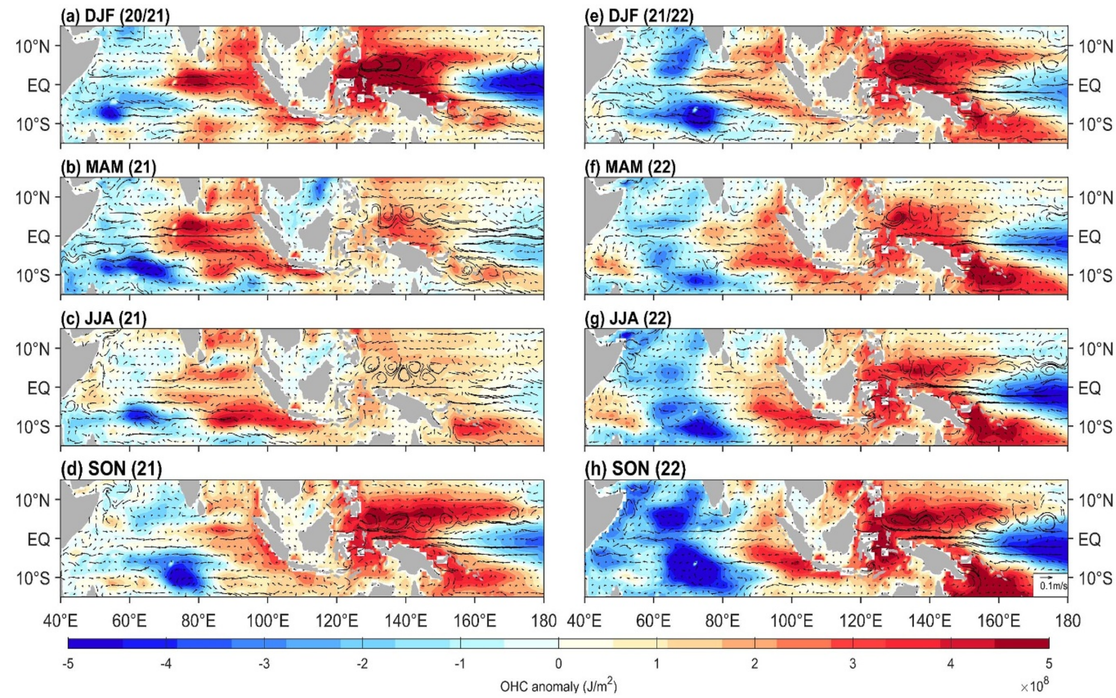

Figure 3. Spatial distribution of OHCa (indicated by shading) and mean ocean current anomalies (represented by vectors) for upper 100 m from DJF 2020/2021 to SON 2022. The panels (a)–(h), arranged by temporal evolution, demonstrate how OHCa change over time.

oceanic Kelvin waves that propagate eastward from the eastern Indian Ocean to the western Pacific Ocean (figure 4(a)). These Kelvin waves are generated in the equatorial Indian Ocean, becoming coastal Kelvin waves when they arrive on the west coast of Sumatra, and then propagate along southern Sumatra and Java into the Makassar Strait through the Lombok Strait (Pujiana *et al* 2013, 2019, Pujiana and McPhaden 2020). Comparing multi-year and single-year La Niña events, we found that anomalous warm water can propagate eastward into the western Pacific during the decay phase of the first La Niña event under a multi-year La Niña event (figure S5). After JJA (1), the warmer pattern in the western Pacific and the cooler pattern in the eastern Pacific do not change. Combined with the seasonal locking of ENSO, it is likely that a La Niña event can redevelop into a multi-year event.

The evolution of the three-dimensional ocean temperature along the equatorial Indo-Pacific for multi-year and single-year La Niña events from SON (0) to JJA (1) presented a warm maximum in the subsurface layer at approximately 100 m (figures 5(a) and (b)). During the multi-year La Niña events, subsurface warm anomalies in the eastern Indian Ocean were particularly prominent. This warm anomaly developed in the fall, peaked in the winter, and began to decline in the spring, following a general pattern of ENSO evolution. However, the warm anomaly in the western Pacific did not reach its peak until MAM (1) instead of DJF (1). This indicates that the anomalous warm water signal in the subsurface layer of the eastern Indian Ocean could be transmitted back to the western Pacific during the decay phase of La Niña, and delay the eastward movement of warm water. In MAM (1), most of the warm water still remained in the western Pacific, which also explains why anomalous westerly winds and more precipitation continued to occur in the western Pacific during multi-year events. This process delays the decay of La Niña in first year and favors its redevelopment into a multi-year event. In contrast, the intensity reflected by the subsurface layer during a single-year La Niña event is relatively weak, and the warm anomaly in the subsurface layer of the eastern Indian Ocean is obviously weaker. This causes weak feedback to the decay of La Niña and makes it easier for warm water in the west to spread eastward, resulting in a quick decay of La Niña events and even a transition to El Niño events within a year.

During the triple-dip 2020–2023 La Niña event, anomalous warming in the subsurface layer of the eastern Indian Ocean was consistently high and extended westward, displaying a sharp temperature contrast to the SST of the eastern Indian Ocean region. Throughout the winter of 2020/2021, the anomalous subsurface warm water in the eastern Indian Ocean became notably larger than that in the western Pacific. Despite the western Pacific warm water spreading eastward the following spring and summer, the feedback from the subsurface eastern Indian Ocean sustained warm water accumulation in

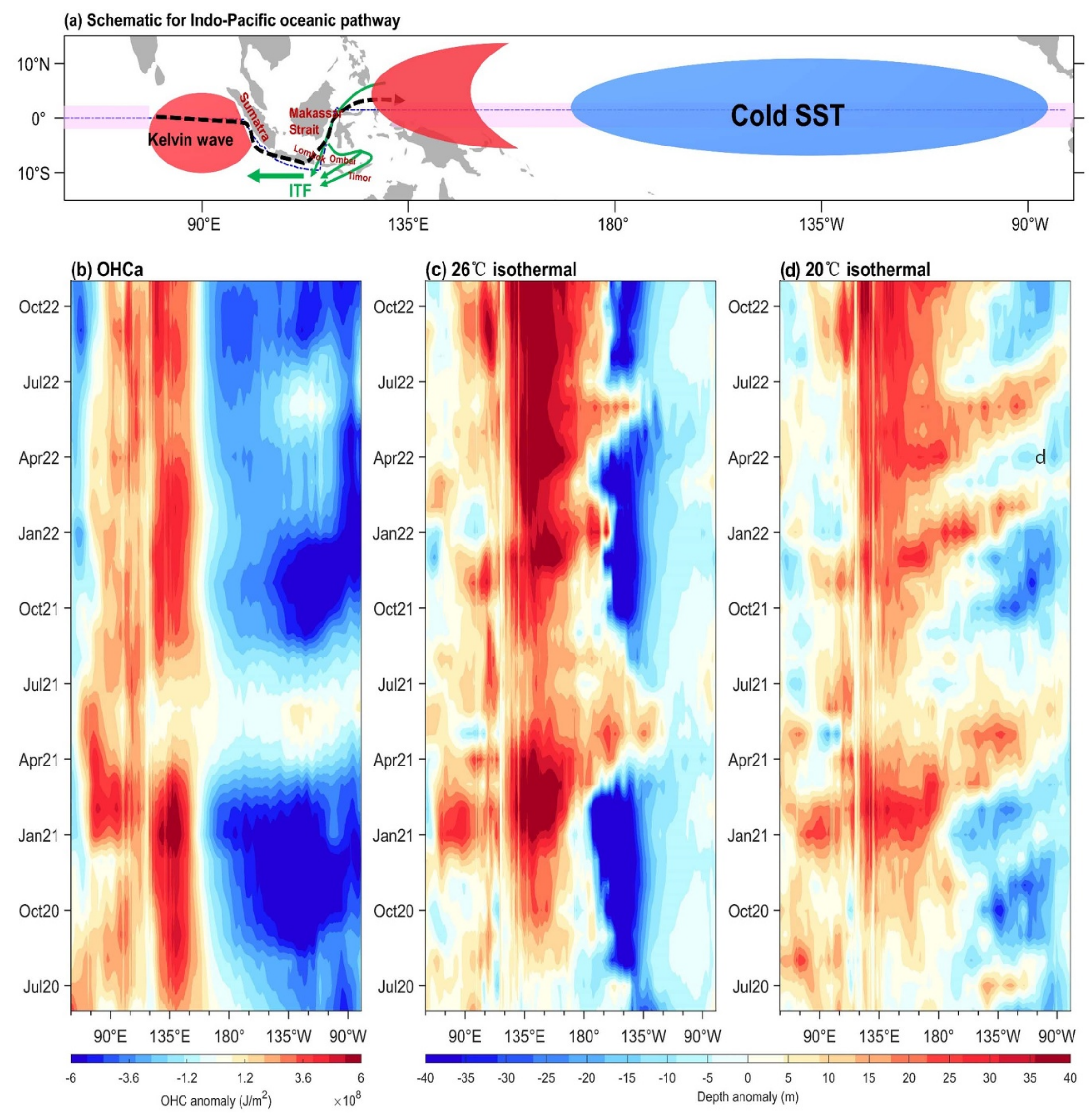

Figure 4. Hovmöller diagrams depict temporal evolution of oceanic conditions from eastern Indian Ocean to Pacific Ocean via Indo-Pacific pathway. (a) Schematic of the Indo-Pacific Oceanic pathway. Two red areas show warm OHCa of eastern Indian Ocean and western Pacific Ocean, while blue area in eastern Pacific Ocean means cold anomalies associated with La Niña event. The green arrows show main pathways of ITF (Makassar Strait for main inflow, and Lombok, Ombai, and Timor Strait for three outflow pathways from west to east). The black dashed arrow shows eastward propagation of Kelvin waves through Indo-Pacific pathway. Hovmöller diagrams of (b) upper 100 m OHCa, (c) 26 °C isotherm depth anomalies, (d) 20 °C isotherm depth anomalies, which illustrate anomalies in thermocline depth from the eastern Indian Ocean (60° E–100° E) to Pacific (120° E–80° W) along oceanic pathway (100° E–120° E, blue dashed line in figure (a)) from June 2020 to November 2022. The eastern Indian Ocean and Pacific data are averaged within a 2° S–2° N latitudinal band (marked with light red in (a)).

the western Pacific. As a result, a negative zonal temperature gradient in the equatorial Pacific persisted and contributed to the re-development of La Niña during the summer and fall of 2021. Moving into the winter of 2021/2022, although anomalous warm water in the equatorial eastern Indian Ocean was not very obvious, there remained large warm anomalies on both sides of the equator, which extended far westward. In 2022, the evolution of La Niña was unique as it persisted throughout the year without significant weakening. Correspondingly, anomalous warm water in the eastern Indian Ocean did not weaken either. These warm anomalies in the subsurface layer of the eastern Indian Ocean propagated eastward by equatorial and coastal Kelvin waves through the Indo-Pacific Ocean channel, contributing to the buildup of heat in the western Pacific throughout the triple-dip 2020–2023 La Niña event. In the following sections, we will examine the eastern Indian Ocean warm anomalies in relation to the volume transport of ITF.

5. Anomalous increase of ITF heat transport

Previous studies have shown that persistent positive ITF heat transport during the period from 2006

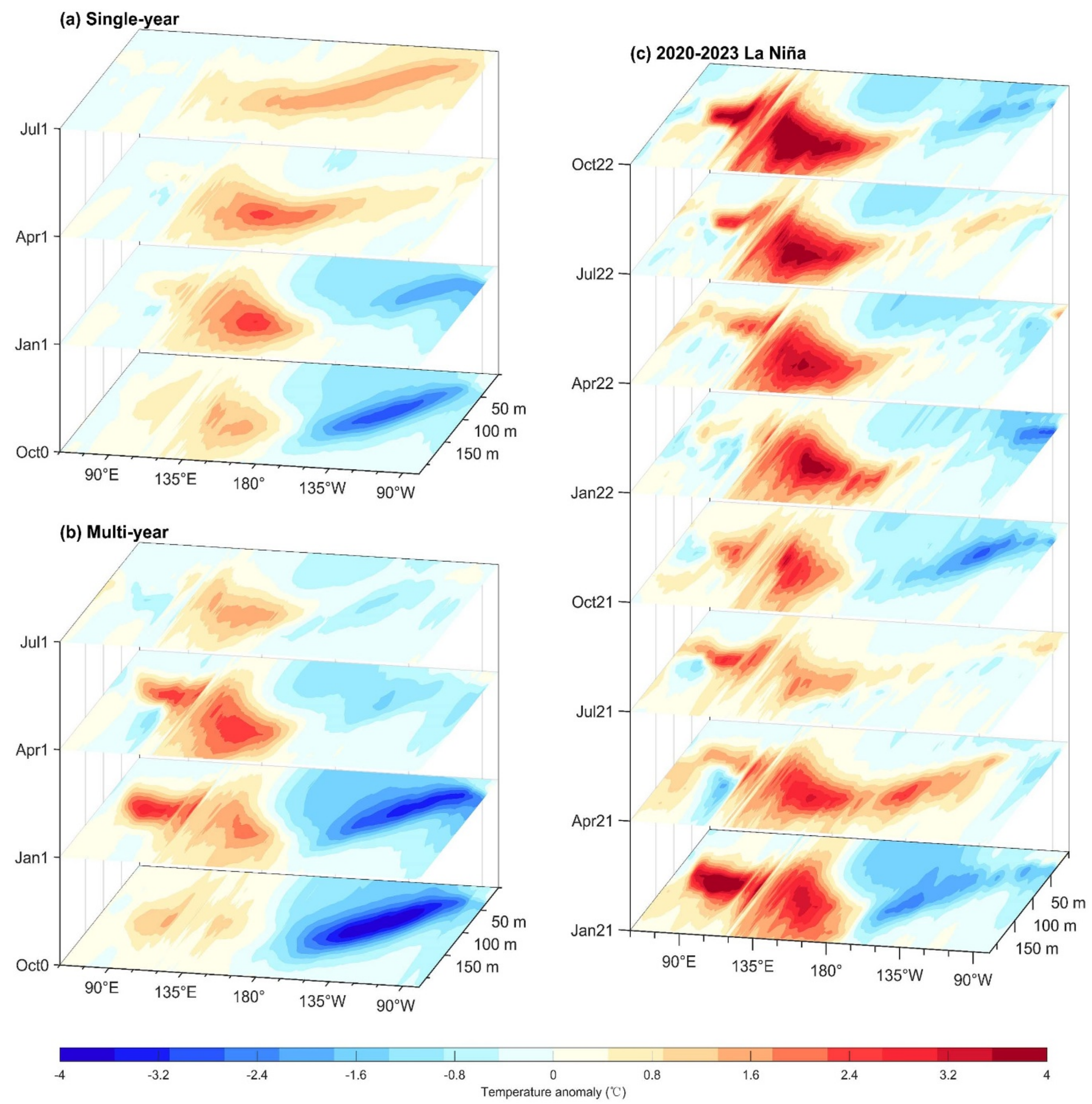

Figure 5. Temporal evolution of oceanic temperature (shading) for (a) a composite of single-year data, (b) a composite of multi-year data, and (c) a triple-dip La Niña composite (averaged over the years 2020, 2021, 2022, and 2023) in the eastern Indian Ocean (60°E–100°E), Pacific (120°E–80°W), and along the oceanic pathway (100°E–120°E). The data are averaged within 2°S–2°N latitudinal band.

to 2014 contributed to the rapid increase in tropical Indian Ocean warming (Lee *et al* 2015, Nieves *et al* 2015, Ummenhofer *et al* 2017). Mayer *et al* (2018) observed a strong reduction in ITF heat transport during the extreme El Niño event of 2015/2016, which prevented the subsequent occurrence of cold La Niña conditions in winter 2016. In contrast, we report here an anomalous increase in ITF heat transport (of approximately 0.2 PW) during the triple-dip La Niña event between 2020 and 2023 (figures 6(a) and (d)). This increase in heat transport occurred from the winter of 2020/2021–2022/2023 and had a significant impact on the subsurface layer at about 100–150 m, primarily driven by the maximum subsurface velocity (figure 6(c)). After the first La Niña event of 2020/2021 reached maturity, the subsurface temperature of the ITF began increasing by approximately 1 °C and persisted for a whole year. Although this subsurface warm anomaly weakened during the fall of 2021, it was increased by more than 1 °C again after the second La Niña event of 2021/2022 (figure 6(b)).

Differences between composite multi-year and single-year La Niña events indicate that volume transport and related heat transfer through ITF are weaker in single-year events than multi-year events (as depicted in figure S6). Although warm water enters the subsurface layer of the Indian Ocean during both multi-year and single-year La Niña events via ITF, the associated anomalies are much smaller during single-year events, with warm water being mainly confined to the western Pacific and little transmission into the Indian Ocean. Warm water restricted to the western Pacific in single-year events is more likely to migrate to the eastern Pacific during the decay process, causing the La Niña phenomenon to decay more quickly, thereby increasing the likelihood of it

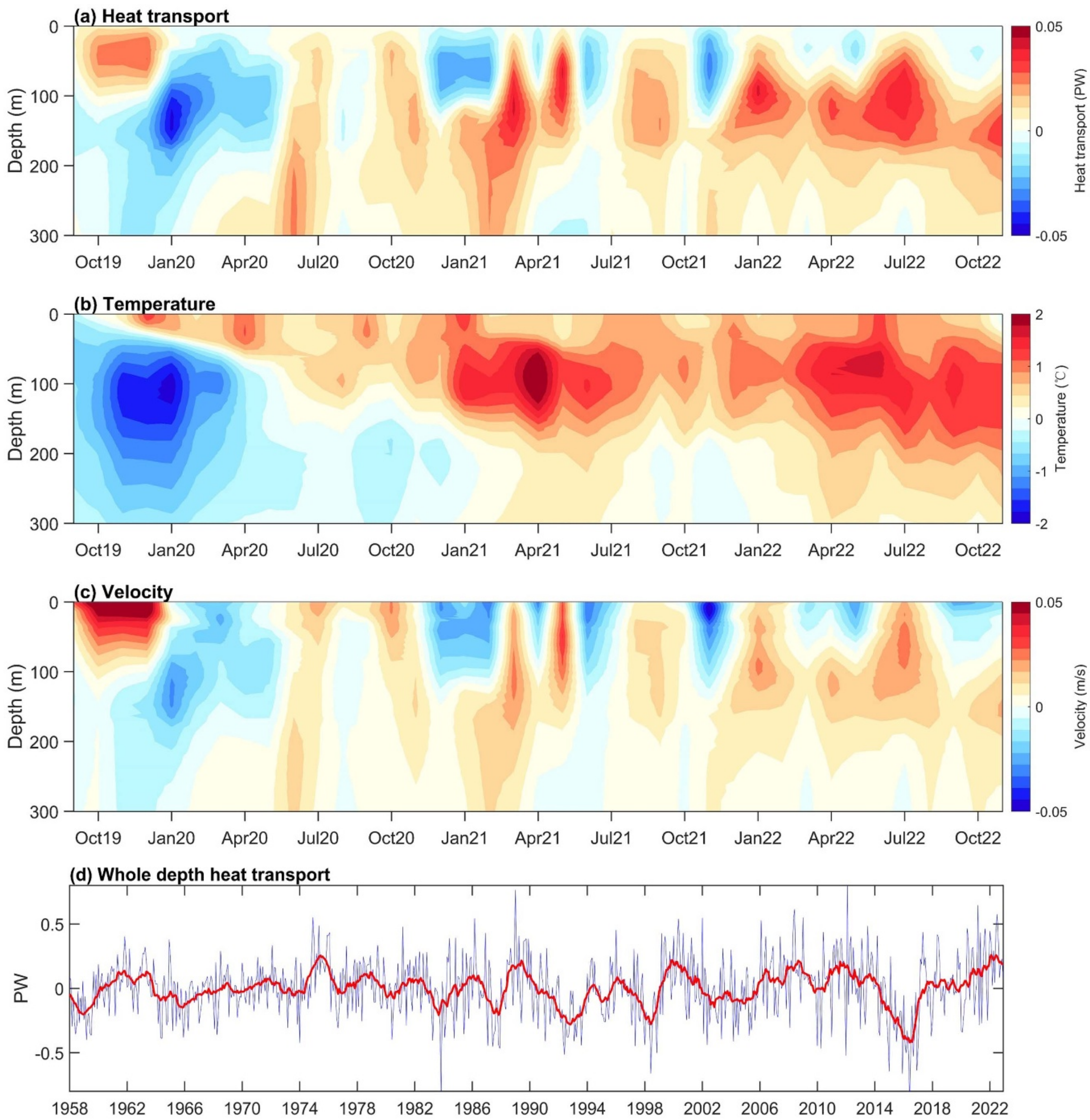

Figure 6. Temporal evolution of vertical profiles for ITF; (a) heat flux anomalies (in PW; 1 PW = 10^{15} W), (b) temperature anomalies (°C), and (c) velocity anomalies (m s^{-1}) at outflow section of eastern Indian Ocean (114°E, 8°S–22°S) over the period from March 2020 to November 2022. The anomalies are averaged within the 8°S–22°S latitudinal range. (d) Anomalous whole depth ITF heat transport from 1958 to 2023 at the eastern Indian Ocean outflow section (114°E, 8°S–22°S). Red line shows 12-month running mean.

becoming an intermediate state or developing into an El Niño event in the following year. Under multi-year La Niña conditions, the anomalous increase in ITF volume transport extracts a large amount of heat from the tropical Pacific Ocean to the eastern Indian Ocean, greatly coupling the Indo-Pacific warm pool. Accelerated tropical Pacific heat loss may promote a swing toward a prolonged La Niña condition. The highly connected Indo-Pacific warm pool extends the recharge–discharge area, maintaining a warm anomaly in the western Pacific during the decay phase (MAM) of La Niña events and preventing a phase transition in the temperature state of the Pacific during MAM–JJA. The increased heat transport through the ITF during a multi-year La Niña strongly connects Indo-Pacific warm anomalies and extends the recharge–discharge area.

6. Summary and discussions

In this paper, we elucidate the differences in Indo-Pacific oceanic connections between multi-year and single-year La Niña events, and demonstrate the roles of the Indo-Pacific subsurface Kelvin waves and ITF volume transport in prolonging the rare triple-dip 2020–2023 La Niña event. Interactions between tropical basins are instrumental in prolonging multi-year La Niña events. The eastern Indian Ocean played a role in the triple-dip 2020–2023 La Niña event through the Indo-Pacific oceanic pathway. The anomalous subsurface warm signals in the eastern Indian Ocean were transmitted to the western Pacific during the decay phase of La Niña, delaying the eastward expansion of warm water. In the meantime, an anomalous increase in ITF volume and heat transport during the triple-dip 2020–2023 La Niña event led to subsurface warm anomalies in the eastern Indian Ocean, connecting the Indo-Pacific warm pool and extending the recharge–discharge region. The combination of subsurface Kelvin wave propagation and ITF volume transport ultimately contributed to maintaining the heat content in the western Pacific during the decay phase of La Niña events (schematic in figure 4(a)), prolonging the rare triple-dip 2020–2023 La Niña event.

Similar triple-dip events occurred in 1973–1976 and 1998–2001, following extreme El Niños, associated with recharge oscillator dynamics. All three triple-dip events show similar patterns of eastern Indian Ocean warm heat content anomalies propagating eastward from the eastern Indian Ocean to the western Pacific Ocean via the Indo-Pacific oceanic pathway (figure S7). The triple-dip La Niña events enable the recovery of massive heat deficits in the equatorial band of the upper ocean discharged by extreme El Niños (Wu *et al* 2019, Iwakiri and Watanabe 2021). However, the trigger mechanism for the 2020–2023 triple-dip La Niña event remains unknown, as it did not follow an extreme El Niño. A possible factor may be the extreme positive IOD event of 2019, with a prolonged negative IOD from 2020 to 2023. Previous studies have presented that anomalous easterly winds along the equator associated with positive IOD events weaken the fall Wyrtki jets (McPhaden *et al* 2015), forced directly by equatorial westerlies that occur during monsoonal transition seasons (April–May and November, Wyrtki 1973), which are important for the transfer of warm water from the western to the eastern Indian Ocean (Rao *et al* 1989, Schott and McCreary 2001).

After the peak phase of the 2019 positive IOD, the tropical Indian Ocean displayed strong eastward current anomalies during winter 2019/2020 and spring 2020. The piling up of water transported eastward (figure S8) by the Wyrtki jets off the coasts of Java and Sumatra deepened the thermocline depth (Schott and McCreary 2001), which indued warm anomalous subsurface water in the eastern Indian Ocean. In addition, the extreme event in 2019 and subsequent negative IOD may have contributed to its initiation by decreasing sea level anomalies in the eastern Indian Ocean, leading to an increase in ITF transport. These factors all likely contributed to the initiation the rare 2020–2023 triple-dip La Niña event. It is common to see a strong positive IOD event before triple-dip La Niña events (figure S7). Strong positive IOD events usually occur along with multi-year La Niña events, while weak ones occur with the normal single-year La Niña. Wang *et al* (2016) pointed out that SSTa in the eastern Indian Ocean associated with the IOD can be initiated by springtime Indonesian rainfall deficit through the local surface wind response. Both air–sea interactions and surface–subsurface interactions contributed to the development of the IOD. A recent study by Li *et al* (2023) shows that the development processes for the 1998–2001 and 2020–2023 triple-dip events were different, and very much related to mean state changes in the tropical Pacific. The mechanism of how strong IOD events can trigger multi-year La Niña events needs further investigation.

Data availability statement

The monthly SST data were downloaded from www.metoffice.gov.uk/hadobs/hadisst. The monthly 10 m wind data were from www.psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html. The monthly precipitation data were from www.psl.noaa.gov/data/gridded/data.gpcp.html. The monthly OHC data were from www.ocean.iap.ac.cn/ftp/cheng/IAP_Ocean_heat_content_0_2000m/.

The ORAS5 reanalysis data were downloaded from www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis.

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