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Freshwater Contributions to Decadal Variability of the Indonesian Throughflow

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Key Points:

- A global ocean model is used to show how freshwater impacts the decadal variability of transport through the main Indonesian Throughflow pathway
- Wind-driven advection of South China Sea freshwater induces an upstream pressure gradient that reduces transport
- Freshwater input is modulated by atmospheric circulation changes associated with Pacific decadal variability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The Makassar Strait, the main passageway of the Indonesian Throughflow (ITF), is an important component of Indo-Pacific climate through its inter-basin redistribution of heat and freshwater. Observational studies suggest that wind-driven freshwater advection from the marginal seas into the Makassar Strait modulates the strait's surface transport. However, direct observations are too short (<15 years) to resolve variability on decadal timescales. Here we use a series of global ocean simulations to assess the advected freshwater contributions to ITF transport across a range of timescales. The simulated seasonal and interannual freshwater dynamics are consistent with previous studies. On decadal timescales, we find that wind-driven advection of South China Sea (SCS) waters into the Makassar Strait modulates upper-ocean ITF transport. Atmospheric circulation changes associated with Pacific decadal variability appear to drive this mechanism via Pacific lower-latitude western boundary current interactions that affect the SCS circulation.

Plain Language Summary

The Makassar Strait plays an important role in regional climate as the main pathway in the Indonesian Seas through which tropical Pacific waters flow into the Indian Ocean. Observations from moorings in Makassar Strait indicate that the flow of fresher waters from adjacent shallow seas can impact surface transport through the Strait on seasonal and interannual timescales. However, because these direct measurements are sparse, they cannot resolve Makassar Strait transport on decadal timescales. Using global ocean model simulations, we explore what factors affect surface transport on these longer timescales. We first show that the ocean model skillfully reproduces seasonal and interannual freshwater impacts on surface transport. On decadal timescales, we find that freshwater input indeed influences Makassar transport. Specifically, fresh surface water from the South China Sea (SCS) plays an important role. This freshwater influence is likely driven by variability from the Pacific Ocean which impacts SCS currents through large-scale, surface wind changes.

1. Introduction

The Indonesian Throughflow (ITF) consists of a series of low-latitude ocean passageways through which an estimated 15 Sverdrups (1 Sv = 10^6 m^3 s^{-1}) of Pacific Ocean waters are exported to the Indian Ocean. Through air-sea interactions, the heat and freshwater transport through the ITF affects regional climate on a range of timescales (T. Lee et al., 2019; Mayer et al., 2018; Sprintall et al., 2014; Ummenhofer et al., 2020). The ITF's role in decadal climate variability has been highlighted by studies that attribute the temporary reduction in global surface warming in the early 21st century (2003–2012) to increased heat transport through the ITF (S.-K. Lee et al., 2015; Liu et al., 2016; Nieves et al., 2015). However, despite its importance, a comprehensive understanding of the drivers of ITF variability on these longer timescales is lacking.

While the large-scale ITF transport is established by the pressure gradient between the tropical Pacific and Indian Oceans (Clarke & Liu, 1994; Potemra, 2005; Wyrtki, 1987), ITF flow through its various passageways does not vary simultaneously. Several observational studies have suggested that localized pressure gradient anomalies can modulate ITF transport through individual straits on seasonal and interannual timescales (Gordon et al., 2003; Gordon et al., 2012, 2014; T. Lee et al., 2019). Here we explore how freshwater transport-related pressure gradient anomalies impact decadal variability of the Makassar Strait, the main passageway of the ITF.

Makassar Strait waters account for nearly 80% of the total ITF transport by volume (Gordon et al., 2010). These waters are sourced from the western Pacific through the Mindanao-Sulawesi Passage and flow westward through

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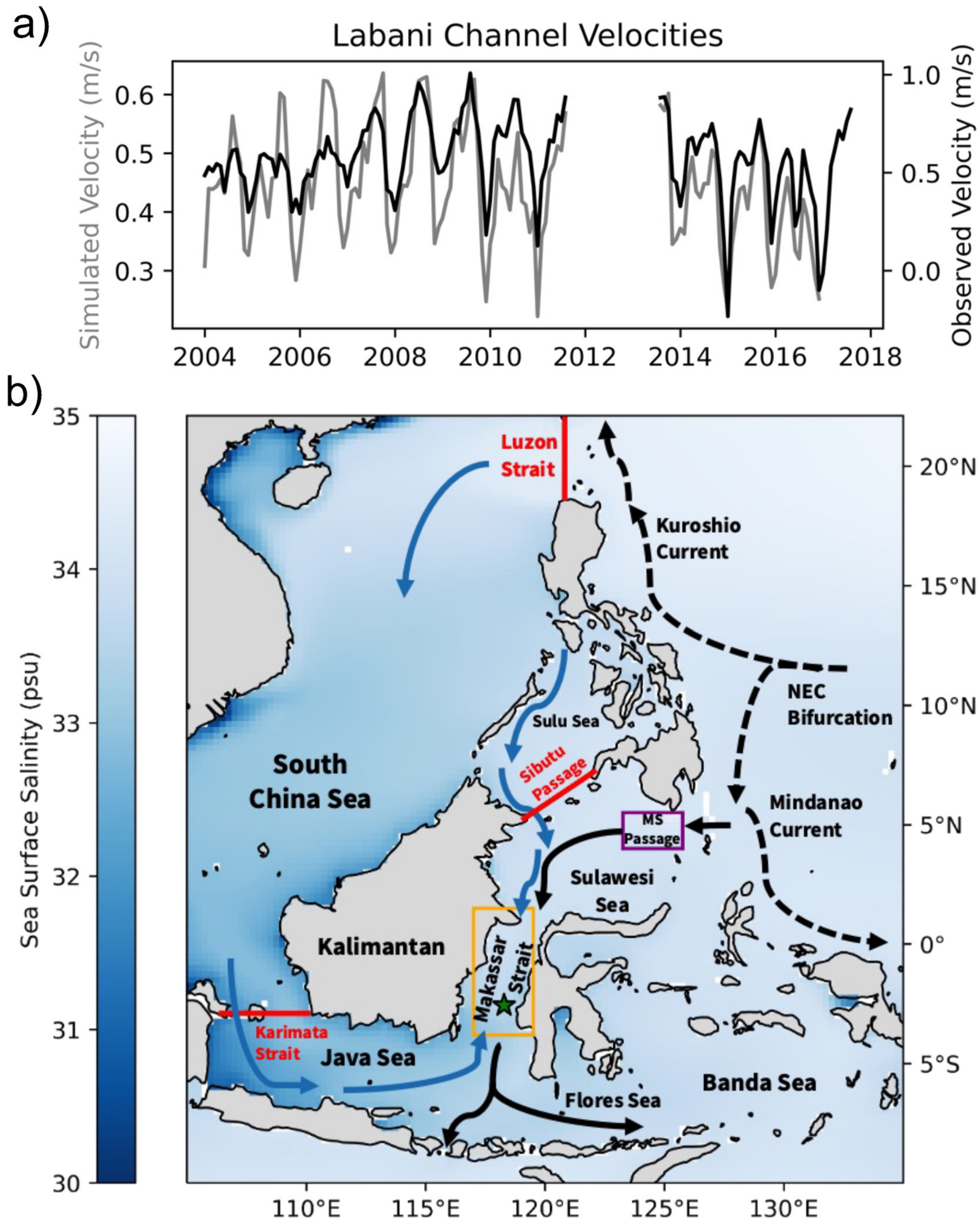

Figure 1. Comparison of surface (40–130 m) southward velocities at the Labani channel in southern Makassar Strait from mooring observations (black line) and co-located ocean model data for the same period (gray line) (a). Annual mean (1960–2017) simulated sea surface salinity in the Indonesian Seas (blue shading). Arrows indicate the main ITF pathway through Makassar (black solid arrows), freshwater pathways of South China Sea (SCS) and Java Sea surface waters (blue arrows), and NEC bifurcating into the Kuroshio and Mindanao boundary currents (black dashed arrows) (b). The Makassar Strait and Mindanao-Sulawesi Passage (MS Passage) areas used to calculate the local ITF density gradient (orange and purple boxes respectively), and the location of the Labani mooring (green star) are indicated. Key passageways in the SCS (Luzon, Sibutu, and Karimata Straits) and their transects for analysis(red) are also indicated.

the Sulawesi Sea before turning southward into the Makassar Strait (Figure 1b black arrows). Beyond this main ITF pathway, fresher surface waters from the South China Sea (SCS) and Java Sea also contribute to the Makassar Strait (Figure 1 blue arrows). This input of lower density waters decreases the pressure gradient between the Makassar Strait and waters upstream in the eastern Sulawesi Sea and reduces ITF flow. Currently 13 years

10.1029/2023GL103906

of in situ Makassar Strait velocity measurements from moorings in the Labani Channel are available (Gordon et al., 2019). To contextualize our study of decadal variability, we summarize these observation-based understanding of how these marginal freshwater inputs impact Makassar surface transport on seasonal and interannual timescales.

Ocean current velocities through the Makassar Strait are thermocline intensified, with the velocity maximum core between 100 and 120 m. In the upper 200 m, Labani mooring observations exhibit a seasonal cycle of southward velocities that peaks during late boreal summer (July, August, September; JAS) and reaches minimum values during boreal winter (November, December, January; NDJ) (Figure 1a). Gordon et al. (2003) attributed this variability to the seasonally-reversing monsoon winds which advect low-salinity surface waters from the Java Sea and SCS into Makassar (Figure 1b). The injection of buoyant waters during boreal winter reduces Makassar Strait surface density relative to the waters upstream, generating a pressure gradient anomaly that decreases southward surface flow. When the monsoon winds reverse during boreal summer, the freshwater is advected out of Makassar Strait and surface transport increases. Though it remains to be conclusively verified, the seasonal freshwater plug is supported by high-resolution satellite observations which suggest that local precipitation and runoff from the Maritime Continent are additional factors contributing to the seasonal ITF freshwater plug (T. Lee et al., 2019).

Surface velocities in the Labani channel increased considerably during 2008–2009 compared to 2004–2007 (Figure 1a), coinciding with a shift from El Niño to La Niña conditions. This reduced surface transport during El Niño years has been attributed to increased SCS freshwater input through the Sibutu Passage (Gordon et al., 2012). Subsequent studies have invoked the relationship between phasing of the El Niño Southern Oscillation (ENSO) and the latitude of the North Equatorial Current (NEC) bifurcation (Gordon et al., 2014, 2019) to explain ENSO's influence on Sibutu Passage freshwater transport. During El Niño events, the trade winds weaken and/or reverse, leading to positive wind-stress curl anomalies in the western North Pacific that shift the NEC bifurcation northward (D. Hu et al., 2015; Kim et al., 2004; Qiu & Chen, 2010). This shift weakens the Kuroshio Current, resulting in greater leakage of western boundary current waters into the SCS through the Luzon Strait (D. Hu et al., 2015; van Sebille et al., 2009). Conversely, during La Niña periods, the Pacific trade winds strengthen and shift the NEC bifurcation southward, intensifying the Kuroshio and decreasing Luzon Strait leakage. Because upper Luzon inflow is matched by commensurate changes in Sibutu Passage southward flow (Figure S1 in Supporting Information S1), ENSO modulates the associated freshwater plug transport across the Sibutu Passage (Gordon et al., 2012; Wei et al., 2016).

With only 13 years of in situ velocity data, observations are insufficient to resolve the mechanisms and drivers of Makassar Strait transport on decadal timescales. Similarly while previous modeling studies have identified the freshwater plug mechanism on seasonal and interannual timescales, these simulations are too short to resolve decadal variability (Jiang et al., 2019; Tozuka et al., 2009; Wei et al., 2016). In this study, we utilize global ocean general circulation model simulations that span 59 years (1958–2017) to investigate how freshwater transport modulates surface Makassar transport as well as the relationship between ITF transport and Pacific decadal variability.

2. Materials and Methods

2.1. Observations

We utilized in situ mooring-based observations of ocean current velocity to evaluate the skill of the ocean model in characterizing Makassar Strait dynamics (Figure 1a, Figure S2 in Supporting Information S1). Specifically, we use velocity data from moorings deployed in the Labani Channel (2.51°S, 118.27°E) as part of the International Nusantara Stratification and Transport program (INSTANT) and the Monitoring the ITF (MITF) program (Gordon et al., 2008, 2010, 2012; Sprintall et al., 2009; Susanto et al., 2012). Combined, the two programs provide 13 years of subsurface velocity data from 2004 to 2017 (with a gap between August 2011 and August 2013). Quality controlled and processed velocity data from 40 to 630 m depth (around Makassar Strait sill depth) from Gordon et al. (2019) are used for model validation.

2.2. Ocean Model

We utilized model output from the Nucleus for European Modeling of the Ocean version 3.6 (Madec et al., 2017). The global ocean model (ORCA025) is configured with a 0.25° horizontal resolution tripolar grid and is composed of 46 vertical levels with thickness varying from 6 m at the surface to 250 m at the deepest level (Wagner & Böning, 2021). ORCA025 is forced by JRA55-do (Tsujino et al., 2018), a global atmospheric reanalysis product that spans 1958–2017. Common to global ocean models, sea surface salinity (SSS) in ORCA025 is restored to observed climatology through a restorative freshwater flux (Levitus et al., 1998) to prevent unrealistic drifts in the model salinity budget. In the Indo-Pacific, this restorative flux is small compared to the total freshwater flux, implying that it does not significantly impact our findings (Figure S3 in Supporting Information S1).

Following initialization with hydrography from the World Ocean Database (Levitus et al., 1998) and a 30-year spin-up using 1980–2009 JRA55-do forcings, ORCA025 was then branched into three different simulations (*Hindcast*, *Buoyancy*, and *Winds*, c.f. Wagner & Böning, 2021). In *Hindcast*, ORCA025 was forced by interannually varying buoyancy (heat and freshwater) fluxes and surface wind-stress, providing a historical estimate of the global ocean state from 1958 to 2017. For the two other simulations, interannual variations in JRA55-do forcing was restricted to either buoyancy fluxes (*Buoyancy* simulation) or wind-stress (*Winds* simulation), while the climatological cycle was applied to the other component. These two additional simulations separate the contributions of buoyancy and wind forcings. Unless otherwise stated, all simulated results are shown using the *Hindcast* simulation. To ensure our results are insensitive to model initialization, we restrict analysis to the 1960–2017 period. While the ocean model underestimates the absolute magnitude of southward velocities relative to the Labani mooring data in the upper 40–130 m (Figure 1a), it simulates the Makassar Strait seasonal cycle and response to ENSO forcings reasonably well (Figure 1a, Figure S2 in Supporting Information S1). See Supporting Information S1 for detailed model validation and Ryan et al. (2021); Ummenhofer et al. (2020); Wagner and Böning (2021) for further assessment of model skill.

2.3. Assessment of Freshwater Contribution

Because low-density freshwater from the SCS and Java Sea contributes directly to the Makassar Strait (Figure 1b, orange box) while not affecting the upstream waters at the Mindanao-Sulawesi Passage (Figure 1b, purple box), the density difference between these two regions characterizes the marginal seas' impact on the local pressure gradient. Because salinity only contributes meaningfully to this density gradient in the upper 130 m (Figure S4 in Supporting Information S1) we focus our analysis of density gradients and ITF transport on the upper 130 m (U130m). While the U130m density gradient exerts a dominant influence on ITF transport, density differences below 130 m can also modulate U130m flow. Sea surface height (SSH) differences more accurately integrate density anomalies below 130 m, however here U130m density is utilized to isolate the halosteric (freshwater) component of pressure gradient changes. Nonetheless, we verify that the local SSH gradient strongly covaries with U130m density gradient on seasonal-decadal timescales ($r = 0.78–0.94$, Figure S5 in Supporting Information S1). The mechanisms and pathways of the ITF buoyant pools are examined through regional U130m velocity and salinity anomalies (Figures 2 and 3) and surface properties in the broader tropical Pacific (Figure 4). U130m salinity and velocity anomalies in regions where the seafloor is shallower than 130 m are scaled according to their depth.

2.4. ITF and SCS Transport

We calculate a 57-year (1960–2017) timeseries of U130m Makassar Strait southward transport (Sv) across the entire channel at the Labani mooring latitude (2.5°S). In the remainder of this study, this timeseries of Upper 130 m Strait Transport is referred to as "UST" with southward flow as positive (Figure S6a in Supporting Information S1). The UST timeseries is decomposed using Butterworth filters (order = 5) into the seasonal (highpass filter, cutoff = 1 year), interannual (bandpass filter, cutoff = 3–7 years), and decadal components (lowpass filter, cutoff = 8 years) (Figures S6b–S6d in Supporting Information S1). For the decadal component, a quadratic trend was used to remove the secular trend. Periods of low and high UST were identified for each timescale for composite analysis. NDJ (JAS) months were chosen as reduced (elevated) transport periods on seasonal timescales based on the seasonal cycle of U130m velocities (Figure S2a in Supporting Information S1). For interannual and decadal components, reduced (elevated) UST periods were determined as the lower 20% (upper 80%) quantiles of the filtered data. Volume transport through the Luzon, Sibutu, and Karimata Passages (transects in Figure 1b) were calculated to assess SCS circulation in ORCA025 (Figure S1 in Supporting Information S1). Freshwater transport into Makassar Strait through the Sibutu and Karimata Passages is determined (reference salinity = 34.8 psu) to characterize the freshwater contributions of the SCS and Java Sea respectively (Figures 2 and 3).

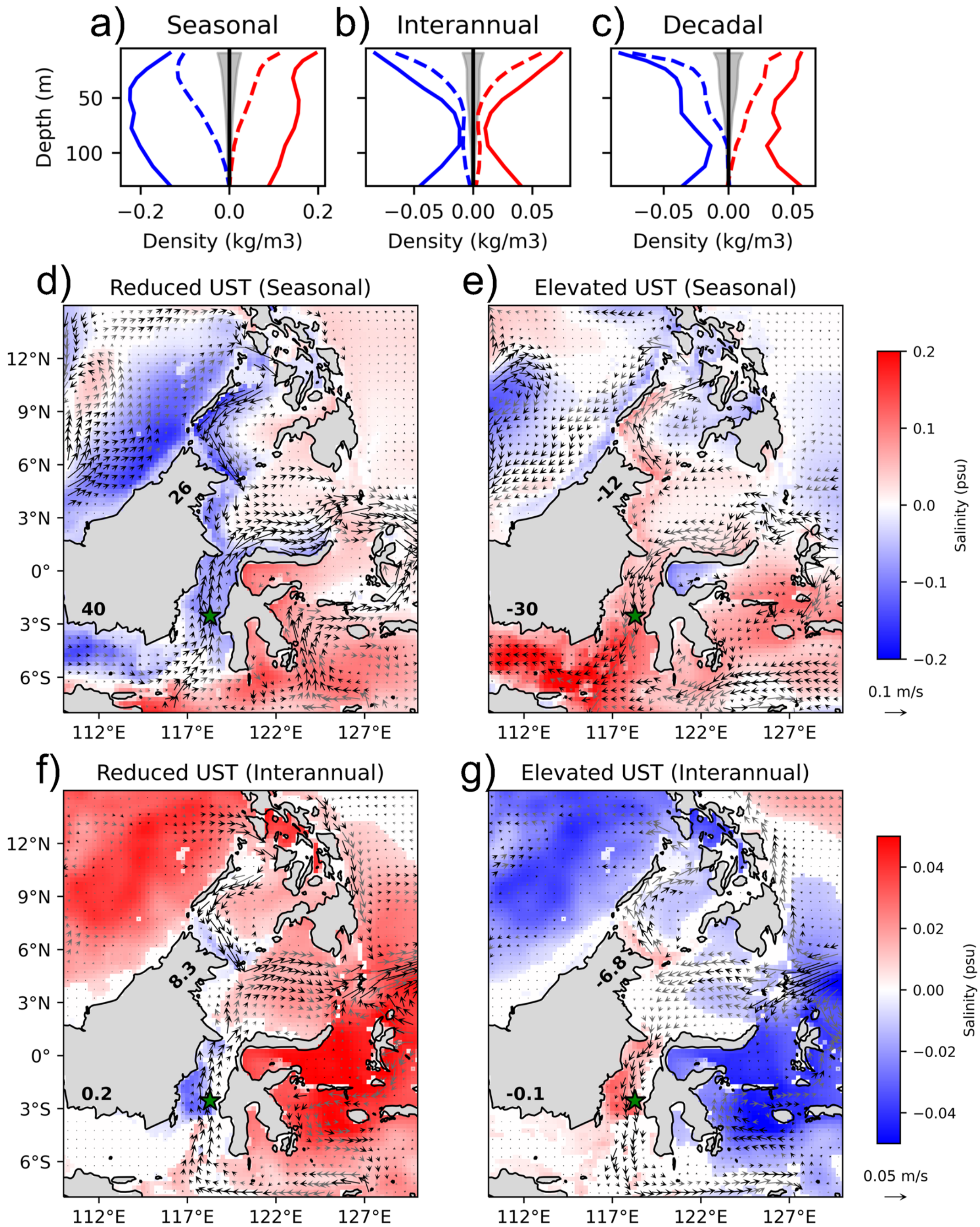

Figure 2. Density difference anomalies in the upper 130m between the Makassar Strait (Figure 1b, orange box) and Mindanao-Sulawesi Passage (Figure 1b, purple box) calculated during reduced (blue lines) and elevated (red lines) upper strait transport (UST) periods on seasonal (b), interannual (c), and decadal (d) timescales. Density difference anomalies are calculated with both salinity and temperature varying (solid lines) and with temperature held constant (dashed lines). Composite maps of U130m salinity (in color) and velocity (vectors) anomalies during periods of low and high UST on seasonal (d, e) and interannual timescales (f, g). Freshwater transport anomalies (in mSv, 10^{-3} Sverdrups) into Makassar Strait through the Sibutu Passage and Karimata Passage (transects in Figure 1b) are shown in the top left and bottom right of Kalimantan respectively. Only salinity anomalies significant at the 90% level are shown. Both velocity anomalies significant at the 90% level (black vectors) and those below (gray vectors) are shown. Labani mooring location is indicated (green star).

Density and freshwater advection analysis was also decomposed into seasonal, interannual, and decadal timescales using the filters as described above. The significance of composite anomalies was assessed by using Monte-Carlo resampling of the original data set and constructing 90% confidence intervals from the resampled random distribution.

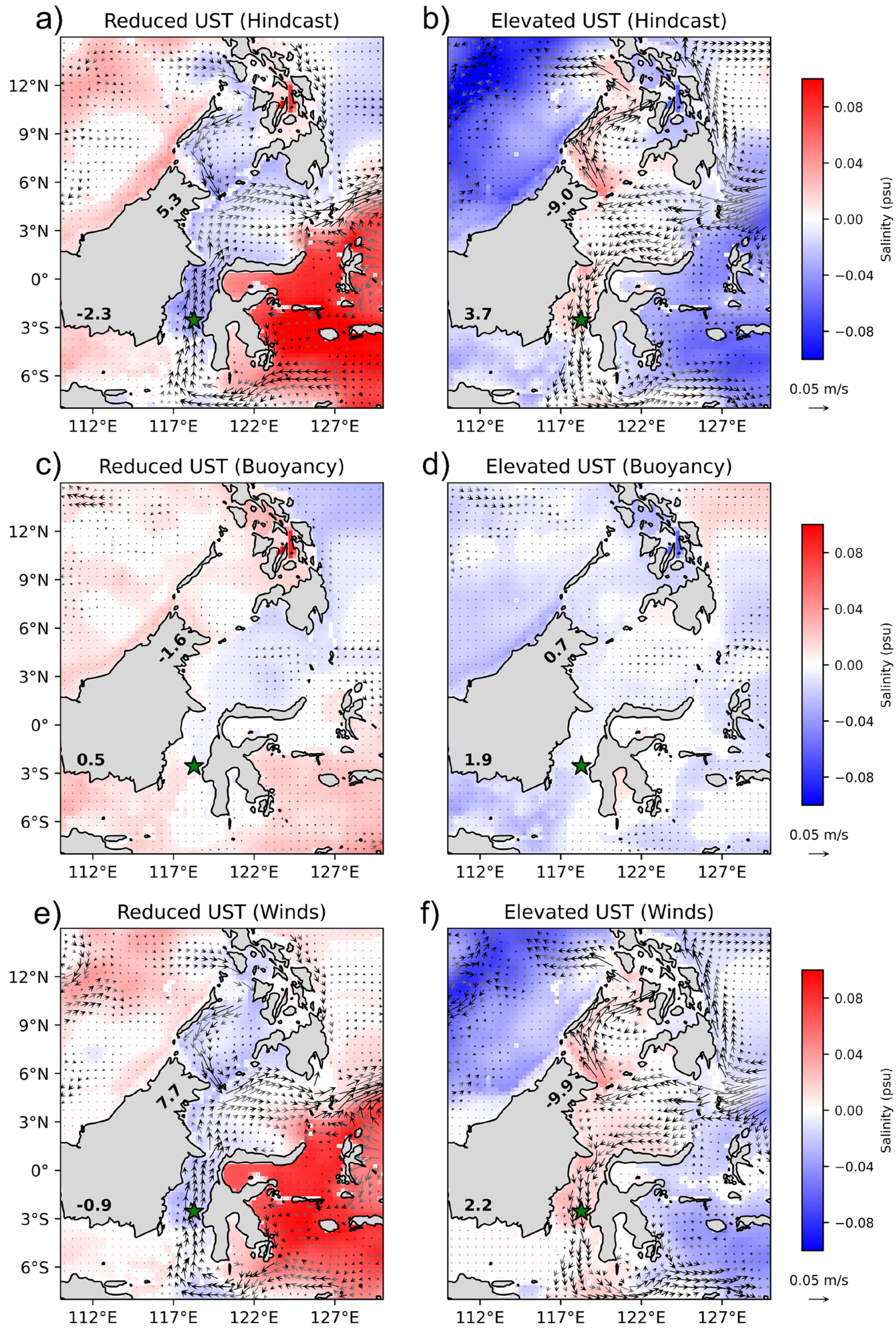
a) Reduced UST (Hindcast)
b) Elevated UST (Hindcast)
c) Reduced UST (Buoyancy)
d) Elevated UST (Buoyancy)
e) Reduced UST (Winds)
f) Elevated UST (Winds)
5.3
-2.3
-9.0
3.7
-1.6
0.5
0.7
1.9
7.7
-0.9
-9.9
2.2
12°N
9°N
6°N
3°N
0°
3°S
6°S
112°E
117°E
122°E
127°E
Salinity (psu)
0.08
0.04
0.00
−0.04
−0.08
0.05 m/s

Figure 3.

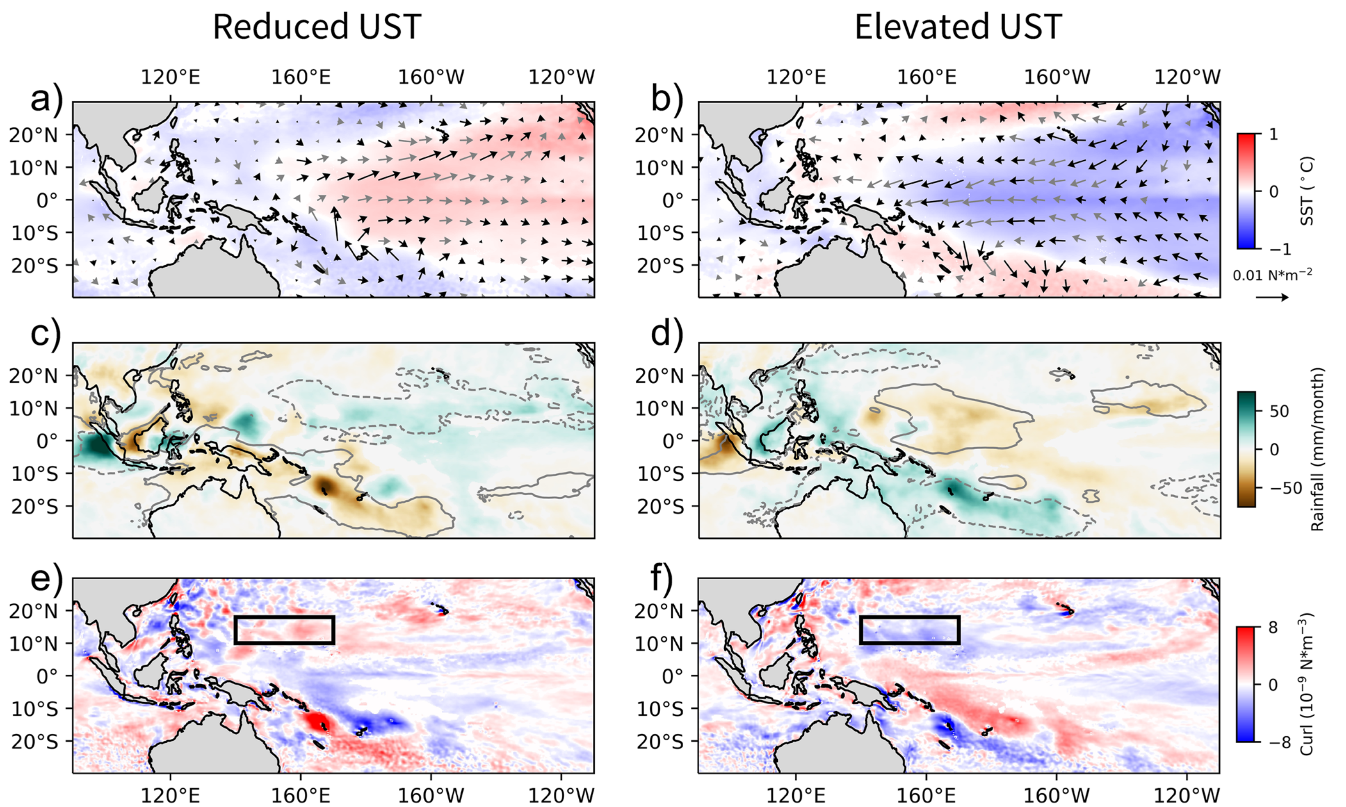

Figure 4. Composite maps of Pacific surface fields from JRA55-do and ORCA025 during decadal low UST (a, c, e) and high UST (b, d, f) periods. SST (color) and surface wind-stress (vectors) anomalies (a, b). Precipitation (color) and SSS (contours, where anomalies above 0.05 psu are within solid contours, anomalies below −0.05 psu are within dashed contours) (c, d). Wind stress curl anomalies (color) derived from u,v wind-stress anomalies, also included is the western North Pacific box (black) where wind-stress curl correlates strongly with the NEC bifurcation latitude (e, f). Only anomalies significant at the 90% level are shown except for wind-stress vectors, where both significant anomalies (black) and insignificant anomalies (gray) are shown.

3. Freshwater Advection on Multiple Timescales

For all three timescales, simulated reduced (elevated) UST periods are associated with negative (positive) density difference anomalies between Makassar and the Mindanao-Sulawesi passage (Figures 2a–2c). In the ocean model, salinity contributes significantly to this density gradient on seasonal and interannual timescales (Figures 2a and 2b dashed lines), consistent with observations (Gordon et al., 2003, 2012). Here we find that salinity also contributes to the density gradient variability on decadal timescales (Figure 2c dashed lines). We examine how the pathways of the simulated freshwater anomalies on seasonal and interannual timescales compare with previously proposed mechanisms based on observations.

Low UST periods on seasonal timescales (NDJ months) are marked by freshening and increased SCS and Java Sea freshwater transport (26 and 40 mSv respectively, Figure 2d) into Makassar Strait. Conversely, high UST periods (JAS months) are associated with positive salinity anomalies and reduced SCS and Java Sea freshwater input (−30 and −12 mSv, Figure 2e). Interannual variability of UST is also characterized by Makassar Strait salinity variations (Figures 2f and 2g); however, unlike the seasonal response, freshwater transport variability is found mostly along the SCS route (8.3 and −6.8 mSv) whereas the Java Sea contributes minimally (0.2 and −0.1 mSv). Consistent with Gordon et al. (2003), monsoon winds-related freshwater input through the Java Sea and SCS modulates seasonal UST, while the ENSO-sensitive SCS route contributes to interannual variability.

Figure 3. Composite maps of U130m average salinity (in color) and velocity (vectors) anomalies during periods of decadal low UST (a, c, e) and high UST (b, d, f) from the *Hindcast* (a, b), *Buoyancy* (c, d), and *Winds* (e, f). Freshwater transport anomalies (in mSv, 10^{-3} Sverdrups) into Makassar Strait through the Sibutu Passage and Karimata Passage (transects in Figure 1b) are shown in the top left and bottom right of Kalimantan respectively. Only salinity anomalies significant at the 90% level are shown. Both velocity anomalies significant at the 90% level (black vectors) and those below (gray vectors) are shown. Labani mooring location is indicated (green star).

10.1029/2023GL103906

On decadal timescales, reduced UST is associated with increased freshwater transport into Makassar Strait through the Sibutu Passage (5.3 mSv) along with a decrease in Makassar Strait U130m salinity (Figure 3a). Based on the U130m salinity and velocity anomalies, we surmise this increased SCS freshwater input is responsible for the Makassar Strait freshening. This is consistent with a complementary −9 mSv reduction in freshwater transport through the Sibutu Passage during elevated UST periods (Figure 3b). In contrast, the Java Sea exhibits salinity changes and freshwater transport variations that oppose the Makassar Strait salinity variations, indicating that the decadal freshwater plug is not transmitted through this passageway and that it may in fact dampen the plug. Although velocity anomalies in the Makassar Strait and western Sulawesi Sea are northward-oriented during reduced UST periods (Figure 3a), absolute flow is still southward because the anomaly vectors are only 10% of the mean flow field (Figure S7 in Supporting Information S1). Thus salinity anomalies in the Sulu Sea can still be advected into the Makassar Strait during reduced UST periods.

To assess the roles of direct freshwater fluxes and wind-driven advection, we compare the anomalies from *Hindcast* to the *Buoyancy* and *Winds* simulations. The *Buoyancy* forcings during low UST produces small counteracting changes in SCS and Java Sea freshwater input (−1.6 and 0.5 mSv through Sibutu and Karimata respectively), and a 0.02 psu freshening in the eastern Sulawesi Sea that would counteract the freshwater plug dynamics. Similarly, *Buoyancy* fluxes during high UST intervals reflect a weak broad-scale freshening (<0.02 psu) that would not contribute to pressure gradient dynamics (Figure 3d). Most importantly, U130m velocities in the ITF pathway vary by less than 0.01 m/s in response to *Buoyancy* forcings during the identified UST periods. In contrast, in *Winds*, salinity and velocity anomalies in the Makassar Strait along with freshwater input through the Sibutu Passage are largely comparable to the *Hindcast* simulation (7.7 vs. 5.3 mSv and −9.9 vs. −9 mSv). This suggests that freshwater fluxes through precipitation and runoff contributed minimally to the generation and dissipation of the decadal ITF freshwater plug. Rather, wind-driven advection of surface freshwater from the SCS through the Sibutu Passage appears to be the dominant driver.

4. Influence of Pacific Decadal Variability

Salinity is not the sole contributor to this local density gradient (Figures 2a–2c; dashed lines vs. solid lines). U130m temperature anomalies during anomalous UST periods show regional patterns quite distinct from salinity (Figure S8 in Supporting Information S1). Particularly, the interannual and decadal anomalies are coherent across the Indonesian Seas, likely associated with Pacific basin-wide interannual (ENSO) and decadal (Interdecadal Pacific Oscillation, IPO) variability modulating the Indo-Pacific Warm Pool (Figures S8c–S8f in Supporting Information S1) (Henley et al., 2015; Trenberth, 1997). That IPO plays a role in modulating decadal UST is further supported by Pacific sea surface temperature (SST) anomalies during anomalous UST periods on decadal timescales (Figures 4a and 4b). During reduced UST intervals, an SST pattern resembling +IPO is observed alongside a weakening of the Pacific trade winds, while enhanced UST is associated with a -IPO pattern and strengthening of the trade winds (Figures 4a and 4b). Enhanced freshwater plug periods (reduced UST) being associated with +IPO and vice versa is consistent with previous studies that attribute coherent Indo-Pacific variability on decadal timescales to the IPO (Dong et al., 2016; T. Lee & McPhaden, 2008).

Similar to the ENSO freshwater plug, the decadal variability of SCS freshwater input to Makassar Strait is modulated by interactions between surface winds and the Pacific western boundary currents. During +IPO-like periods (Figure 4e), the Walker Circulation strengthens and induces positive wind-stress curl anomalies in the western North Pacific (Figure 4e box). These curl anomalies favor a northward migration of the NEC bifurcation, weakening the Kuroshio Current and increasing leakage into the SCS through Luzon Strait (Gordon et al., 2014; D. Hu et al., 2015; Kim et al., 2004; Qiu & Chen, 2010; van Sebille et al., 2009). Because the SCS freshwater route into Makassar varies in concert with upper Luzon Strait leakage (Figure S1 in Supporting Information S1, Gordon et al., 2012), SCS freshwater injection increases, reducing UST (Figure 3a). By similar mechanisms, reduced SCS input is observed during a -IPO whereby negative wind-stress curl anomalies shift the NEC southward and weaken Luzon Strait leakage (Figure 3b and Figure 4f).

While the focus here is on the freshwater plug mechanism, Pacific decadal variability also influences large-scale ITF transport through regional rainfall changes and wind-driven sea level variations (Dong et al., 2016; S. Hu & Sprintall, 2016, 2017; T. Lee & McPhaden, 2008). During +IPO, weaker Pacific trade winds (Figure 4a) and reduced rainfall over the western Pacific and Maritime Continent (Figure 4c) weaken the inter-basin pressure gradient and reduce overall ITF transport, while a -IPO induces strengthened inter-basin transport through complimentary mechanisms (Figures 4b and 4d). Because of their common driver (IPO), isolating the relative contributions of the large-scale (inter-basin) and local (freshwater plug) pressure gradients to Makassar Strait transport is challenging. A comparison of these two pressure gradients (large-scale and local) to decadal UST shows that they largely covary (Figure S9 in Supporting Information S1), but that during a period of decoupling in the 1960s, decadal UST decreases with the local pressure gradient. Interestingly, while both the large-scale and local pressure gradients increase in the 2000s, decadal UST remains reduced for several years. This indicates that perhaps other mechanisms along the ITF pathway may also modulate surface flow through pressure gradient anomalies.

5. Conclusions

We assessed how freshwater impacts surface transport through the main passageway of the ITF on various timescales using an eddy-permitting global ocean model (ORCA025). We show that the distinct freshwater pathways which modulate upper Makassar Strait transport on seasonal (<1 year) and interannual (3–7 years) timescales are consistent between ORCA025 and observations (Gordon et al., 2003, 2012). On decadal timescales, which direct measurements cannot resolve, we find that freshwater contributes to local pressure-gradient anomalies that impact surface ITF transport. Specifically wind-driven advection of low-salinity waters from the SCS via the western Sulu Sea appears to dominate this decadal freshwater plug with minimal contributions from direct freshwater fluxes despite their considerable role in large-scale inter-basin pressure gradients. This freshwater advection mechanism, which impacts the local density gradient in the upper 130 m, is important to overall ITF transport considering 73% of Makassar volume transport occurs in the upper 300 m.

From a large-scale perspective, this decadal freshwater plug is driven by changes in western Pacific surface winds which affect a latitudinal shift in the NEC bifurcation and modulate the SCS flow into Makassar. These surface wind variations appear to be a component of basin-wide decadal mode of variability (IPO), which explains how the IPO influences the Makassar freshwater plug on decadal timescales. However, NEC variability is not solely explained by Pacific basin-wide modes (ENSO and IPO), with recent studies highlighting NEC sensitivity to the Southern Annular Mode (Qiu & Chen, 2010; L.-C. Wang et al., 2022). This complexity of NEC bifurcation movement may explain periods of discrepancy between ENSO and IPO indices and interannual and decadal UST (Figures S4c and S4d in Supporting Information S1). We also note that the Pacific to Indian Ocean pressure gradient which drives total inter-basin transport must also be considered and that it often, but not always, covaries with the freshwater plug.

How exactly the Pacific atmospheric circulation will change in response to global warming is still unclear, with the contributions of internal and external forcings currently unresolved (Heede et al., 2020; Wu et al., 2021). This study, which identifies a relationship between ITF surface transport and tropical Pacific winds on decadal timescales, highlights the importance of clarifying atmospheric changes in a warming climate.

Data Availability Statement

JRA55-do is available from the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (https://climate.mri-jma.go.jp/pub/ocean/JRA55-do/jra55do_latest.html). The Niño 3.4 index and IPO tripolar index used in this study are available from NOAA (https://psl.noaa.gov/data/climateindices/list/). Makassar Strait observations from the Labani channel moorings are available as accompanied by Gordon et al. (2019) (https://doi.org/10.7916/d8-p78a-zm51). The integration of ORCA025 simulations was performed at the North-German Supercomputing Alliance (HLRN) and the Computing Centre at Kiel University. The raw model output data can be downloaded at https://data.geomar.de/downloads/20.500.12085/beb05787-f533-485c-9d91-2d41722631d1//.

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