Decadal variability and long-term trend of Indonesian Throughflow in a warming climate

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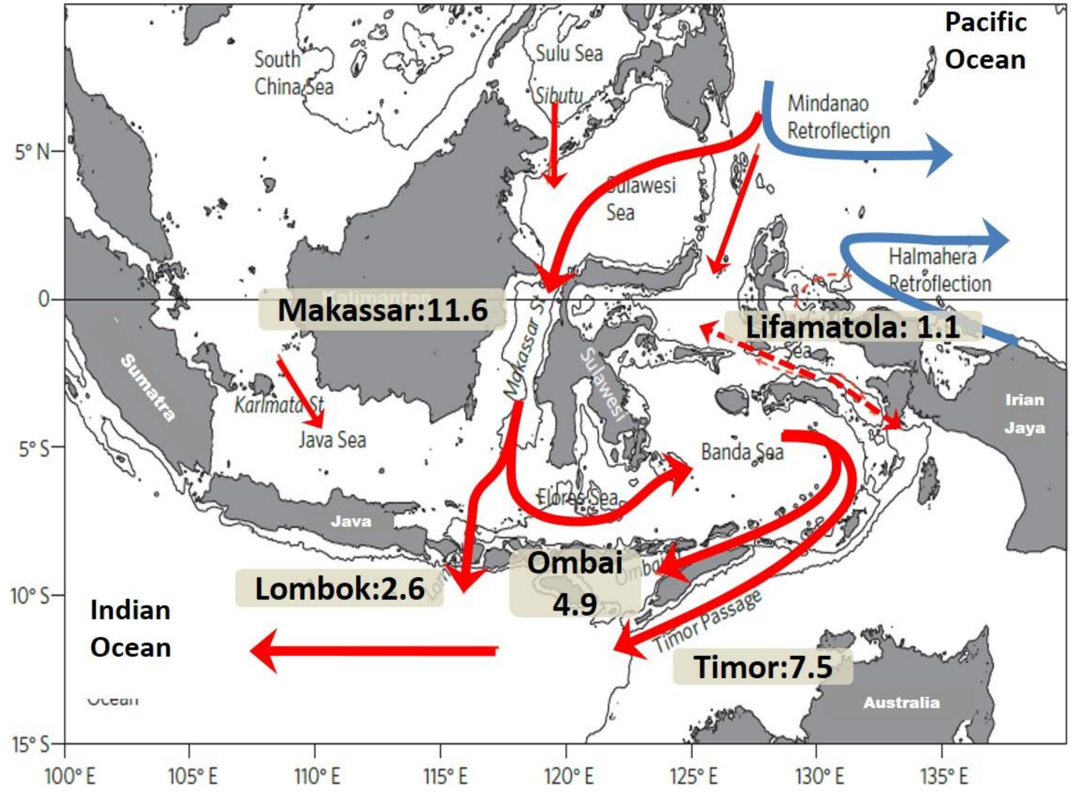
OUTLINES

1. Introduction
2. Is there a robust trend in ITF during the past decades?
3. Will the ITF be weakening in the future?
4. What controls the decadal changes of ITF?
5. Summary

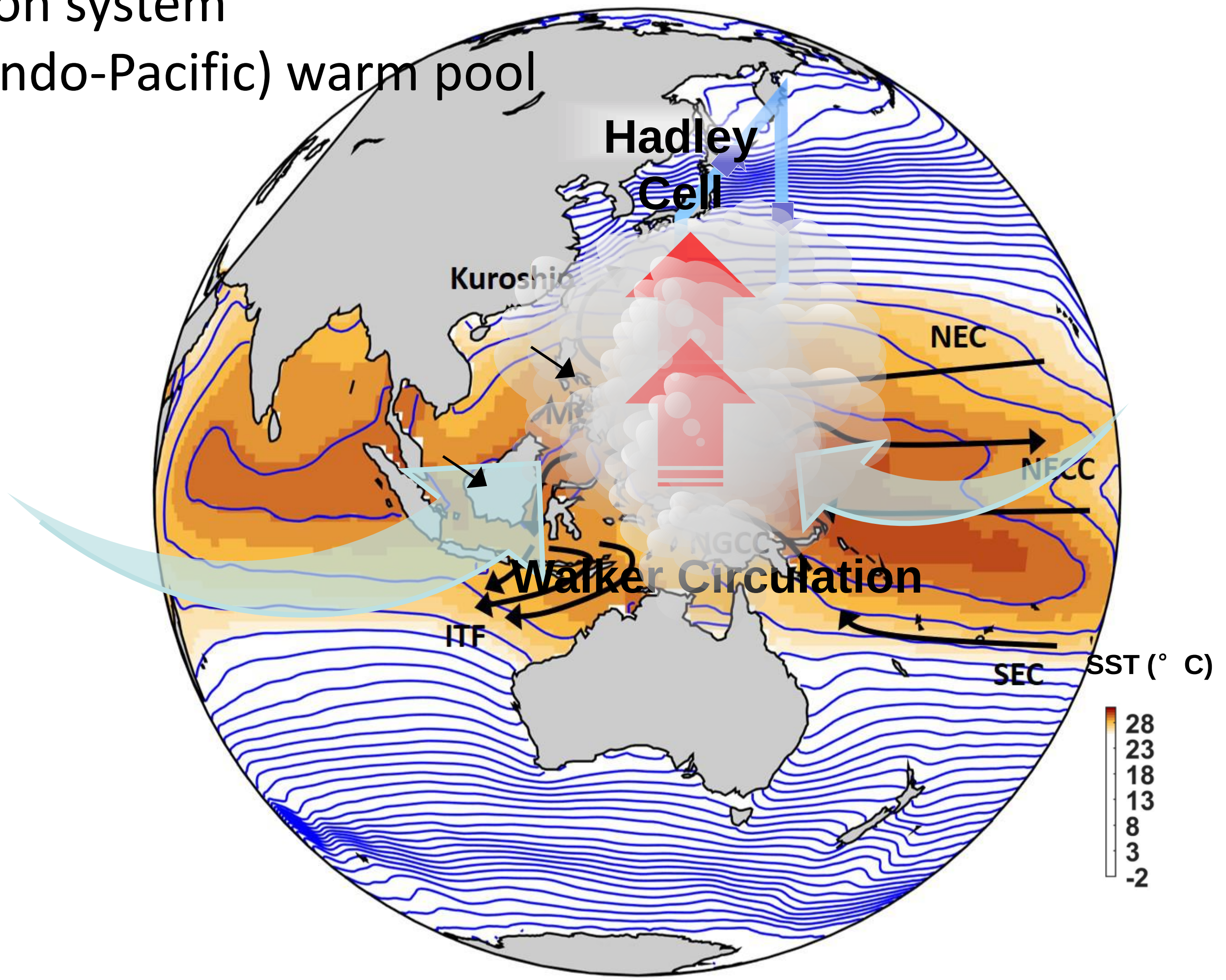
1. Introduction

Why is the ITF important?

- The ONLY pathway that connects ocean basins in the tropics
- Complicated ocean and atmospheric circulation system
- Strong air-sea interaction within the largest (Indo-Pacific) warm pool
- ITF modulate tropical – global climate system



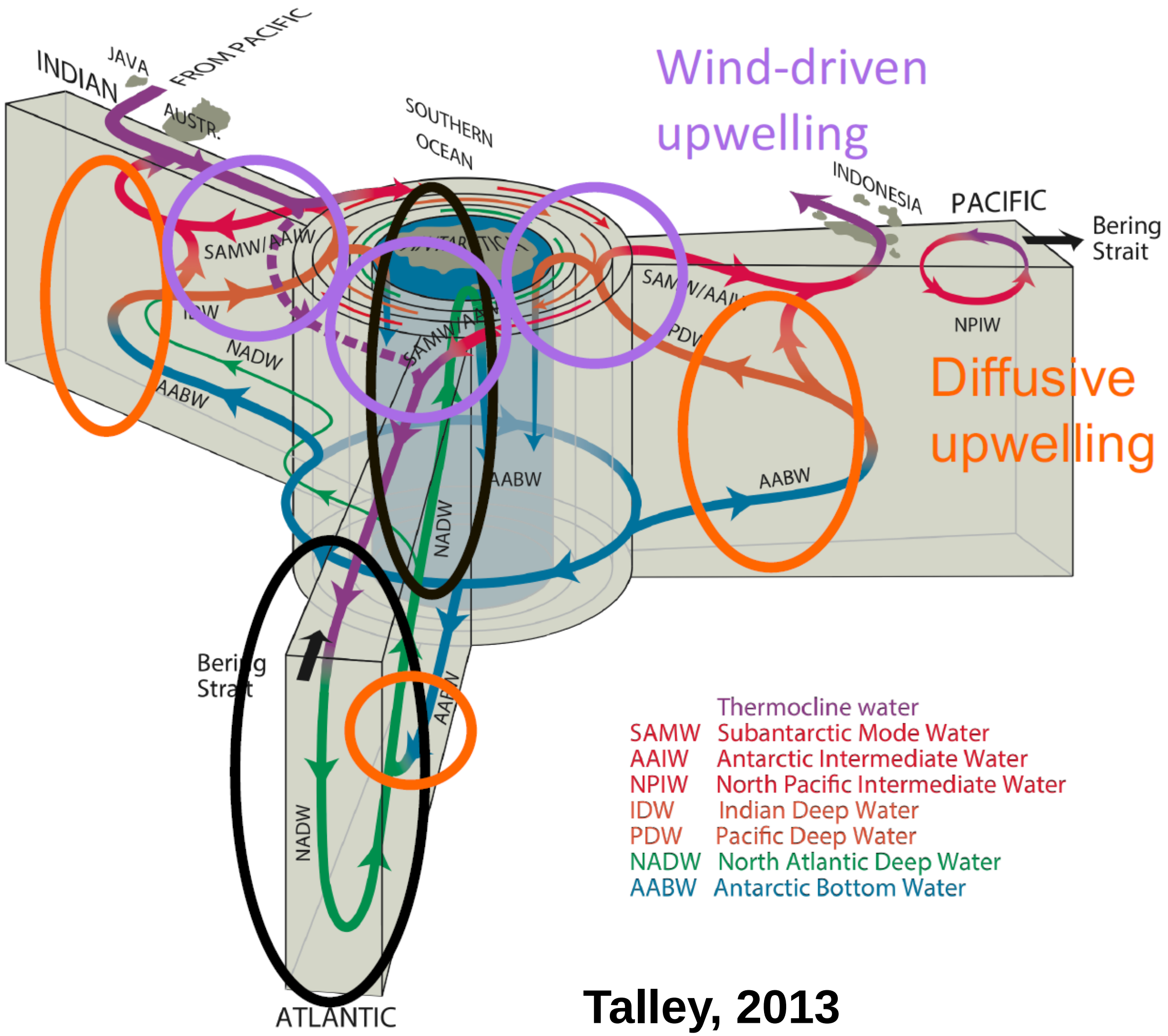
■ ITF structure (Sprintall et al., 2014)



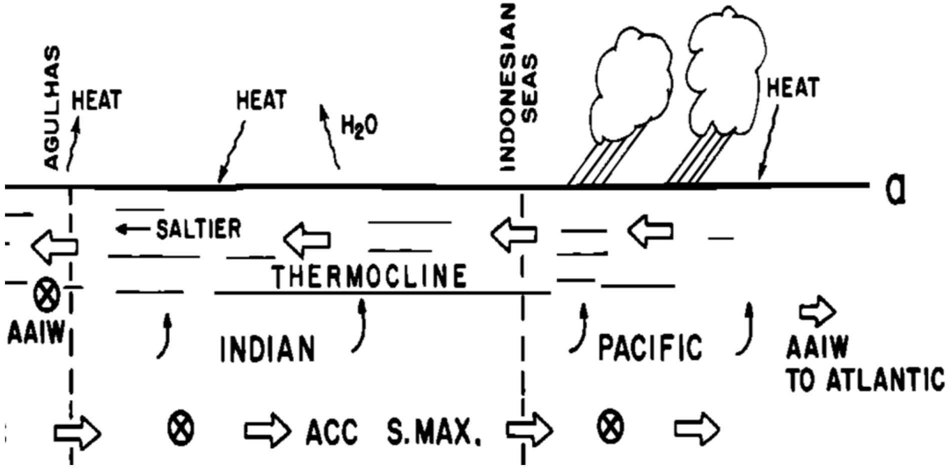
■ Indo-Pacific Climate System (Wang et al., 2018)

Why is the ITF important?

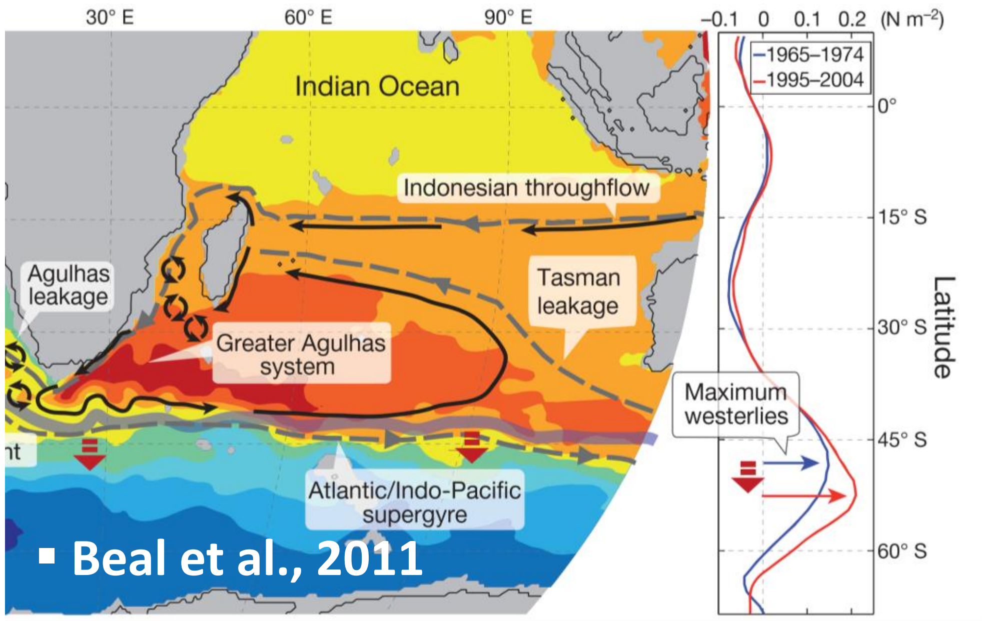
- **Essential part of global thermohaline circulation**
- **Inter-basin exchanges and Indo-Pacific balance of heat and freshwater**



Talley, 2013



- Gordon (1986); Gordon and Fine (1996)

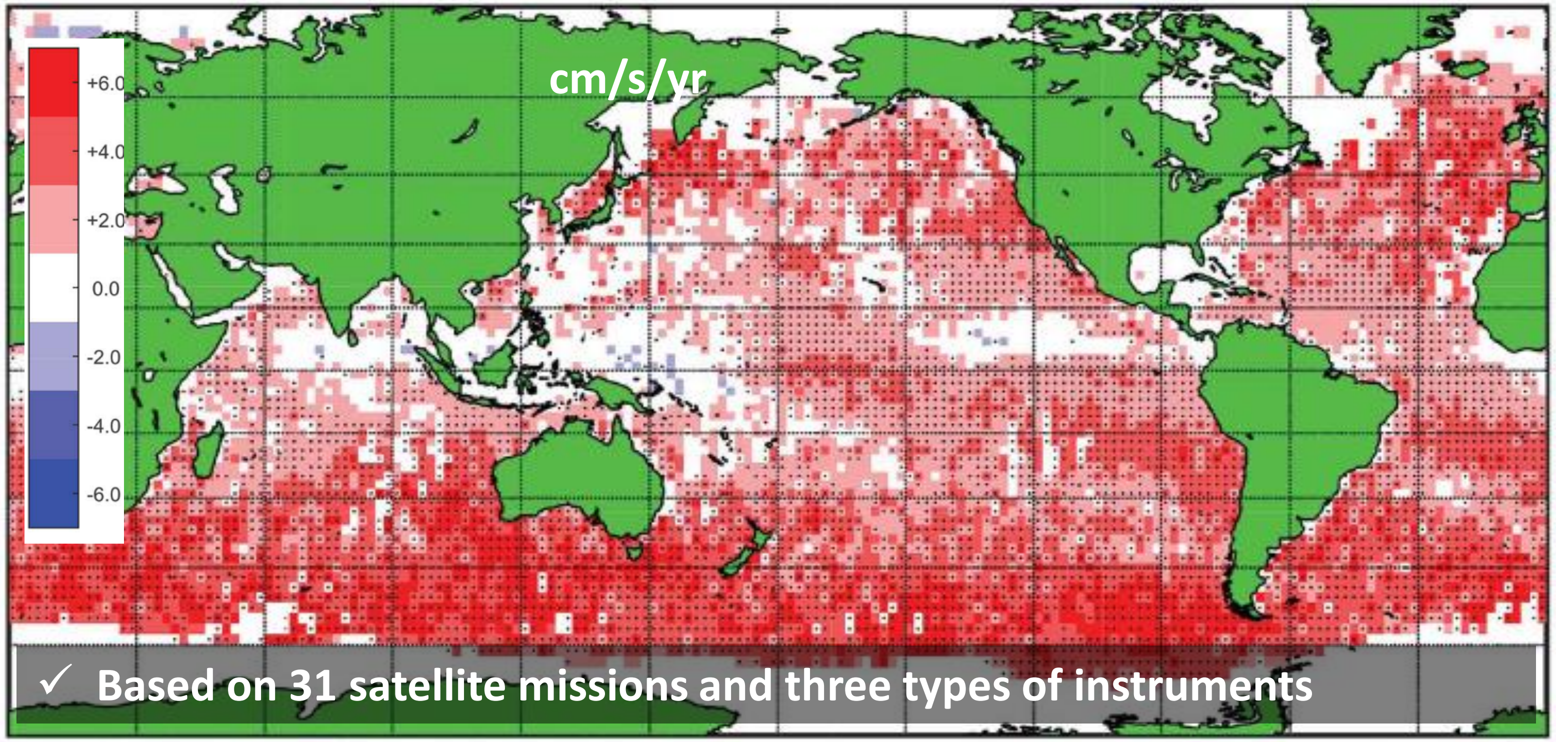


- **Beal et al., 2011**

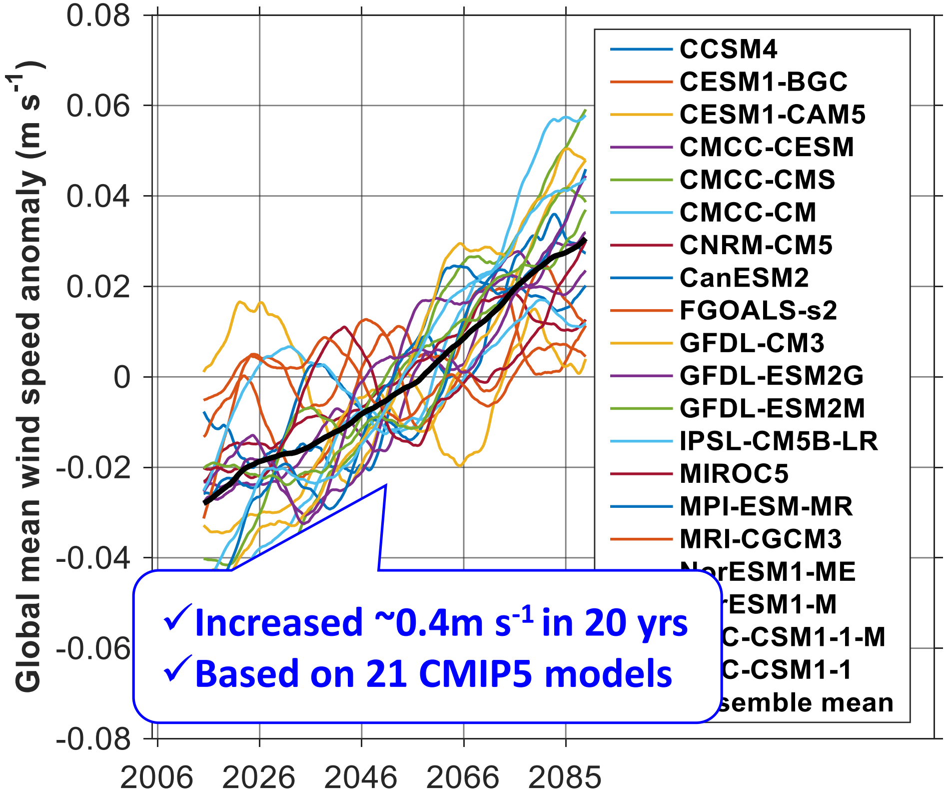
Introduction

■ Oceanic response to global climate warming: sea surface wind

- Trend (1985-2018) in sea surface wind observed by multi-satellites (**Young and Ribal, 2019, Science**)

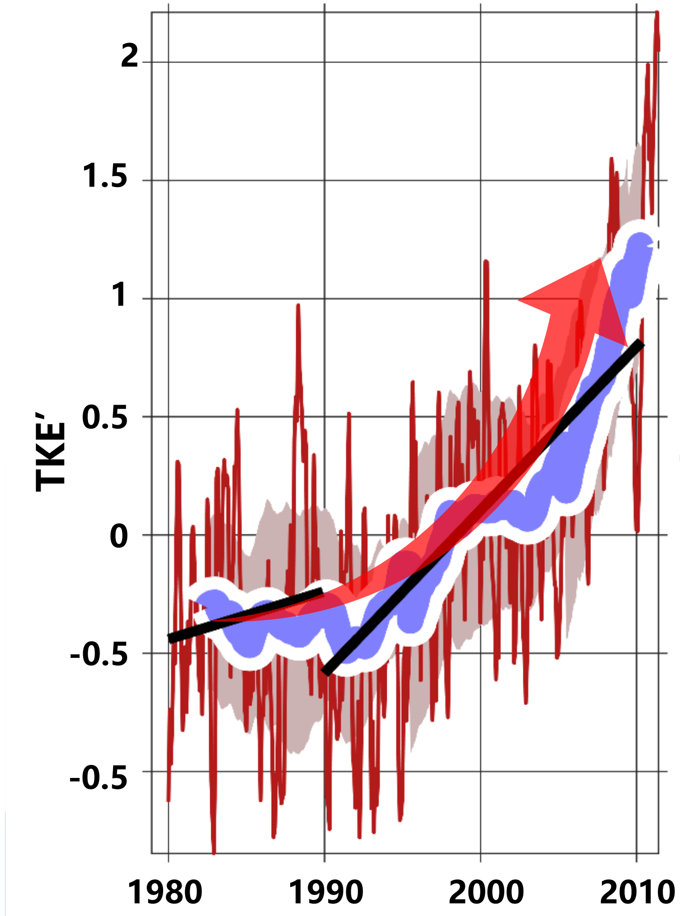


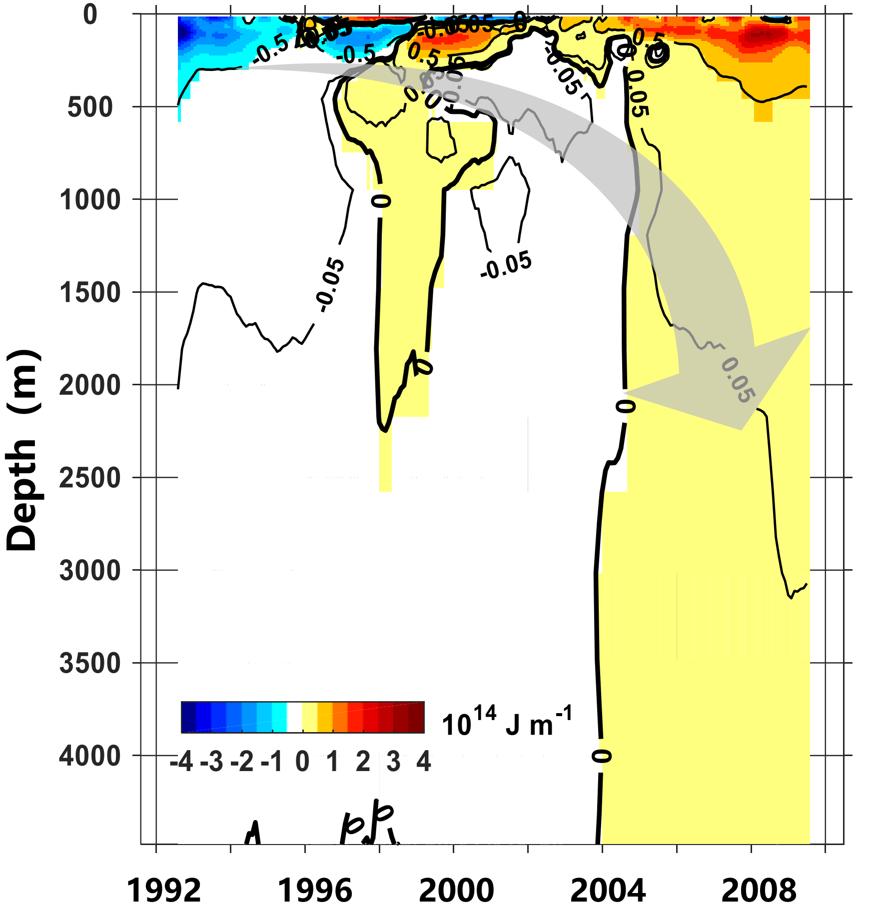
- Projected global mean sea surface wind speed (**Hu et al., 2020, Science Advances**)

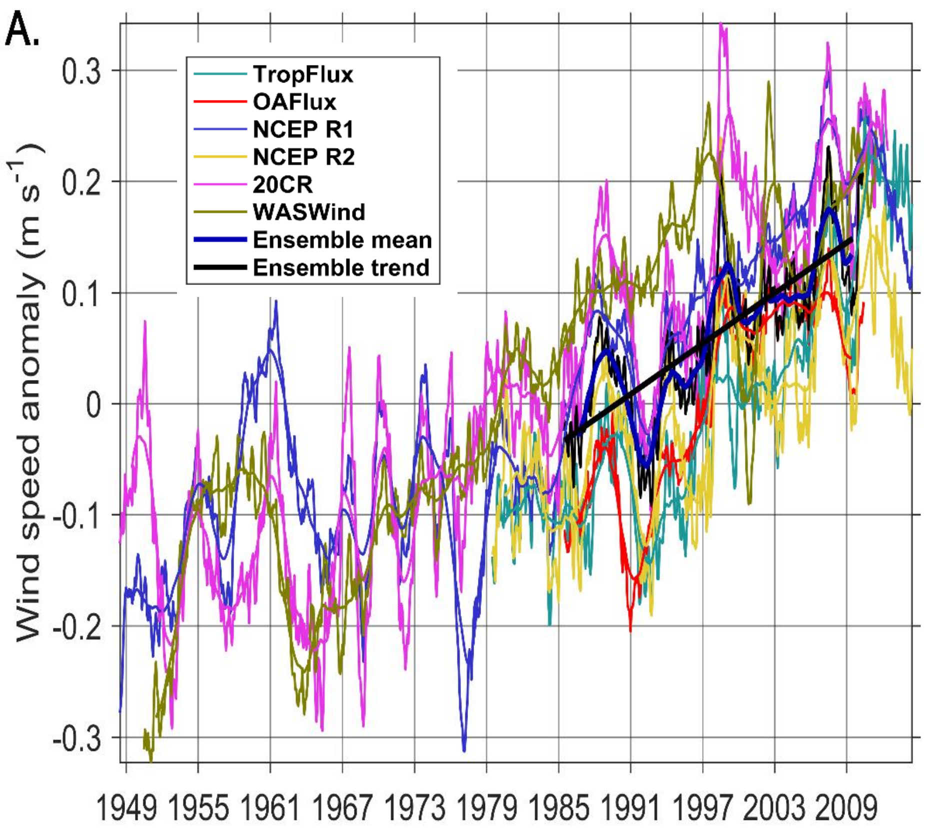


Introduction

- Global mean ocean circulation shows a significant acceleration during the past decades since 1980s
- Intensified sea surface winds play an important role (**Hu et al., 2020, Science Advances**)

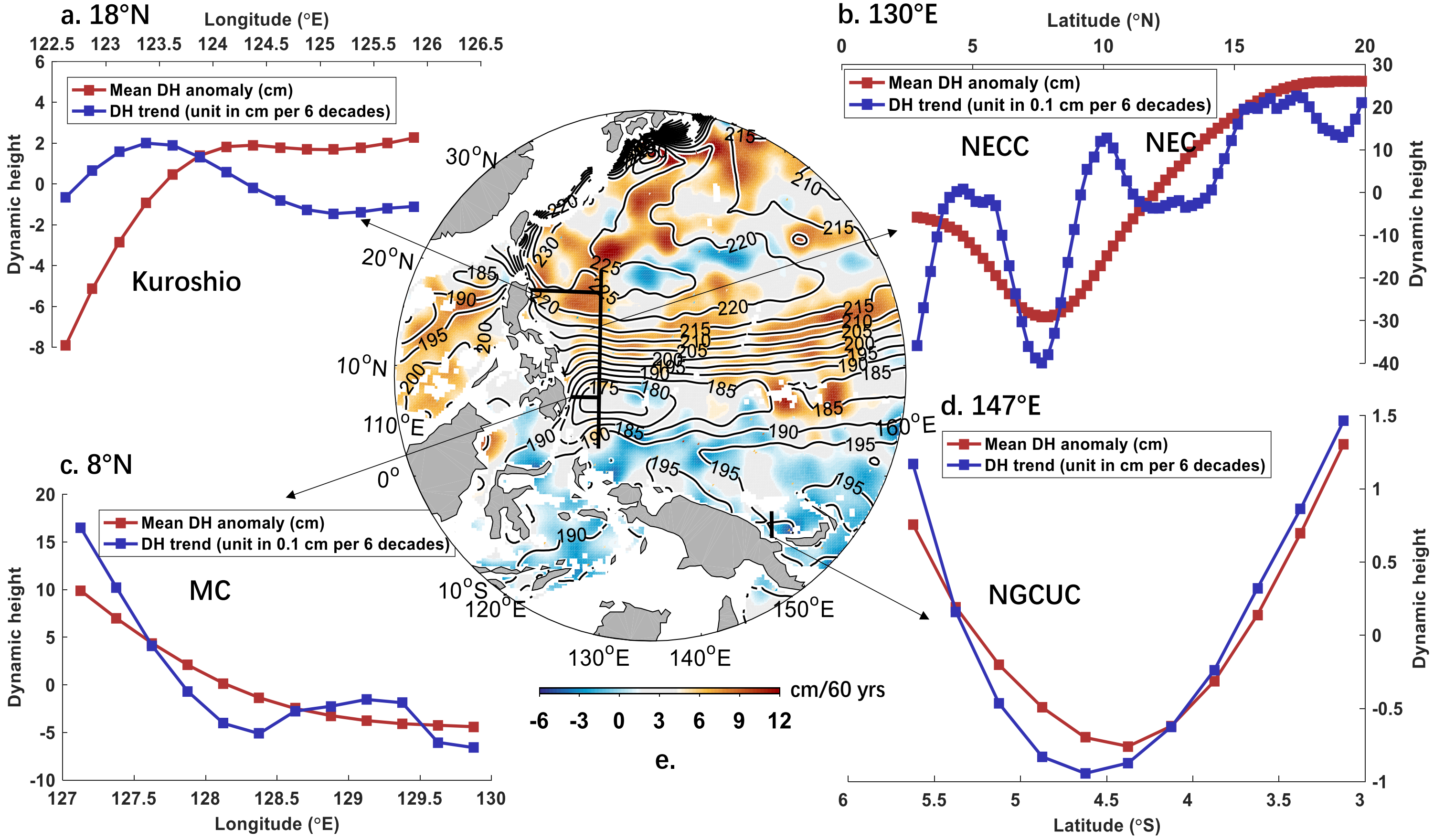


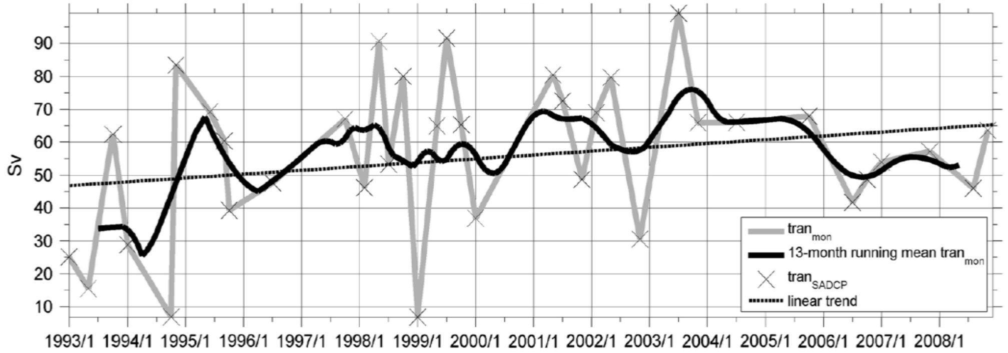




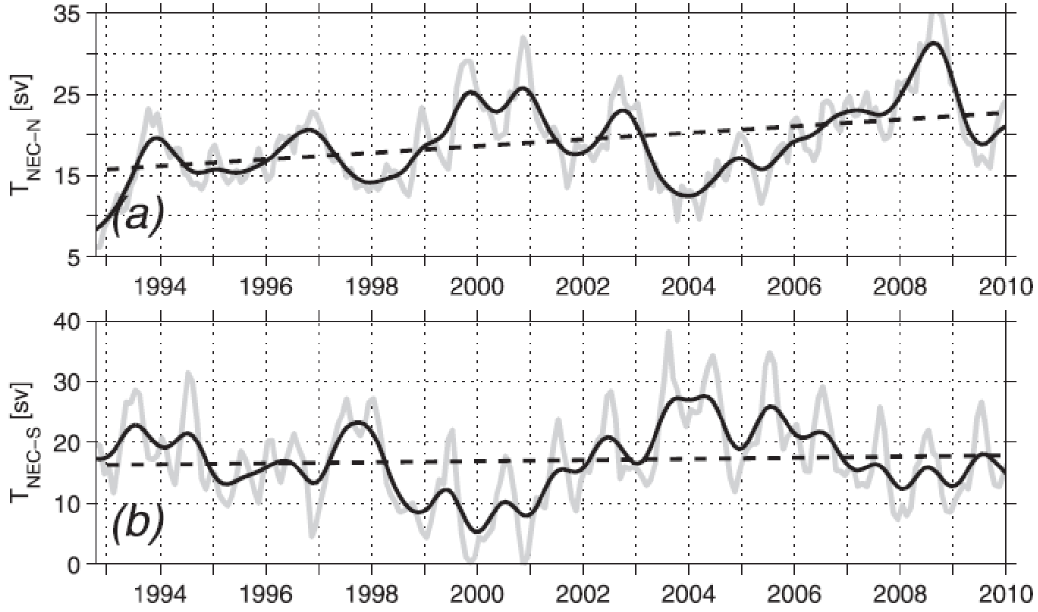
- Evolution of TKE
- Global mean sea surface wind

Introduction





■ NEC trends in repeated shipboard ADCP measurements (Hu S. and Hu D., 2014)



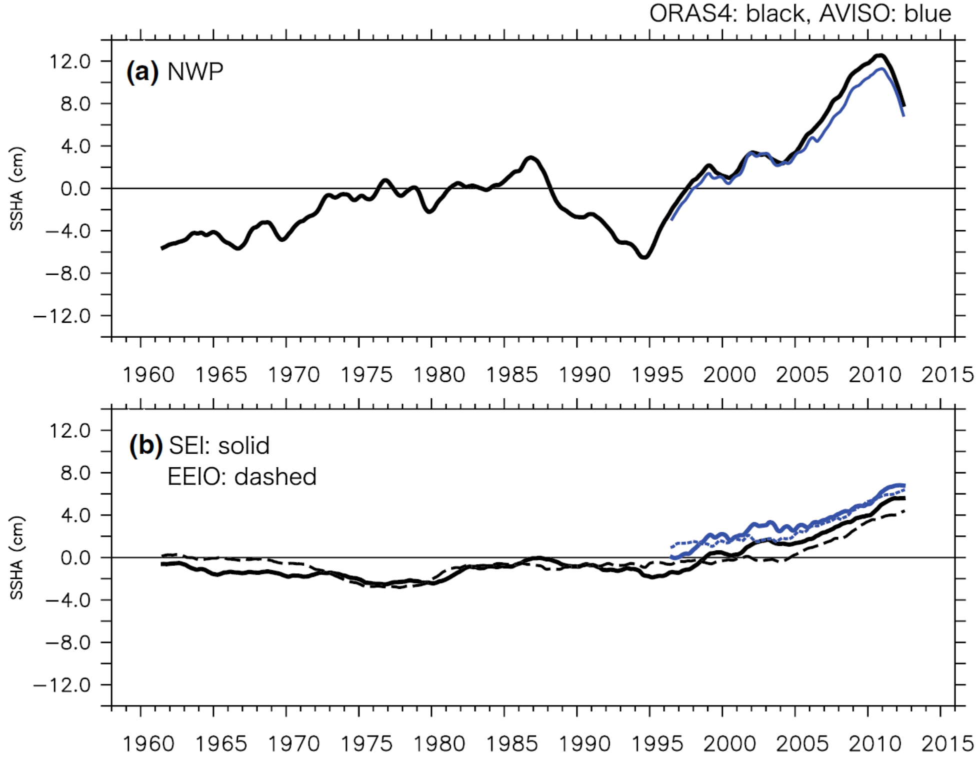
■ **Mean** and **trend** of dynamic height (Hu et al., 2021)

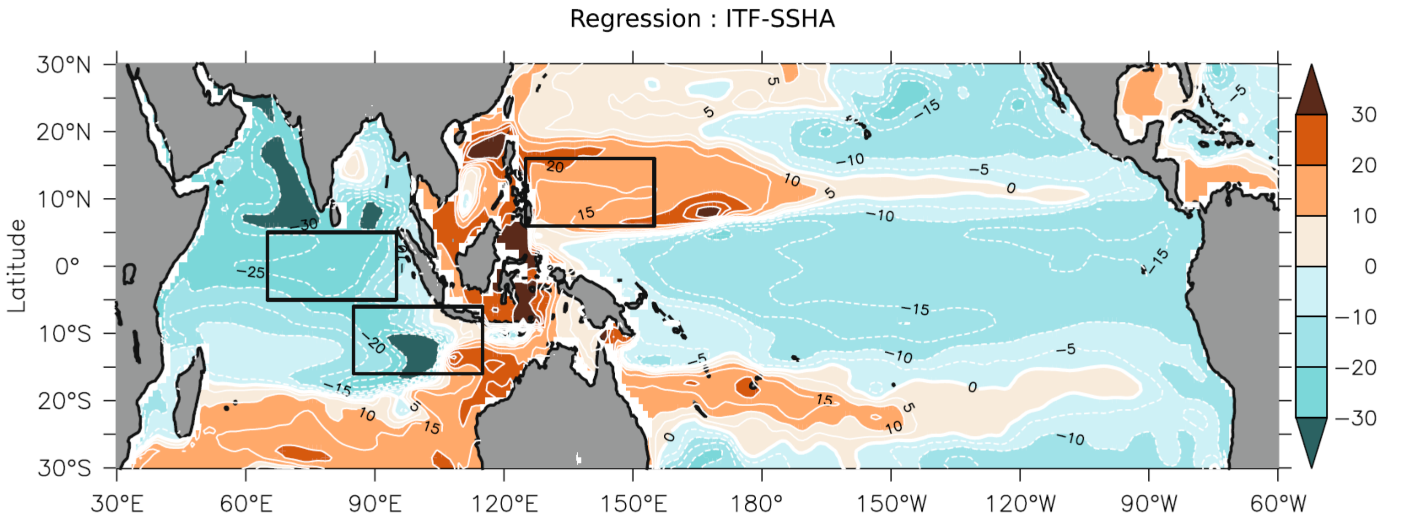
■ NEC trends (Qiu and Chen, 2012)

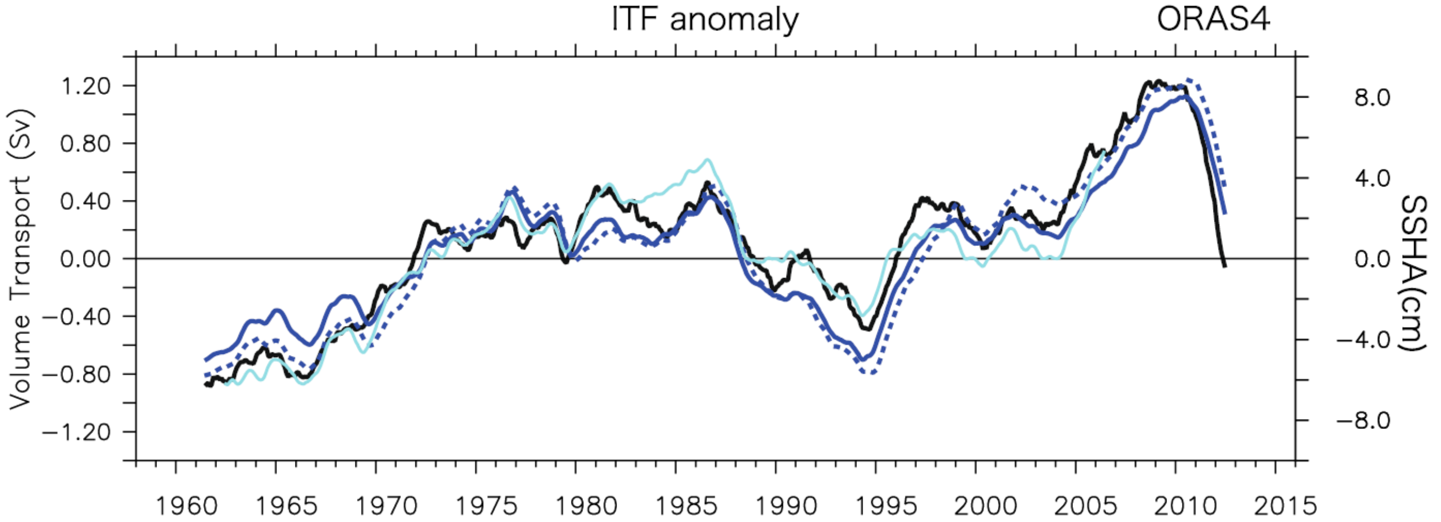
Question 1: Is there a robust trend in ITF during the past decades?

■ Decadal variability of ITF transport in the ECMWF ORA S4 (Shilimkar et al., 2022)

- SSH from ORA S4 is consistent with observations
- The Indo-Pacific SSH difference is a good indicator of ITF transport on decadal time scales
- Increasing of ITF transport during 1958-2015 (as seen from the figures)

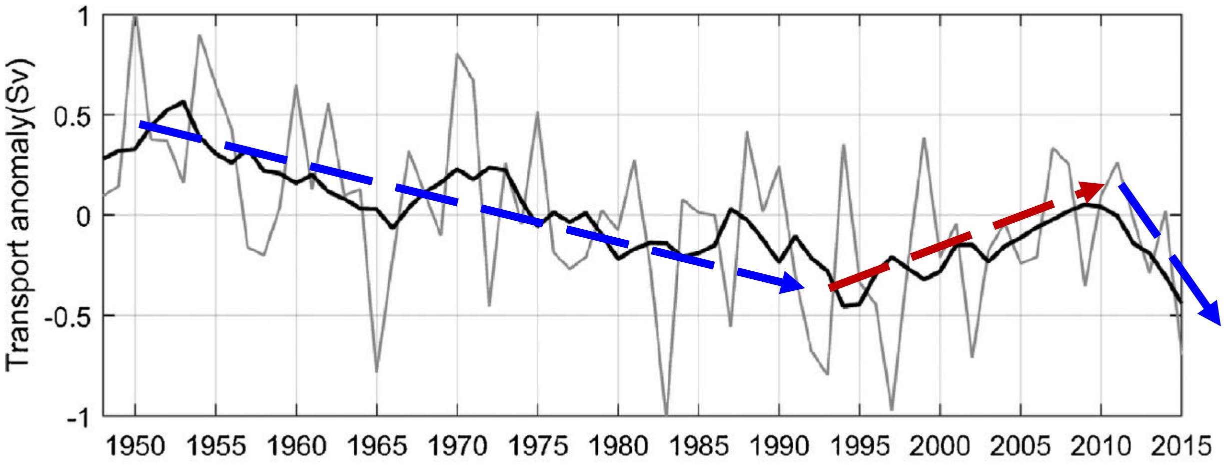




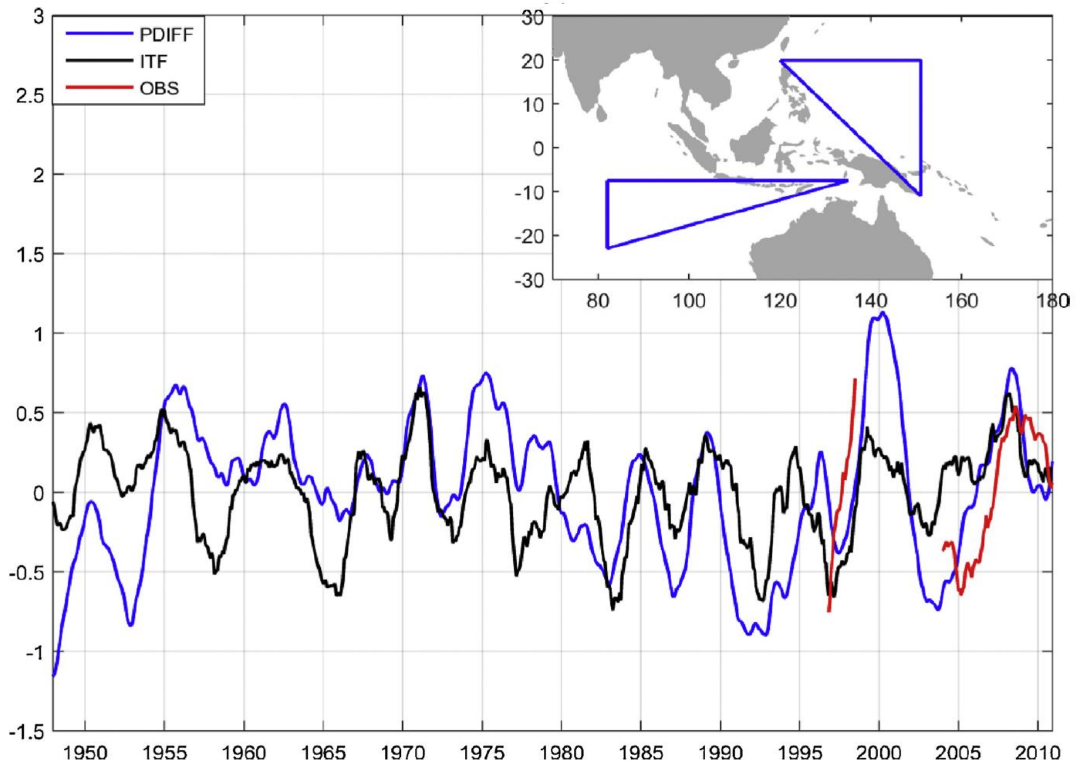


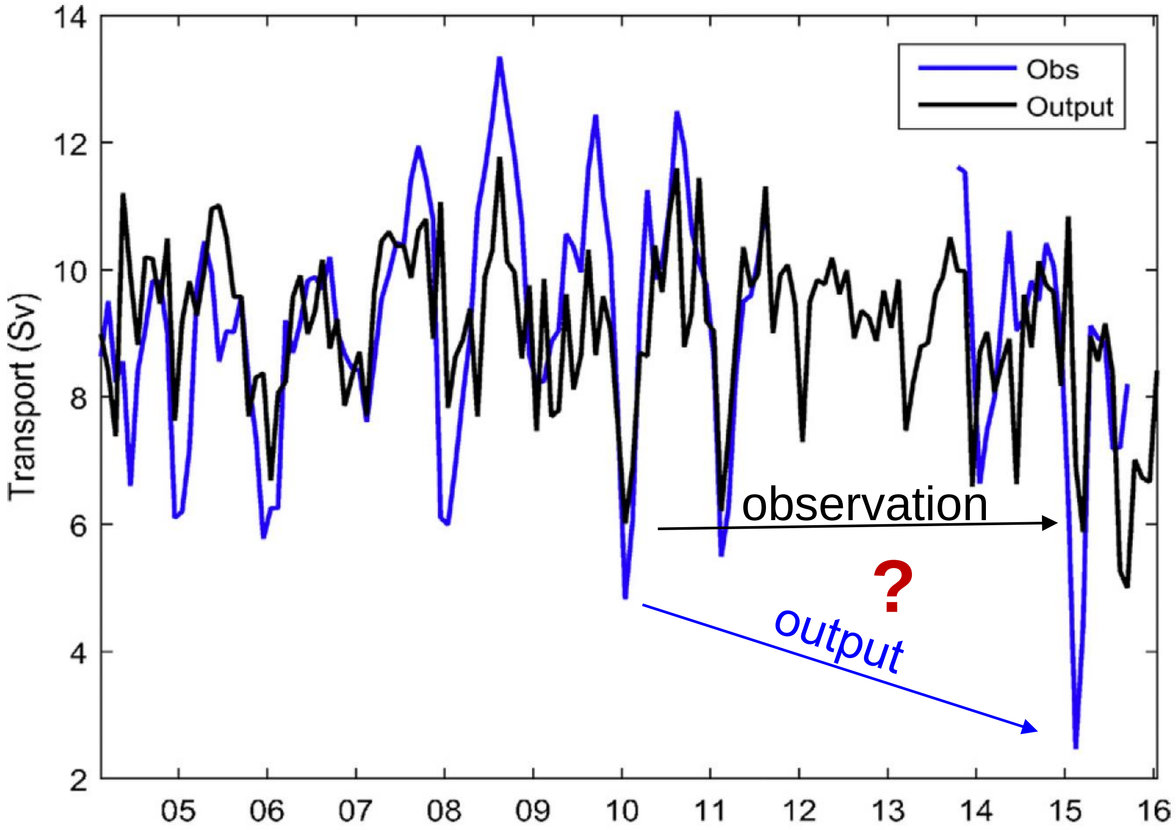
- NWP: 6-16N, 125-155E
- EEIO: 5S-5N, 65-95E
- SEI: 6-16S, 85-115E

■ Overall decrease of ITF during 1948-2016? (Li et al., 2018)



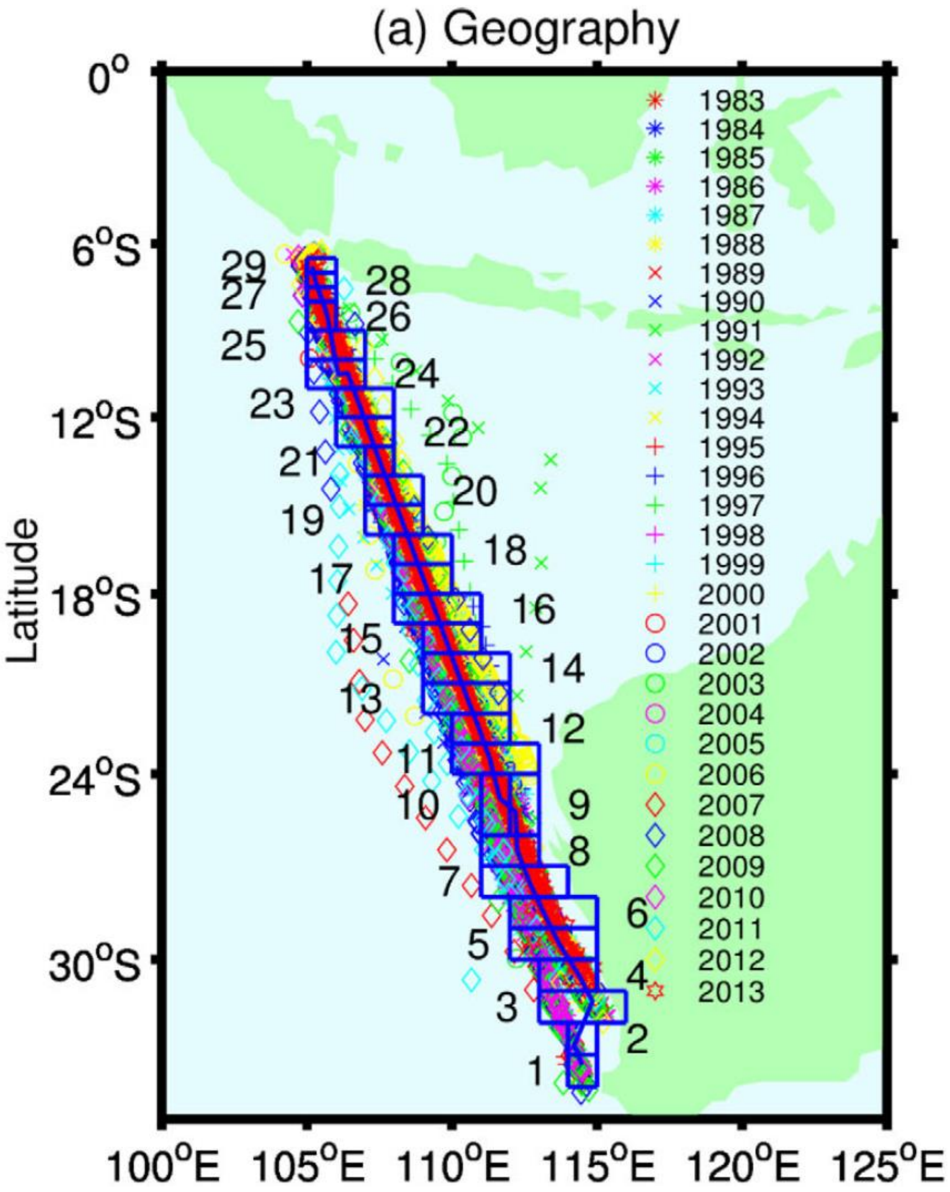
Data: NCEP wind stress & MITF
Method: back-propagation neural network; 2004-2011 for training the network; 2013-2015 for validation
Result: **decrease during 1948-1995; increase during 1995-2013; decrease 2013-2016**

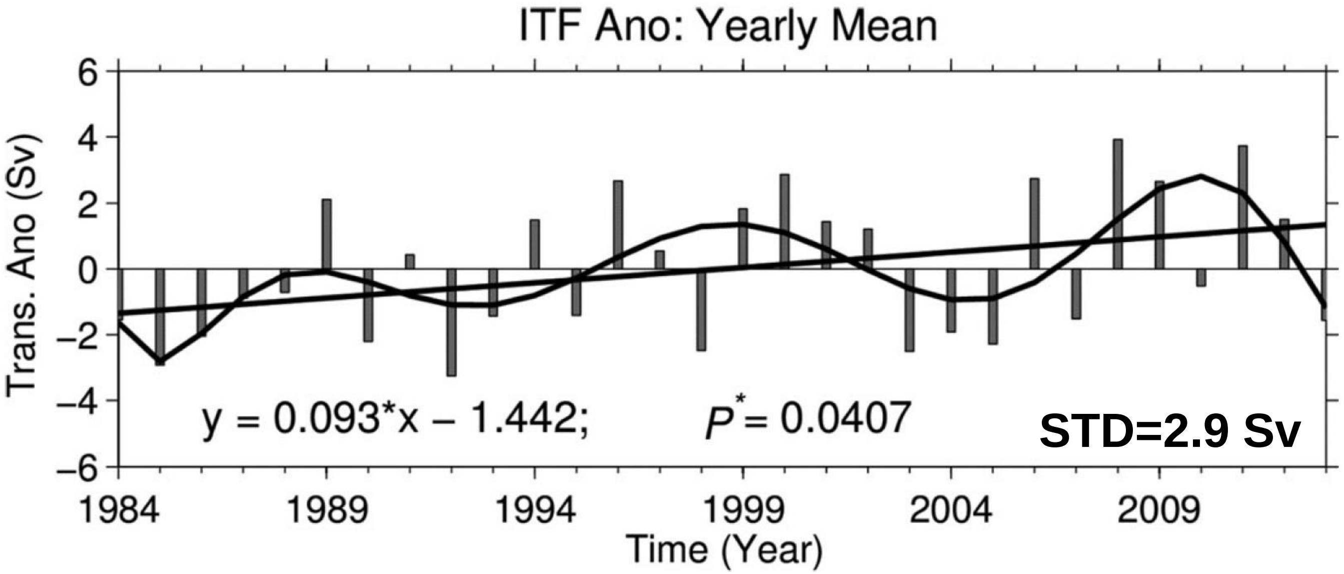


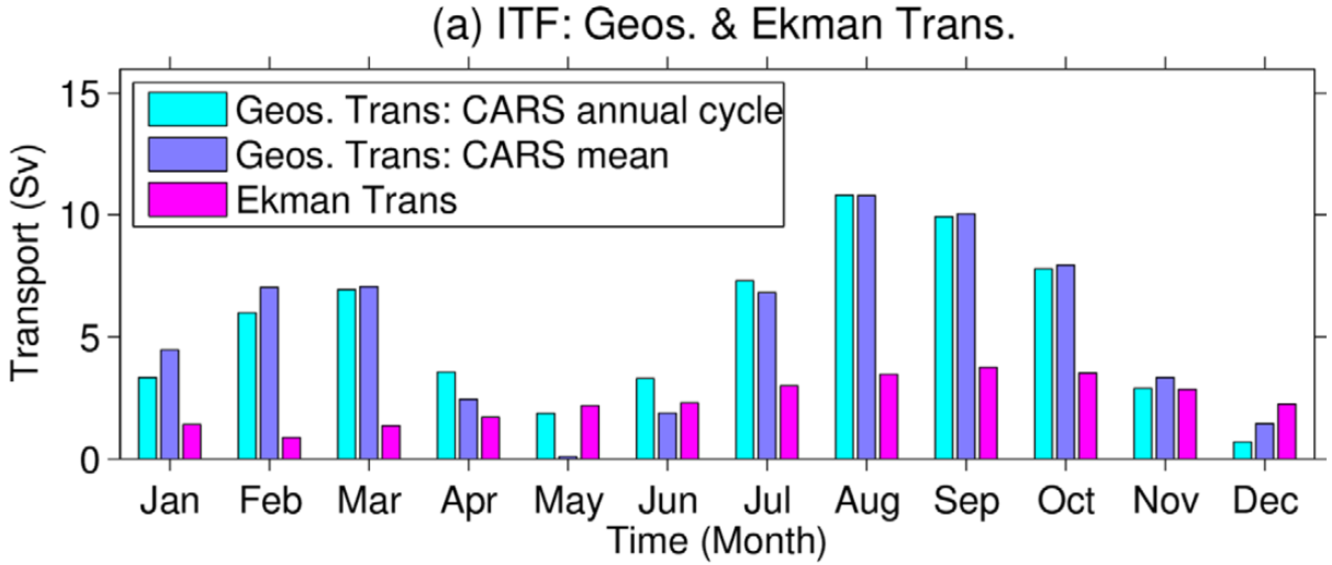


- ITF transport based on 30 year IX1 XBT data **(Liu et al., 2015)**
- **Increasing trend of ~ 1 Sv decade^{-1} during 1984-2013, STD=2.9 Sv**

Observation-based results







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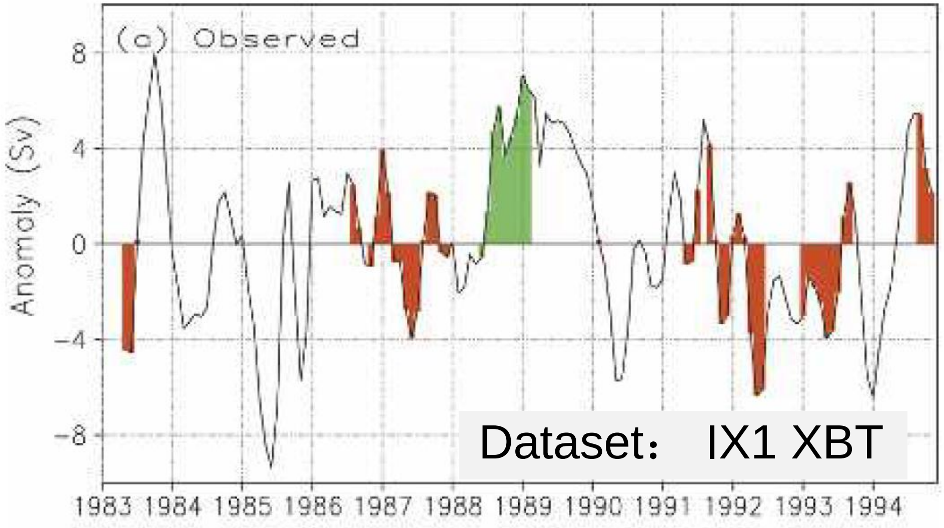
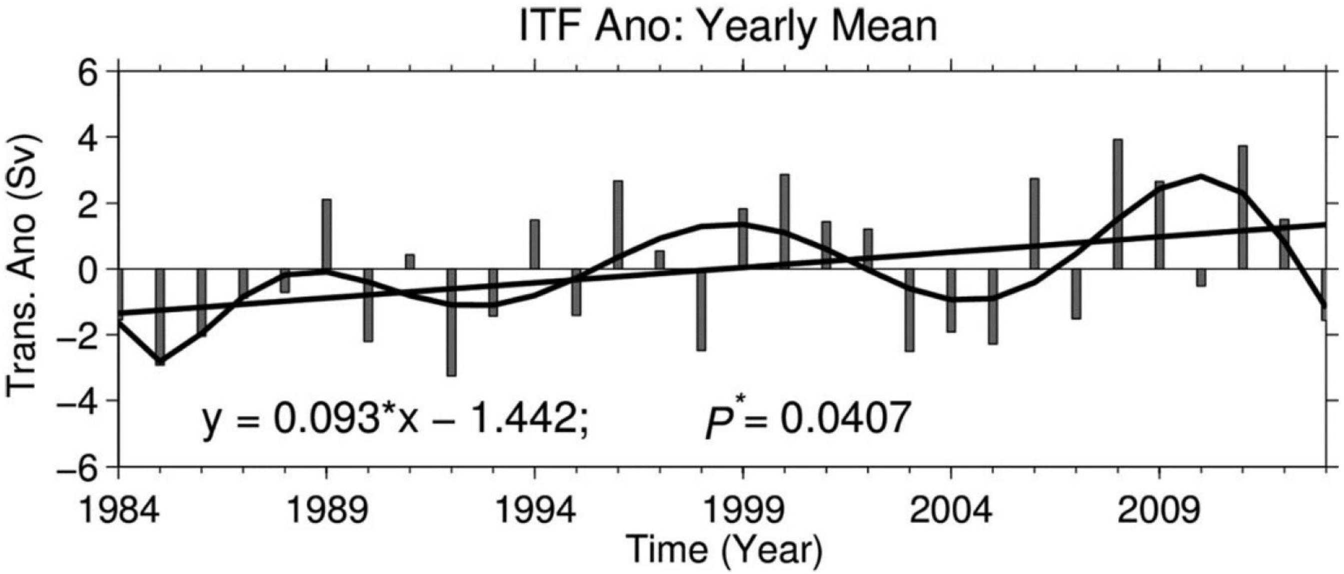
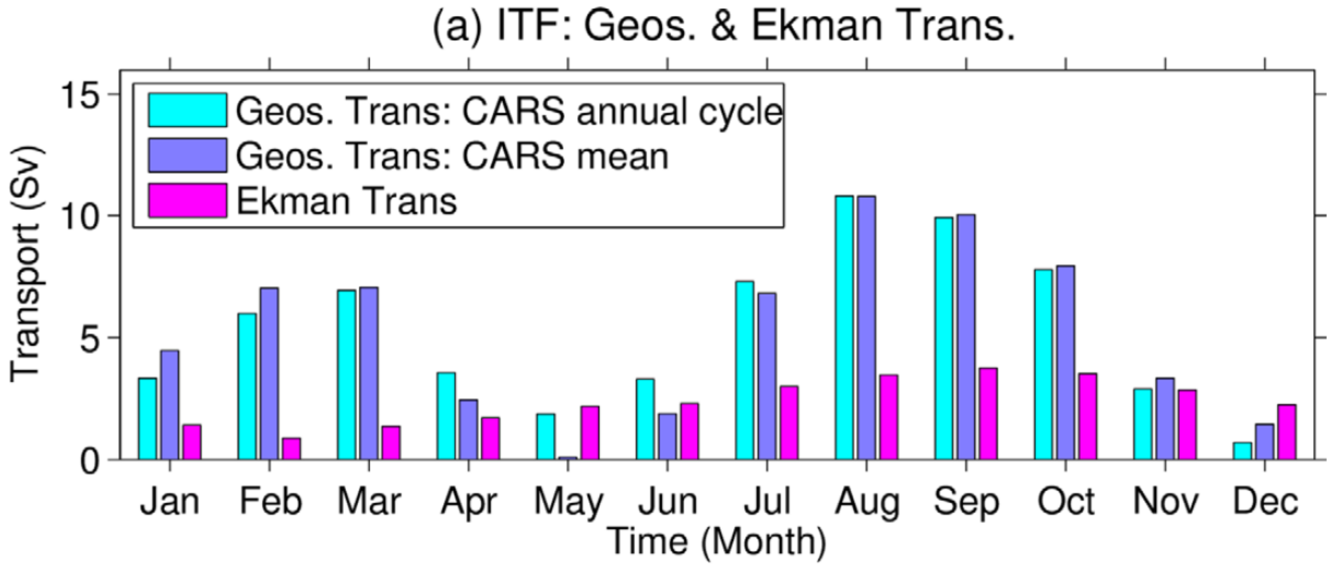


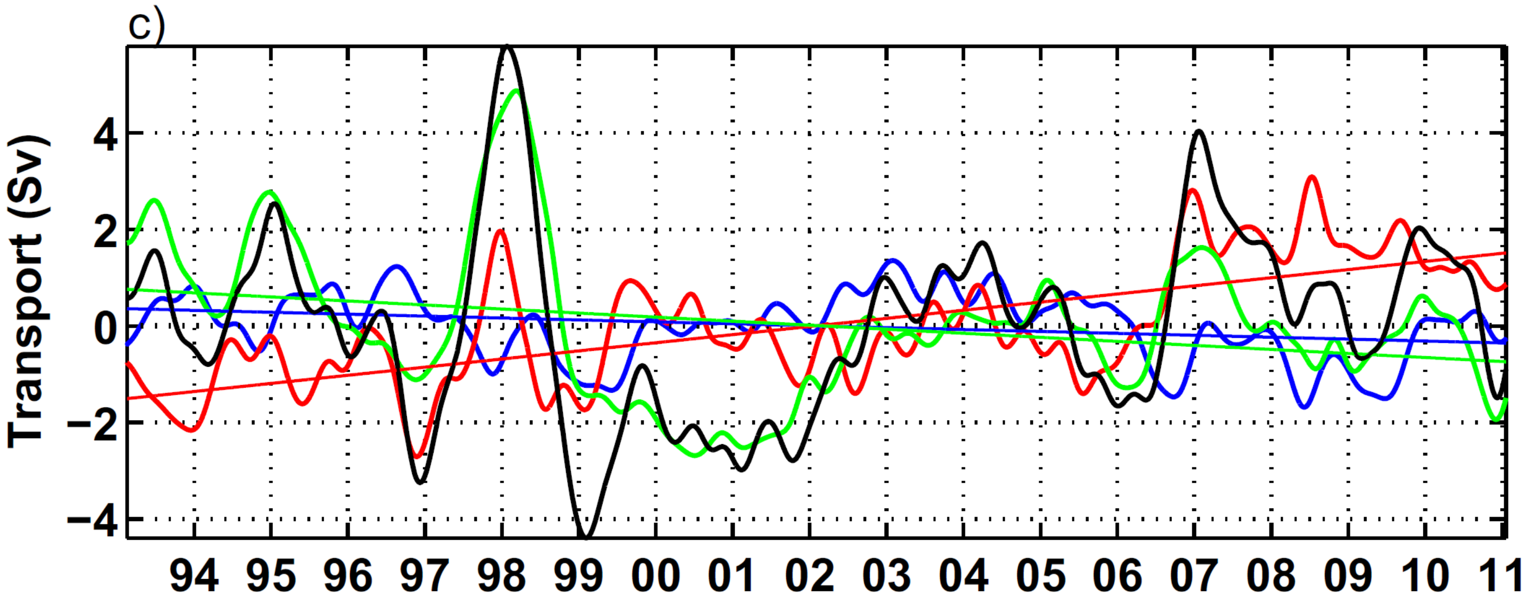
Meyers, 1996

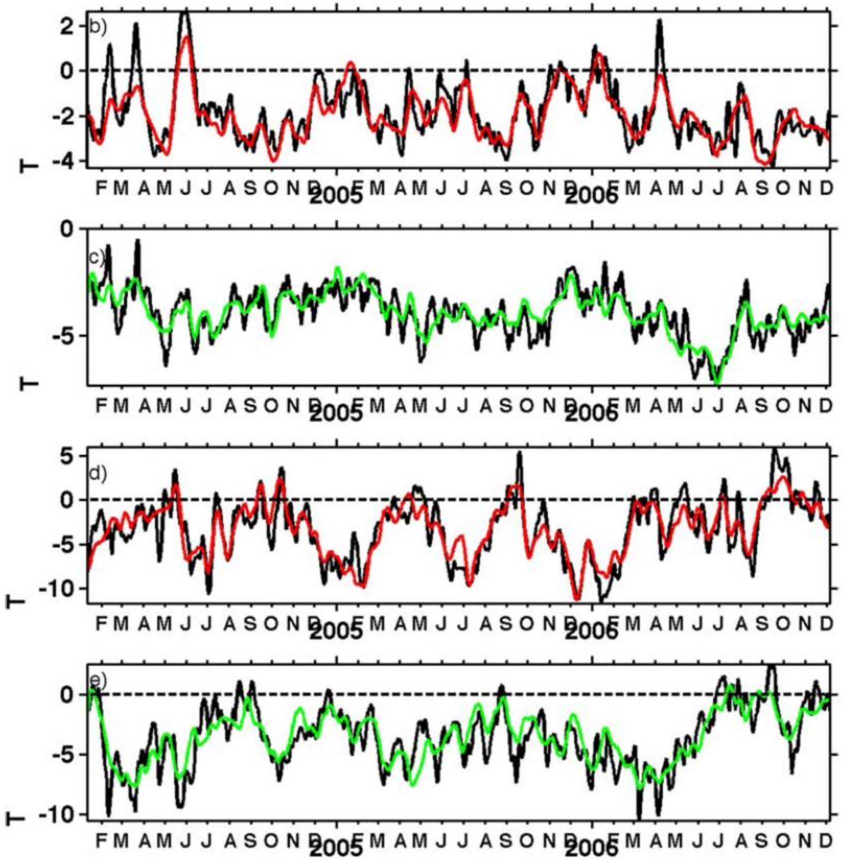




■ ITF transport since the satellite era begins

Observation-based results





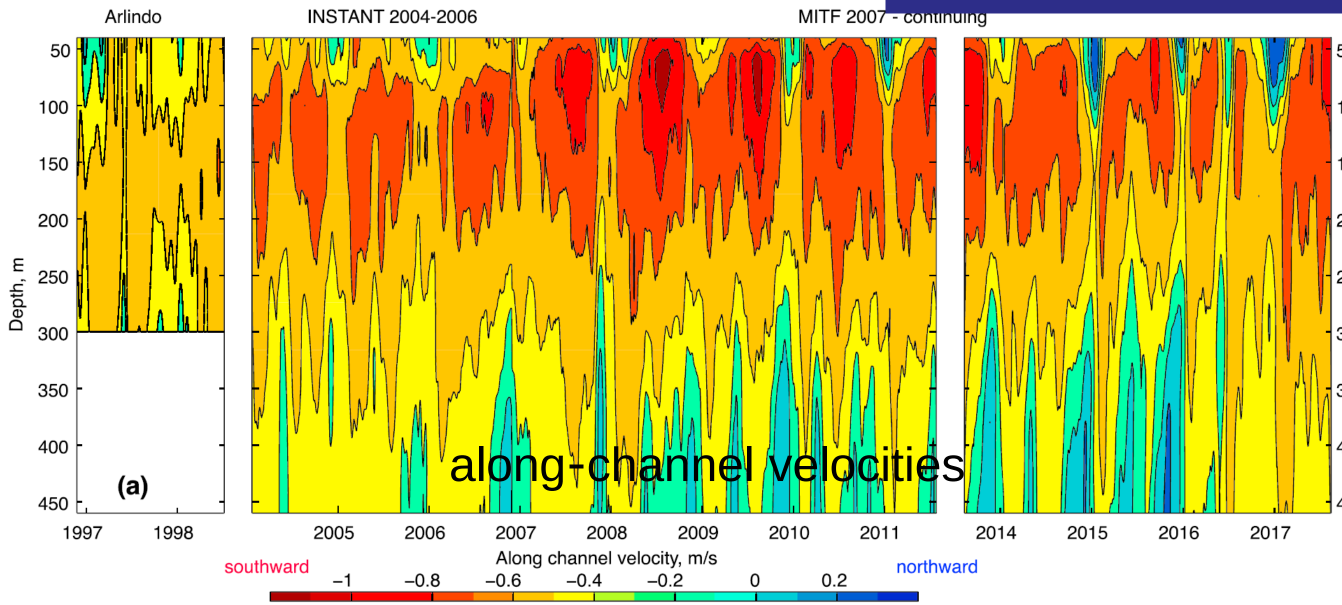
- ✓ Significant increase of 0.6 Sv in both the **upper layer of Lombok Strait and Timor Passage**, and in the **lower layer of Timor Passage** (0.77 Sv), due to enhanced trade wind
- ✓ Decrease of transport in both the upper and lower layers of **Ombai Strait** of 0.5 Sv and 2.5 Sv
- ✓ **Overall small decrease of 0.5 Sv in total ITF transport through all three passages over 1992-2011 (Sprintall and Révelard, 2014)**

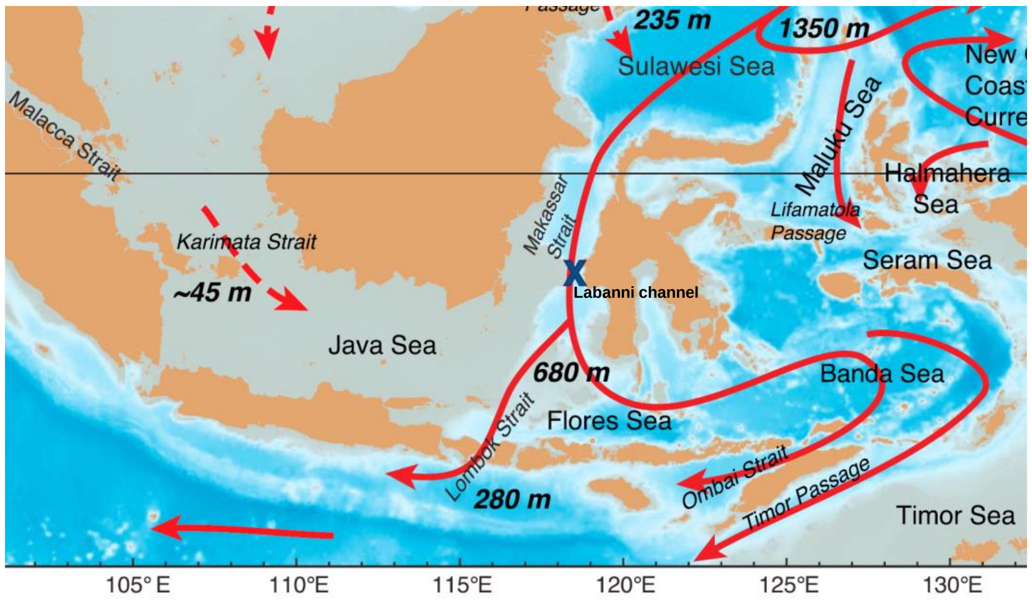
A proxy 18 year ITF transport time series is developed, with focus on the three outflow passages of Lombok, Ombai, and Timor (Sprintall and Révelard, 2014)

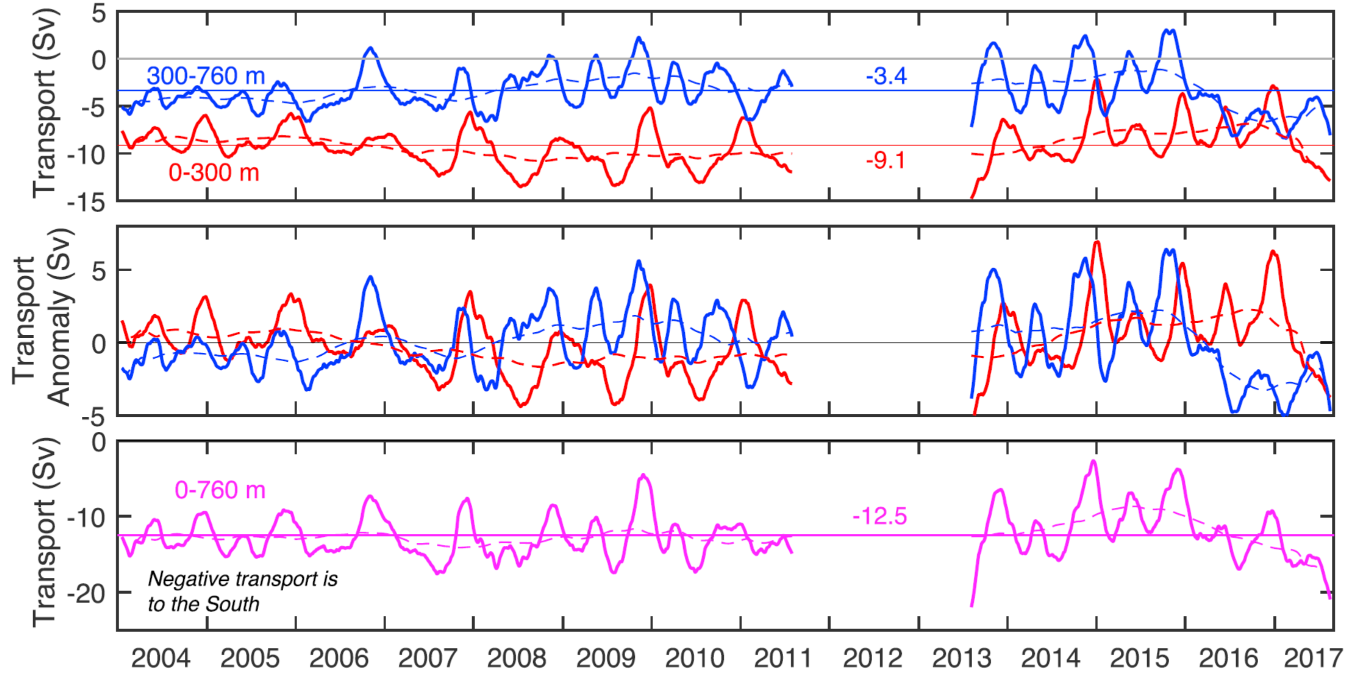
■ Makassar Strait Throughflow (MST): a major component (~78%) of ITF

Observation-based results

- ✓ Stronger southward transport and shallower velocity maximum: boreal summer & La Niña, than winter & El Niño
- ✓ Makassar Strait Throughflow decreased during the 2015 El Niño to ~10 Sv, increasing to ~20 Sv during the 2017 La Niña
- ✓ **Overall increasing in MST during 2004-2013, decrease over 2013-2015, and increase after 2016**







Gordon et al., 2019

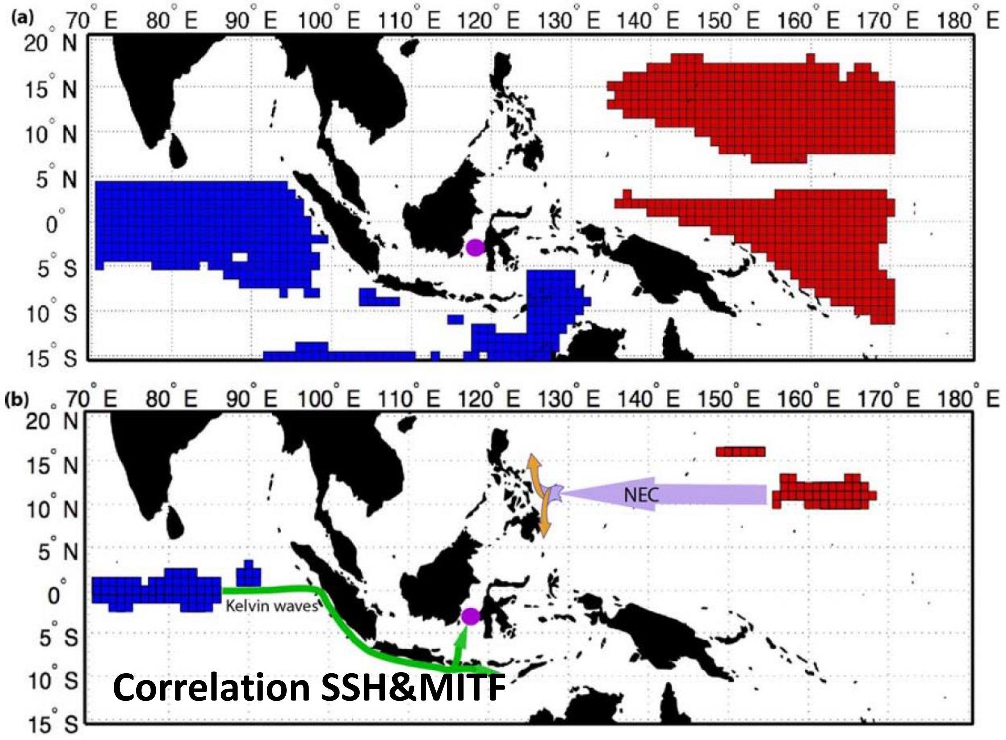
■ ITF transport since the satellite era begins

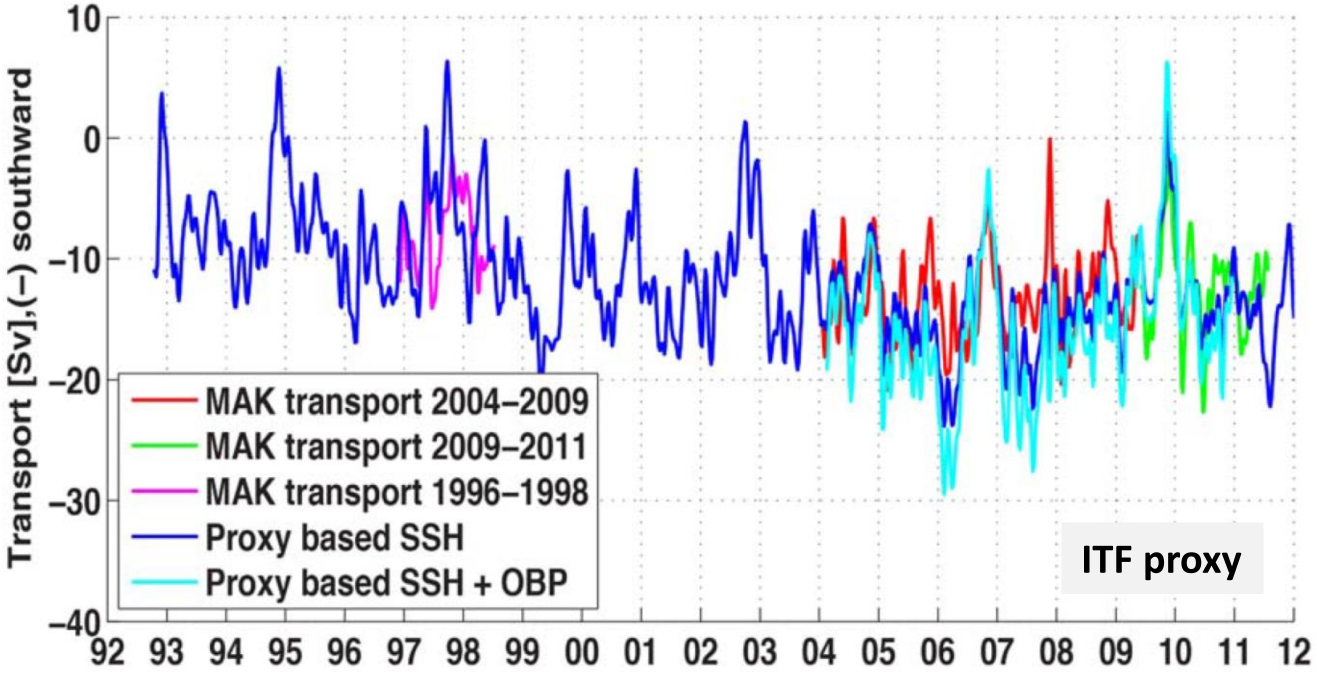
Observation-based results

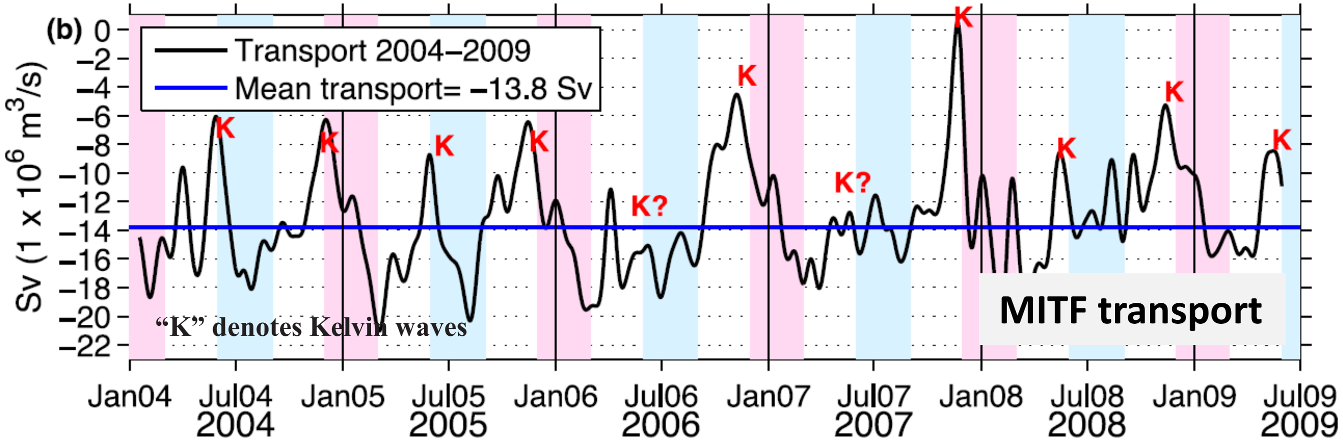
Data: AVISO SSH & GRACE OBP
Method: ITF proxy
Result: Overall increasing trend during 1992-2012

Susanto and Song, 2015

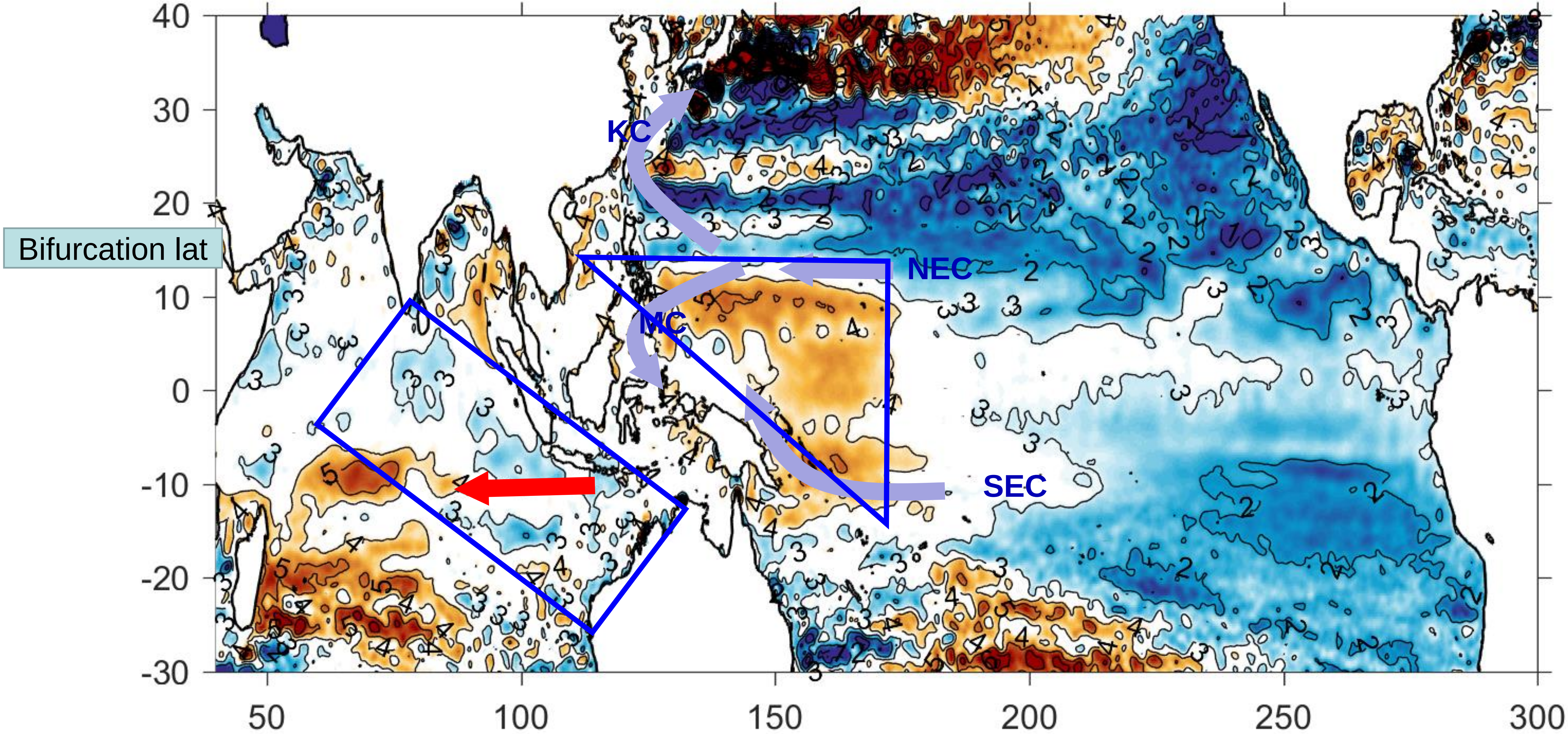
$$Q = \frac{r_1 g}{\lambda + r_1 f} H_1 \Delta\eta + \frac{r_2 g}{\lambda + r_2 f} H_2 (\Delta p_b - \Delta\eta)$$





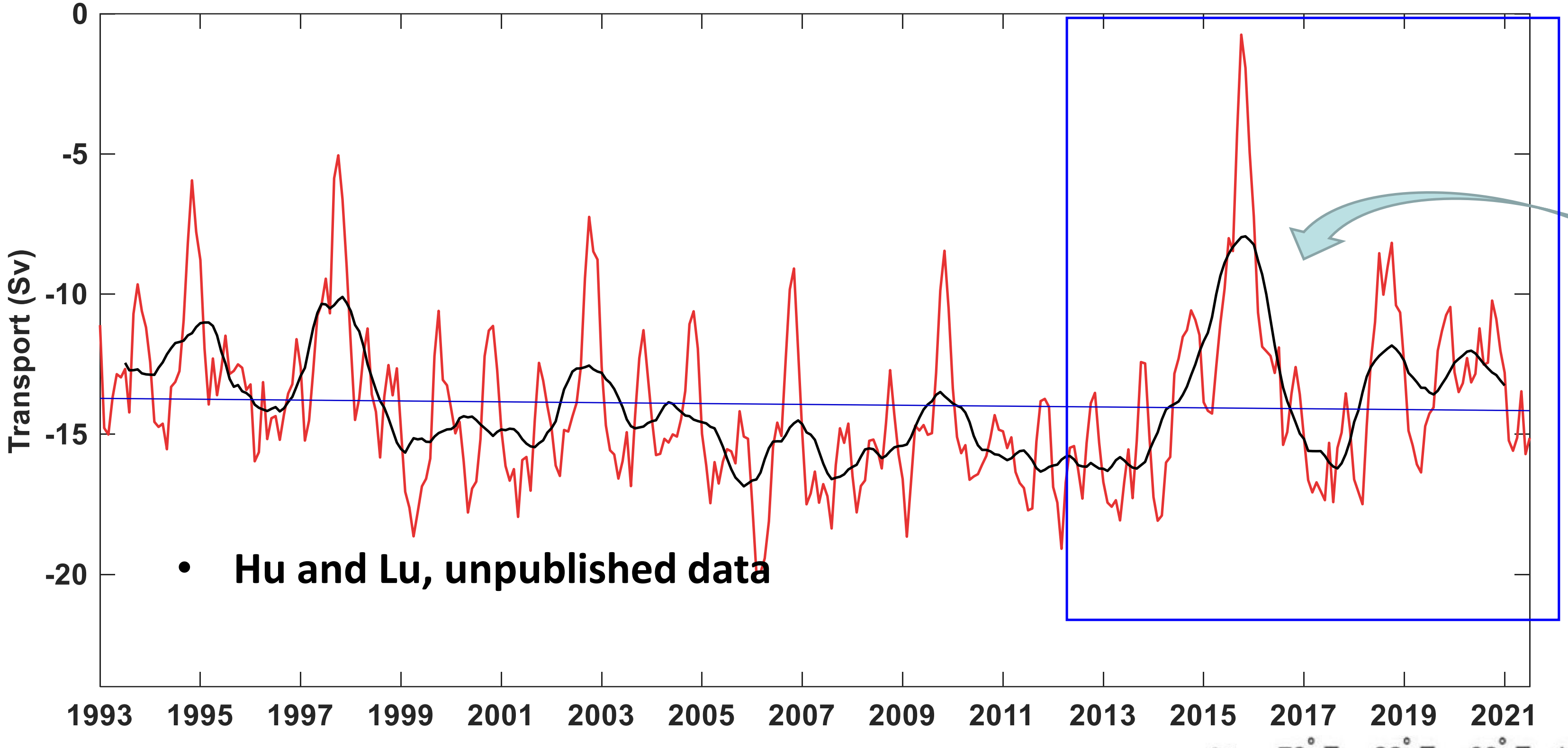


■ How about up to date changes in ITF?

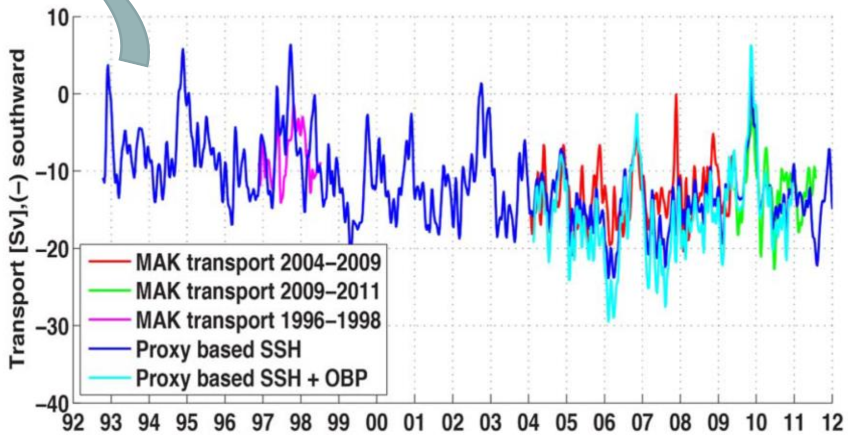


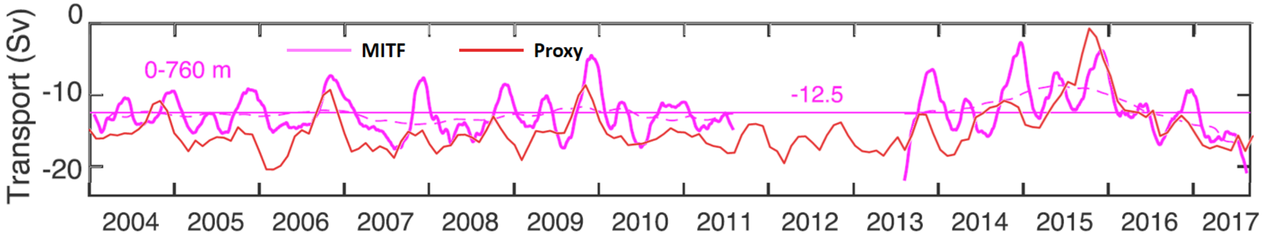
■ **Linear trend of SLA during 1993-2021, cm decade^{-1}**

■ Updated ITF proxy 1993-2021 (AVISO SSH)

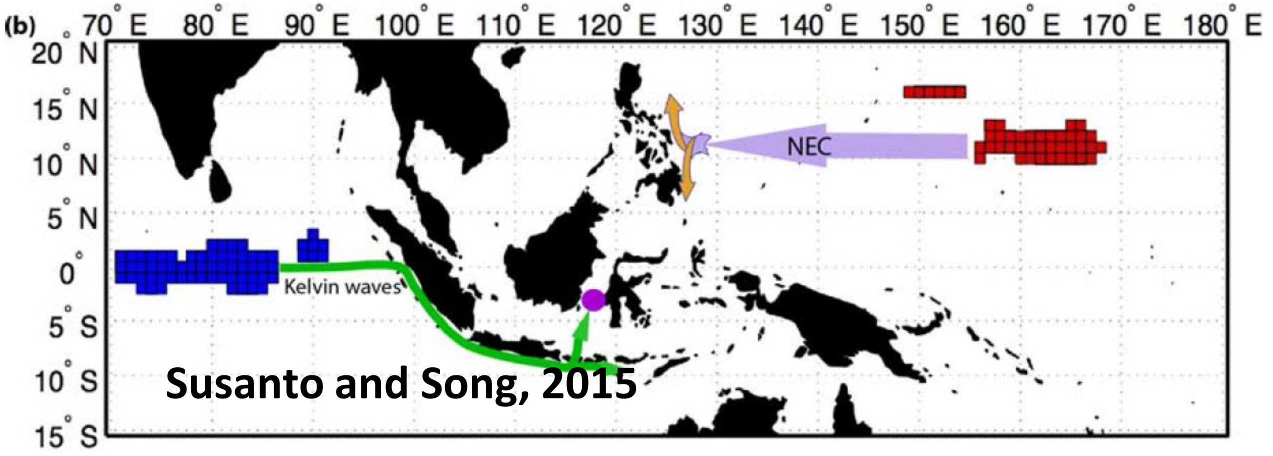


STD=2.9 Sv
$STD_{decadal}$=0.8 Sv
Trend(1993-2012)=-1.9 Sv decade^{-1}
Trend(1993-2021)=-0.2 Sv decade^{-1}



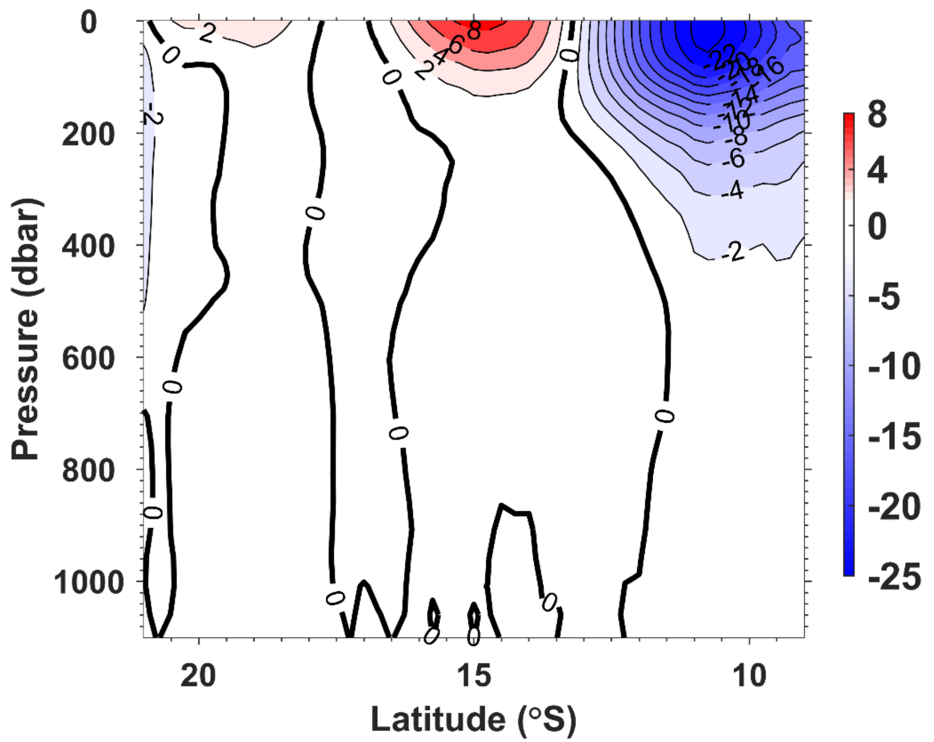


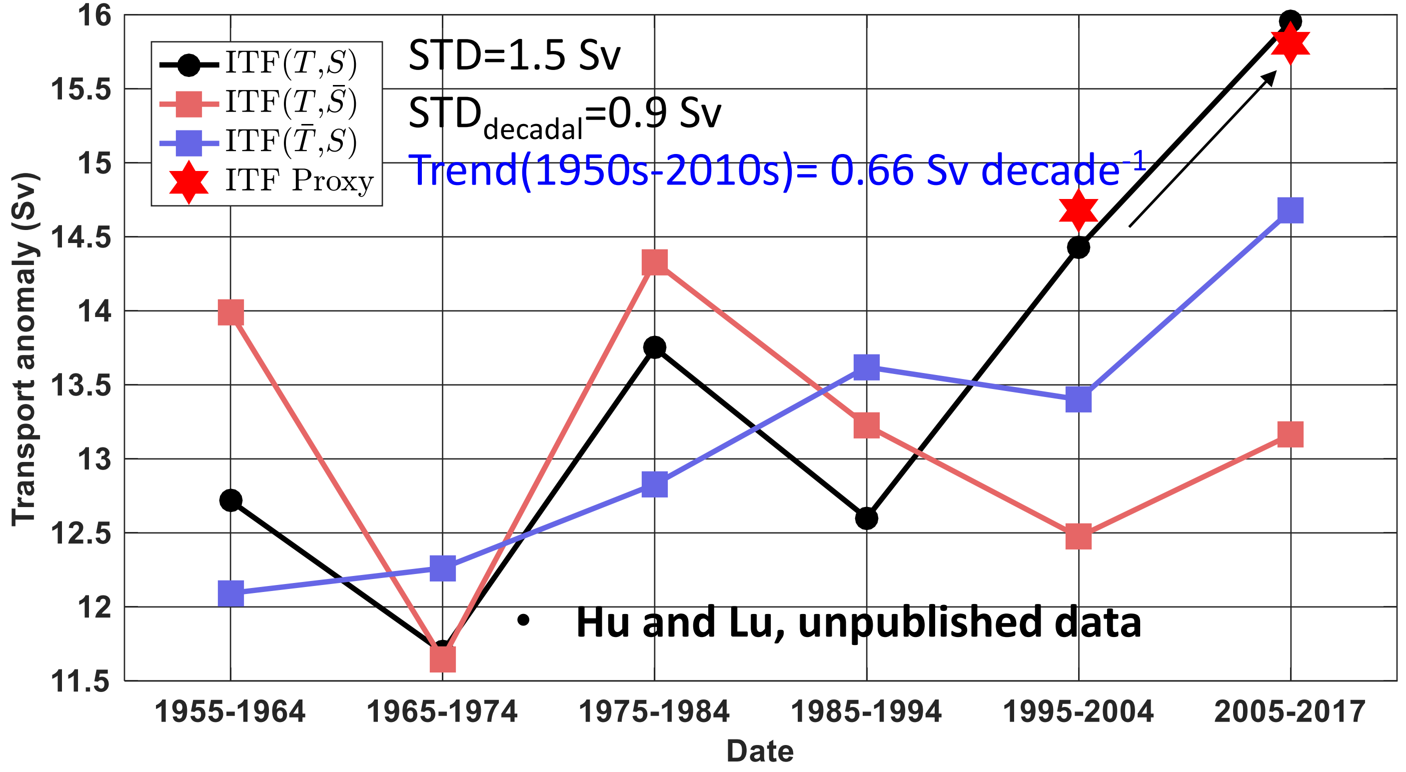
The ITF proxy matches the observed MITF data

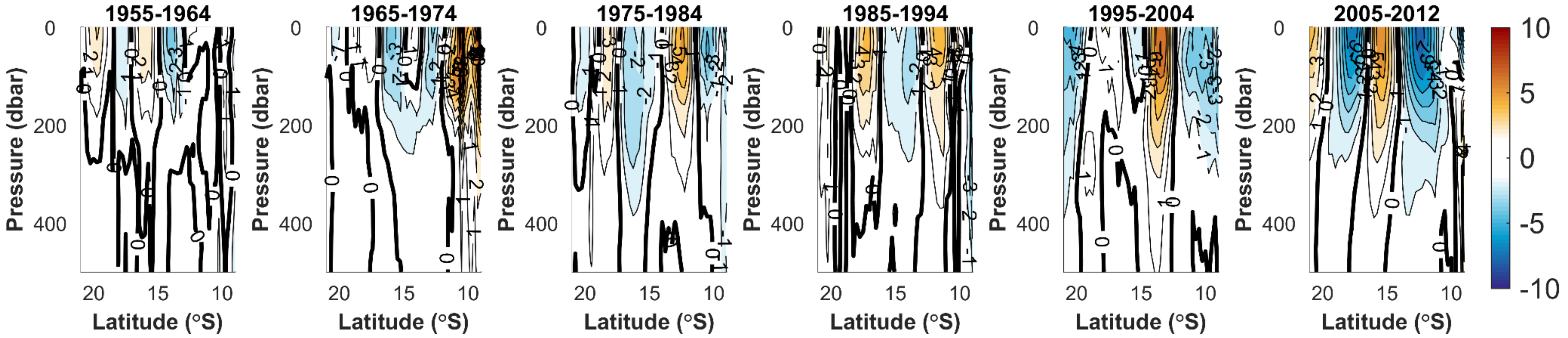


■ ITF transport at 114° E: WOA2013

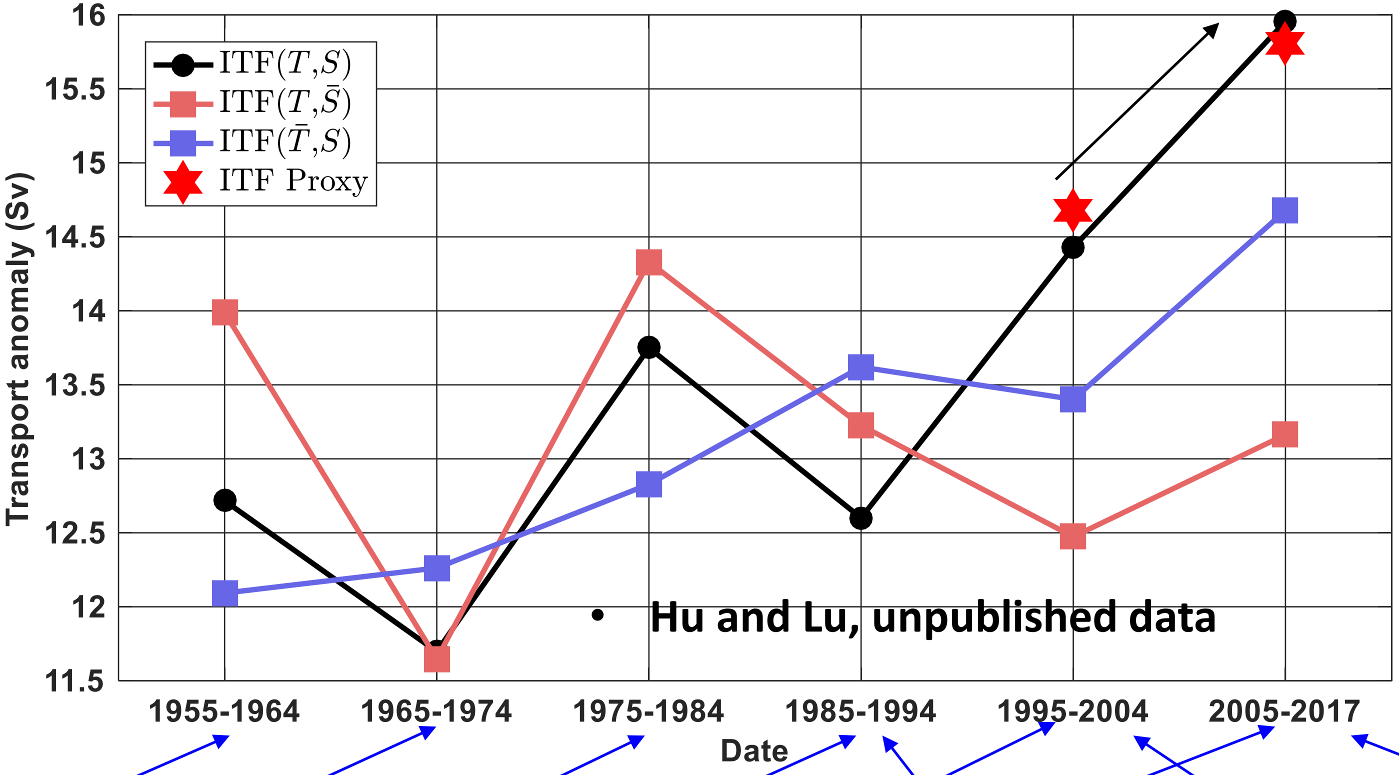
- Hu and Lu, unpublished data







■ **ITF transport** (geostrophic component) **at 114° E: WOA2013**



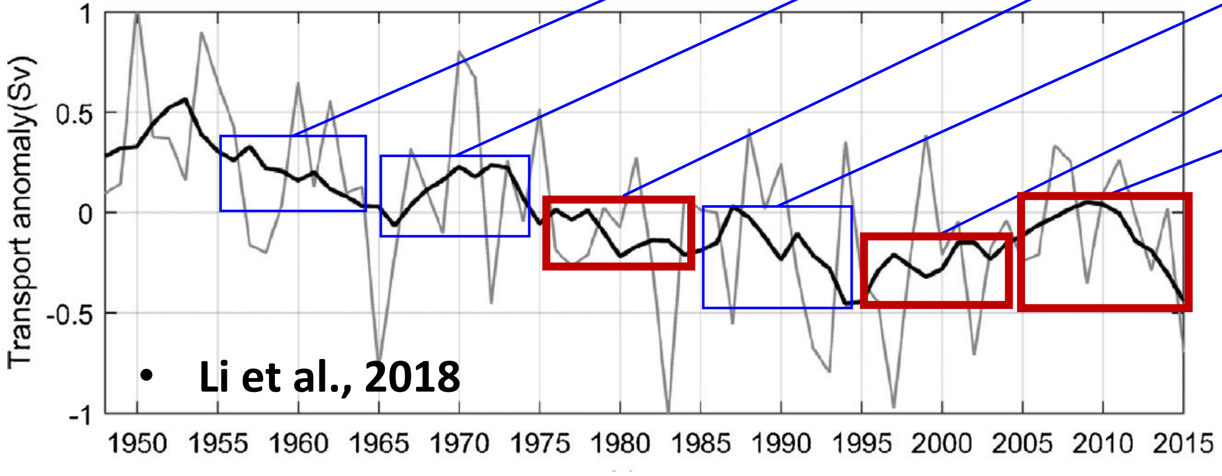
STD=1.5 Sv

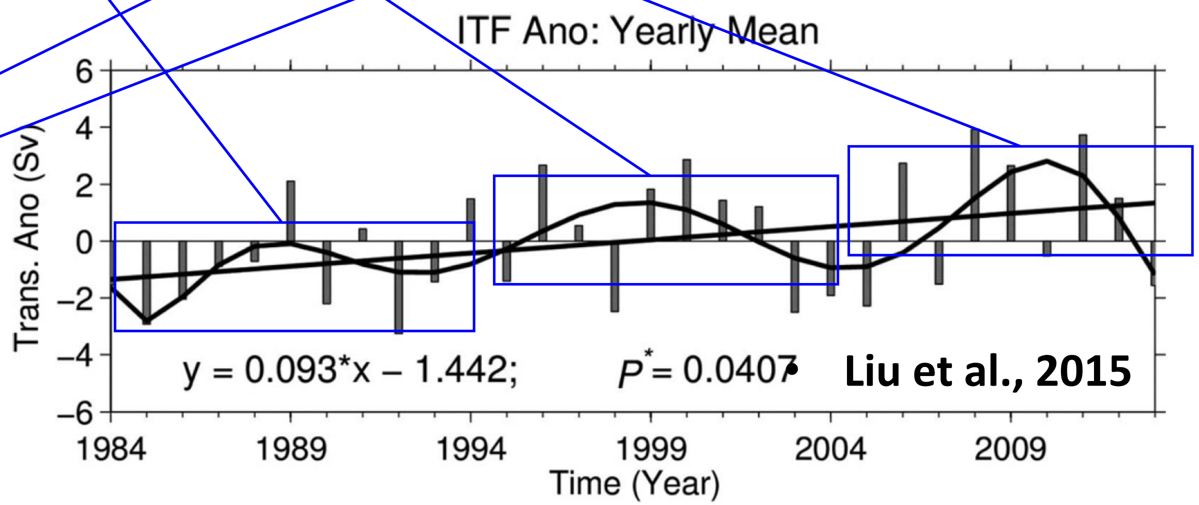
$STD_{decadal}$=0.9 Sv

Trend= 0.66 Sv decade^{-1}

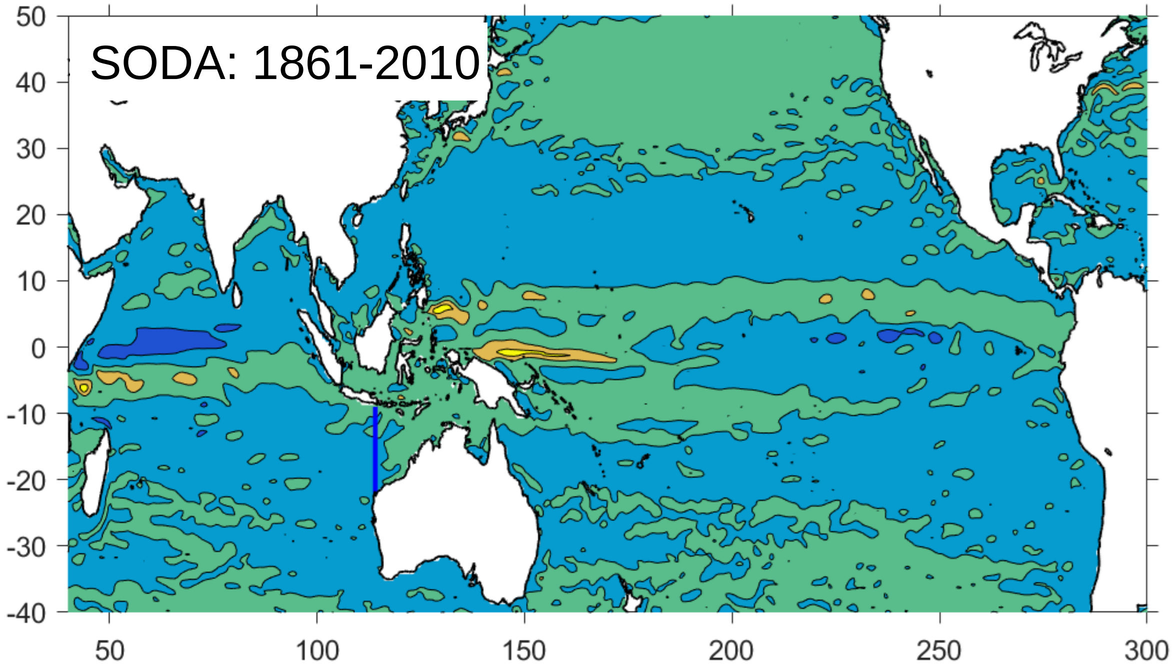
Minimum：1965-1974；1985-1994

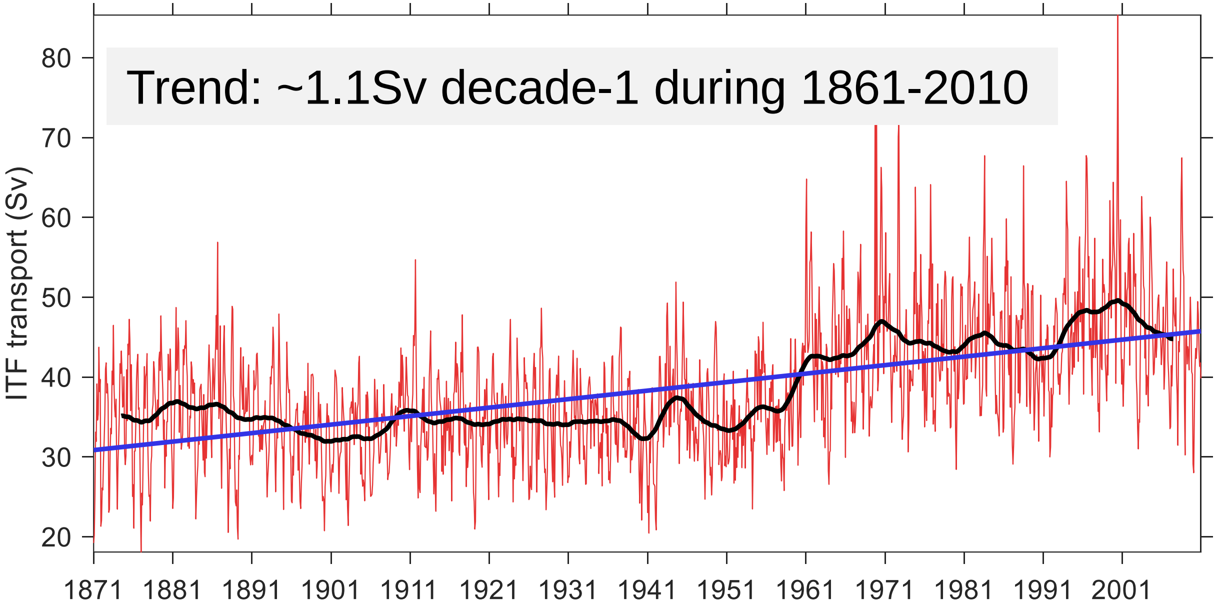
Maximum：1955-1964；1975-1984；2005-2017

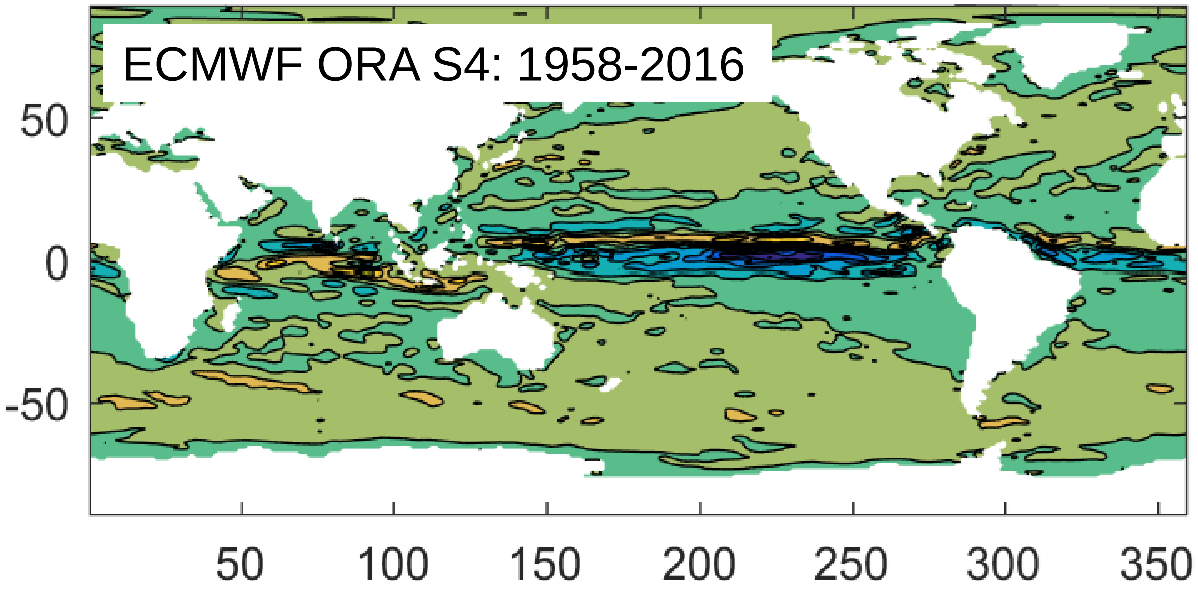


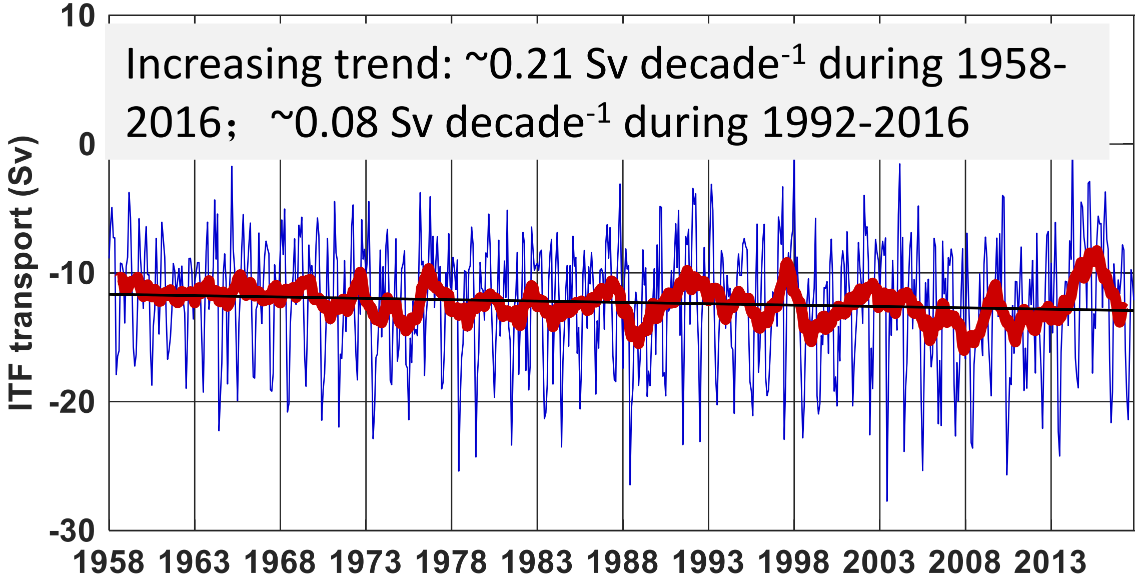


■ **Reanalysis**: depends on data products







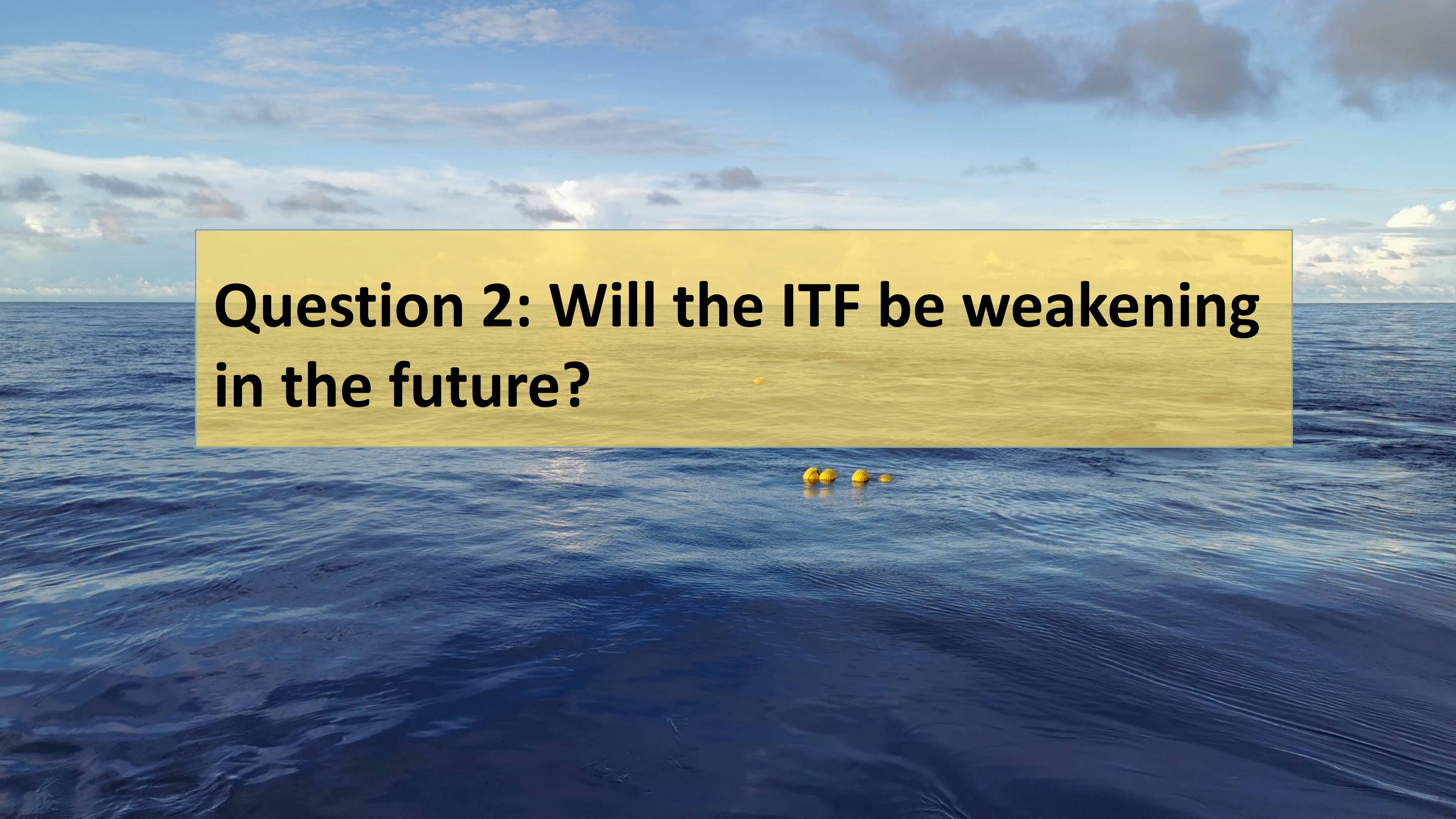


2. Is there a robust trend in ITF during the past decades?

- A robust increasing trend in ITF transport during since 1990s when many observations are available; the trend during 1992-2021 is much weaker than that during 1992-2012 and weaker than decadal variation
- The ITF transport over a longer period (e.g., since 1950s) is likely increasing, but may need more evidence

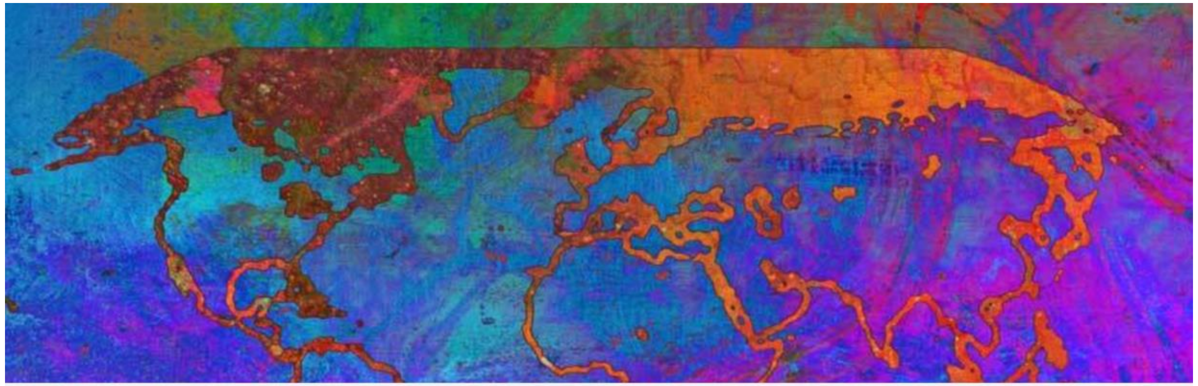
Table. Multi-decadal trends in ITF transport: past decades

Period	Trend (positive for strengthening of ITF)	Date sets	References
1959-2015	• Increasing of ITF	ECMWF ORA S4	Shilimkar et al., 2022
1992-2011	• Increase in transport through Timor+Lombok • decrease of total ITF, -0.28 Sv decade^{-1}	Proxy based on AVISO SLA	Sprintall and Révelard, 2014
1984-2013	• Increasing of total ITF • 1.12 Sv decade^{-1}	IX1 XBT,	Liu et al., 2015
1992-2012	• Significant increase of ITF	AVISO SSH & GRACE OBP	Susanto and Song, 2015
1970-2010	• Slight decrease: -0.4 Sv decade^{-1}	Proxy using reanalysis	Hu and Sprintall, 2017
1993-2021	Increase in 1992-2012, 2.0 Sv decade^{-1} **Increase in 1992-2021, 0.2 Sv decade^{-1}**	AVISO SLA & GRACE OBP	Hu & Lu, unpublished data
1950s-2010s	**Increase of ITF, 0.66 Sv decade^{-1}**	WOA2013	Hu & Lu, unpublished data



Question 2: Will the ITF be weakening in the future?

3. Will the ITF be weakening in the future?

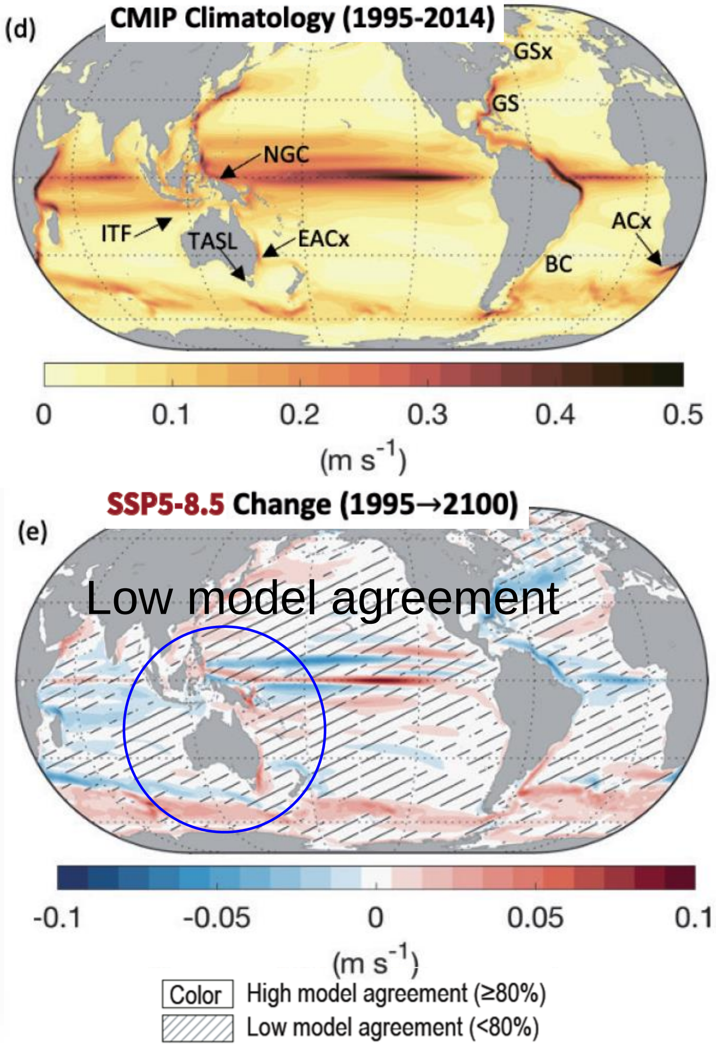


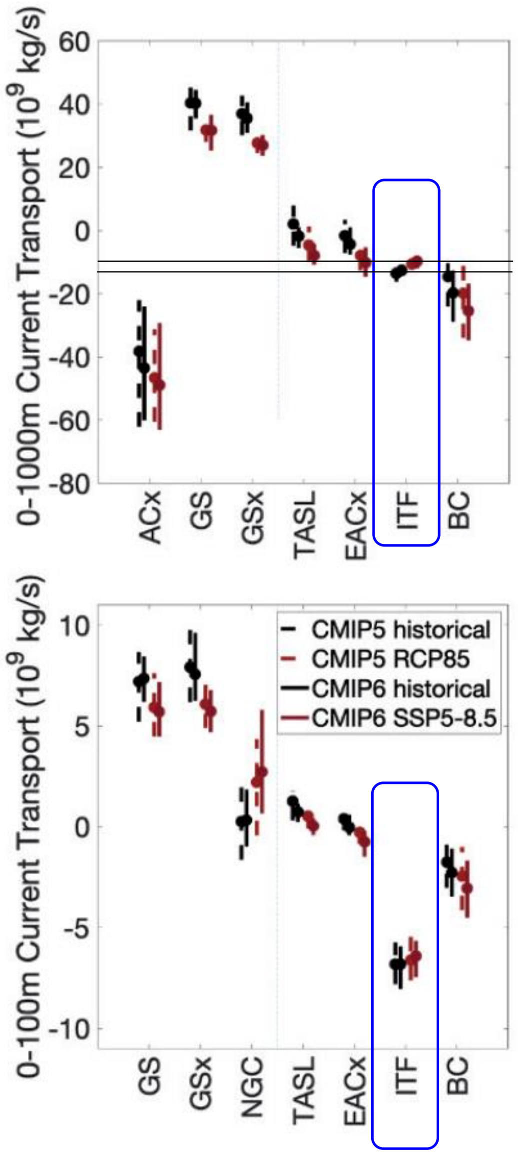
Climate Change 2021: The Physical Science Basis

There is *high confidence* that many ocean currents will change in the 21st century in response to changes in wind stress. There is *low confidence* in 21st century change of Southern Ocean circulation, despite *high confidence* that it is sensitive to changes in wind patterns and increased ice-shelf melt. Western boundary currents and subtropical gyres have shifted poleward since 1993 (*medium confidence*). Subtropical gyres, the East Australian Current Extension, the Agulhas Current, and the Brazil Current are projected to intensify in the 21st century in response to changes in wind stress, while the Gulf Stream and the Indonesian Throughflow are projected to weaken (*medium confidence*). All of the four main eastern boundary upwelling systems are projected to weaken at low latitudes and intensify at high latitudes in the 21st century (*high confidence*). {2.3.3, 9.2.3}

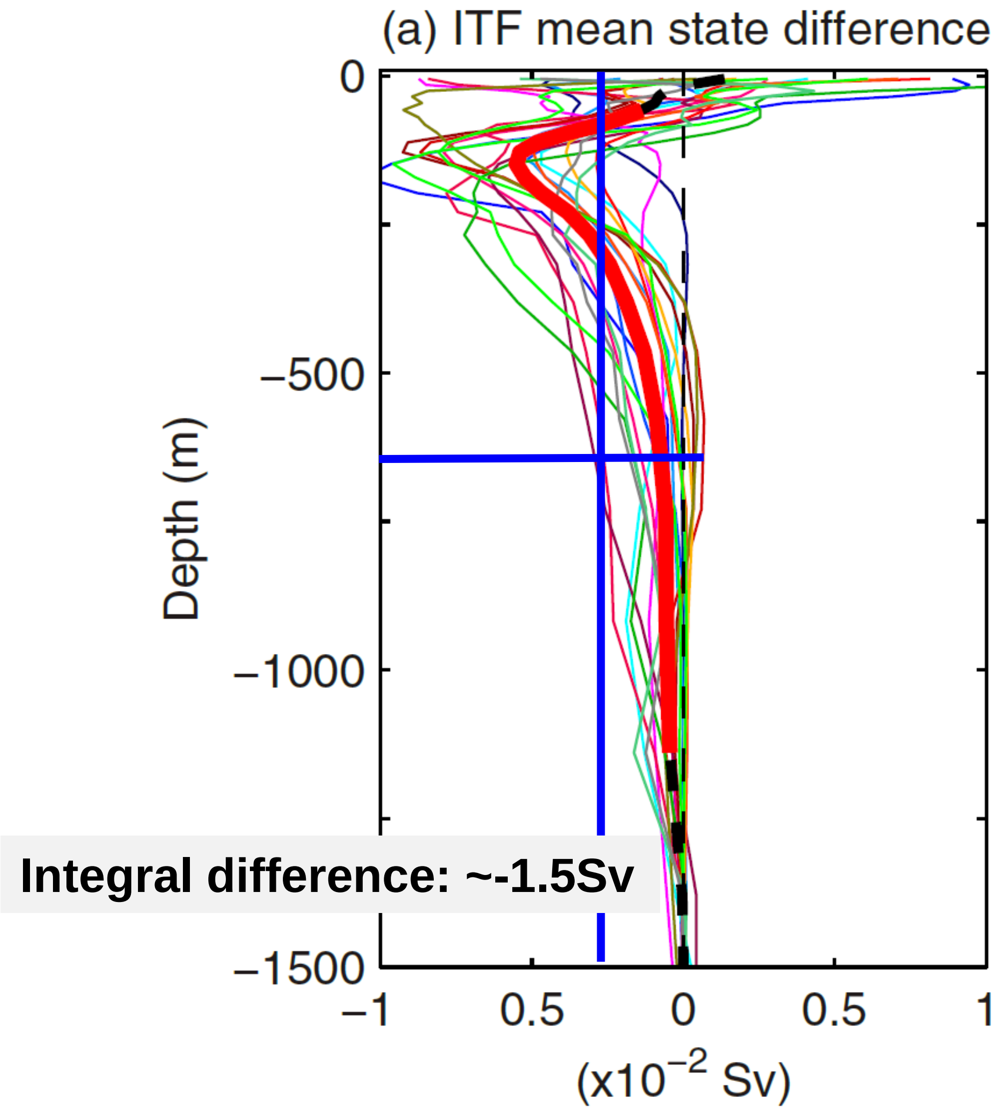
IPCC AR6

Surface speed (0-100 m)

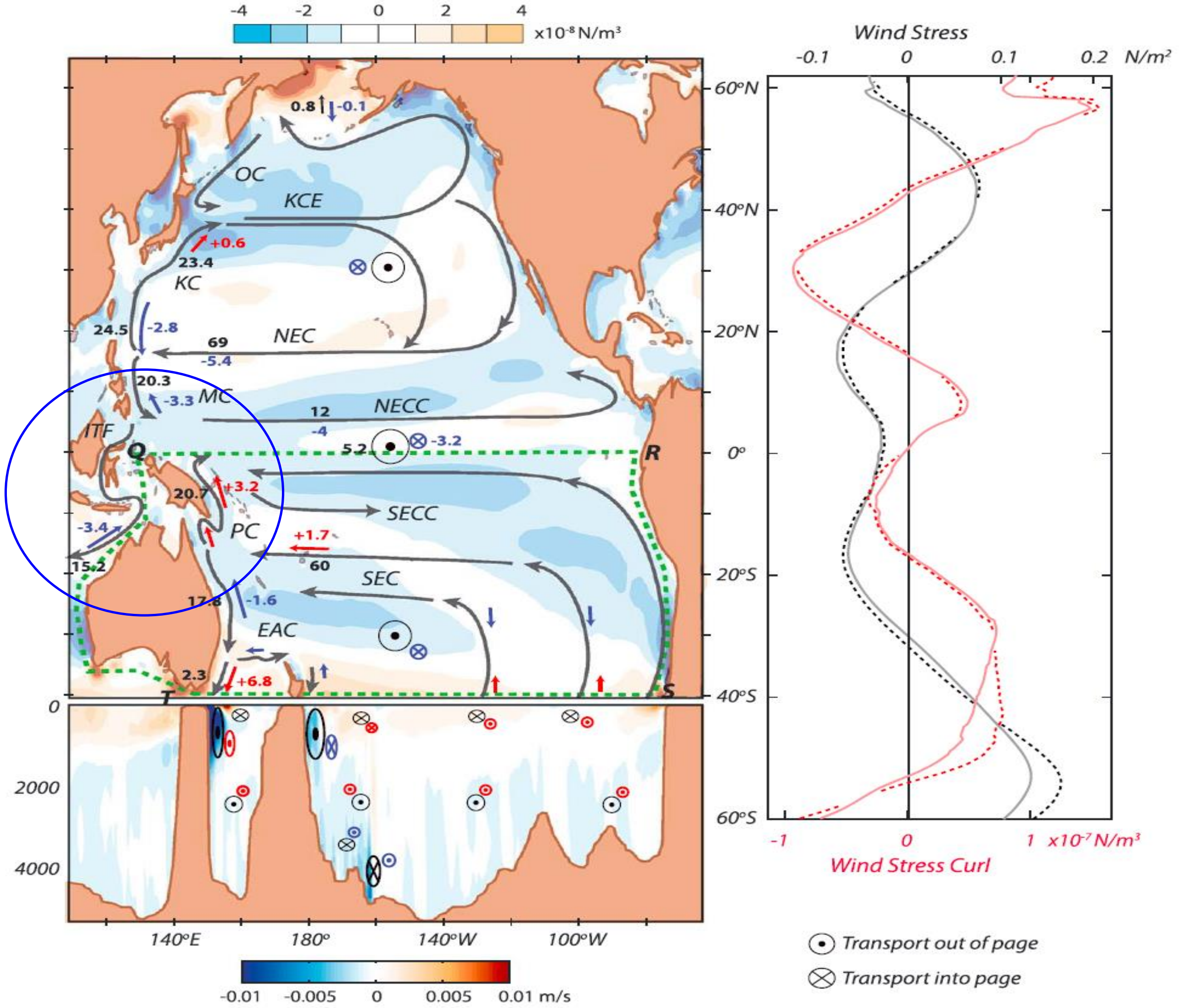




■ Future projection of ITF transport



Future change: future (2006-98; RCP4.5) minus historical (1907–99) periods (**Santoso et al., 2022**)

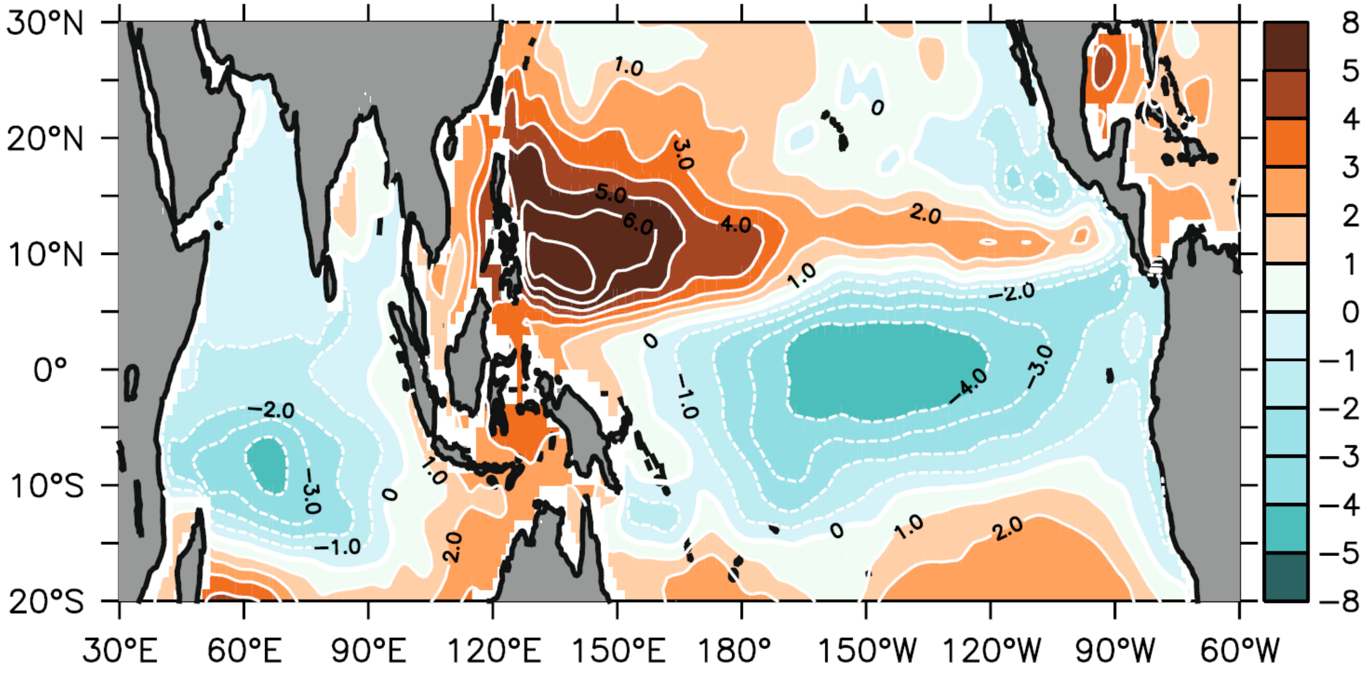


Future change: 2050–2100 from **RCP8.5** relative to 1900–2000 from the historical simulations, **a decrease of 3.4 Sv** in ITF, i.e., -0.36 Sv decade^{-1} (**Sen Gupta et al., 2016**)

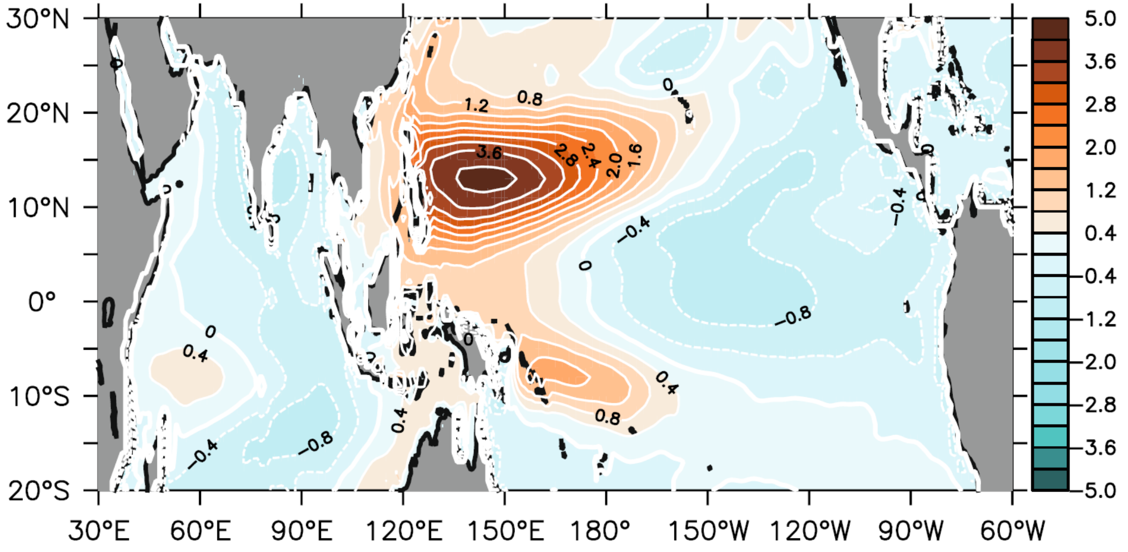
■ CMIP model biases

- Decadal changes in SSHAs over the NWP region in the CMIP5 simulations are significantly underestimated, which may lead to a weaker ITF (Shilimkar et al., 2022)

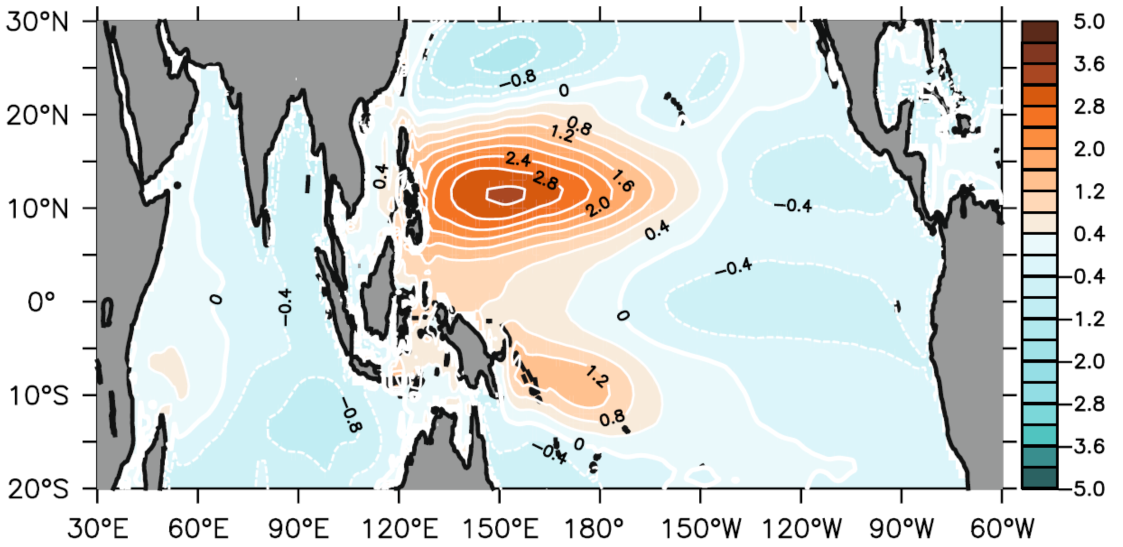
Decadal variance of SSH: Observation



Decadal variance of SSH: CMIP5 HIST



Decadal variance of SSH: CMIP5 RCP8.5



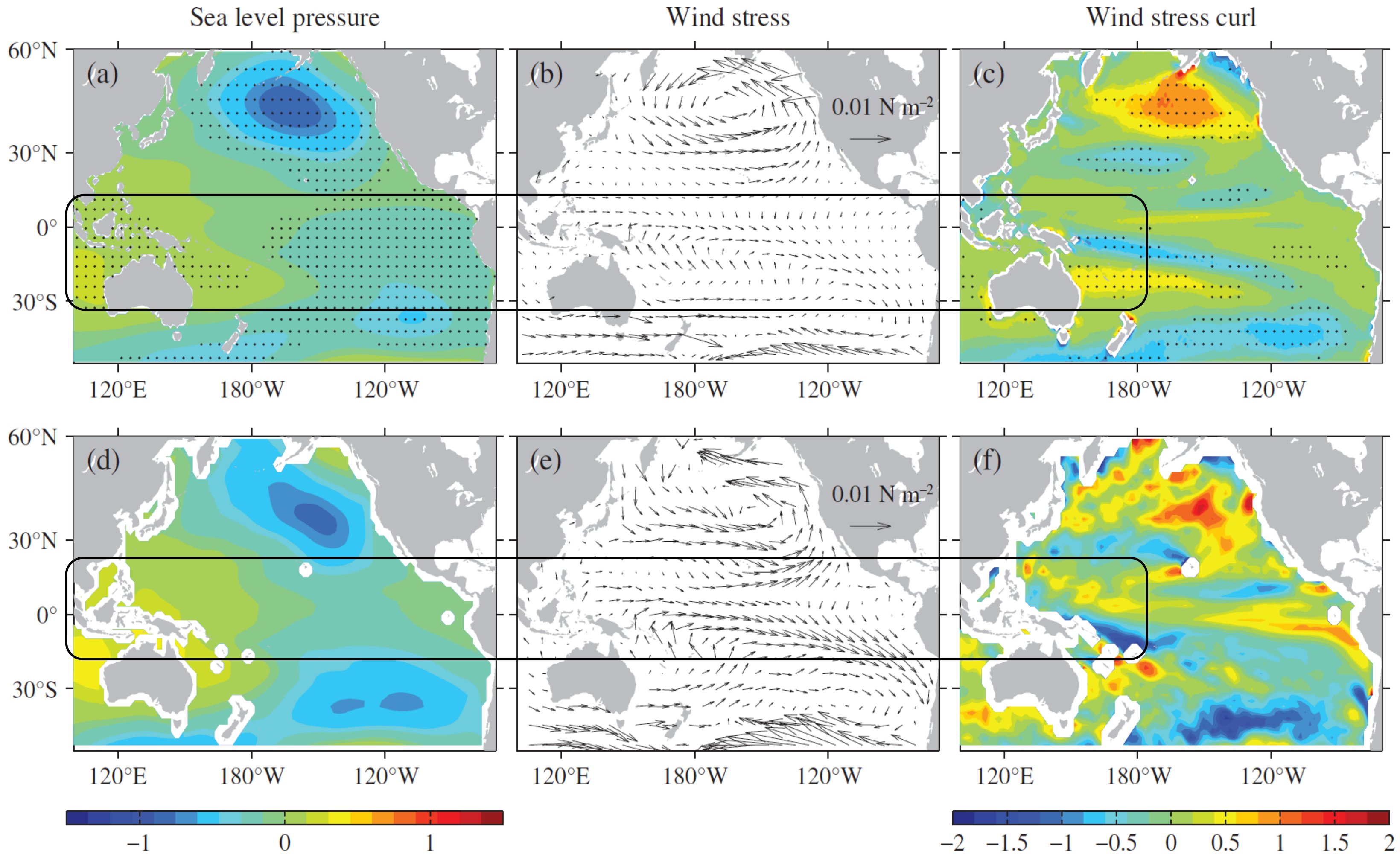
Shilimkar et al., 2022

■ CMIP model biases

- Decadal changes in SSHAs over the NWP region in the CMIP5 simulations are significantly underestimated, which may lead to a weaker ITF (Shilimkar et al., 2022)
- Wind forcing patterns in the northwestern tropical Pacific (at ~12° N) are not well reproduced by CMIP5 models (Lyu et al., 2016)

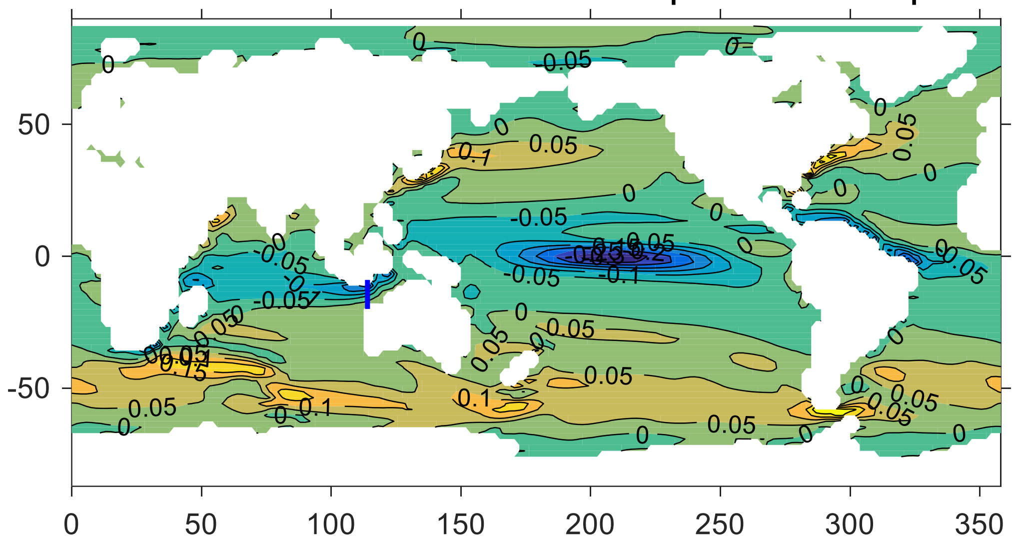
Interdecadal variability patterns: **CMIP5**

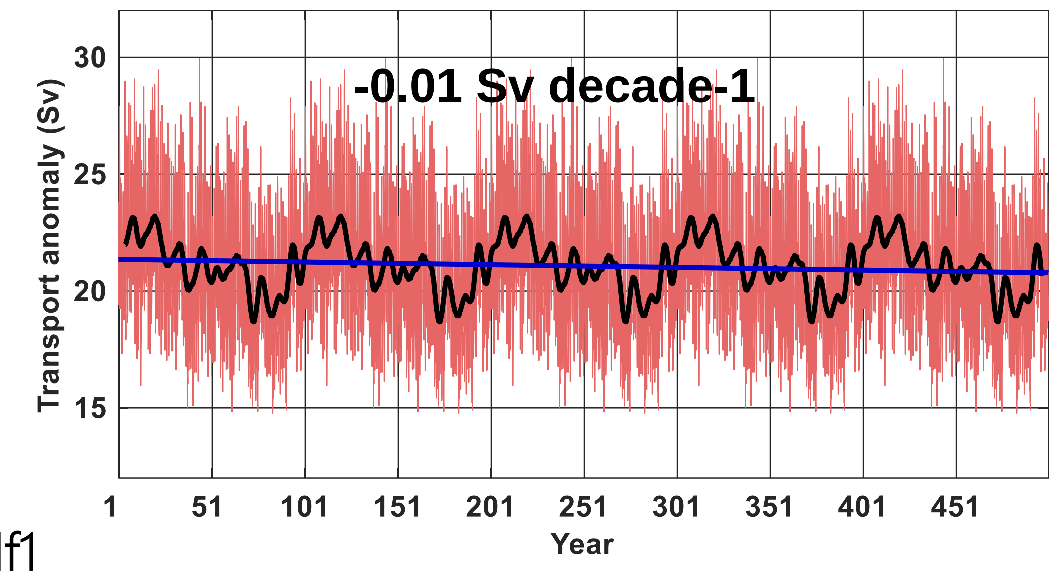
Interdecadal variability patterns: **Observation**



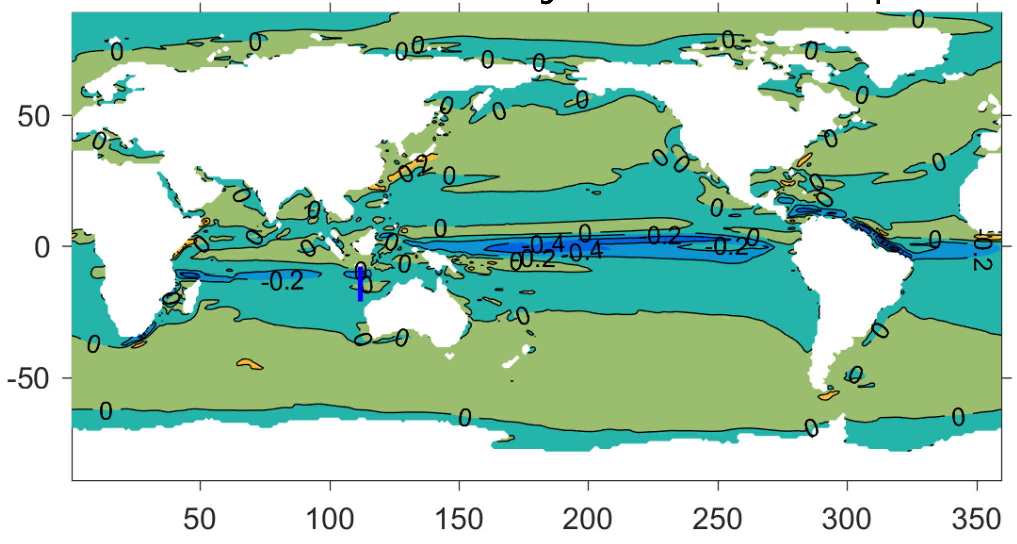
■ **CMIP model biases:** Influence of coarse model bathymetry?

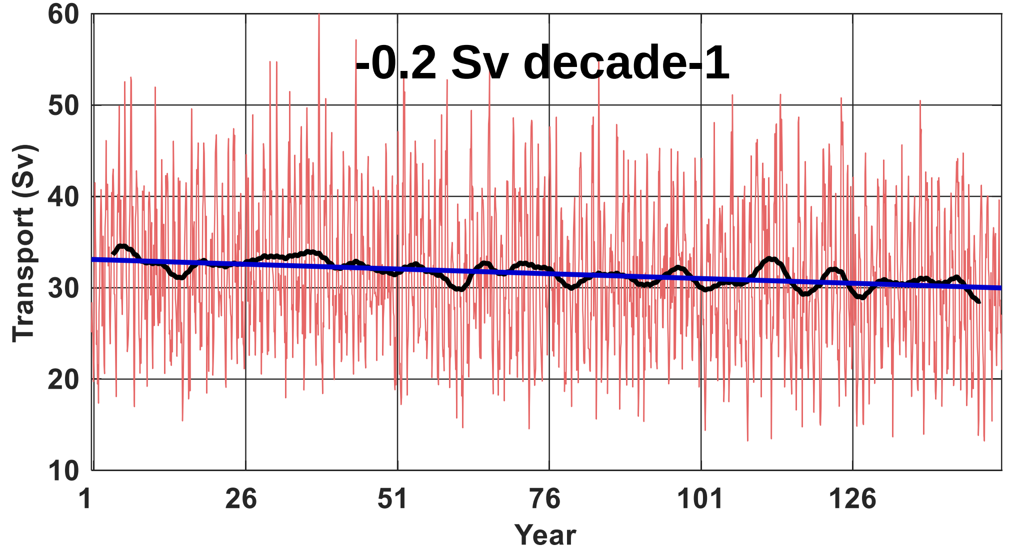
CMIP6.CMIP.UA.MCM-UA-1-0.1pctCO2.r1i1p1f1





CMIP6.CMIP.E3SM-Project.E3SM-1-0.1pctCO2.r1i1p1f1





3. Will the ITF be weakening in the future?

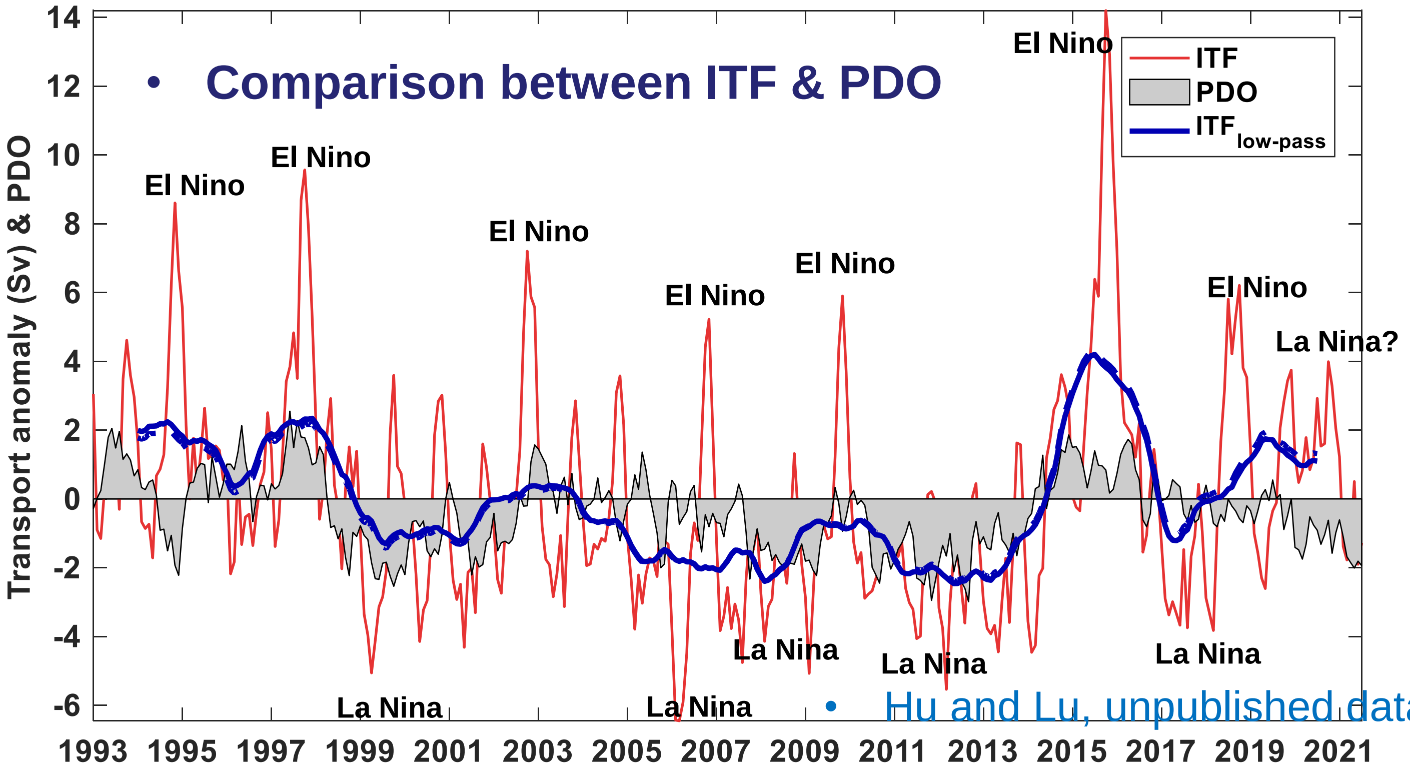
- **Most of CMIP models predict weakening of ITF in a warming climate, but is not consistent with historical trends in the past decades; Significant model biases exist in the SLA/wind field of the northwestern Pacific Ocean**
- **Decadal variability has an order of about 2 Sv; multi-decadal trend has an order of 0.2~0.6 Sv decade^{-1}**
- **We have no enough evidence to say the ITF will certainly be weaken in the future**

Table. Multi-decadal trends in ITF transport: past decades vs. future projection

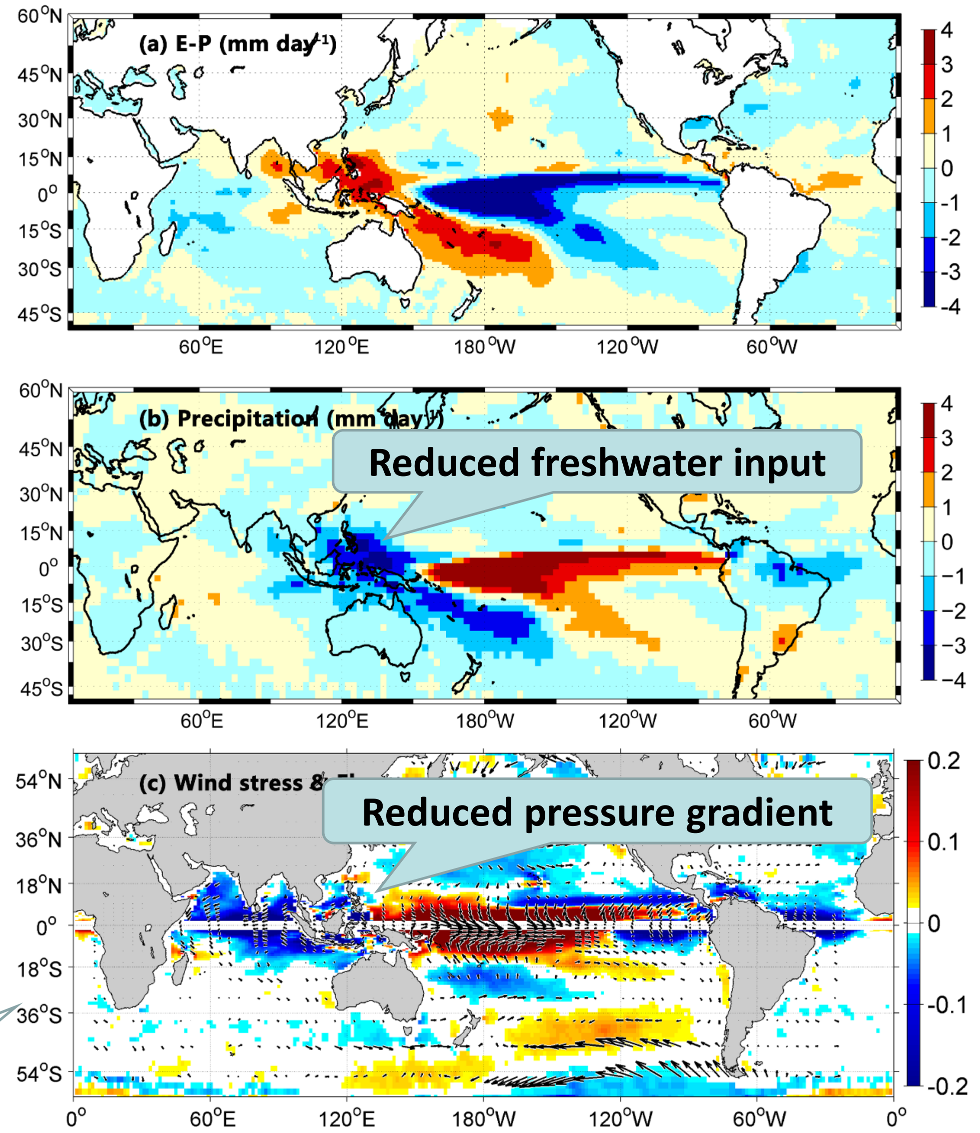
Period	Trend (positive for strengthening of ITF)	Date sets	References
1959-2015	• Increasing of ITF	ECMWF ORA S4	Shilimkar et al., 2022
1992-2011	• Increase in transport through Timor+Lombok • decrease of total ITF, -0.28 Sv decade^{-1}	Proxy based on AVISO SLA	Sprintall and Révelard, 2014
1984-2013	• Increasing of total ITF • 1.12 Sv decade^{-1}	IX1 XBT,	Liu et al., 2015
1992-2012	• Significant increase of ITF	AVISO SSH & GRACE OBP	Susanto and Song, 2015
1970-2010	• Slight decrease: -0.4 Sv decade^{-1}	Proxy using reanalysis	Hu and Sprintall, 2017
1993-2021	Increase in 1992-2012, 2.0 Sv decade^{-1} **Increase in 1992-2021, 0.2 Sv decade^{-1}**	AVISO SLA & GRACE OBP	Hu & Lu, unpublished data
1950s-2010s	Increase of ITF, 0.66 Sv decade^{-1}	WOA2013	Hu & Lu, unpublished data
2050–2100	• Relative to historical simulations in 1900–2000 • -3.4 Sv (-0.36 Sv decade^{-1})	CMIP5 - RCP8.5	Sen Gupta et al., 2016
2006–2098	• Relative to 1907–1999 simulations • -1.5 Sv (-0.15 Sv decade^{-1})	CMIP5 – RCP4.5	Santoso et al., 2022

4. What controls the decadal changes of ITF?

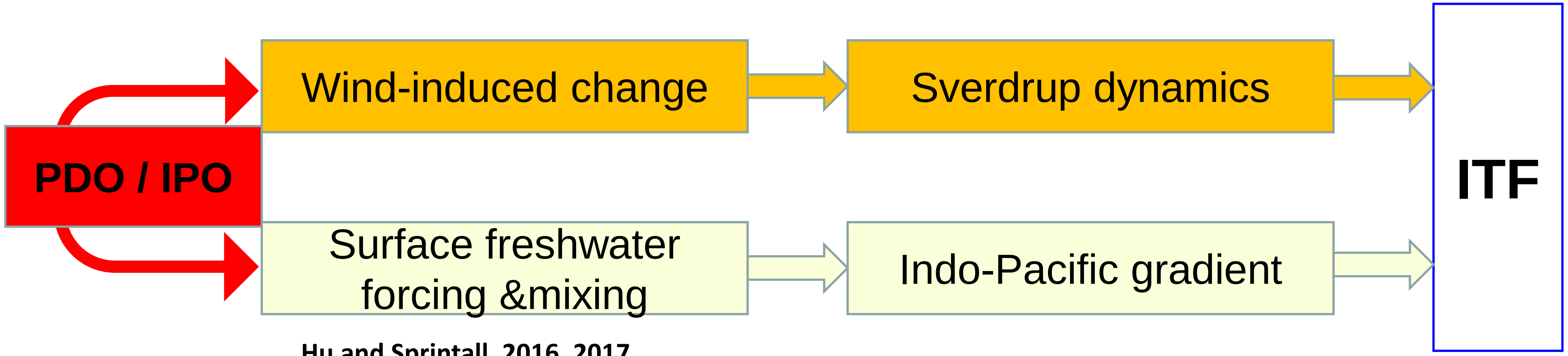
- Pacific climate modes on decadal time scales: PDO/IPO
- Wind forcing & buoyancy forcing



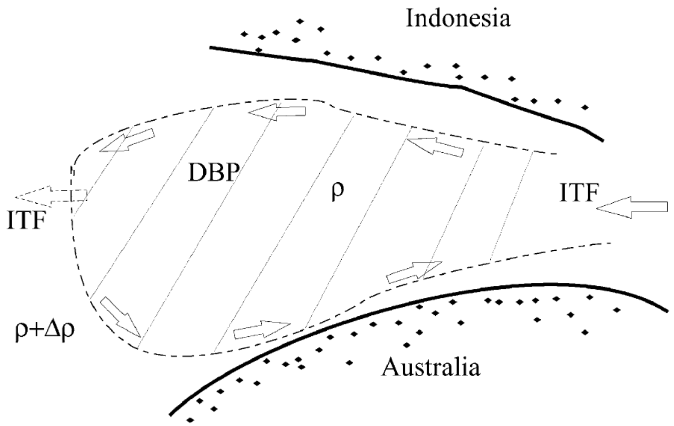
• Hu and Lu, unpublished data



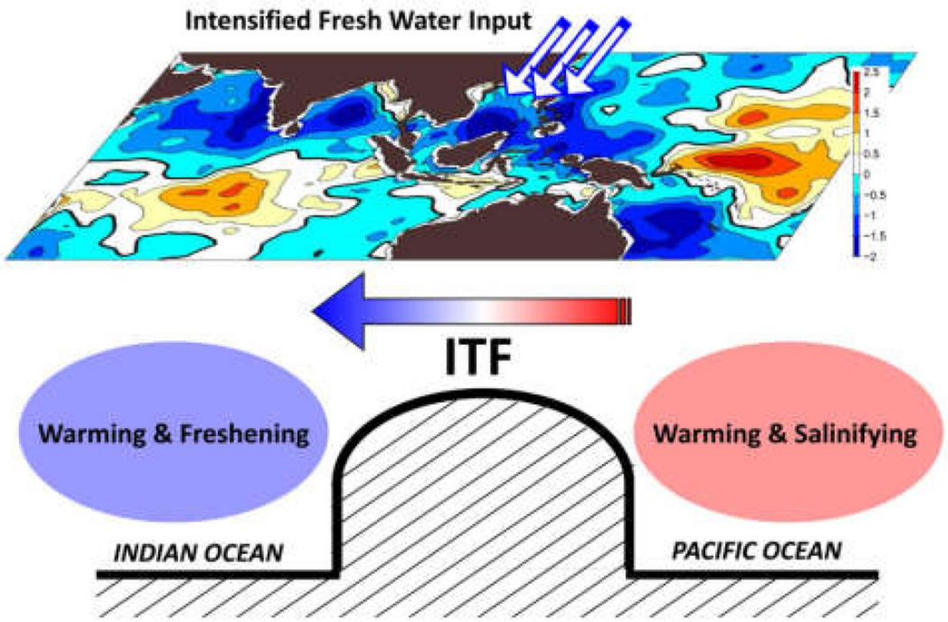
Composite fields of (a) E-P, (b) precipitation and (c) wind stress and Ekman pumping over **IPO positive phases minus negative phases** during 1979–2010. (**Hu and Sprintall, 2017**)



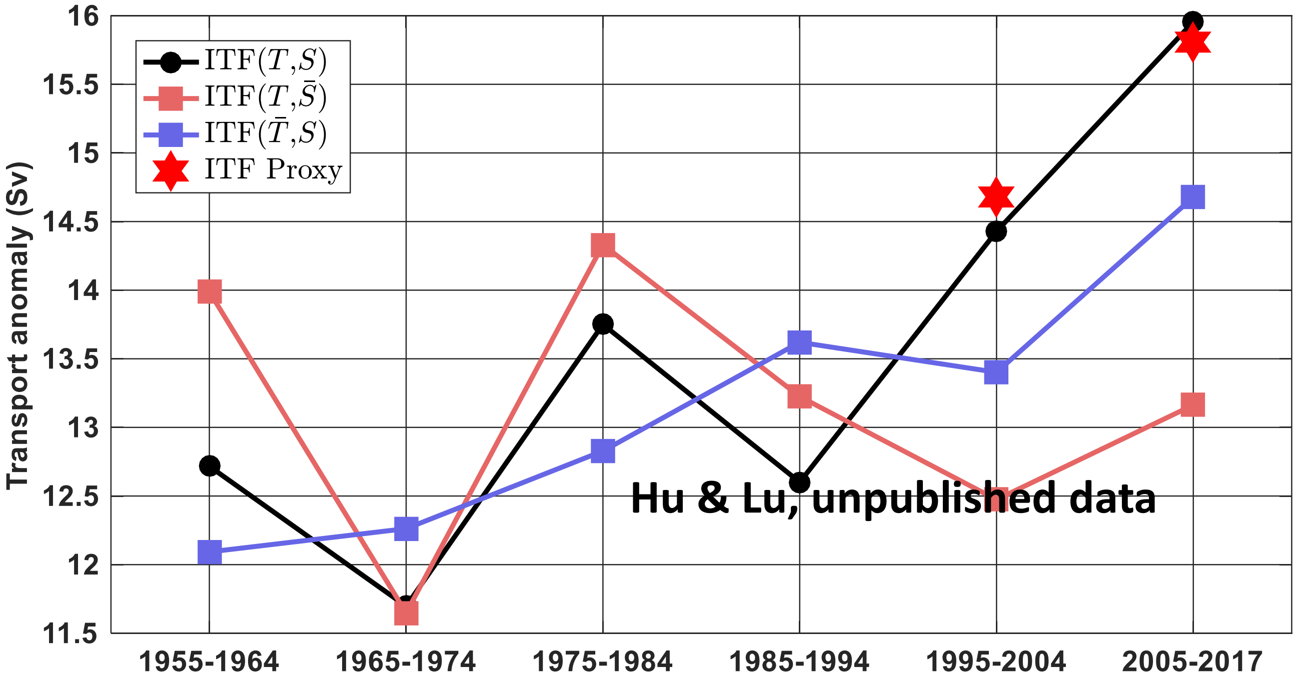
Hu and Sprintall, 2016, 2017



Andersson and Stigebrandt, 2005

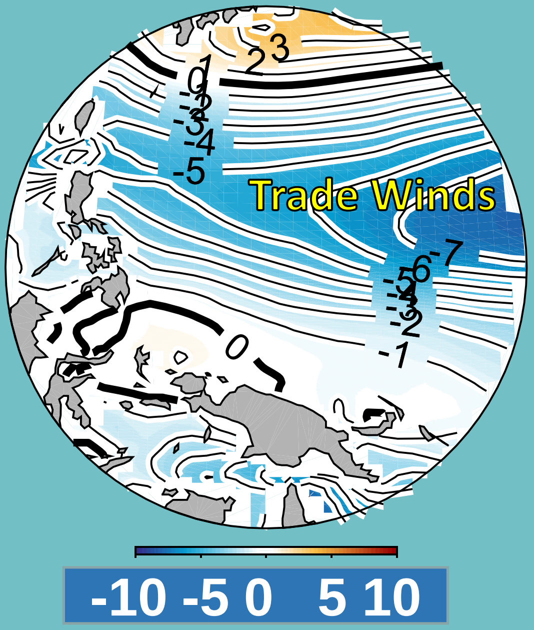


Hu & Sprintall, 2017b

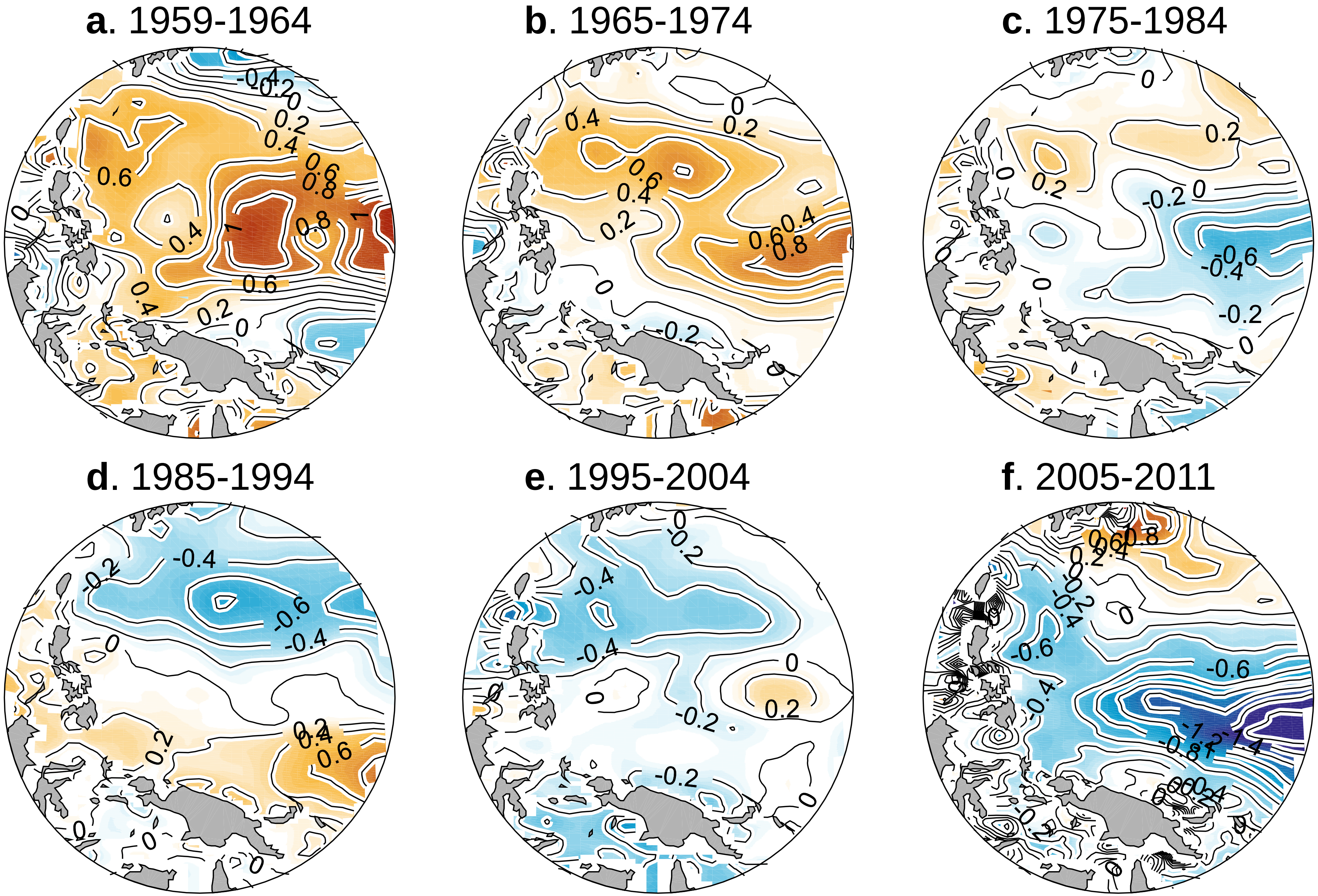


- **Salinity effect seems to play an dominant role in ITF trend as shown in WOA13**

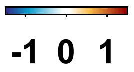
- **Zonal wind stress in the tropical western Pacific Ocean was strengthened during 1959-2011 (ORAS3)**
- **Significant decadal fluctuation in τ_x**



- **Mean zonal wind stress**



- Zonal wind stress anomalies averaged over various decades (**Hu et al., 2021**)

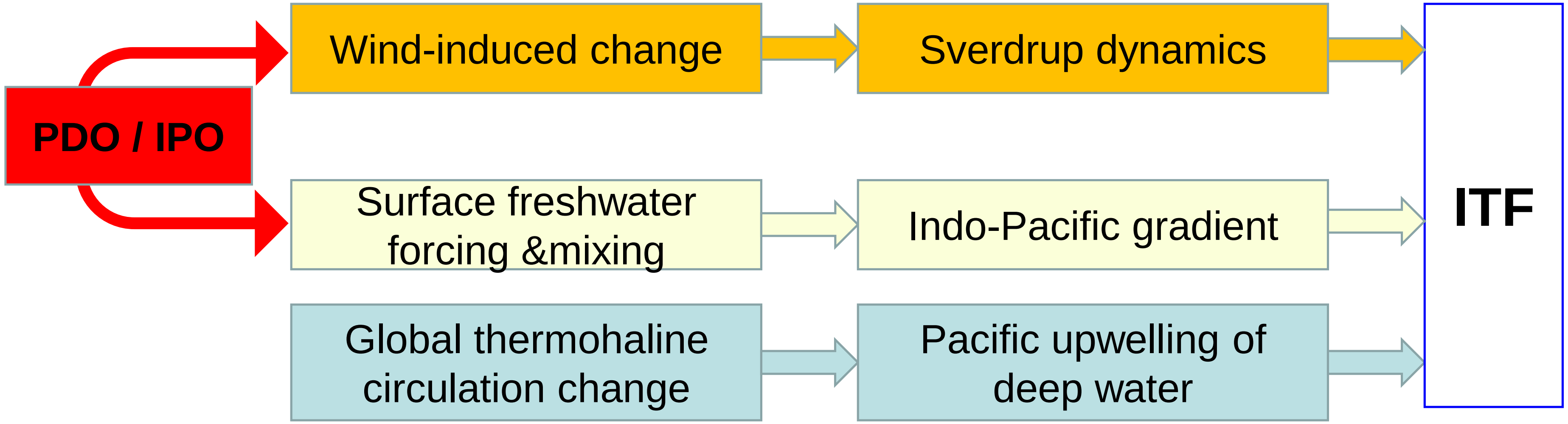


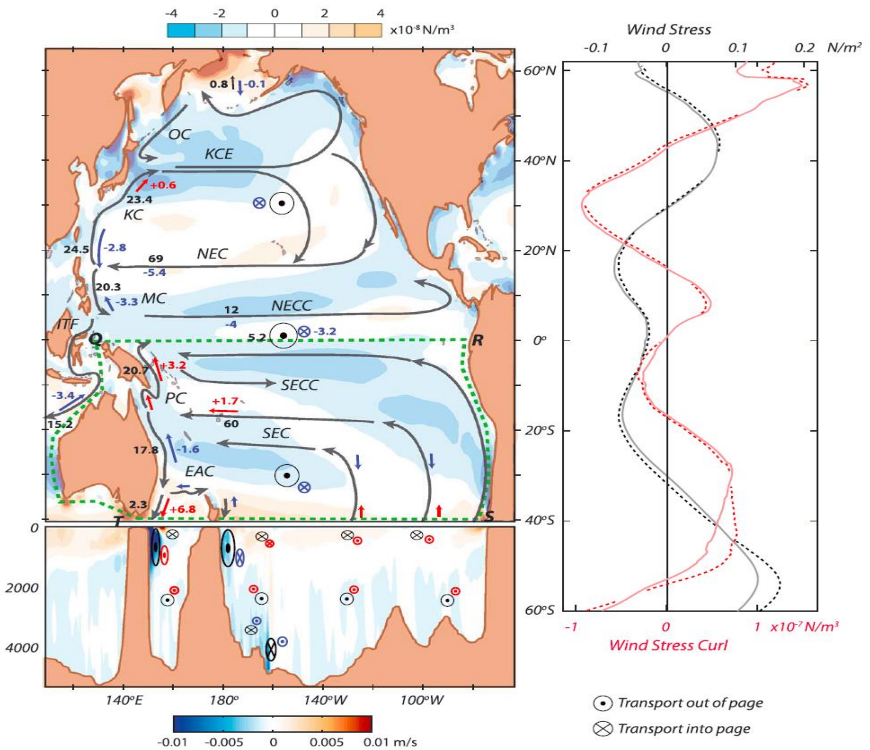
10^{-2} Pa

- ✓ Projected ITF decrease related to **deep ocean circulation**
- ✓ Winds-changes in the upper ocean circulation cannot explain the projected ITF decrease

Hu et al., 2015

Sen Gupta et al., 2016



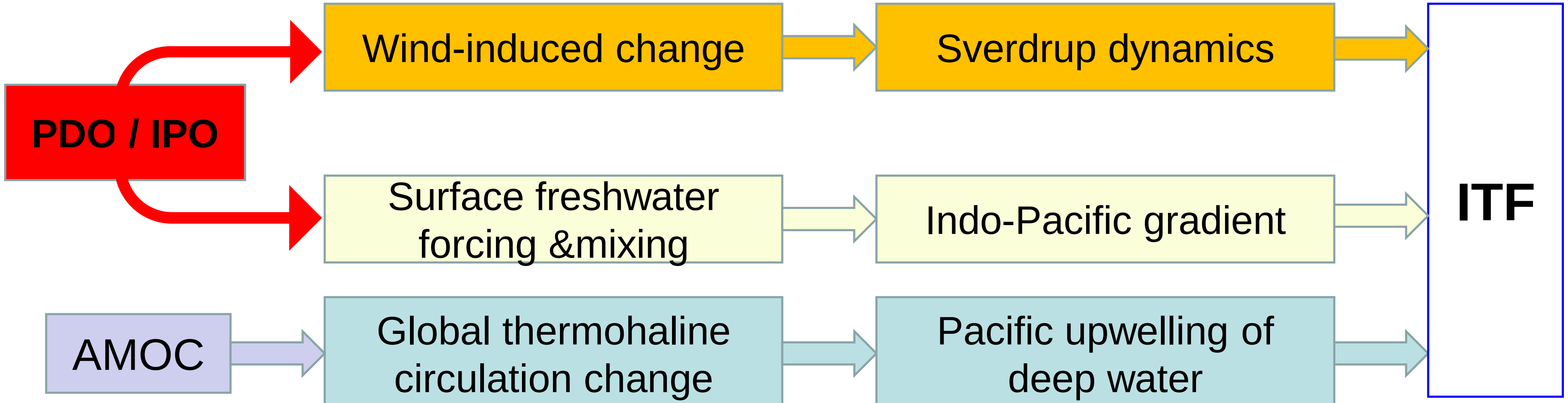


Pacific western boundary currents and their roles in climate

Dunxin Hu[1], Lixin Wu[2], Wenju Cai[2,3], Alex Sen Gupta[4], Alexandre Ganachaud[5], Bo Qiu[6], Arnold L. Gordon[7], Xiaopei Lin[2], Zhaohui Chen[2], Shijian Hu[1], Guojian Wang[3], Qingye Wang[1], Janet Sprintall[8], Tangdong Qu[9], Yuji Kashino[10], Fan Wang[1] & William S. Kessler[11]

Both the Mindanao Current and the ITF are projected to weaken (Fig. 5). The reduced ITF is not fully accounted for by the projected wind-induced changes through Sverdrup dynamics that exclude an influence from upwelling deep water. This exclusion is an invalid assumption because such upwelling is important on timescales relevant for climate change. It is conceivable that a projected slowdown of the global thermohaline circulation[98] would drive a weakening in upwelling of deep water in the South Pacific, contributing to the projected ITF decrease, and following the notion that the ITF is in part supported by the upwelled deep water associated with the compensating flow for the global thermohaline circulation[2].

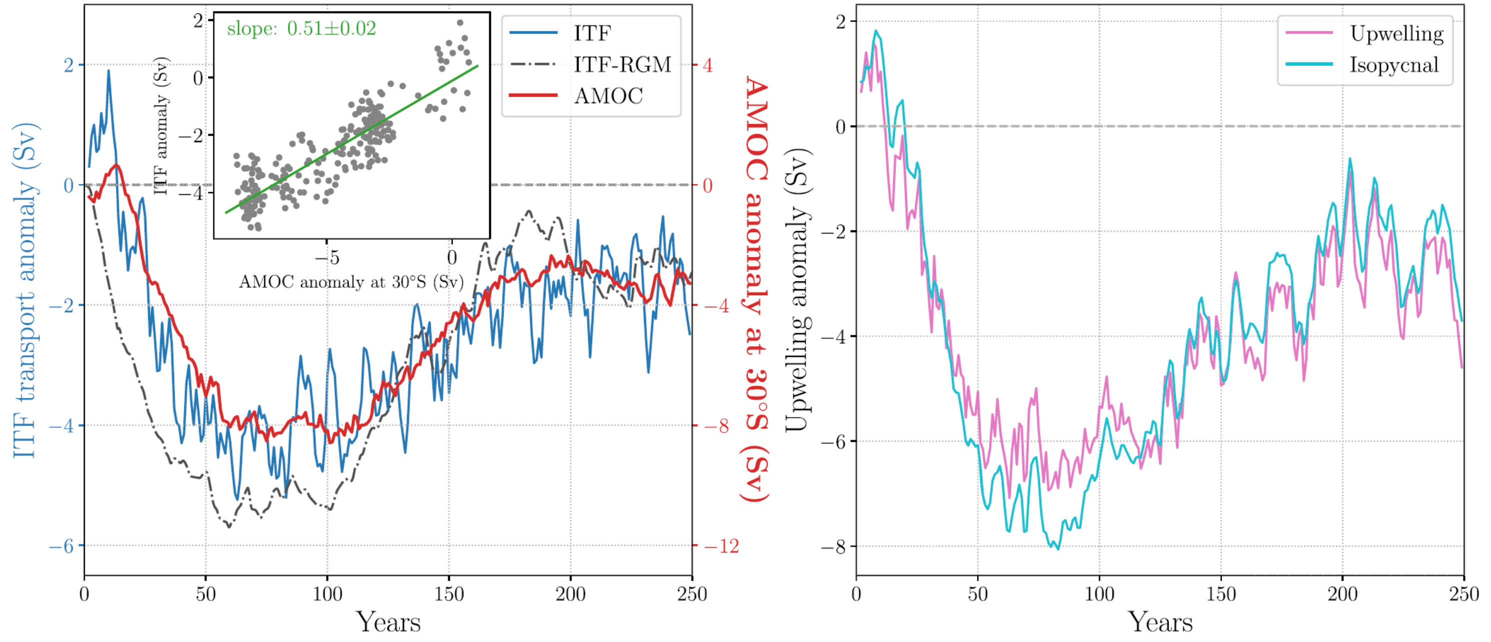
Hu et al., 2015



Sun and Thompson, 2020

- ✓ Decadal changes in AMOC may also trigger that of ITF through changing the upwelling of Pacific deep water

Sun and Thompson, 2020



(a) Changes in the AMOC strength at 30◦S (red; Sv) and ITF volume transport (blue; Sv) in the CCSM4 abrupt 4xCO2 experiments; (b) Changes in the upwelling rates in the Pacific basin at 800-m depth (purple) and its contribution due to isopycnal movement (**Sun and Thompson, 2020**).

Summary

■ Is there a robust trend in ITF in the past decades?

- Robust increasing trend since 1990s when many observations are available; the trend during **1992-2021** is much weaker than that during 1992-2012 and weaker than decadal variability
- ITF trend over a longer period (e.g., since 1950s) depends on datasets and is of much uncertainty

■ Will the ITF be weakening in the future?

- Most of CMIP models predict a weakened ITF in a warming climate
- Future projections is not consistent with what happened in the past decades
- Significant model biases exist in the SLA/wind field of the northwestern Pacific Ocean
- Projected weakening in CMIP models is much less than interannual to decadal variability

■ What controls the decadal changes of ITF?

- Decadal variability has an order of about 2 Sv; multi-decadal trend has an order of 0.2~0.6 Sv decade^{-1}
- Pacific decadal variability (e.g., PDO/IPO) play an important role through wind forcing & freshwater/buoyancy forcing;
- Changes in SP deep circulation & AMOC may contribute to decadal changes of ITF
- **Speculate**: 10 decades of time series are needed to separate the long term trend from variability

THANK YOU

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