A Quasi-Global Eddying Simulation of OFES2 Forced by JRA55-do

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Contents

- OFES2 forced by JRA55-do vs OFES forced by NCEP reanalysis
  (OFES: OGCM for the Earth Simulator based on MOM3)

- An increase of the Indonesian Throughflow by internal tidal mixing
  (Sasaki et al. 2018 GRL)

Why We Developed OFES2

- No sea-ice and tidal models in OFES.

- Several issues in the OFES

Unrealistic water mass properties within the Indonesian Seas due to underestimation of vertical mixing (Masumoto et al. 2008)

Unrealistic water properties in the subsurface of subtropical North Pacific due to unrealistic wind stress distribution of NCEP reanalysis (Kutsuwada et al., 2019)

Unrealistic paths of Kuroshio detaching from Kyushu and Gulf Stream not turning northward and no Azores current.

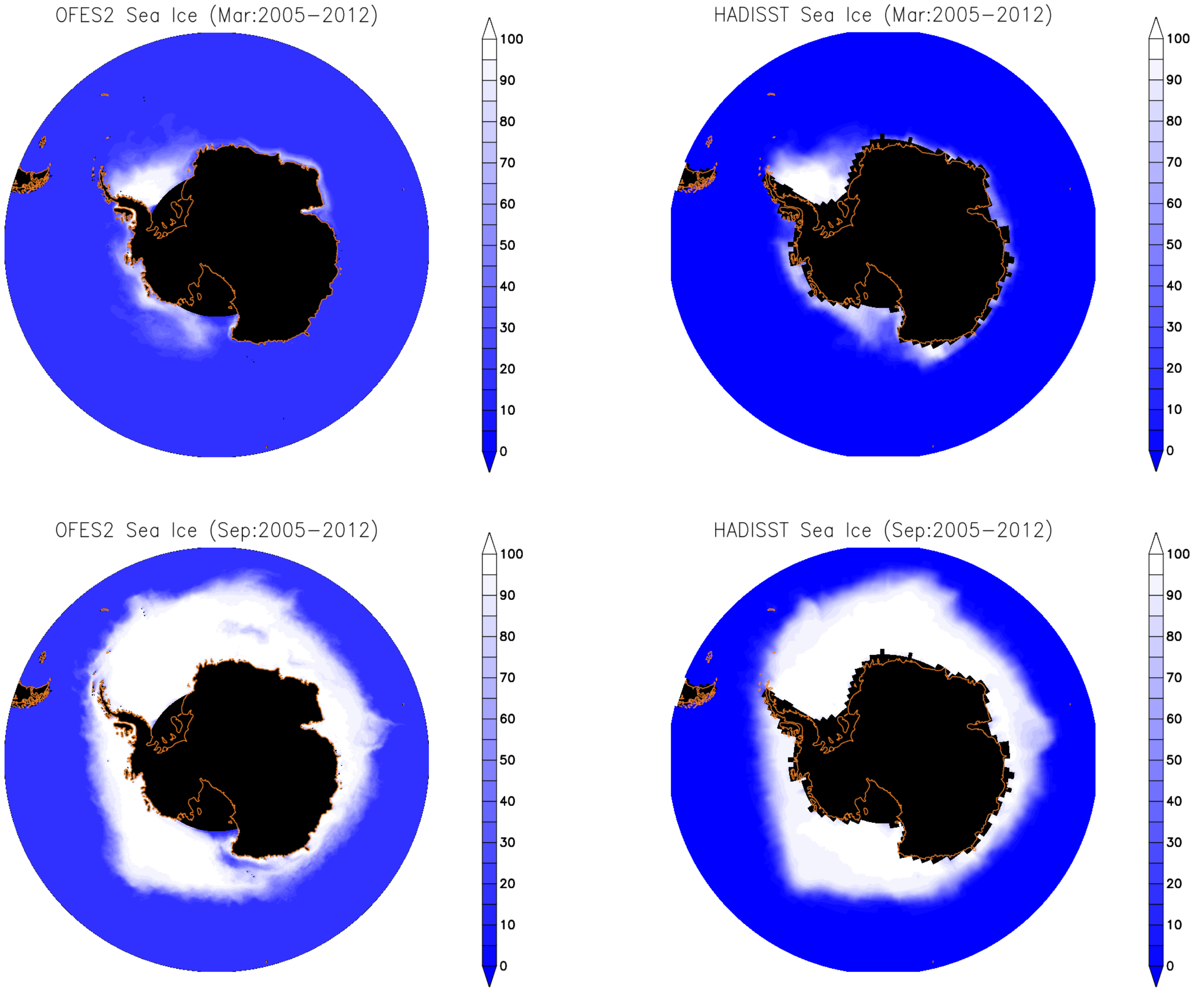
⇒ A new version of OFES (OFES2) with sea-ice model and tidal mixing scheme forced by a new developed atmospheric data to force the OGCM (JRA55-do).

Model Description of OFES2 Compared with OFES

	OFES2	OFES
Domain	76°S-76°N	75°S-75°N
Horizontal Resolution	0.1°	0.1°
Number of Vertical Levels	105	54
Maximum Depth	7,500 m	6,065 m
Bathymetry Data	ETOPO1	OCCAM 30'
Sea Ice Model	Komori et al. 2005	-
Horizontal Mixing Scheme	Bi-harmonic	Bi-harmonic
Vertical Mixing Scheme	Noh & Kim 1999	KPP
Tidal Mixing Scheme	St. Laurent et al. 2002	-
SSS Restoring	15 days to WOA13	6 days to WOA98
North & South Boundary	T & S restoring within 3° from boundary	T & S restoring within 3° from boundary
T & S Restoring at All Depths	Merginal seas and their mouths	-
Atmospheric Forcing	JRA55-do (3 hourly) 55km	NCEP (daily) 200km
River Runoff	CORE2 (daily climatology)	-
Bulk Formula	Large & Yeager 2004	Rosati & Miyakoda 1988
Momuntum Flux	Bulk formula using relative wind speed	NCEP (daily)
Hindcast Period	1958-2016	1950-2017
Initial Condition	T & S of OFES on Jan 1, 1958	OFES climatlogical run
Output	Daily mean per 3 day until 1989 Daily mean from 1990 Monthly mean	Snapshot per 3 day from 1980 Monthly Mean

Long-term Mean State
OFES2 vs OFES

Sea Ice Concentration (2005-2012)



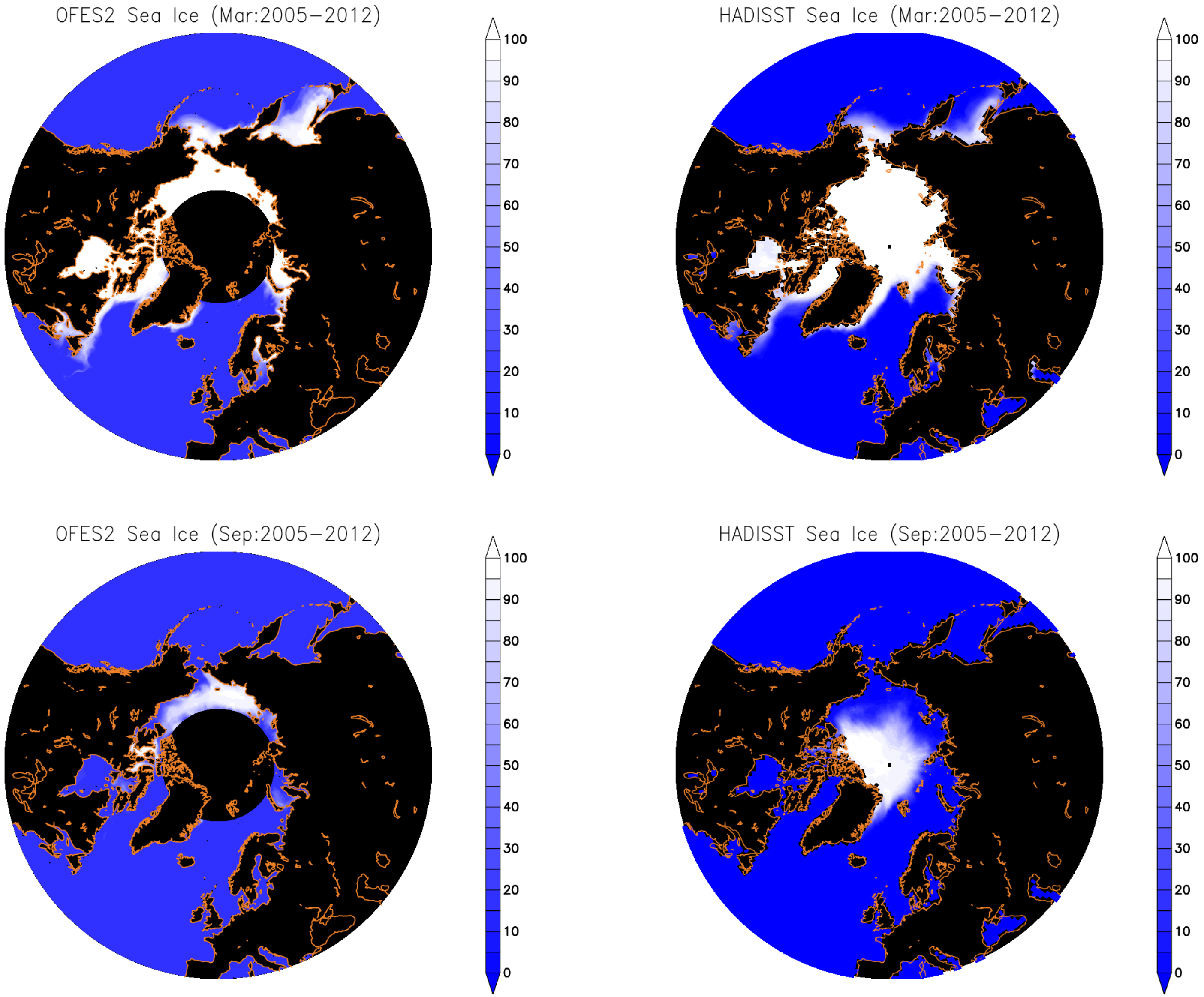
March

September

OFES2

HADISST

Sea Ice Concentration (2005-2012)



March

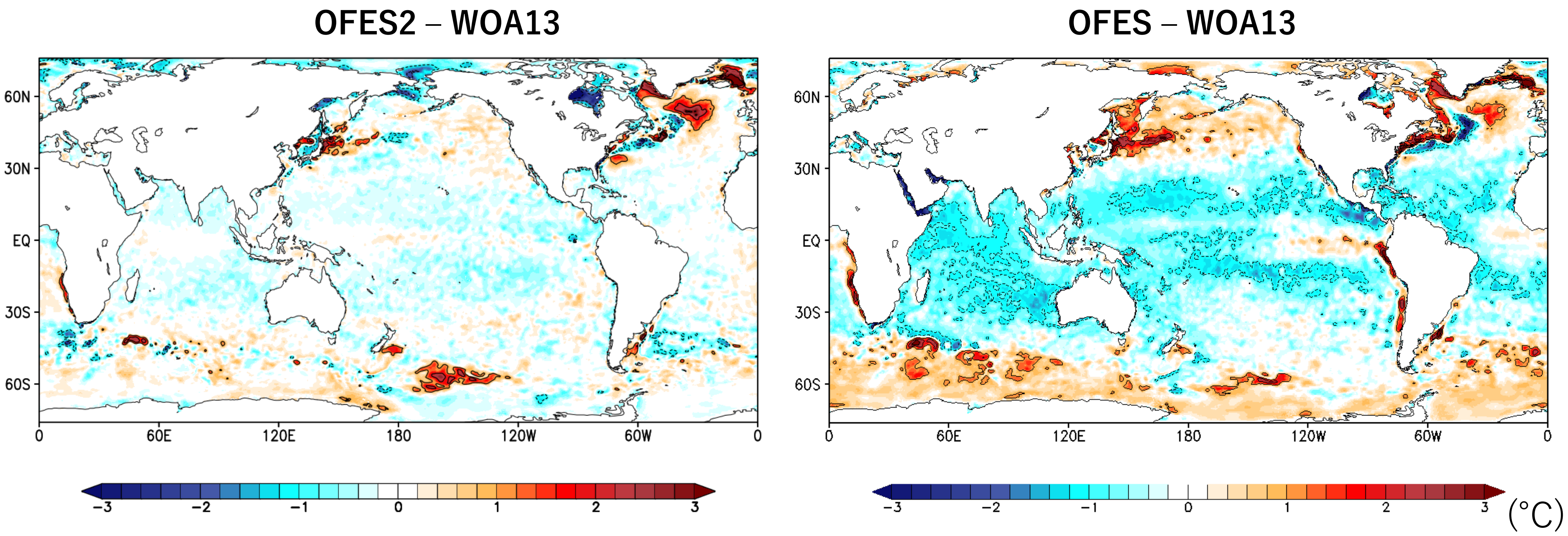
September

Unrealistic sea ice cover in Chukchi Sea in summer

OFES2

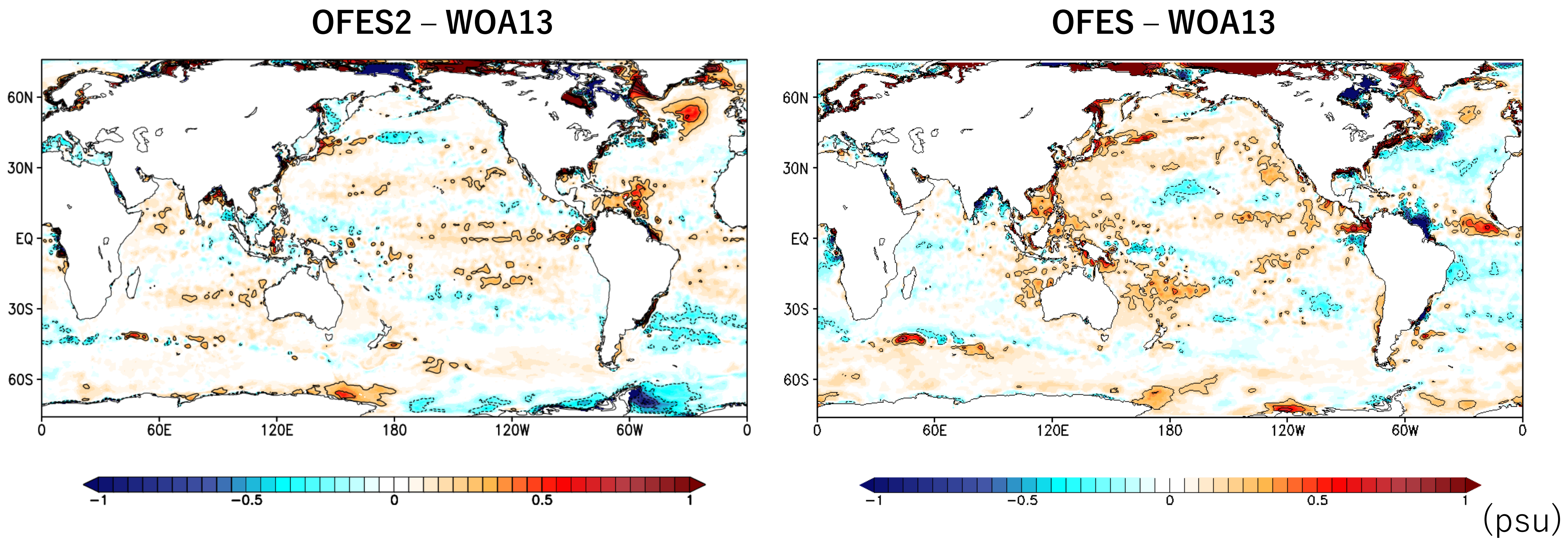
HADISST

SST Bias against WOA13 over 2005-2012



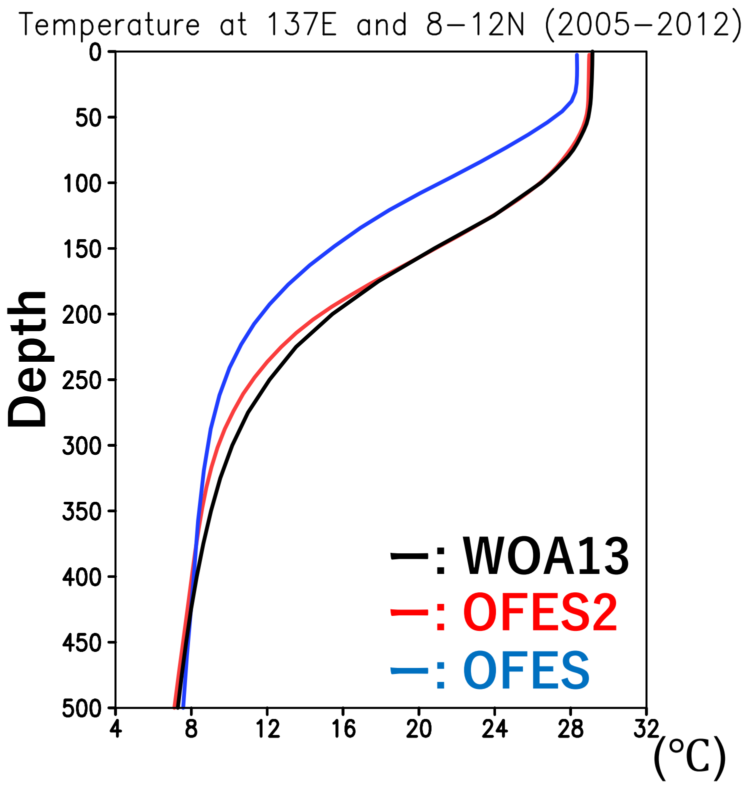
Atmospheric Data:	**JRA55-do**	**NCEP**
Bulk Formula:	**Large and Yeager (2004)**	**Rosati and Miyakoda (1988)**
Sea Ice Model:	◯	×
Time Scale of SSS Restoring:	**15 day to WOA13 SSS**	**6 day to WOA98 SSS**
River Runoff:	**CORE2**	×

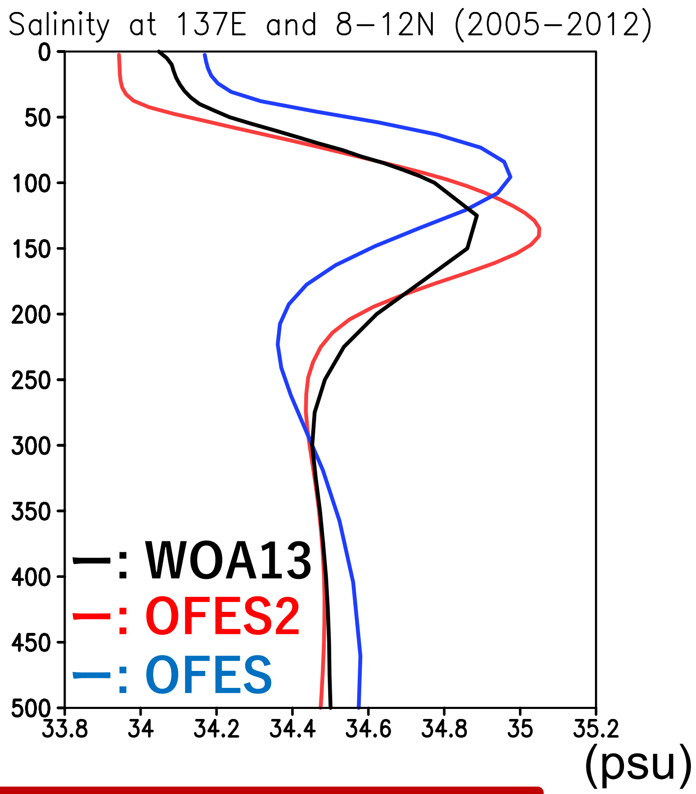
SSS Bias against WOA13 over 2005-2012

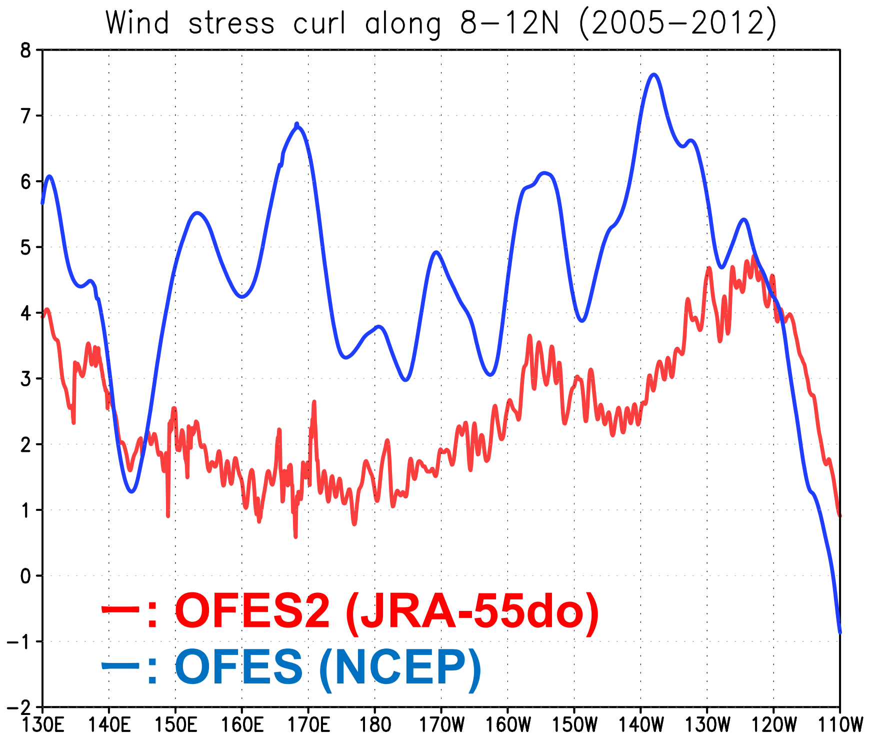


Atmospheric Data:	**JRA55-do**	**NCEP**
Bulk Formula:	**Large and Yeager (2004)**	**Rosati and Miyakoda (1988)**
Sea Ice Model:	○	×
Time Scale of SSS Restoring:	**15 day to WOA13 SSS**	**6 day to WOA98 SSS**
River Runoff:	**CORE2**	×

Water Property in Subtropical North Pacific (137E, 8-12N)







The reliability of the wind product is a key for simulating realistic oceanic fields not only at the ocean surface but also in the subsurface ocean as suggested by Kutsuwada et al. (2019).

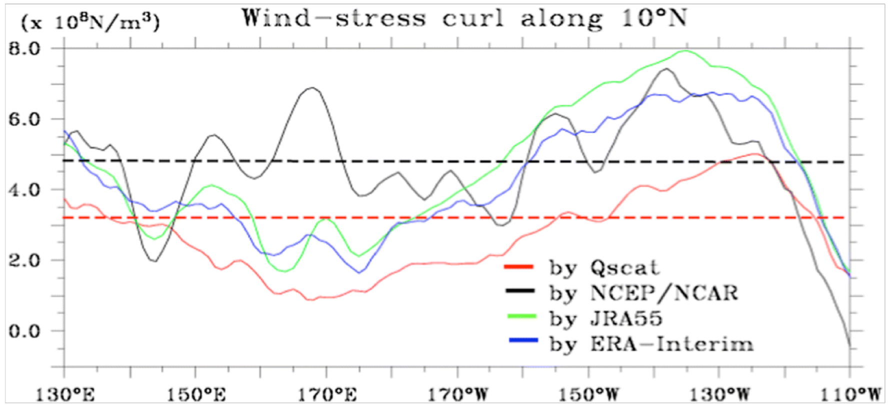
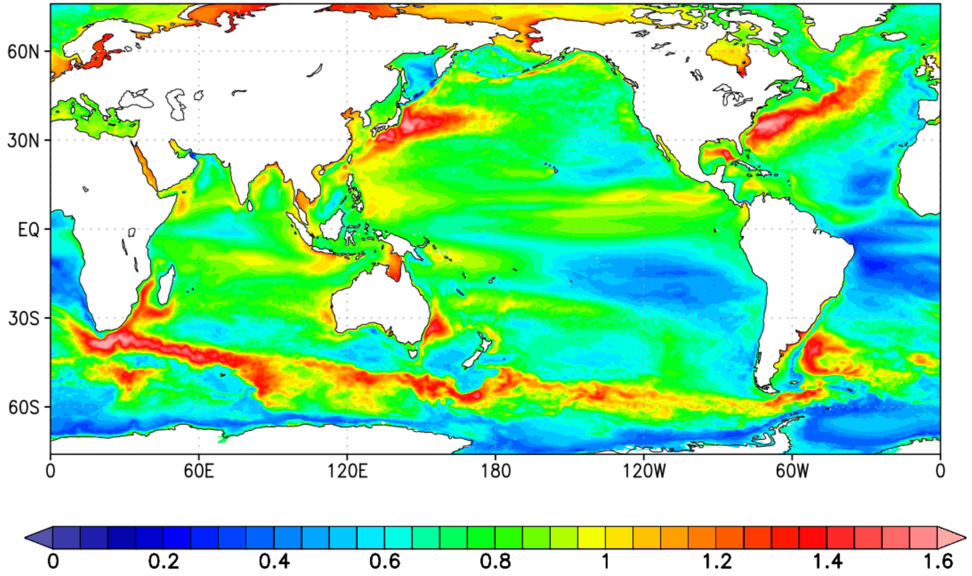


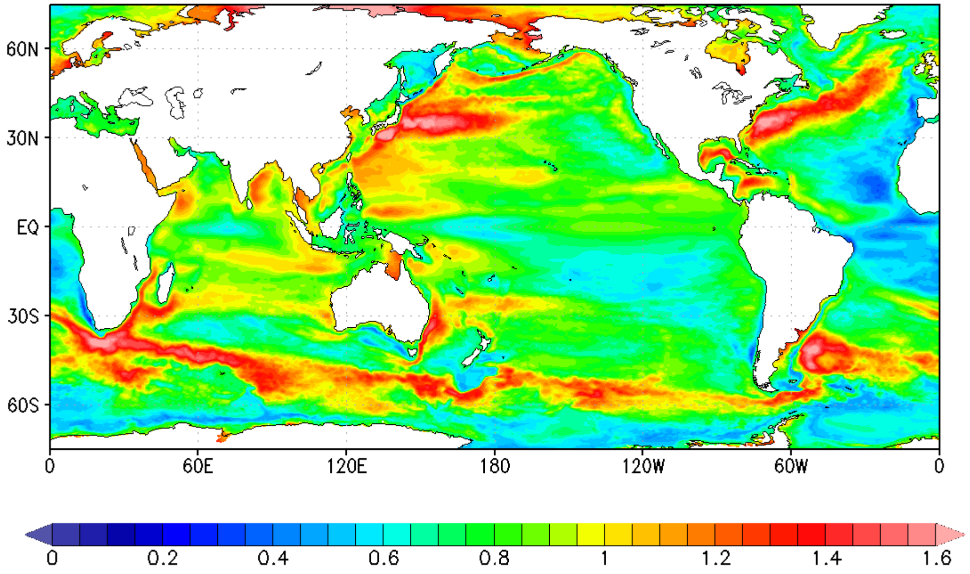
Fig. 3b in Kutsuwada et al. 2019

SSH Variability over 1993-2016

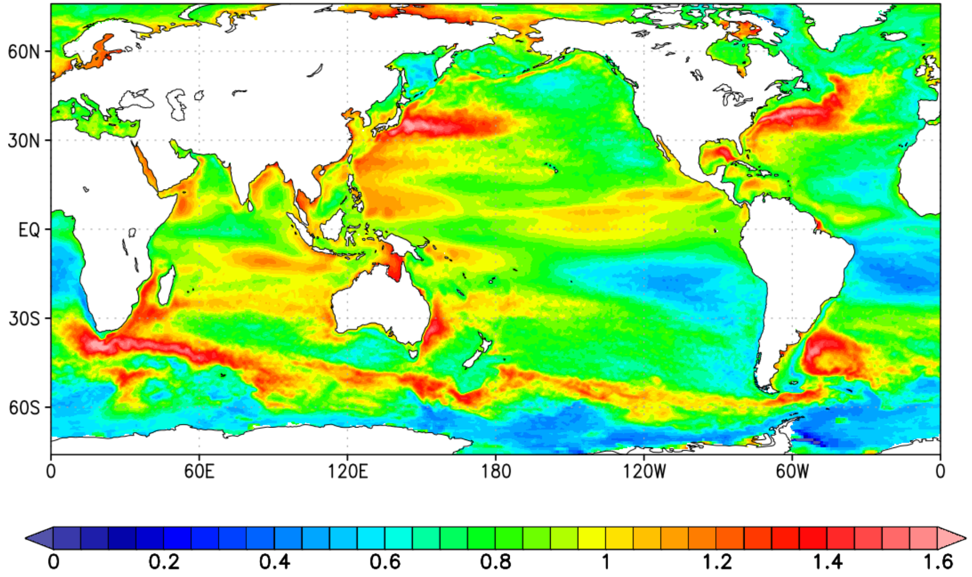
OFES2 (bulk formula using relative velocity)



OFES (forced by NCEP wind stress)

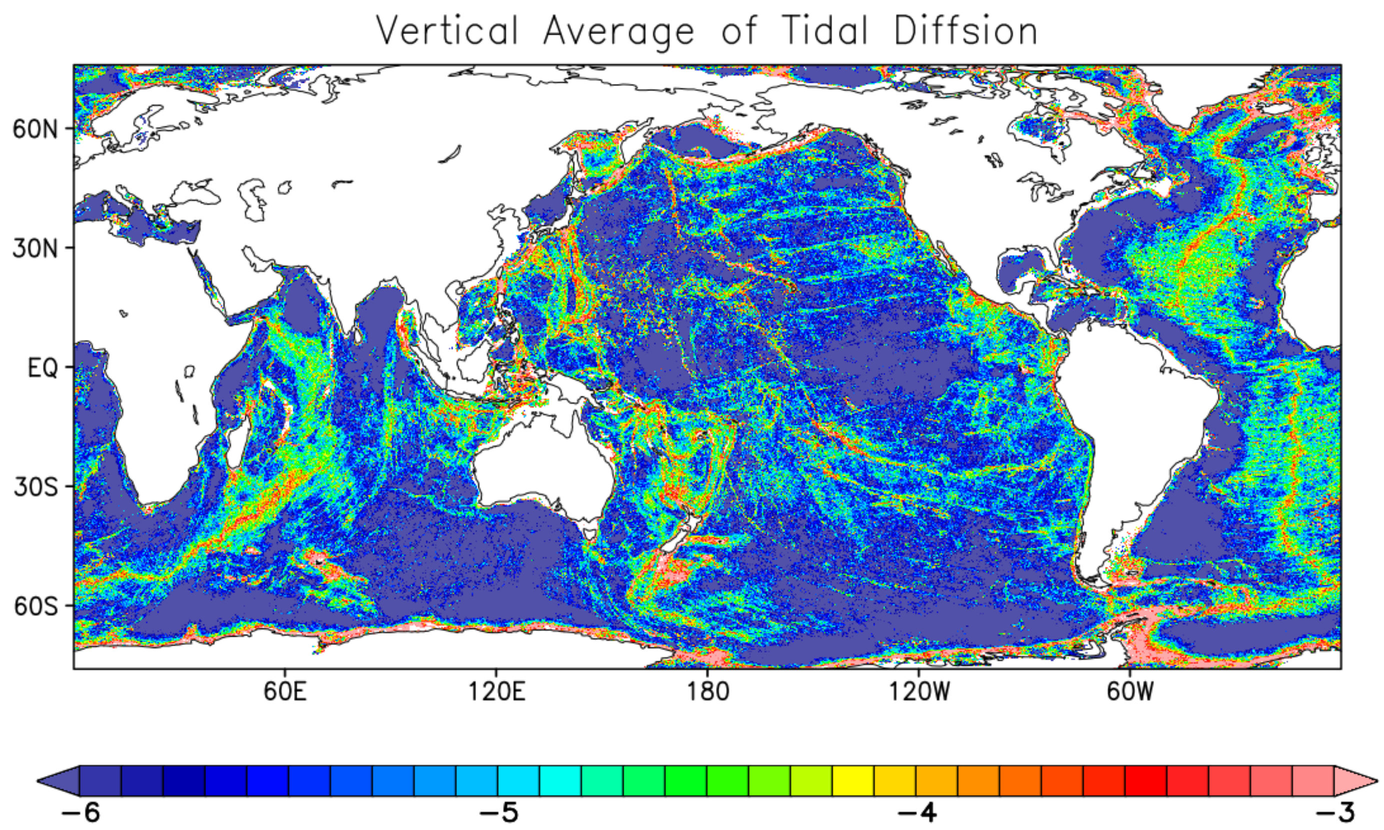


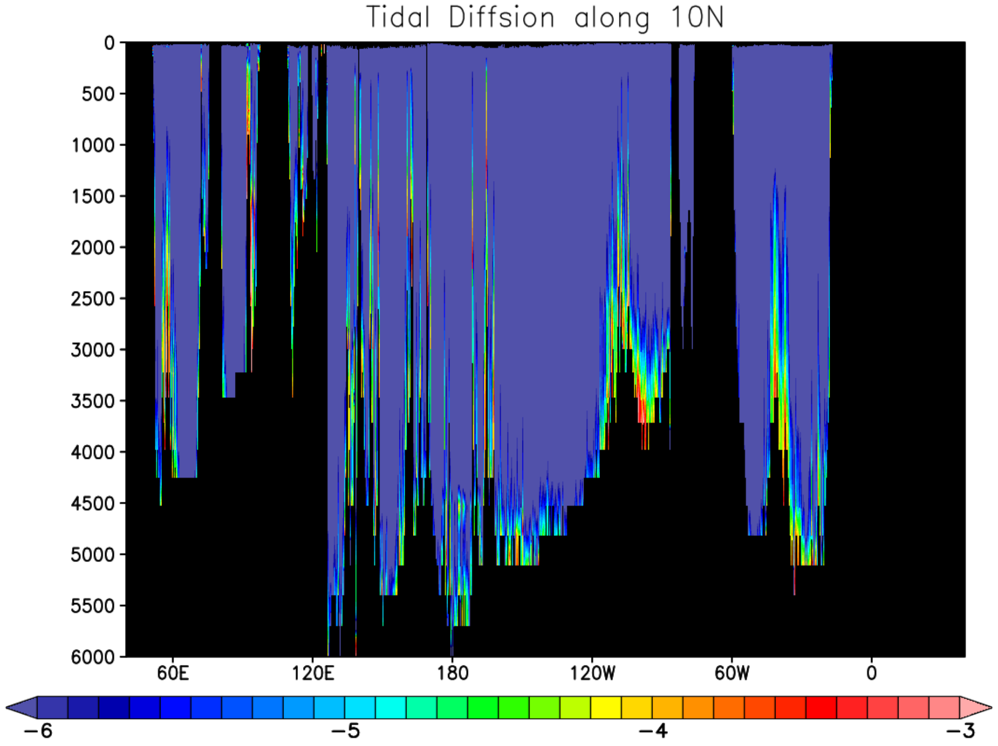
AVISO Observation



- The magnitude of SSH variability is relatively small in OFES2 and large in OFES compared to the AVISO.
- Unrealistic path of the Gulf Stream and no Azores Current in both OFES2 and OFES.

Vertical Diffusivity in OFES2 (using St. Laurent et al. 2002)



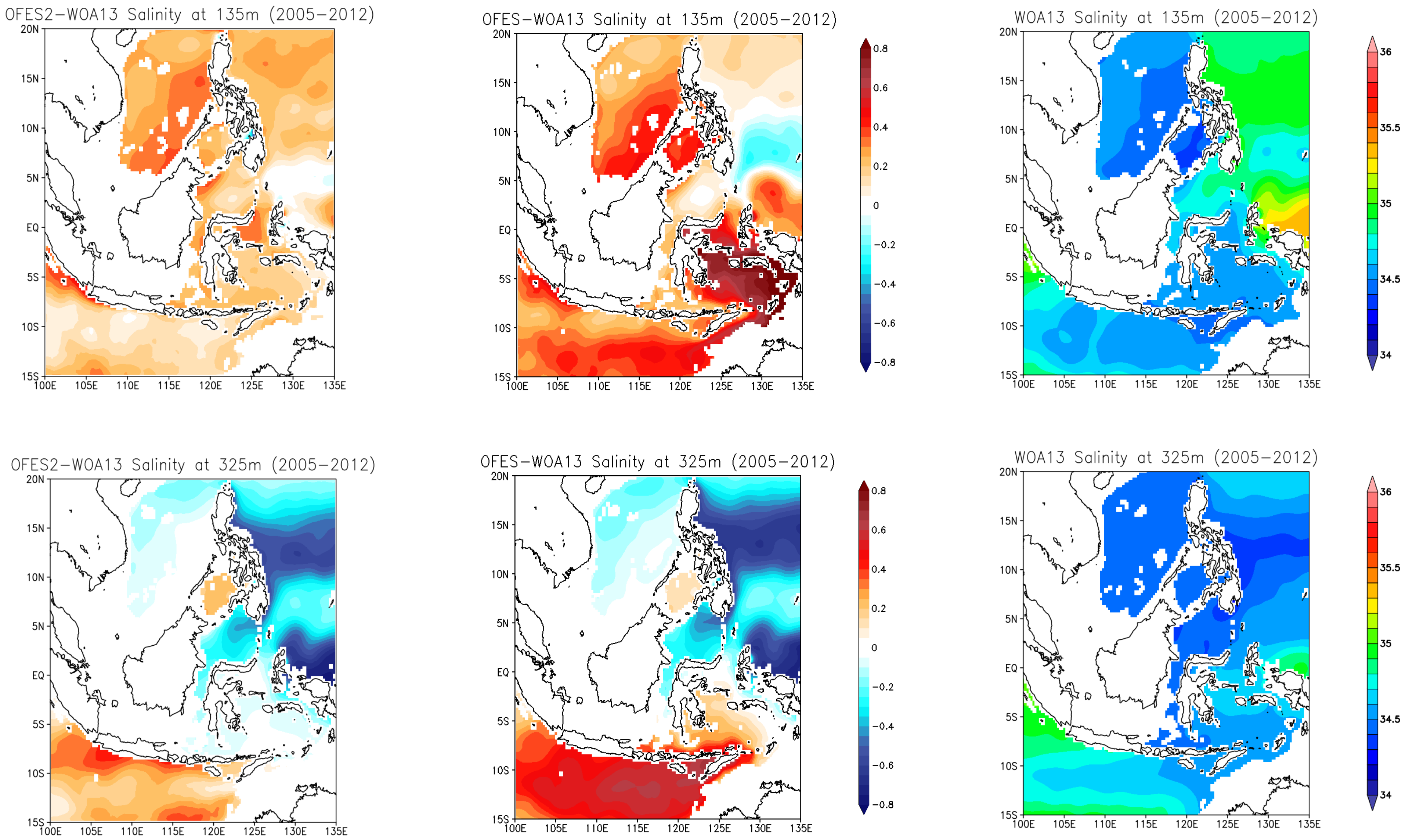


Daily mean vertical diffusivity (log10 $m^2\ s^{-1}$) on December 1, 2016 estimated from the tidal mixing scheme (St. Laurent et al. 2002).

Constant K1 and M2 speed from FES2020 model Slope of bottom topography	→	Energy Flux at Bottom	→	3D Vertical Diffusivity

Salinity in the Indonesian Seas over 2005-2012

OFES2 (with tidal mixing parameterization) | **OFES (No Tidal Mixing)** | **WOA13** | (psu)

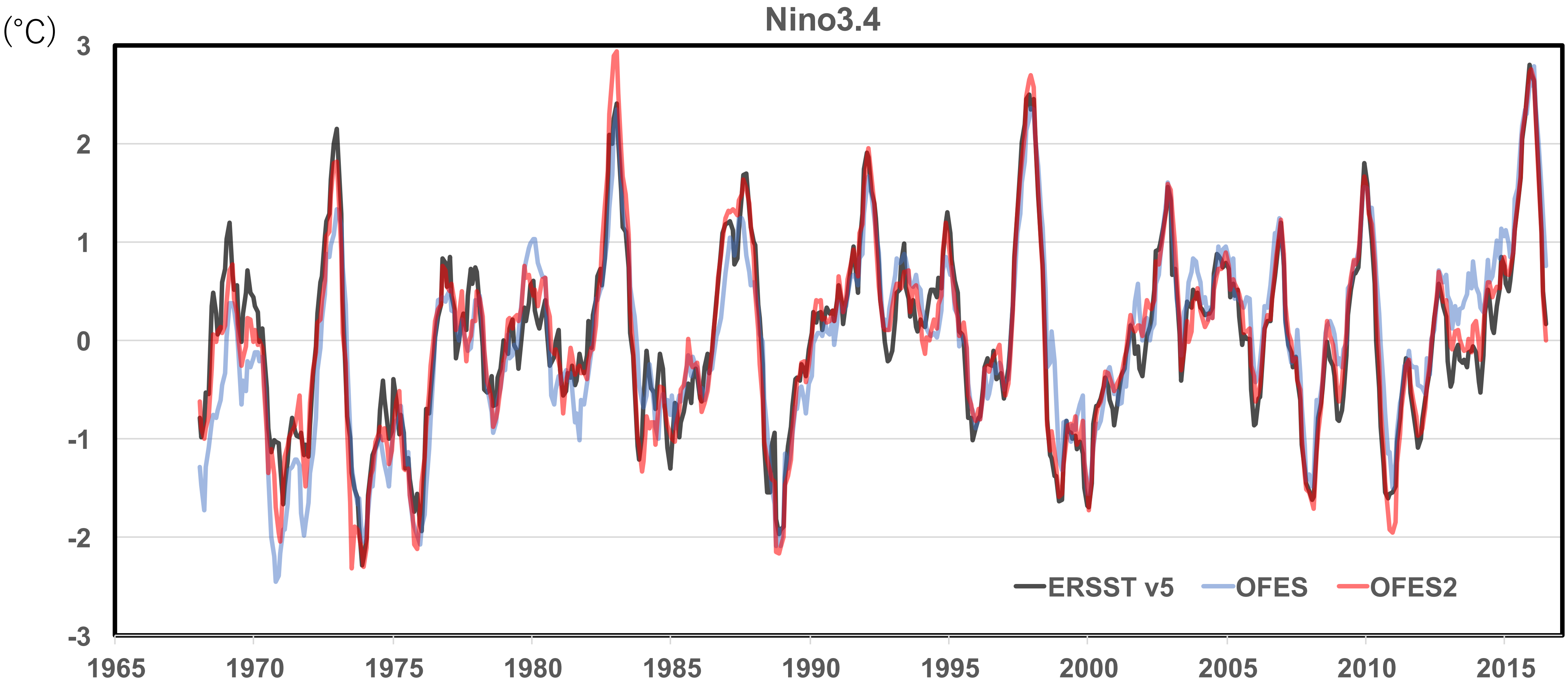


135 m

325m

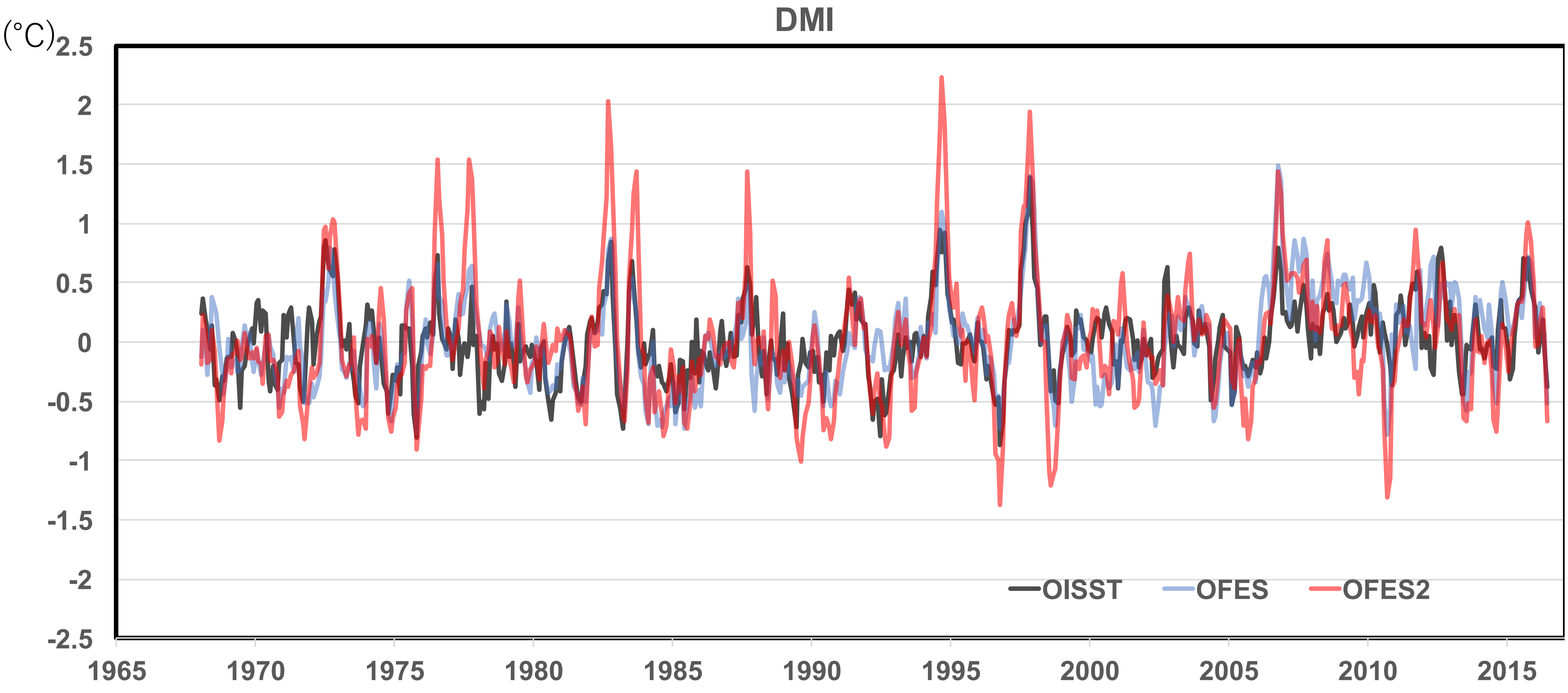
Climate Variability
OFES2 vs OFES

Nino3.4 Monthly SST Anomaly

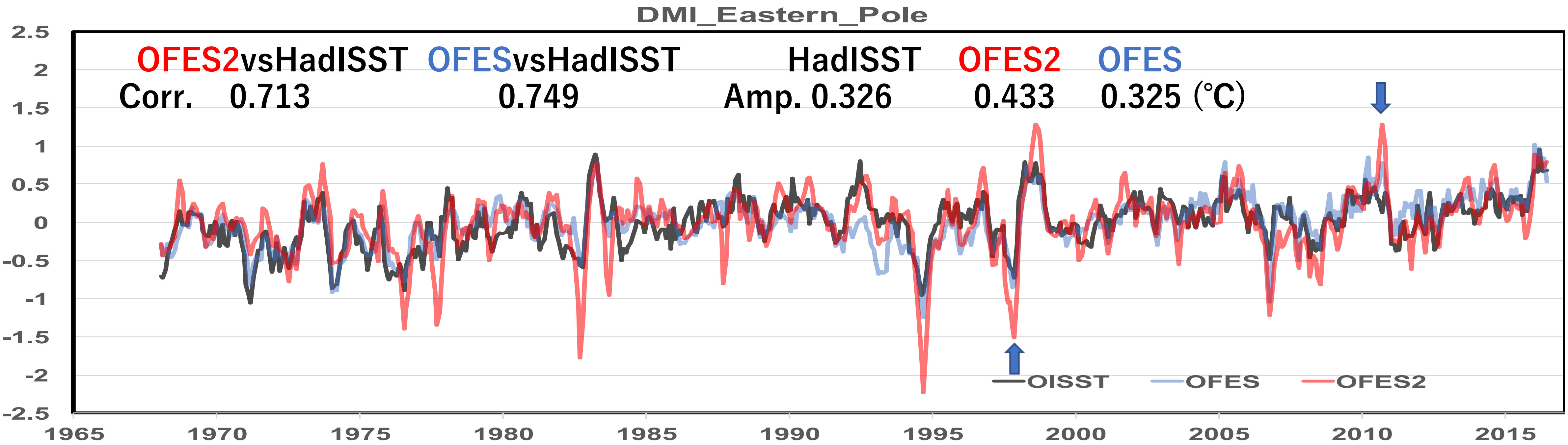


	OFES2 vs ERSST v5	OFES vs ERSST v5
Correlation	0.966717129	0.895990331

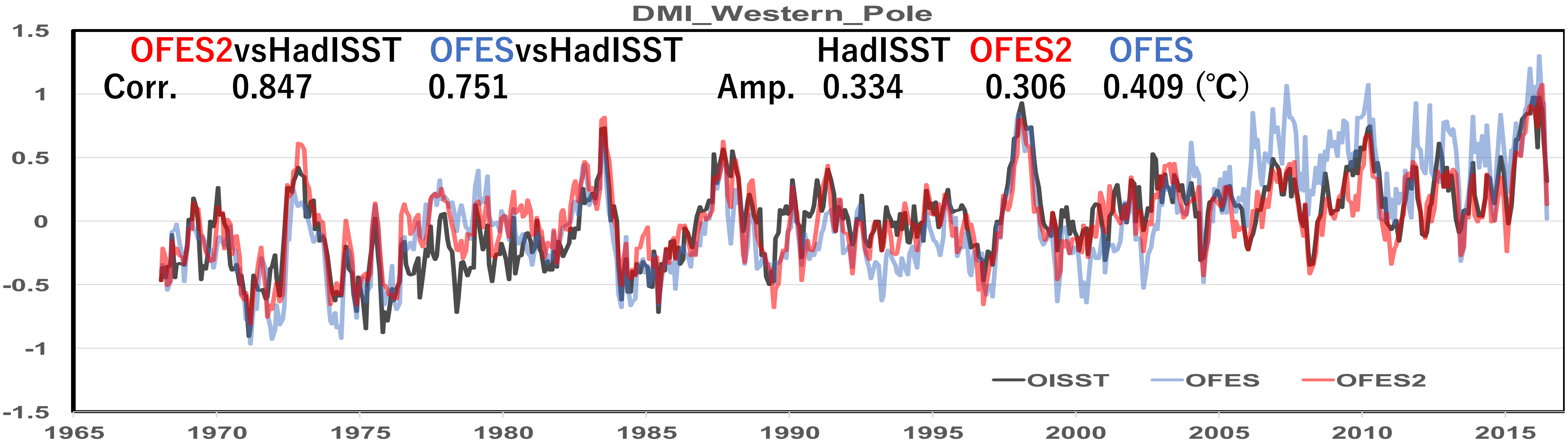
Monthly Dipole Mode Index (SSTA Difference Between Eastern and Western Poles)



	OFES2 vs HADISST	OFES vs HADISST		HADISST	OFES2	OFES
Correlation	0.714	0.659	Amplitude (℃)	0.318	0.520	0.384



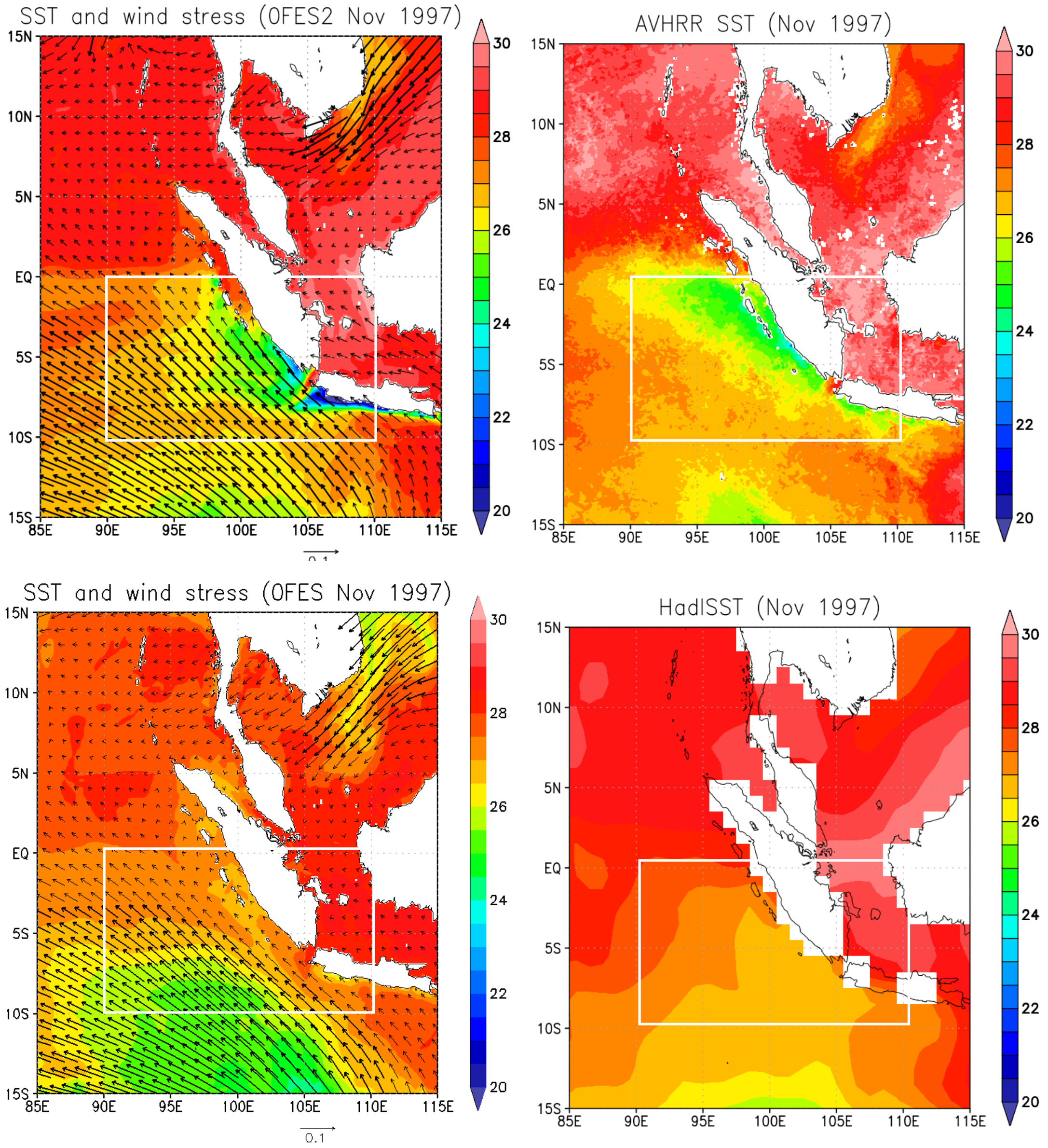
DMI_Eastern_Pole
OFES2vsHadISST OFESvsHadISST HadISST OFES2 OFES
Corr. 0.713 0.749 Amp. 0.326 0.433 0.325 (℃)
OISST
OFES
OFES2
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015



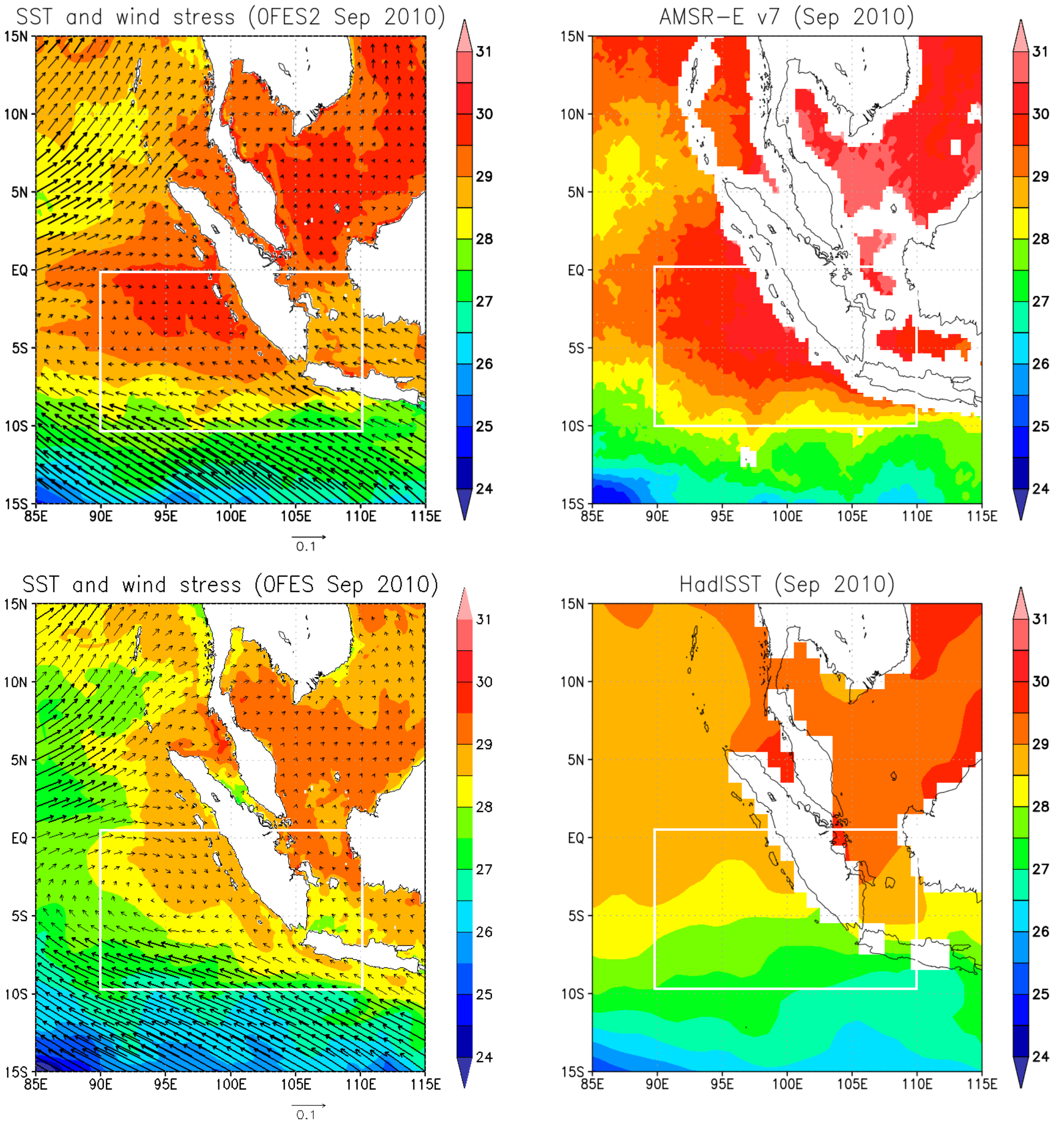
DMI_Western_Pole
OFES2vsHadISST OFESvsHadISST HadISST OFES2 OFES
Corr. 0.847 0.751 Amp. 0.334 0.306 0.409 (℃)
OISST
OFES
OFES2
1.5
1
0.5
0
-0.5
-1
-1.5
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

SST and Wind Stress in positive (Nov. 1997) and negative (Sep. 2010) IOD Events

Nov 1997 (Positive IOD)



Sep 2010 (Negative IOD)



Summary (OFES2)

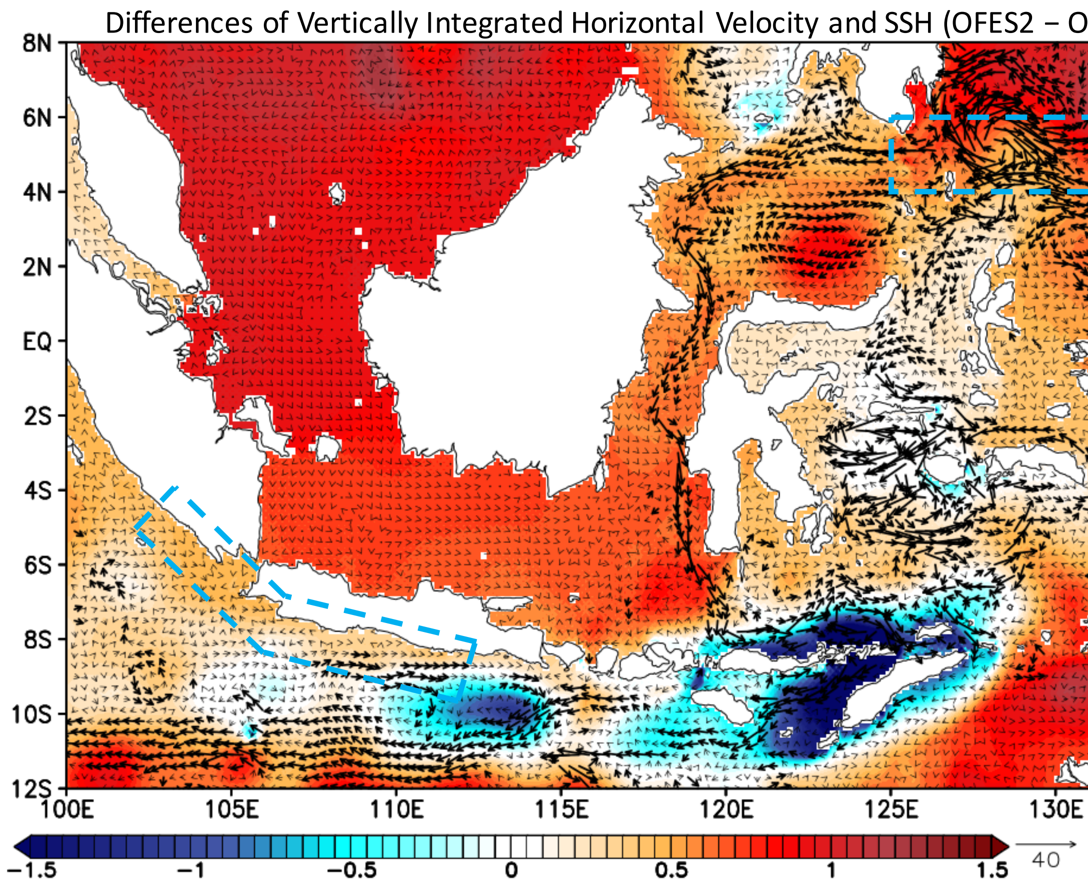
OFES2 forced by JRA55-do improves several oceanic aspects compared with OFES forced by NCEP reanalysis.

- SST and SSS biases
- Water properties in the subsurface of the Indonesian Seas and the subtropical Western Pacific
- Realistic cold SST in the eastern pole of the IOD

Several issues still remain in OFES2.

- Unrealistic path of the Gulf Stream
- No Azores Current

An Increase of the Indonesian Throughflow by internal tidal mixing



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Sasaki et al. (2018, GRL)

Introduction (Vertical Mixing)

- **A major role of vertical mixing in the global meridional overturning. circulation** (e.g. Bryan 1987; Tsujino et al. 2000)
- **Enhanced vertical mixing observed over rough bottom topography.** (Polzin et al. 1997; Whalen et al. 2012; Kunze 2017)
- **Tidal mixing scheme for OGCM representing the vertical mixing.** (e.g. St. Laurent et al. 2002)
- **Impacts of tidal mixing schemes upon the deep meridional overturning circulation and the deep water masses and the ocean energy budget.** (Simmons et al. 2004; Jayne 2009)

However, impacts of tidal mixing on the basin-scale upper-ocean circulation are less well known.

Fig.2 in Polzin et al. 1997

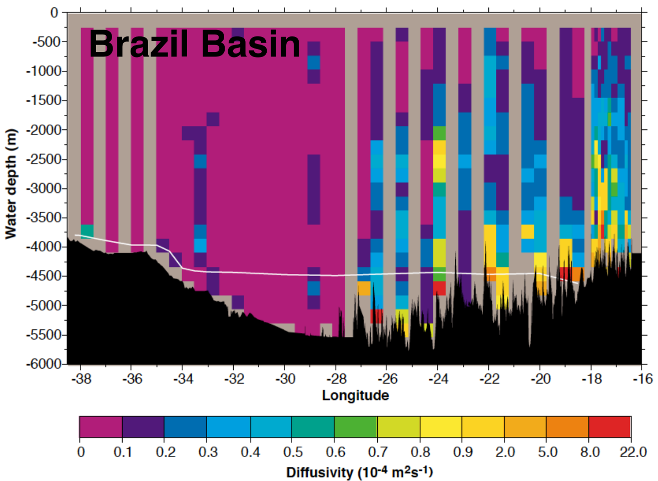
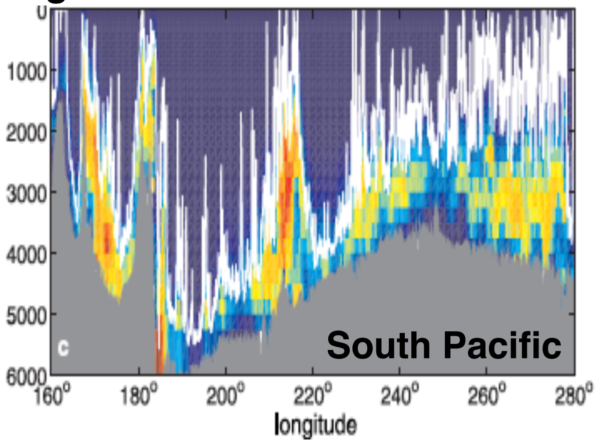


Fig2c in St. Laurent et al. 2002



Introduction (Indonesian Seas)

- **Enhanced vertical mixing occurs.**
  (Ffield and Gordon 1996; Nagai et al. 2017)

- **A tidal mixing significantly alters the water mass properties.** (Gordon et al. 2003)

- **A tidal mixing scheme in OGCM improves the water mass properties.**
  (Koch-Larrouy et al. 2007; Cuypers et al. 2017)

How tidal mixing influences on the transport of Indonesian Throughflow (ITF), which advects warm water from the Pacific to Indian Ocean, has not yet been examined.

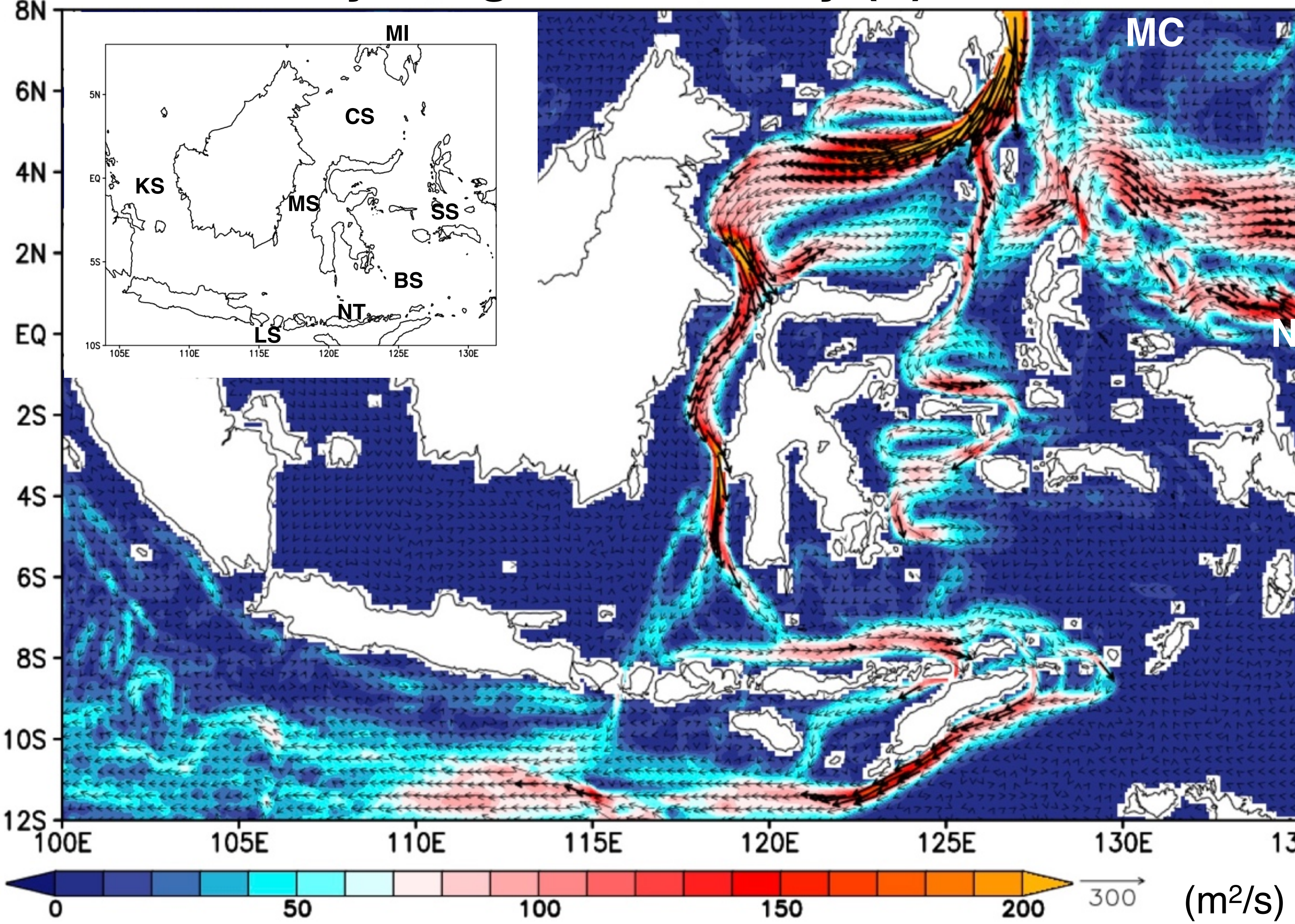
Introduction (ITF Transport)

- The island rule controlled by the large-scale winds
  (Godfrey 1989)
- The pressure gap between the western Pacific and Indian Ocean (Wyrtki 1987)
- A good correlation between the SSH (corresponding to the pressure gap) and the ITF transport variations in both seasonal and interannual timescales
  (Potemra et al., 1997; Shinoda et al. 2012; Susanto & Song 2015)

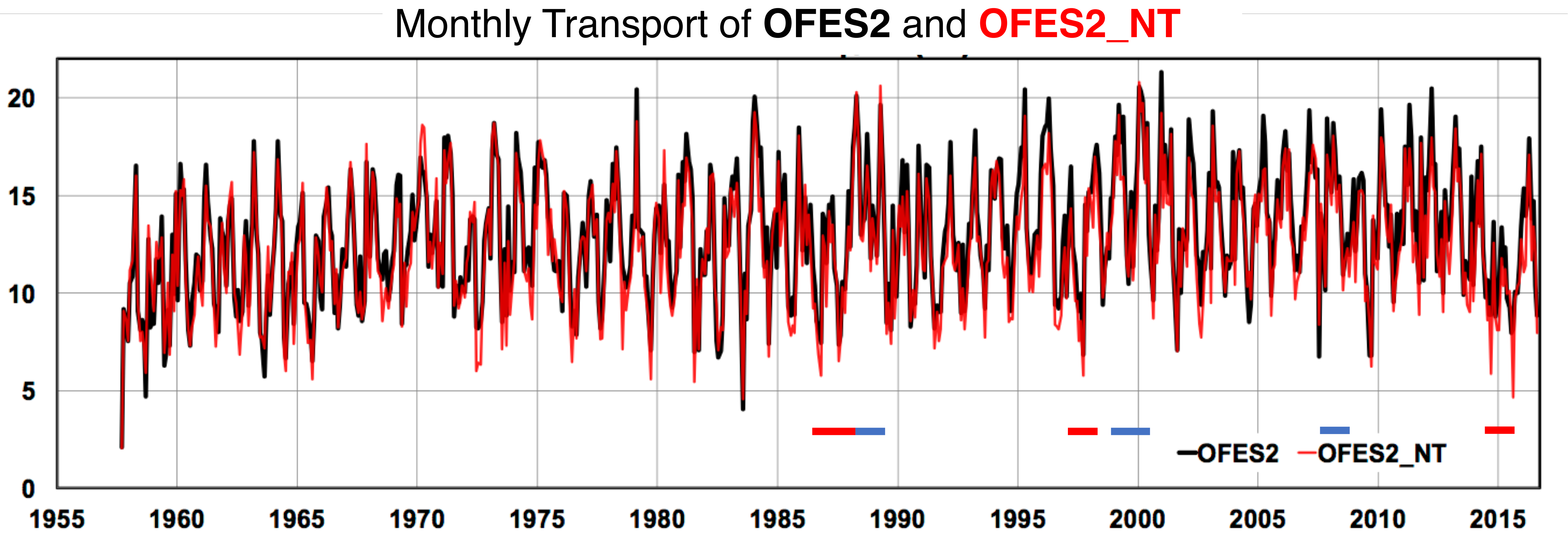
We examine impacts of tidal mixing on the ITF transport by comparing OFES2 (with the tidal mixing scheme) and OFES2_NT without the tidal mixing scheme.

ITF in OFES2

Vertically Integrated Velocity ($\vec{V}$) in 1995-2016

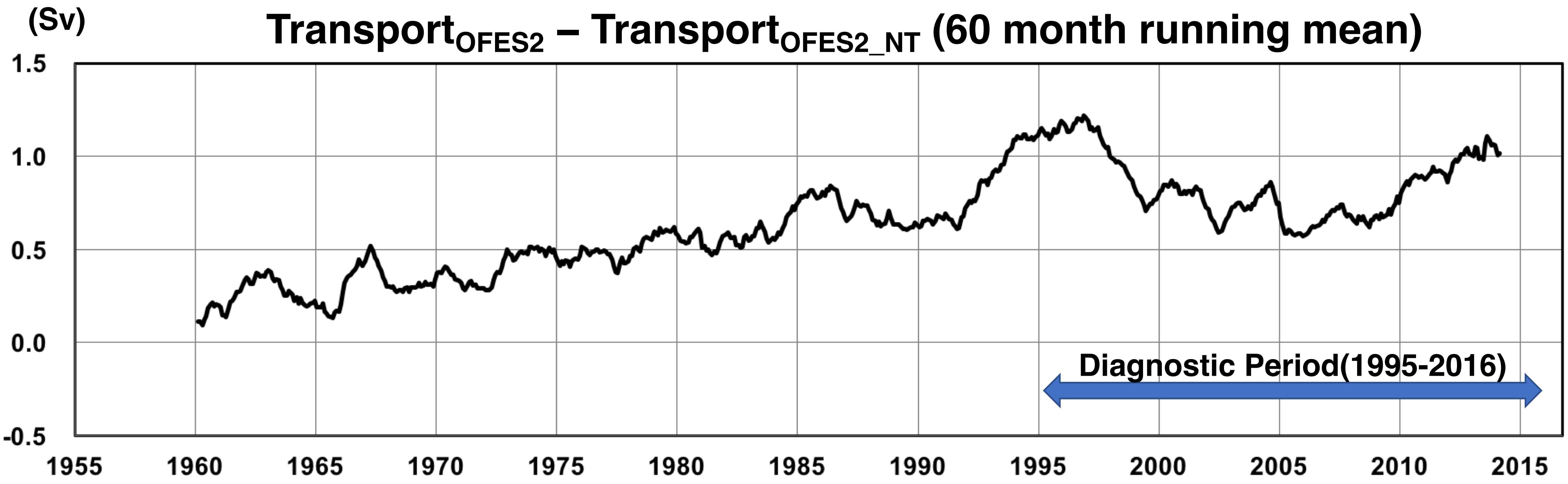


ITF Transport in OFES2 and OFES2_NT



- Large (small) transport in summer (winter) (e.g. Masumoto & Yamagata 1996)
- Small (Large) transport in El Niño (La Niña) years (e.g. Meyers 1996)
- ITF transport in **OFES2 (13.83 Sv)** is larger than in **OFES2_NT (12.95 Sv)** during 1995-2016. (15 Sv in the INSTANT observation during 2004-2006, Gordon et al. 2010)

ITF Transport in OFES2 and OFES2_NT



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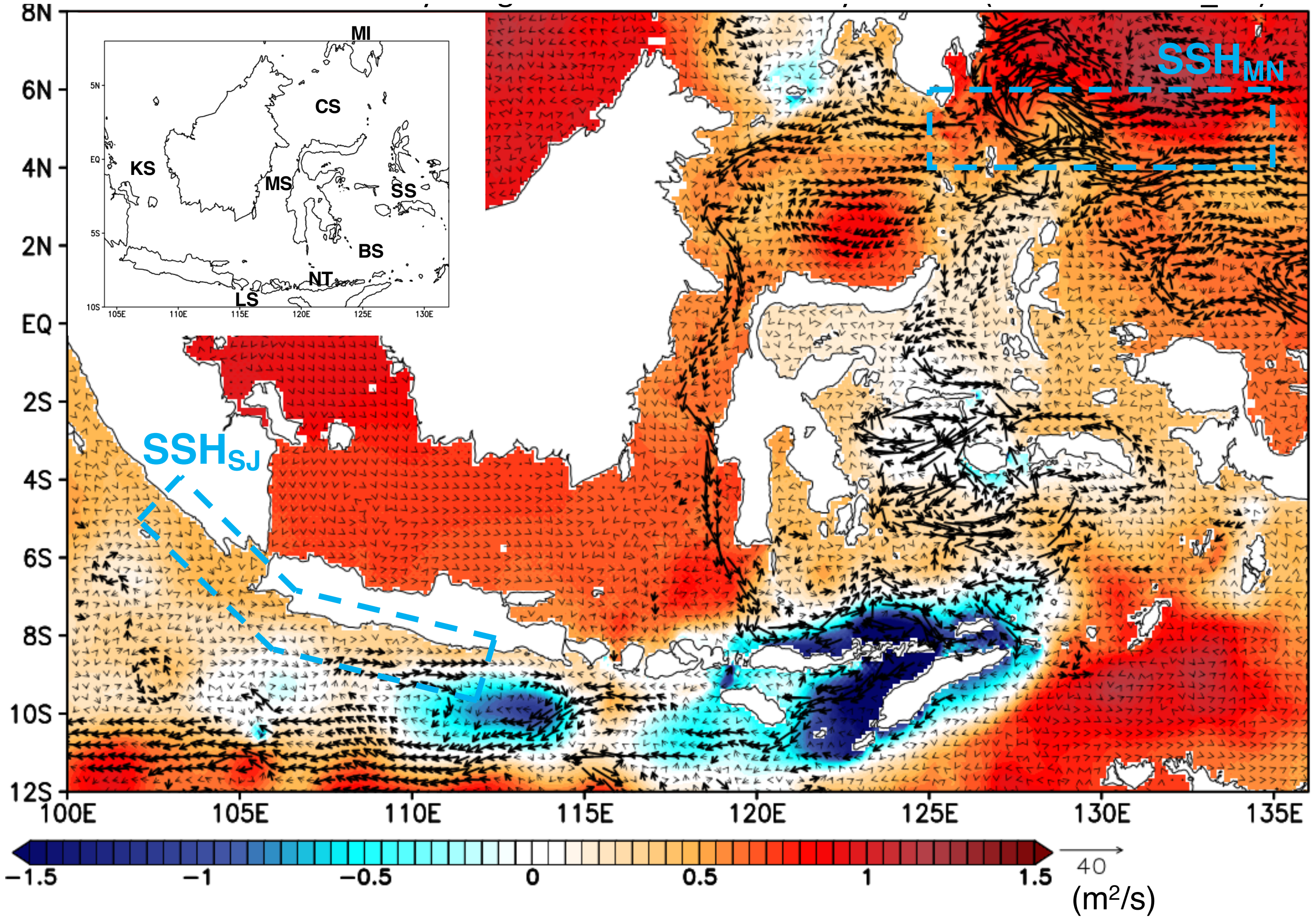
ITF (OFES2 minus OFES2_NT)

$\overrightarrow{V}_{OFES2} - \overrightarrow{V}_{OFES2\_NT}$ & $SSH_{OFES2} - SSH_{OFES2\_NT}$ in 1995-2016



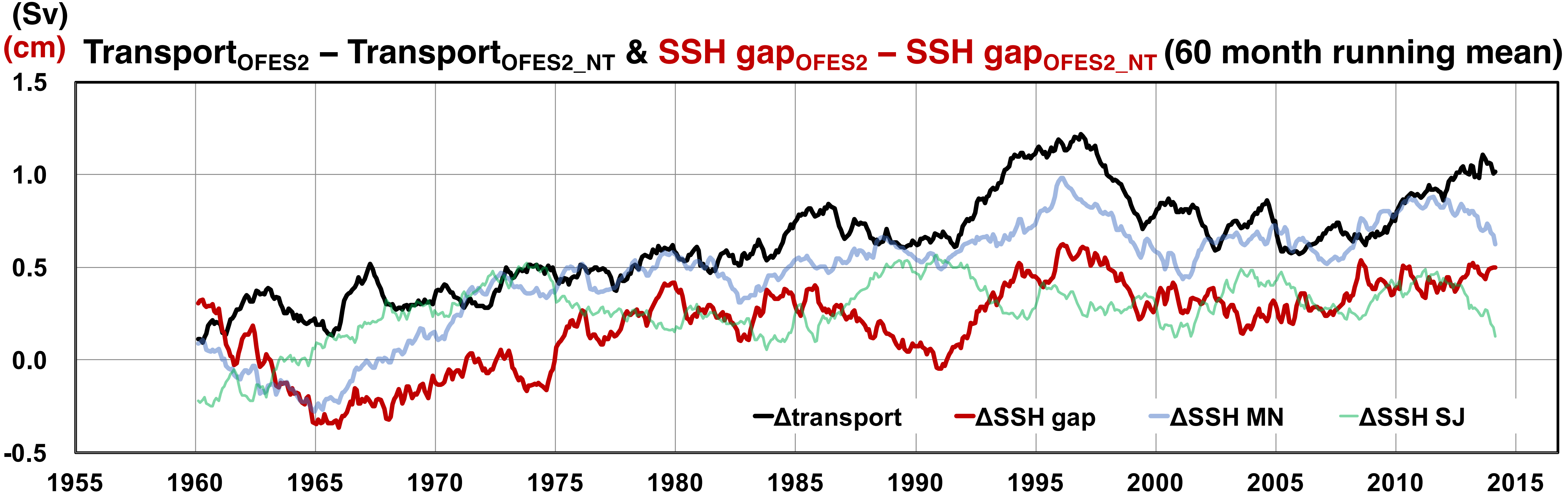
Prominent positive ΔSSH in the Western Pacific makes large SSH gap between the Pacific and Indian Oceans in OFES2.

⇒This large SSH gap increases the ITF transport in OFES2.

ΔITF :0.88 Sv
ΔSCSTF:0.022 Sv
South China Sea Throughflow (SCSTF) is not considered.

SSH gap index: SSH_{MN} - SSH_{SJ}

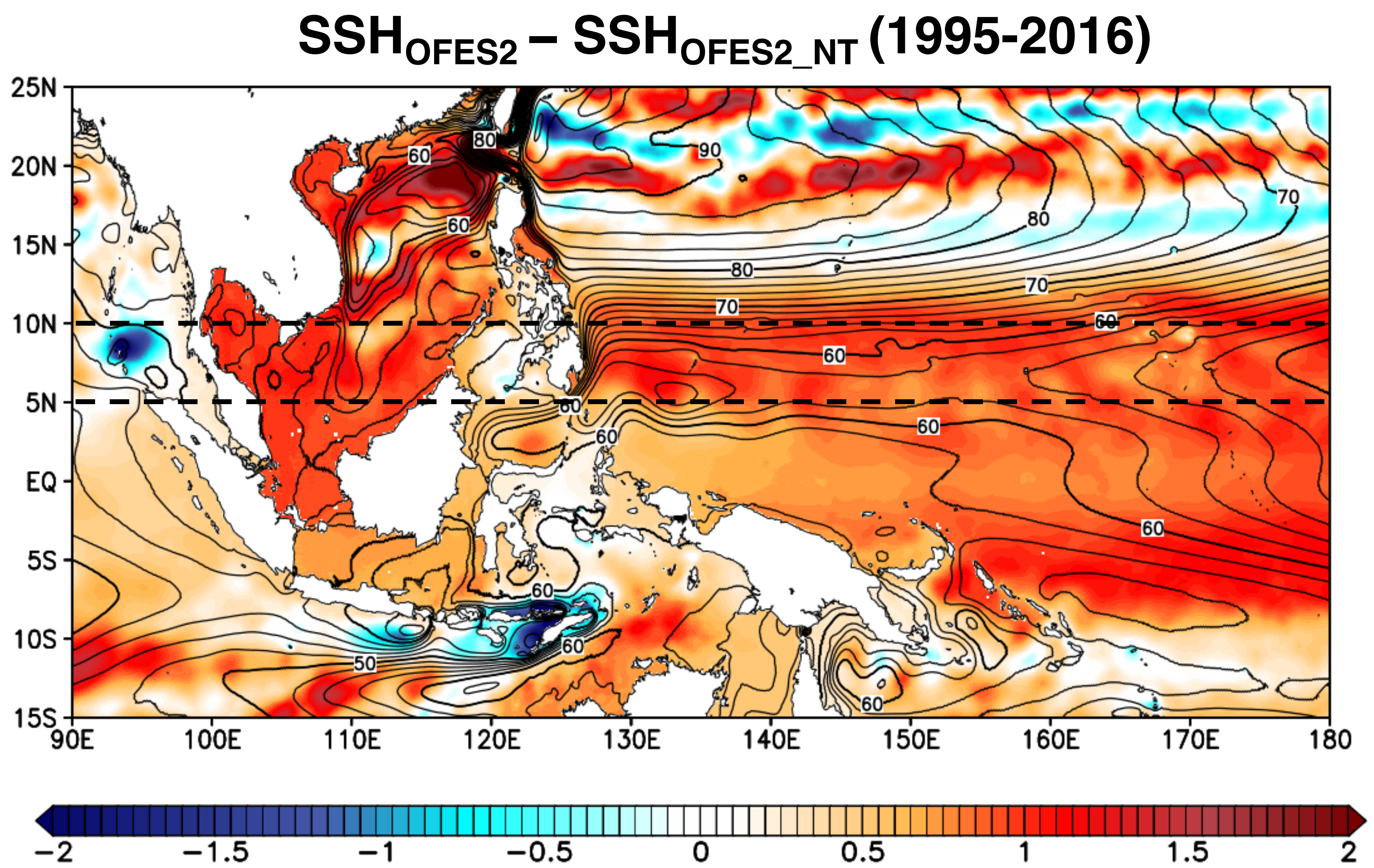
ΔITF Transport & ΔSSH Gap (OFES2 minus OFES2_NT)



Time series of the differences of **ITF transport** and **SSH gap index (SSH_{MN} – SSH_{SJ})** between OFES2 and OFES2_NT are well correlated.

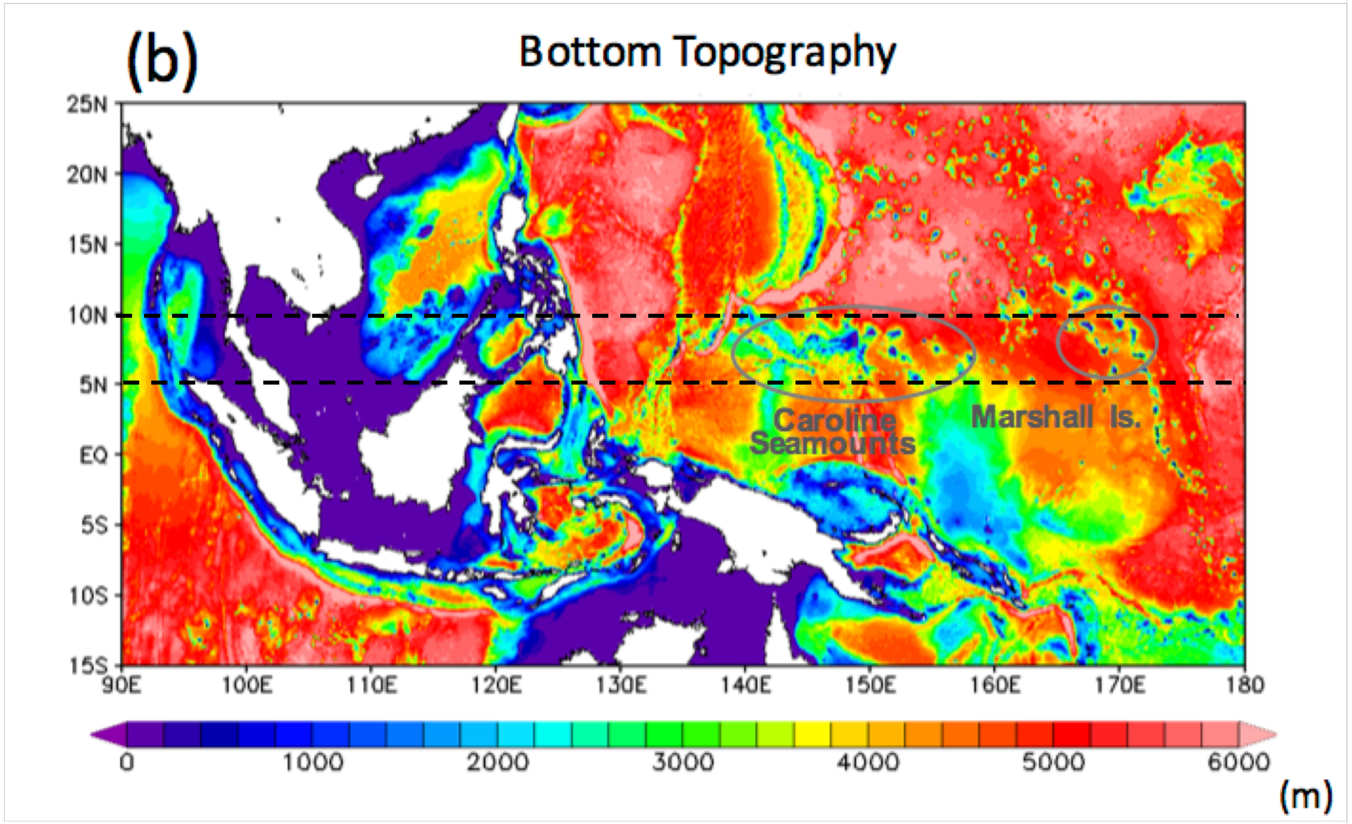
⇒***The increase of ITF transport in OFES2 is supported by the pressure gap increase.***

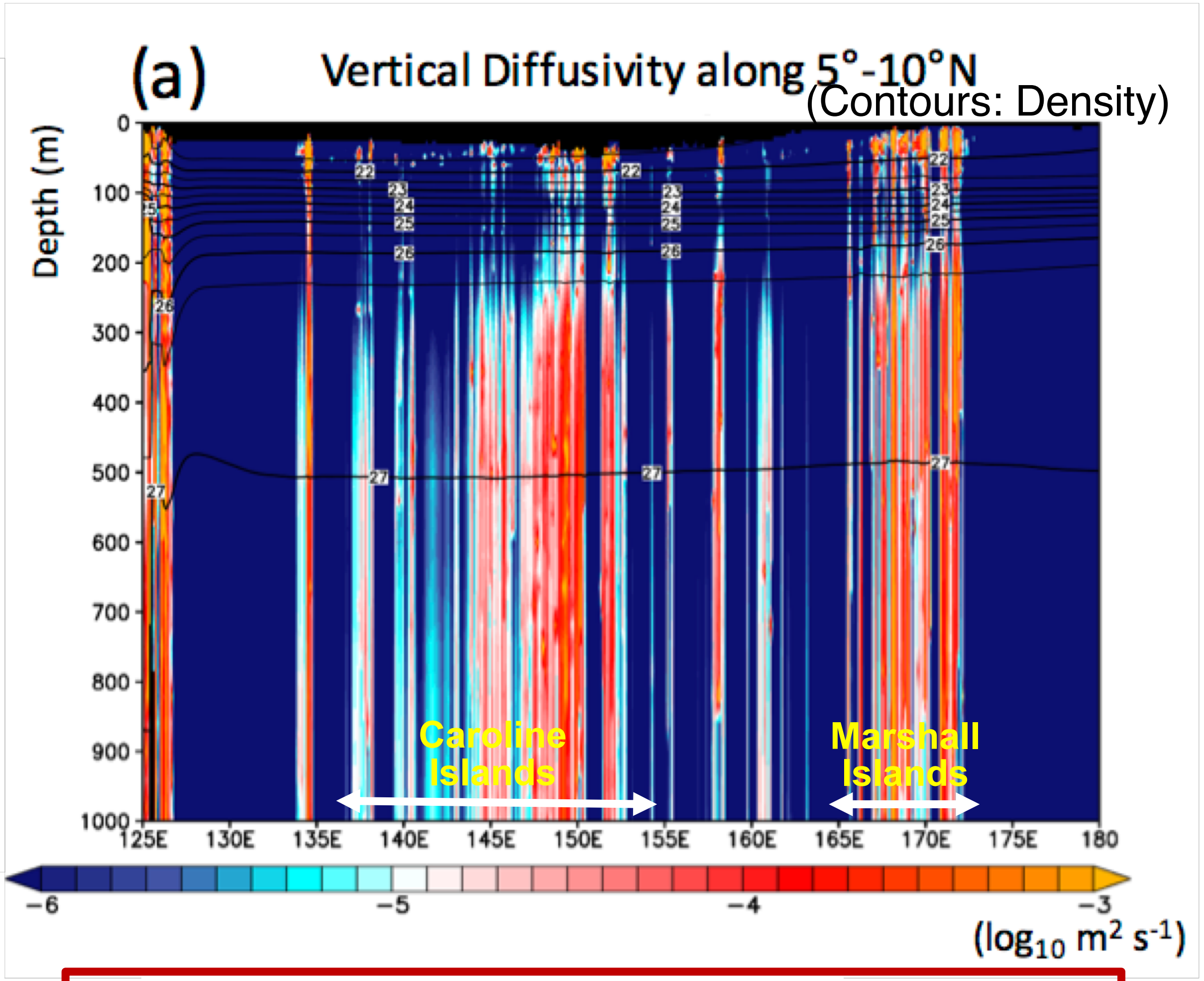
SSH Differences (OFES2 minus OFES2_NT)



Prominent SSH rise (≈ 1 cm) along 5°-10°N over the whole western Pacific in OFES2 compared to OFES2_NT.

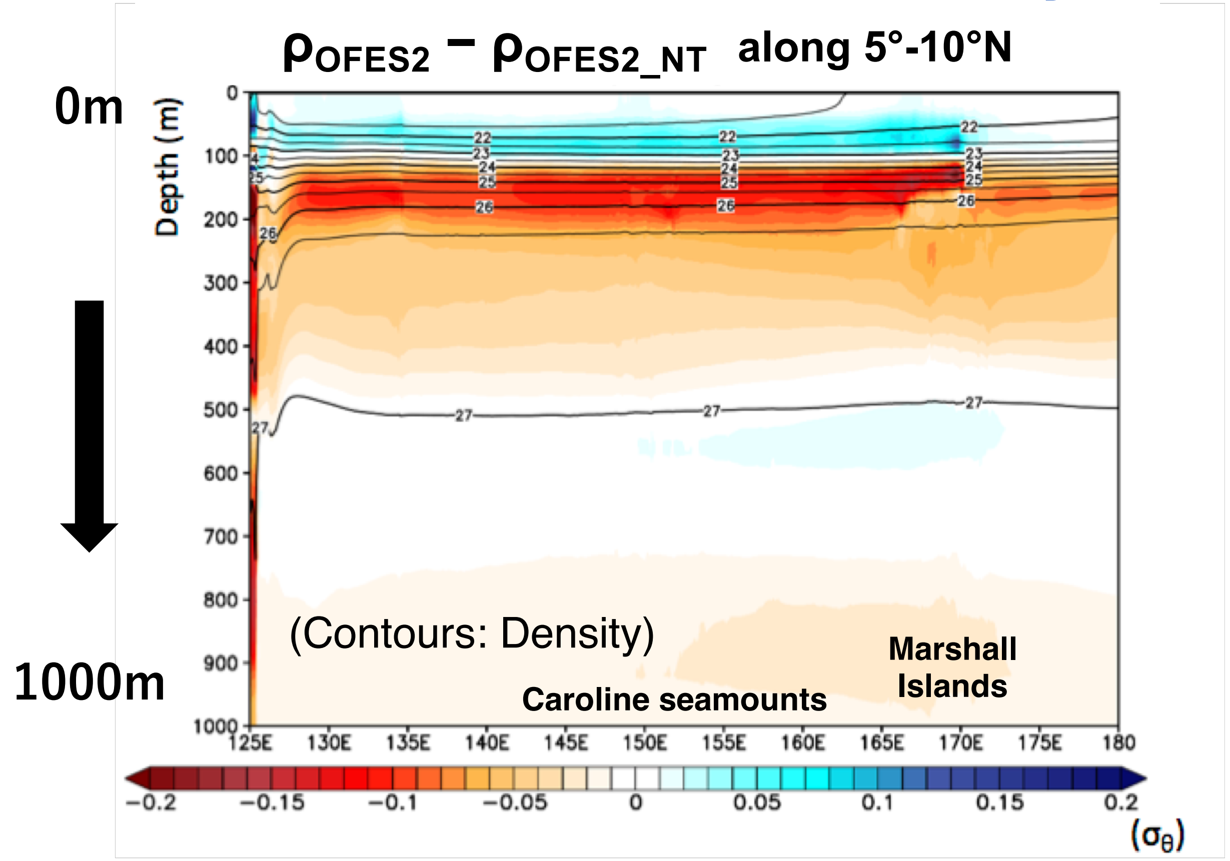
Vertical Diffusivity averaged over 5°-10°N in the Western Pacific

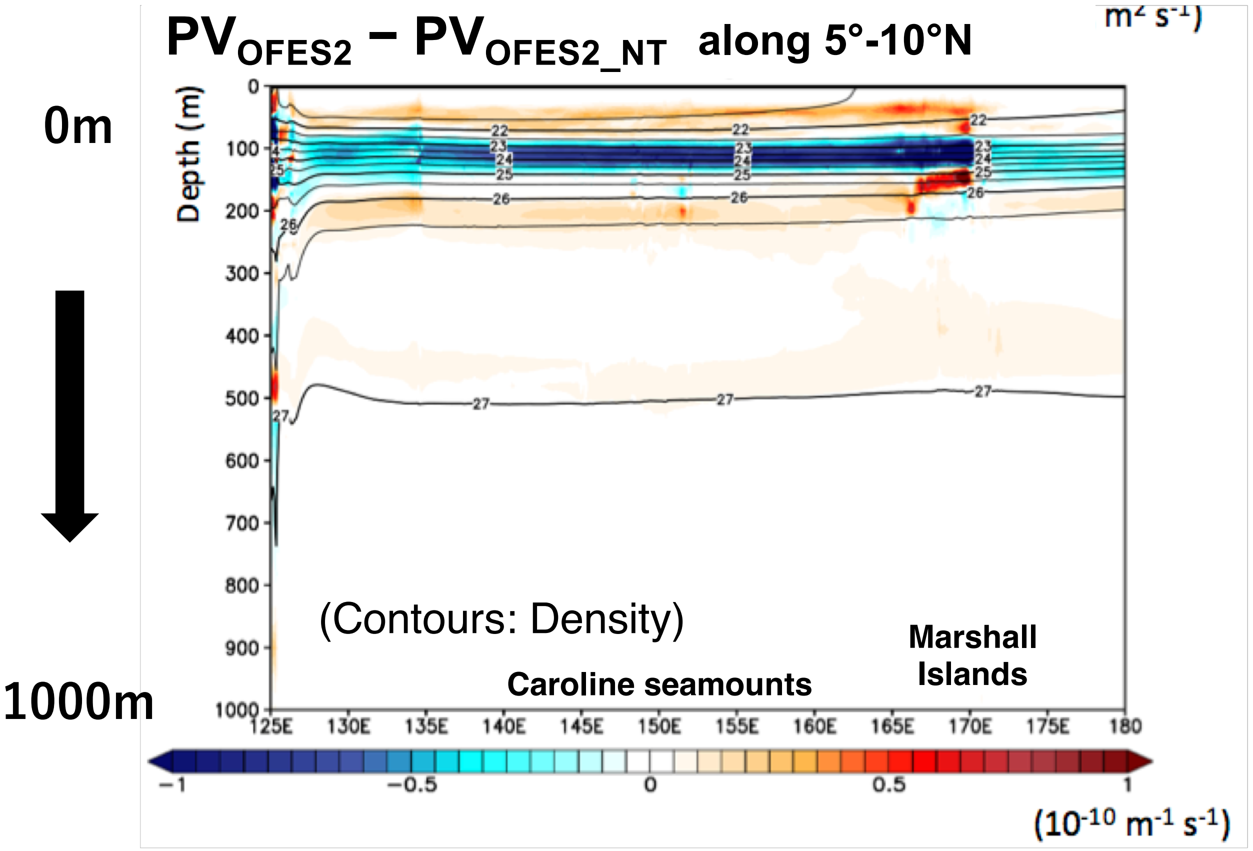




Shallow and rough topographies around the Caroline and Marshall Islands → **Locally enhanced diffusivities extending upward into the lower thermocline**

Differences of Density and PV Averaged over 5°-10°N





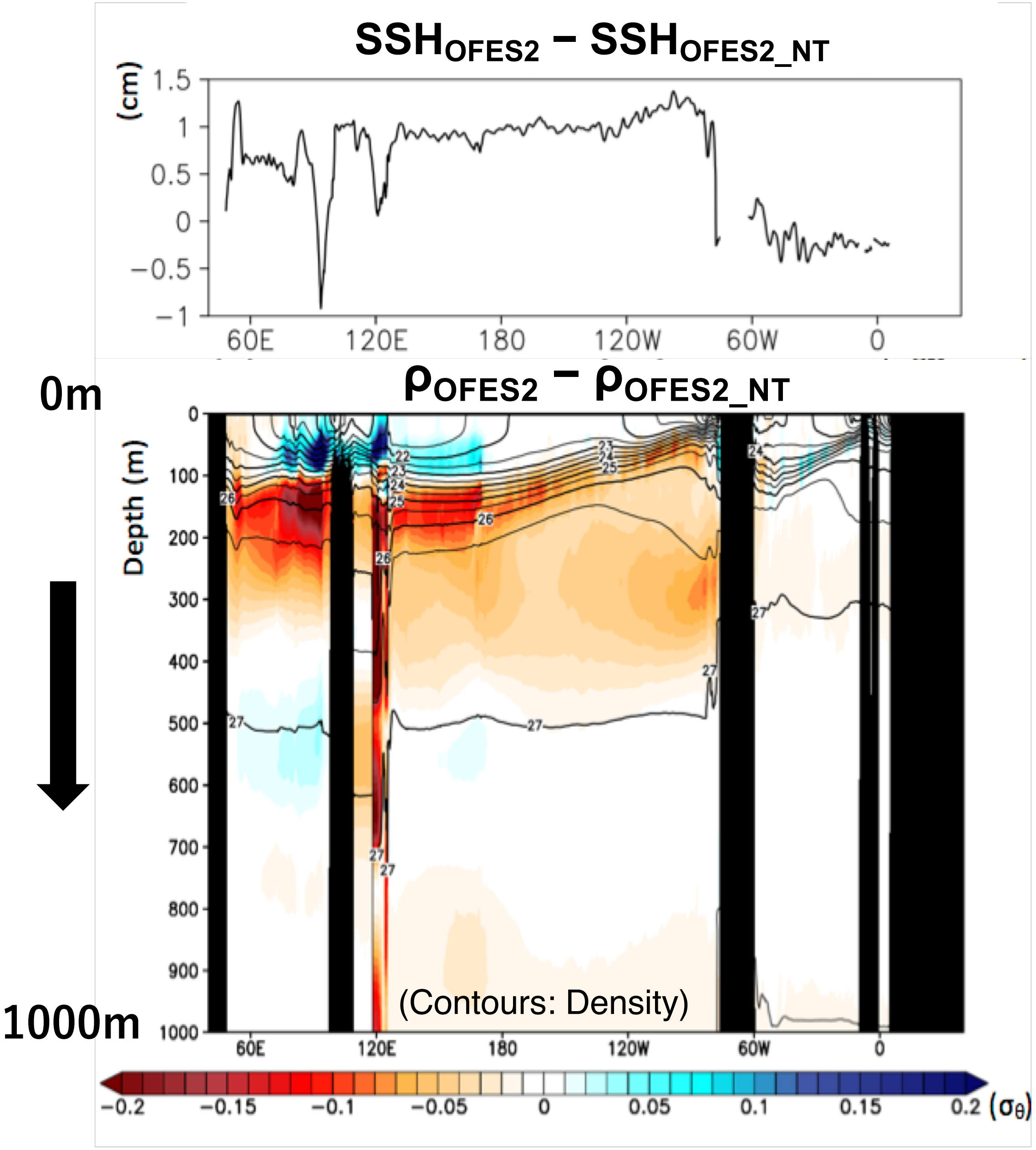
・**The density in OFES2 decreases much in the lower thermocline and below it (< $0.1\sigma_\theta$).**

⇒ The SSH in OFES2 raises due to a net increase of buoyancy (density decrease) for the water column considering dynamic height (=∫(1/ρ) dp).

・**Changes in density and PV extend westward from the Marshall Island.**

⇒ Westward propagations of the signal via Rossby waves.

Differences of Density and SSH Averaged over 5°-10°N

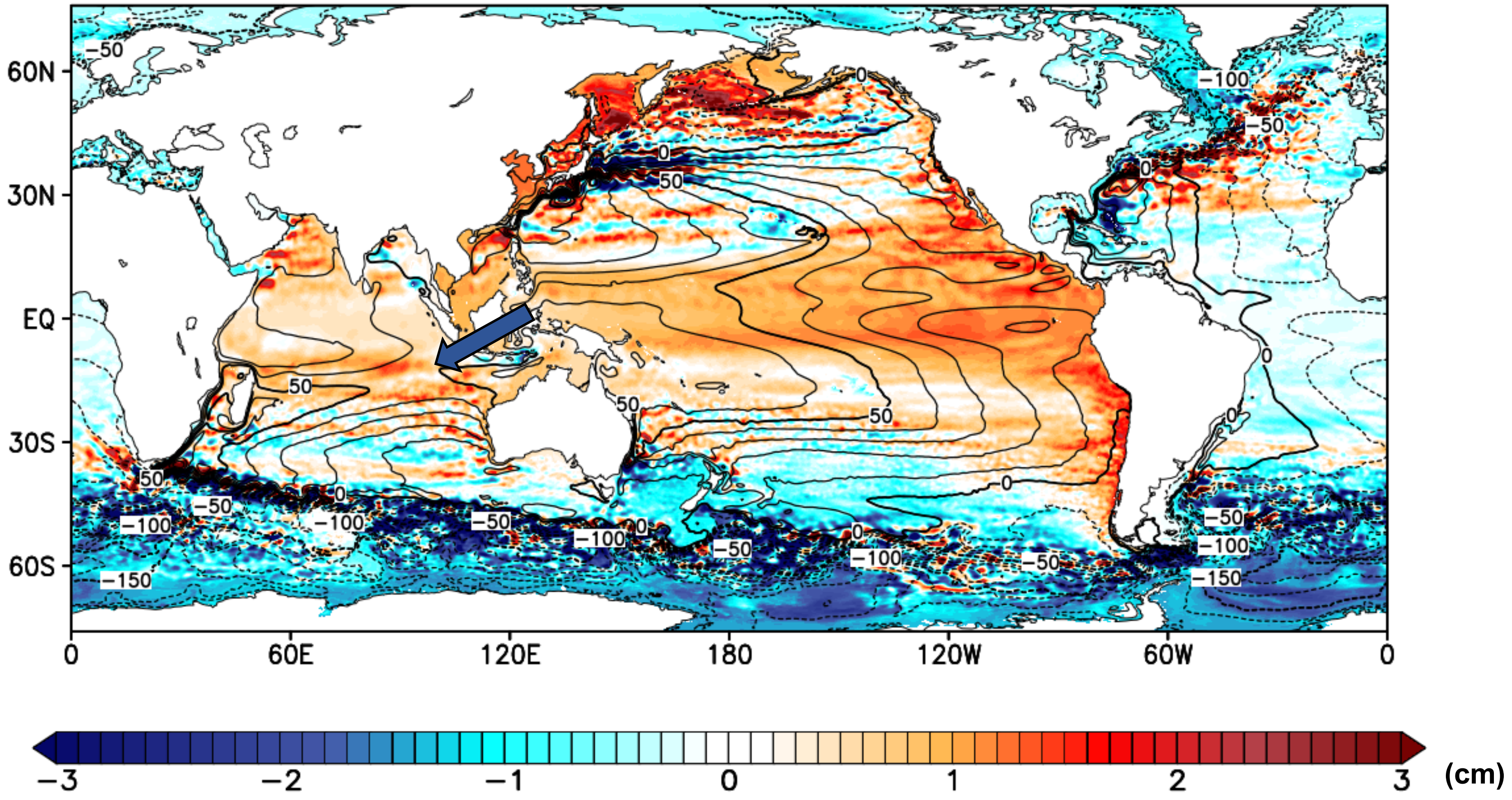


Large SSH rise in the Pacific Ocean in OFES2, due to enhanced diffusivity over many islands chains in the tropical Pacific.

Buoyancy increase in OFES2 spreads over whole basin of the Pacific via Rossby and Kelvin waves (Furue et al. 2015)

SSH Differences (OFES2 – OFES2_NT)

SSH_{OFES2}–SSH_{OFES2_NT} (Contours: SSH in OFES2)



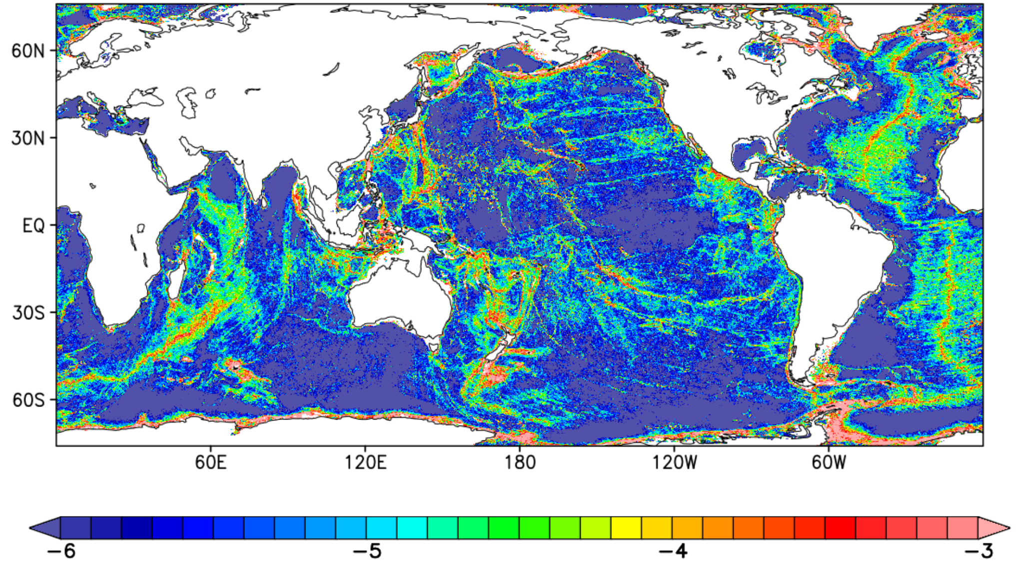
The basin-scale SSH rise in the tropical Pacific increases the pressure gap between the Pacific and Indian oceans, and then ITF transport strengthens in OFES2 compared with OFES2_NT.

Summary (ITF in OFES2)

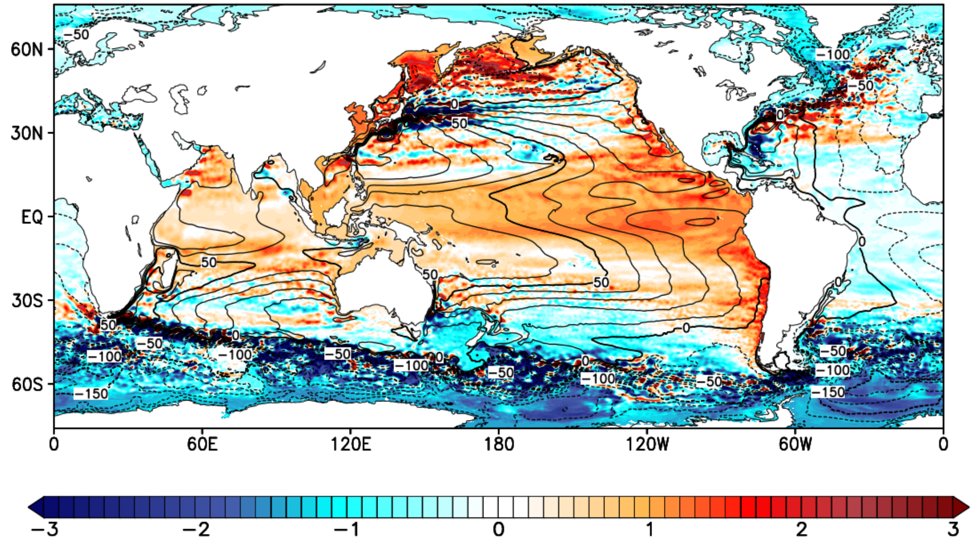
A comparison between two OGCM simulations with and without a tidal mixing scheme shows that the ITF transport increases with tidal mixing.

Many Island Chains in the tropical Pacific. → **Enhanced vertical mixing increases buoyancy of water column via water mass property change in vertical.** → **The SSH rises much in the tropical Pacific, which strengthens the ITF transport.**

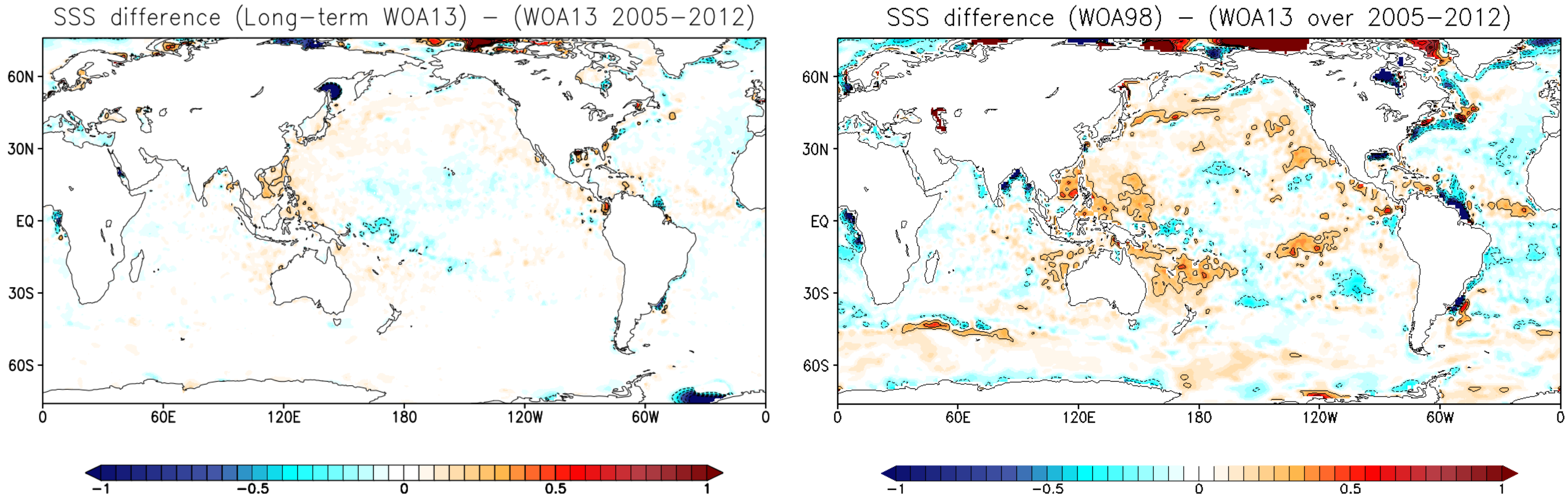
Vertical Mean Diffusivity in OFES2



SSH (OFES2) – SSH (OFES2_NT)

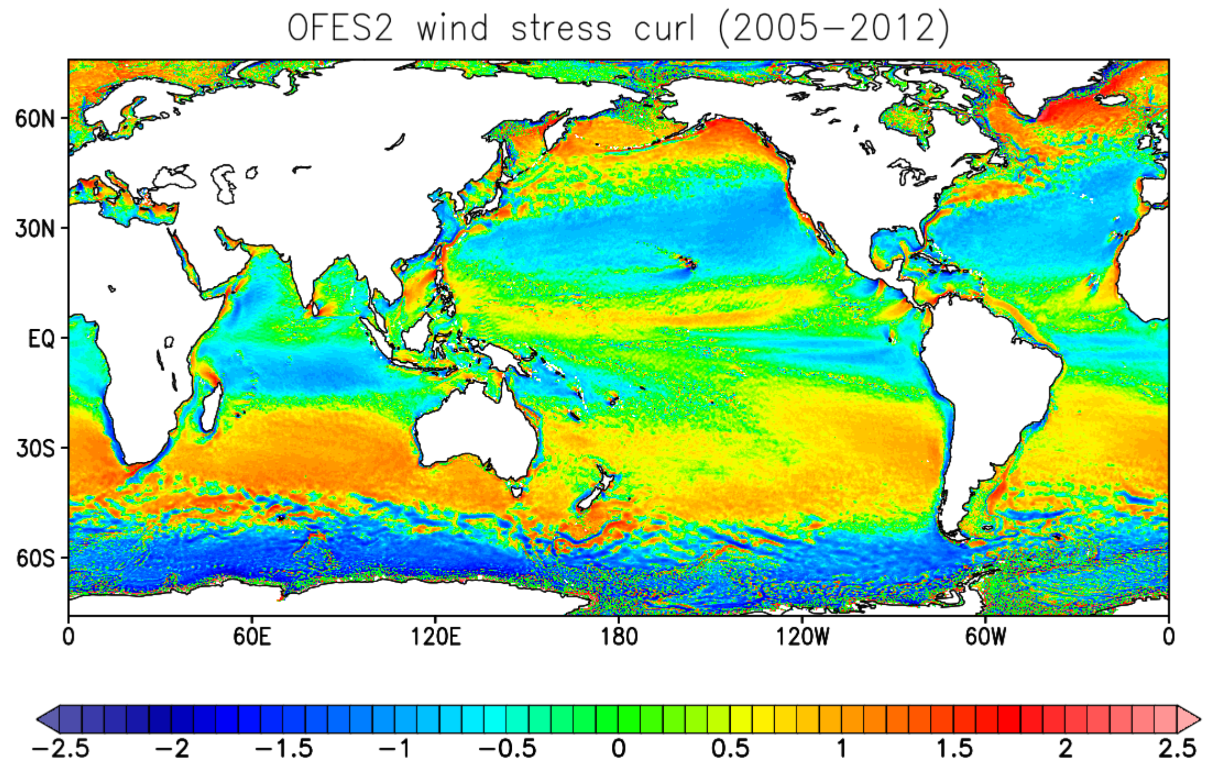


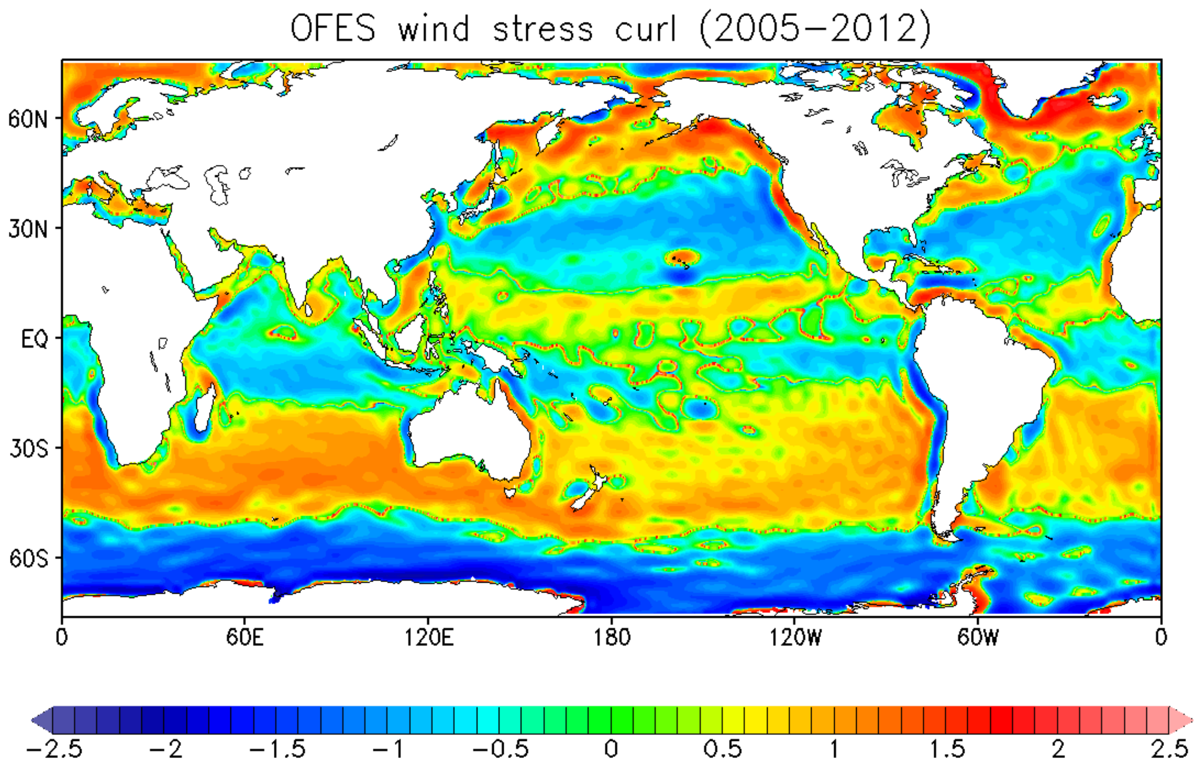
Difference between SSS using restoring and WOA13 SSS (2005-2012)



SSS bias in OFES is similar to SSS difference between WOA98 and WOA13(2005-2012) due to strong restoring with 6 day.

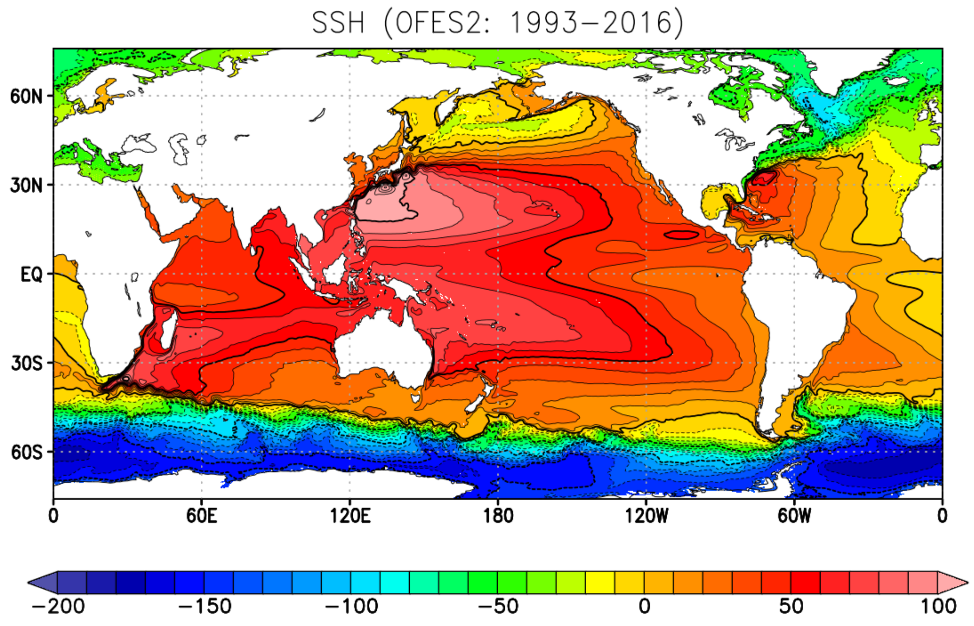
Wind Stress Curl (2005-2012)

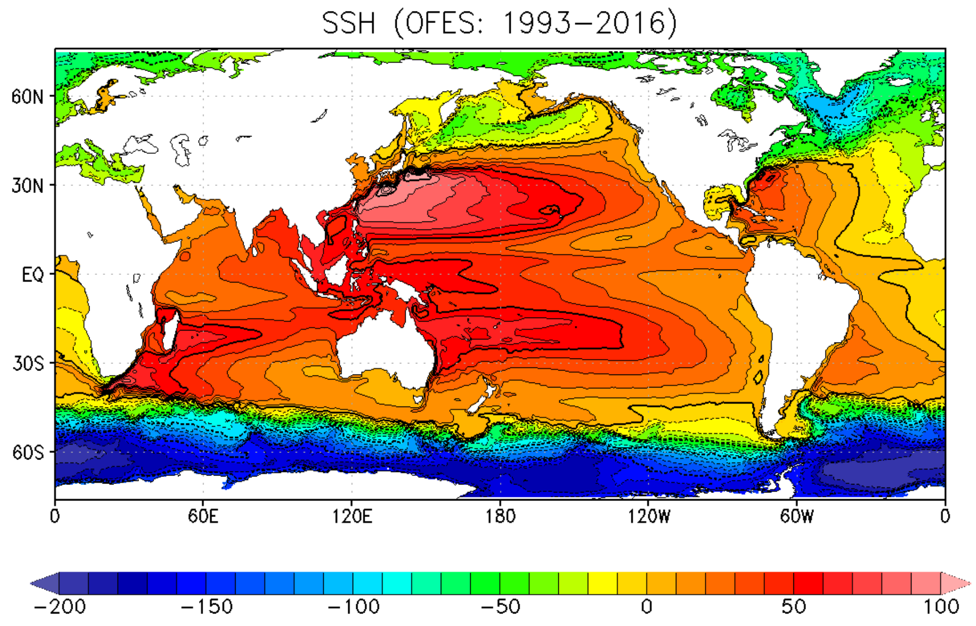


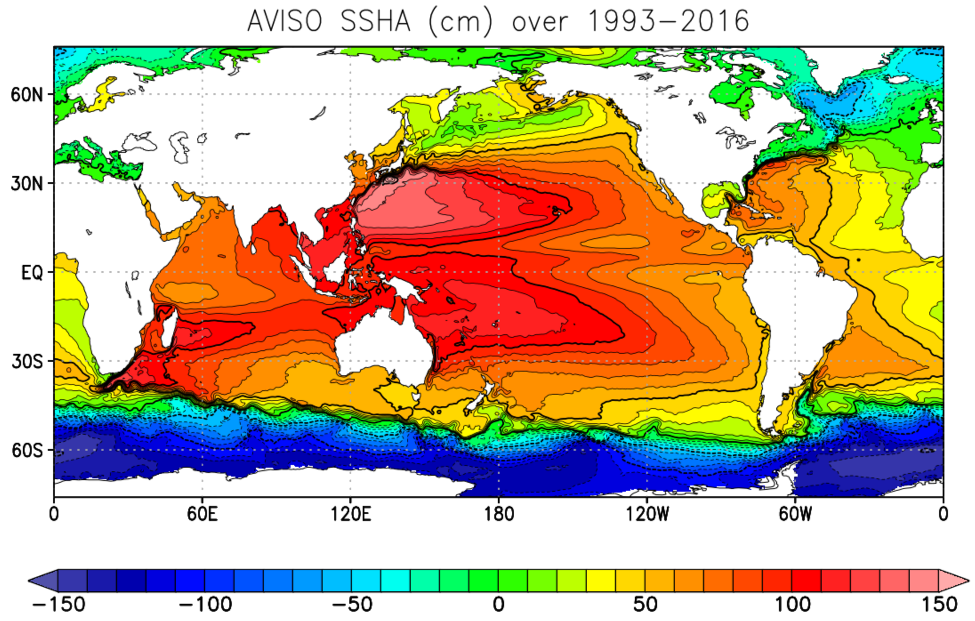


common logarithm scale (10^{-7} N m^{-3})

Long-term SSH over 1993-2016







OFES2 demonstrates the SSH distribution of subtropical gyres in the South and North Pacific more realistically than OFES.

The issues of no Azores Current and not turning northward of the Gulf Stream remain in OFES2.

Tidal Mixing Scheme (St. Laurent et al. 2002)

Energy Flux at bottom：$E(x,y) = \rho N_b u^2 s^2/2\ \kappa$ [Wm^{-2}] (1)

Vertical Diffusivity：$Kv(x,y,z) = \Gamma q\ E(x,y)\ F(z) / (\rho N^2)$ (2)

Dissipation Function in Vertical: $F(z)=[e^{-(H-Z)/\zeta}]/[\zeta(1-e^{-H/\zeta})]$ (3)

ρ：density, N：buoyancy frequency (N_b at bottom)

u: barotropic tidal speed (K1 and M2 from FES2012 model, Carrère et al. 2012)

s, κ：slope and wavenumber of topography (ETOPO1, Amante & Eakins 2009)

Γ：mixing efficiency of turbulence (=0.2)

q：dissipation efficiency (=0.3)

H：bottom depth

ζ：vertical decay scale(=500m)

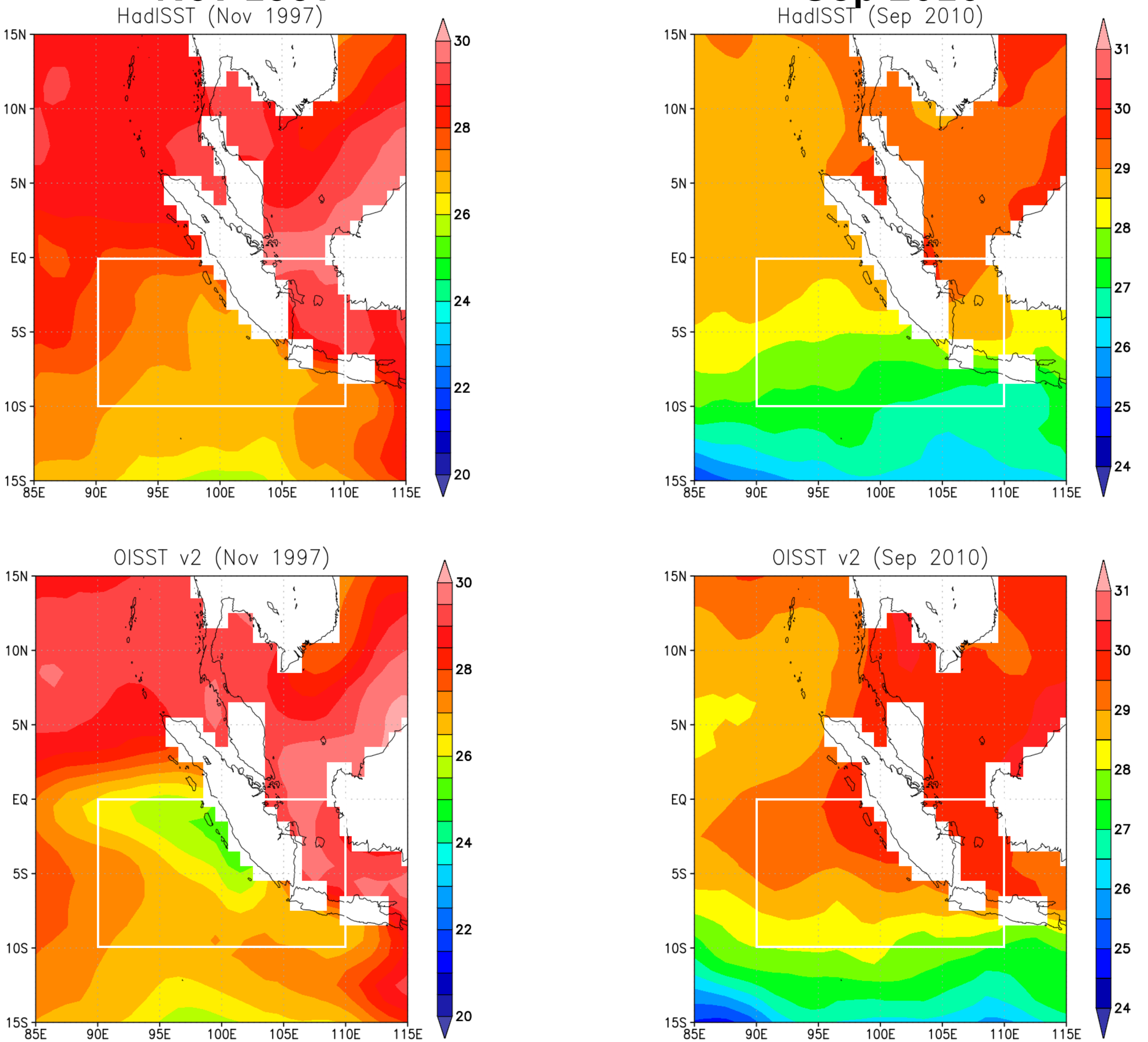
SST in positive (Nov. 1997) and negative (Sep. 2010) IOD Events

Nov 1997

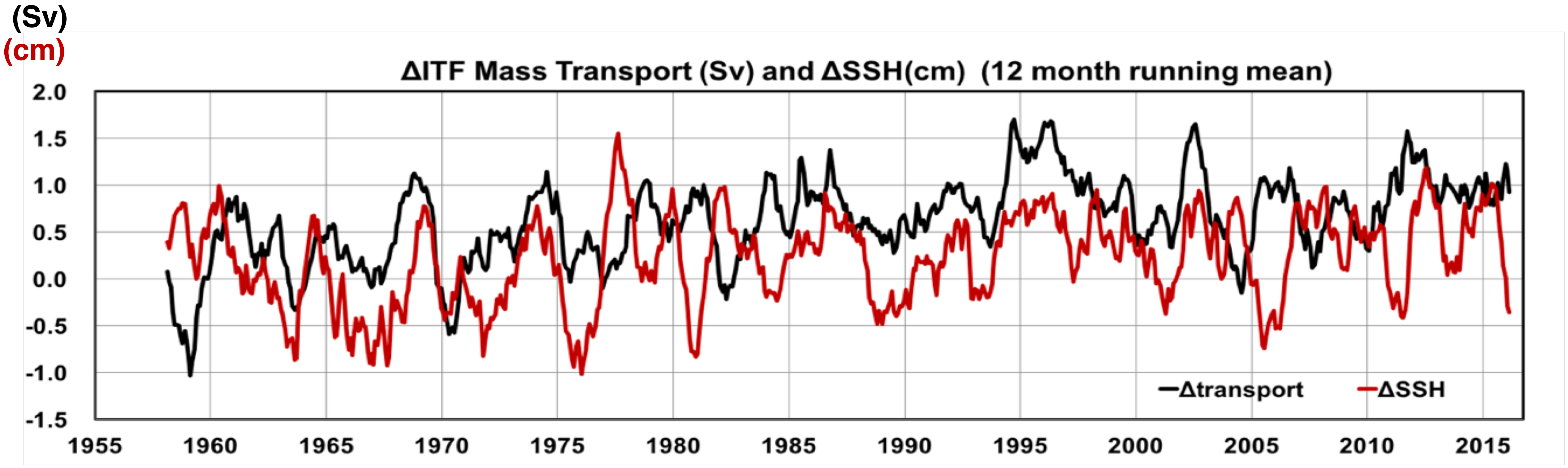
Sep 2010

HadISST (1871-present)

OISST v2 (1981-present)



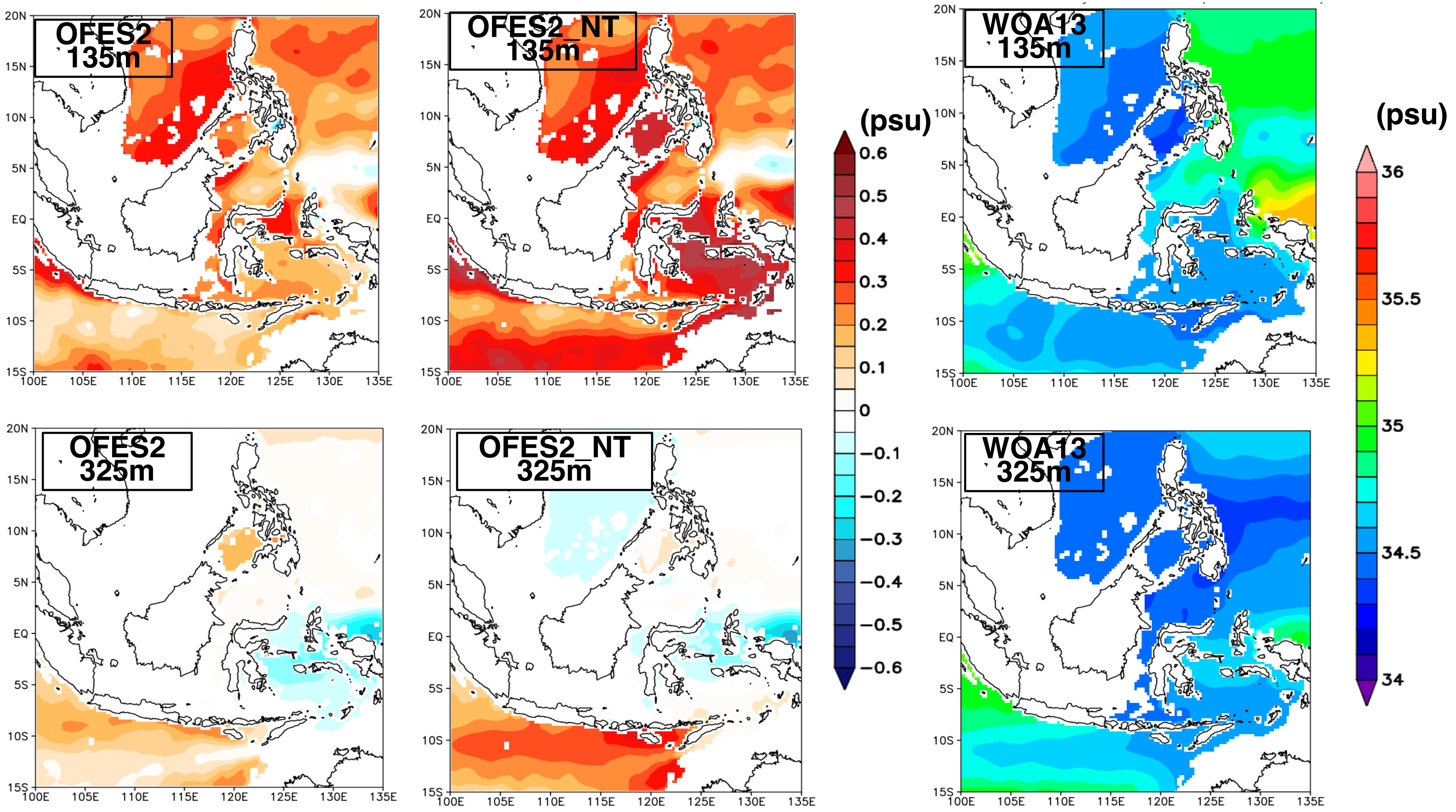
ΔITF Transport & ΔSSH gap (OFES2 minus OFES2_NT)



Time series of **ΔITF transport** and **ΔSSH gap between the Western Pacific and Indian Oceans** are correlated in a interannual timescale.

However, these variations are not correlated with El Niño and La Niña events.

Salinity in the Indonesian Seas (OFES2 vs OFES2_NT)



The implementation of a tidal mixing scheme improves the water-property in the Indonesian Seas as well as in previous studies. It is possible that including the local effects of tidal mixing may improve more the water-property (e.g. Koch-Larrouy et al. 2007).

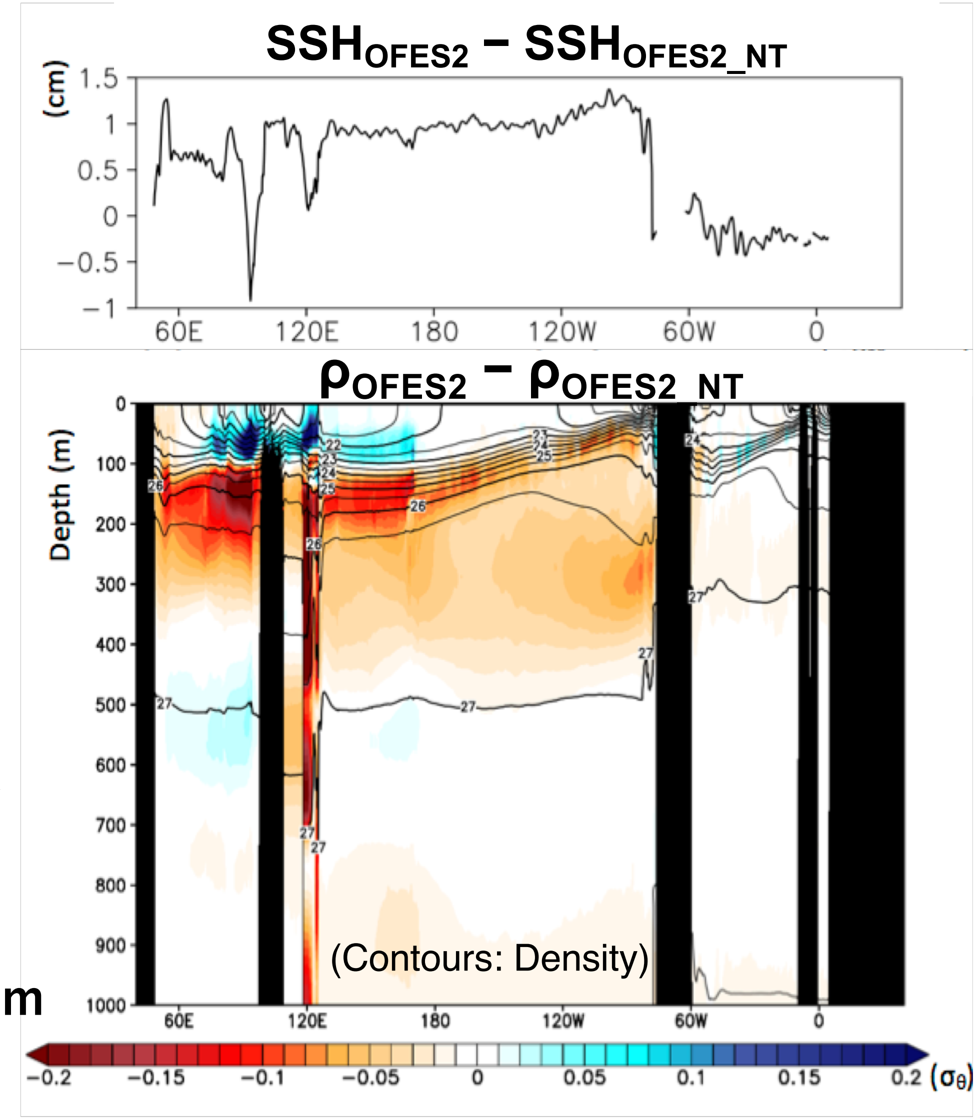
Differences of Density and SSH Averaged over 5°-10°N

The enhanced diffusivities over **many rough topographies in the tropical Pacific**

Buoyancy increase for the water column and its spreading over whole basin via Rossby and Kelvin waves (Furue et al. 2015)

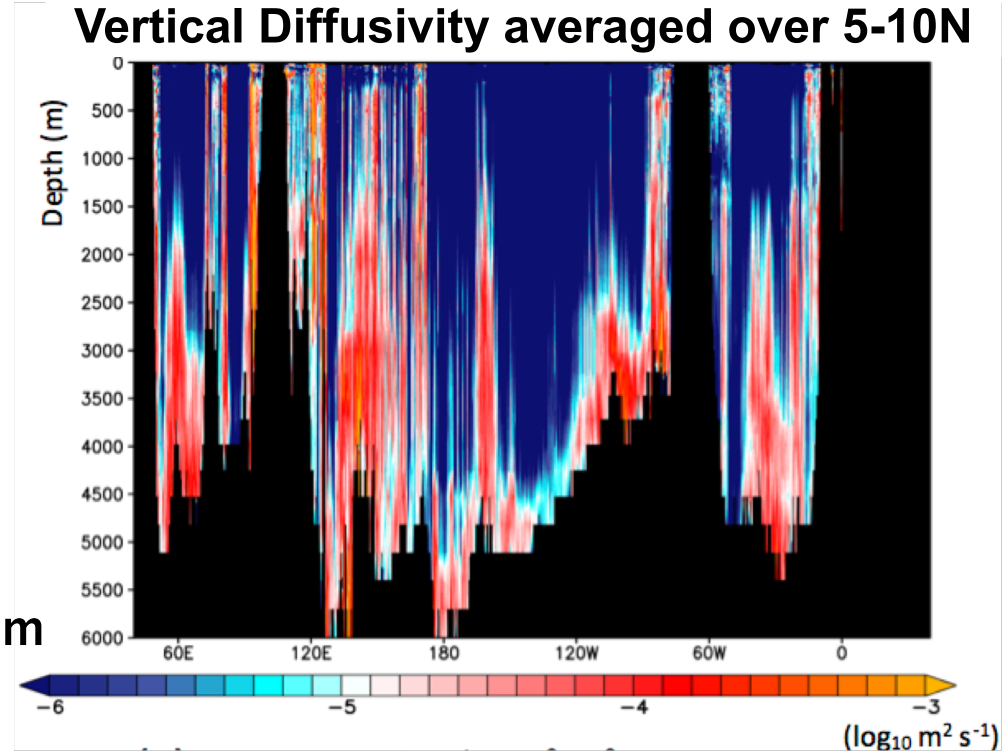
Large SSH rise in Pacific in OFES2

0m



1000m

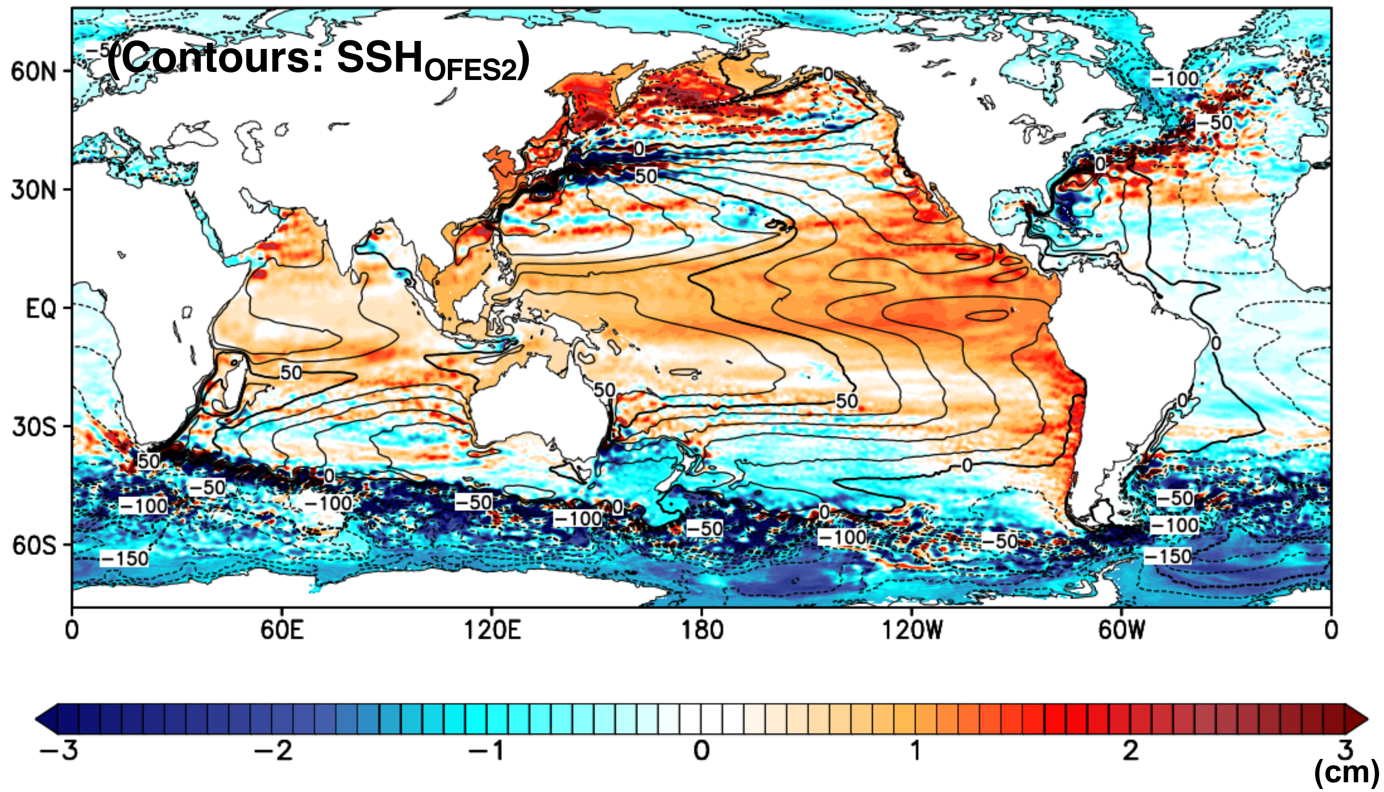
0m



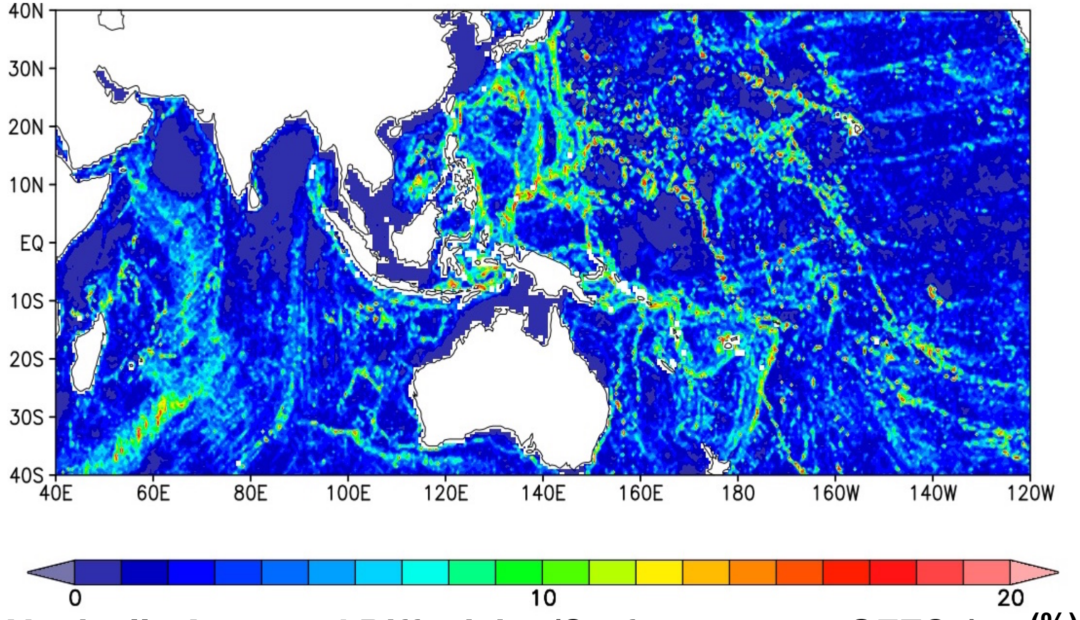
6000m

SSH Differences (OFES2 – OFES2_NT)

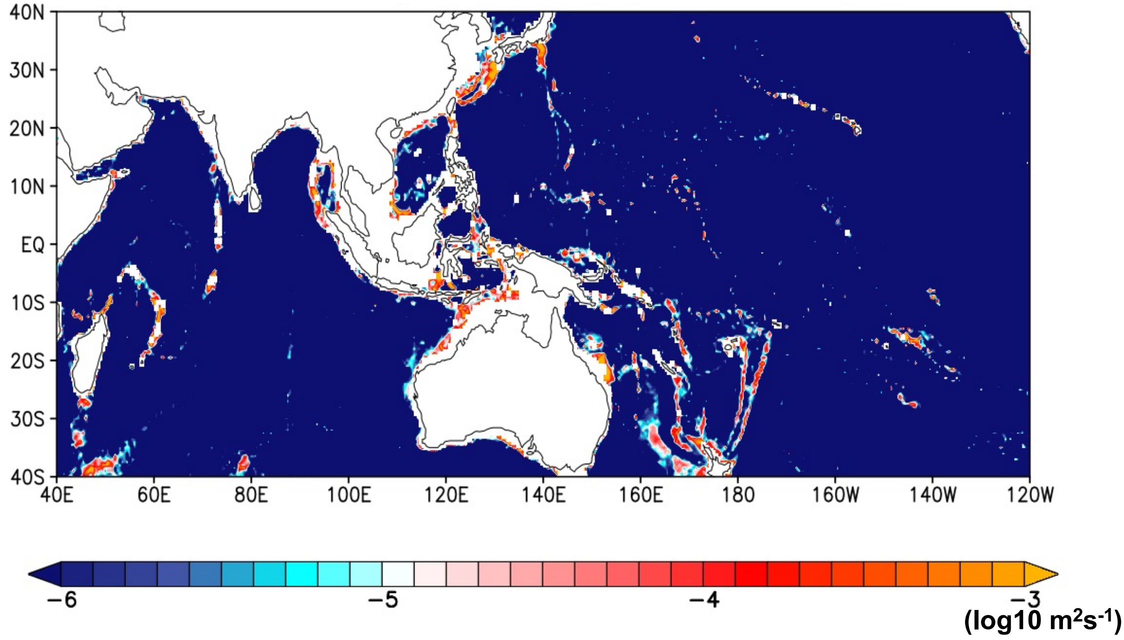
SSH_{OFES2}–SSH_{OFES2_NT}



Topographic Slope (OFES2)



Vertically Averaged Diffusivity (Surface-1000m, OFES2)



Large diffusivities around numerous islands in the tropical Pacific increase the basin-scale SSH via buoyancy increase for the water column.

The impacts of localized mixing spread over the whole basin via Rossby and Kelvin waves (Furue et al. 2015).