Turbulent mixing in the Indonesian Seas – Modeling and observation

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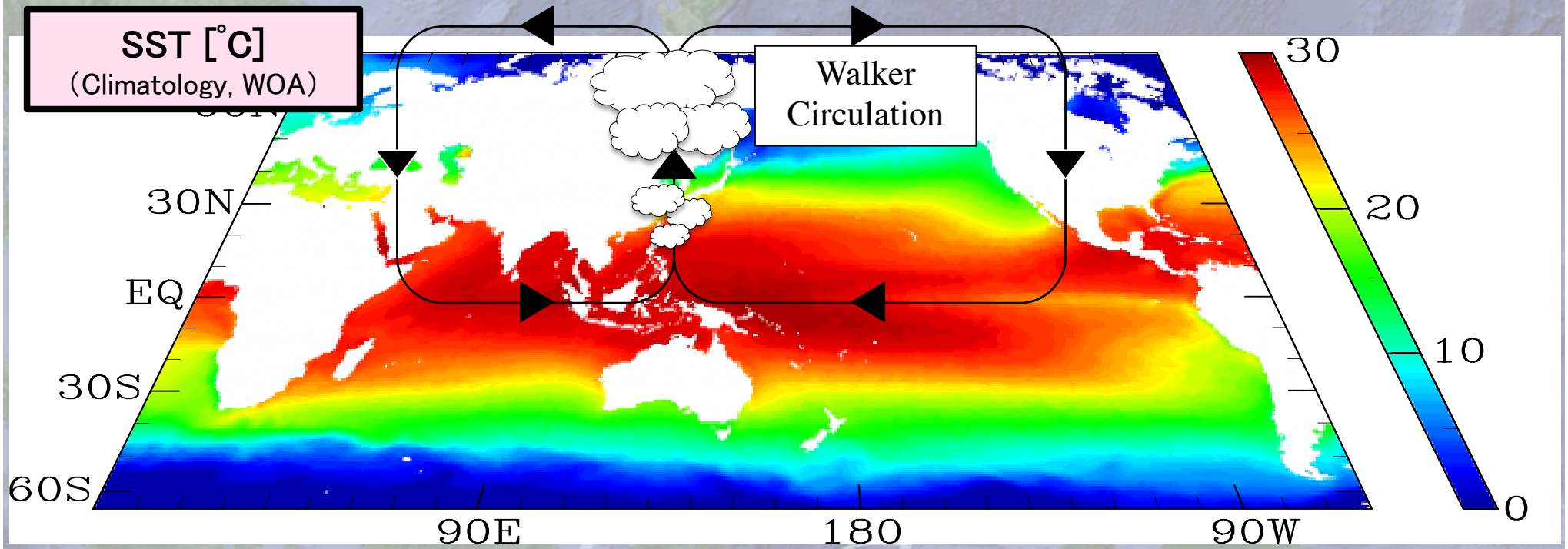
Roles of the Indonesian Seas (IS) in oceanic/atmospheric circulation



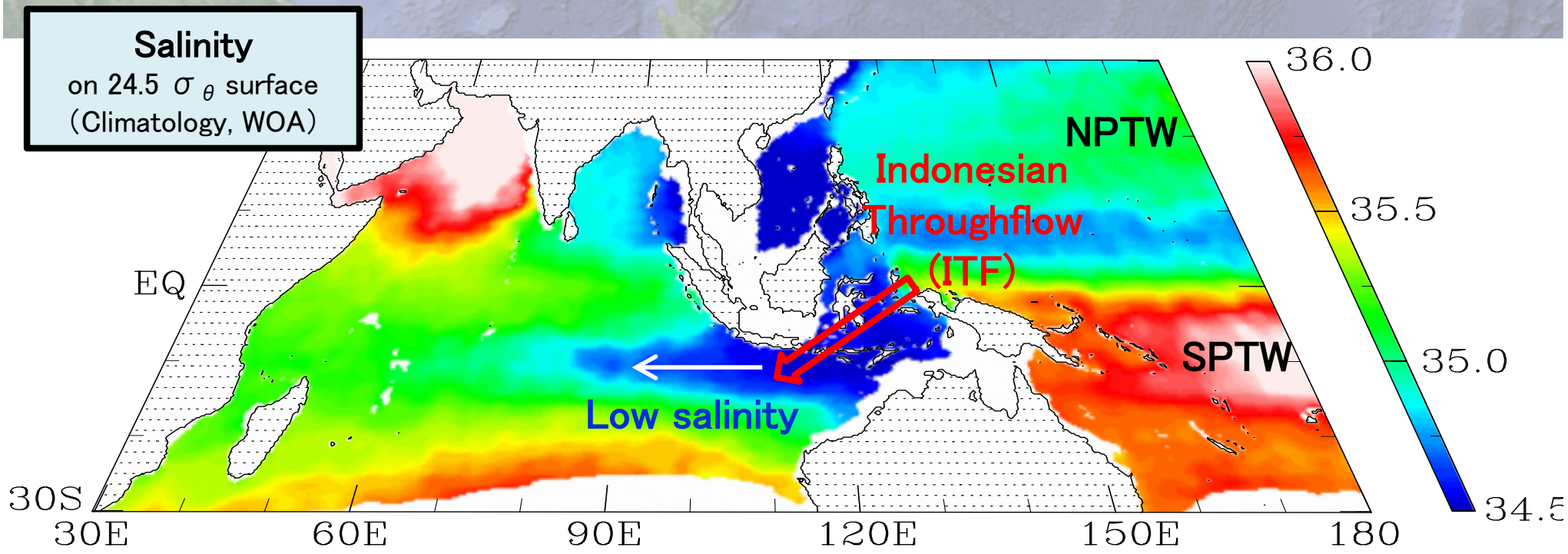
Sea Surface Temperature (SST) in the Indonesian Seas

- ✓ Warmest SST of the world
- ✓ Key region of the climate system
- ✓ Atmospheric deep convection, affecting the Walker Circulation, occurs above this region

ITF & Water-mass transformation

- ✓ The ITF carries the Pacific water to the Indian Ocean through the Indonesian Seas
- ✓ Properties of the ITF water are significantly changed within the Indonesian Seas.
- ✓ Attenuated ITF water affects the large-scale ocean circulation (e.g., Gordon, 2005)

Roles of the Indonesian Seas (IS) in oceanic/atmospheric circulation



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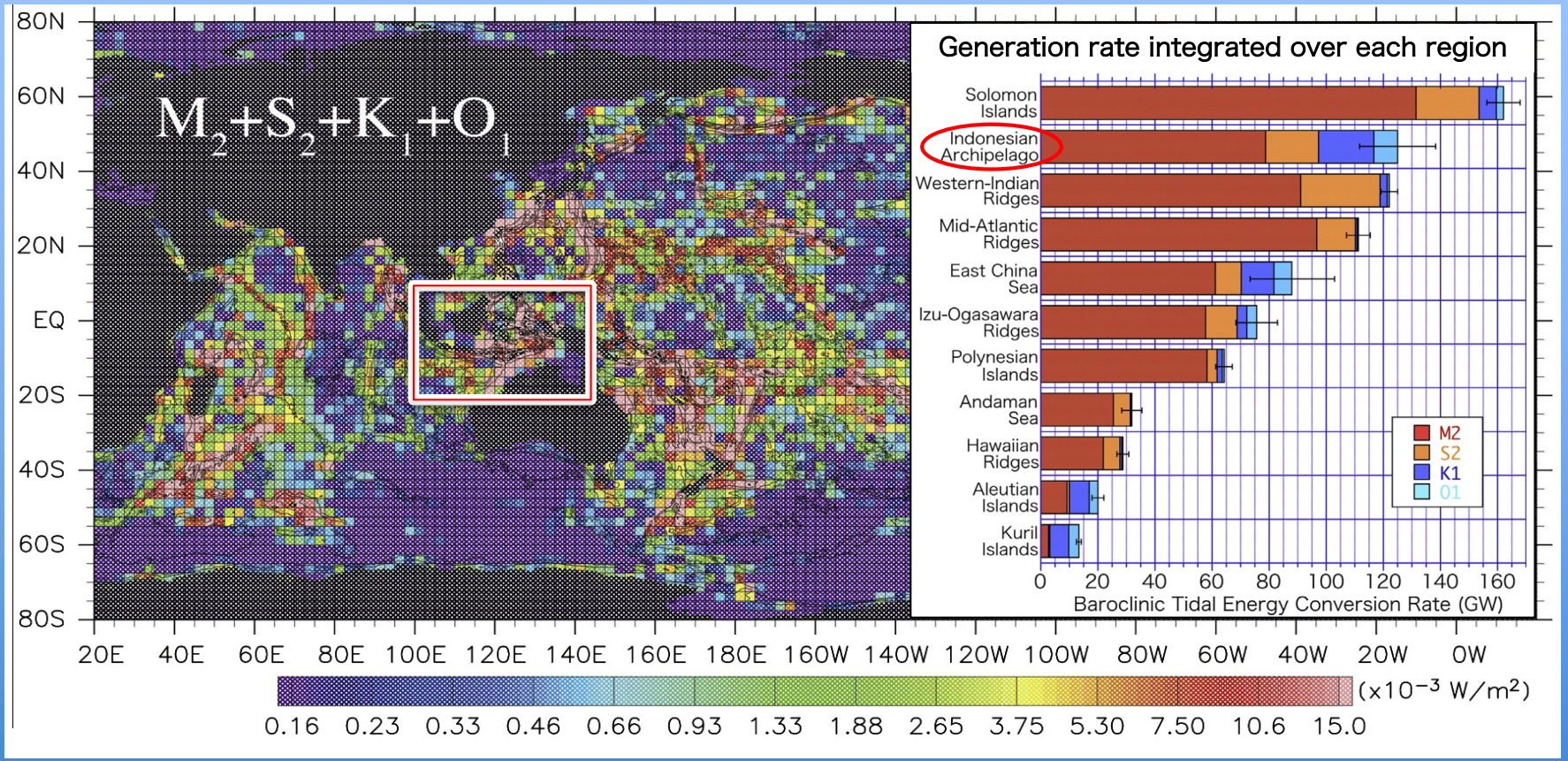
- ✓ The IS are a quite important area for understanding oceanic/atmospheric circulation.
- ✓ **'Tidal mixing'** is thought to be a major factor contributing to the SST/water-mass transformation in the IS.

Tidal mixing in the Indonesian Seas (IS)

A global map of **the generation rate of internal tides**
calculated from high resolution numerical model (Niwa and Hibiya, 2014)

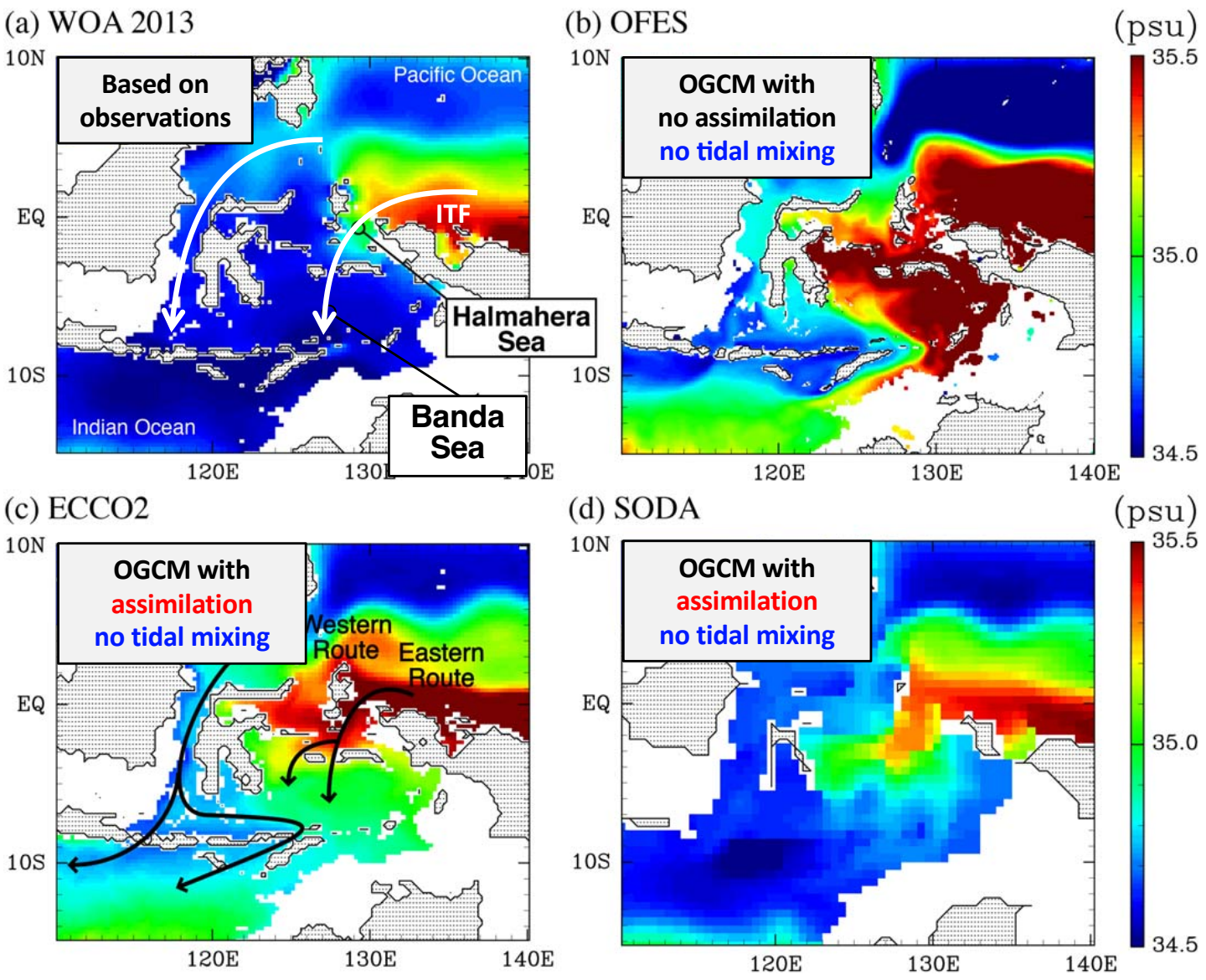


Indonesian Seas are one of **the most significant internal-tide generation regions** in the world.

▶ **Tidal mixing** induced by breaking of internal tides is expected to be **much enhanced in the IS**.

Importance of tidal mixing of the IS for predicting the ocean state

Salinity at a depth of 150 m (annual mean climatology) (Nagai et al., 2017)



▸ **Implying the importance of tidal mixing in reproducing the water-mass transformation in the IS**

Previous studies on estimates of tidal mixing in the IS

Blue : Model based study, Pink : Observation based study

Ffield and Gordon (1992)	Simple 1-D vertical diffusion model	$K_V = 1 \sim 2\times10^{-4}$ m^2/s (in area-average)
Alford et al. (1999)	Direct microstructure measurements (in the central part of Banda Sea)	$K_V \sim 0.1$ cm^2/s (local value)
Hatayama (2004)	2-D nonhydrostatic model (for Makassar Strait)	K_V reaches 6×10^{-3} m^2/s above the Dewakang Sill
Koch-Larrouy et al. (2007)	Based on St. Laurent et al.'s (2002) tidal mixing parameterization	Obtained a map of K_V ($K_V \sim 1\times10^{-4}$ m^2/s in area-average)
Robertson (2010)	3-D numerical model	$K_V \sim 6\times10^{-4}$ m^2/s (in area-average)
Koch-Larrouy et al. (2015) Bouruet-Aubertot et al. (2018)	Direct microstructure measurements (Halmahera/Banda Seas, Ombai Strait)	K_V is highly enhanced in the Halmahera/Ombai Straits
Nagai and Hibiya (2015)	High resolution 3-D numerical model	Obtained a map of K_V ($K_V \sim 1\times10^{-4}$ m^2/s in area-average)
Purwandana et al. (2020)	Thorpe scale method + Historical CTD dataset	Obtained a map of K_V (consistent with Nagai's work)

Kartadikaria et al. (2011), Cuypers et al. (2017), Nugroho et al. (2018) and others…

Previous studies on tidal mixing in the IS

Koch-Larrouy et al. (2007)	Based on St. Laurent et al.'s (2002) tidal mixing parameterization	Obtained a map of K_V (K_V~1×10^{-4} m^2/s in area-average)

Tidal mixing parameterization (St. Laurent et al., 2002)

Vertical diffusivity

$$k_{tides} = \Gamma E(x,y) q F(z) / \rho_0 N^2$$

Γ : Mixing efficiency = 0.2

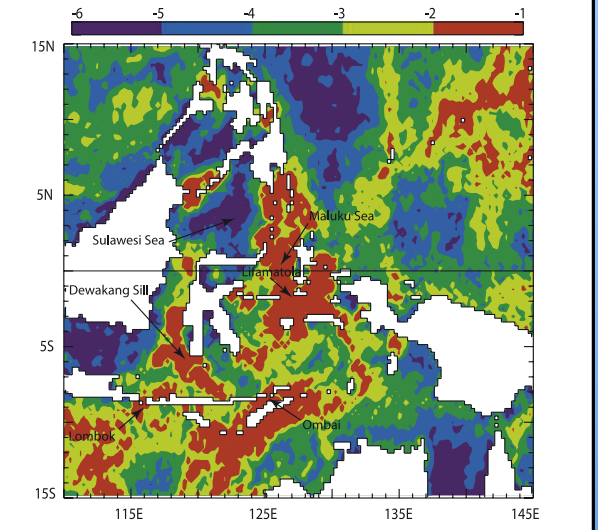
E(x,y) : Baroclinic energy conversion

q : Energy dissipation efficiency

F(*z*) : Vertical structure function

N : Buoyancy frequency

Distribution of E(x,y) obtained using barotropic model (W/m²)



【**Two significant assumptions in KL07's parameterization**】

✓ ***q* = 0.3 → *1***

Internal waves dissipate all of their energy at the generation sites. (i.e., no propagation)

✓ *F(z)* : **Bottom-enhanced** profile → **Surface-enhanced** profile

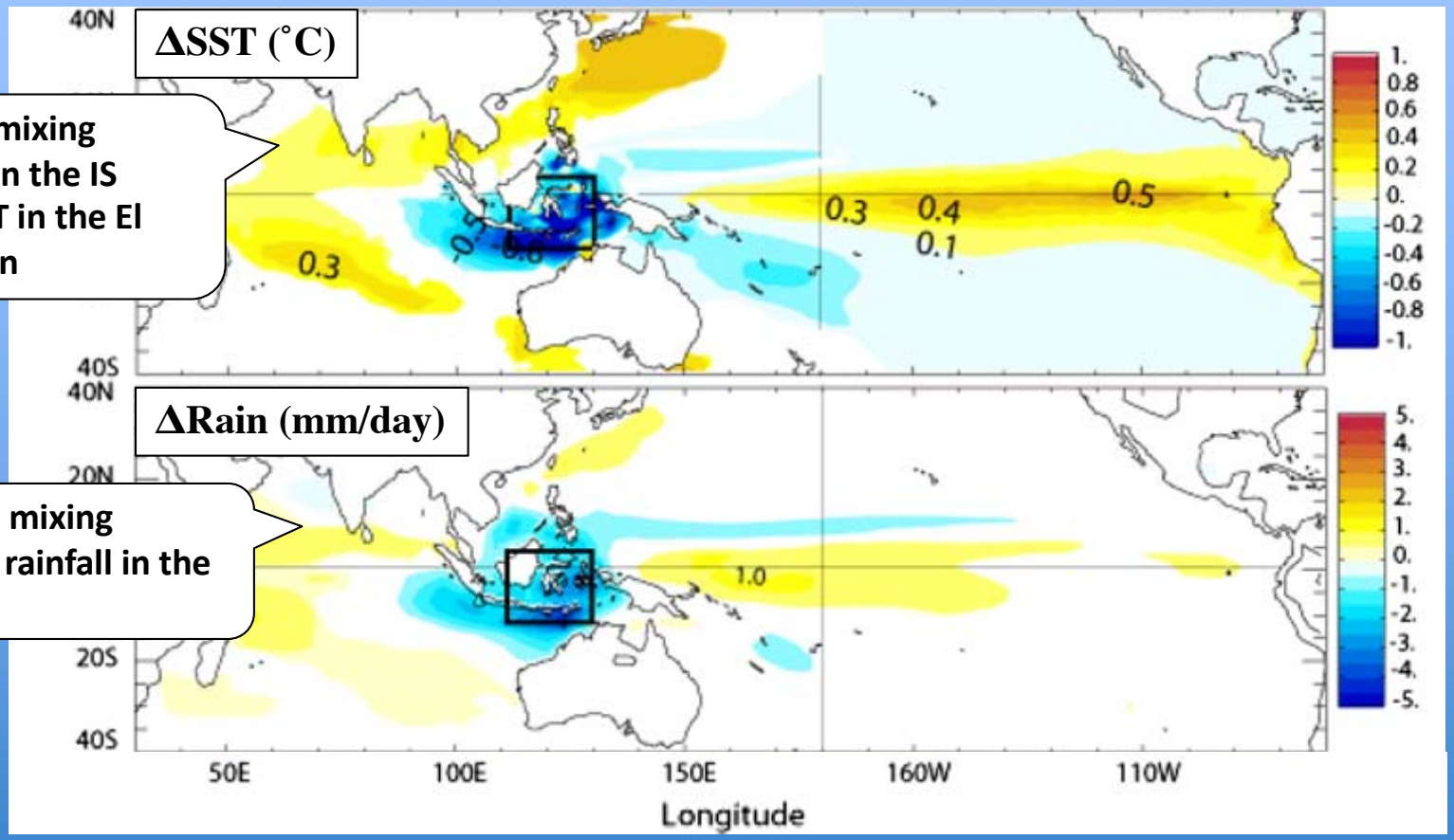
Effects of tidal mixing in the IS on large-scale oceanic/atmospheric circulation

Koch-Larrouy et al. (2010), Sprintall et al. (2014)

Koch-Larrouy et al. (2007)

- ✓ Investigated the effects of the parameterized tidal mixing on atmosphere/ocean
- ✓ Using an **air-sea coupled model**

Differences in SST/rainfall between coupled simulations 'with' and 'without' tidal mixing



Tidal mixing
- ✓ **Cools SST in the IS**
- ✓ **Warms SST in the El Nino region**

Tidal mixing
- ✓ **Decreases rainfall in the IS**

Effects of tidal mixing in the IS on large-scale oceanic/atmospheric circulation

Blue : Ocean model, Pink : Air/sea coupled model

Jochum and Potemra (2008)	Air/sea coupled model + **K_V simply enhanced in the IS ($K_V = 1 \times 10^{-4}$ m²/s)**	Local/remote effects of tidal mixing are suggested
Koch-Larrouy et al. (2010) Sprintall et al. (2014)	Air/sea coupled model + tidal mixing estimated by Koch-Larrouy et al. (2007)	Local/remote effects of tidal mixing are suggested
Sasaki et al. (2018)	OGCM + **Tidal mixing parameterization** (based on St. Laurent et al. (2002))	Tidal mixing in the IS increases the mean ITF transport (0.88 Sv)

However…

- ✓ “Idealized tidal mixing” or “tidal mixing parameterizations” were used in the model calculation
- ✓ **Physical processes** of the tidal mixing effects **were not well discussed**

【Objectives of my research】

- ✓ **To make a more plausible estimate of tidal mixing intensity in the IS.**
- ✓ **To discuss the physical mechanisms of tidal mixing effects on the ocean states of the IS.**

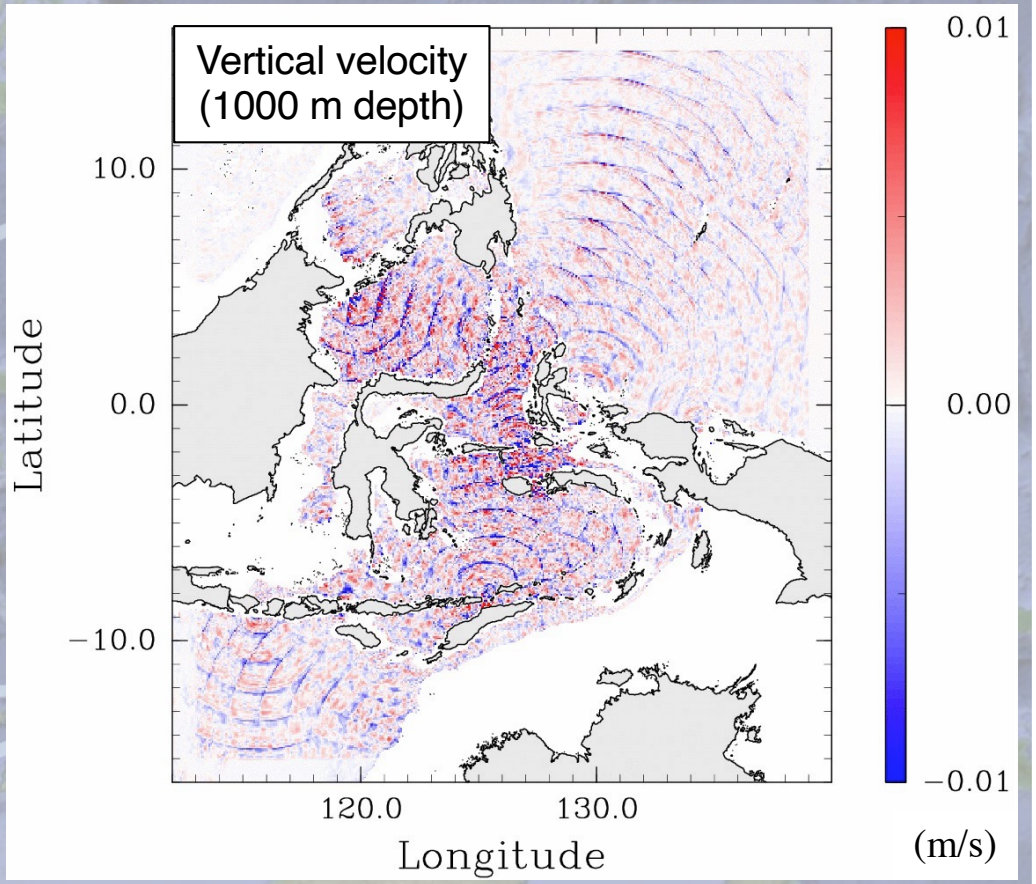
Estimates of tidal mixing intensity in the IS (Nagai and Hibiya, 2015)

Nagai and Hibiya (2015)

- ✓ High-resolution ($\Delta x \sim 1$km) 3-D baroclinic tide model.
- ✓ Energy dissipation (ε) of M_2 internal tides => **Distribution of vertical diffusivity (K_V) is estimated.**

Model setting

- ✓ MITgcm (**Hydrostatic** approximation)
- ✓ Δx, $\Delta y = 0.01^\circ$, $\Delta z = 5$ m $\sim$ 1200m (2800 × 3200 × 100 grids)
- ✓ **No mean-flow**
- ✓ Initial condition : **Horizontally uniform stratification**
- ✓ Forcing : M_2 barotropic tide (TPXO 7.2)
- ✓ **Constant viscosity/diffusivity**
  - $A_H = K_H = 10$ m^2 s^{-1}
  - $A_V = 10^{-4}$ m^2 s^{-1}, $K_V = 10^{-5}$ m^2 s^{-1}



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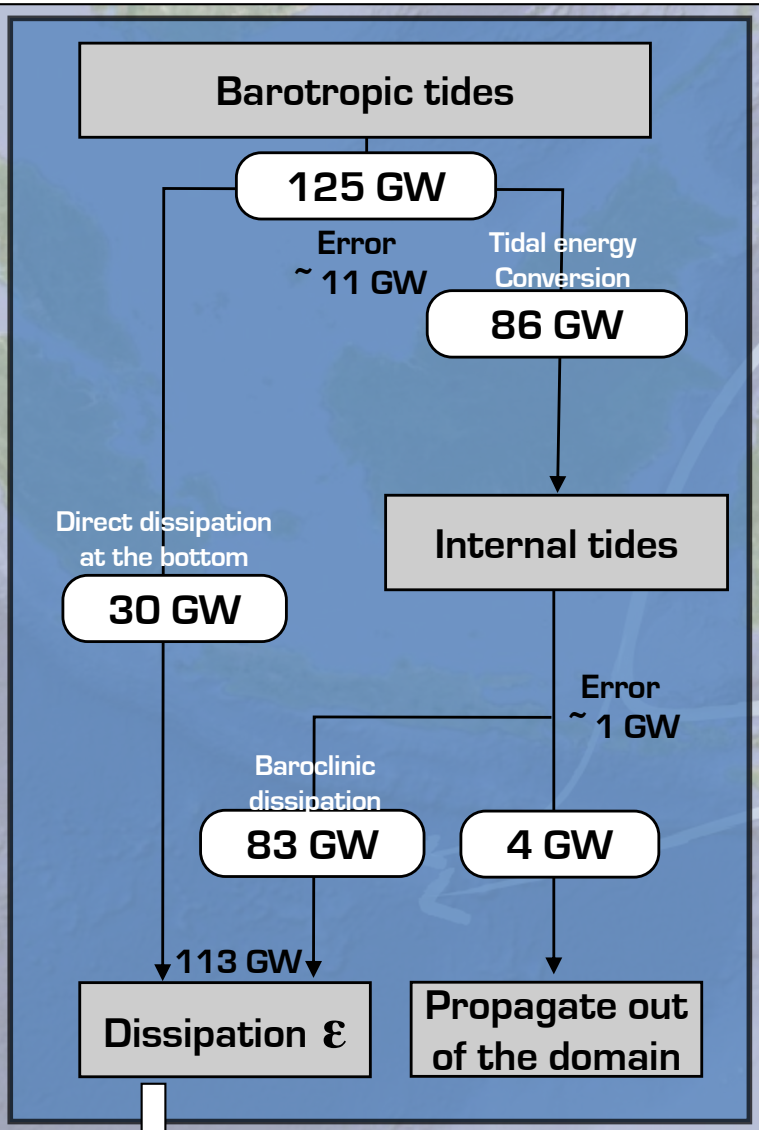

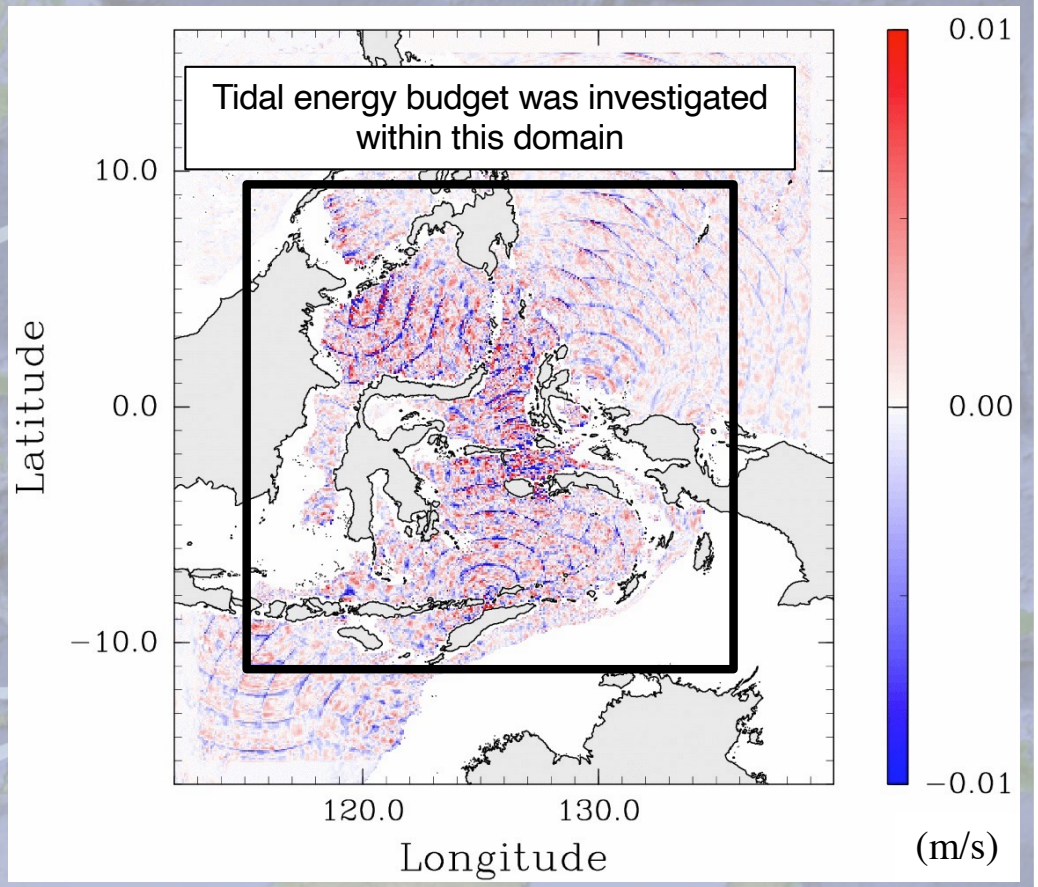

- ✓ **Internal tides of 86 GW are generated by barotropic tides**
- ✓ **Only 4 GW of internal tide energy propagates out of the IS**
- ✓ **Remaining 83 GW is dissipated within the IS.**

Vertical diffusivity K_V is estimated using Osborn's formula ($K_V = 0.2\ \varepsilon / N^2$)

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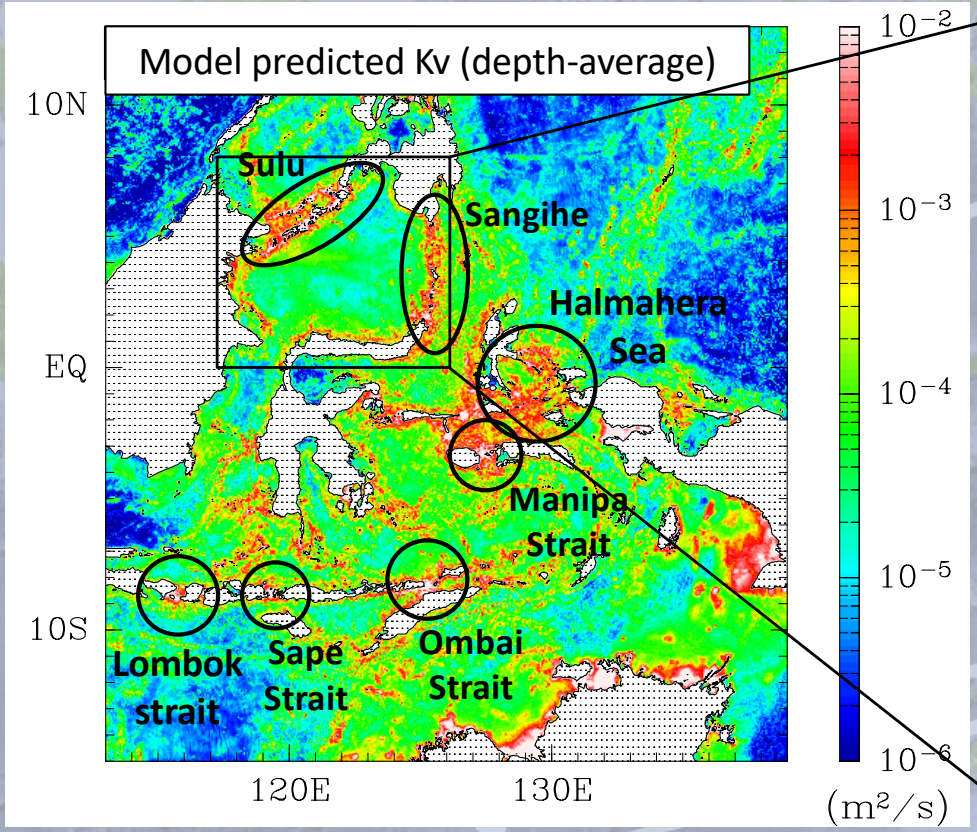

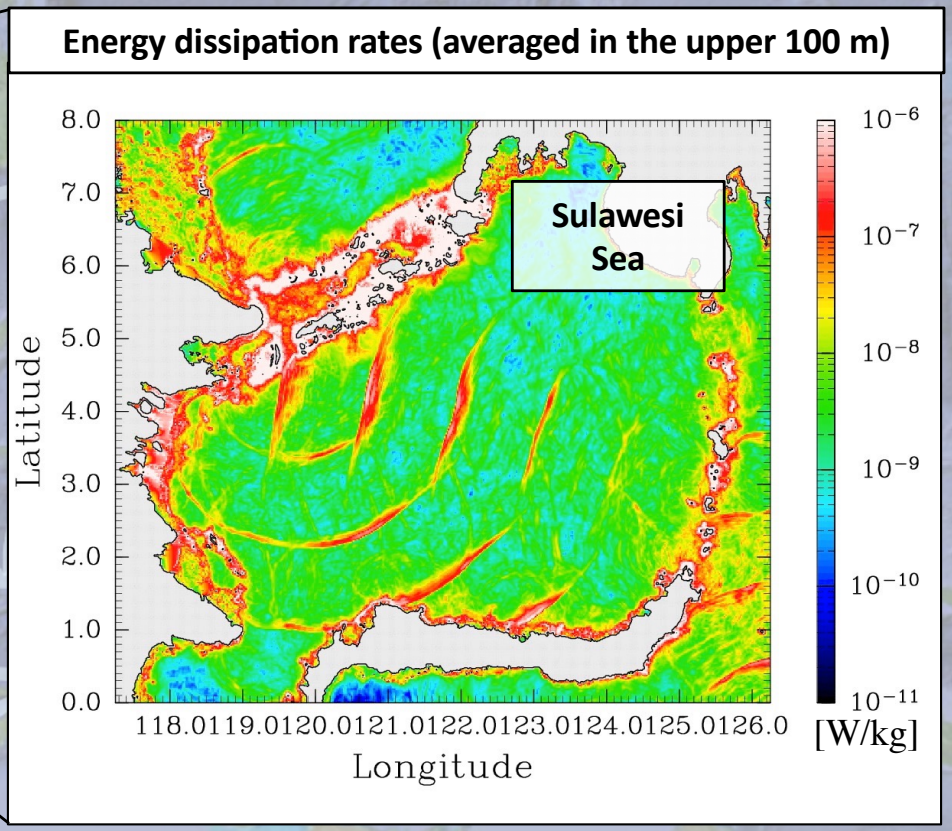

- ✓ **"Mixing hotspots"** are localized in the **narrow tidal straits** of the archipelago (e.g., Lombok Straits), in which energetic internal tides are generated by strong barotropic tidal currents.
- ✓ Mixing is also enhanced on the pathway of internal solitary waves, which are observed in many locations
- ✓ Much different distribution compared to Koch-Larrouy et al.'s (2007) parameterization
- ✓ (Probably) More realistic map of vertical diffusivity is obtained.

Estimates of tidal mixing intensity in the IS (Nagai and Hibiya, 2015)

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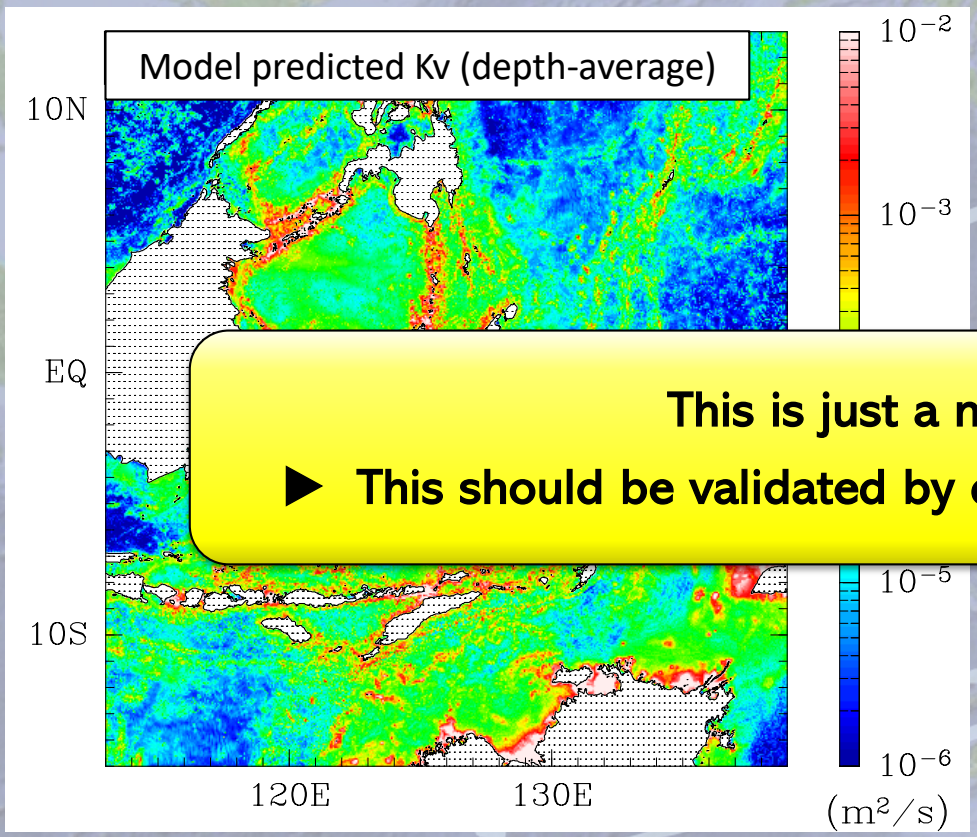

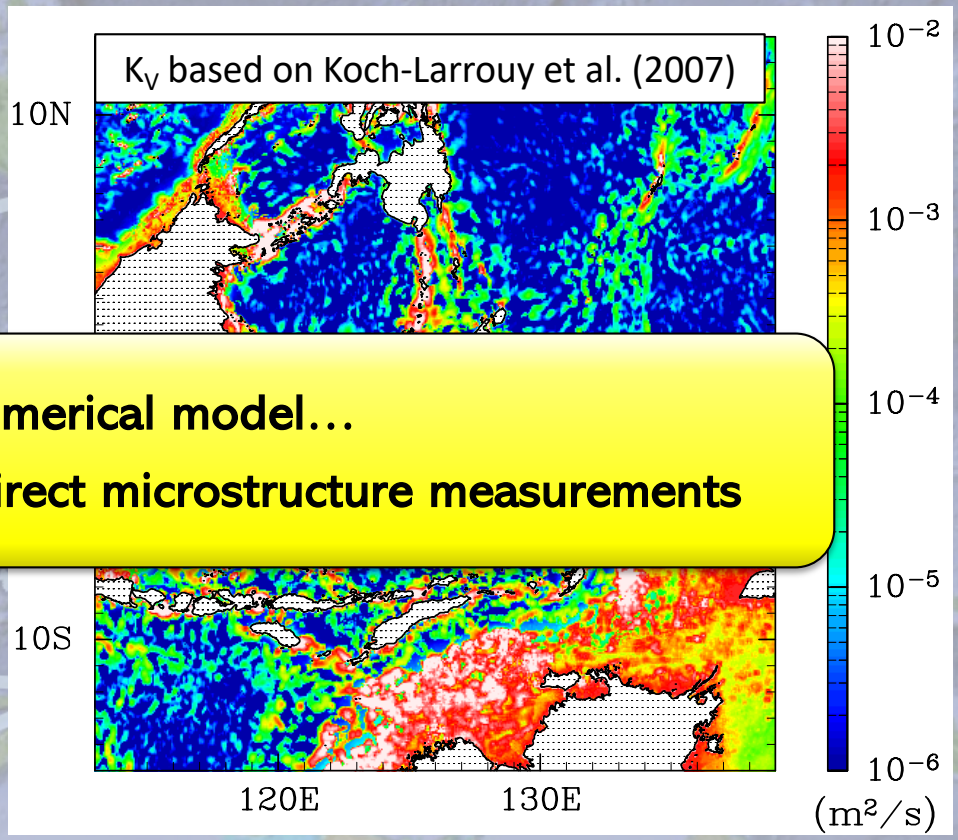

This is just a numerical model…

▶ **This should be validated by direct microstructure measurements**

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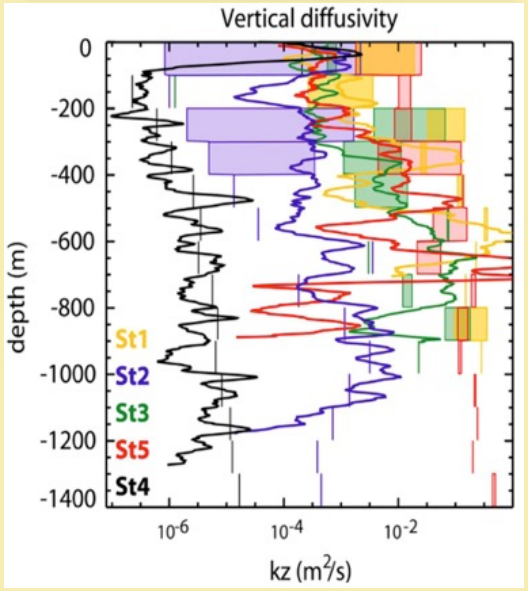
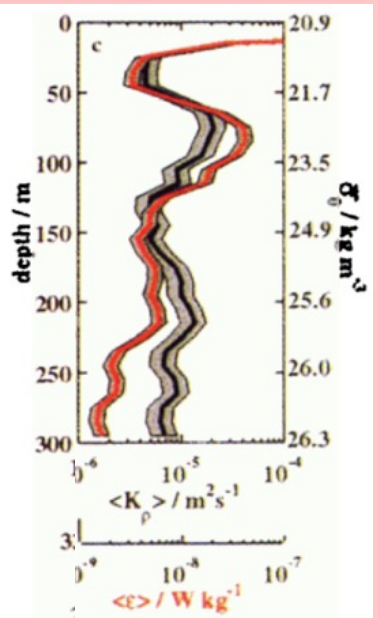
Previous microstructure measurements in the IS

Koch-Larrouy et al. (2015)

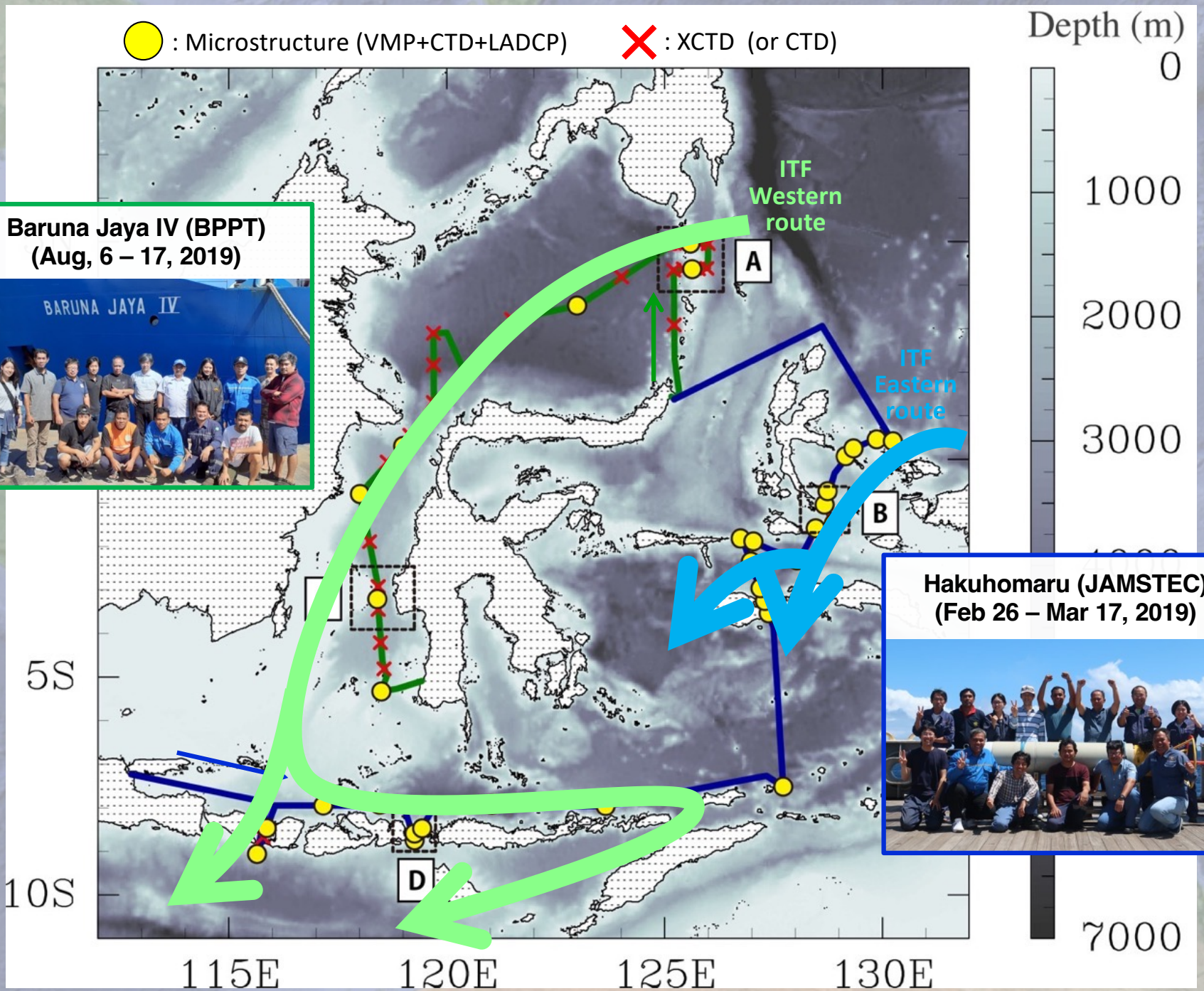


Alford et al. (1999)



In the Indonesian Seas, direct microstructure measurements are **largely lacking**. Microstructure measurements have been carried out only in **6 stations**.

Extensive direct microstructure measurements in the IS (Nagai et al., 2021)



Extensive direct microstructure measurements in the IS (Nagai et al., 2021)

Microstructure data (ε : Energy dissipation rates) | **Horizontal velocity/Temperature/Salinity**

VMP-6000 | VMP-X | LADCP/CTD | XCTD



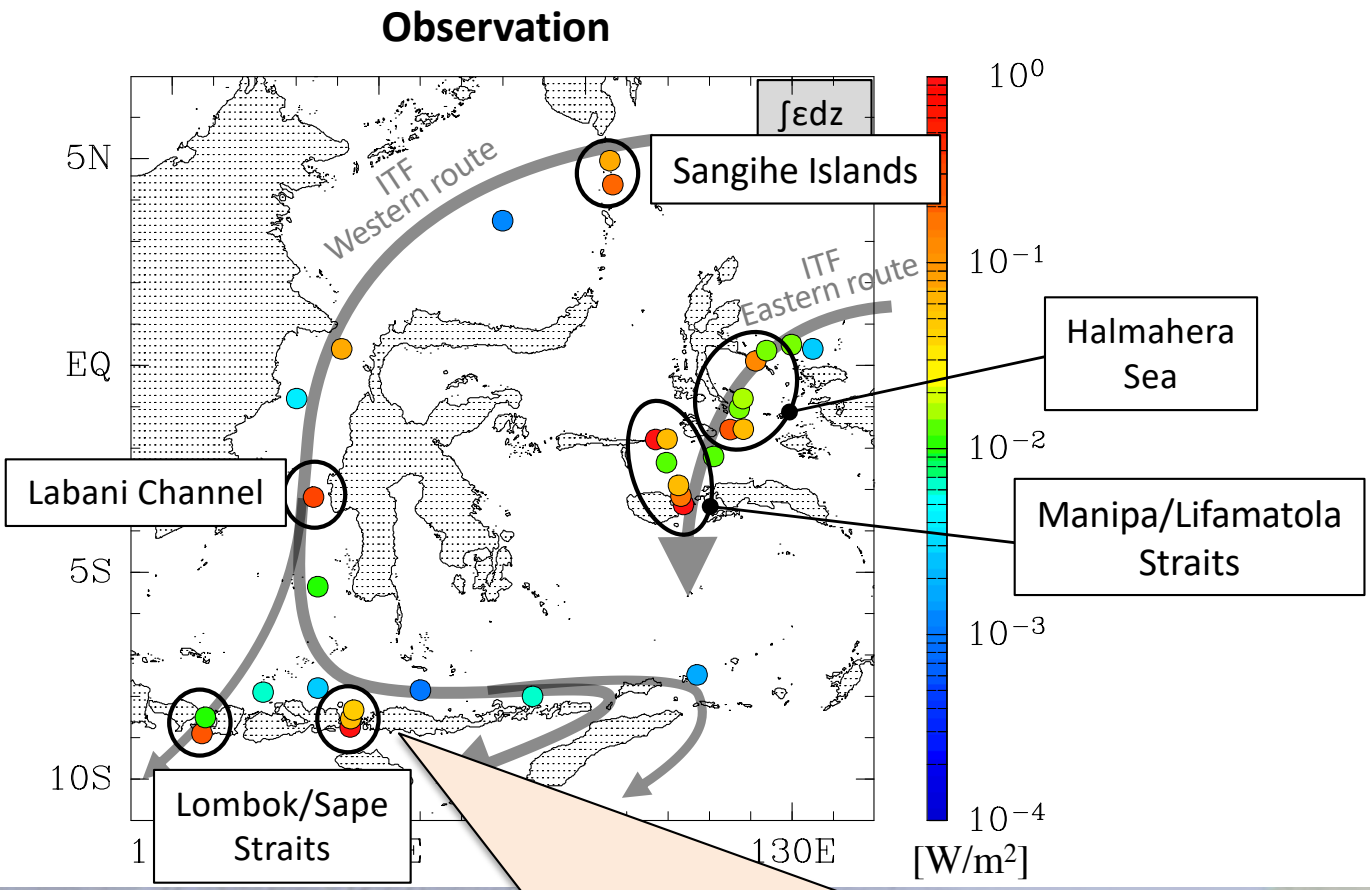

	VMP-6000	VMP-X	LADCP/CTD	XCTD
Hakuhomaru	58 profiles	24 profiles	78 profiles	0 profiles
BJ4	38 profiles	0 profiles	34 profiles	23 profiles

A total of 120 profiles were obtained at 32 stations

For the Hakuhomaru cruise, we have also obtained
- ✓ Shipboard ADCP data
- ✓ Multibeam bathymetry data

Extensive direct microstructure measurements in the IS (Nagai et al., 2021)

Color : Depth-integrated energy dissipation rates (ε)

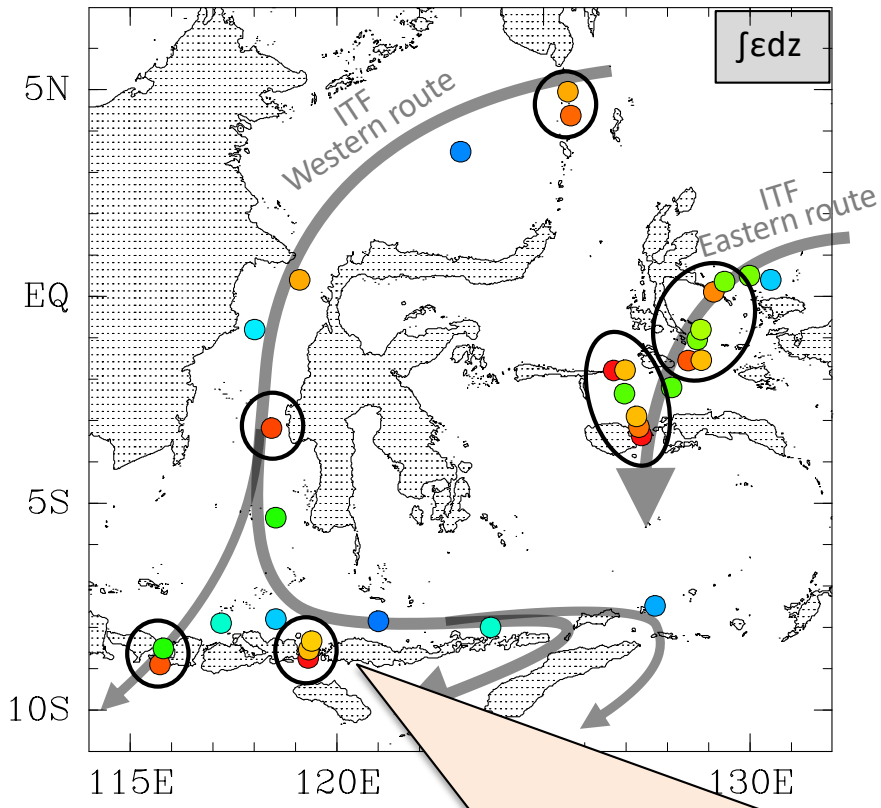


- Mixing hot-spots are found in narrow straits

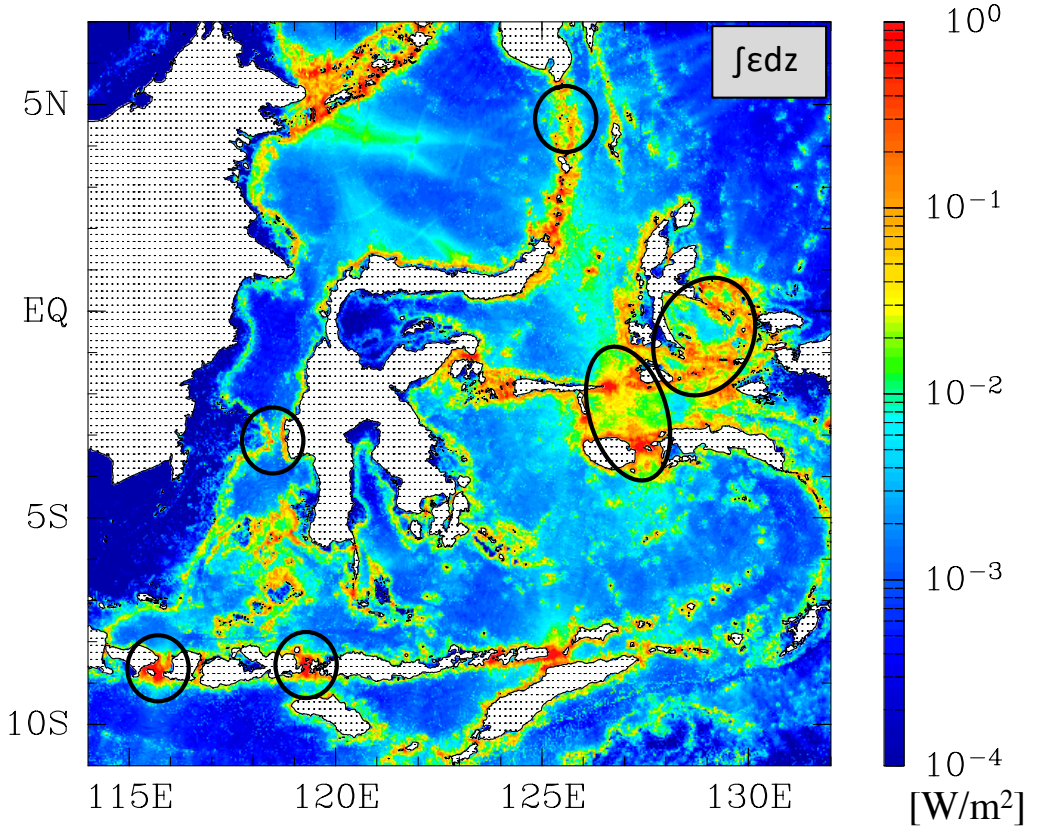
Extensive direct microstructure measurements in the IS (Nagai et al., 2021)

Color : Depth-integrated energy dissipation rates (ε)

Observation



M2 baroclinic tide model
(Nagai and Hibiya, 2015)

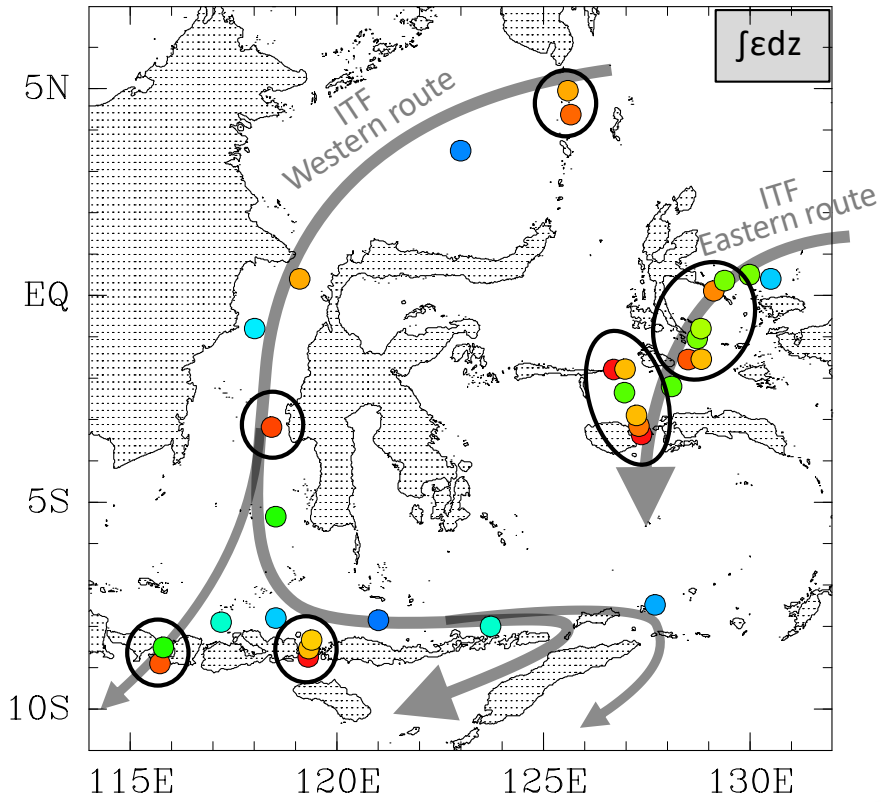


- Mixing hot-spots are found in narrow straits

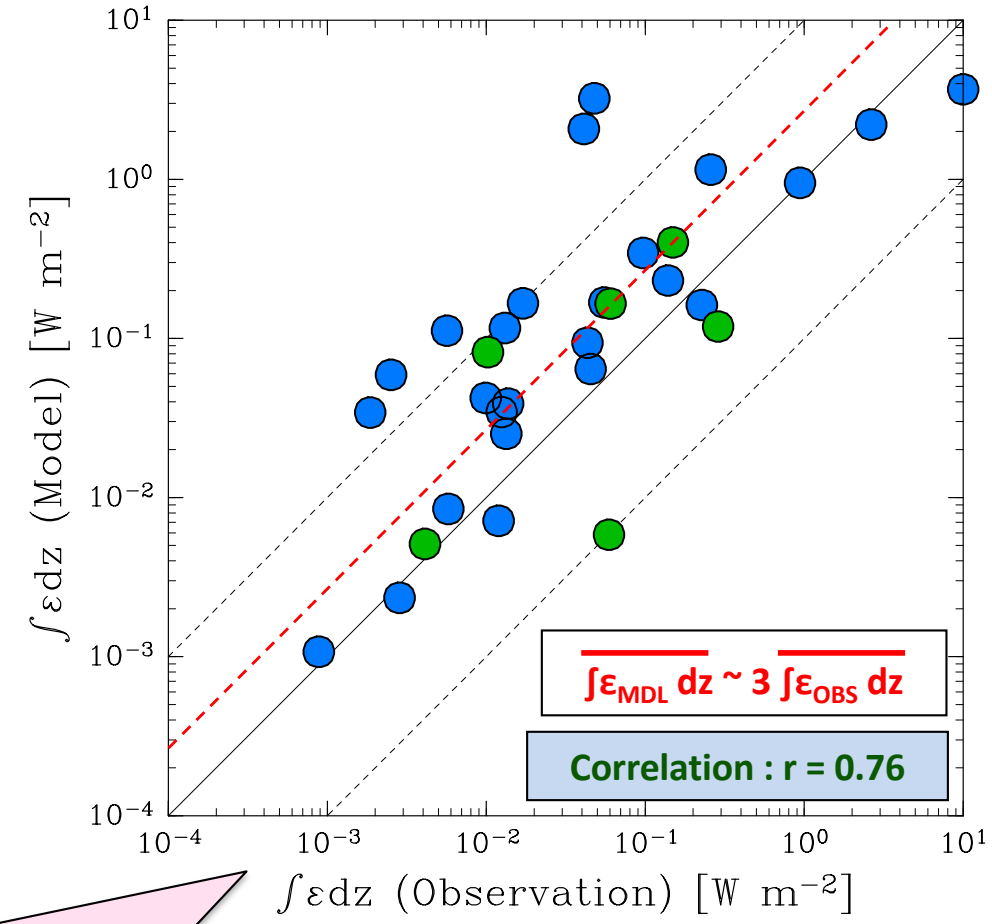
=> Observed results are generally consistent with the model prediction

Extensive direct microstructure measurements in the IS (Nagai et al., 2021)

Observation

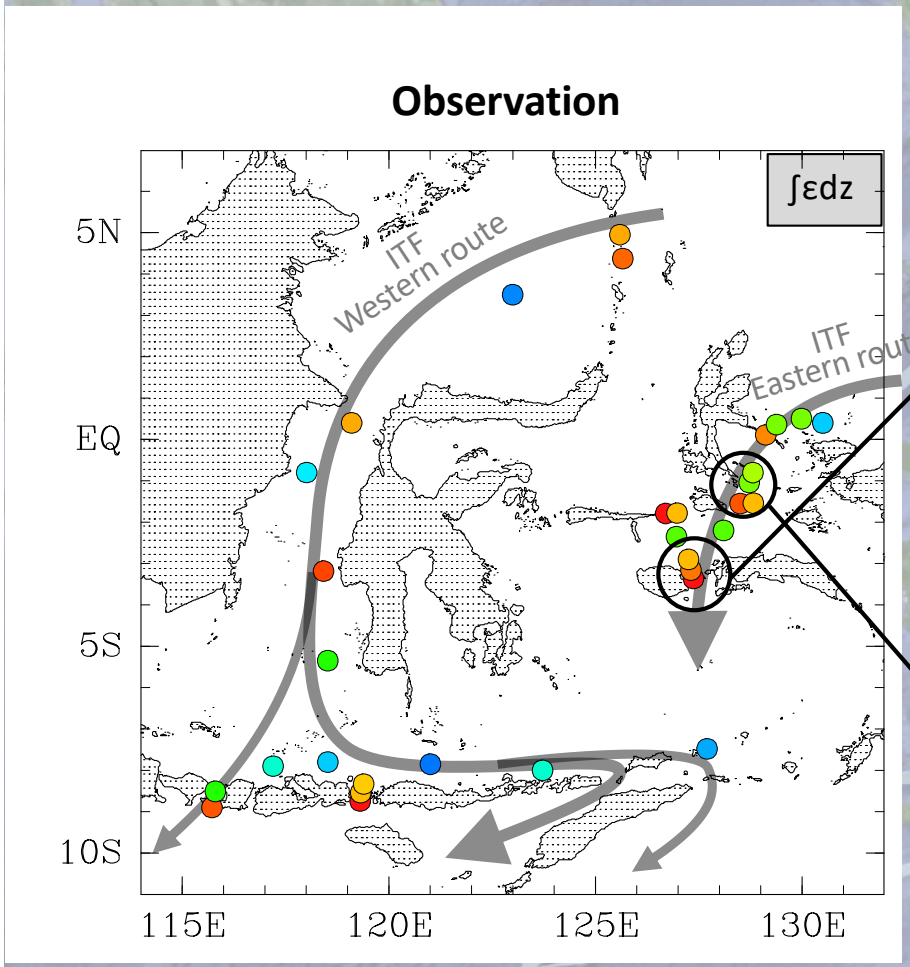


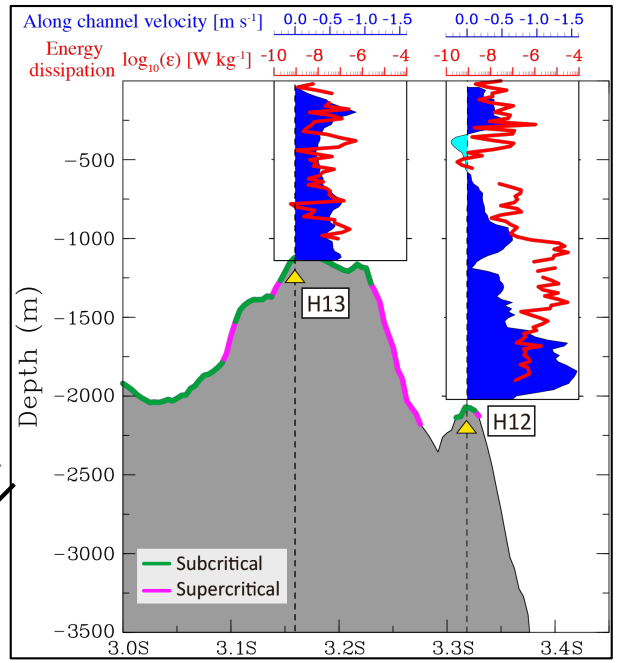
Scatter plots (Observation vs Numerical model)



The numerical model is generally consistent with observations, although there is a tendency to overestimate.

Extensive direct microstructure measurements in the IS (Nagai et al., 2021)





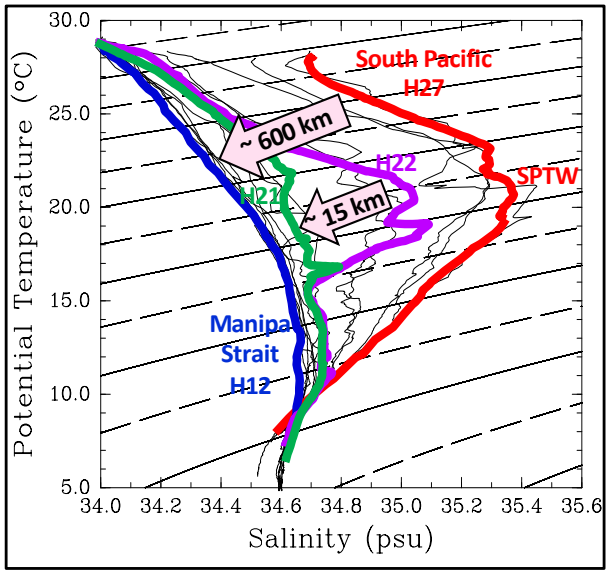
In the Manipa Strait

- ✓ **The strongest turbulence (ε> 10^{-5}W/kg)** was observed
- ✓ **Strong tide-topography interaction** on a **super-critical topography**

⇩

- ✓ **Intense downslope jet & K-H instability**

T-S plots along the Eastern route of the ITF



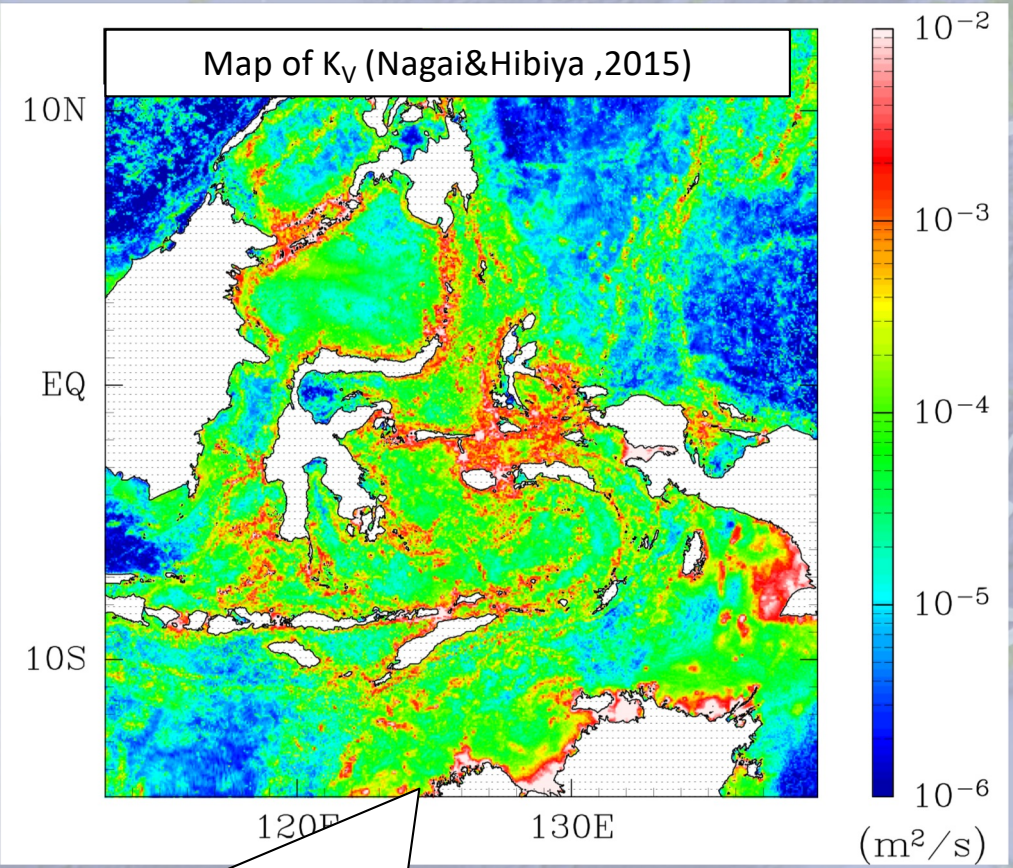
In the south Halmahera Sea

- ✓ **Rapid watar-mass transformation** occurs
- ✓ Observed vertical mixing cannot explain the rapid water-mass transform-ation.
- ✓ Possible role of horizon-tal mixing (caused by tide-induced submeso-scale eddies)

Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)

Some previous studies (Koch-Larrouy et al.; 2010, Kida and Wijffels, 2012; Sprintall et al., 2014) showed that idealized or simply parameterized **tidal mixing cools the SST in the IS**

=> However, physical processes were not well investigated.



Through the observation, the validity of Nagai and Hibiya's (2015) model is confirmed.

Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)

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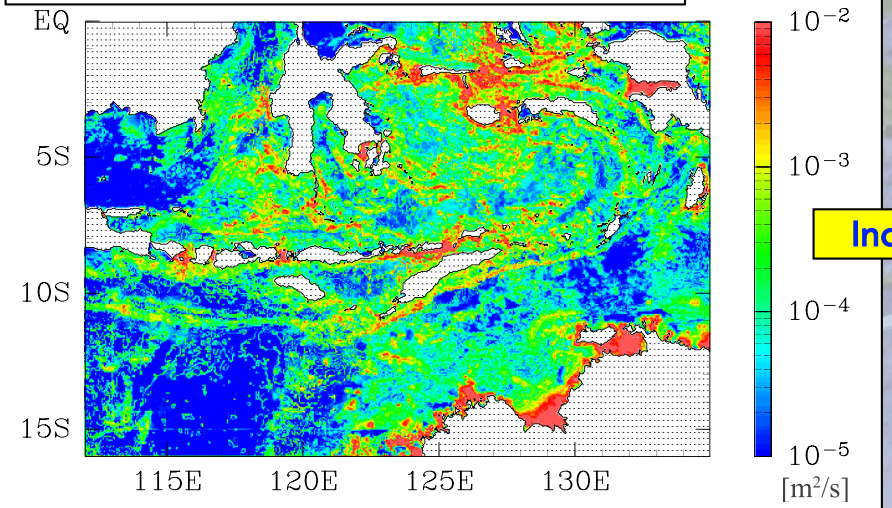
Nagai and Hibiya (2020)

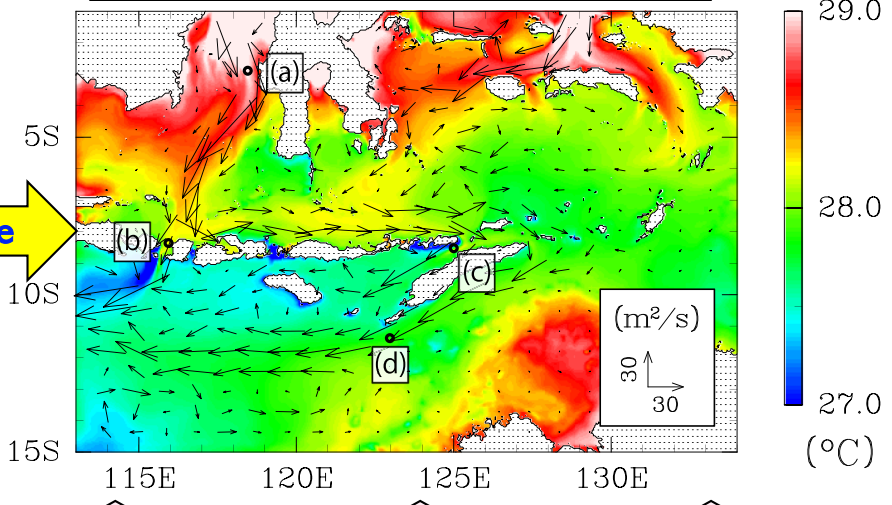
- Incorporated the map of K_V (Nagai and Hibiya, 2015) into a regional ocean model
- Investigated the effects of tidal mixing on the SST around the IS
- Discussed the corresponding physical processes

Map of K_V (Nagai and Hibiya, 2015)



Incorporate

Reginal ocean model (MITgcm)



Wind

Surface Heat

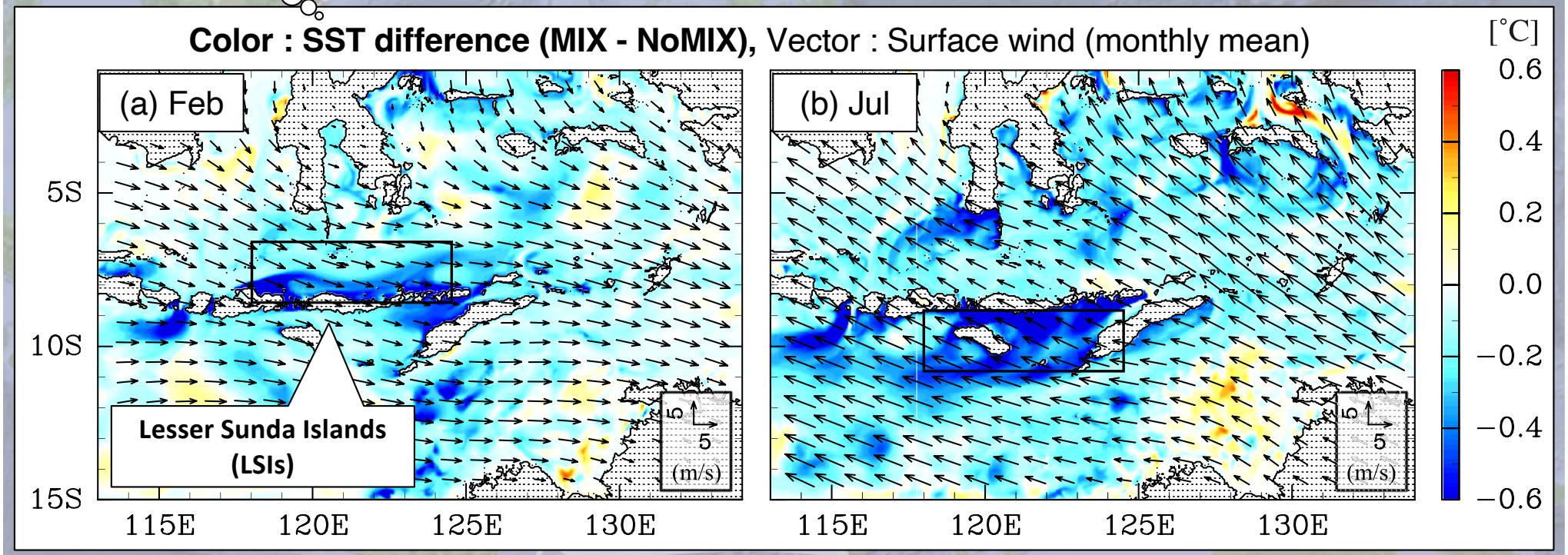
Horizontal B.C. (ECCO2)

Climatological monthly mean forcing

Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)

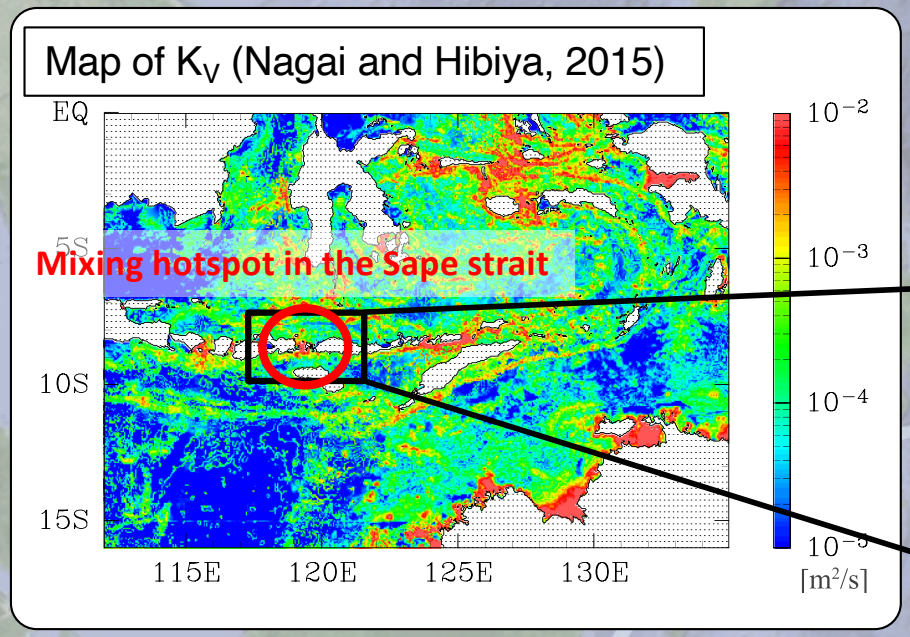
Blue color shows the cooling effects of tidal mixing

MIX : Experiment with tidal mixing
NoMIX : Experiment without tidal mixing

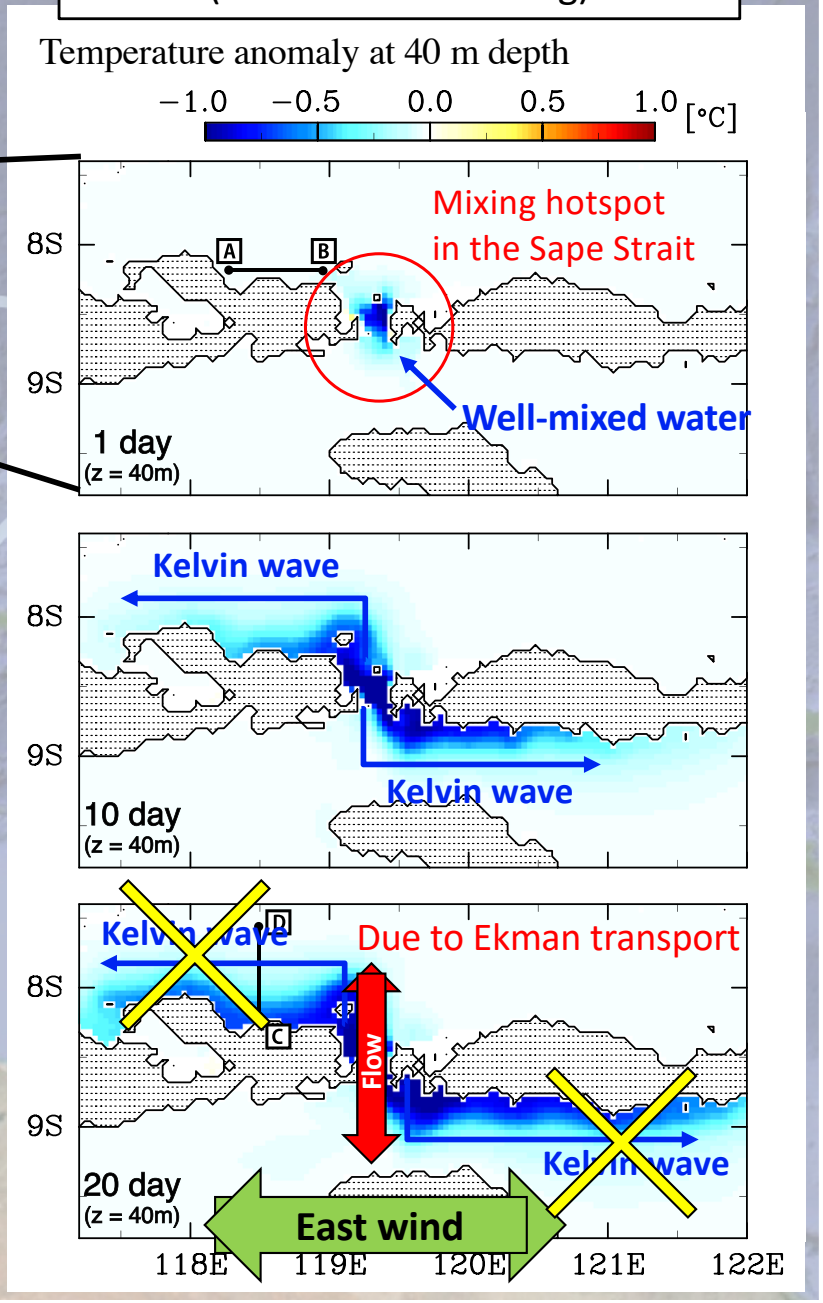


- Tidal mixing significantly cools the SSTs along the northern (or southern) coast of the "Lesser Sunda Islands" when the northwest (or southeast) monsoon is established.
  => Implying the combined effects of tidal mixing and Ekman transport.

Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)



Results of idealized experiment (without wind forcing)



We found that

1. Mixing hotspots in the narrow tidal straits of the LSIs make well-mixed water accompanying cold SST anomaly.
2. (If there is no wind forcing) Cold SST anomalies propagate **along both the northern and southern coasts of the LSIs** as **baroclinic Kelvin waves.**
3. If **west (or east) winds** exist,

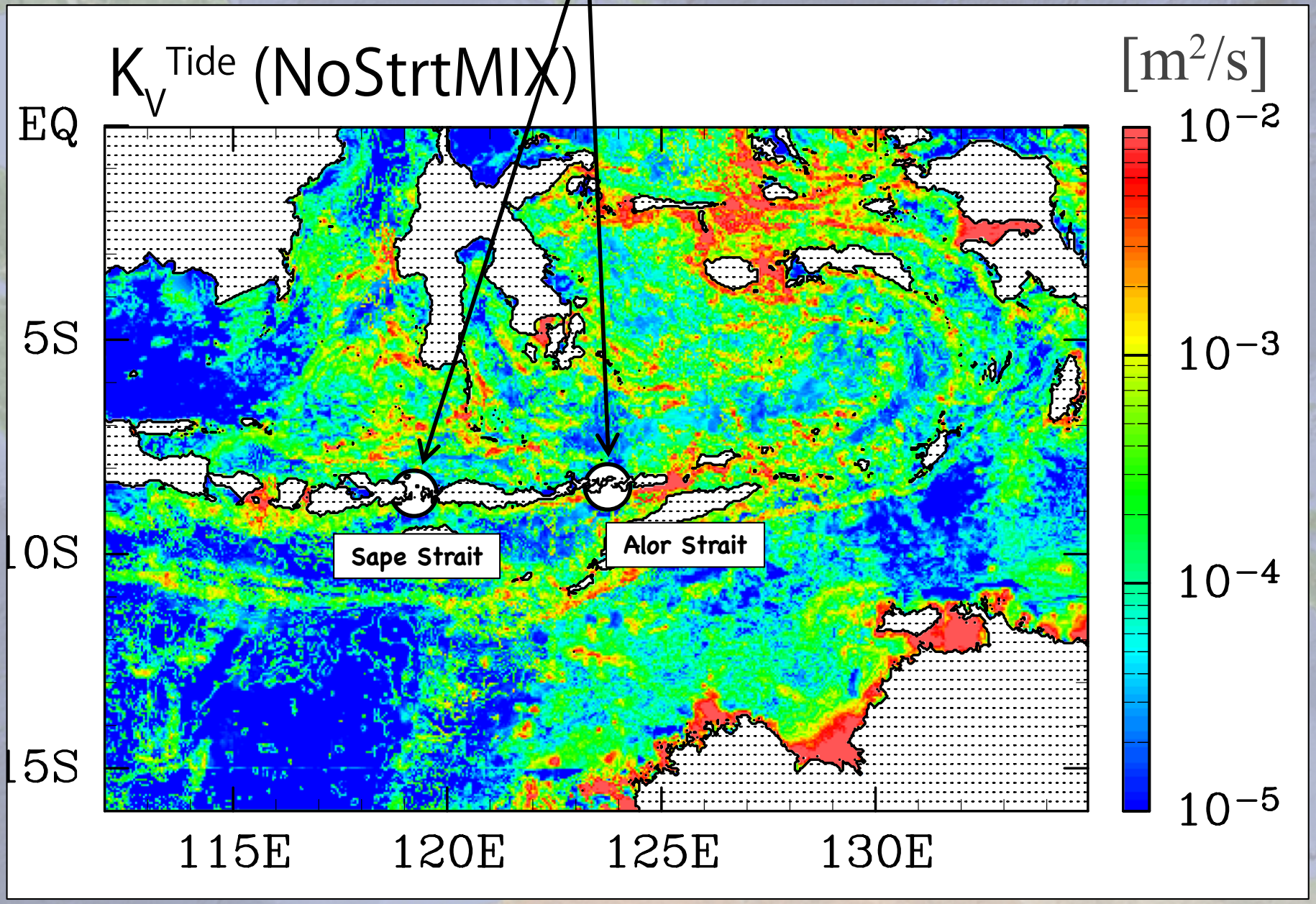
➢ Ekman transport causes strong northward (or southward) flow in the narrow straits that prevent the Kelvin wave propagating along the **southern (or northern) coast** of the LSIs.

➢ Finally, SST cooling occurs only in **the north (or south)** of the LSIs.

Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)

Additional experiment

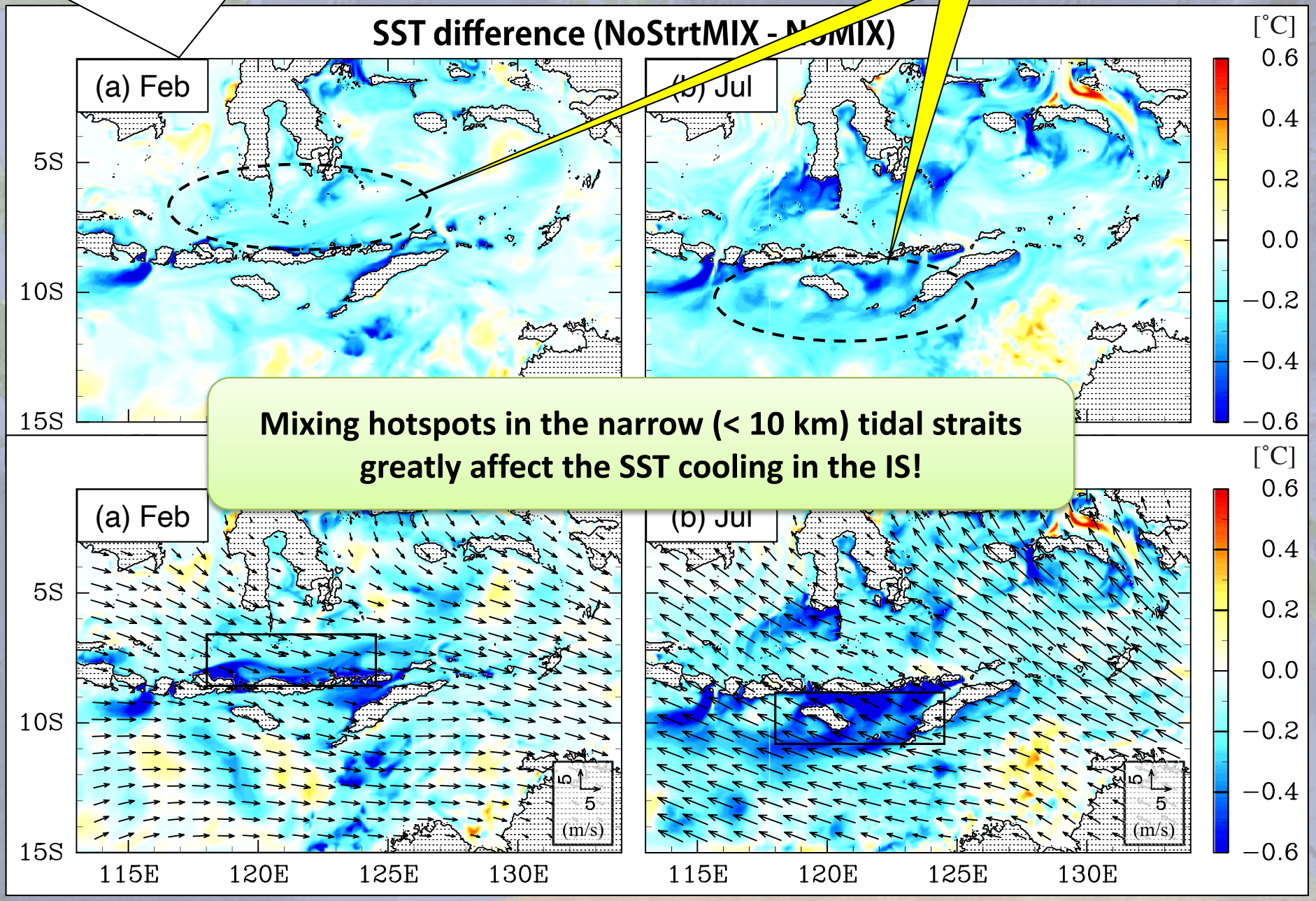
NoStrtMIX : Vertical diffusivity in two narrow straits are completely removed.



Effects of tidal mixing on the SST cooling around the IS (Nagai and Hibiya, 2020)

Blue color shows the **cooling effects of tidal mixing without mixing hotspots in the narrow straits**

SST cooling is obviously weak



Mixing hotspots in the narrow (< 10 km) tidal straits greatly affect the SST cooling in the IS!

Summary

- ✓ Tidal mixing in the Indonesian Seas is thought to play an important role in changing oceanic/ atmospheric circulation.

Estimates of tidal mixing

- ✓ Area-averaged vertical diffusivity is of the order of 10^{-4} m^2/s
- ✓ Mixing hotspots are localized in narrow tidal straits (e.g., Lombok, Ombai, Manipa Straits)
- ✓ Internal solitary waves might play a role in distributing the turbulence energy in the IS
- ✓ Numerical model tends to overestimate the mixing intensity

Effects of tidal mixing

- ✓ Tidal mixing in the Indonesian Seas affects not only the local phenomena, but also the remote phenomena (e.g., El-Nino region).
- ✓ Mixing hotspots in narrow tidal straits affect the SSTs in the Indonesian Seas through Ekman transport.

Key conclusion

- ✓ **Mixing hotspots in narrow (< 10km) tidal straits may have a large impact on regulating SST in the Indonesian Seas, although they are hardly resolved in the existing OGCMs.**
- ✓ For an accurate prediction of oceanic/atmospheric phenomena related to the Indonesian Seas, **resolving the narrow straits in OGCMs might be important**.

Future problem

Estimates of tidal mixing

- ✓ Mixing scheme in numerical models should be developed
  (Currently, there is no “best” scheme that correctly models internal wave breaking.)
- ✓ Tidal mixing caused by other tidal constituents (S2, K1, O1)
- ✓ Effects of mean flow (the ITF) on the mixing intensity/distribution
  (Nugroho et al. (2018) conducted the numerical simulation, but grid resolution was low (~10km)…)
- ✓ Mixing processes of internal solitary waves (which are not observed in the IS)

Effects of tidal mixing

- ✓ Physical mechanisms of remote effects of tidal mixing in the Indonesian Seas are still unknown

  => This should be discussed (focusing on the roles of atmospheric/oceanic phenomena).

(Koch-Larrouy et al., 2010) Differences in SST/rainfall between coupled simulations ‘with’ and ‘without’ tidal mixing