5th workshop on waves and wave-coupled processes

FIO-ESM: the earth system model coupled with ocean surface waves

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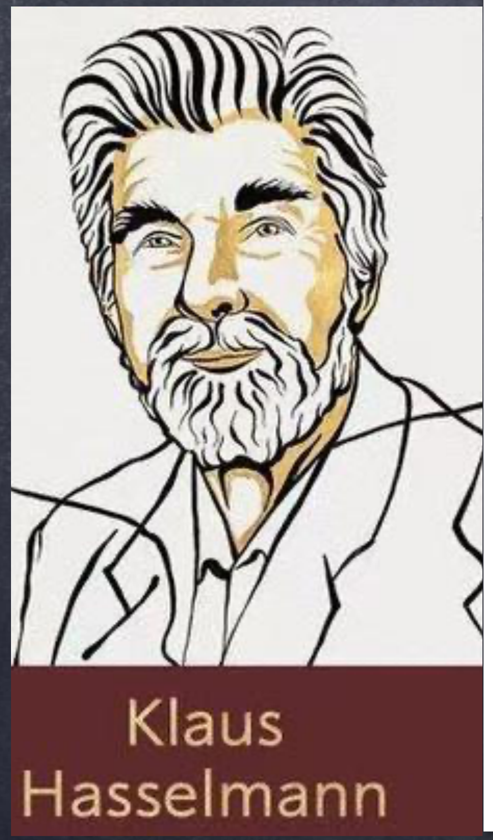
11 April, 2024

Outline

- Background
- FIO-ESM v1.0 development
- FIO-ESM v2.0 development
- Perspectives on the FIO-ESM

Background

Question:
Is the ocean surface waves the low-hanging fruit?



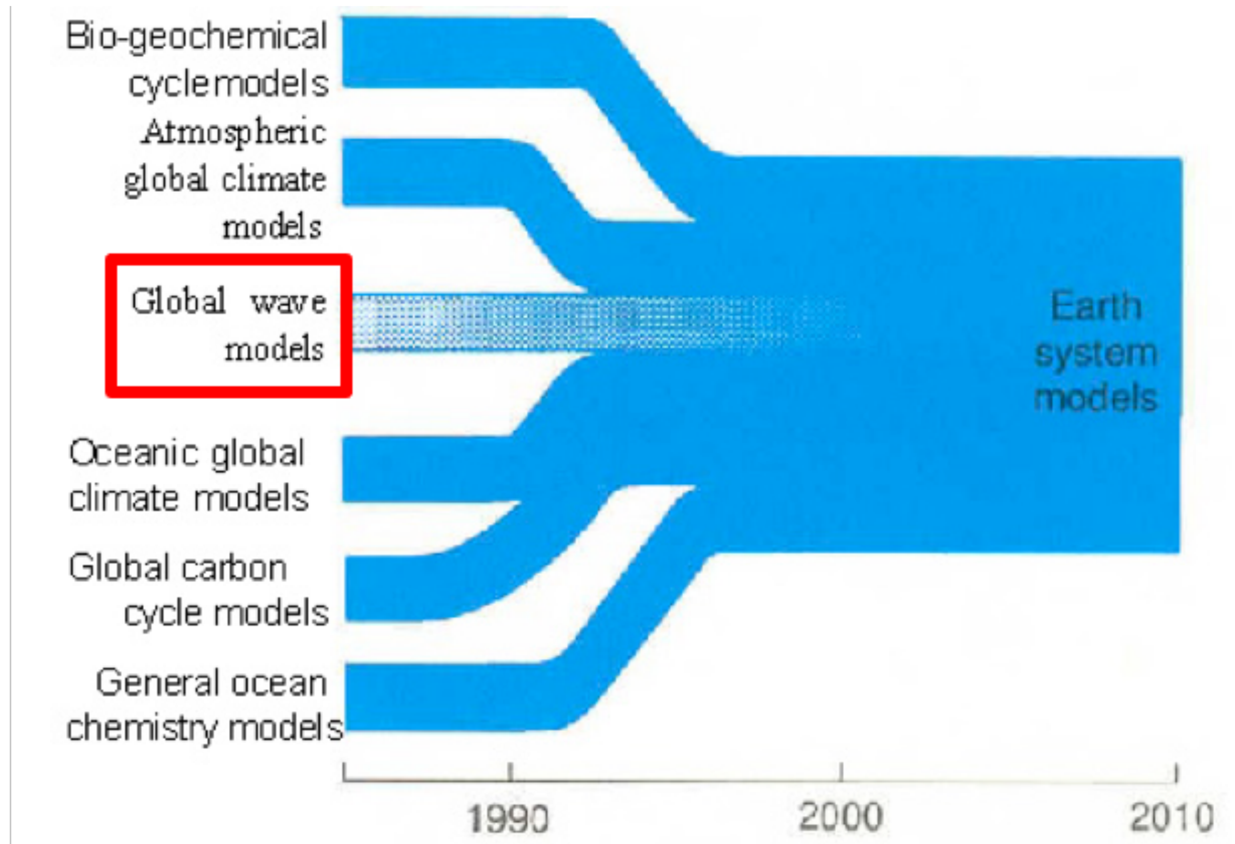
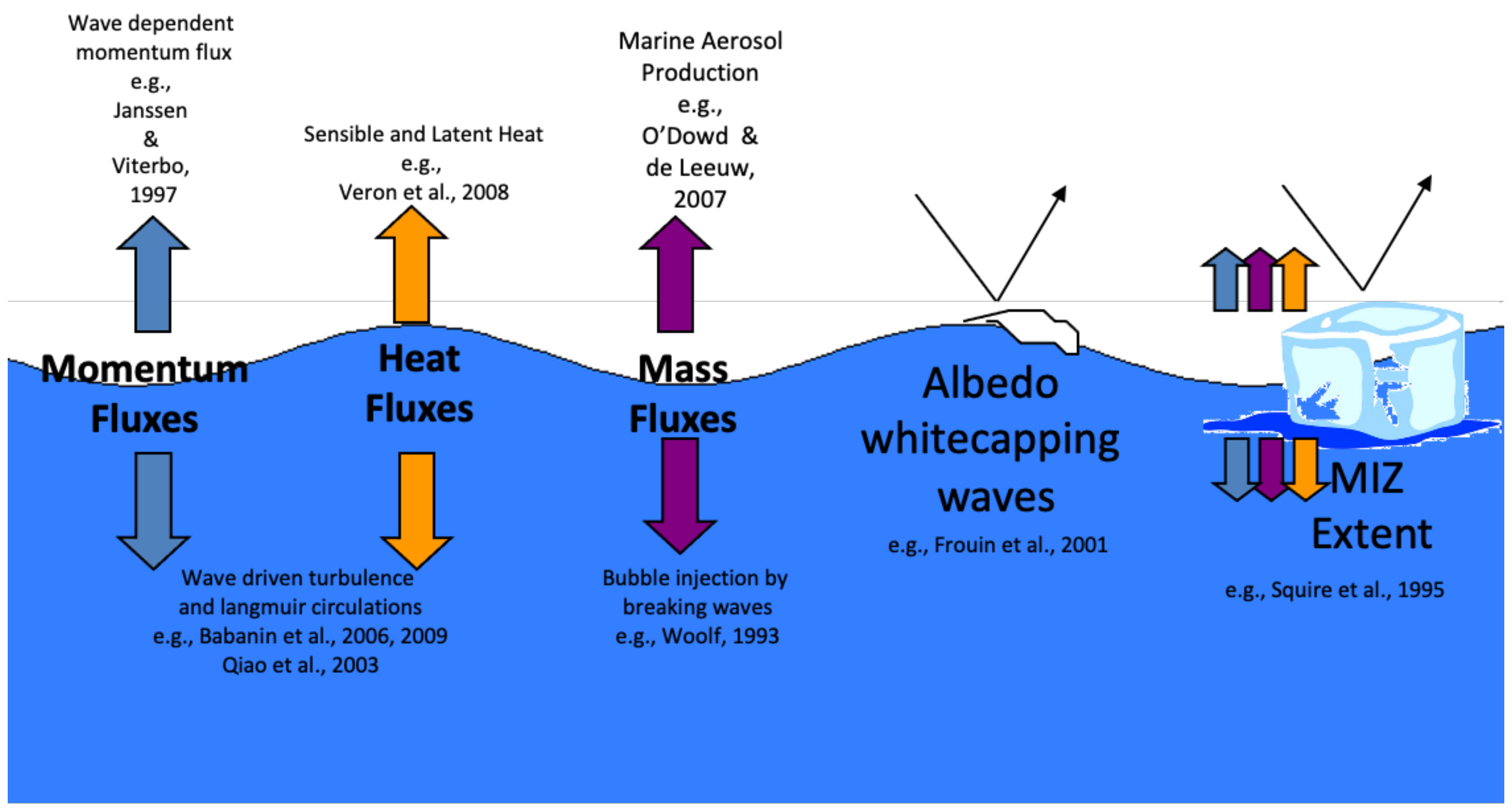


Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle models developed in the context of the World Climate and Global Change programs.

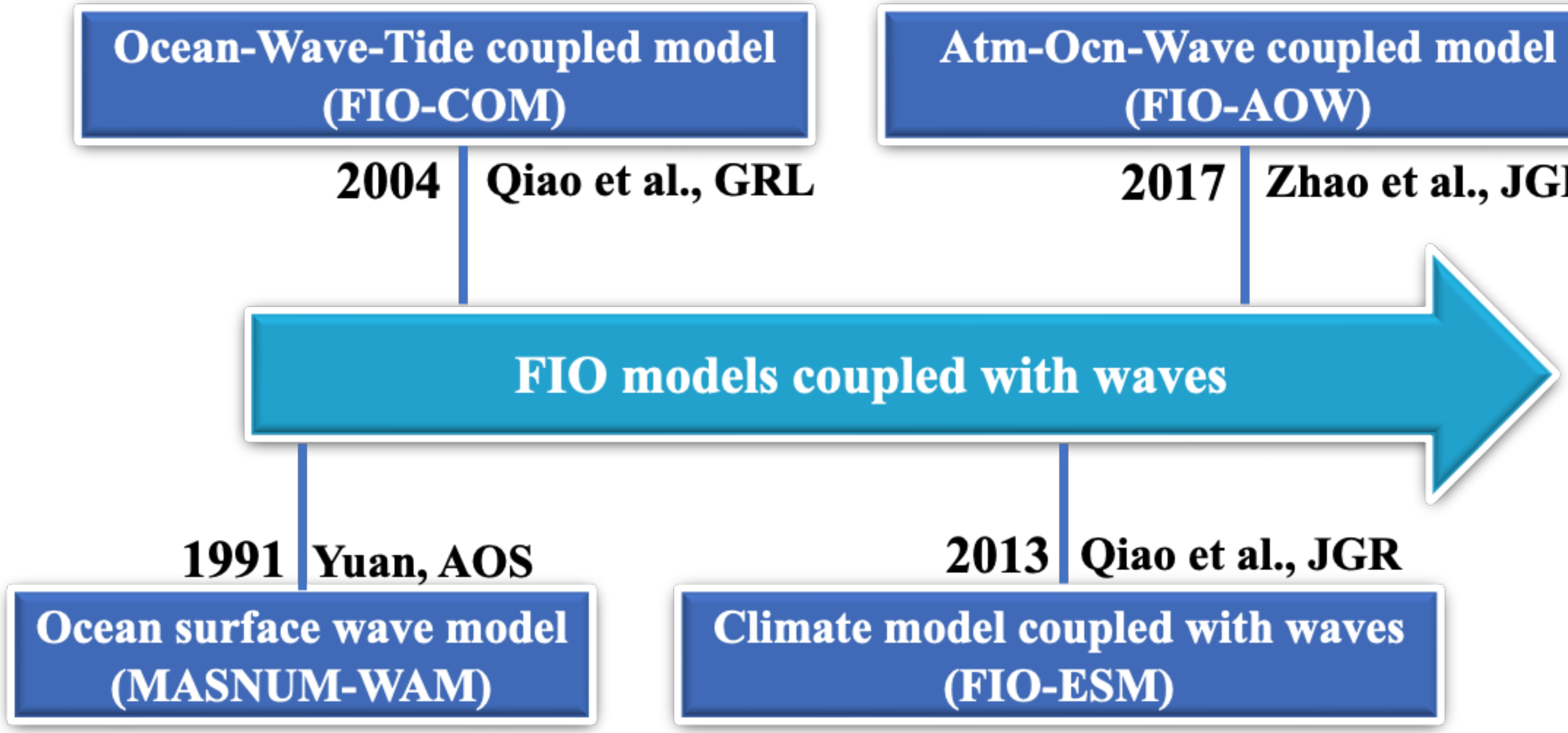
Hasselmann, 1991



Effects of ocean surface waves in the climate system

Background

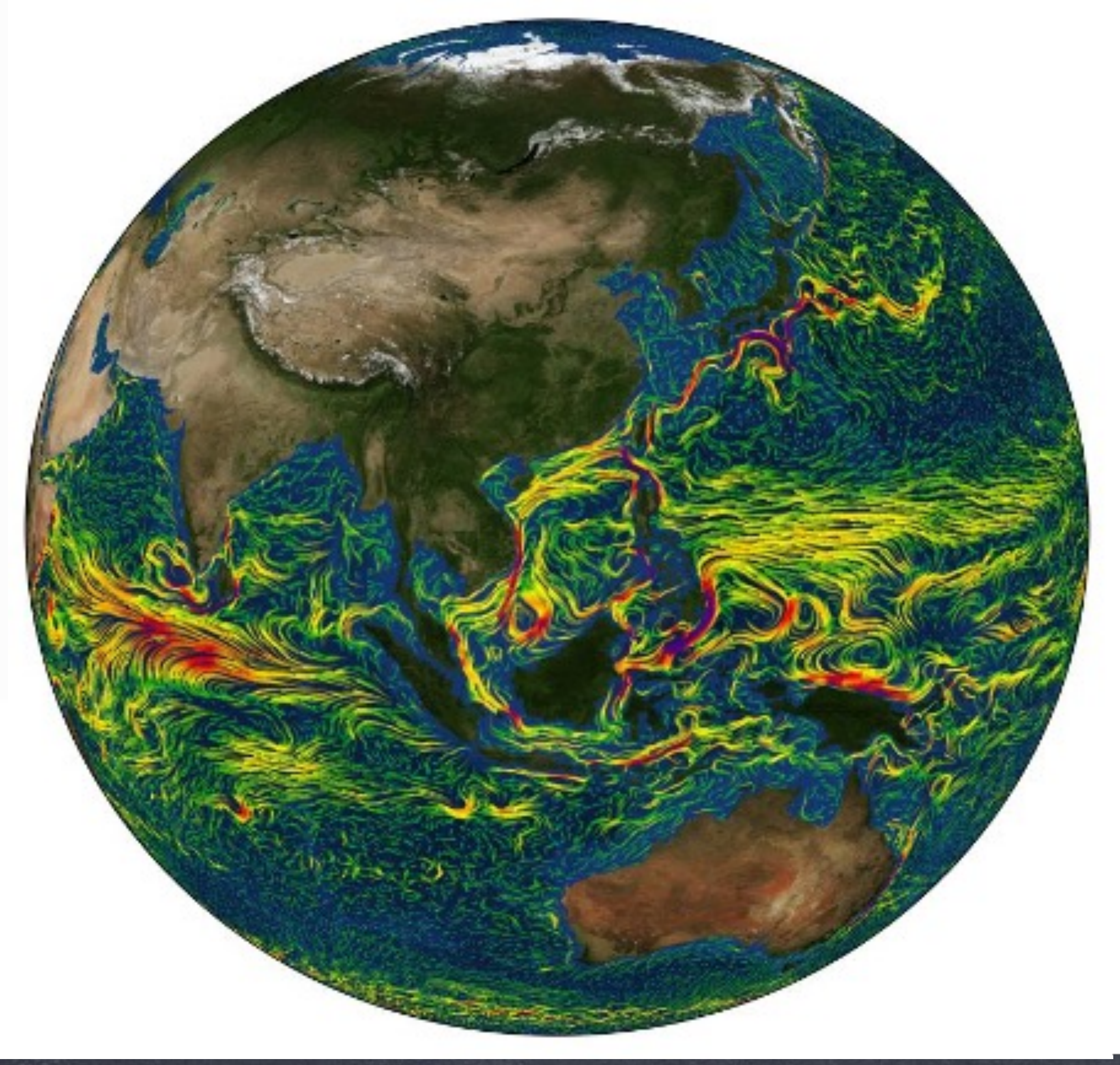
FIO models coupled with ocean surface waves

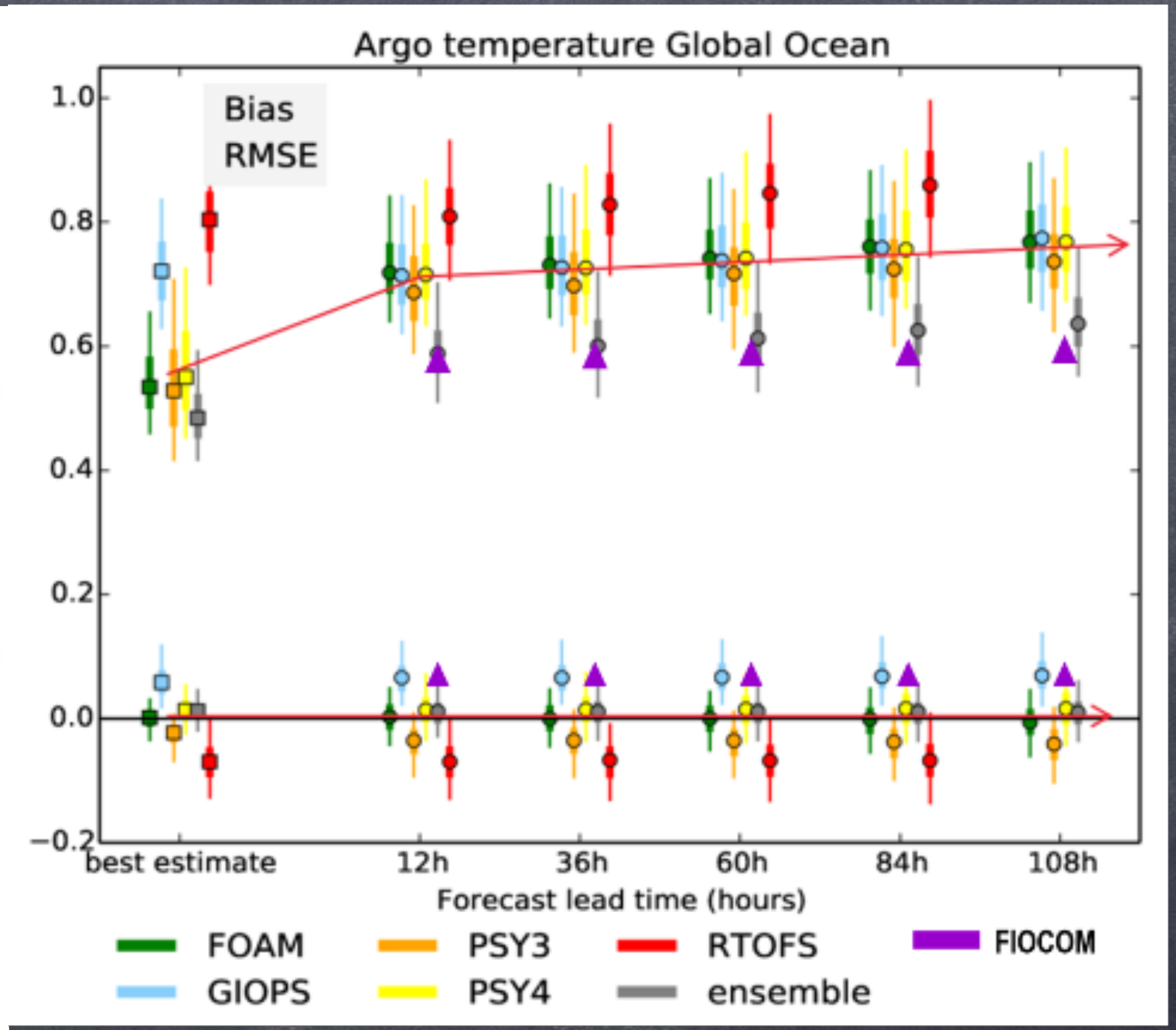


Advances in the FIO models

Background

FIO models coupled with ocean surface waves
(1) FIO-COM

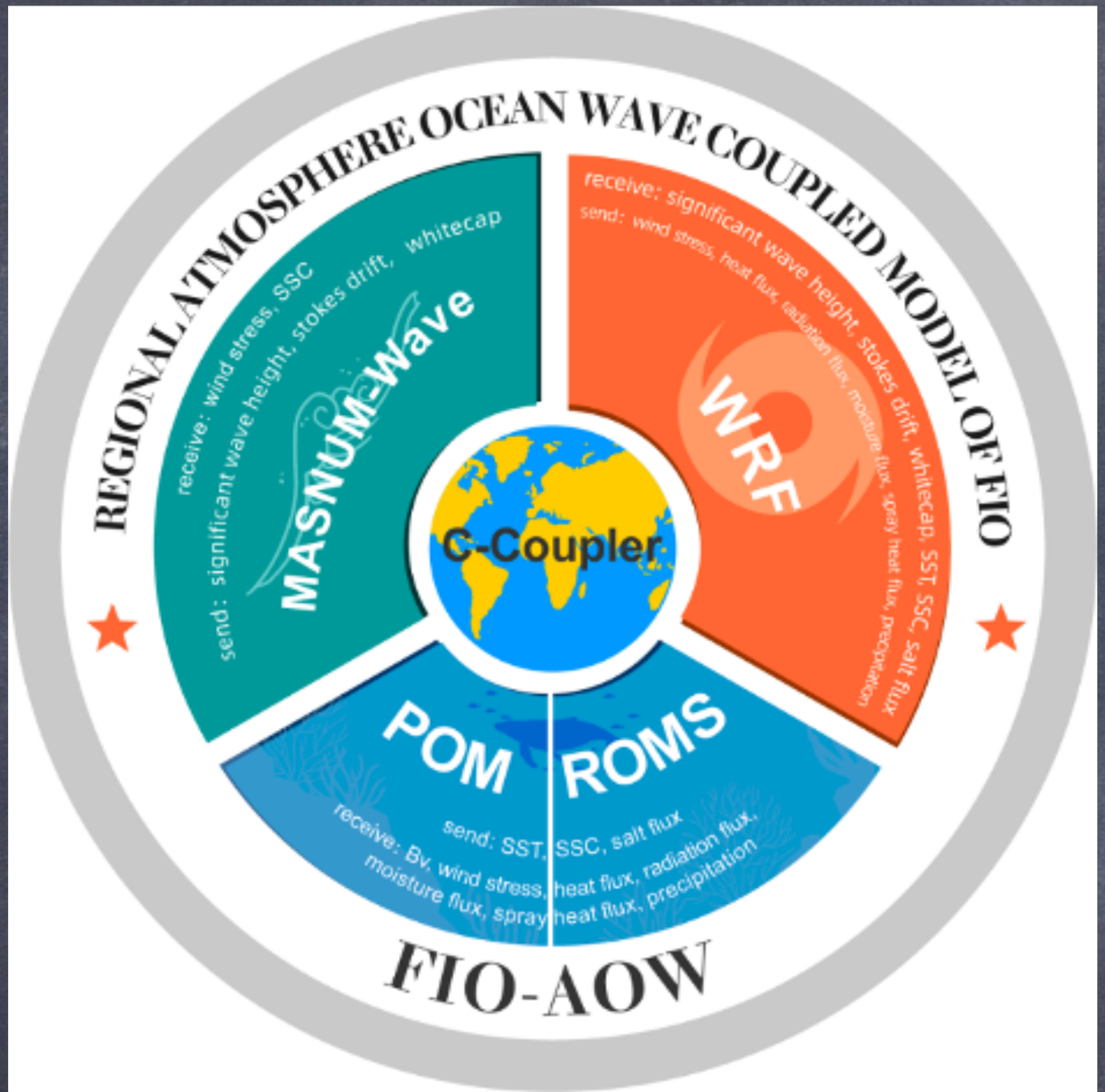


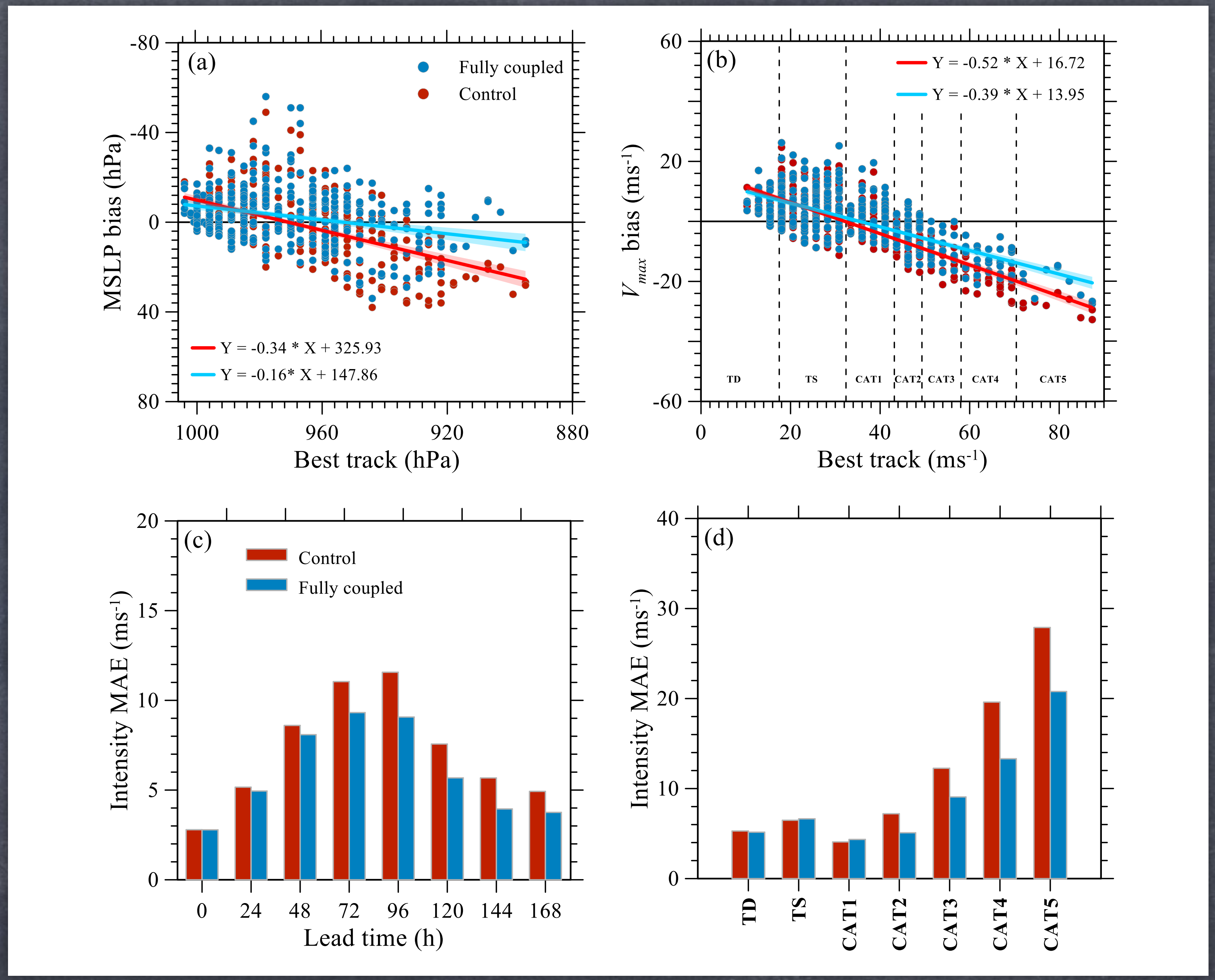


- Good performance on the upper ocean by considering the wave-induced mixing
- Develop the first ocean-wave-tide coupled model, and provide operational service through the WETSPAC official website, and APP
- 1/10° is on operation, 1/32° is on developing

Background

FIO models coupled with ocean surface waves
(2) FIO-AOW



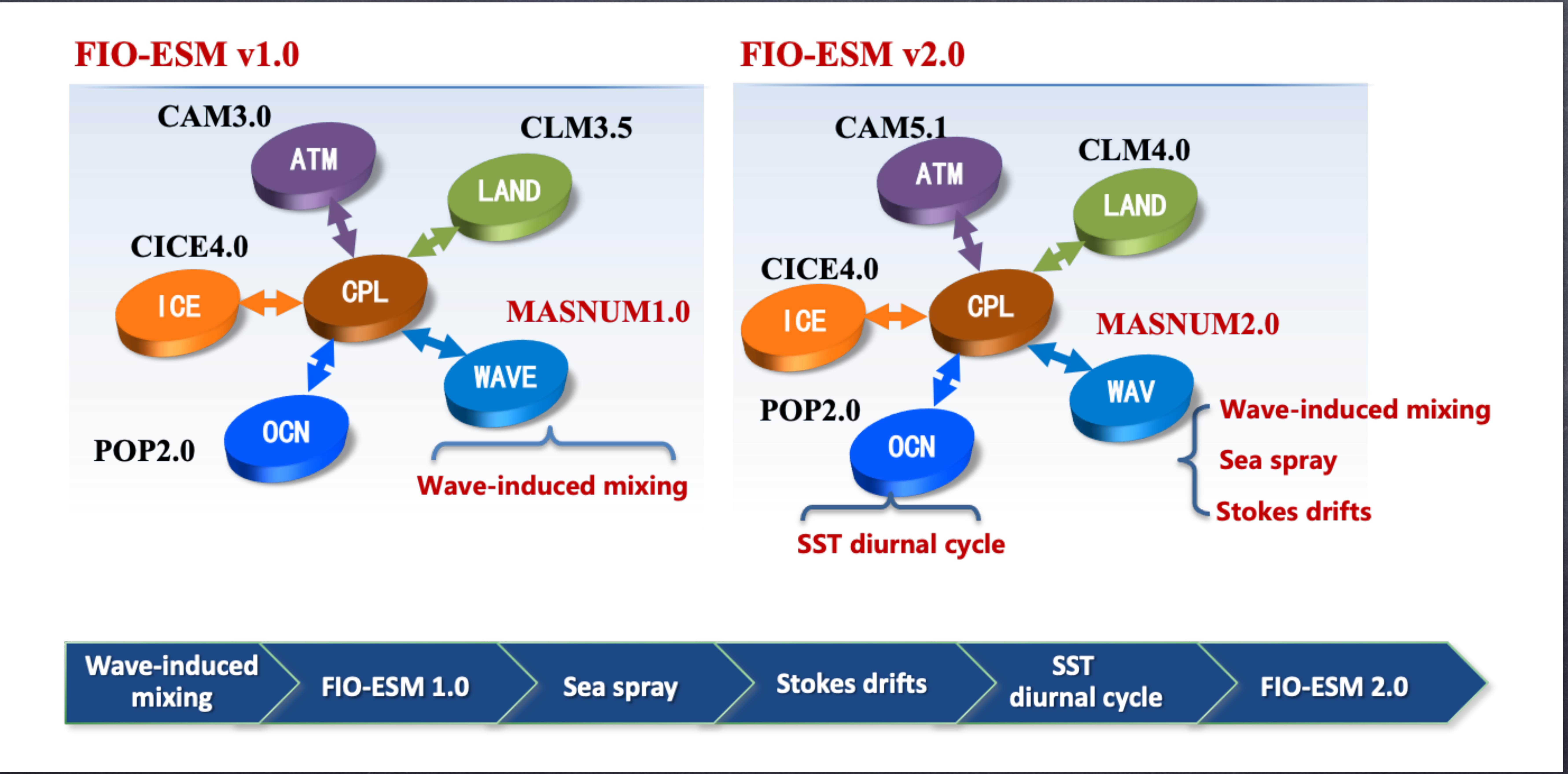


- Atmosphere(WRF)-Ocean(ROMS)-Wave(MASNUM)-tide coupled model, 75°E-165°E; 20°S-50°, 1/30 °*1/30 °; vertical 50 layers
- Consider the bv, sea-spray effects, improve the typhoon strength
- Strong typhoon (>41.5m/s) biases is reduced by 32%
- Super typhoon (>51.0m/s) biases is reduced by 58%

Zhao et al., 2017, 2022, JGR-Oceans

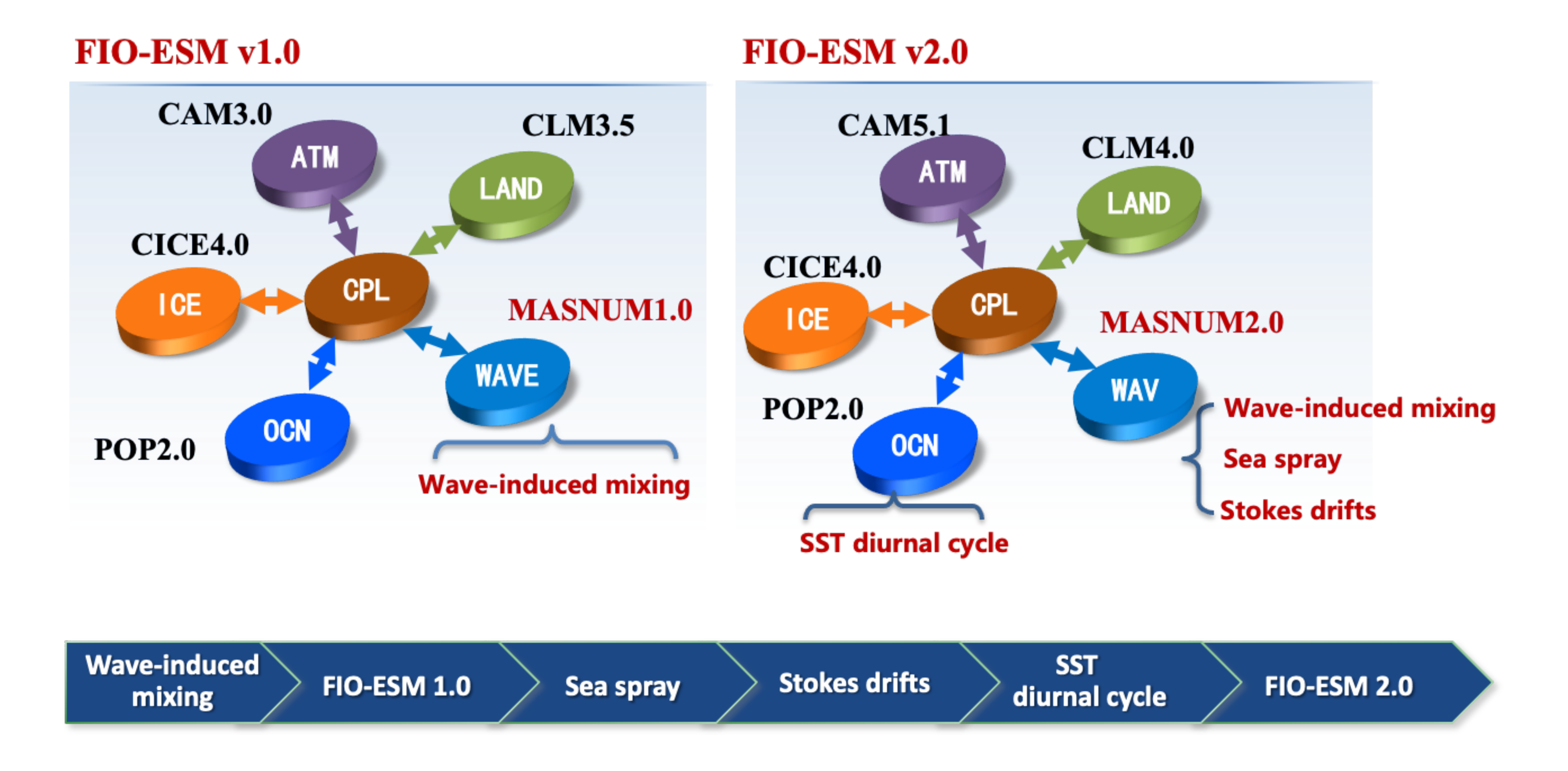
Background

FIO models coupled with ocean surface waves
(3) FIO-ESM



Background

FIO models coupled with ocean surface waves
(3) FIO-ESM



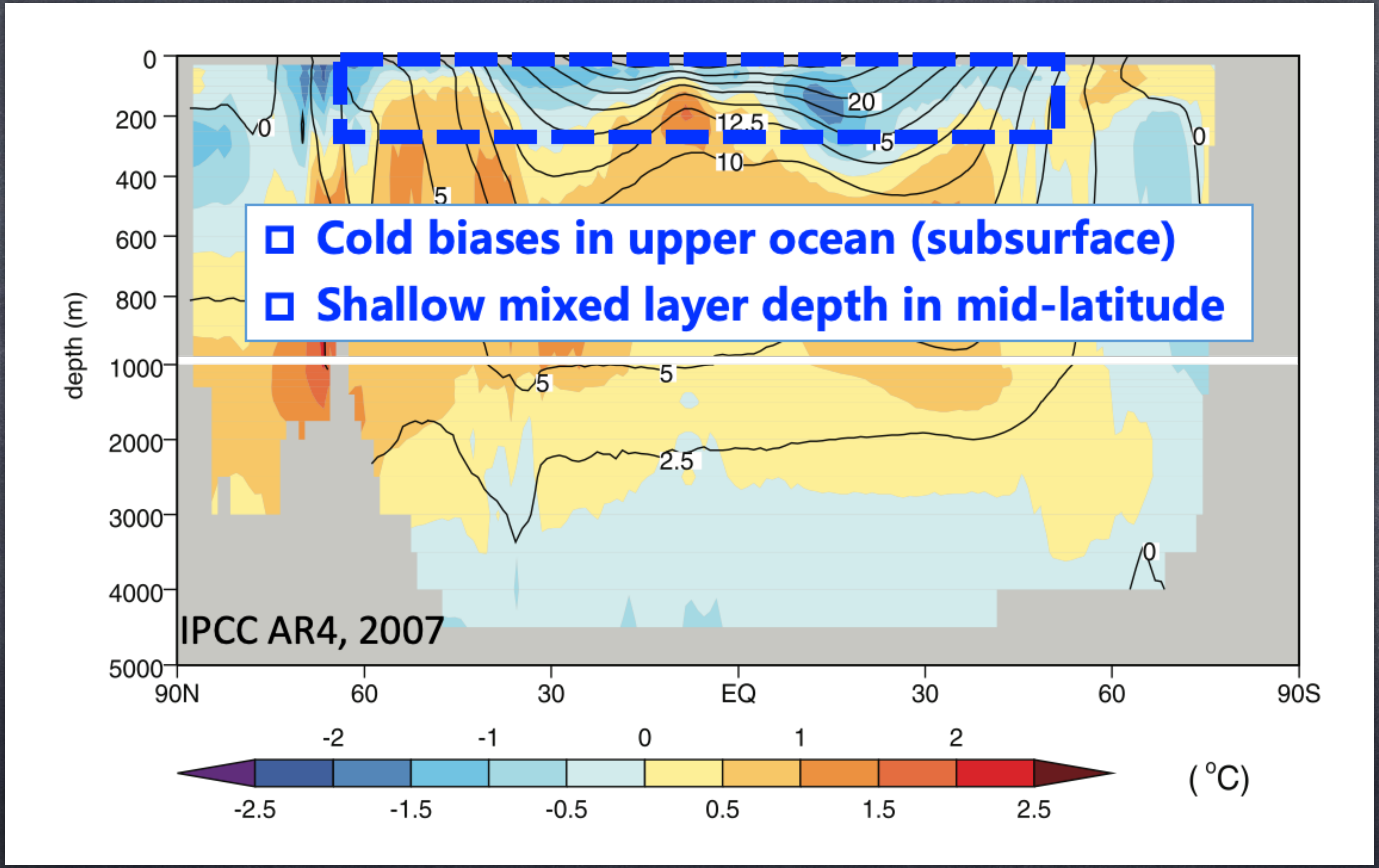
Ocean surface waves is the low-hanging fruit for improving the simulated ability

Outline

- Motivation
- FIO-ESM v1.0 development
- FIO-ESM v2.0 development
- Perspectives on the FIO-ESM

FIO-ESM v1.0 Development

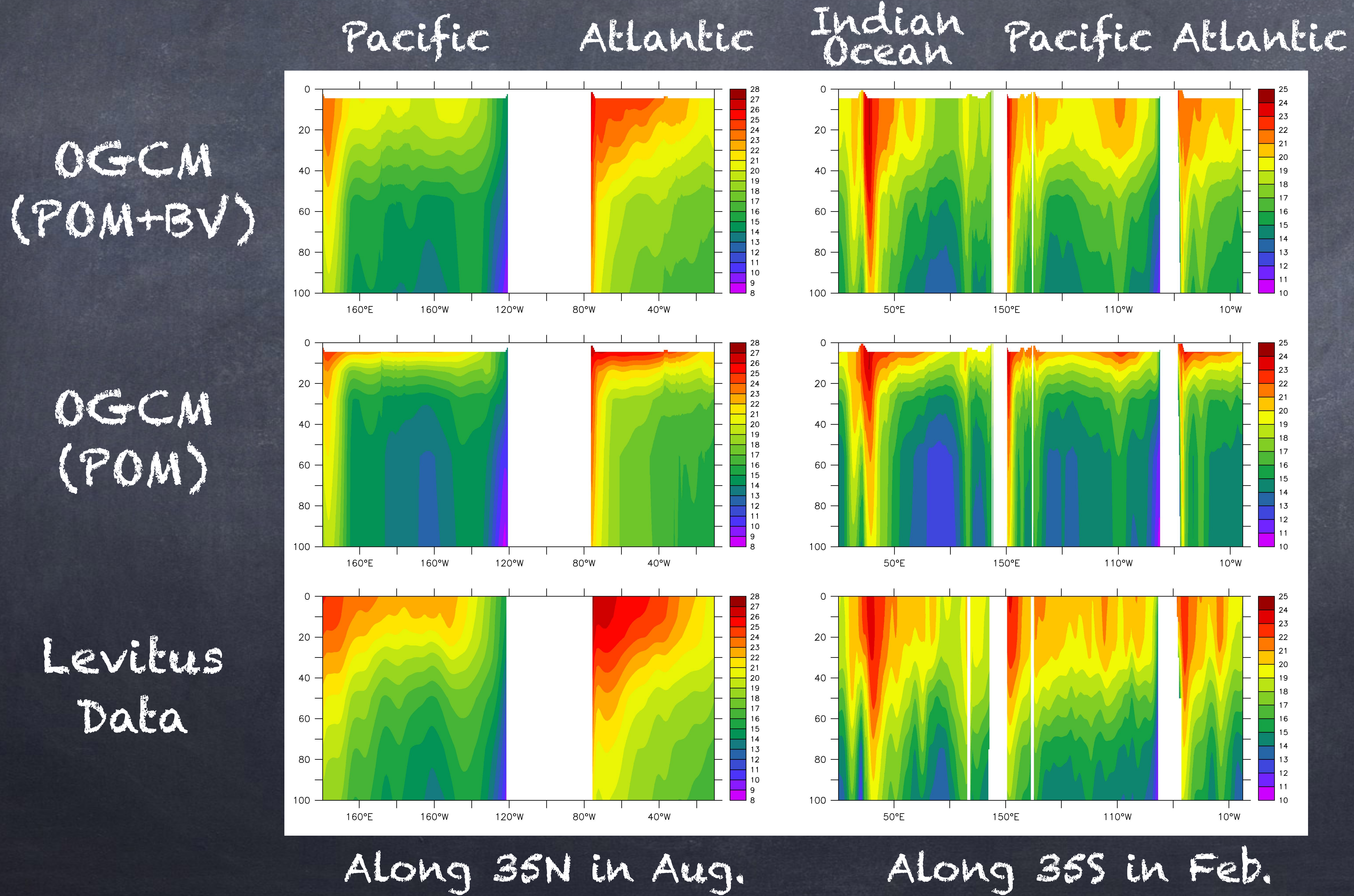
Common problems nearly all ESM faced



Zonal average ocean temperature biases (Multi-model mean)

FIO-ESM v1.0 Development

Common problems nearly all OGCMs faced:
SST is overheating and Mixed Layer Depth is shallow in summertime



Bv can improve the upper ocean temperature structure

FIO-ESM v1.0 Development

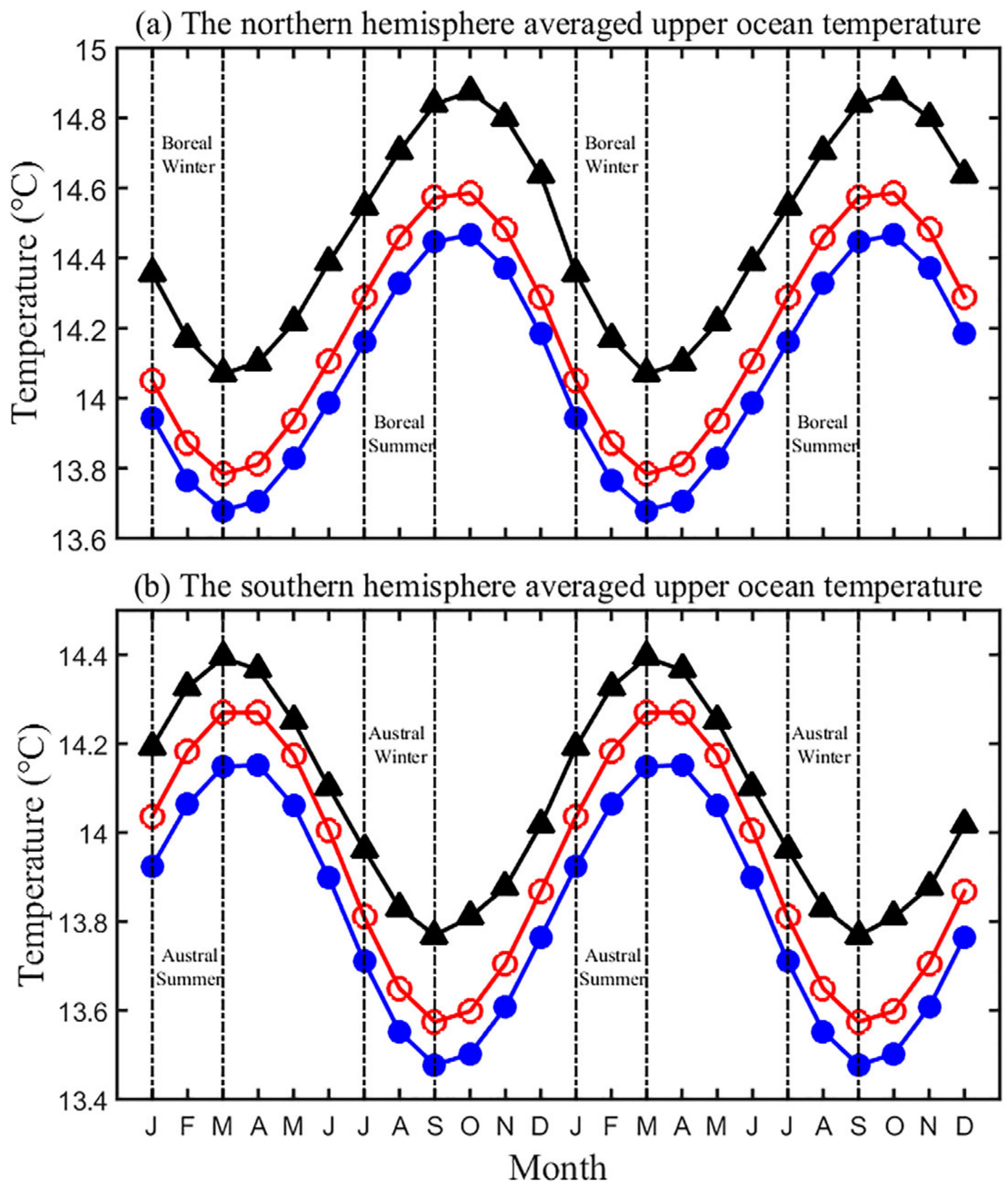
BV effects on ESMs

Upper Ocean (400 m) temperature evolution in middle latitude (20-40 degrees)

Black: EN4 dataset

Blue: without BV

Red: with BV effects



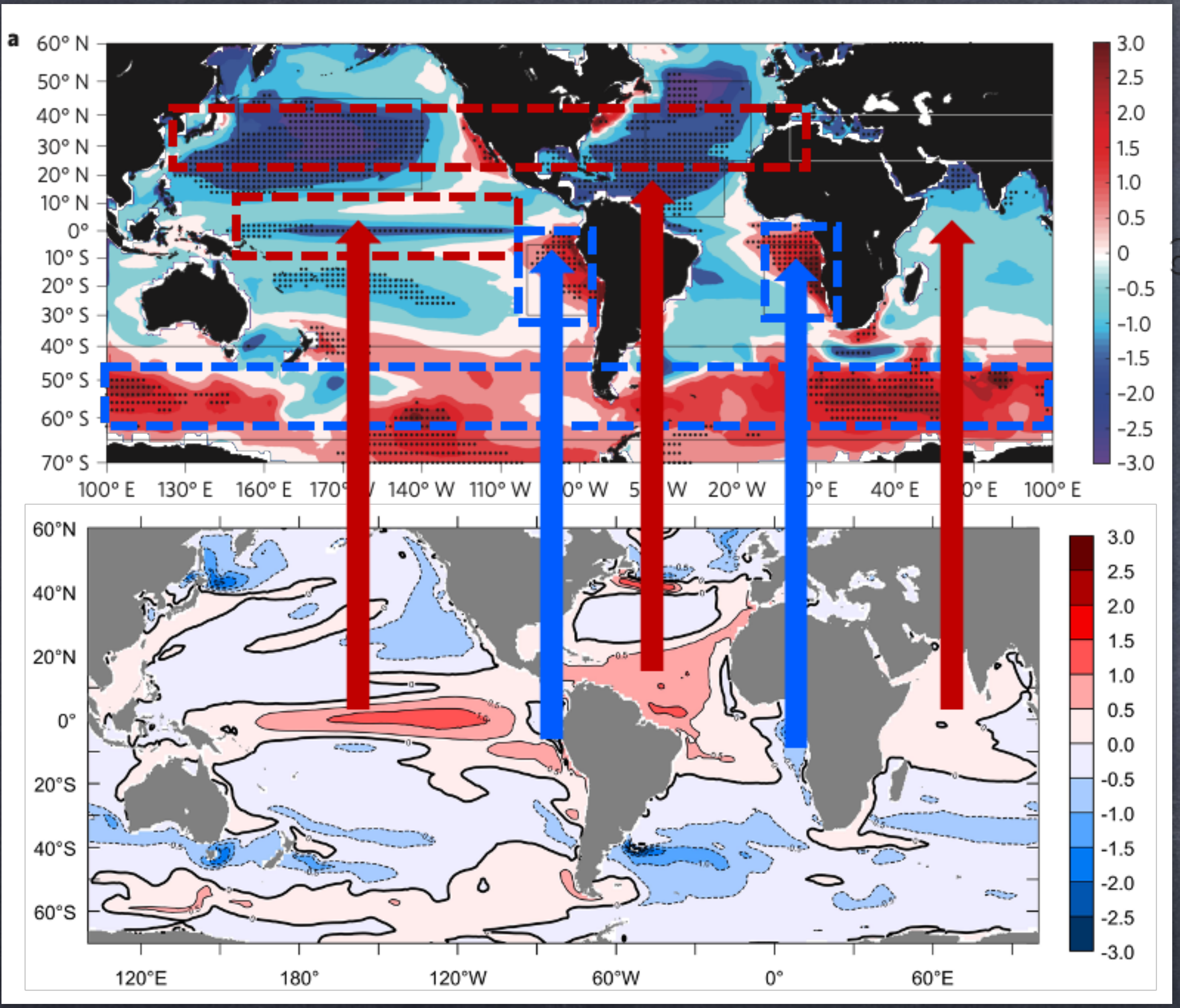
Huang et al., 2012, JGR; Chen et al., 2018, JGR; 2020, JOL

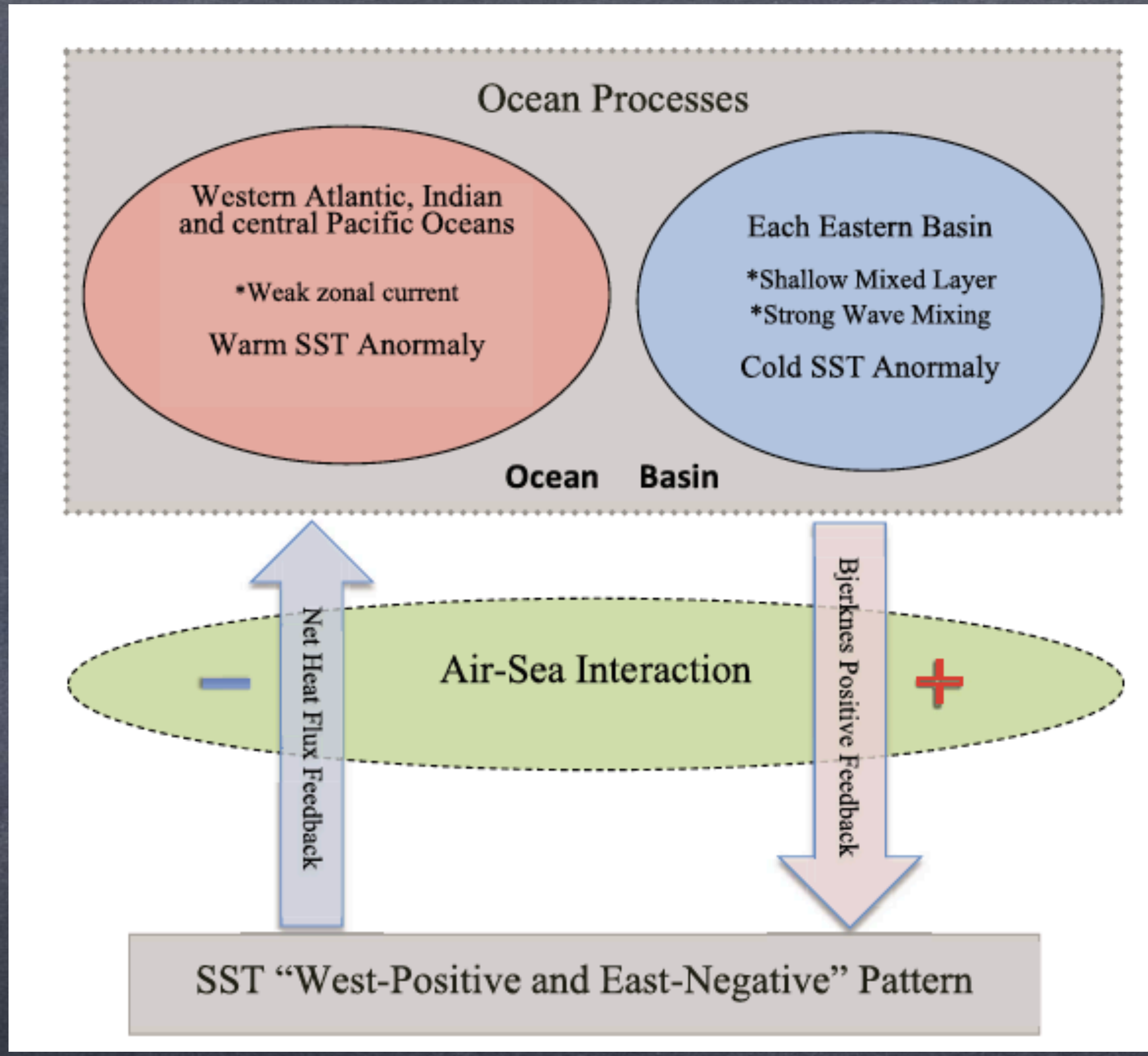
FIO-ESM v1.0 Development

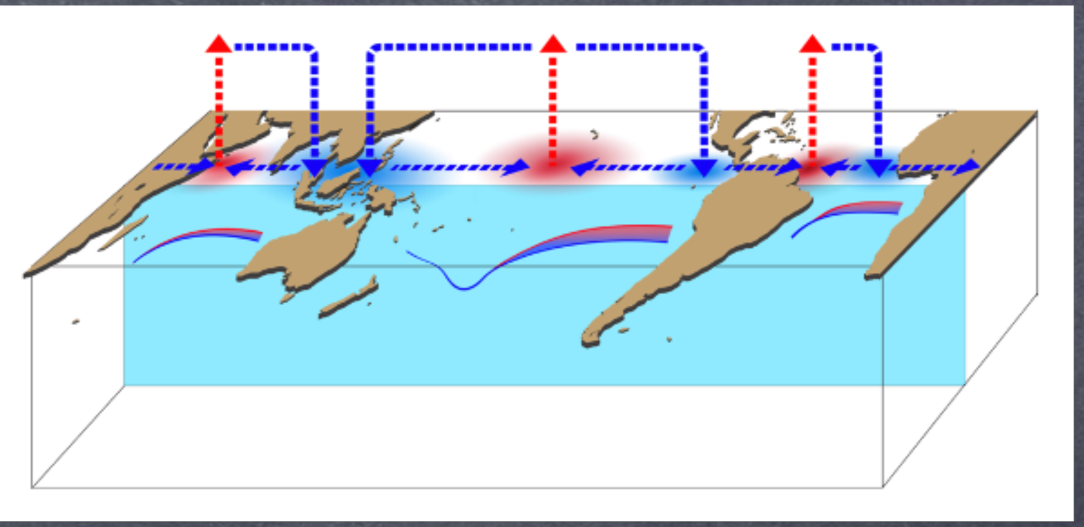
BV effects on ESMs

SST biases

BV effects







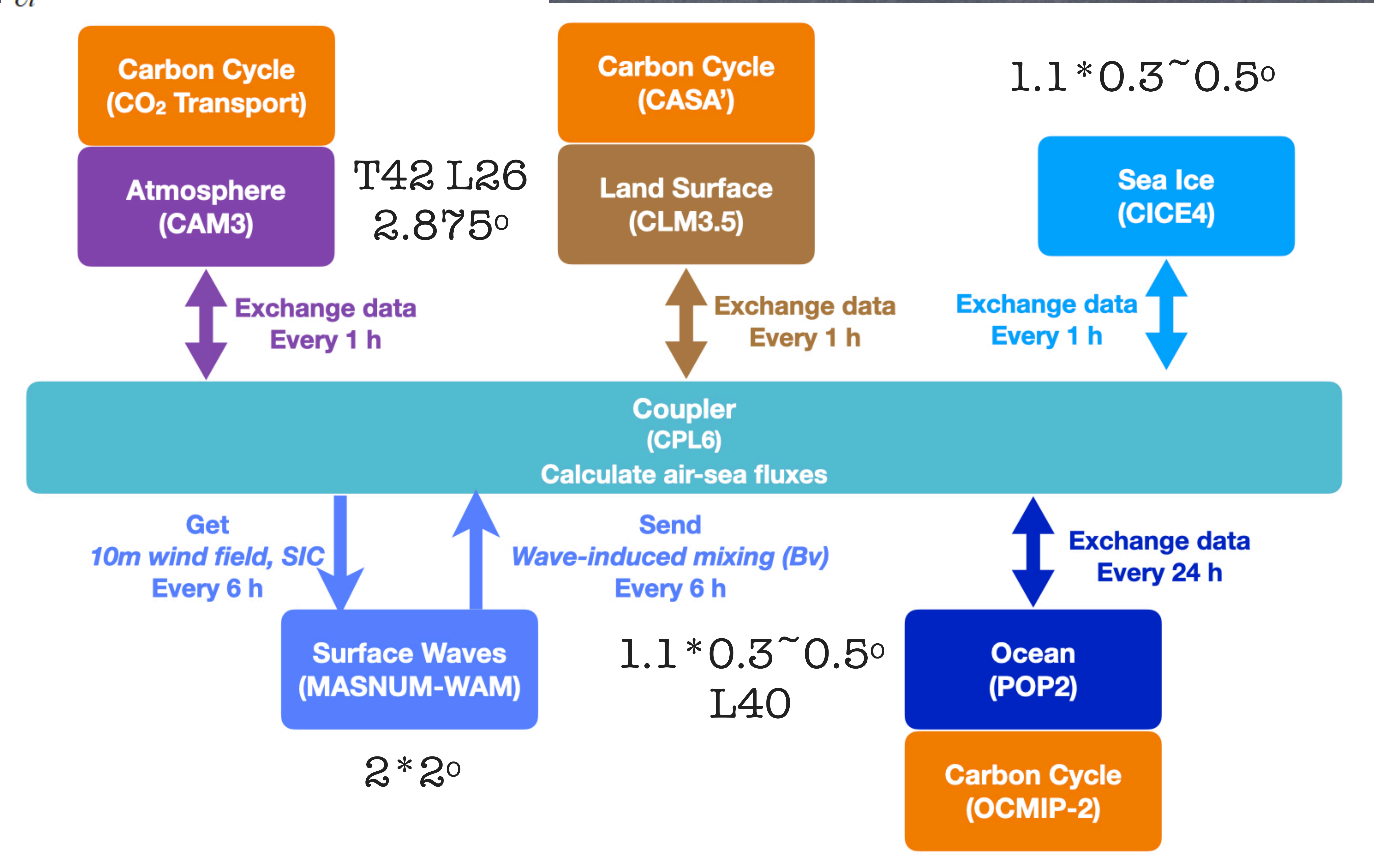
Schematic response of tropical SST to BV effect in climate system

- FGCM-0 (IAP/LASG, China) : Song et al., 2007, 2012; Huang et al., 2008
- CCSM3 (NCAR, USA) : Song et al., 2011; 2012
- BCC-CSM2 (BCC, China) : Wu et al., 2016

FIO-ESM v1.0 Development

FIO-ESM v1.0 framework

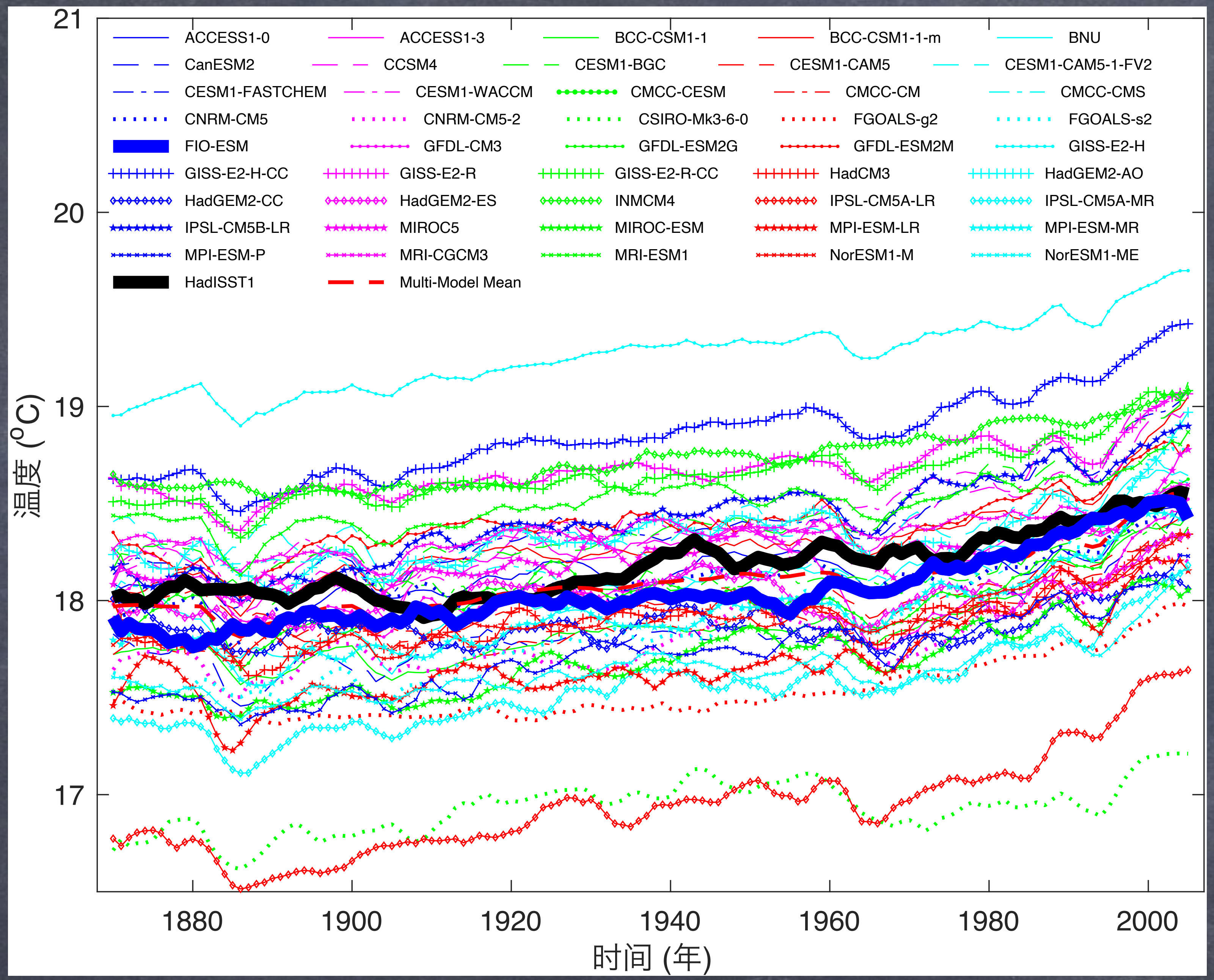
$$\frac{\partial}{\partial t}CO_2 + \Im(CO_2) = ExternalSource + f_{ao} + f_{al}$$

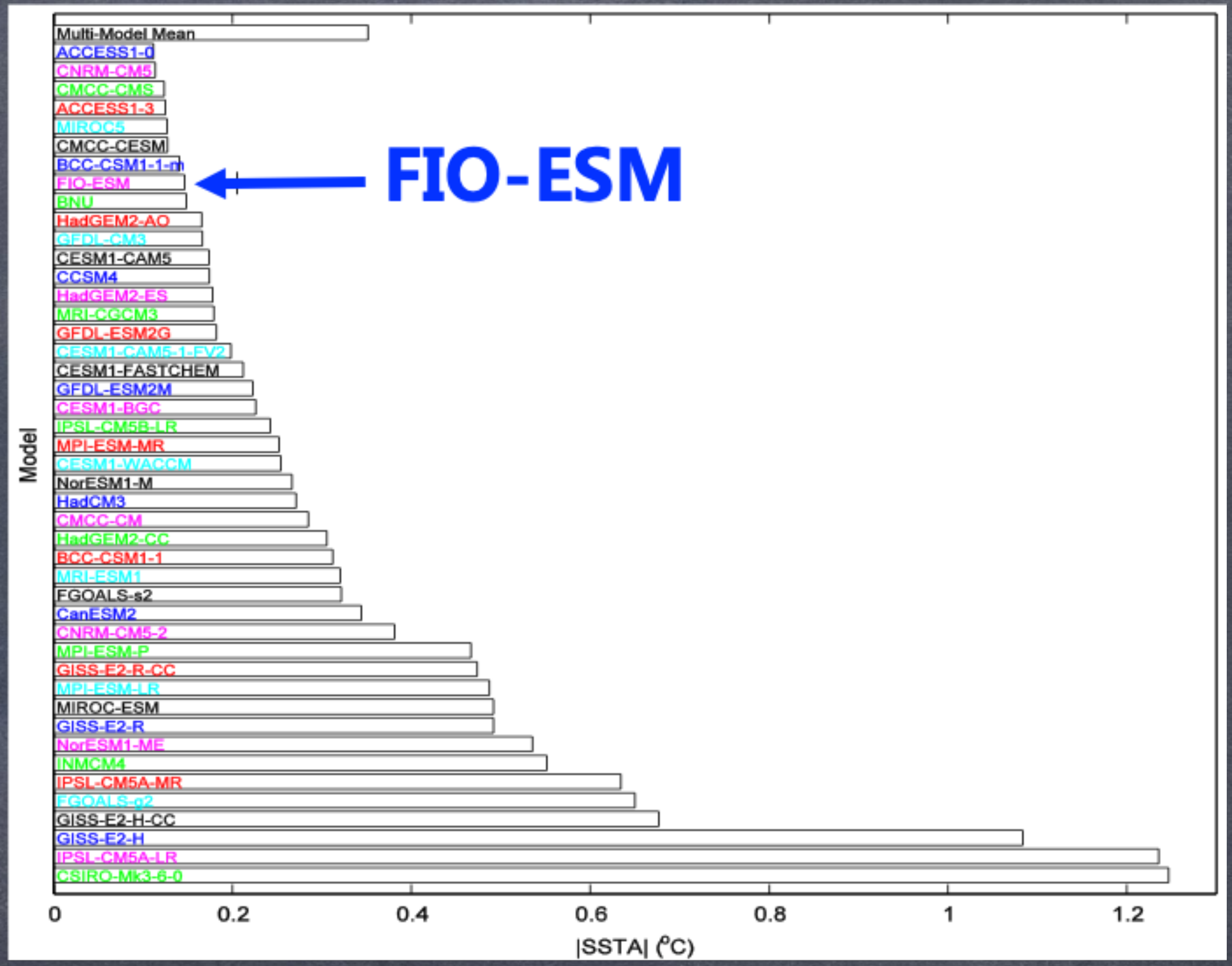


- Participate the CMIP5 organized by WGCM/WCRP
- FIO-ESM v1.0 is the only one coupled with wave model

FIO-ESM v1.0 Development

Progress in FIO-ESM v1.0 simulated ability



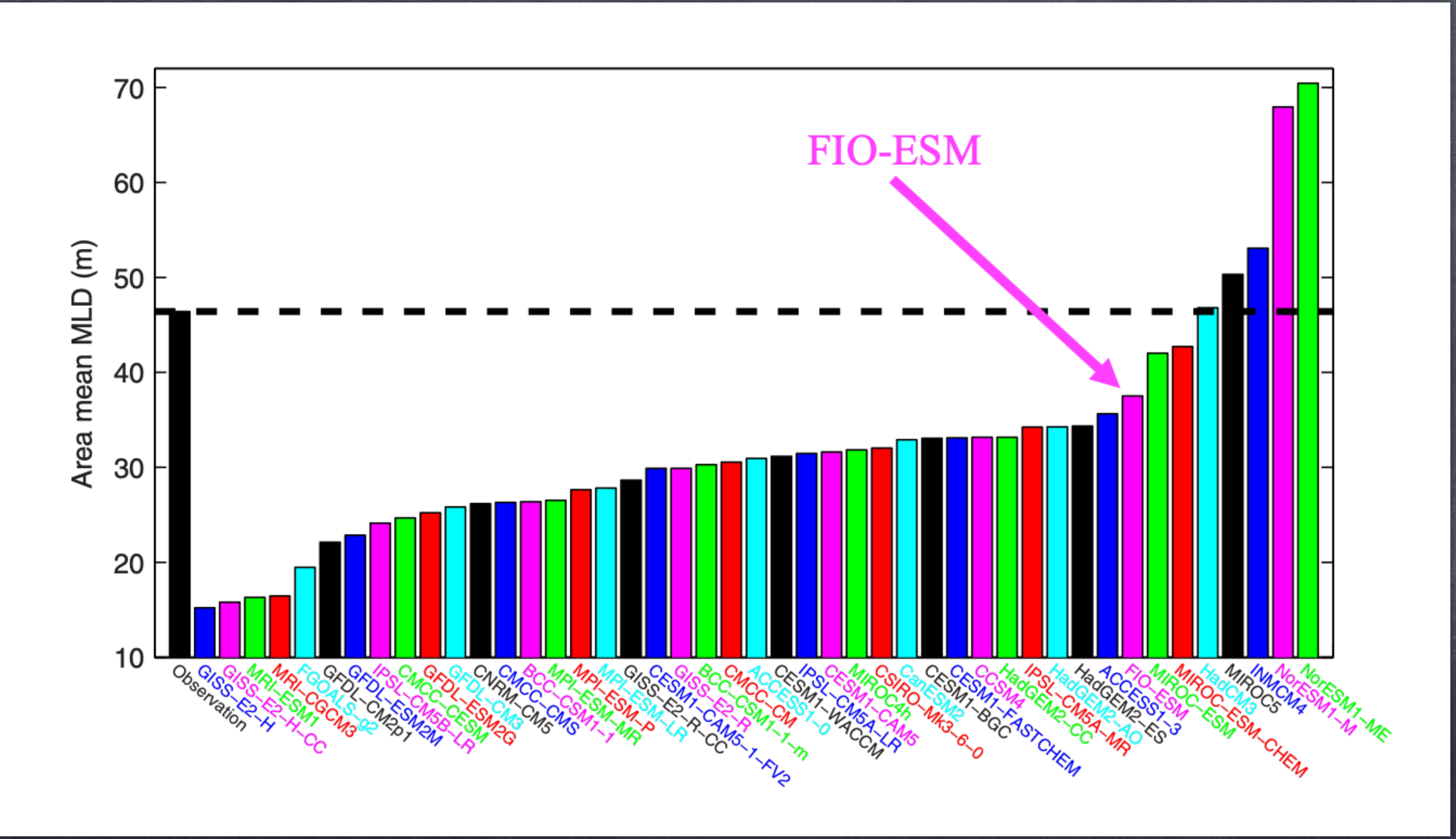


- Thick Black Line: HadISST
- Thick Red Line: Multi-model mean
- Thick Blue Line: FIO-ESM v1.0 (Rank: 8/45)
- Thin Color Line: other CMIP5 models

Global Annual Mean SST Evolution (1850 - 2005)

FIO-ESM v1.0 Development

Progress in FIO-ESM v1.0 simulated ability



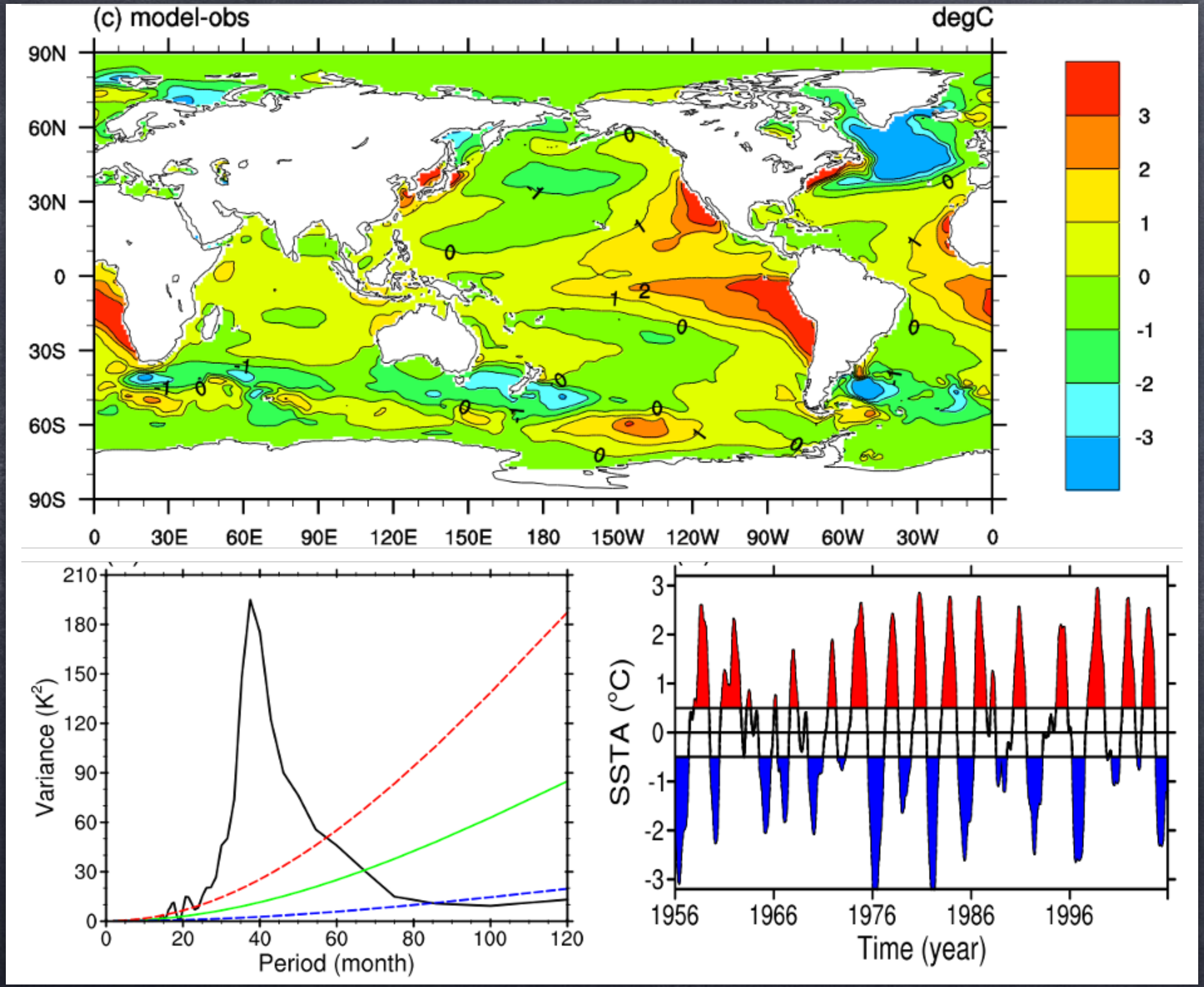
Mixed layer depth over the Southern Ocean

FIO-ESM v1.0 Rank: 6/45

Huang et al., 2014, JGR

FIO-ESM v1.0 Development

Deficiency of FIO-ESM v1.0



SST biases

Warm SST biases over tropical Pacific

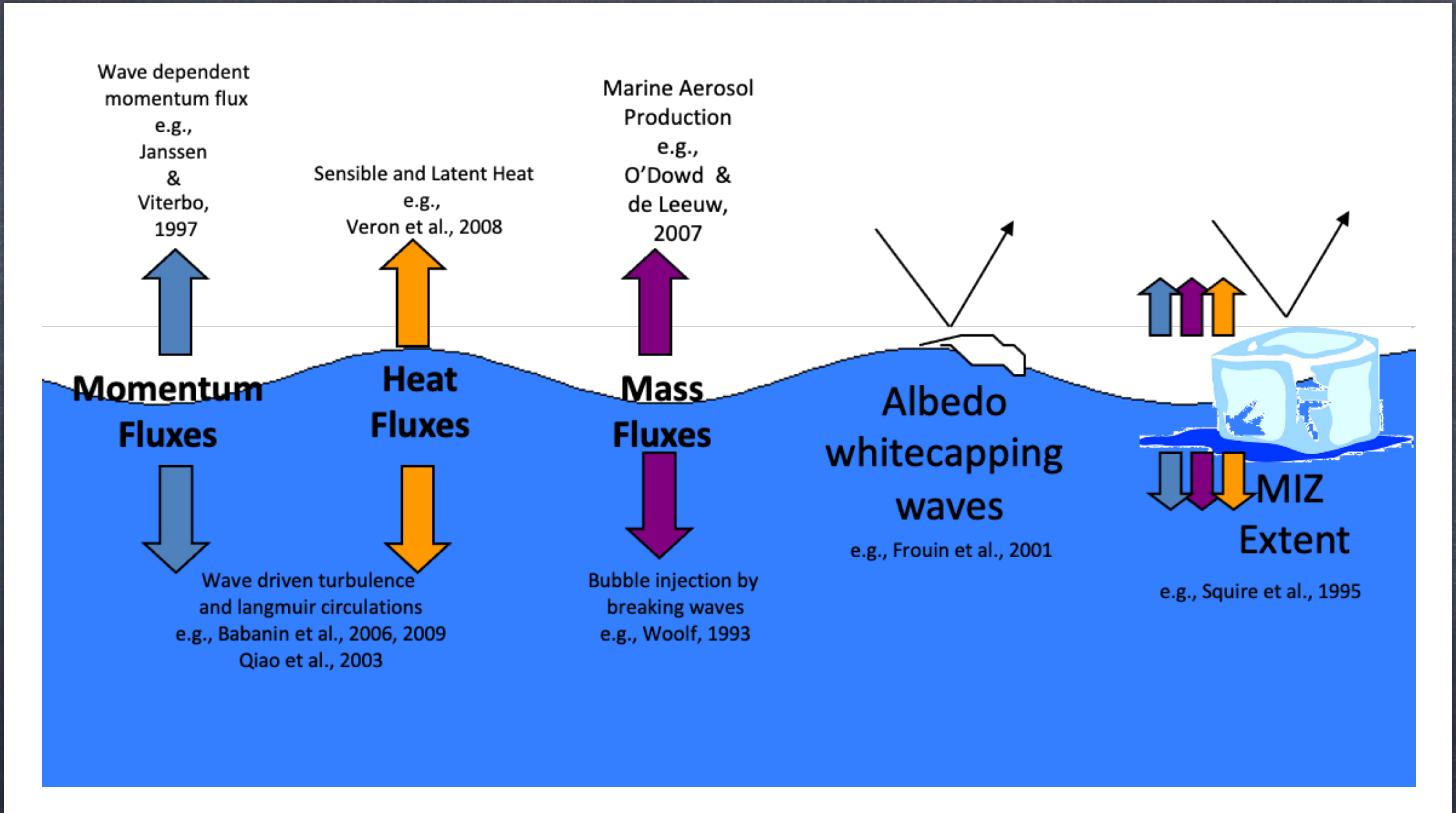
ENSO biases

Too strong, regularity, spurious phase locking

Chen et al., 2019, Climate Dynamics

FIO-ESM v1.0 Development

Deficiency of FIO-ESM v1.0



Effects of ocean surface waves in the climate system

Outline

- Motivation
- FIO-ESM v1.0 development
- FIO-ESM v2.0 development
- Perspectives on the FIO-ESM

FIO-ESM v2.0 development

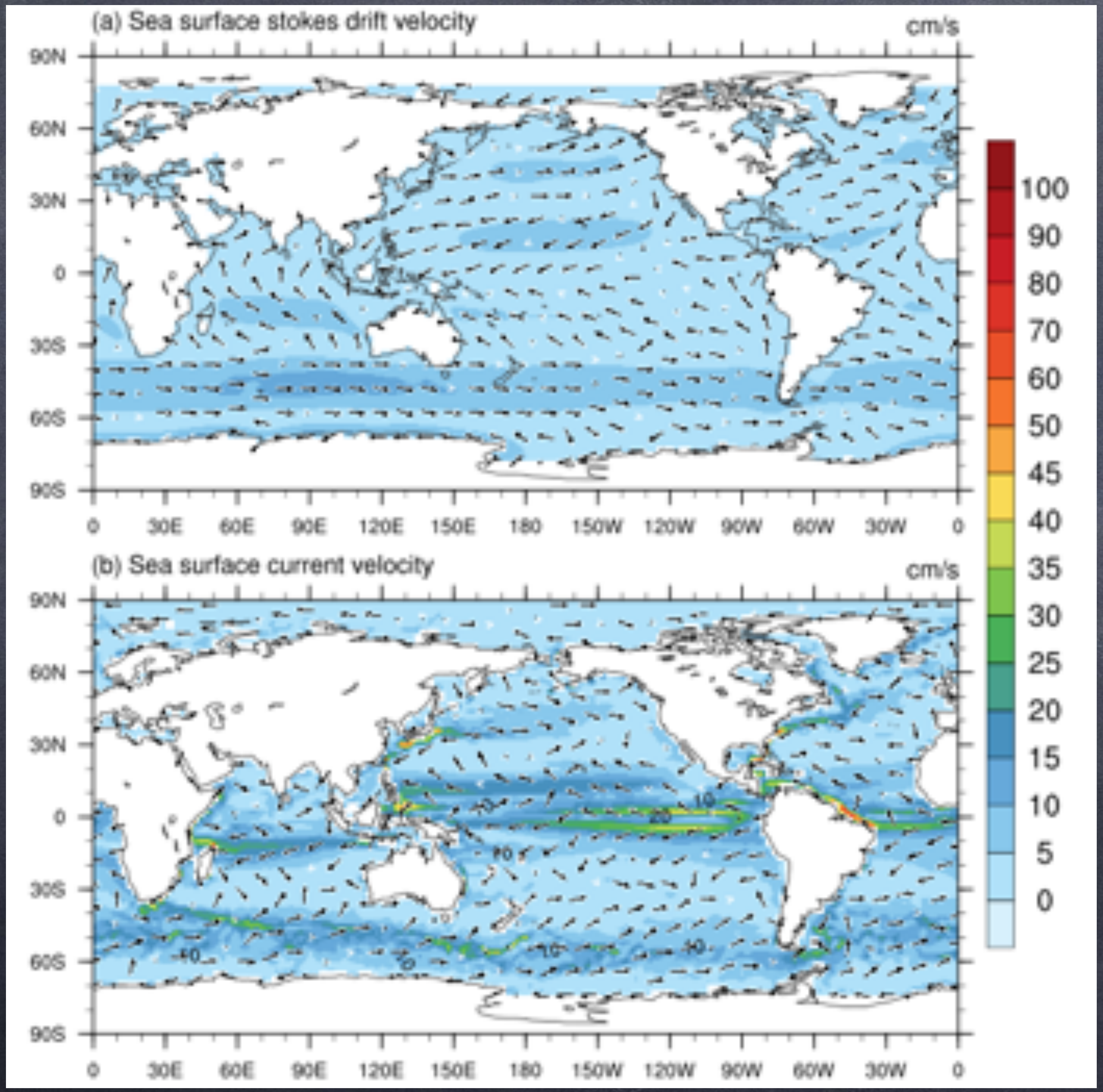
(1) Distinctive Physical Processes

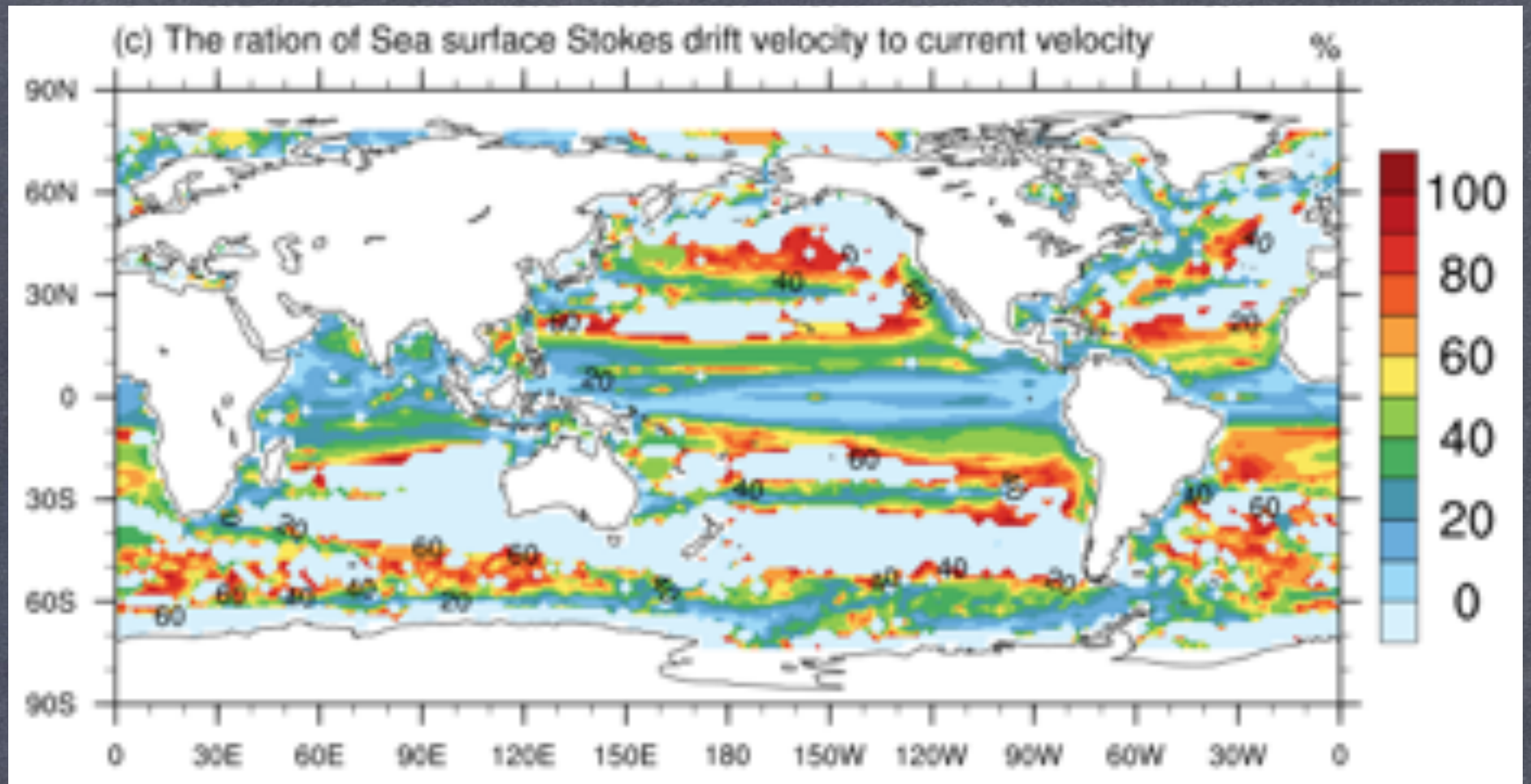
a. Stokes drift (air-sea flux)
b. Sea spray (latent and sensible flux)
c. SST diurnal cycle (sensible heat flux)
d. Wave-induced mixing, BV (ocean)

FIO-ESM v2.0 development

(1) Distinctive Physical Processes

a. Stokes Drift (air-sea flux)





Surface fluxes:

Momentum $\vec{\tau} = \rho_A |\Delta\vec{V}| C_d \Delta\vec{V}$

Latent heat $H = \rho_A |\Delta\vec{V}| C_h \Delta\theta$

Sensible heat $E = \rho_A |\Delta\vec{V}| C_e \Delta q$

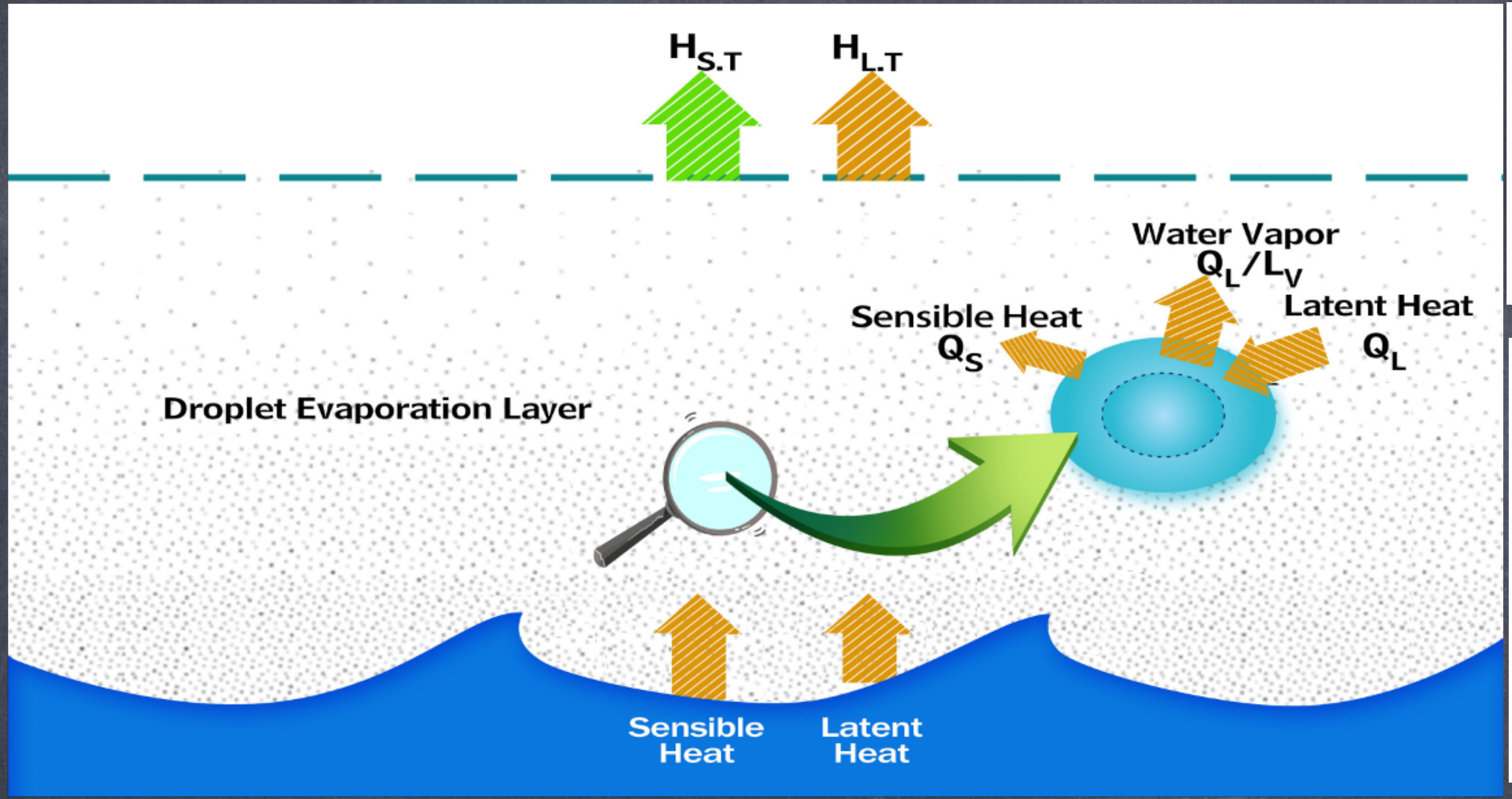
$\Delta\vec{V} = \vec{V}_A - \vec{V}_O$ → $\Delta\vec{V} = \vec{V}_A - \vec{V}_O - \vec{V}_S$

Bao et al., 2020, JGR

FIO-ESM v2.0 development

(1) Distinctive Physical Processes

b. Sea Spray (latent and sensible flux)



$$H_{S,T} = H_S + H_{S,sp}$$

$$H_{L,T} = H_L + H_{L,sp}$$

$$H_{S,sp} = \beta \overline{Q_S} - (\alpha - \gamma)\overline{Q_L} = \rho_s c_{ps}\left(T_s - T_{eq,100}\right)V_S(u_*)$$

$$H_{L,sp} = \alpha \overline{Q_L} = \rho_s L_v \left\{1 - \left[\frac{r(\tau_{f,50})}{50\mu\text{m}}\right]^3\right\} V_L(u_*)$$

$$T_{eq,100} = T_a + \frac{M_W L_v(T_{ev}) D_W(T_{ev},r)}{R k'_a(T_{ev},r)} \times \left\{\frac{e_{sat}(T_a) f}{T_a} - \frac{e_{sat}(T_{ev}) \exp\left[y(T_{ev},r,s)\right]}{T_{ev}}\right\}$$

Equilibrium temperature of droplets with 100 um initial radius

$$\tau_f = \frac{H_{1/3}}{2u_f\ (r_0)}$$

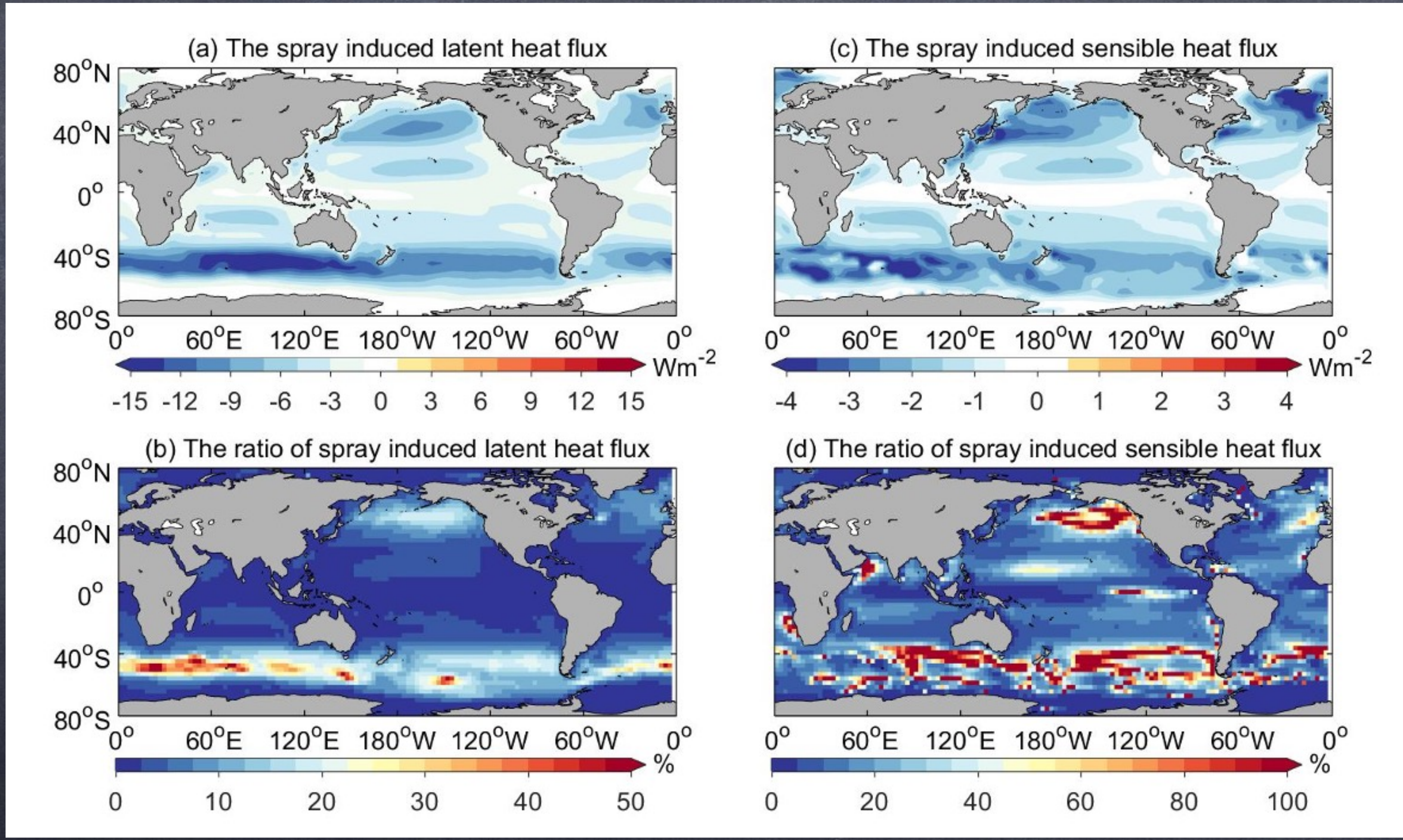
Residence time in the air for 50 um droplets

Andreas, 2008; 2015

FIO-ESM v2.0 development

(1) Distinctive Physical Processes

b. Sea Spray (latent and sensible flux)



Latent heat flux

Sensible heat flux

Heat flux induced by sea spray

Ratio of heat flux induced by sea spray to total heat flux

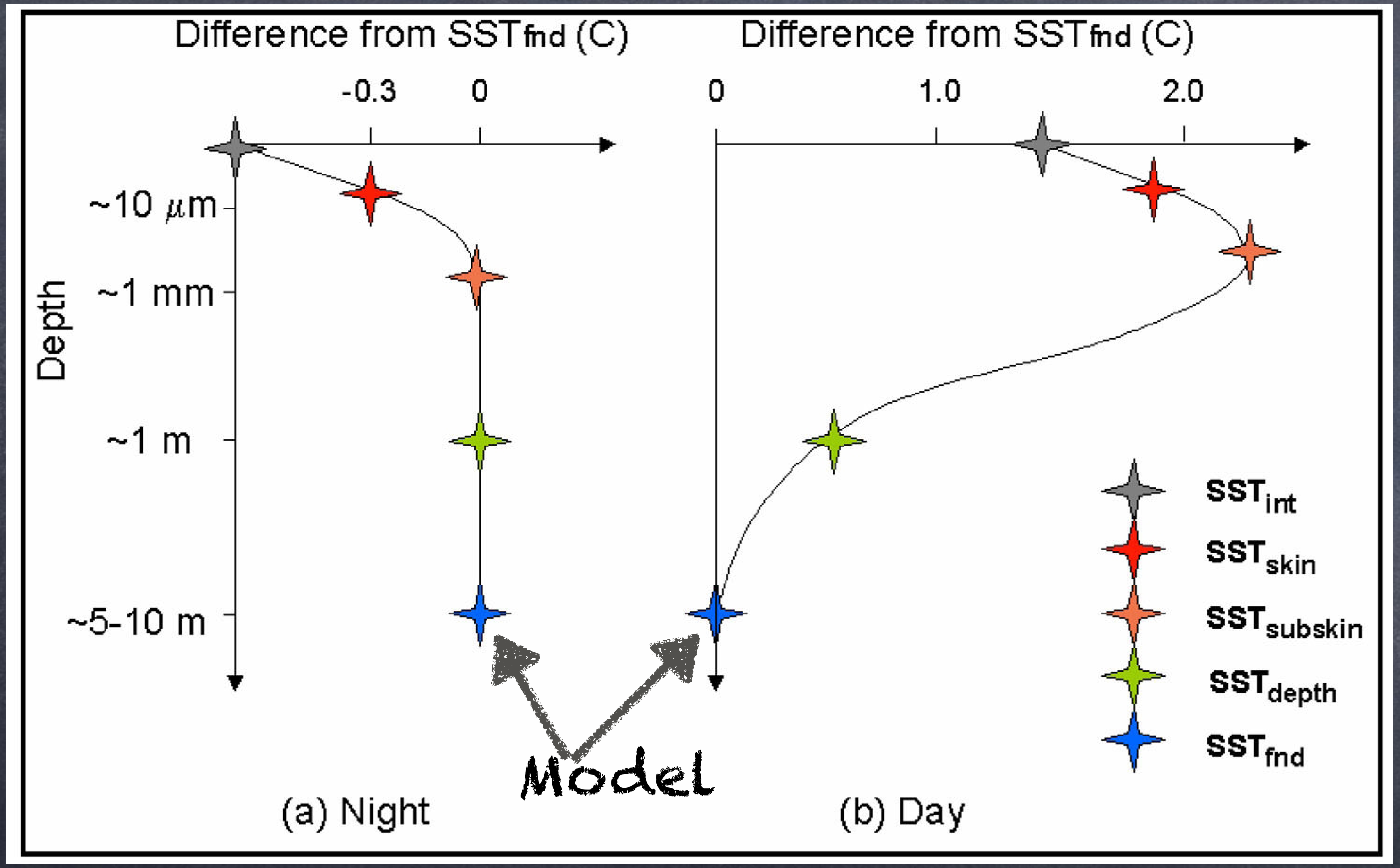
Reach to more than 50%

Song et al., 2022, JC

FIO-ESM v2.0 development

(1) Distinctive Physical Processes

c. SST diurnal cycle (sensible heat flux)



Shortwave:
At least 3 hours

It's easier, just increase coupling frequency to 8/day

Challenge: amplitude

The diagnosed magnitude of the diurnal variability SST for configurations of different flux resolutions

Bernie et al., 2005

FIO-ESM v2.0 development

(1) Distinctive Physical Processes

c. SST diurnal cycle (sensible heat flux)

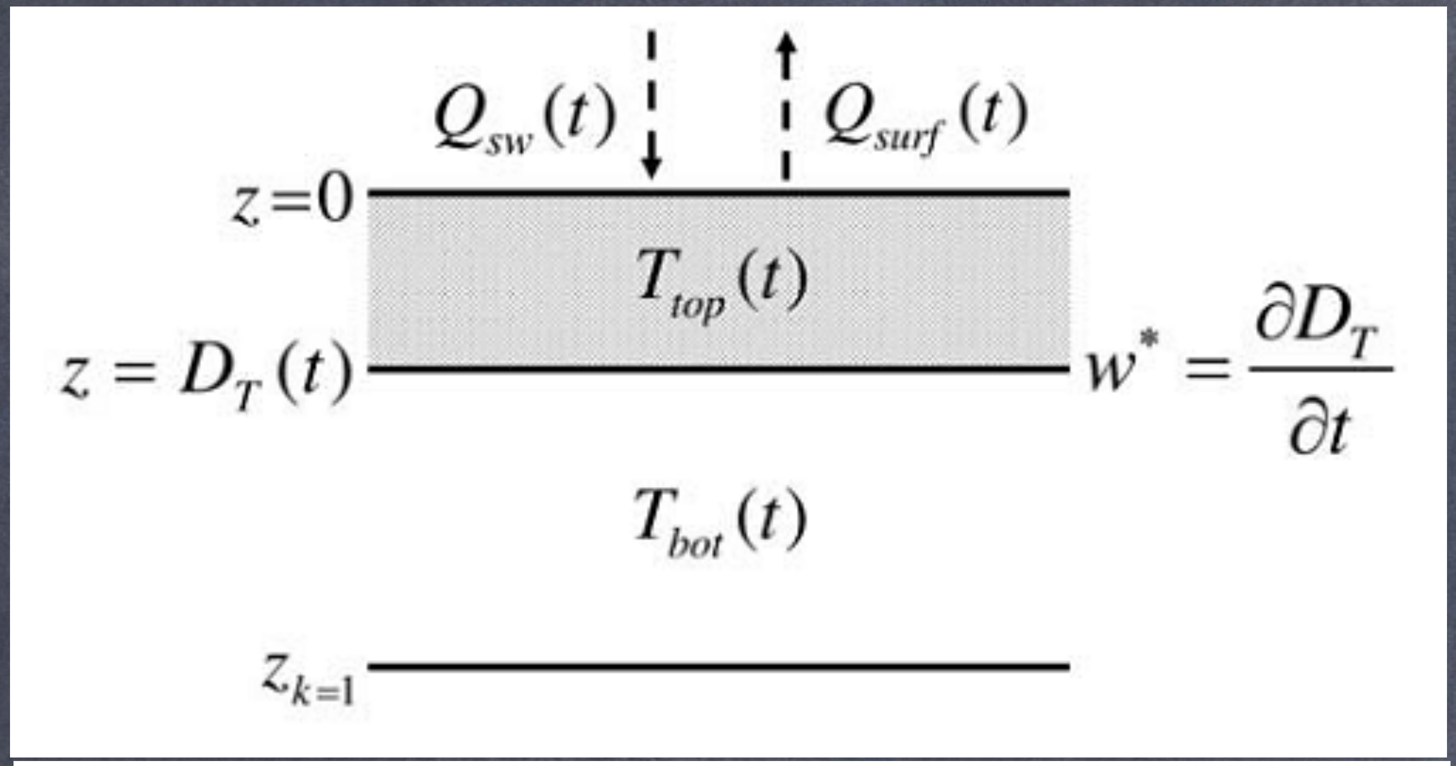
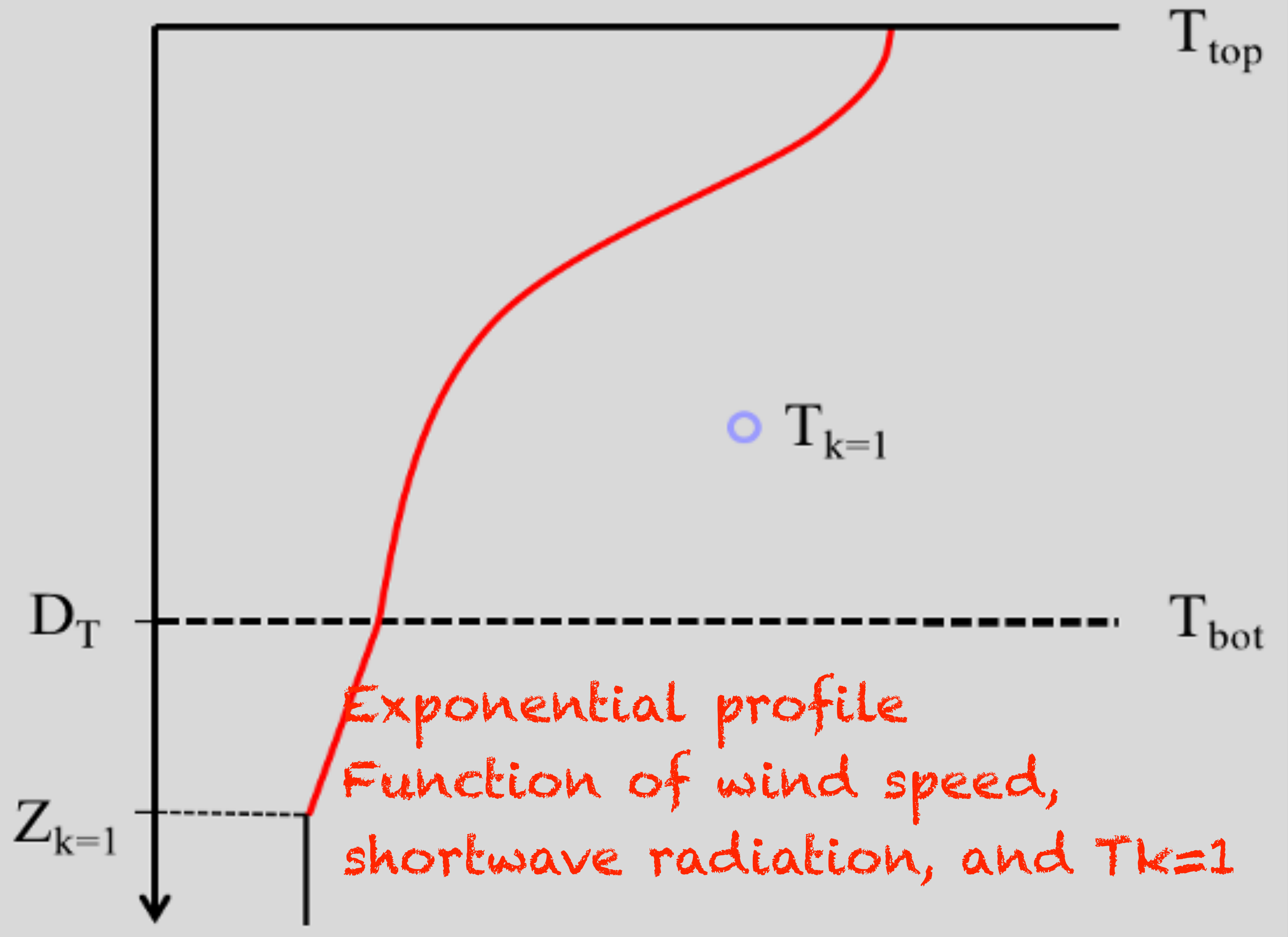


Figure 2. Schematic of sublayer. Q_{sw} denotes heating of ocean by solar shortwave radiation; Q_{surf} represents ocean surface cooling as the sum of latent and sensible heat fluxes and longwave radiation; $z_{k=1}$ is the bottom of the first model level with temperature T_{bot}; $z = D_T(t)$ is time-dependent depth of the sublayer $T_{top}(t)$; $w^* = \partial D_T/\partial t$ is the entrainment velocity at the bottom of the sublayer. See text for further description.

$$D_T = \left(\frac{\rho c_p Ri_c I_\tau}{\alpha g I_s}\right)^{1/2}$$

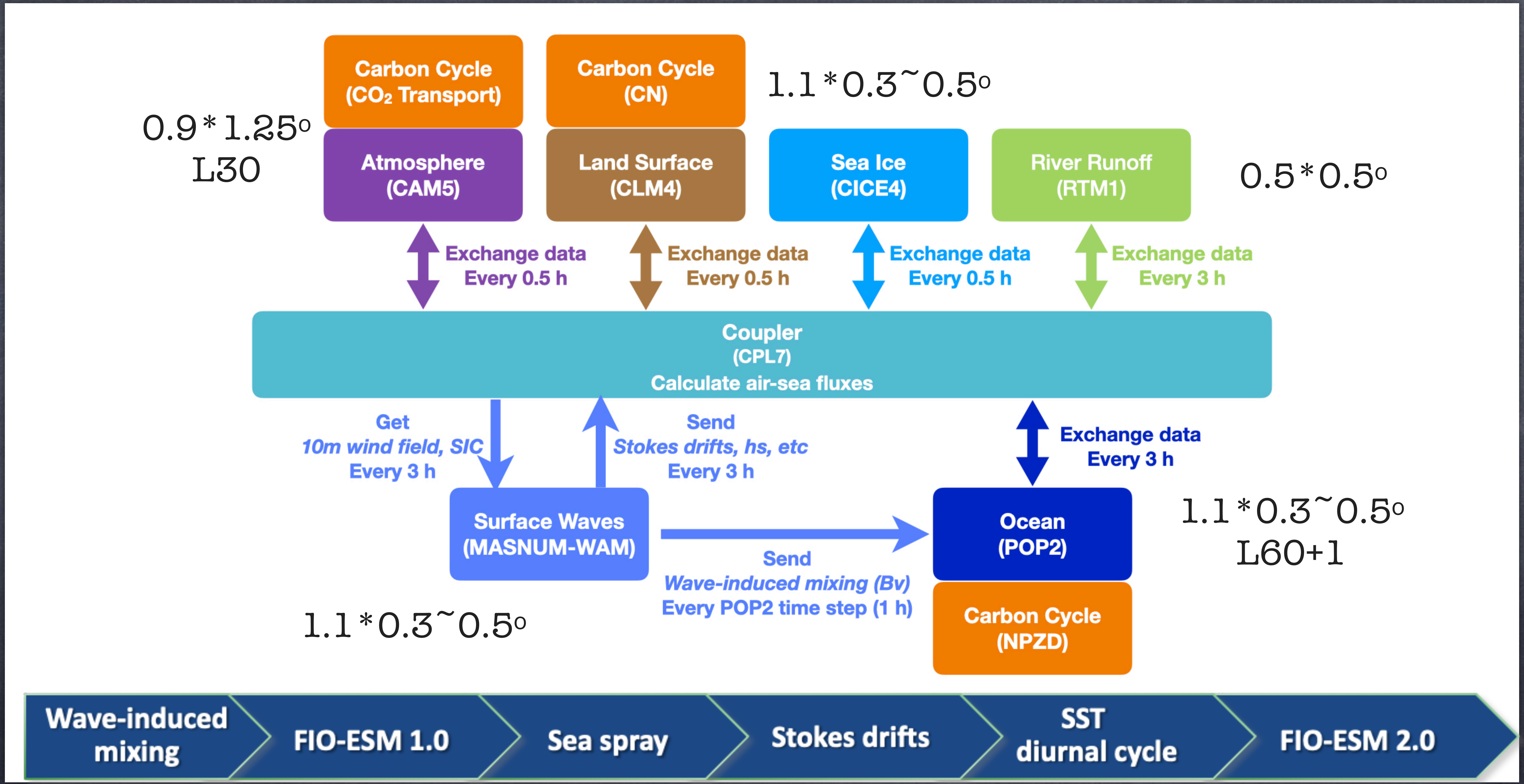
Schiller and Godfrey, 2005



Yang et al., 2017, JAMES

FIO-ESM v2.0 Development

(2) FIO-ESM v2.0 framework

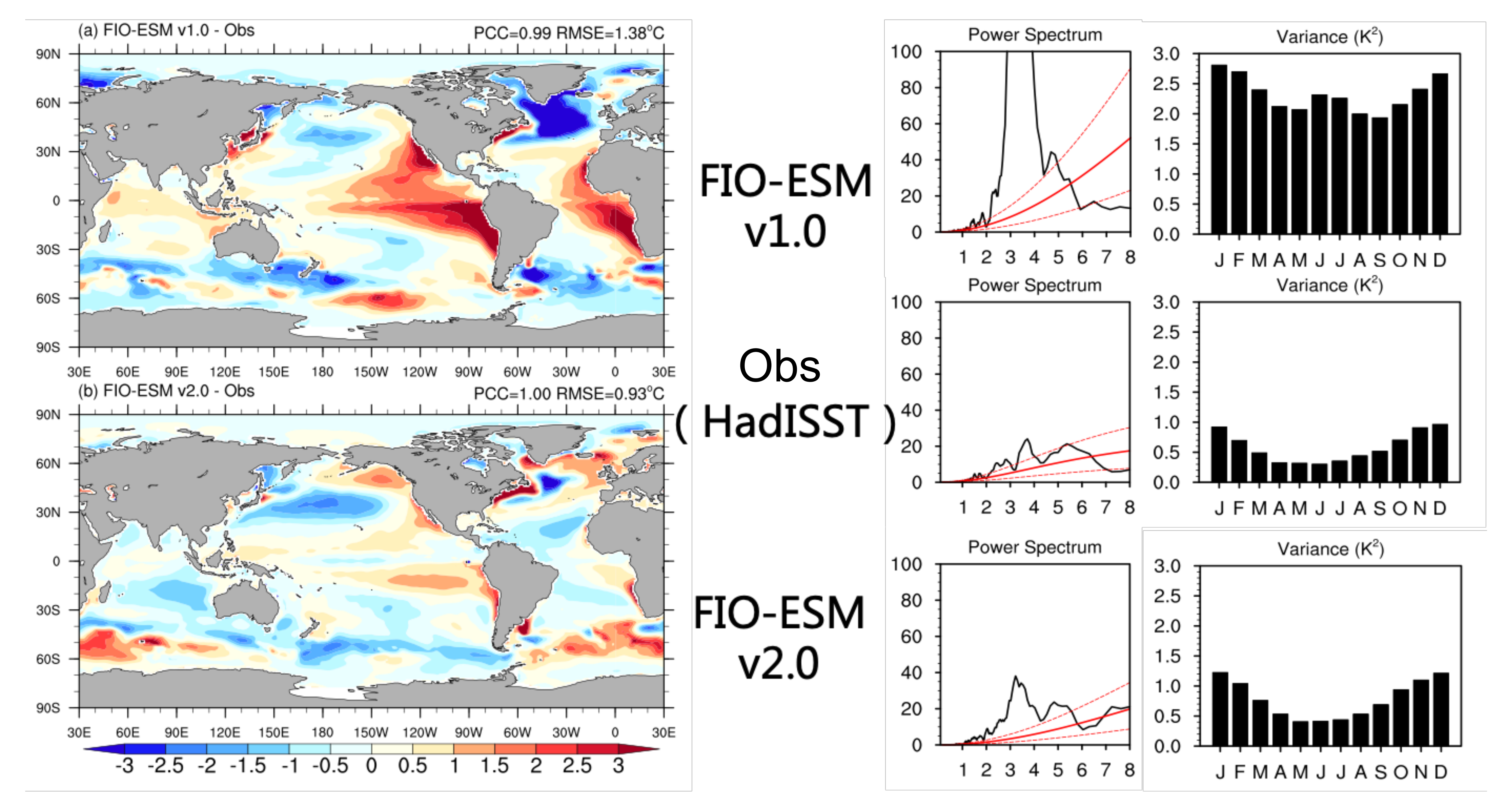


- Participate the CMIP6 organized by WGCM/WCRP
- Incorporate the above distinctive physical processes
- Increase the resolution and coupling frequency

FIO-ESM v2.0 Development

(3) Progress in FIO-ESM v2.0 simulated ability

SST biases reduced by 30% (Tropical 50%)
ENSO is also improved



Bao et al., 2020, JGR

Zhang et al., 2020, JOL

FIO-ESM v2.0 Development

(3) Progress in FIO-ESM v2.0 simulated ability

Global mean SST Rank: 2/48

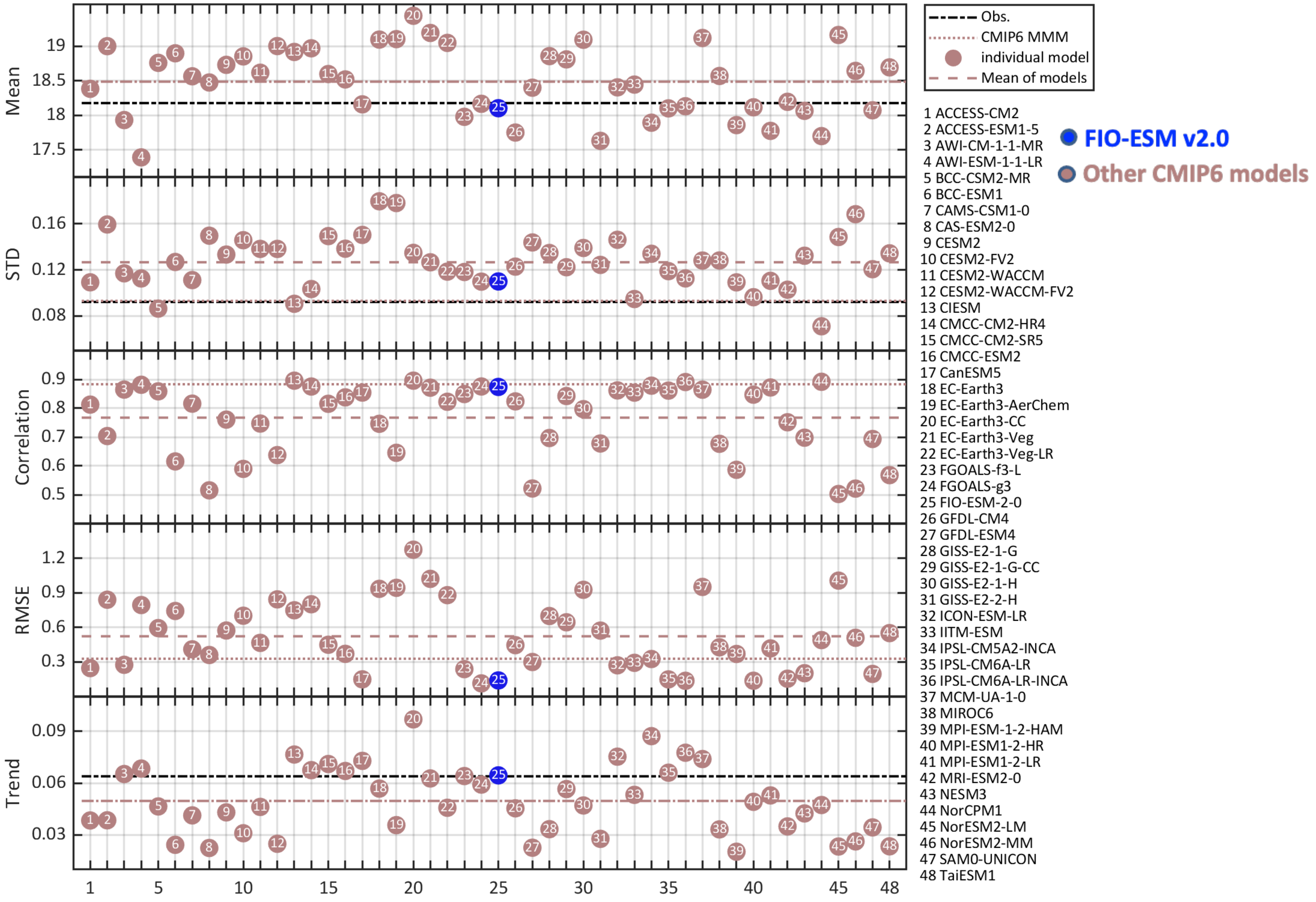
Mean error

STD error

Correlation

RMSE

Long-term trend error

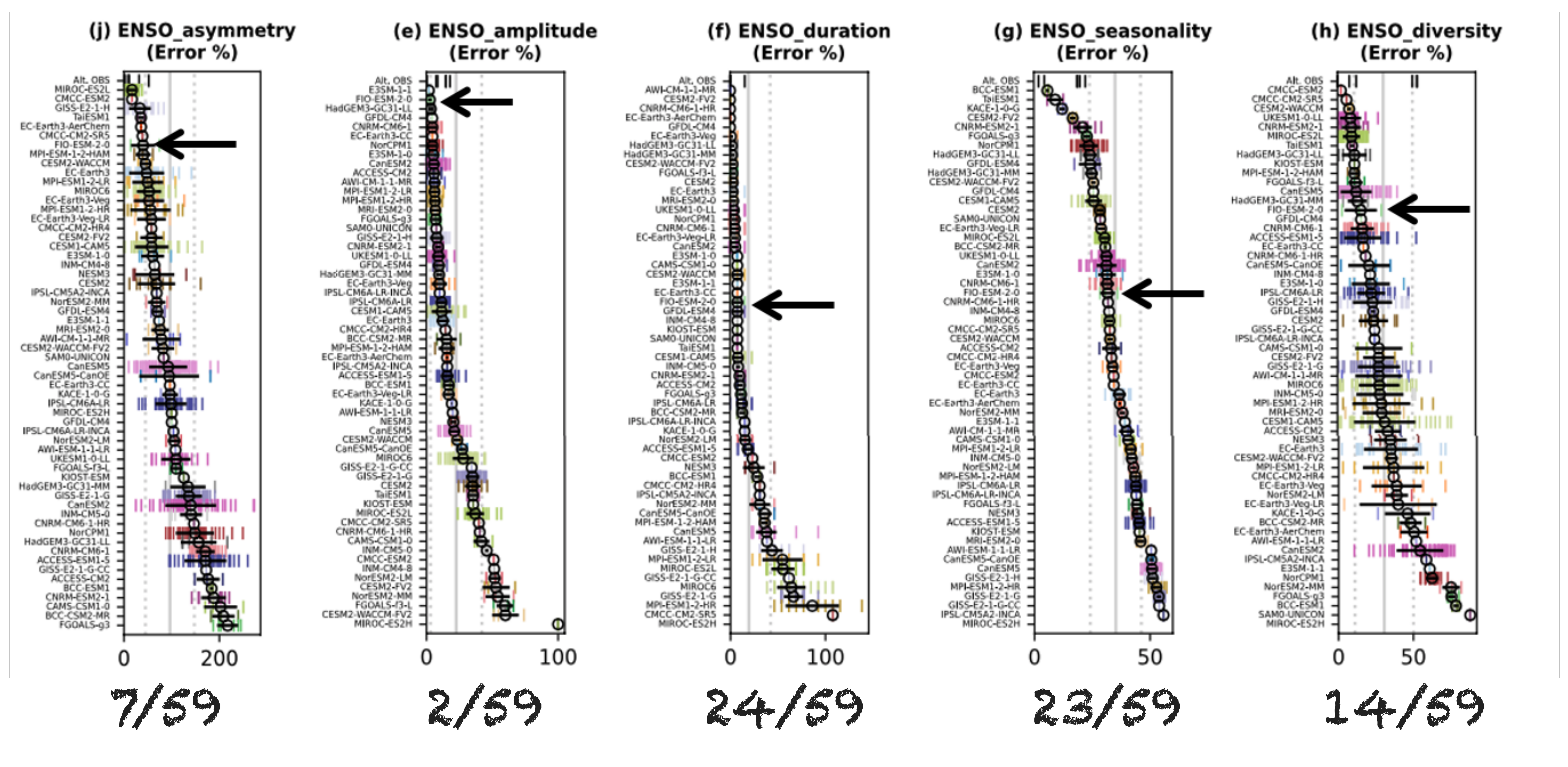


Liu et al., 2022, Deep-Sea Research Part II

FIO-ESM v2.0 Development

(3) Progress in FIO-ESM v2.0 simulated ability

ENSO Rank: 1/59

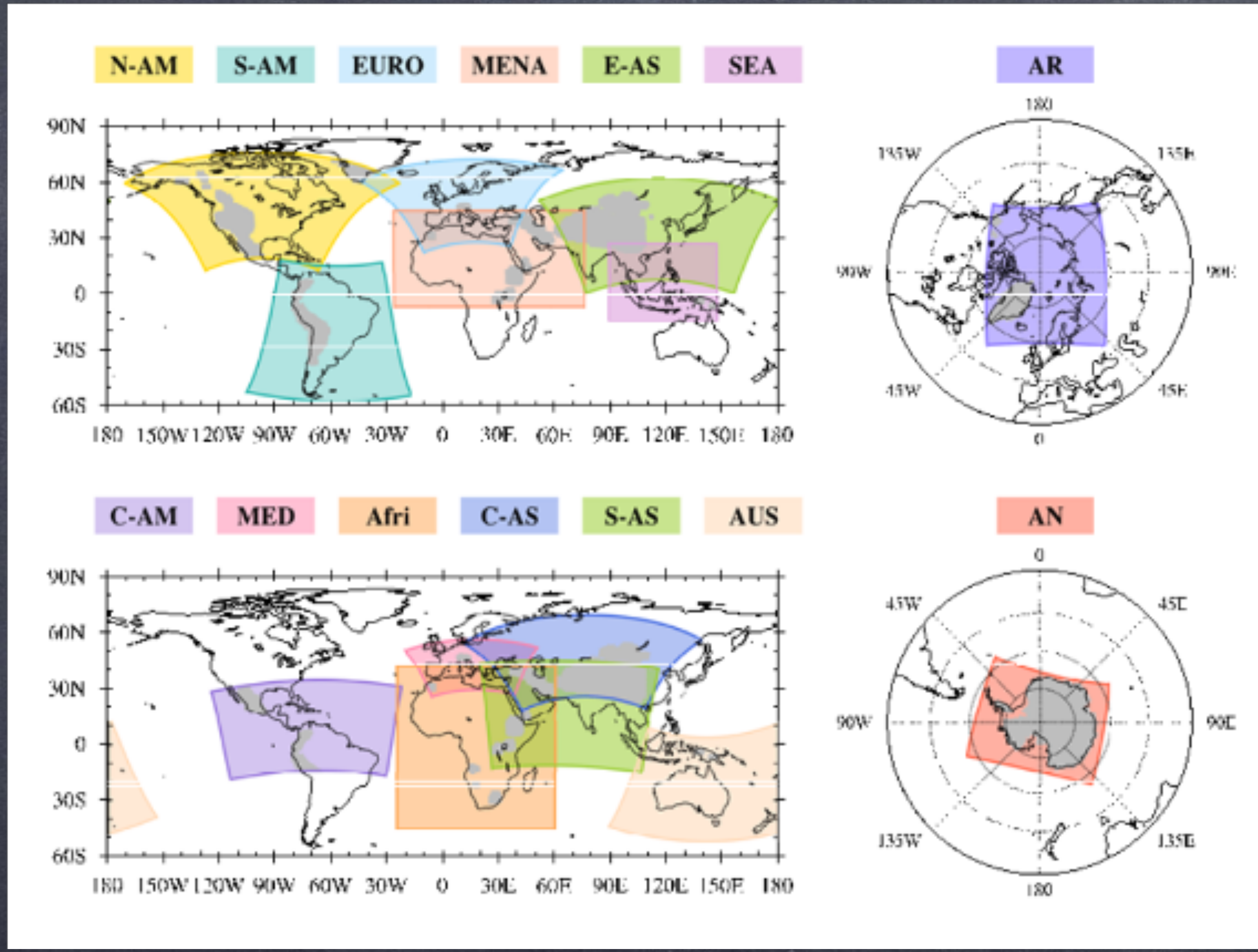


Lee et al., 2021, GRL

FIO-ESM v2.0 Development

(3) Progress in FIO-ESM v2.0 simulated ability

14 CORDEX domain downscaling Rank: 2/37



Evaluation of CMIP6 models toward dynamical downscaling over 14 CORDEX domains

Meng-Zhuo Zhang[1] · Zhongfeng Xu[2] · Ying Han[2] · Weidong Guo[1]

Received: 15 September 2021 / Accepted: 17 May 2022

Abstract

Both reliability and independence of global climate model (GCM) simulation are essential for model selection to generate a reasonable uncertainty range of dynamical downscaling simulations. In this study, we evaluate the performance and interdependency of 37 GCMs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) in terms of seven key large-scale driving fields over 14 CORDEX domains. A multivariable integrated evaluation method is used to evaluate and rank the models' ability to simulate multiple variables in terms of their climatological mean and interannual variability. The results suggest that the model performance varies considerably with seasons, domains, and variables evaluated, and no model outperforms in all aspects. However, the multi-model ensemble mean performs much better than almost all models. Among 37 CMIP6 models, the MPI-ESM1-2-HR and FIO-ESM-2-0 rank top two due to their overall good performance across all domains. To measure the model interdependency in terms of multiple fields, we define the similarity of multivariate error fields between pairwise models. Our results indicate that the dependence exists between most of the CMIP6 models, and the models sharing the same idea or/and concept generally show less independence. Furthermore, we hierarchically cluster the top 15 models with good performance based on the similarity of multivariate error fields to identify relatively independent models. Our evaluation can provide useful guidance on the selection of CMIP6 models based on their performance and relative independence, which helps to generate a more reliable ensemble of dynamical downscaling simulations with reasonable inter-model spread.

Among 37 CMIP6 models, the MPI-ESM1-2-HR and FIO-ESM-2-0 rank top two due to their overall good performance across all domains.

Zhang et al., 2022, Climate Dynamics

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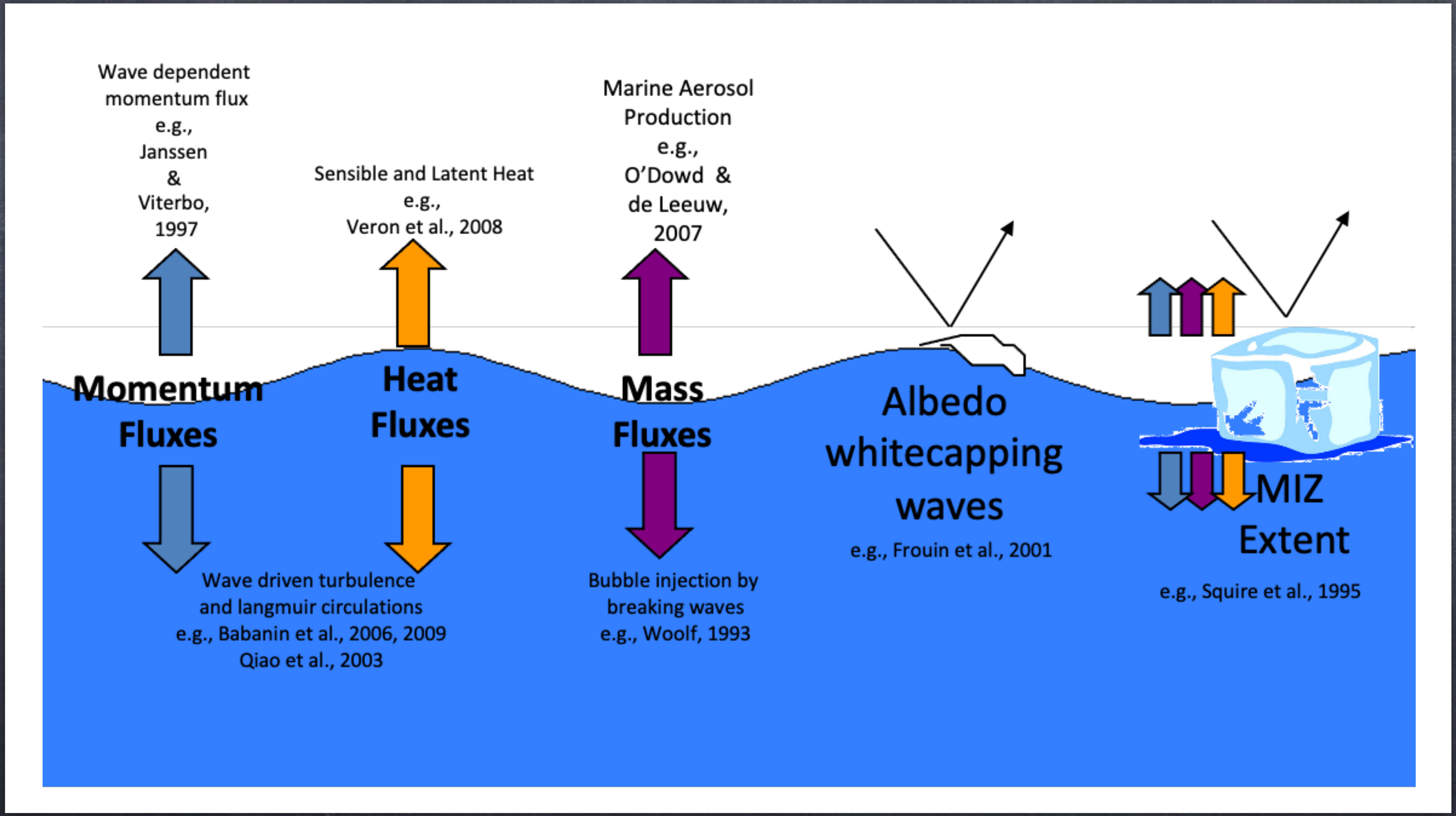
Perspectives on the FIO-ESM

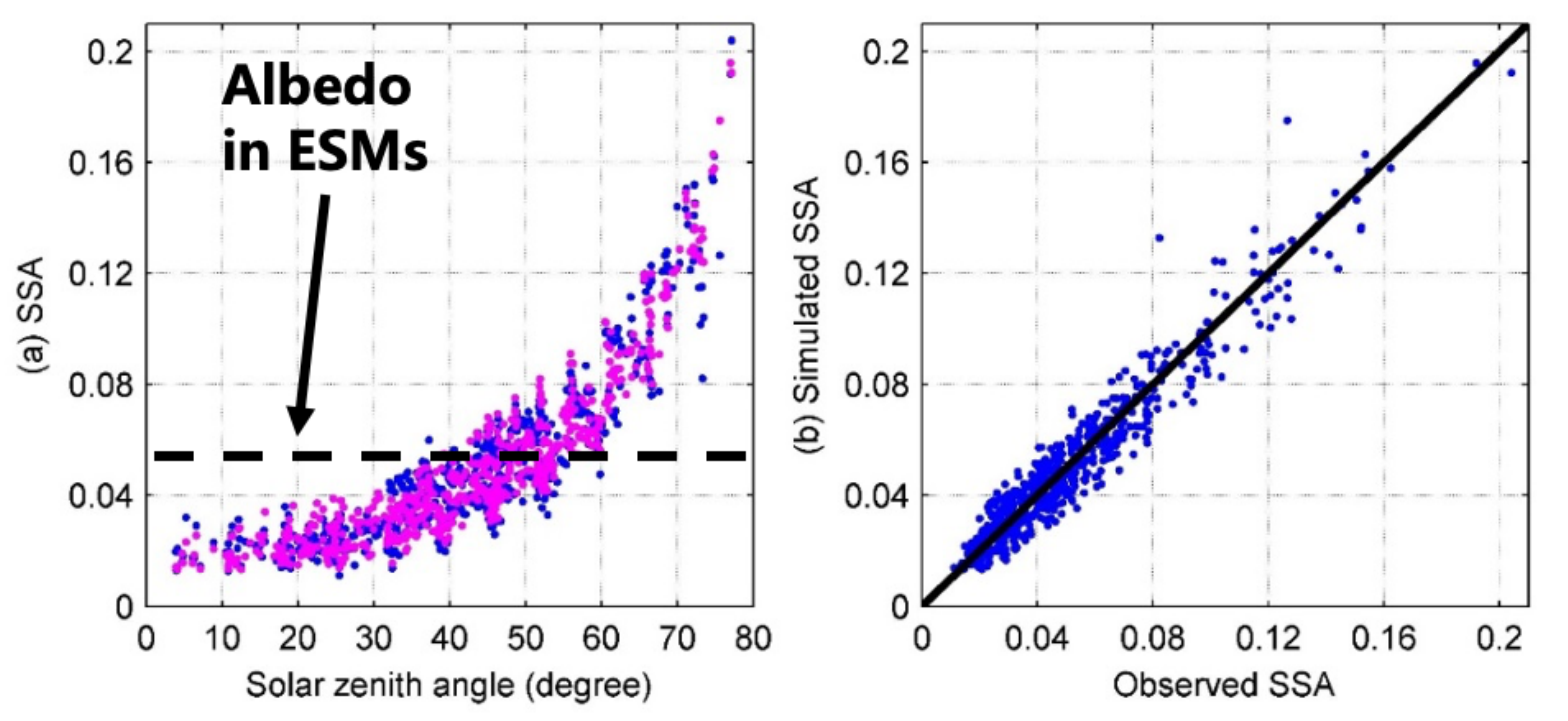
ESMs coupled with ocean surface waves



Perspectives on the FIO-ESM

ESMs coupled with ocean surface waves

(1) Albedo



- Constant -> f(Zenith angle, wave height, wind speed, water vapor pressure)

$$\alpha_{clear} = \frac{0.041}{\mu^{4/3} + 0.083} + 0.0025w - 0.005e_0 - 0.015, \quad \beta \geq 0.5$$

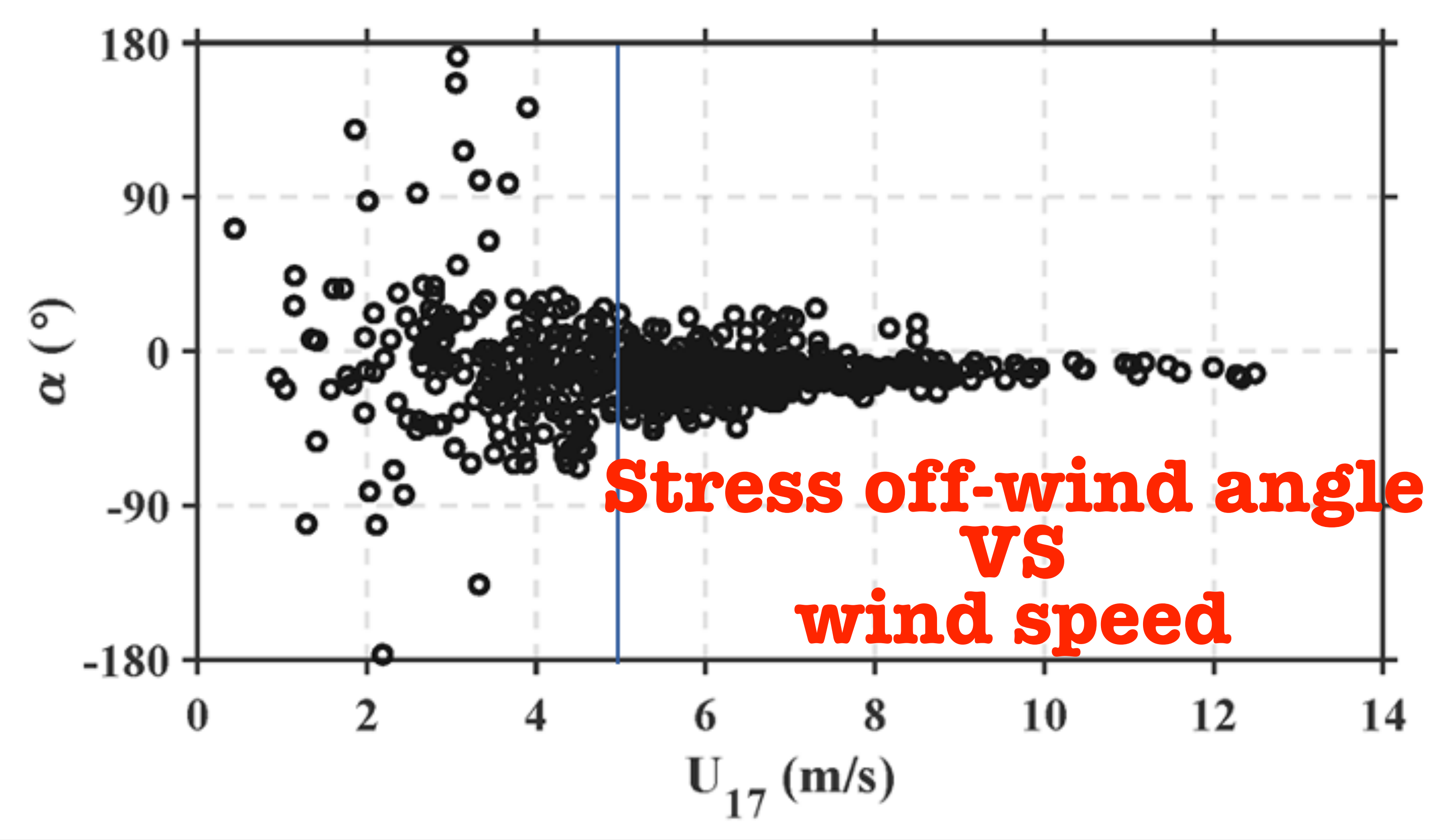
$$\alpha_{cloudy} = 0.046 + 0.021H_s - 0.006e_0, \quad \beta < 0.25$$

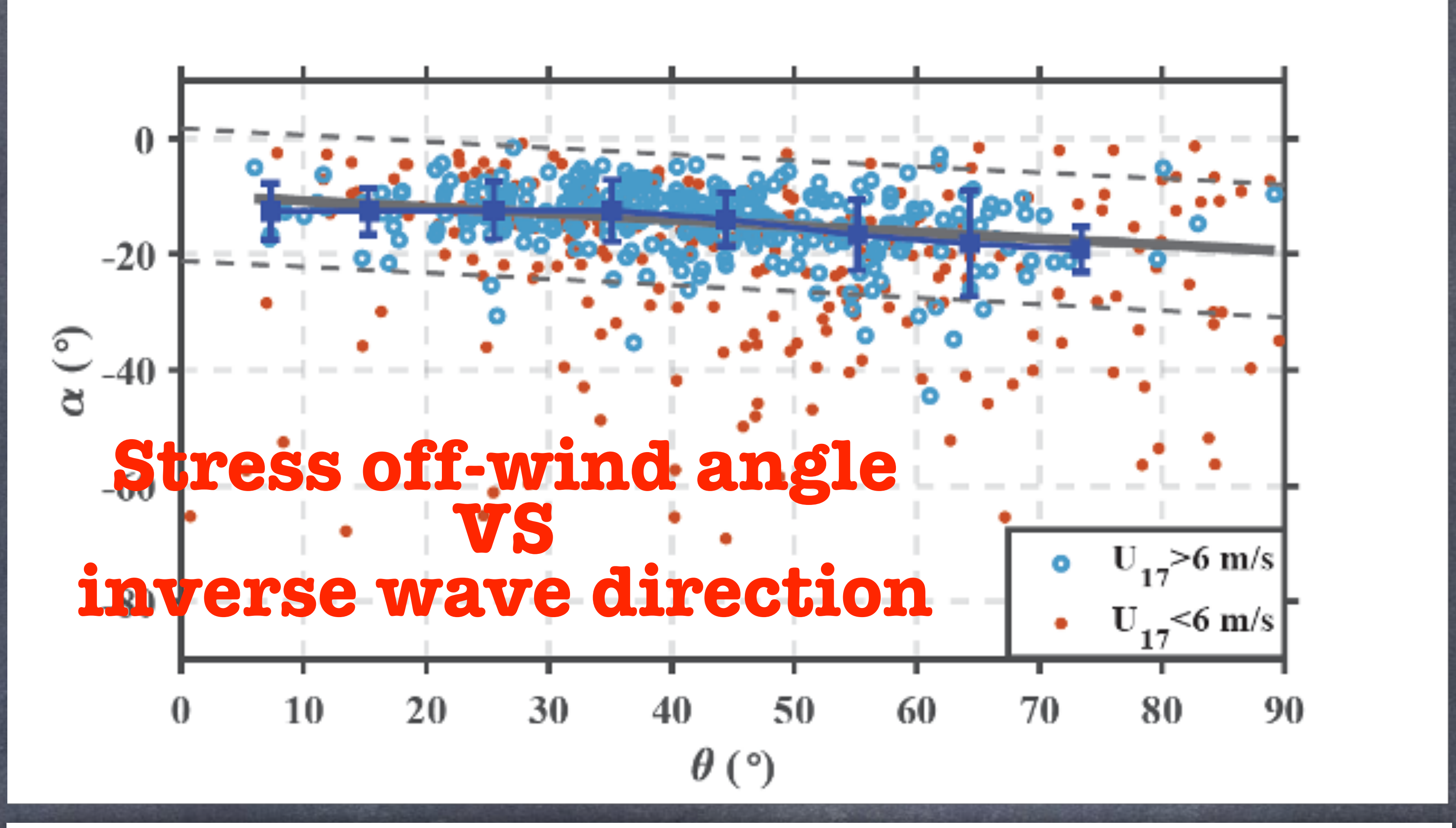
$$\alpha_{mixed} = \frac{\beta - 0.25}{0.3}\alpha_{clear} + \frac{0.55 - \beta}{0.3}\alpha_{cloudy}, \quad 0.25 \leq \beta < 0.55$$

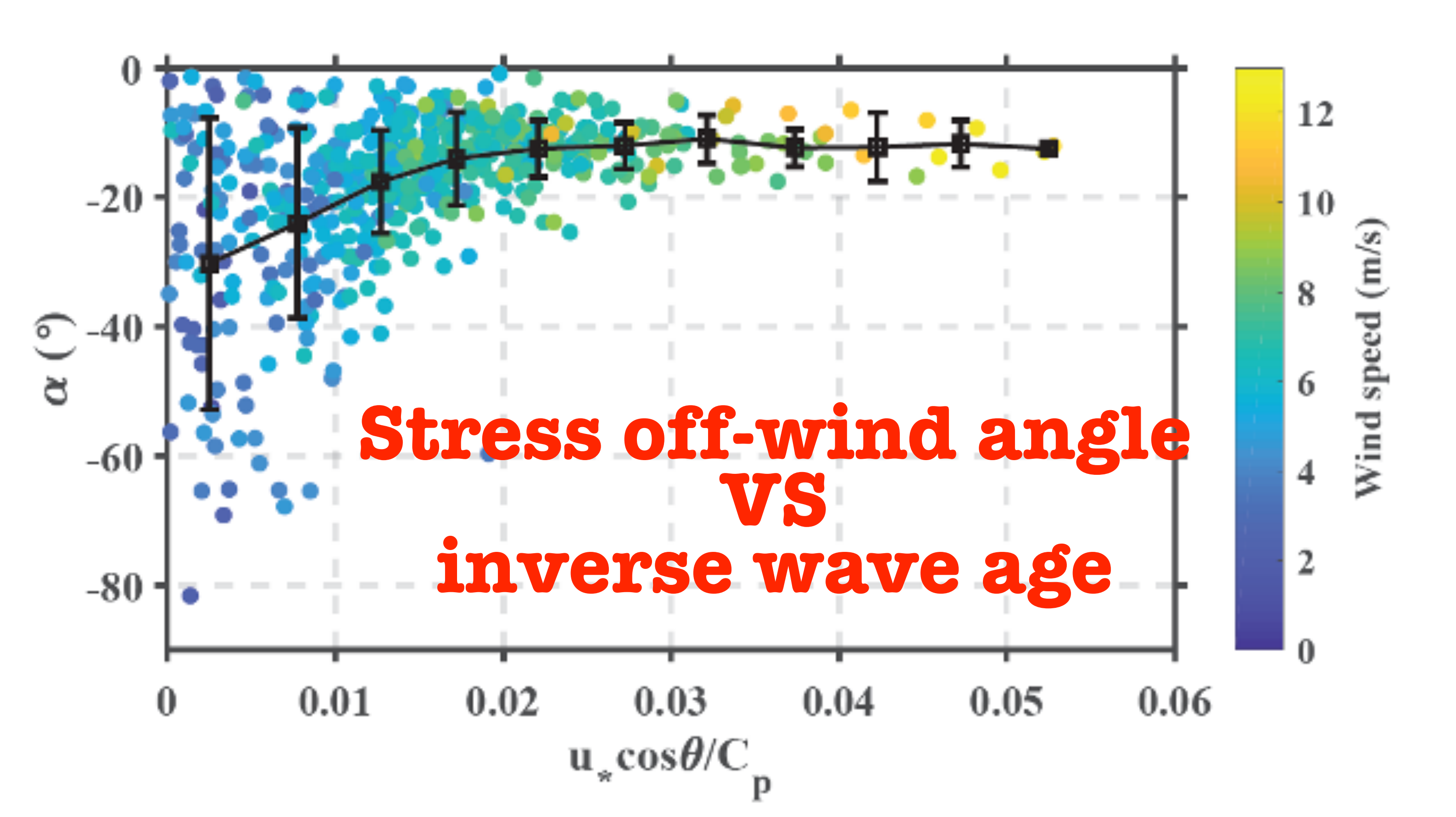
Huang et al., 2019, JGR

Perspectives on the FIO-ESM

ESMs coupled with ocean surface waves
(2) Momentum flux (direction)







Wind stress vector

$$\boldsymbol{\tau} = \boldsymbol{\tau}_x + \boldsymbol{\tau}_y = -\rho_a \langle u'w' \rangle \boldsymbol{i} - \rho_a \langle v'w' \rangle \boldsymbol{j}$$

Stress off-wind angle

$$\alpha = \arctan(\langle v'w' \rangle / \langle u'w' \rangle)$$

directions between wind stress and wind is not same, even opposite

Chen et al., 2018, JGR; Chen et al., 2019, JPO; Chen et al., 2020, JGR; Chen et al., 2020, GRL

Welcome to use FIO-ESM v2.0 products

FIO-ESM v.20 data published in ESGF system

http://doi.org/10.22033/ESGF/CMIP6.9160
http://doi.org/10.22033/ESGF/CMIP6.9161
http://doi.org/10.22033/ESGF/CMIP6.9162
http://doi.org/10.22033/ESGF/CMIP6.9163
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http://doi.org/10.22033/ESGF/CMIP6.9201
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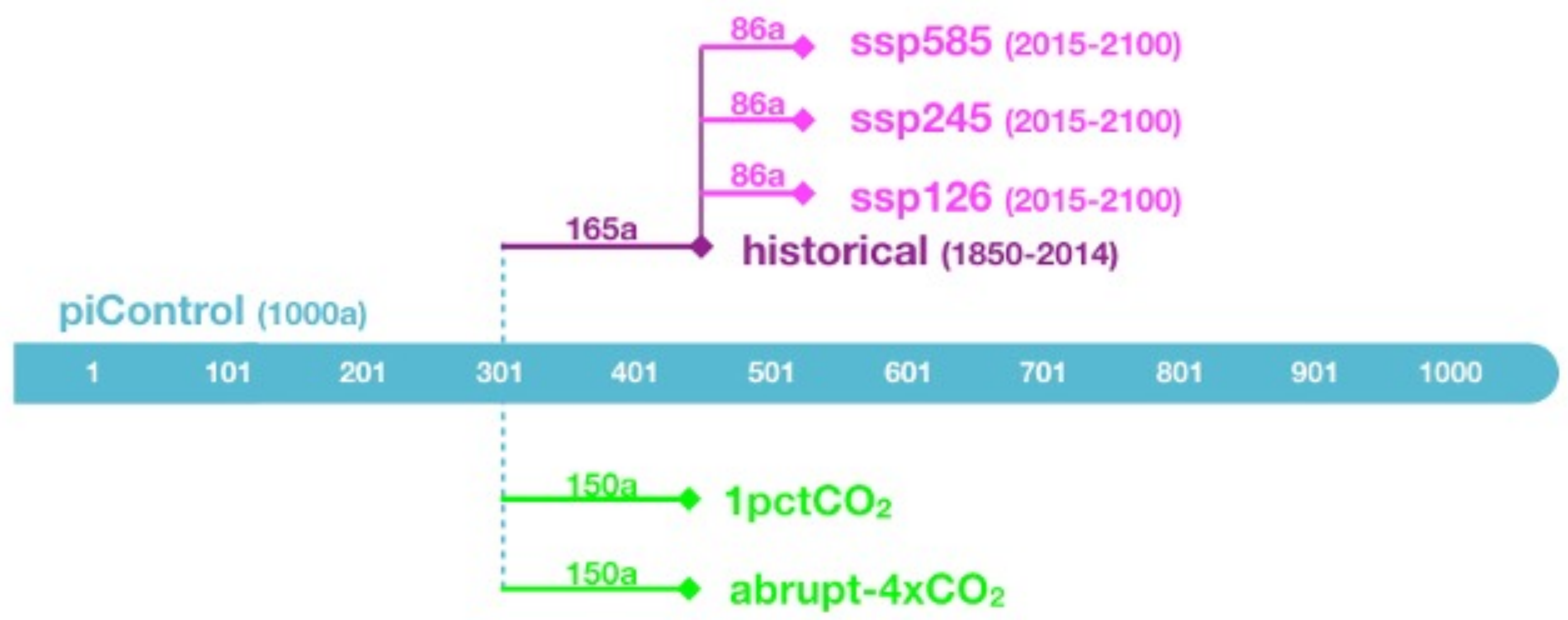
http://doi.org/10.22033/ESGF/CMIP6.9208
http://doi.org/10.22033/ESGF/CMIP6.9209
http://doi.org/10.22033/ESGF/CMIP6.9214

Parent EXP	EXP
DECK	AMIP-simulation 【108 model years】
	Pre-industrial control 【1000 model years 】
	1%yr CO2 increase 【450 model years】
	Abrutp-4xCO2 run 【450 model years】
Historical	1850-2014 【495 model years】
OMIP	Ocean Model Intercomparison Project 【310 model years】
SIMIP	Sea-ice Model Intercomparison Project【all experiments】
GMMIP	Tier-1 AMIP-hist 【435 model years】
	Tier-2 hist-resAMO hist-resIPO 【870 model years】
	Tier-3 amip-TIP amip-TIP-nosh amip-hld 【255 model years】
ScenarioMIP	Scenario Model Intercomparison Project 【765 model years】

FIO-ESM v2.0 in CMIP6
11598 model years

First long-term wave dataset from ESM



Data sharing – wave data

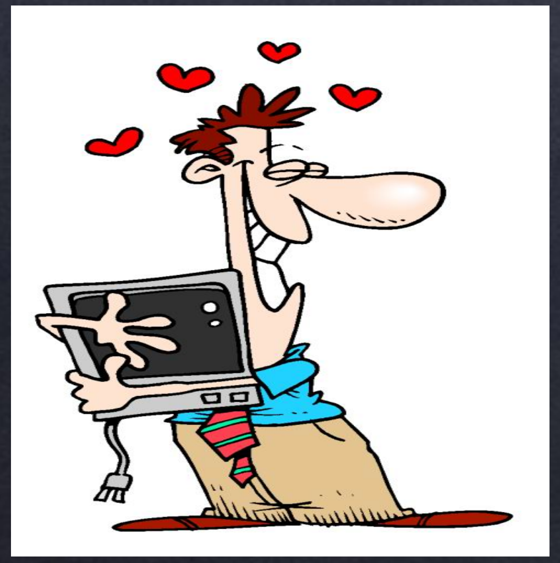
https://doi.org/10.6084/m9.figshare.c.4819503
https://doi.org/10.6084/m9.figshare.c.4839729
https://doi.org/10.57760/sciencedb.02893

Song et al., 2020; Jiang et al., 2023, Scientific Data

Closing Remarks

There is a long way to predicted ocean

- Parameterization scheme according to high-resolution, especially considering the ocean surface waves effects
- New technology, such as AI
- Supercomputer and HPC technology



Thank you for your attentions!