Evaluation of Thermocline Depth Bias in the Seychelles-Chagos Thermocline Ridge (SCTR) simulated by the CMIP6 models

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I. Background

- An open ocean upwelling region in the Indian Ocean, known as the Seychelles-Chagos Thermocline Ridge (SCTR), mainly driven by the curl of local wind stress between the southeast trade wind and equatorial westerlies, produces high biological productivity and become a focused area for tuna fishing activity (Fonteneau et al. 2008).
- The equatorial westerlies generate equatorward Ekman flow, which helps enhances the upwelling off the equator (Xie et al. 2002) and affecting climate variability around the Indian Ocean rim.
- Since the dynamic in the SCTR play an important role in global climate variability especially in the Indian Ocean, the ability of climate model, especially the Coupled Models Intercomparison Project phase sixth (CMIP6) that released recently, to simulate the SCTR is important, whether the CMIP6 models show an improvement or not, compare to the previous CMIP5 generation.
- **Thus, the aim of this study is to evaluate the skills of CMIP6 models in simulating SCTR by comparing with reanalysis data and previous CMIP5 models.**

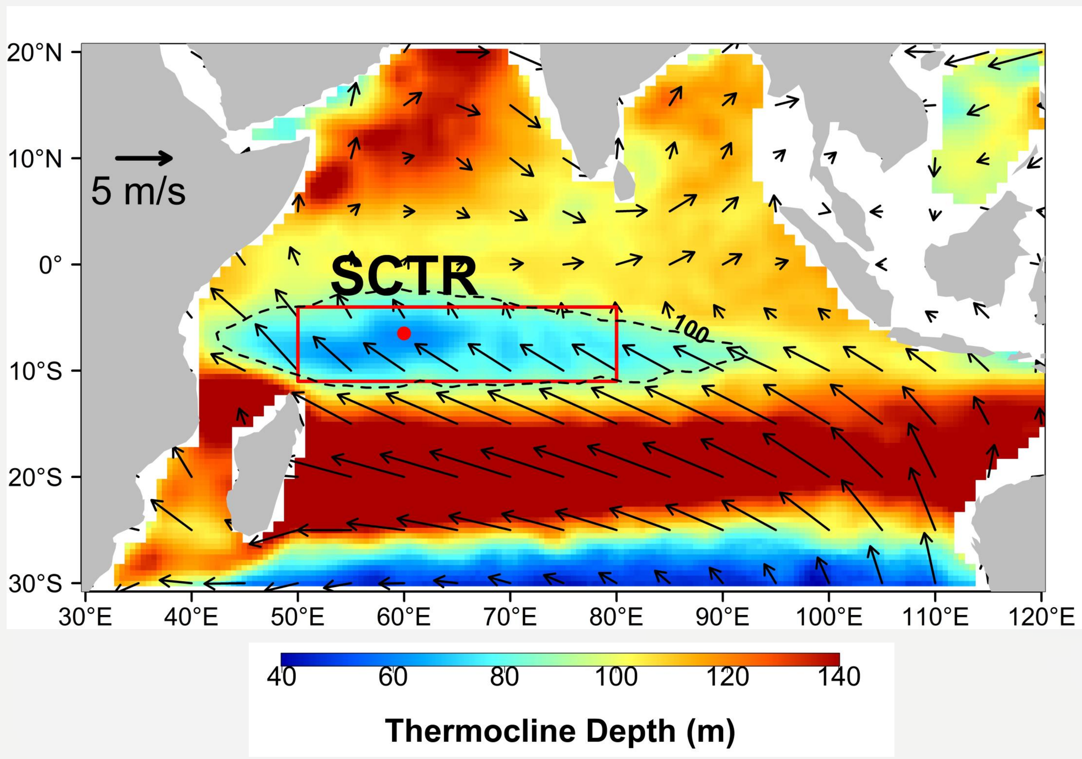

Figure 1. Annual mean of thermocline depth (D20; color in m) from Argo (2004-2018) and surface wind velocity (vector in m/s) from ERA5 (1980-2014). The dashed contour represents 100 m depth of D20 around SCTR (5ºS-10ºS, 50ºE-80ºE; red box). The red dot show the thermocline dome, the shallowest D20 in the band of 5ºS to 12ºS latitude.

II. Data and Method

Parameter	Observation	Model
Temperature	Argo, EN4, and SODA	27 CMIP6 and 25 CMIP5 models, monthly mean historical runs, CMIP6:1980-2014, CMIP5:1999-2014, regrided to 0.5x0.5 resolution
Wind	ERA5	

- Variable was averaged over the SCTR region (5ºS-10ºS and 50ºE-80ºE).
- Bias is calculated by model minus observation.
- The thermocline depth was shown by the 20 ºC isotherm depth (D20).

Table 1. CMIP models used in this study

No.	CMIP6	CMIP5	No.	CMIP6	CMIP5
1	ACCESS-CM2	bcc-csm1-1	15	FIO-ESM-2-0	HadGEM2-ES
2	BCC-CSM2-MR	CanESM2	16	GFDL-CM4	inmcm4
3	BCC-ESM1	CCSM4	17	GFDL-ESM4	IPSL-CM5A-LR
4	CAMS-CSM1-0	CESM1-CAM5	18	GISS-E2-1-G	IPSL-CM5A-MR
5	CanESM5	CMCC-CM	19	GISS-E2-1-G-CC	IPSL-CM5B-LR
6	CESM2	CMCC-CMS	20	KIOST-ESM	MIROC-ESM
7	CESM2-FV2	CNRM-CM5	21	MIROC6	MIROC-ESM-CHEM
8	CESM2-WACCM	CSIRO-Mk3-6-0	22	MPI-ESM-1-2-HAM	MPI-ESM-LR
9	CESM2-WACCM-FV2	FGOALS-g2	23	MPI-ESM1-2-HR	MRI-CGCM3
10	E3SM-1-1-ECA	GFDL-ESM2G	24	MPI-ESM1-2-LR	NorESM1-M
11	E3SM-1-1	GFDL-ESM2M	25	MRI-ESM2-0	NorESM1-ME
12	E3SM-1-0	GISS-E2-R	26	SAM0-UNICON	
13	EC-Earth3	GISS-E2-H	27	TaiESM1	
14	FGOALS-g3	HadGEM2-CC			

III. Results

3.1 Thermocline depth and SST bias

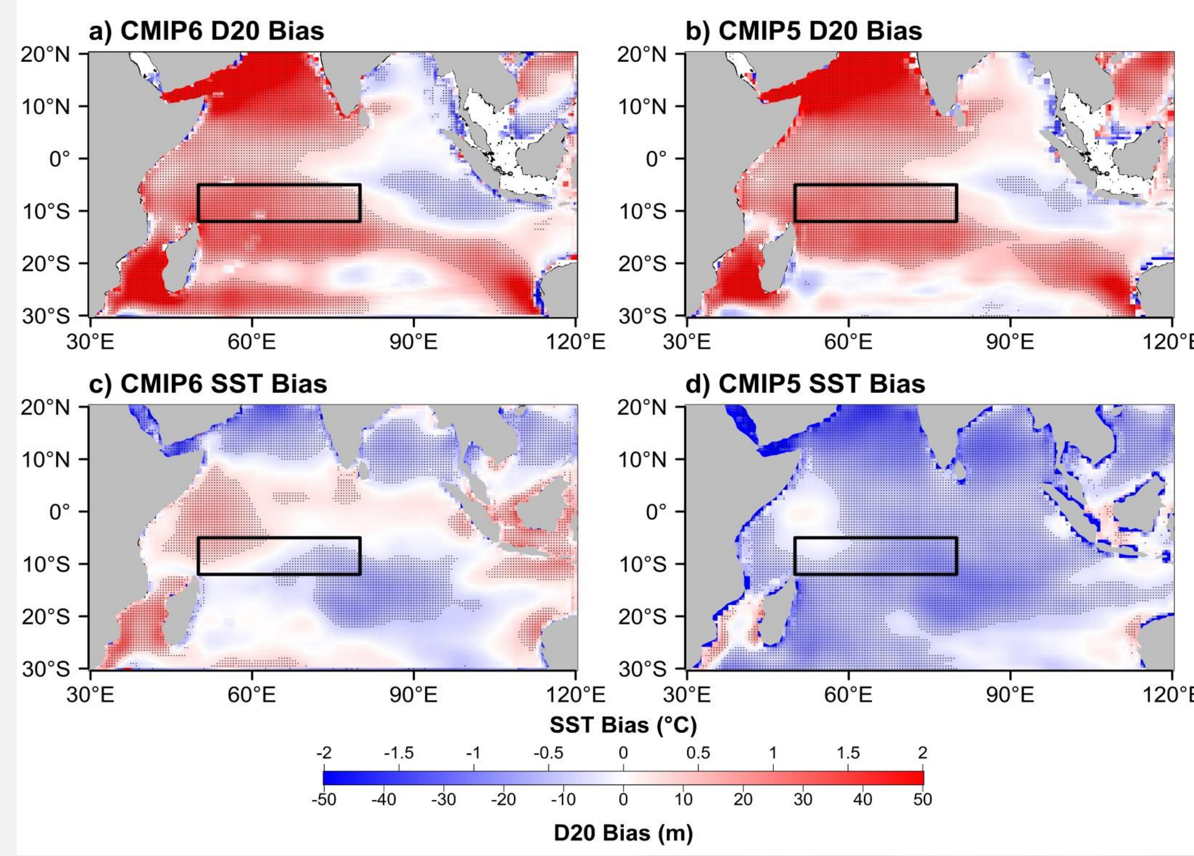

Figure 2. Multi-model ensemble (MME) mean of D20 bias and SST bias from 27 CMIP6 models (a, c) and 25 CMIP5 models (b, d). The hatched area indicates the bias was statistically significant at 95% confidence level based on Student's t-test. The black box indicates SCTR.

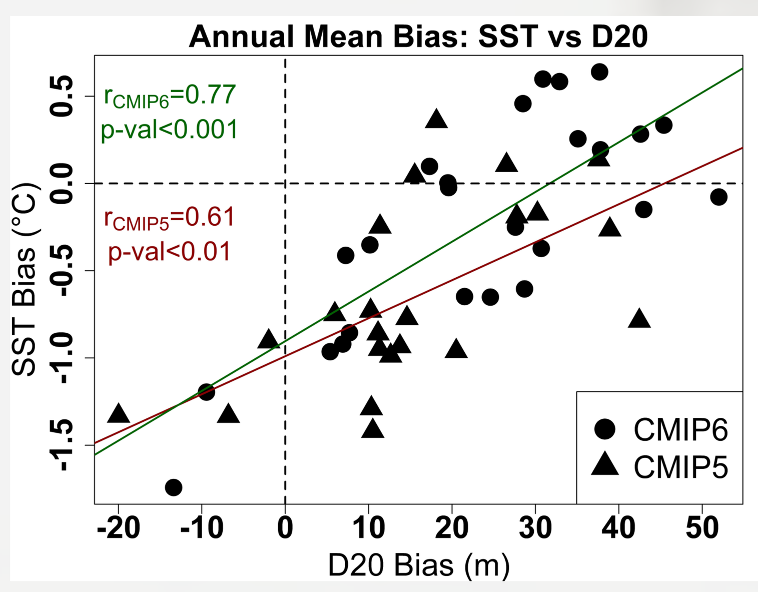

Figure 3. Scatter diagram between annual mean bias of D20 and SST bias averaged over SCTR from 1980 to 2014 for CMIP6 and from 1980 to 1999 for CMIP5. The linear regression lines are shown and the dash lines indicate zero value.

3.2 Thermocline dome displacement

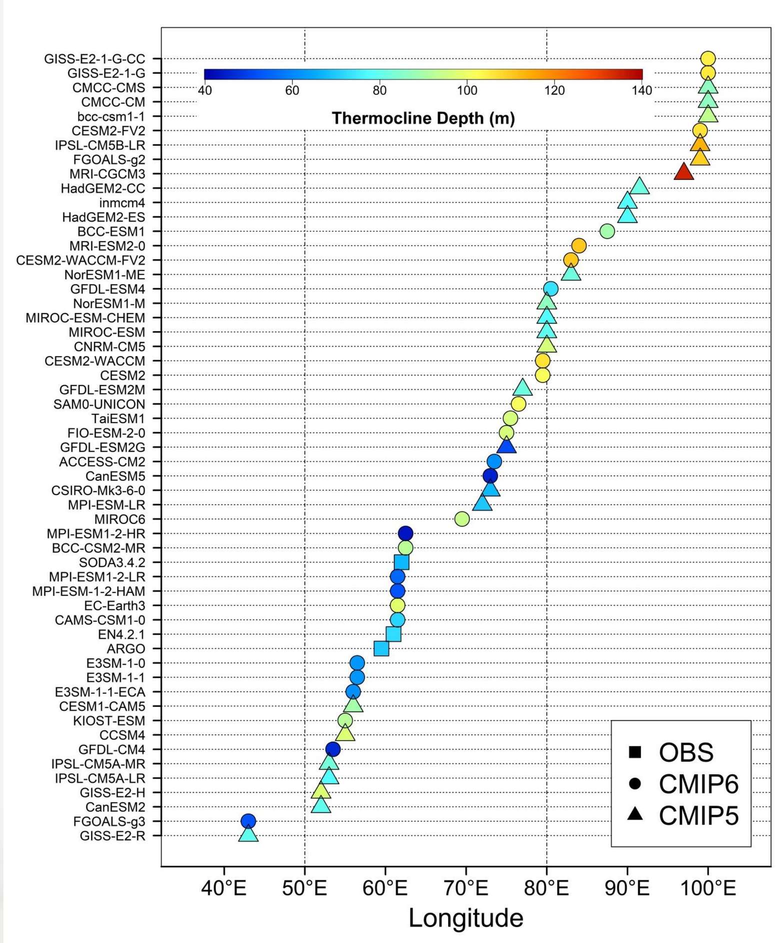

Figure 4. The longitudes of the shallowest annual mean D20 in 5ºS to 12ºS latitude band (thermocline dome) for 27 CMIP6 models (circle), 25 CMIP5 models (triangle), and 3 observations data (square). The color indicates the shallowest D20 depth (in meter). The vertical dash lines show the longitude of SCTR.

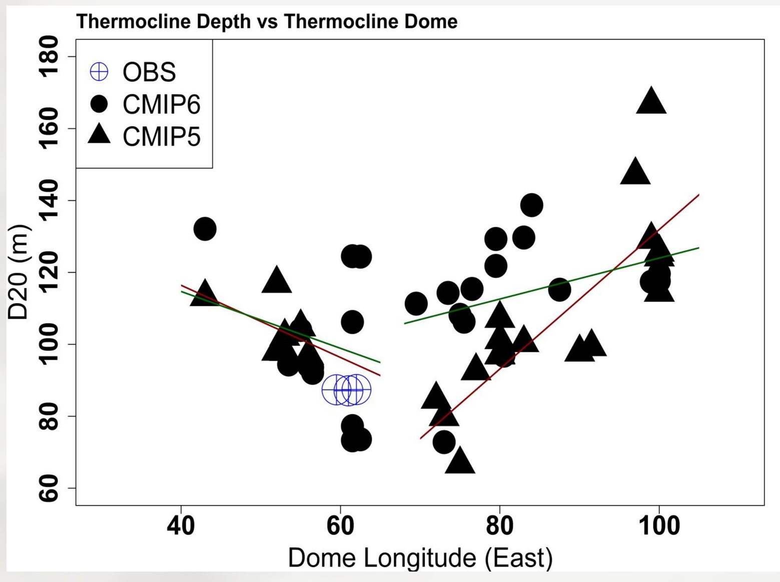

Figure 5. Scatter diagram between thermocline dome longitude and annual mean D20 averaged over SCTR. The linear regression lines are shown by red for CMIP5 and green for CMIP6. As comparison, the Argo, SODA3.4.2, and EN4.2.1 were shown by the blue circles.

3.3 Possible source of biases in CMIP6 models

CMIP5: Nagura et al 2013; Zheng et al 2016; Li et al 2015.

The southwest summer monsoon is too weak over the Arabian Sea

↓

This bias creates a warm SST bias over the western equatorial Indian Ocean

↓

This different in east-west SST produces easterly wind bias in the equatorial Indian Ocean.

↓

Easterly equatorial zonal wind stress bias → weak local Ekman pumping velocity in the SCTR → deeper thermocline depth in SCTR

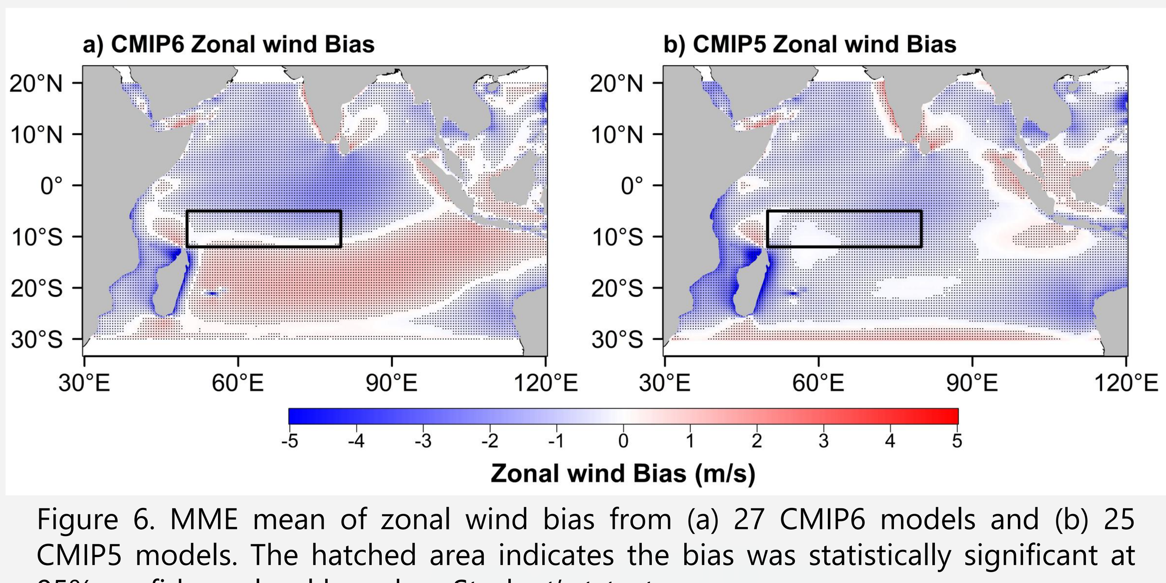

Figure 6. MME mean of zonal wind bias from (a) 27 CMIP6 models and (b) 25 CMIP5 models. The hatched area indicates the bias was statistically significant at 95% confidence level based on Student's t-test.

- The Ekman pumping velocity is estimated as (Yokoi et al., 2008):

$$\nabla \times \left(\frac{\tau}{\rho_o f}\right) = \frac{1}{\rho_o f}\nabla \times \tau + \frac{\beta \tau_x}{\rho_o f^2},$$

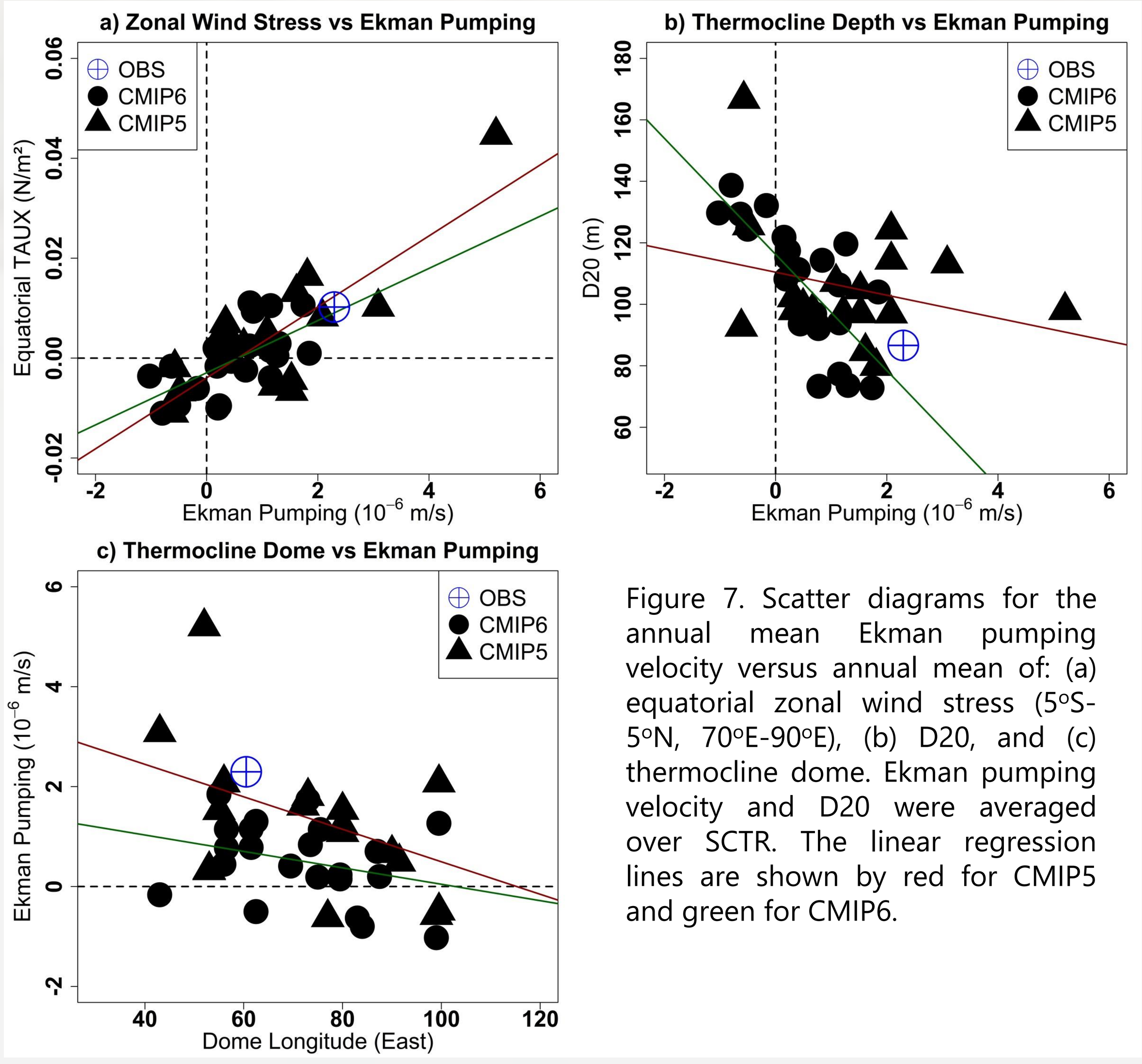

Figure 7. Scatter diagrams for the annual mean Ekman pumping velocity versus annual mean of: (a) equatorial zonal wind stress (5ºS-5ºN, 70ºE-90ºE), (b) D20, and (c) thermocline dome. Ekman pumping velocity and D20 were averaged over SCTR. The linear regression lines are shown by red for CMIP5 and green for CMIP6.

IV. Conclusions

- Most of the CMIP6 models tend to produce considerably deeper SCTR compare to observation, with some improvement compared with CMIP5 models.
- The bias in the SCTR dome location still exist in CMIP6 models but relatively closer to observation than CMIP5 models.
- These biases probably caused by the equatorial easterly wind bias that produce weak Ekman pumping velocity in the SCTR.
- Weak Ekman pumping → a deeper thermocline depth → warmer SST bias, possibly due to weaker thermocline feedback.
- The CMIP6 models are slightly better in simulating the SCTR dome and thermocline depth, compared to CMIP5 models, although the bias still noticeable.

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Take home message:
A good understanding of future SCTR dynamics, by optimizing the climate models simulation, would help us to better understand the future local climate variability especially in the Indian Ocean region and hopefully increase the awareness of climate disaster impact under global warming.

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