Toward realistic simulation of the equatorial Atlantic zonal SST gradient in a CGCM

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Model bias in the annual mean SST (sea surface temperature) along the equatorial Atlantic

Modeling the mean climate state realistically is the first step toward simulating as well as predicting climate variations.

However, …

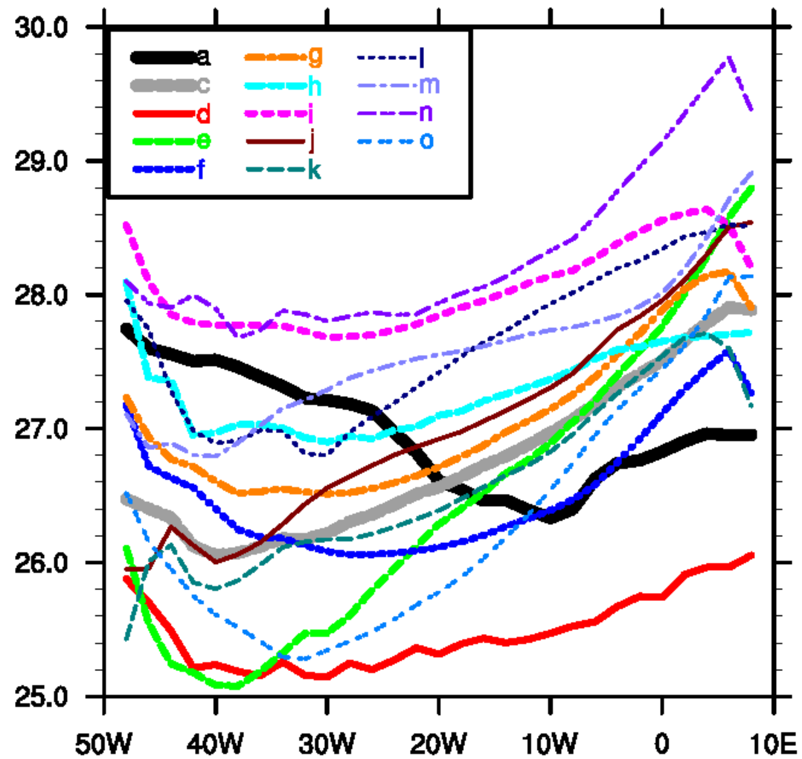
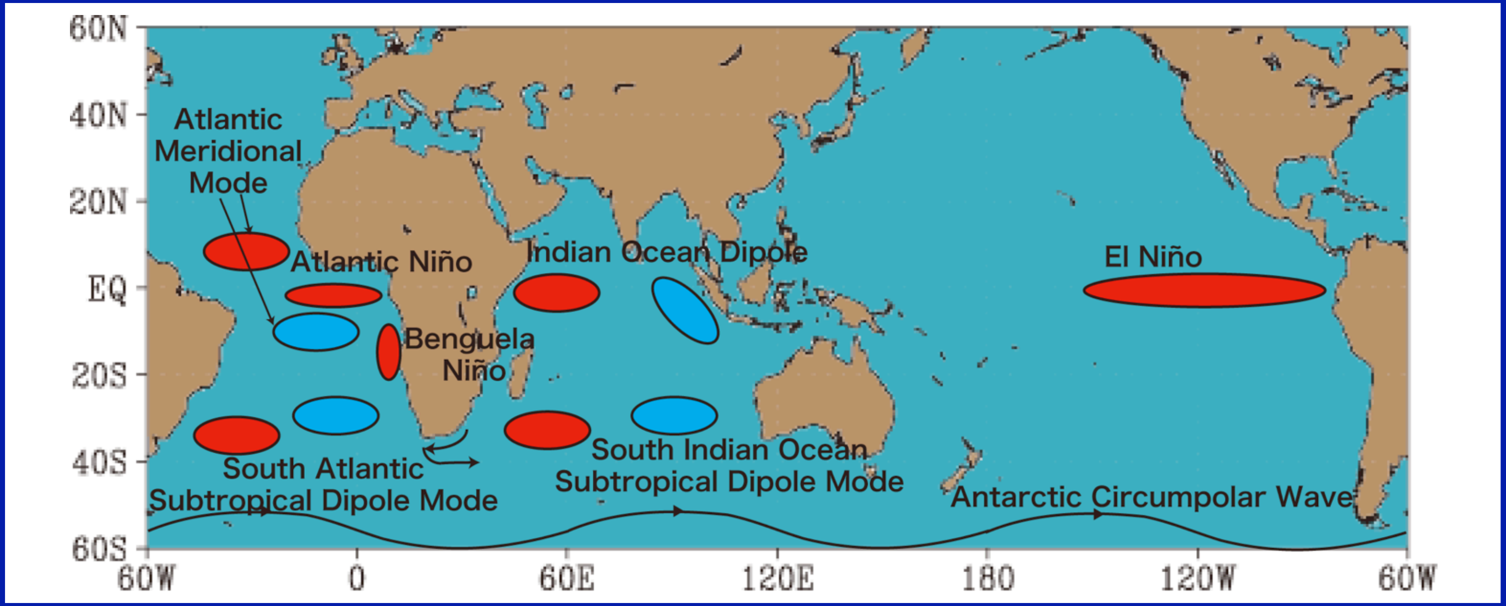


Fig. 2 Annual mean of SST (°C) along the equator in selected CMIP models averaged between 2°S and 2°N. The *thick black and gray lines* show ICOADS observations and the ensemble mean, respectively

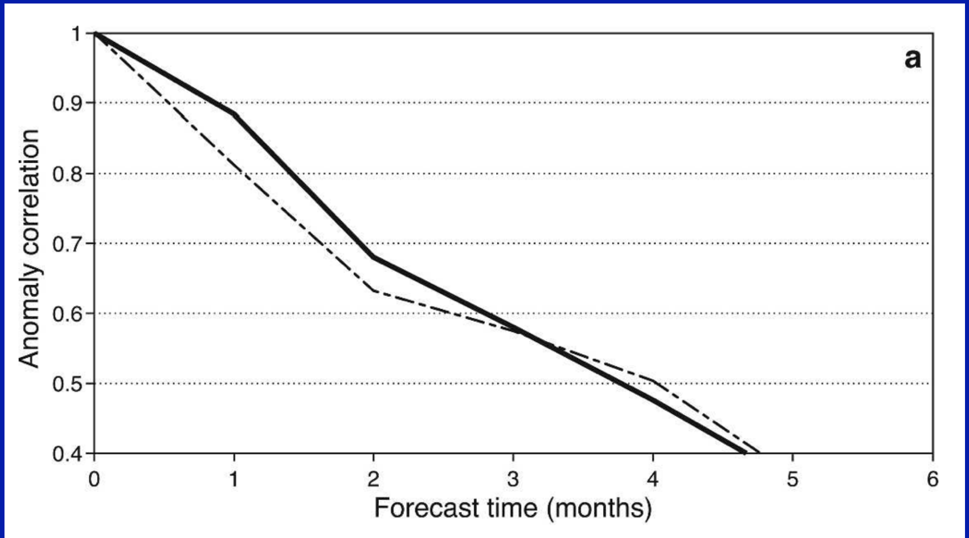
Model/dataset	Label	Model/dataset	Label
Obs	a	mpi_echam5*	l
Reanalysis	b	ncar_ccsm3_0*	m
Ensemble	c	ukmo_hadcm3	n
Cnrm_cm3*	d	ukmo_hadgem1*	o
Csiro_mk3_0	e	bccr_bcm2_0	p
gfdl_cm2_0	f	giss_aom	q
gfdl_cm2_1	g	giss_model_e_h	r
Ingv_echam4	h	giss_model_e_r	s
ipsl_cm4	i	iap_fgoals1_0_g	t
miroc3_2_hires*	j	miub_echo_g	u
miroc3_2_medres*	k	ncar_pcm1	v

Richter and Xie (2008)

Prediction of Atlantic Niño

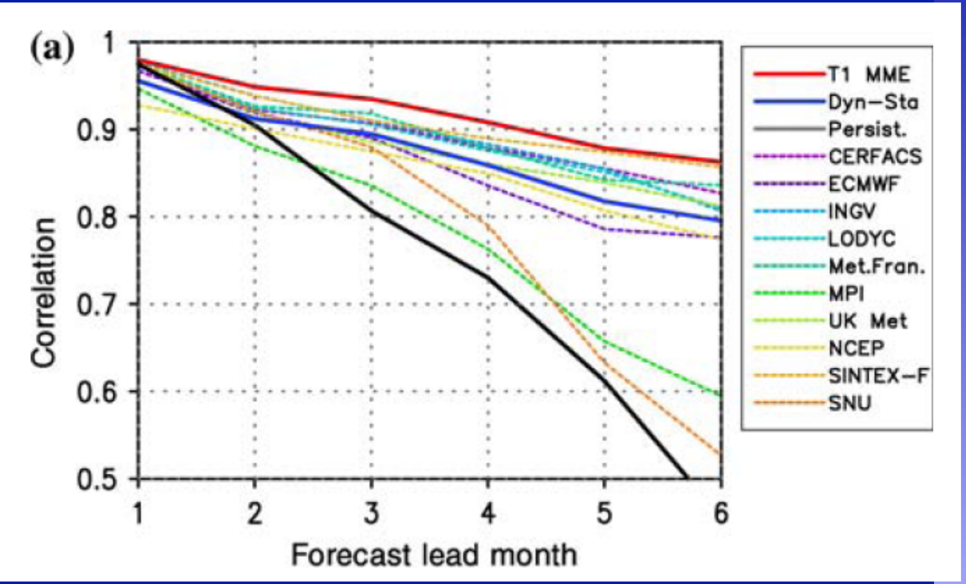


Atlantic Niño Forecast



Stockdale et al. (2006)

El Niño Forecast



Jin et al. (2008)

Possible causes of the model bias

- Underestimated precipitation in northern South America (Chang et al. 2007, 2008; Richter and Xie 2008; Wahl et al. 2010)
- Unrealistic southward shift of the ITCZ in the Atlantic in boreal spring (Richter and Xie 2008)
- Underestimated coastal upweling along the West African coast (Hazeleger and Haarsma 2005; Large and Danabasoglu 2006)
- Underestimated stratus cloud along the West African coast (Yu and Mechoso 1999)
- Spurious barrier layer in the southeastern equatorial Atlantic (Breugem et al. 2008)

Purpose of this study

Most past studies used models with a variety of parameterization schemes, horizontal resolutions, and oceanic and atmospheric components of CGCM. Thus, it was quite difficult to identify the root cause of the model bias in the equatorial Atlantic.

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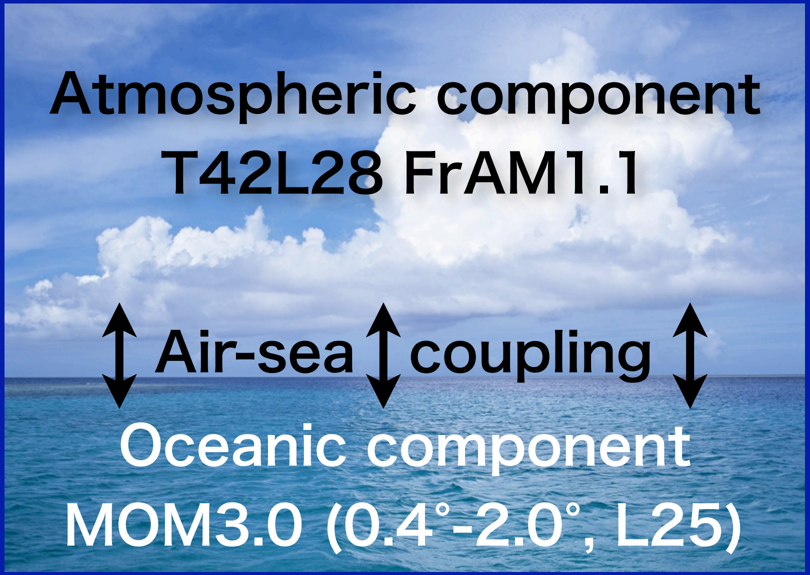
To further narrow down the causes of the model bias, we analyze three versions of the same CGCM differing only in the cumulus convection scheme. Since one version is quite successful in simulating the zonal SST gradient, the present approach may shed new light on the causes of the equatorial Atlantic bias.

University of Tokyo Coupled Model (UTCM)

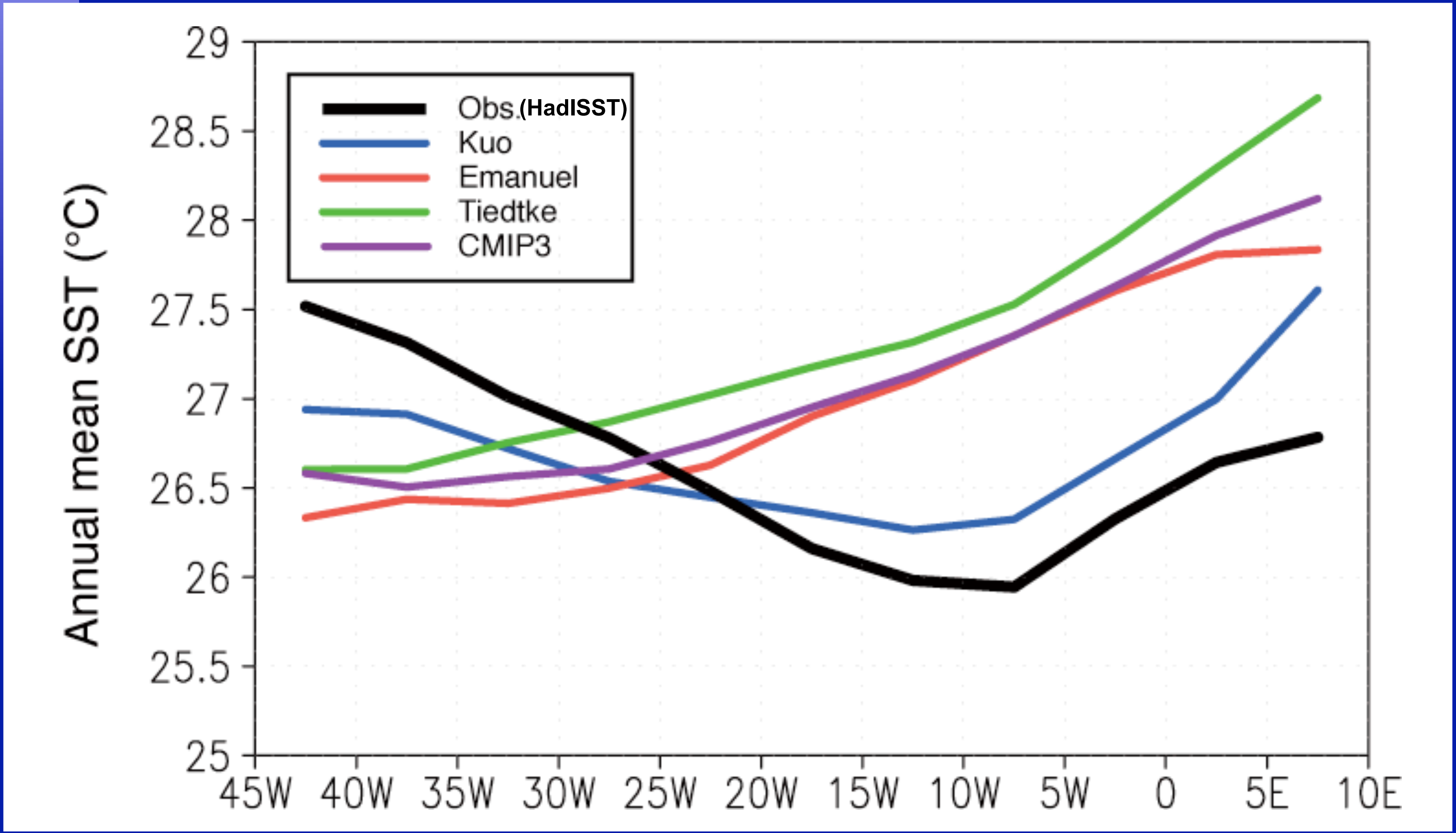


Used for seasonal prediction in our project and was installed in CSIR.

- Ocean model: MOM3 (0.4°-2° in horizontal, 25 vertical levels)
- Atmosphere model: T42L28 FrAM

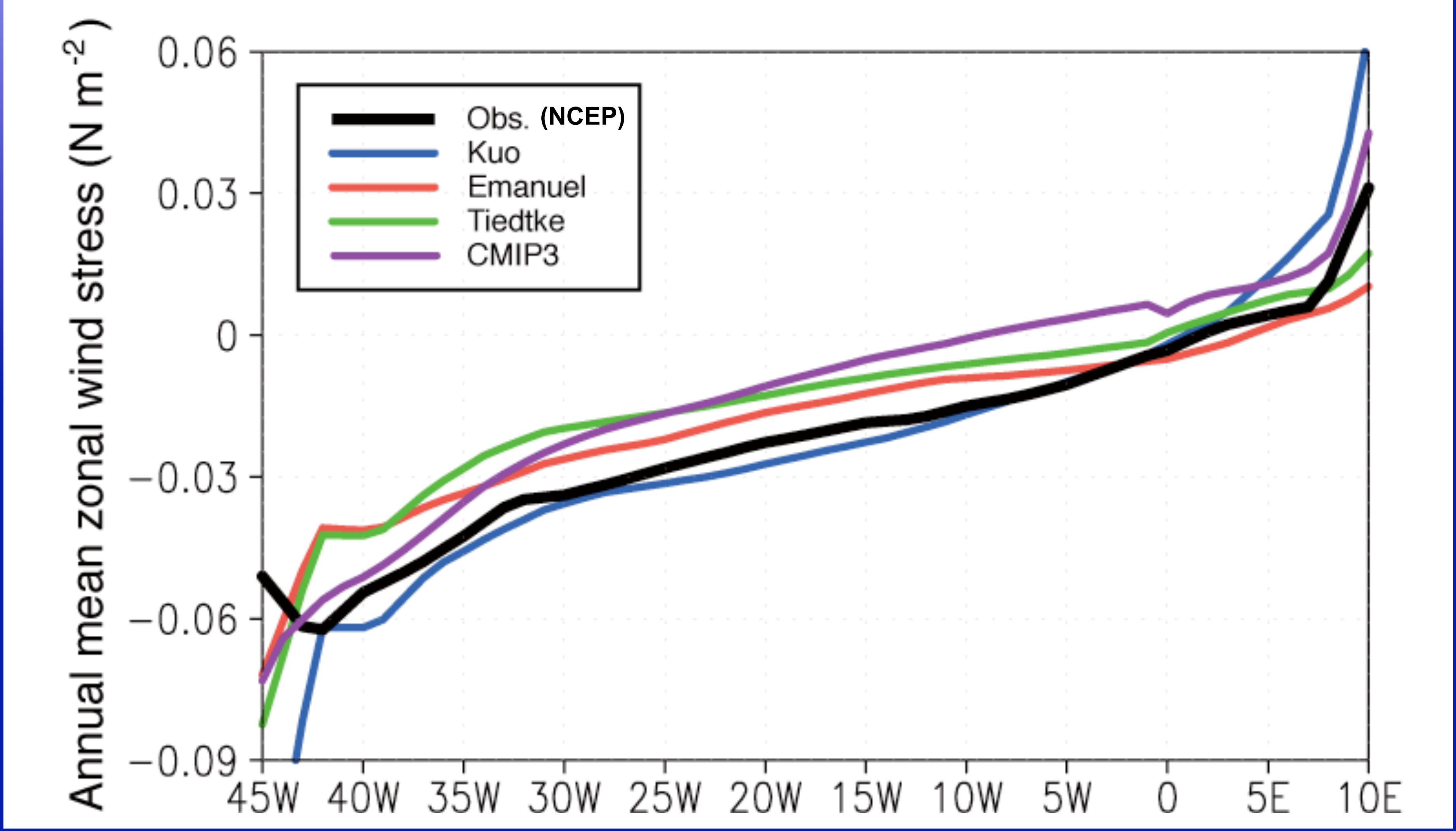
  Cumulus parameterization schemes
  - Kuo (1974)
  - Emanuel (1991)
  - Tiedtke (1989)
- Coupler: UTCM coupler, flux is exchanged daily
- Integrated for 50 years and analyzed the last 30 years

Annual mean SST along the equatorial Atlantic



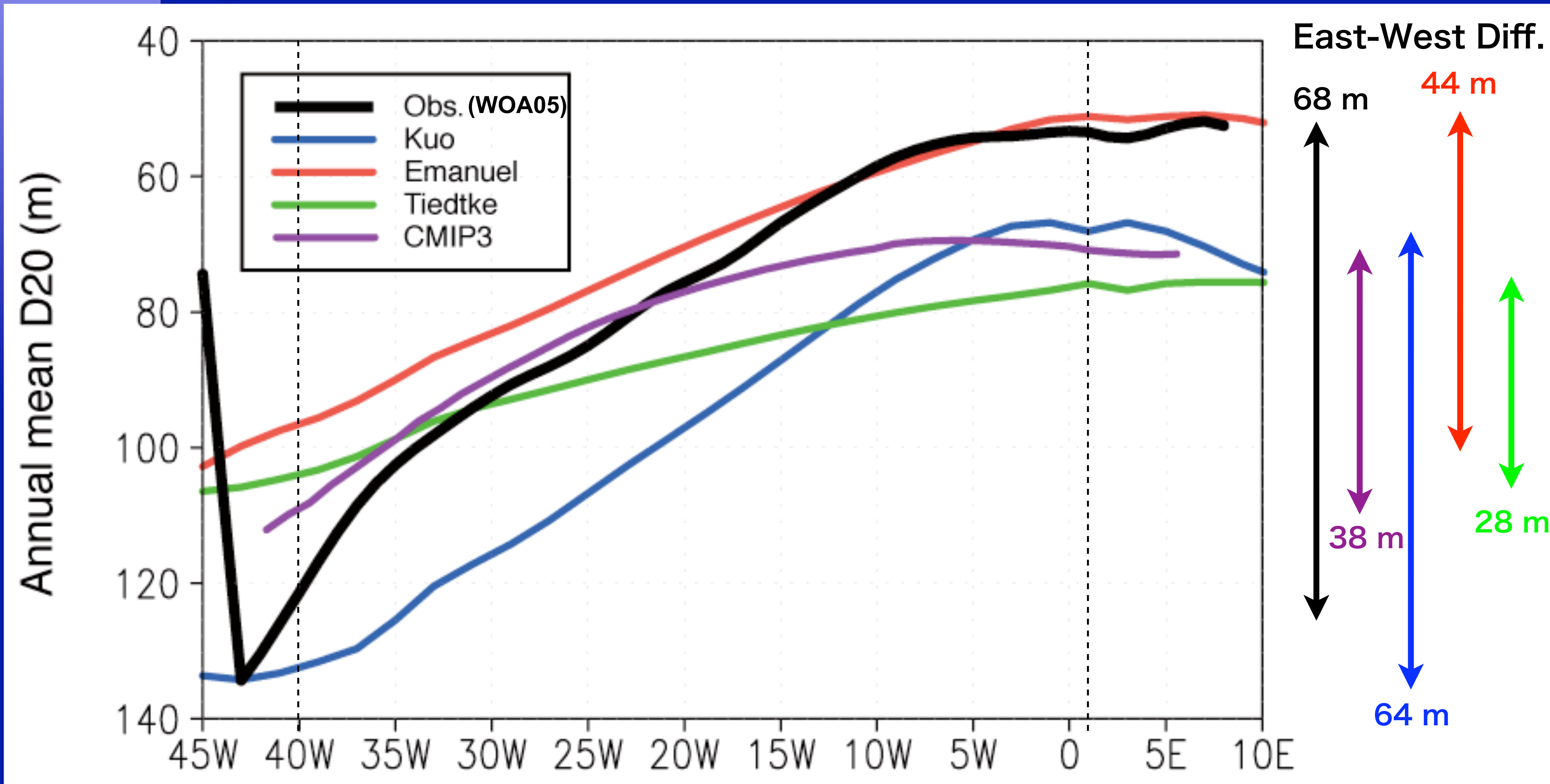
- Only UTCM_Kuo is successful in reproducing the gradient of the annual mean SST along the equatorial Atlantic.

Annual mean zonal wind stress along the equatorial Atlantic



- The annual mean zonal wind stress is also best simulated by UTCM_Kuo, whereas that in others is weaker than observation.

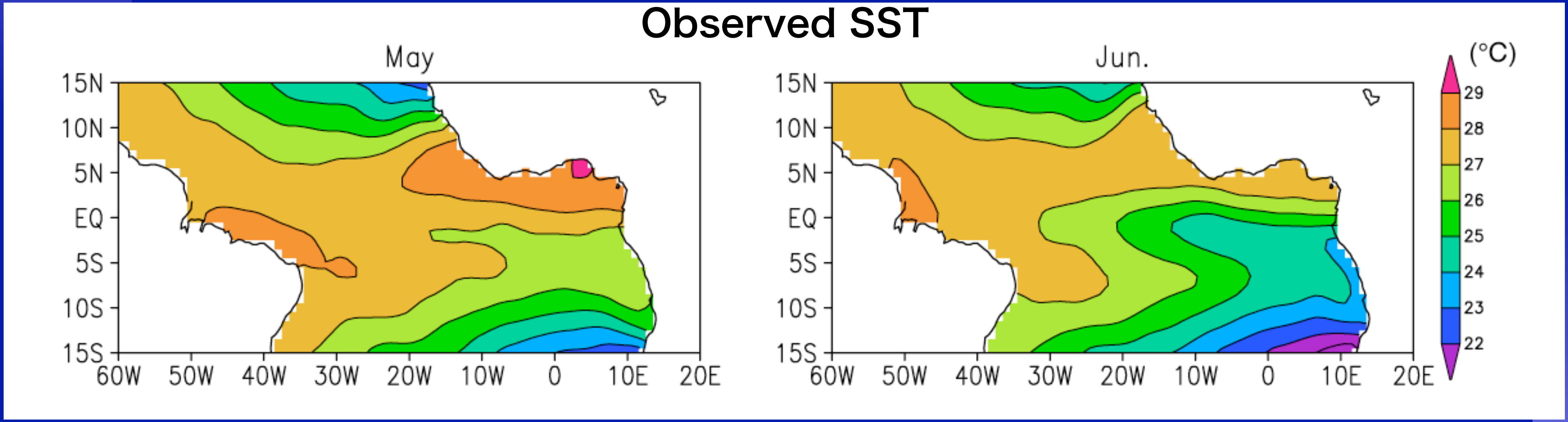
Annual mean thermocline depth along the equatorial Atlantic



- The east-west difference in the equatorial thermocline depth (depth of 20°C isotherm) in UTCM_Kuo is in good agreement with the observation.

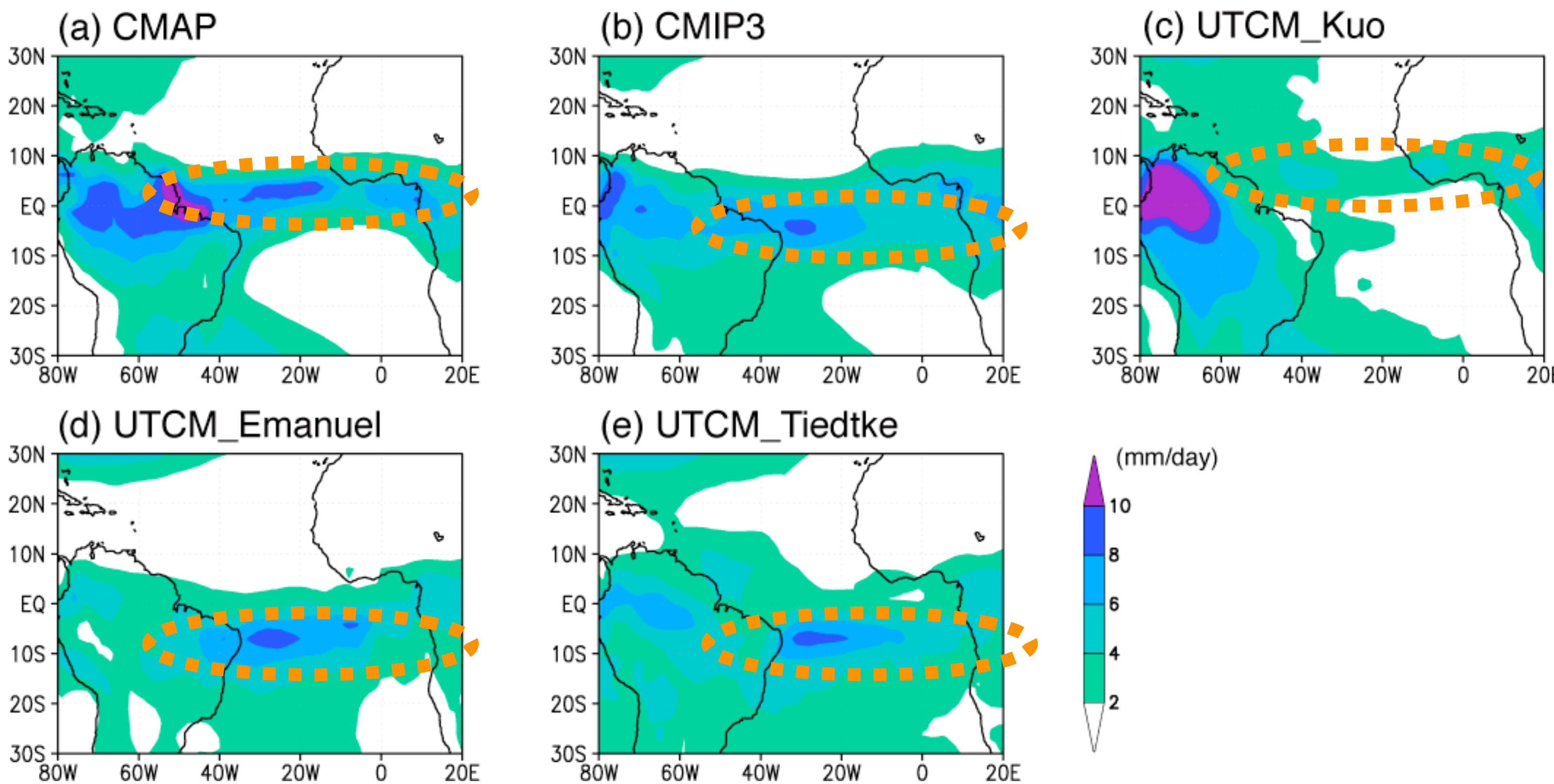
Boreal season is the critical season for the cold tongue development

Our model gives us a good means to improve skills of CGCMs to simulate the mean state in the equatorial Atlantic.



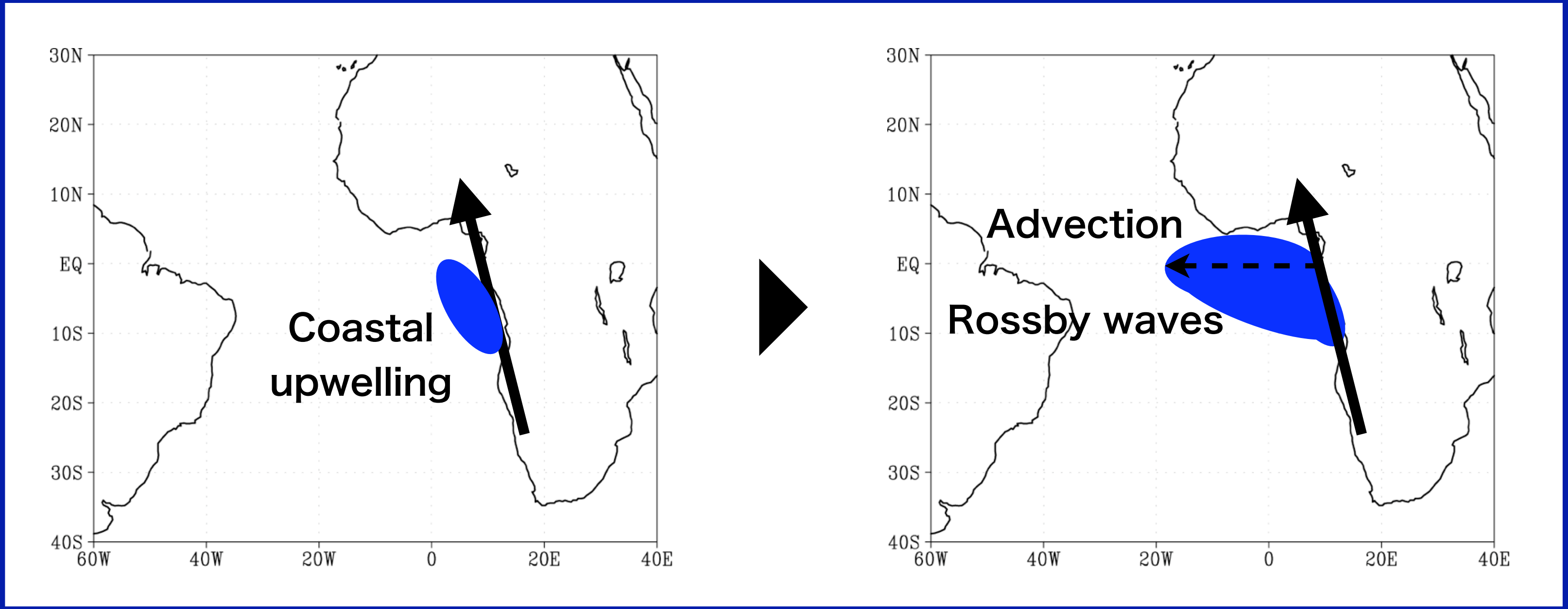
Since the cold tongue of the equatorial Atlantic starts to develop in boreal spring, we focus on this particular season.

Precipitation in boreal spring (1)



- The ITCZ is located to the south of the equator in UTCM_Emanuel, UTCM_Tiedtke, and the ensemble of CMIP3 models, whereas that in the observation and UTCM_Kuo remains north of the equator.

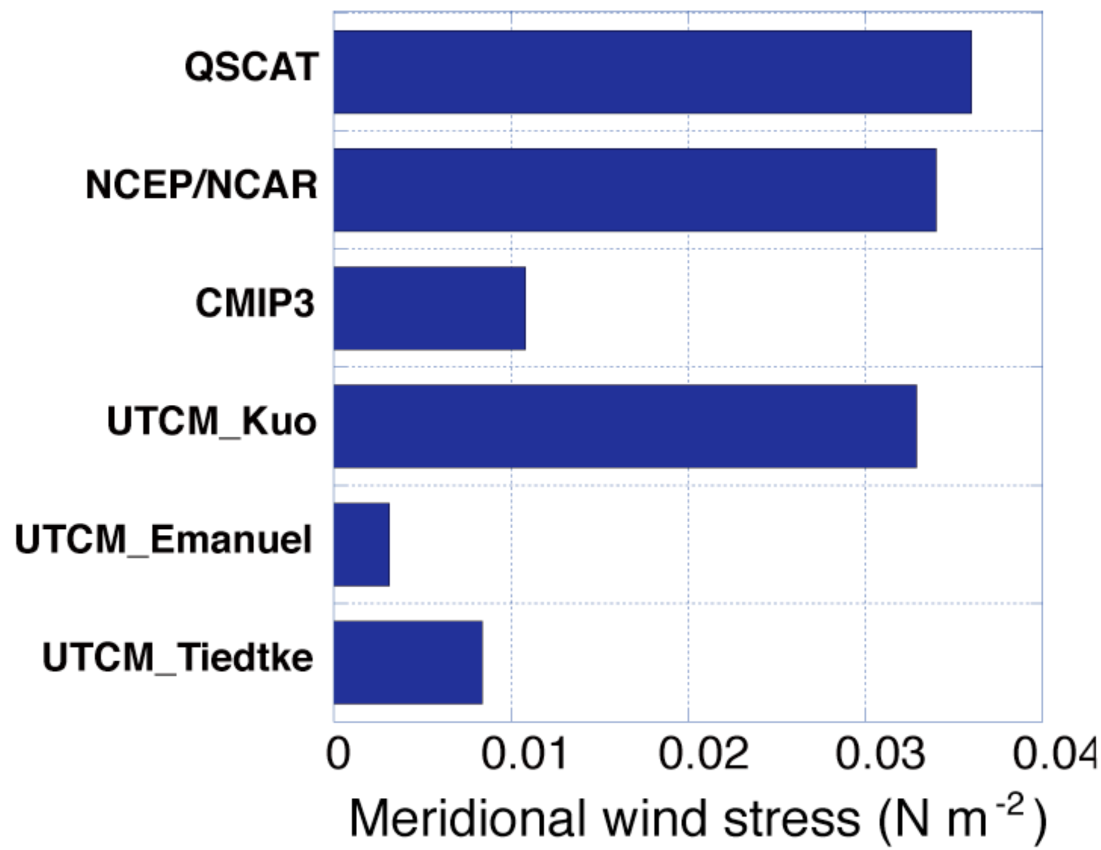
Meridional wind stress along the West African coast

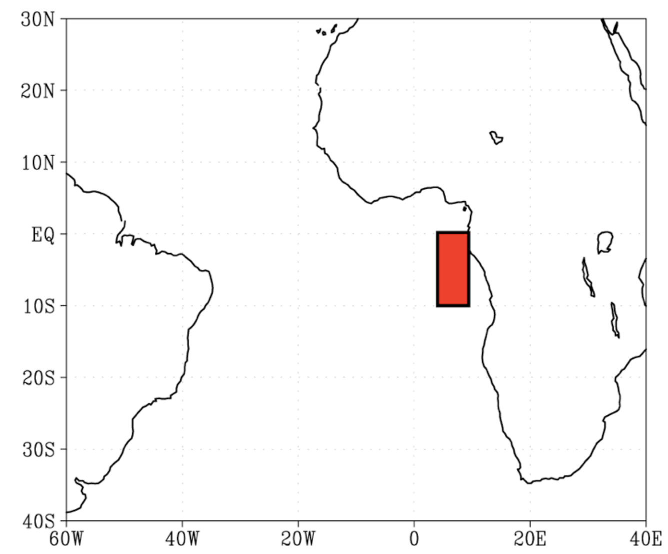


The southerly wind stress in the eastern Atlantic induces coastal upwelling along the West African coast in the Southern Hemisphere, which then extends westward by advection and Rossby wave propagation and generates the cold SST in the eastern equatorial region (Philander and Pacanowski 1981).

We have checked whether this cross-equatorial meridional wind stress plays a role in better simulation of the cold tongue.

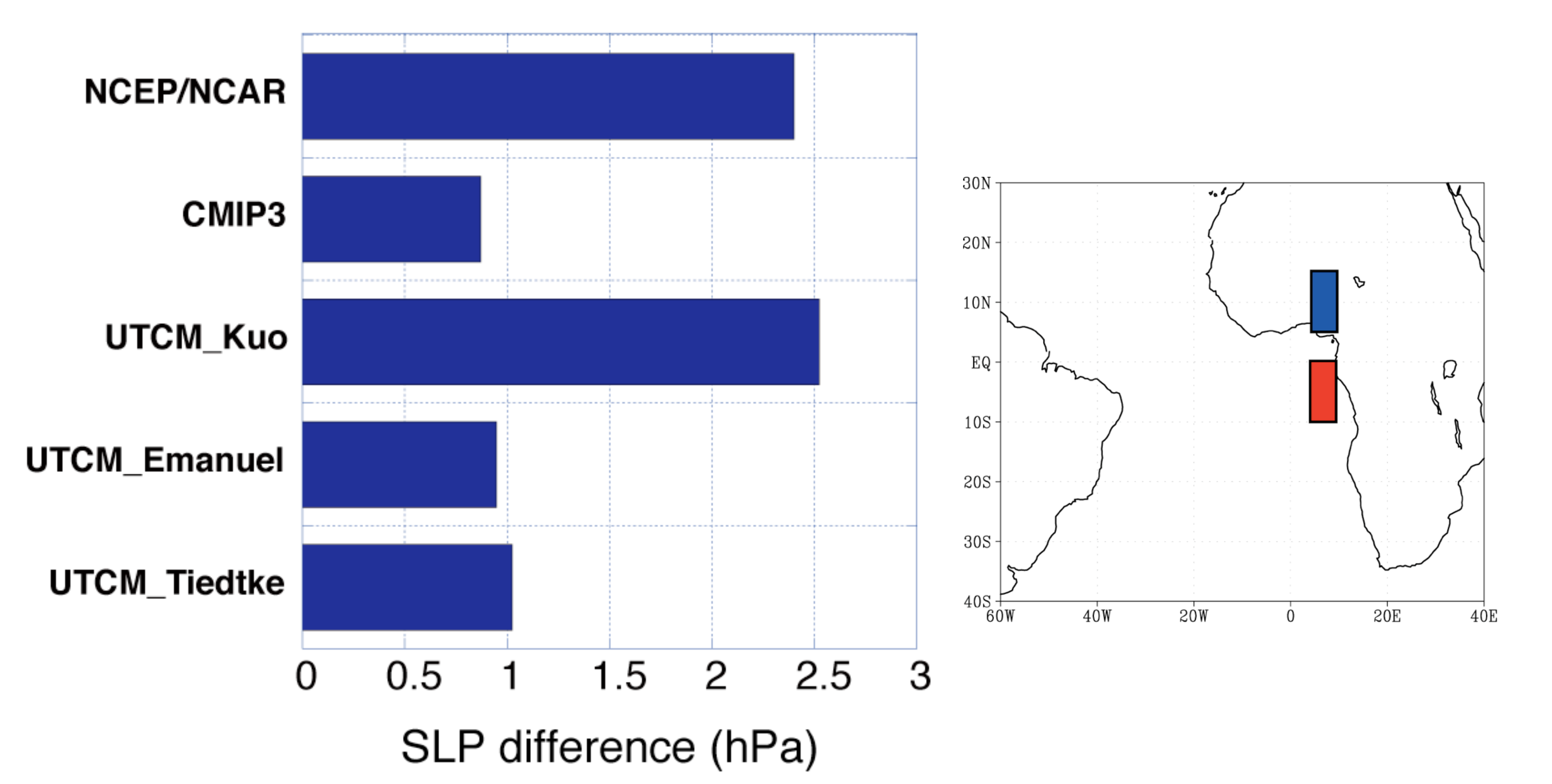
Meridional wind stress along the West African coast





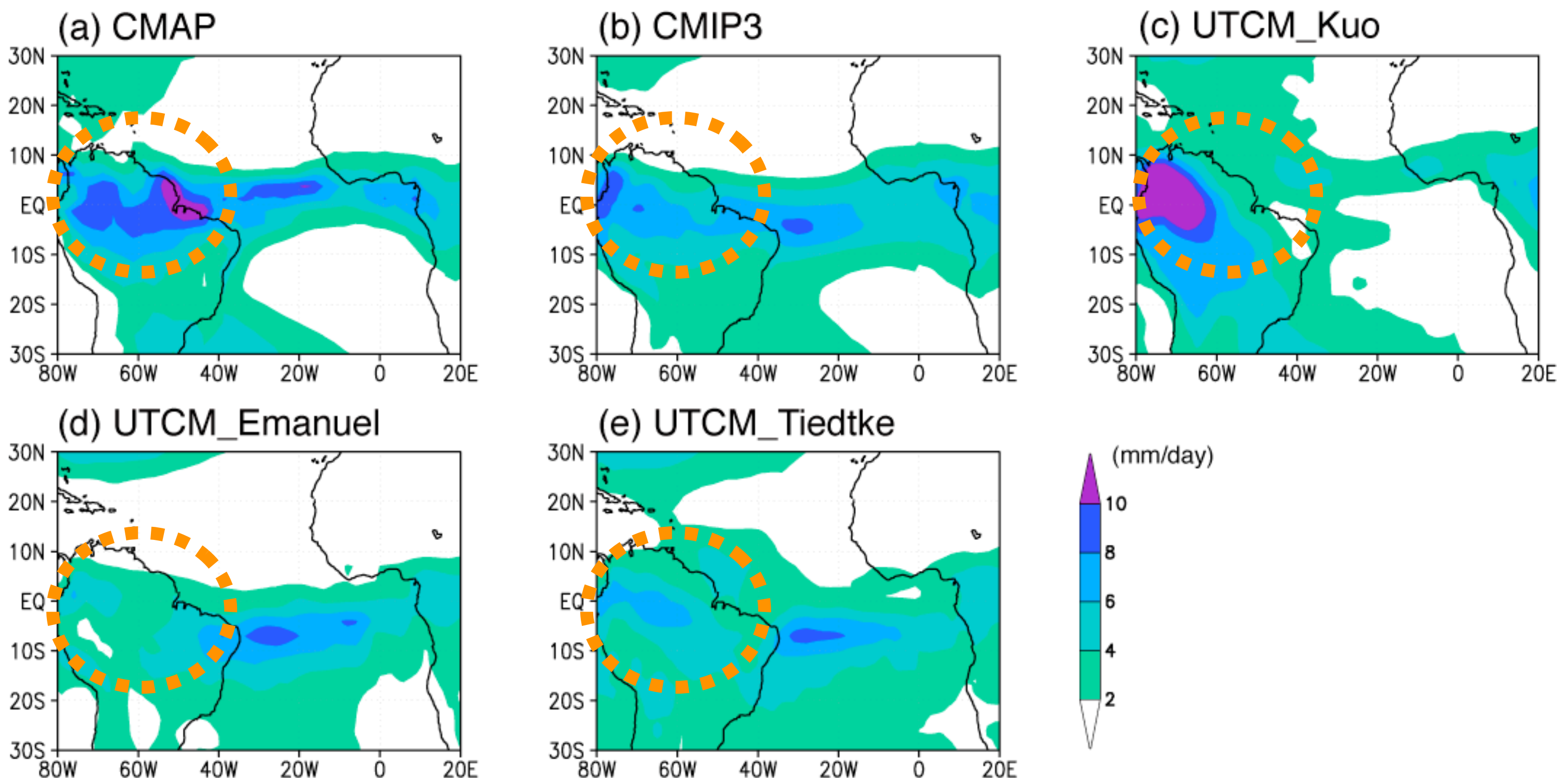
- The simulated southerly wind stress in UTCM_Kuo is very close to that in QSCAT observation and NCEP/NCAR reanalysis data. In contrast, it is significantly weaker in UTCM_Emanuel, UTCM_Tiedtke, and the ensemble mean of CMIP3 models.

Meridional SLP difference



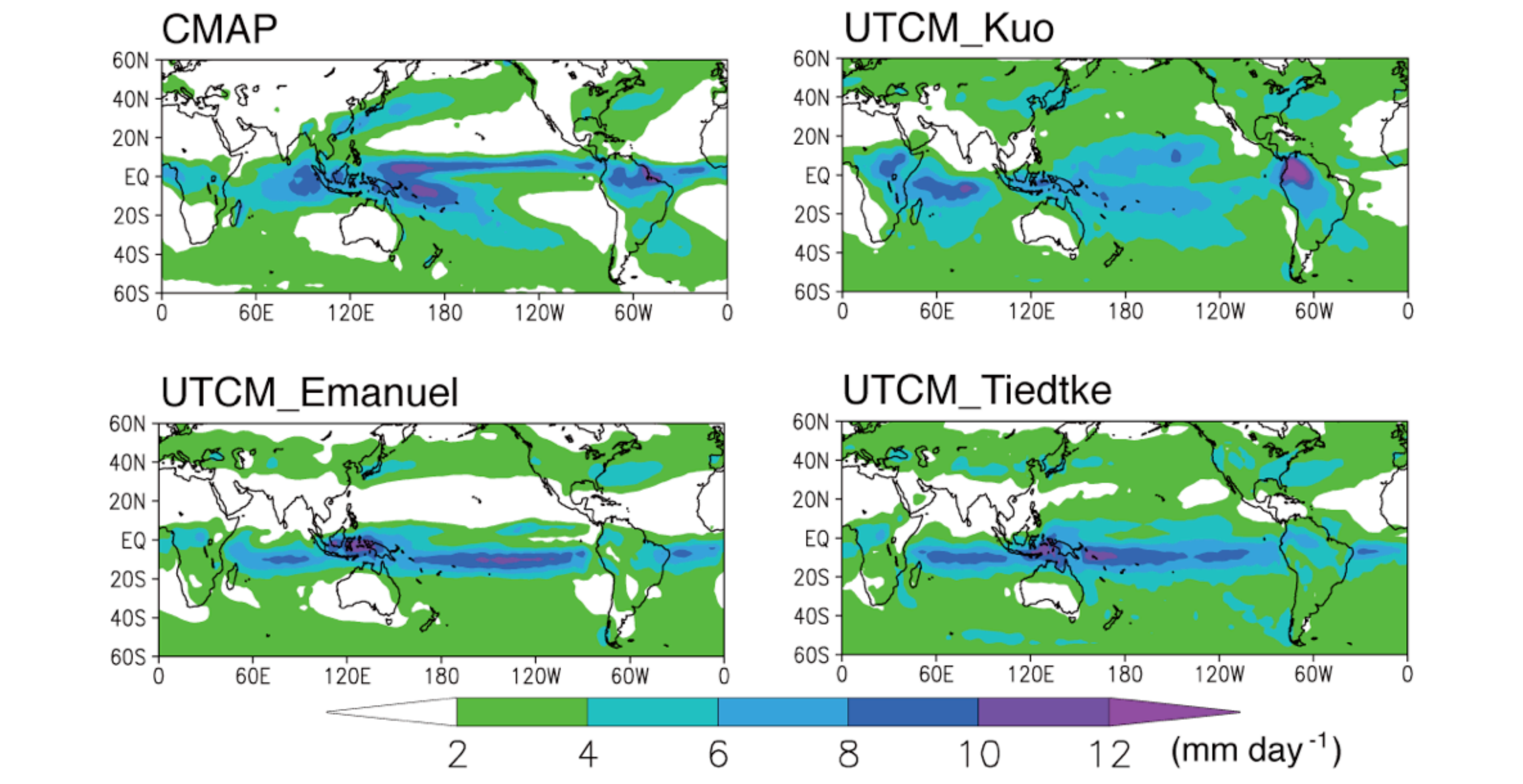
- The meridional SLP difference between the western Sahel region (blue region) and the southeastern tropical Atlantic (red region) in boreal spring in UTCM_Kuo is in good agreement with the observation.

Precipitation in boreal spring (2)



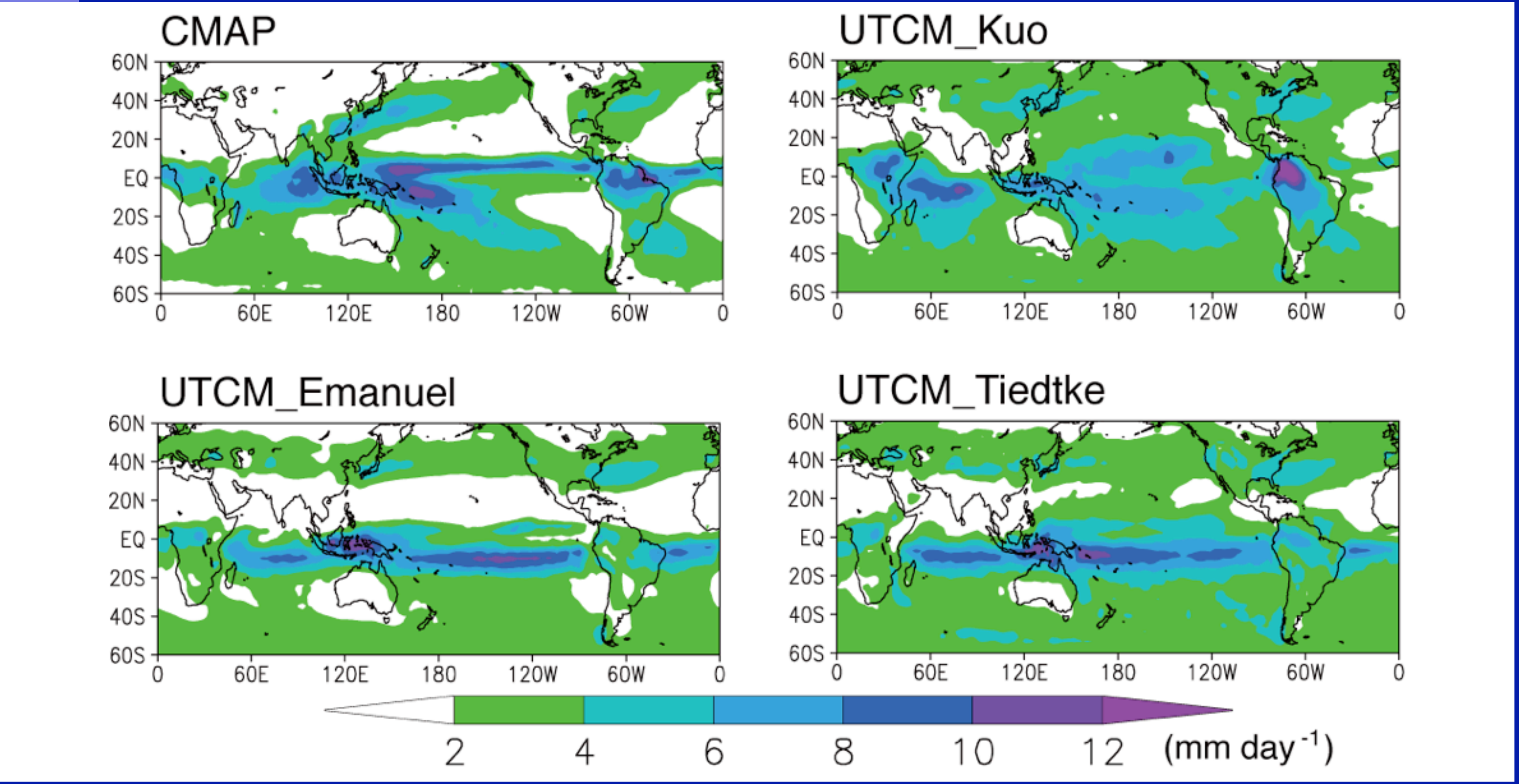
- Only UTCM_Kuo is successful in simulating large precipitation over northern South America. This favors the easterly wind over the equatorial Atlantic that converges toward the northern South America and thus the development of the cold tongue.

Global precipitation in boreal spring



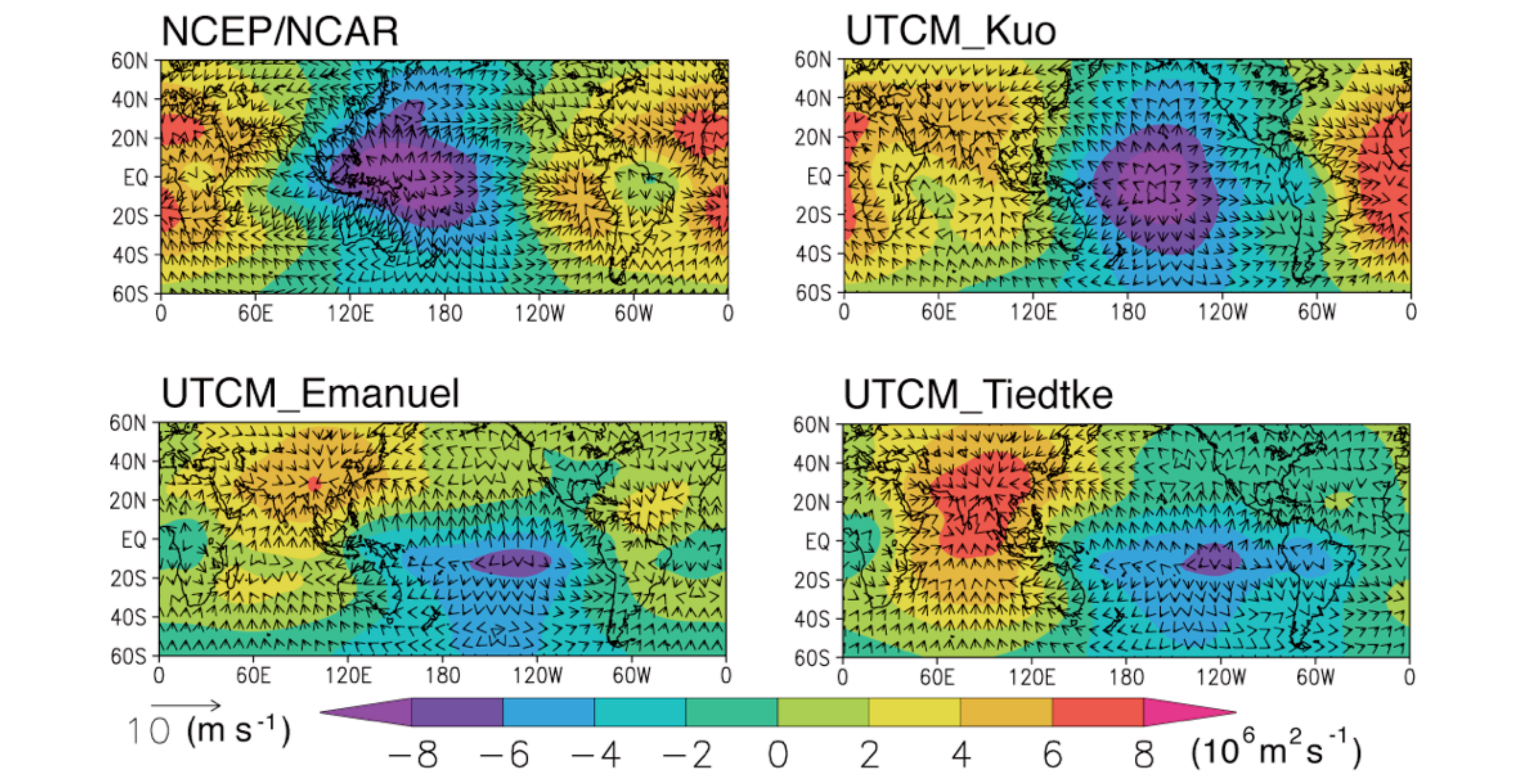
- The Pacific ITCZ is broad and weak in UTCM_Kuo, whereas it is very pronounced in the Southern Hemisphere in UTCM_Emanuel and UTCM_Tiedtke.

Global precipitation in boreal spring



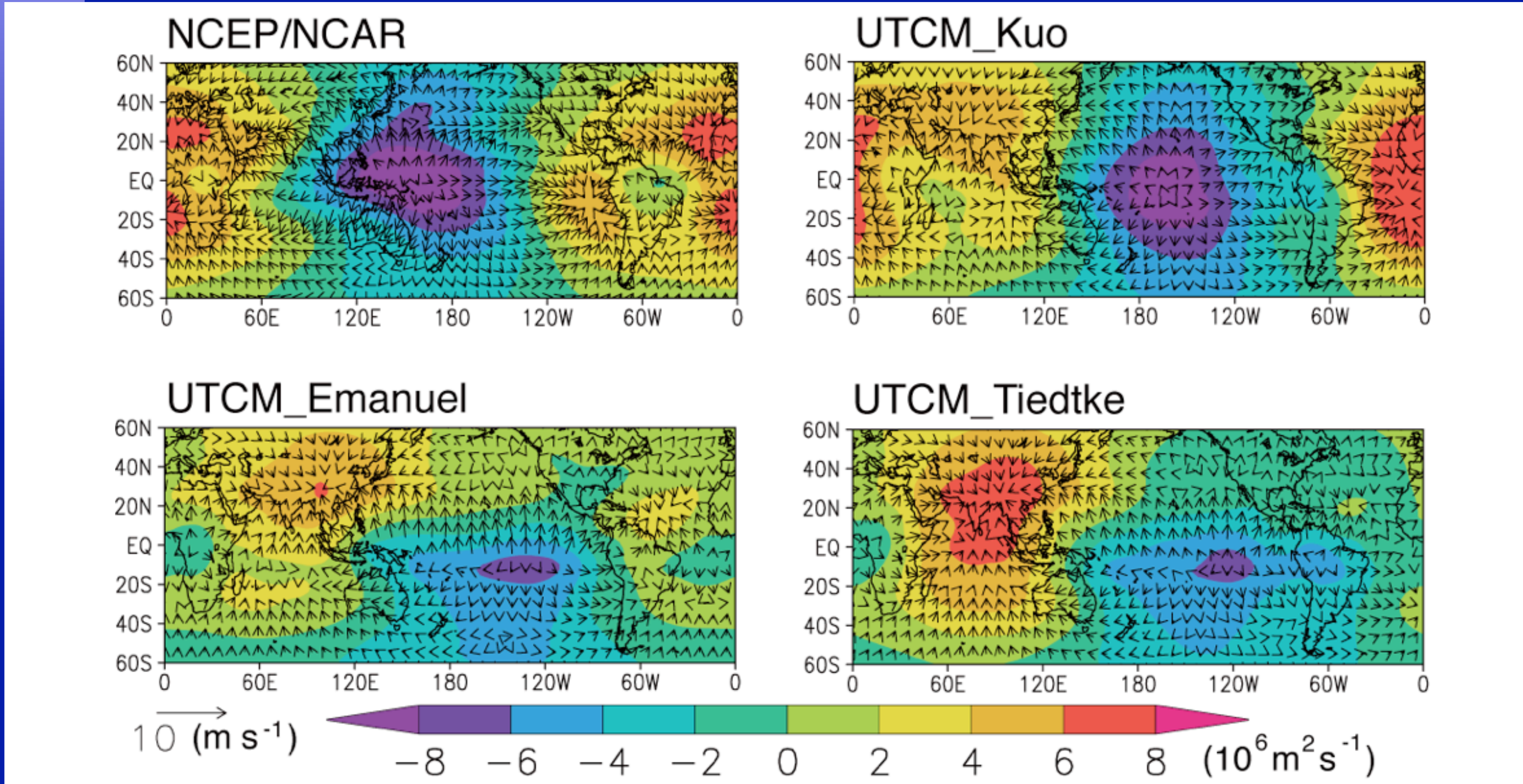
◇ Since the unrealistically strong precipitation in the eastern tropical Pacific along 10°S is relatively close to South America, this bias may have a strong influence on the rainfall over northern South America.

Global velocity potential and divergent wind at 200 hPa in boreal spring



- In contrast to the observation, the divergence is centered
  - around 160°W in UTCM_Kuo,
  - around 130°W in UTCM_Emanuel
  - around 120°W in UTCM_Tiedtke

Global velocity potential and divergent wind at 200 hPa in boreal spring



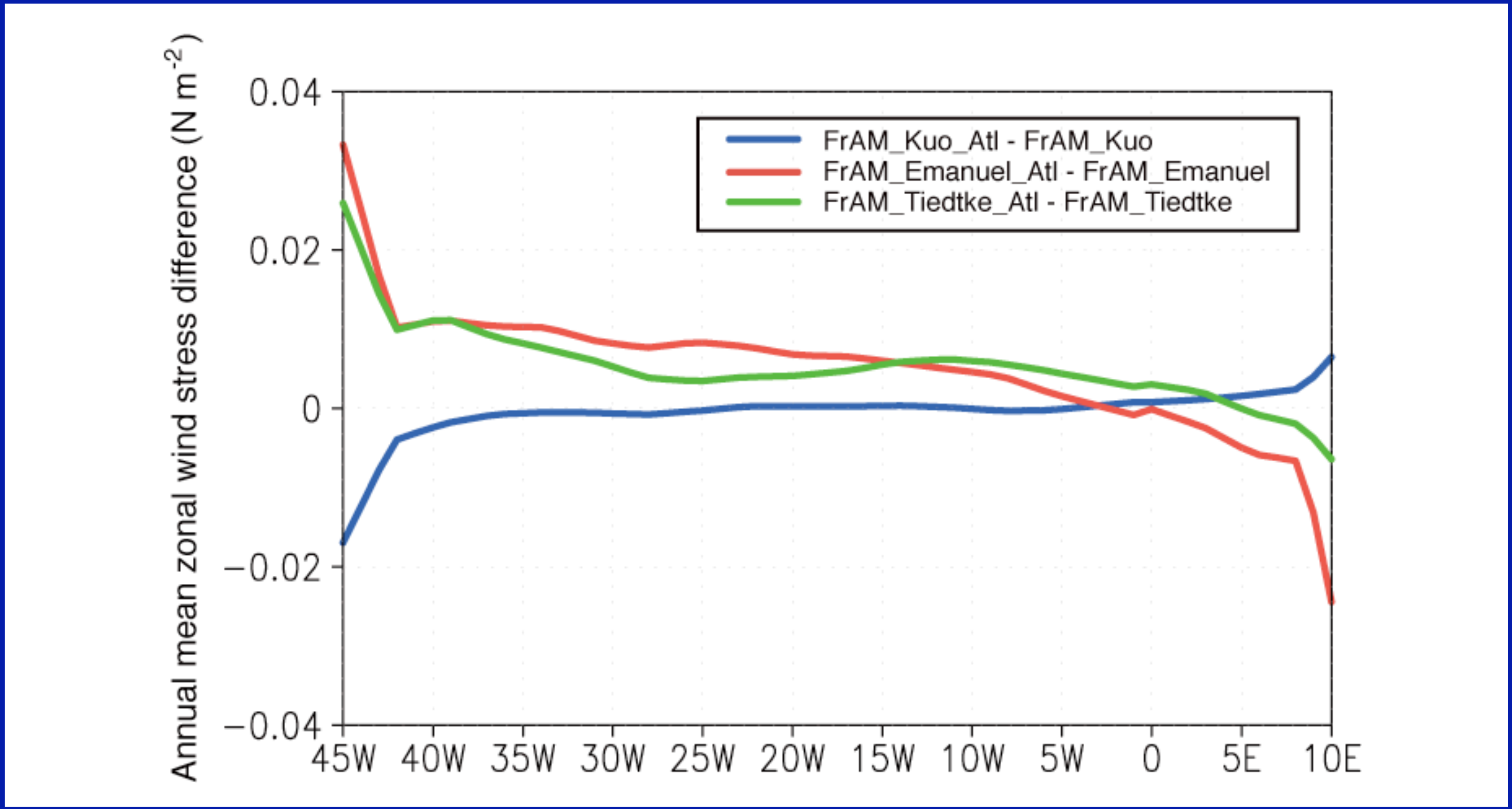
- Because the divergent wind emanating from this divergence center reaches South America in UTCM_Emanuel and UTCM_Tiedtke, it may suppress convection over northern South America.

Control and sensitivity experiments with FrAM

To check whether the model biases in other basins may influence the Atlantic bias, we have conducted uncoupled experiments with three versions of the atmospheric component of UTCM.

Experiments	Tropical Atlantic SST	SST in other area
FrAM_Kuo	HadISST Clim.	HadISST Clim.
FrAM_Emanuel	HadISST Clim.	HadISST Clim.
FrAM_Tiedtke	HadISST Clim.	HadISST Clim.
FrAM_Kuo_Atl	HadISST Clim.	UTCM_Kuo
FrAM_Emanuel_Atl	HadISST Clim.	UTCM_Emanuel
FrAM_Tiedtke_Atl	HadISST Clim.	UTCM_Tiedtke

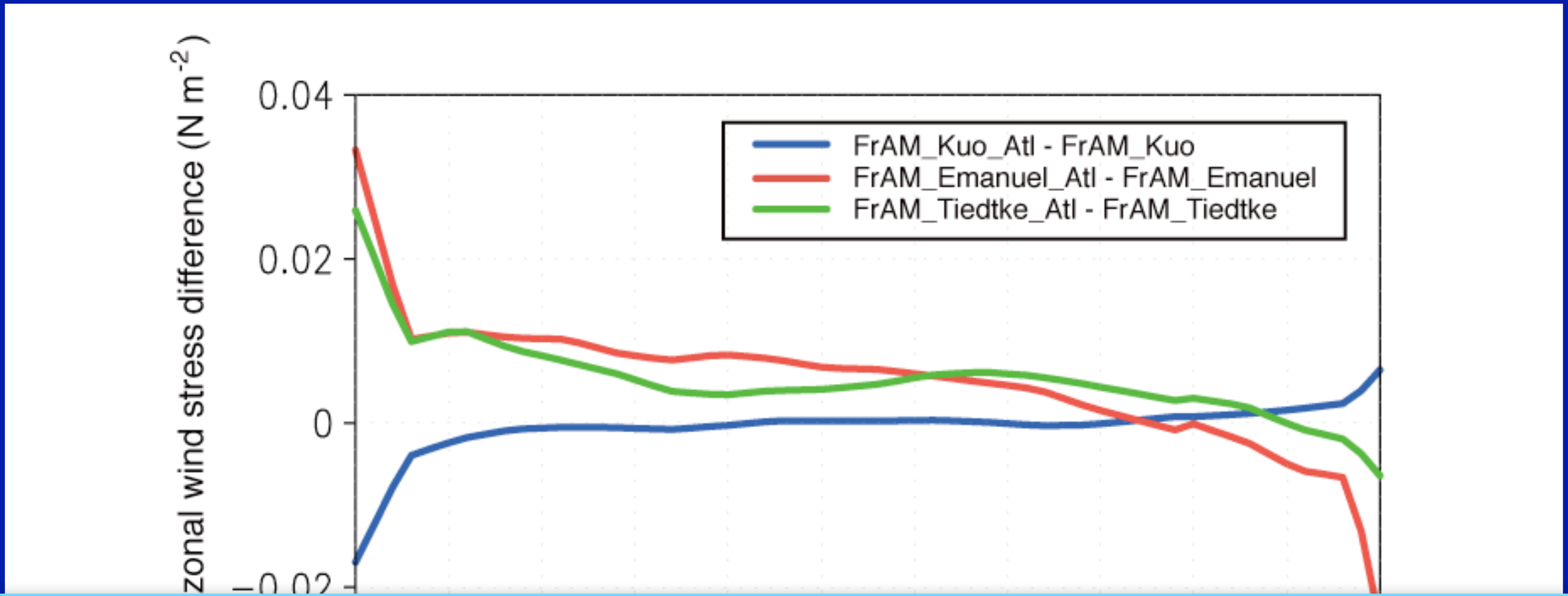
Difference in the annual mean zonal wind stress in the equatorial Atlantic



When only the SST over the tropical Atlantic is realistic:

- The equatorial easterlies are weaker in FrAM with the Emanuel and Tiedtke schemes.
- The equatorial easterlies in FrAM with the Kuo scheme are not influenced by the SST in other basins simulated by UTCM.

Difference in the annual mean zonal wind stress in the equatorial Atlantic



These weaker easterlies with the Emanuel and Tiedtke schemes are expected to be amplified in coupled runs by the local air-sea interaction.

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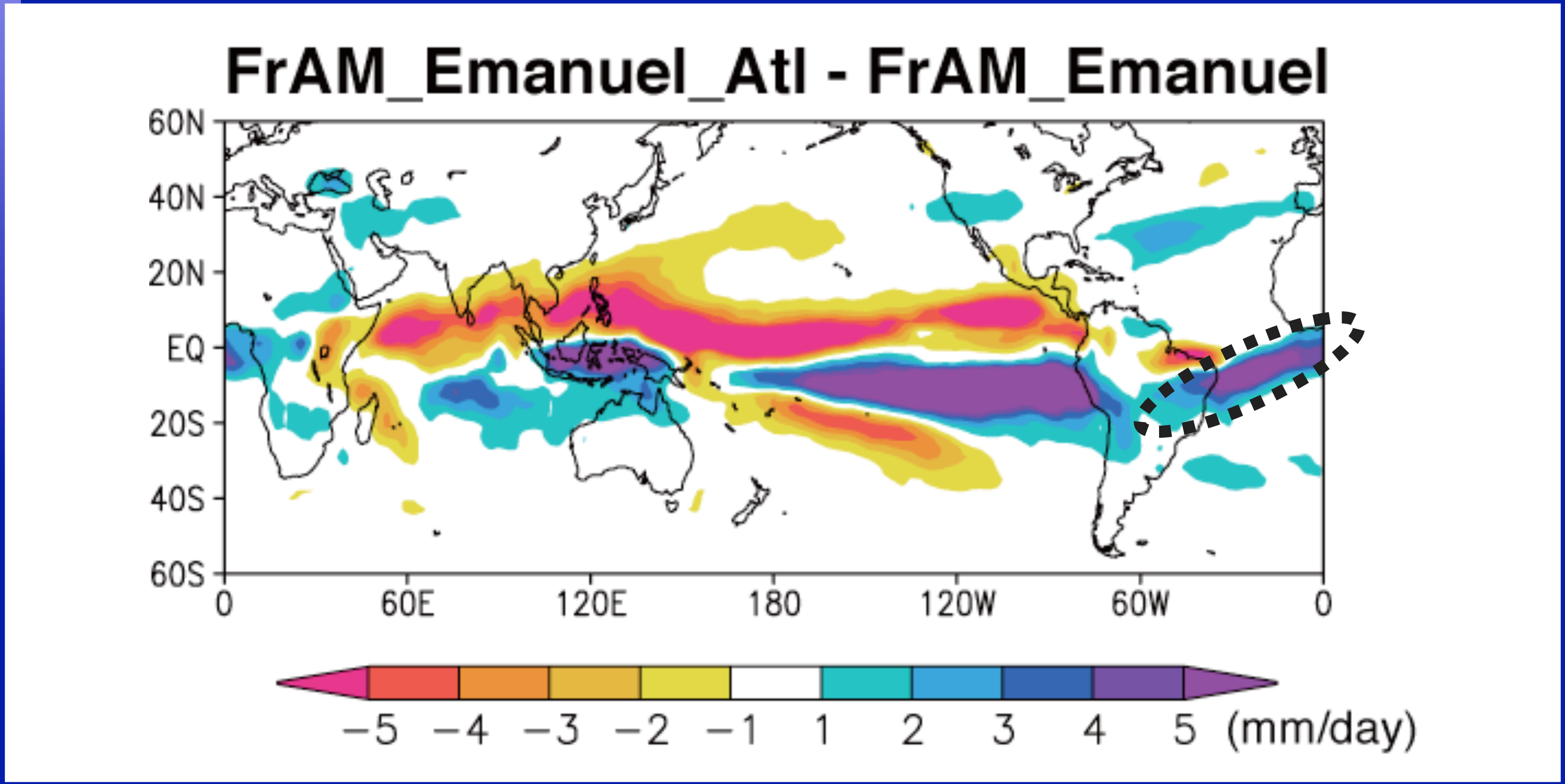
Therefore, the uncoupled experiments support our hypothesis that the biases in the Pacific influence the precipitation over northern South America, and thus the strength of the easterly trade winds in the equatorial Atlantic.

Difference in the precipitation in boreal spring



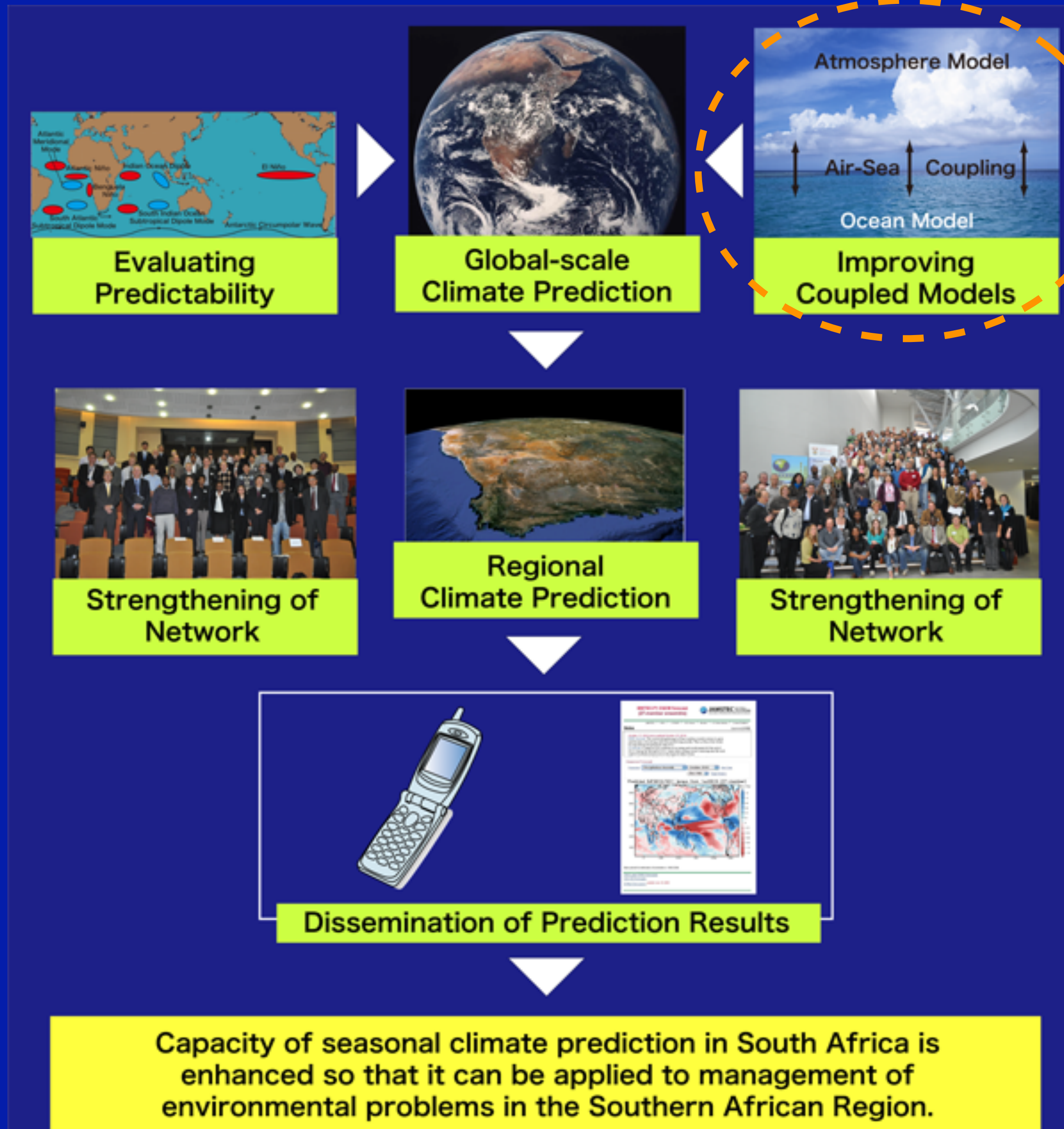
- There exists a strong wet bias across the tropical Atlantic south of the equator. This implies that the biases outside of the tropical Atlantic causes the maritime ITCZ in the Atlantic to shift erroneously southward and may explain the most southerly position of the ITCZ among the coupled runs of UTCM.

Conclusions

- The zonal SST gradient along the equatorial Atlantic is not correctly simulated by any CGCMs, but one version of our model was successful in this aspect.
- Key factors to be successful are high skills in simulating
  - the meridional location of the ITCZ
  - the southerly wind along the west coast of Africa associated with the West African monsoon
  - the precipitation over northern South America

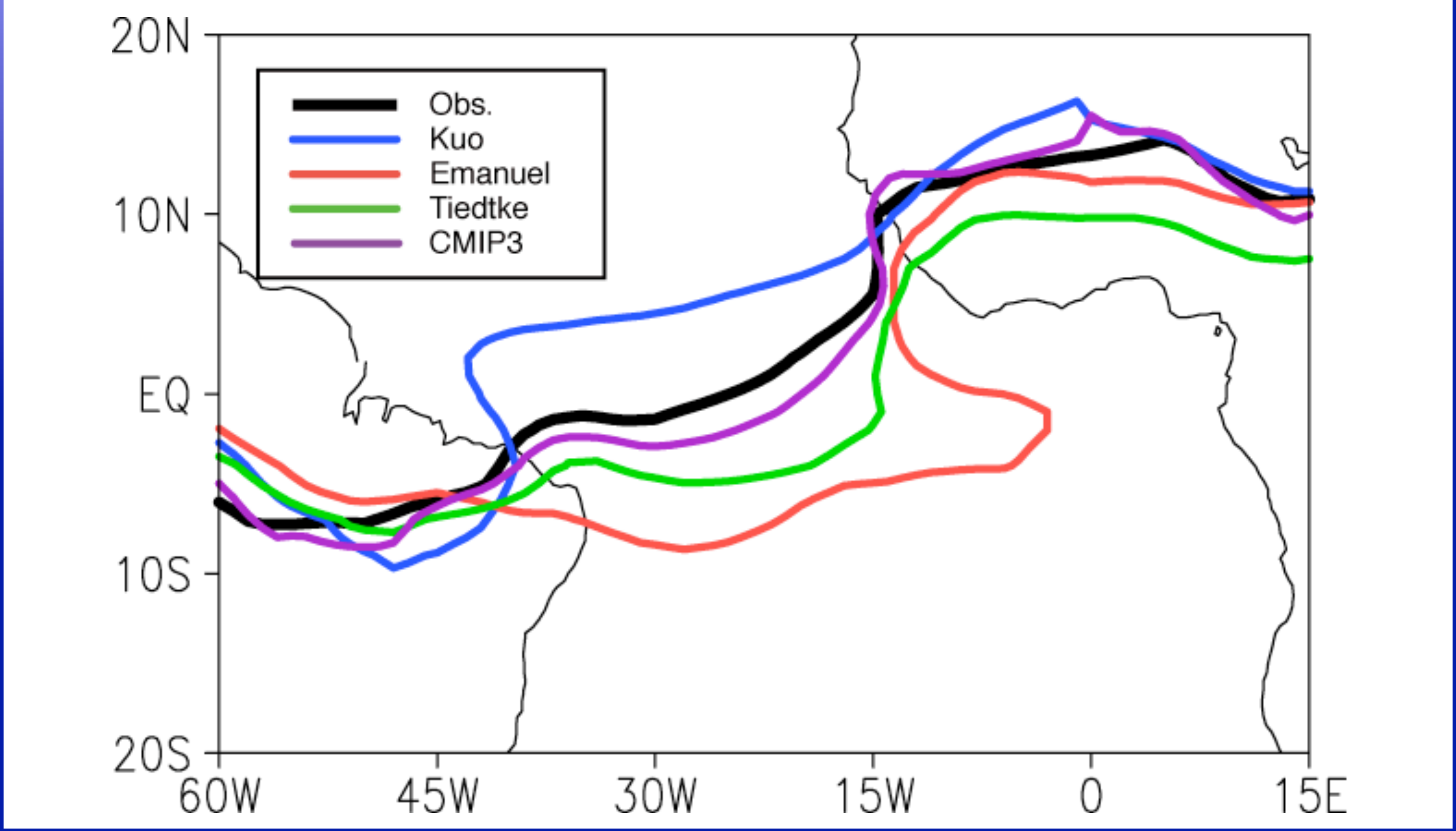
  in boreal spring.
- Model biases in the Pacific contribute to the weaker precipitation over northern South America.

Overview of the Project



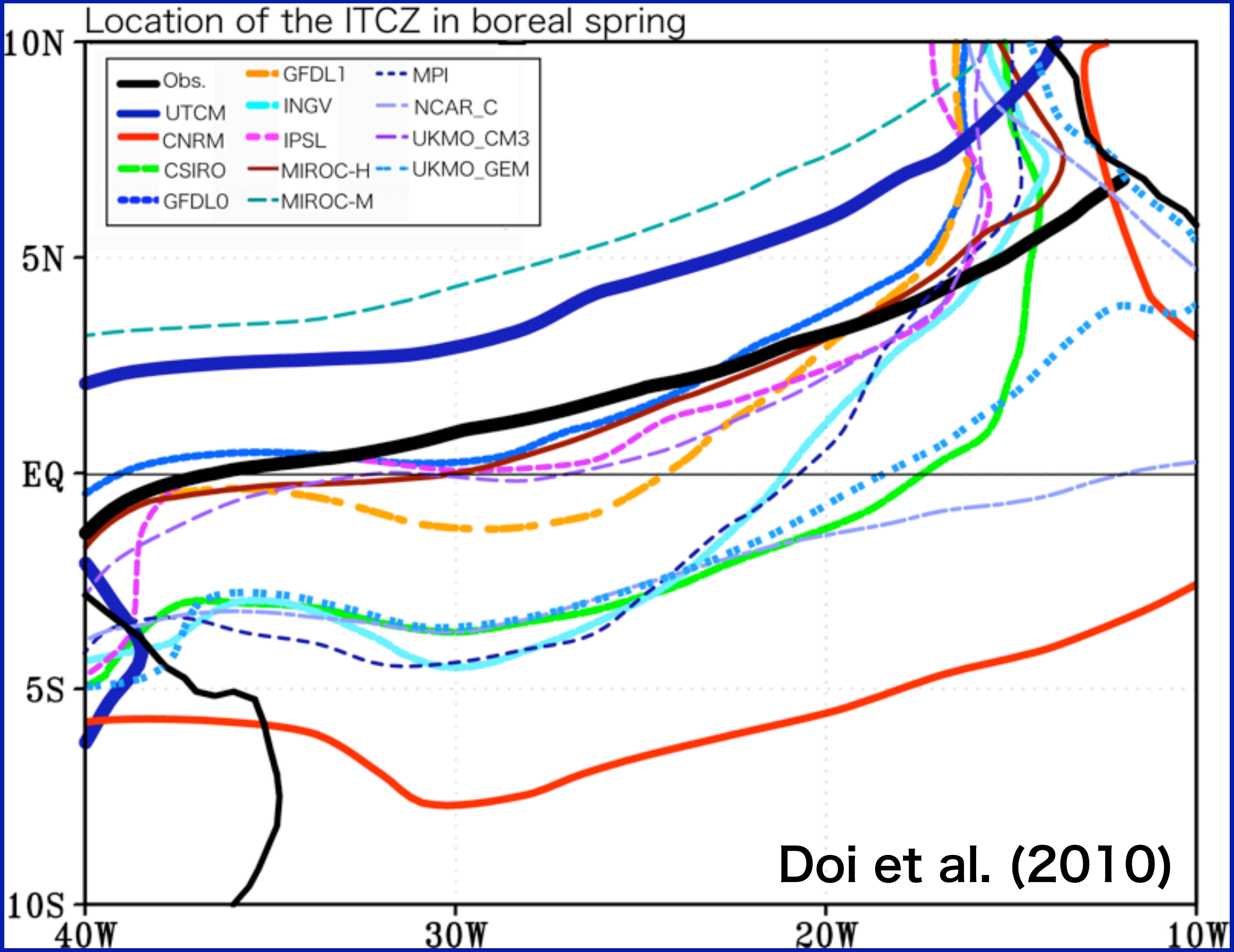
Supplementary Slides

Position of the ITCZ (Intertropical Convergence Zone) in boreal spring



- The ITCZ in UTCM (Kuo) remains to the north of the equator as in observation, but it shifts to the south of the equator in other models.

Position of the ITCZ in boreal spring: CMIP3 models (Richter and Xie 2008; Doi et al. 2010)



- Although the location of the ITCZ may partly explain the success of UTCM (Kuo), some CMIP3 models (e.g. GFDL0, MIROC-H, and IPSL) fail to reproduce the zonal SST gradient even though locations of ITCZ are consistent with observation.

FrAM1.1

- Upgraded version of FrAM1.0 (Guan et al. 2001), originally developed from MRI-GPSM (Chiba et al. 1996)
- T42L28
- Cloud: Slingo and Slingo (1991)
- Gravity wave drag: Palmar et al. (1986)
- Land surface: Viterbo and Beljaars (1995)
- Radiation: Shibata and Aoki (1989), Shibata (1989), Lacis and Hansen (1974)

MOM3.0

- GFDL MOM3.0 (Pacanowski and Griffies 1999)
- Domain: Global, 65°S-65°N
- Resolution: 0.4°-2.0°
- 25 vertical levels
- Vertical mixing: Pacanowski and Philander (1981)
- Horizontal mixing: Smagorinsky (1963), Gent and McWilliams (1990)

UTCM coupler

- Original coupler written by Drs. Chakraborty and Tozuka.
- Coupling interval: Once daily
- No sea ice model -> SIGRID (Thompson 1981) is adopted for sea ice distribution.
- Levitus SST climatology are used poleward of 60°N and 60°S.
- No flux correction between 60°N and 60°S.

Deep convection parameterization schemes

- Kuo：積雲対流による降水量を大規模な水蒸気フラックスの収束（全層積分値）に比例させている。凝結した際に出る熱による加熱は、あるプロファイルに従うと仮定している。簡単なスキームであるため、計算負荷は小さい。
- Tiedtke：積雲対流を大規模な水蒸気フラックスの収束（全層積分値）と境界層乱流に依存させている。具体的には、アップドラフトとダウンドラフトのプルームを考え、連続的にentrainmentやdetrainmentが起こる。アップドラフト中のentrainmentは、水蒸気の大規模収束が強い程、小さくなるようにしている。Detrainmentは起こらない。アップドラフト内で飽和し凝結した水が降水になる。ダウンドラフトは、雲底での質量フラックスの20%で、一定割合のentrainmentとdetrainmentが途中で起こる。
- Emanuel：有限個の空気塊の集合的な効果を考えている。具体的には、(i) 雲底の下から、ある任意の高度（雲底と浮力が中立になる高度の間）まで空気塊を持ち上げる。(ii) 飽和し凝結した水のある割合が降水になり、残りは雲水として残る。(iii) 周囲の空気との混合がある確率分布に基づいて起こる。(iv) 混合後、浮力が中立になる高度まで上昇／下降する。下降した場合は、detrainし、上昇した場合は、凝結した水が降水になった後、detrainする。また、降水が途中で蒸発することも許している。