Long-term impacts of ocean wave-dependent roughness on global climate systems by coupled atmospheric global climate-wave model

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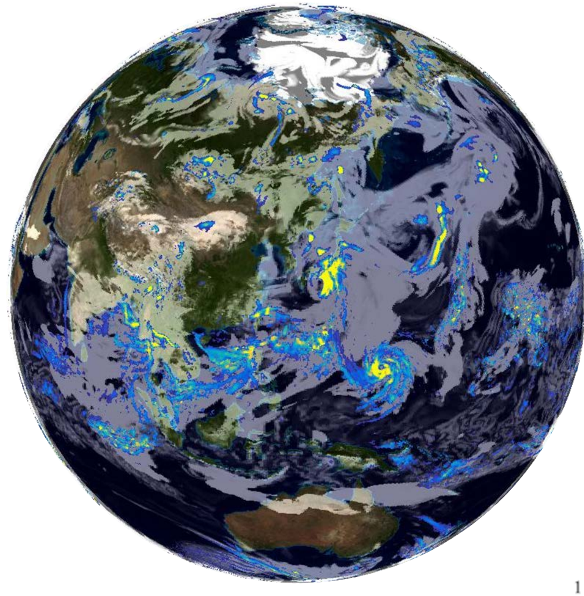
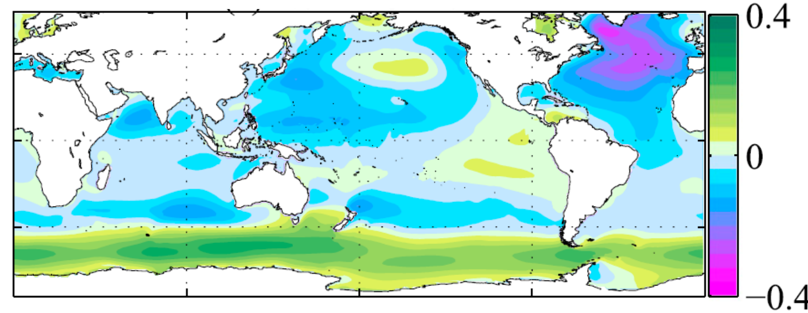
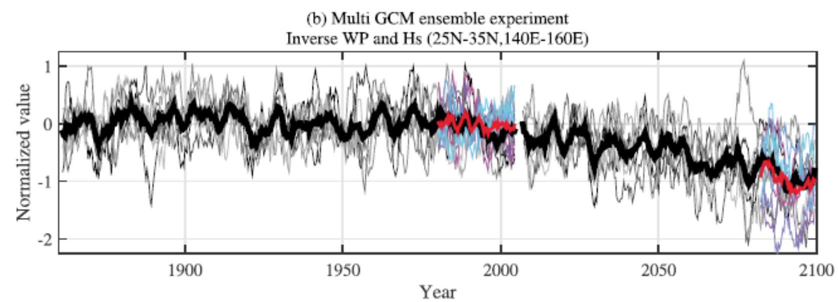
Climate change impacts on ocean wave climate (Mori et al. 2010, 2013; Shimura et al. 2015a, b , 2016a, b)

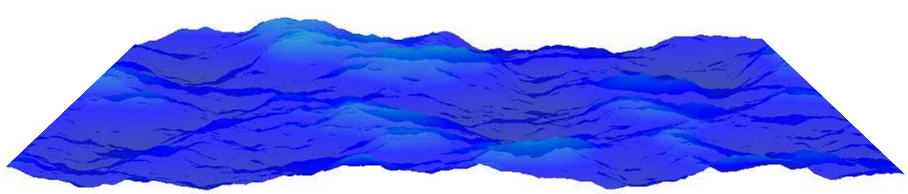
Atmospheric Global Climate Model MRI-AGCM

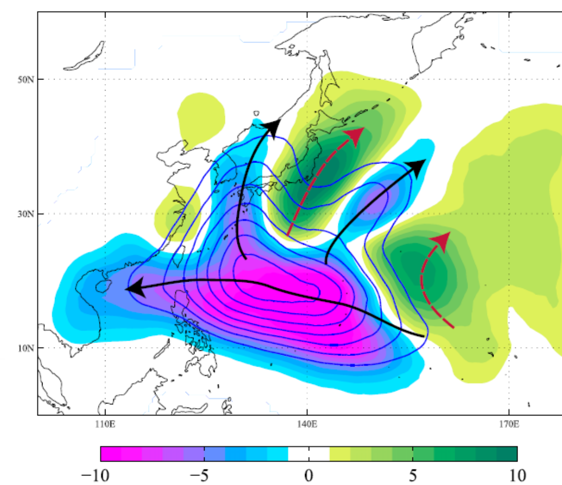






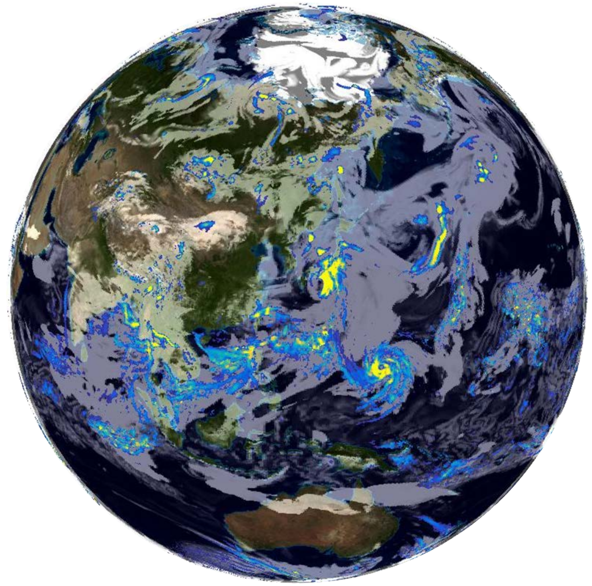
Wind (U_{10})





WAVEWATCH III

Atmospheric Global Climate Model MRI-AGCM



Bulk transfer relation

・Momentum

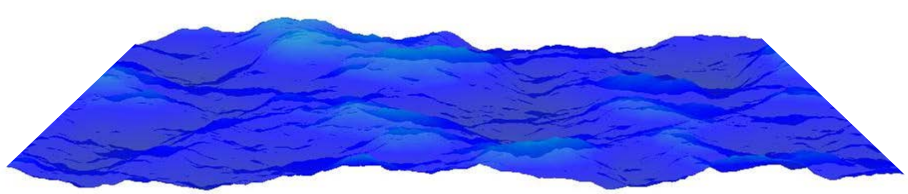
$$u_*^2 = \boldsymbol{C_m} U^2$$

・Heat

$$\overline{w'\theta} = \boldsymbol{C_h} |U| \left(\theta_a - \theta_g\right)$$

Wind (U_{10})

Roughness length (z_{0m})



Previous studies
- Weber et al., 1993
- Janssen and Viterbo, 1996
- Fan et al., 2012
- Charles and Hemer, 2013

WAVEWATCH III

Ocean Wave-Dependent Momentum Roughness Length

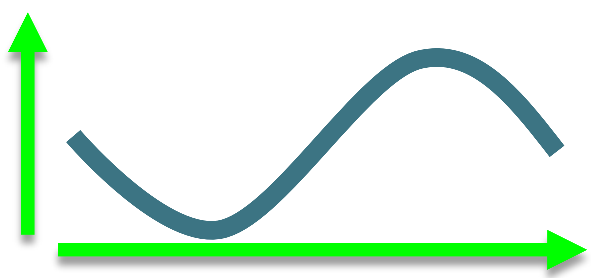
Wind speed dependent (Charnock relation)

$$z_0 = \boldsymbol{\alpha}\frac{u_*^2}{g}$$ ($\boldsymbol{\alpha}$: Charnock parameter)

Wave steepness dependent
(Taylor and Yelland, 2001)

$$\frac{z_{0m}}{H_s} = A_1\left(\frac{H_s}{L_p}\right)^{B_1}$$

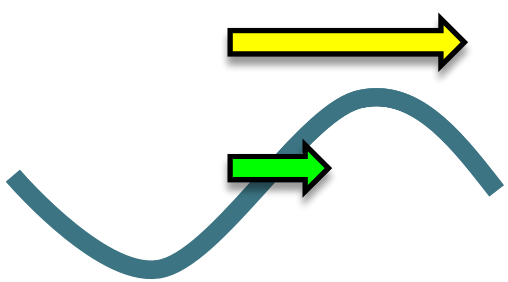
Hs: Significant wave height
Lp: Peak wave length



Wave age dependent
(Drennan et al., 2003)

$$\frac{z_{0m}}{H_s} = A_2\left(\frac{u_*}{c_p}\right)^{B_2}$$

Hs: Significant wave height
Cp: Wind-sea peak wave phase speed



Example of wave-coupled simulation

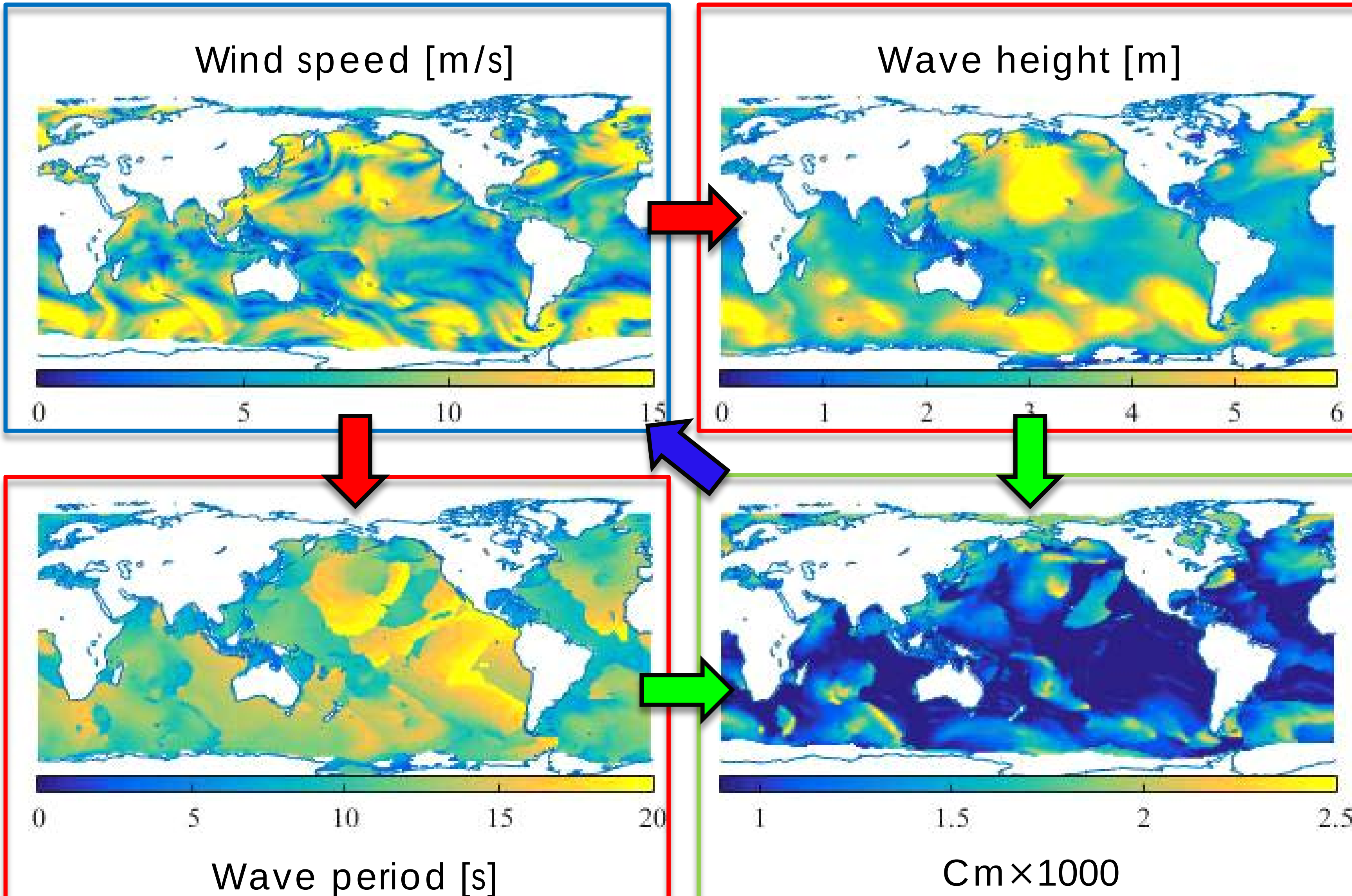
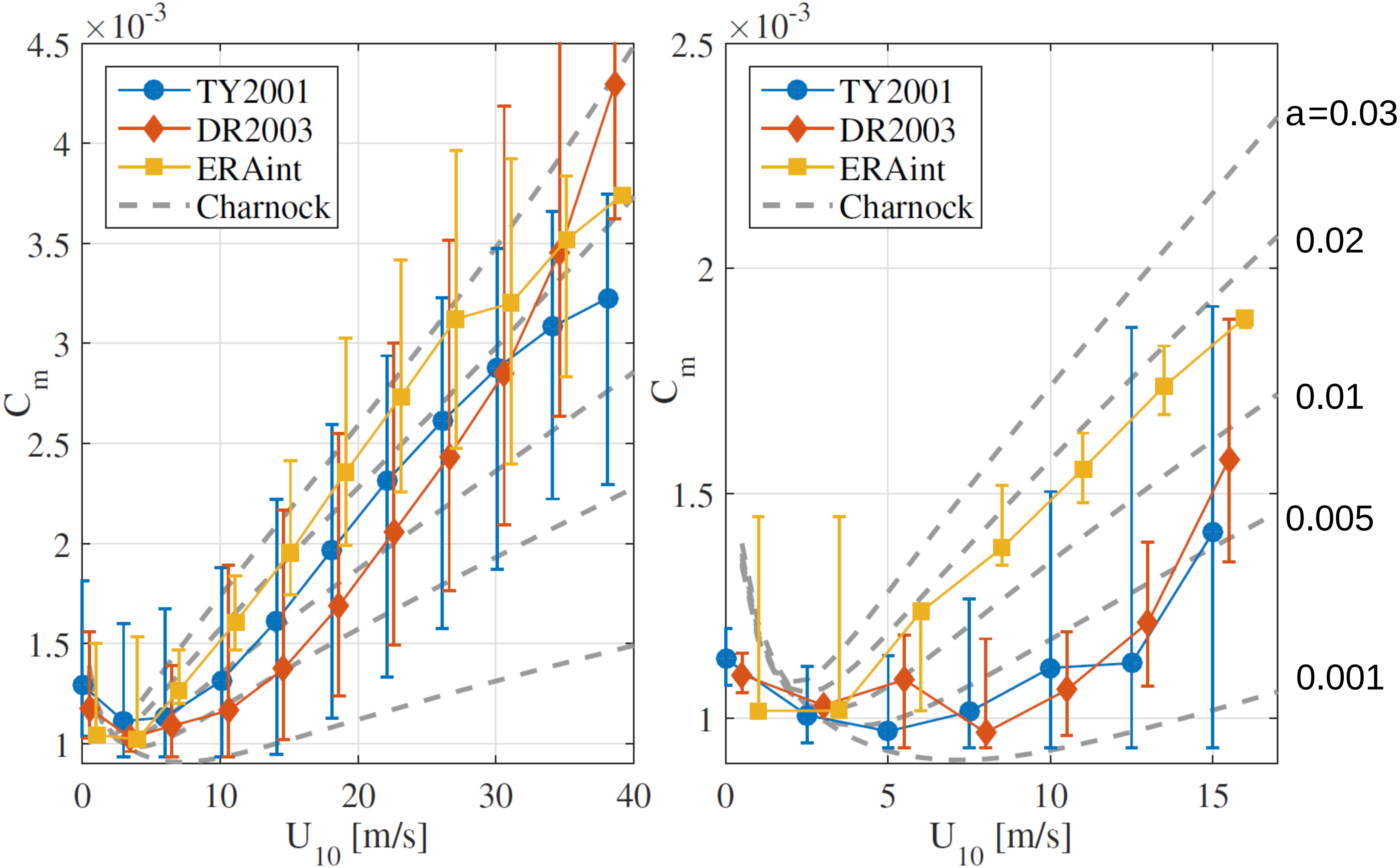


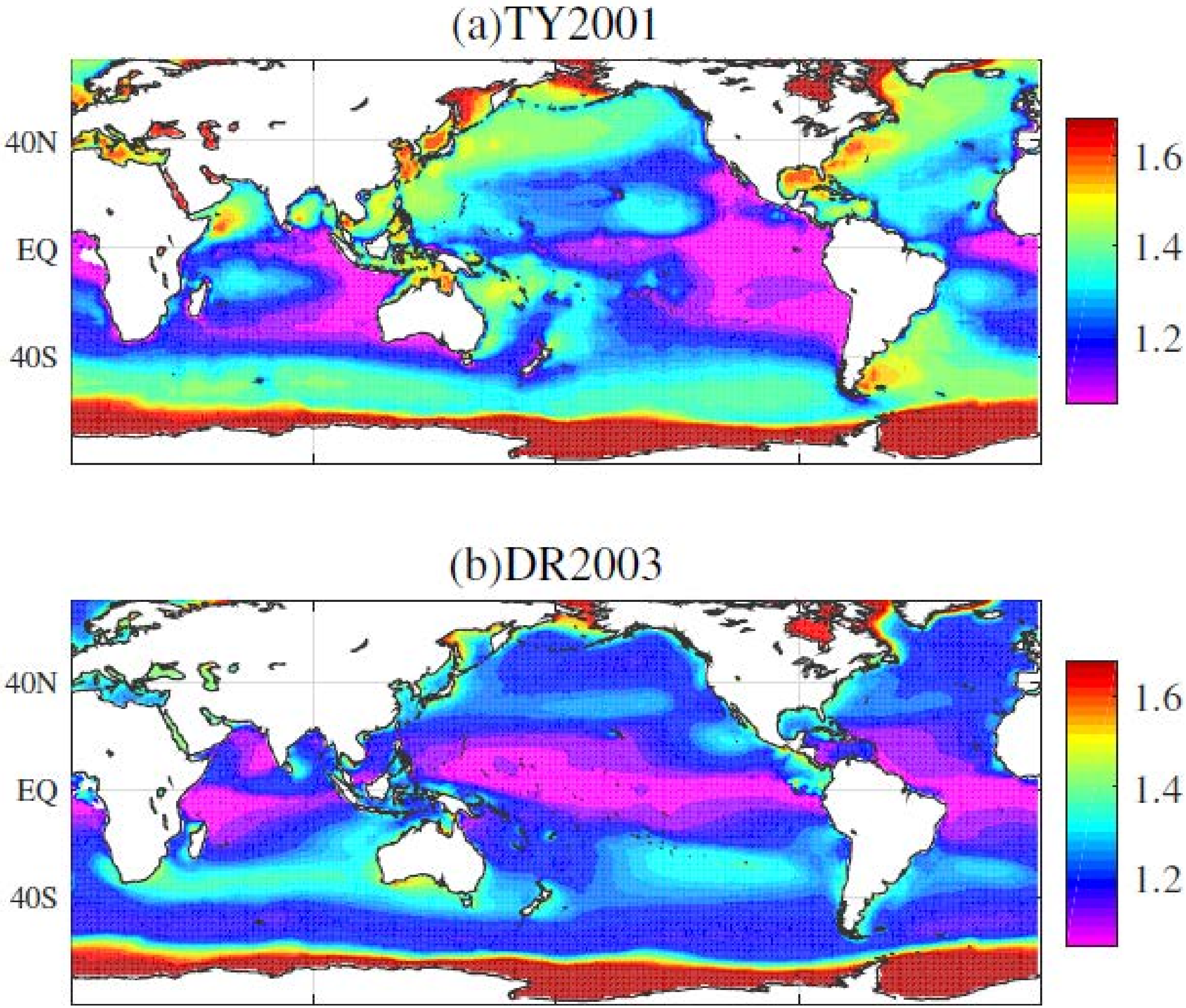
Table 1. Experiment description

Exp. name	Wave	Roughness	Time frame (Initial conditions)	Spatial resolution, GCM/WAVE
CHA0001		$\alpha = 0.001$		
CHA0005		$\alpha = 0.005$		
CHA001	No	$\alpha = 0.01$	1990-2014 (2)	1.125°/—
CHA002		$\alpha = 0.02$ (default value)		
CHA003		$\alpha = 0.03$		
TY2001	Yes	Taylor and Yelland (2001)	1990-2014 (2)	1.125° /1.25°
DR2003	Yes	Drennan et al. (2003)	1990-2014 (2)	1.125° /1.125°

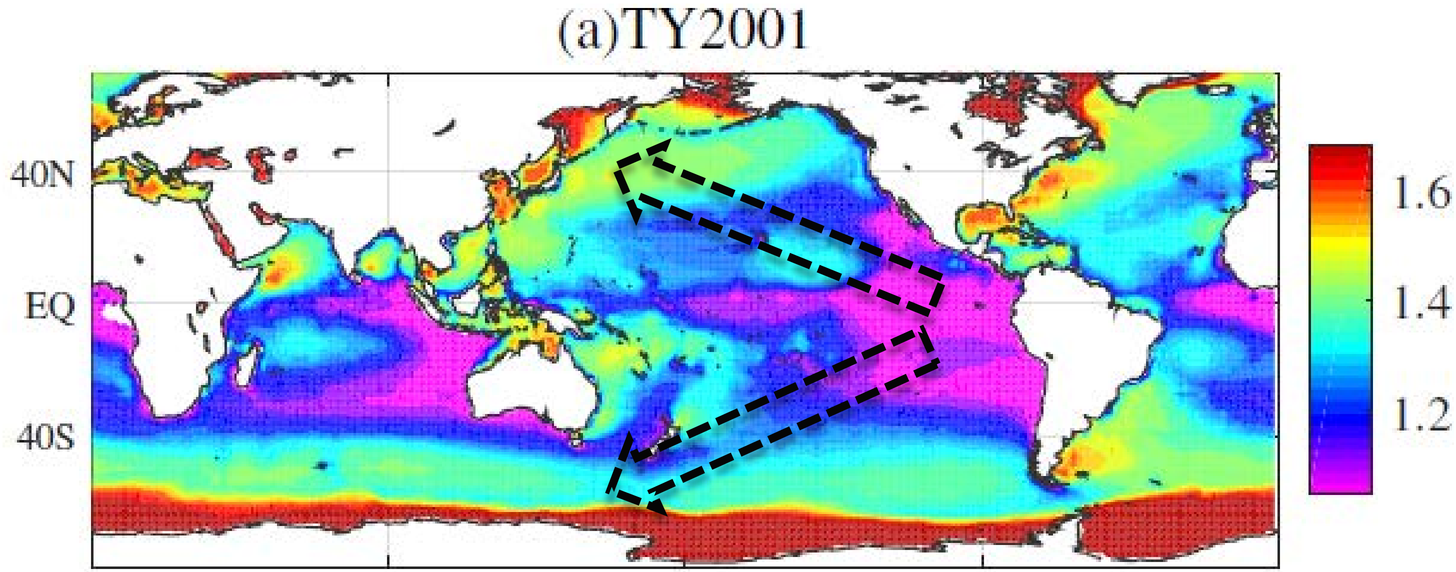


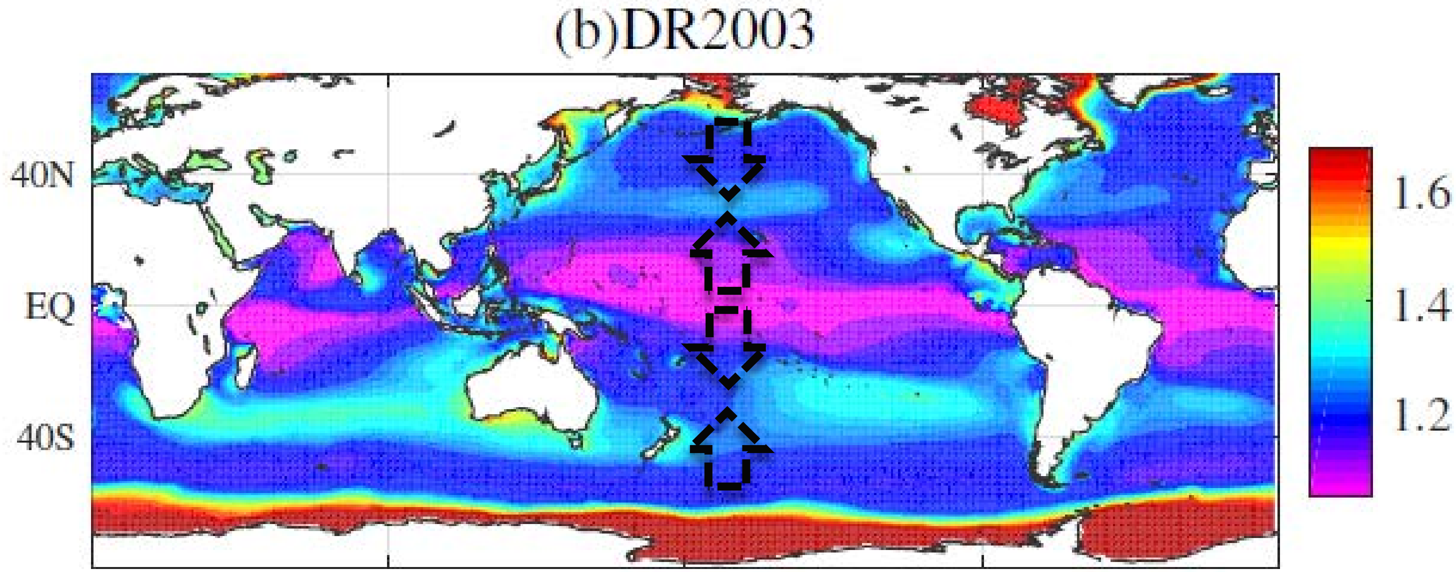
(a) Mid-high North Pacific (b) Equatorial Pacific

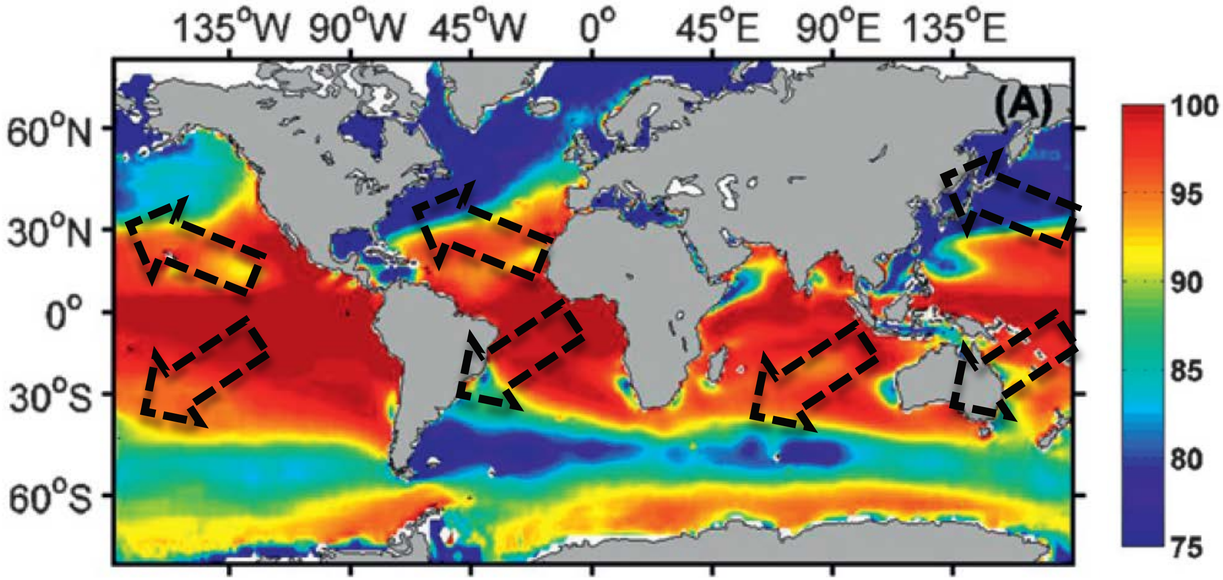
The spatial distribution of C_m climatology (wind speeds: 10 m/s)



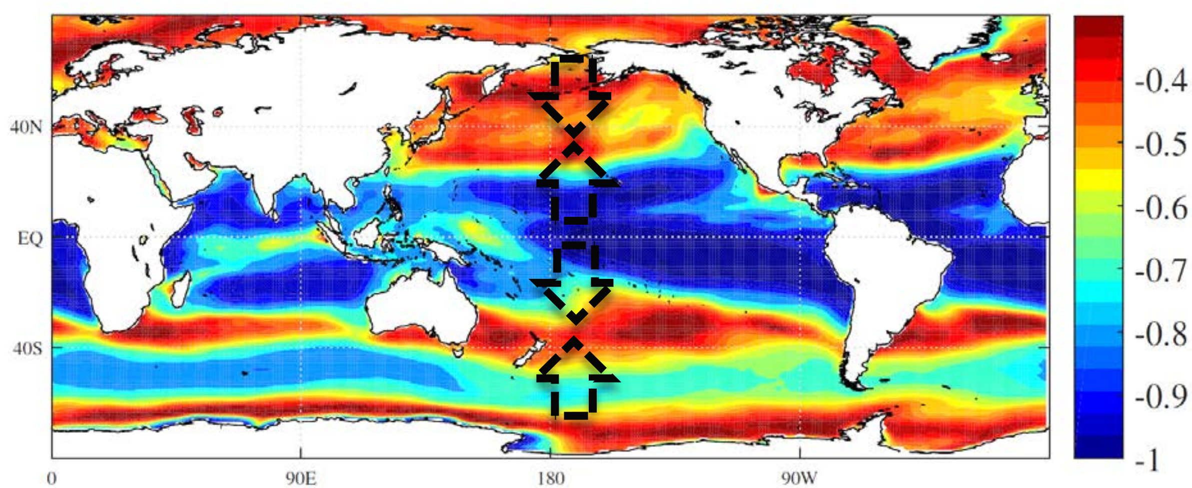
The spatial distribution of C_m climatology (wind speeds: 10 m/s)







Swell probability
Semedo et al.
(2011, J.clim)

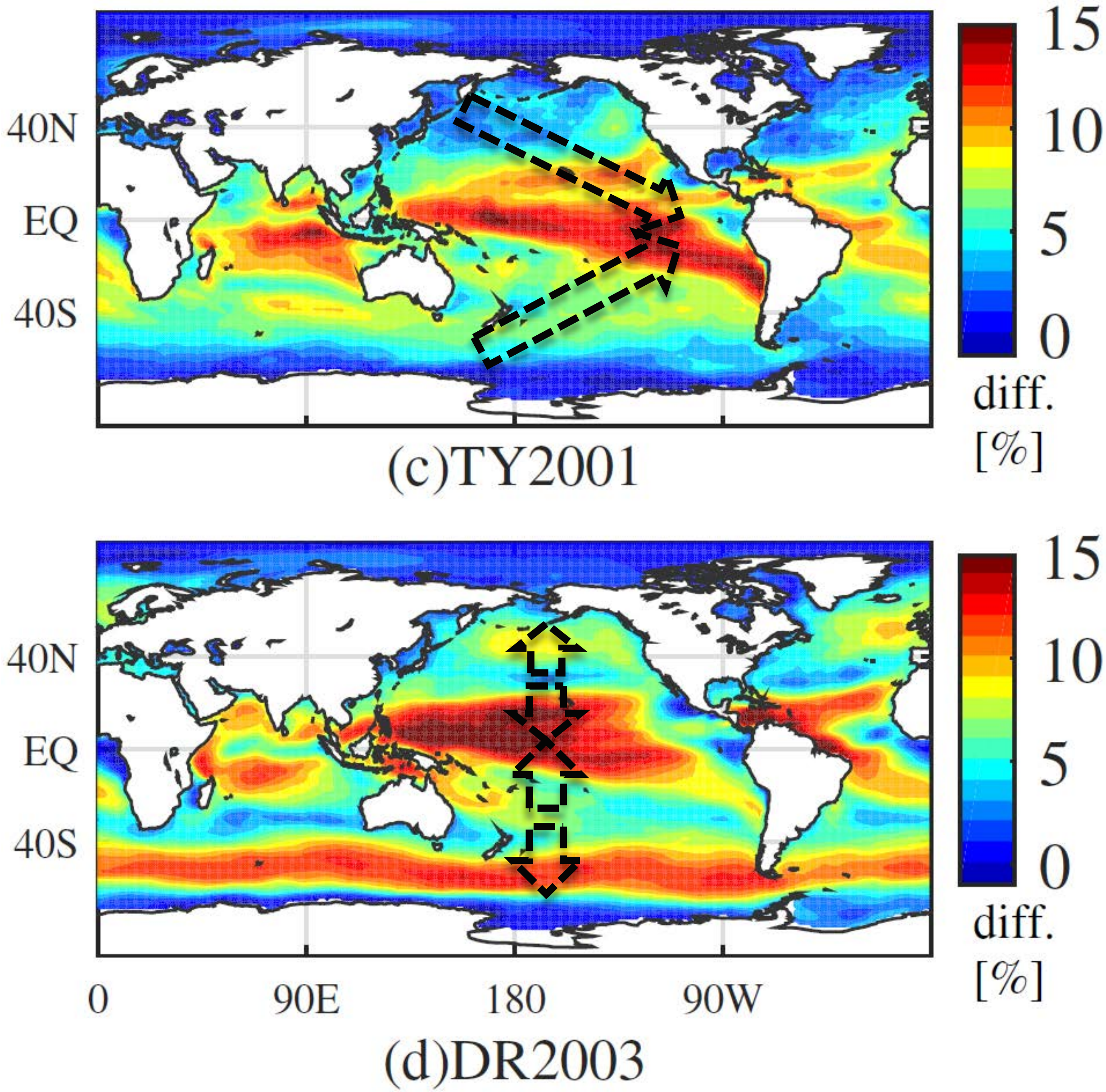


Wind direction stationarity

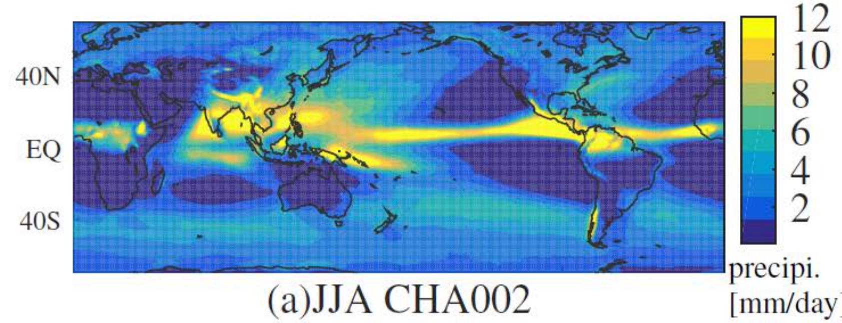
$$WDS_{ann} = \frac{1}{12}\sum_{month=1}^{12}\frac{\sqrt{\left(\sum^{n} u\right)^2 + \left(\sum^{n} v\right)^2}}{\sum^{n}\sqrt{u^2 + v^2}},$$

Figure 12. Wind direction stationarity (WDS_{ann}). Note that the value is multiplied by -1.

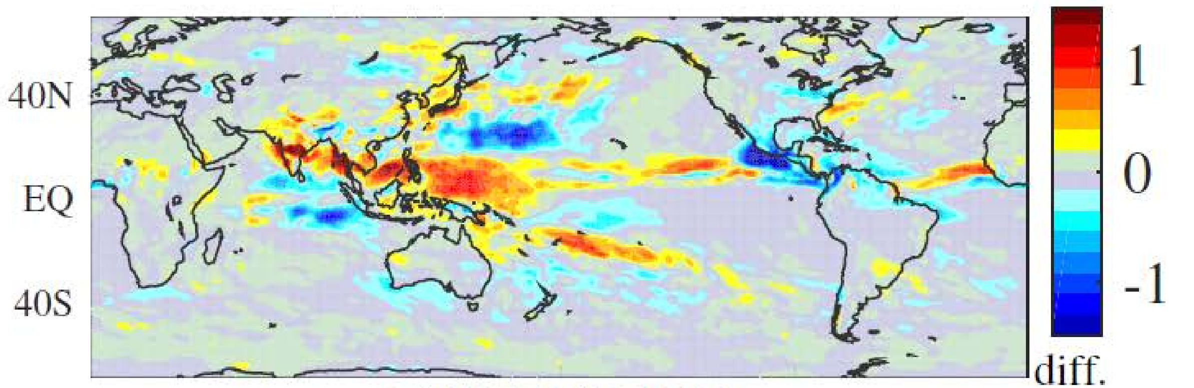
Sea surface wind speed climatology (diff. from CHA002)



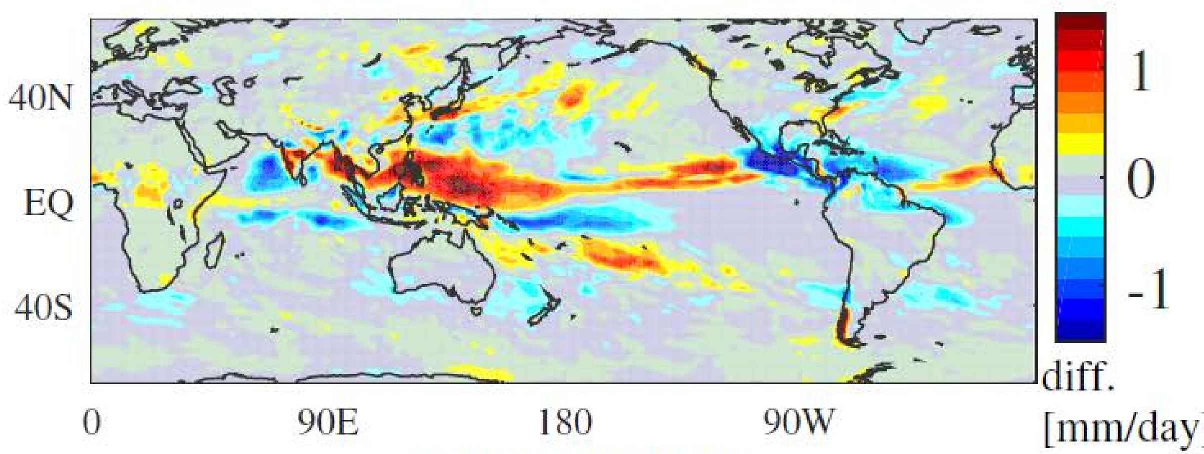
Precipitation climatology
JJA



(a)JJA CHA002



(c)JJA TY2001



(d)JJA DR2003

Precipitation and Haley circulation (JJA)

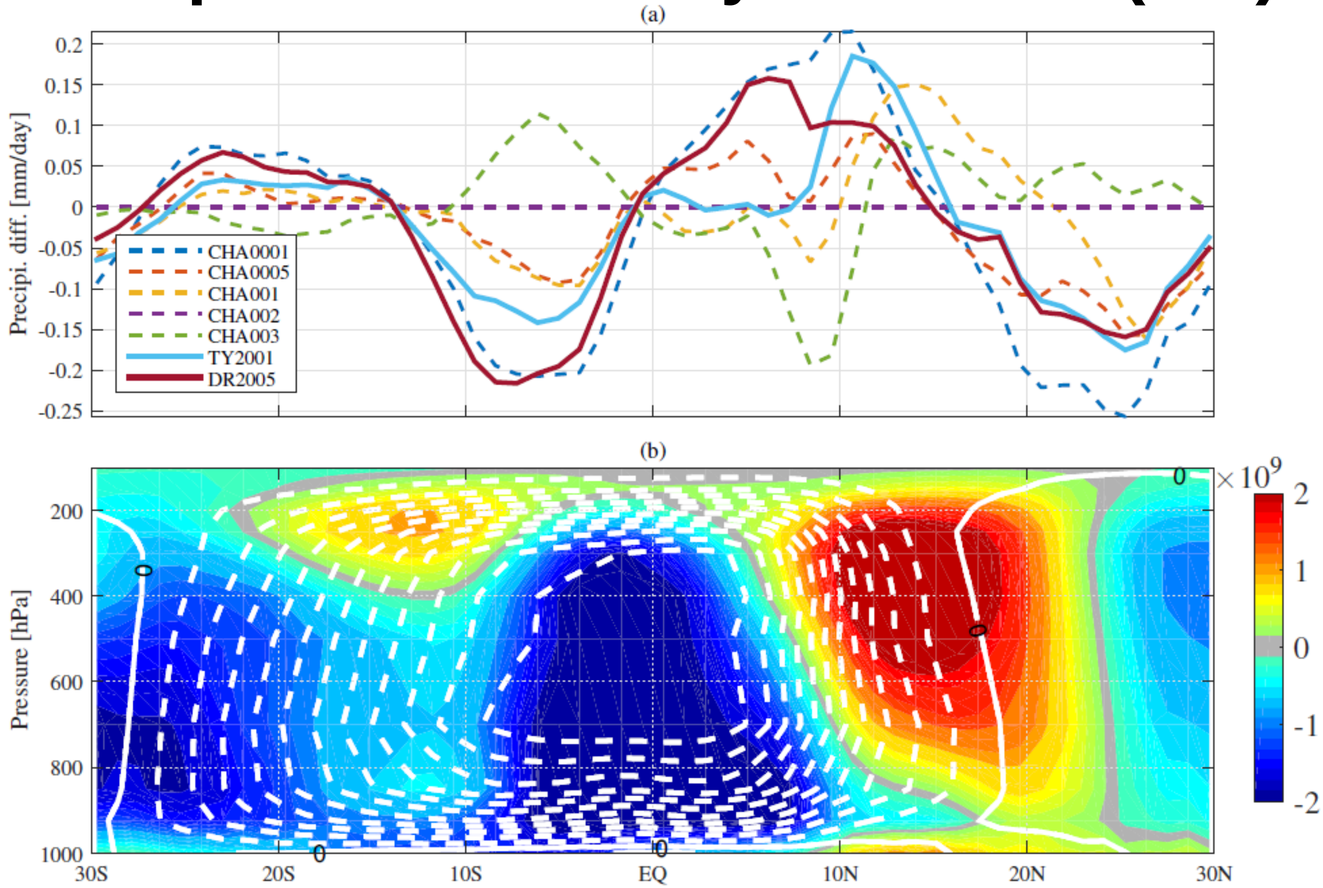


Figure 8. Panel (a): zonal mean precipitation climatology differences between all the experiments and CHA002 in JJA. Panel (b): Hadley circulation (mass stream functions) in JJA for CHA002 (white contour lines). Dashed contours indicate negative values, and solid contours indicate positive values. The contour interval is 2×10^{10} kg/s. The color shading shows the first EOF mode of the Hadley circulation among seven experiments indicating the representative difference among experiments.

EOF1 Percent variance: 87%

Sea surface wind, precipitation and Haley circulation

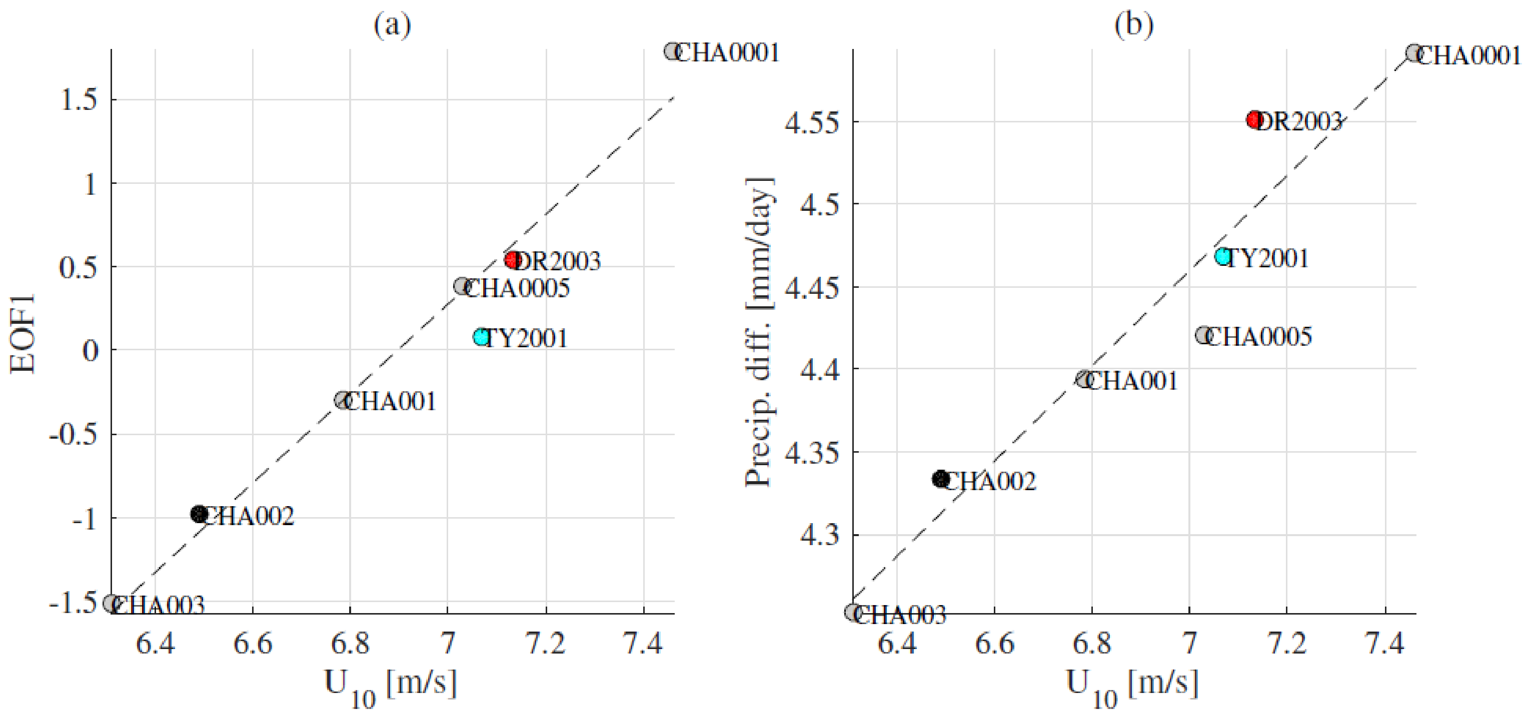


Figure 9. Panel (a): the relationship between U_{10} climatology at low latitudes and the Hadley circulation (represented by the coefficients of first EOF mode). Panel (b): the relationship between U_{10} climatology at low latitudes and the equatorial north-south differences in precipitation.

Precipitation and Haley circulation (DJF)

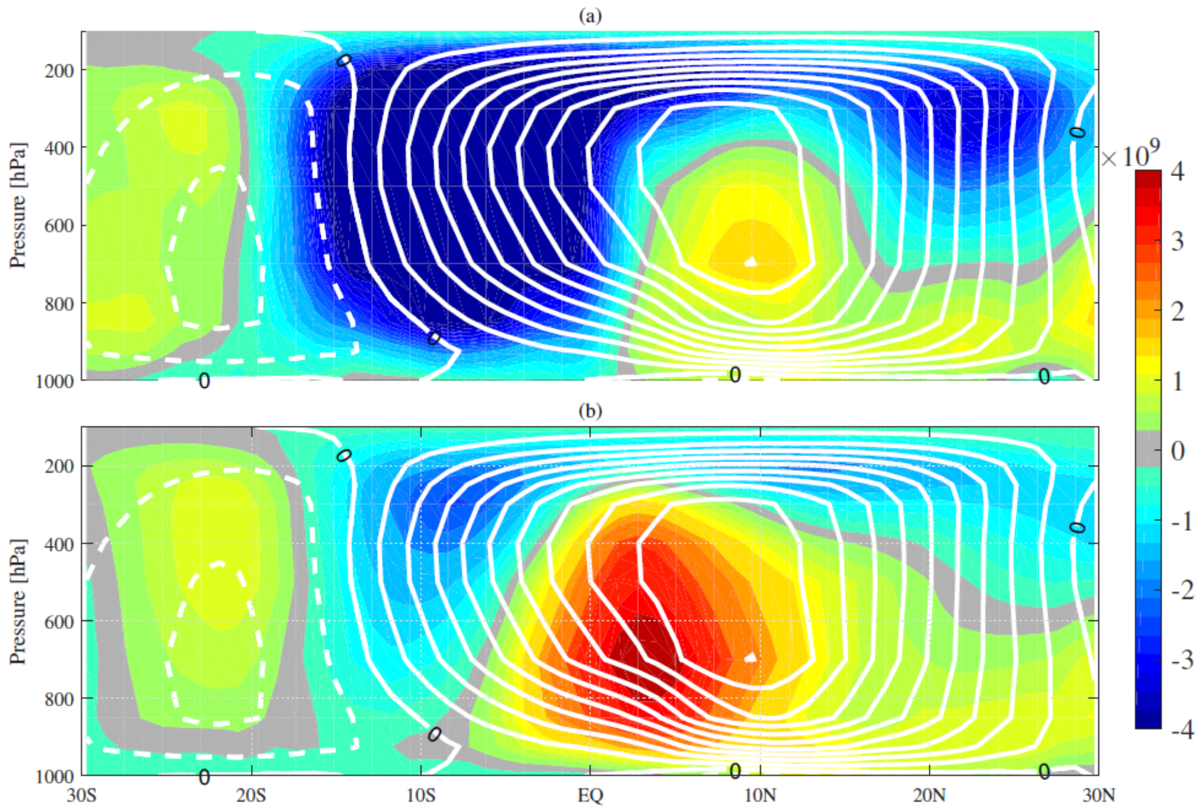


Figure 11. Panel (a): Hadley circulation (mass stream functions) in DJF for CHA002 (white contour lines). Dashed contours indicate negative values, and solid contours indicate positive values. The contour interval is 2×10^{10} kg/s; the color shading shows the difference between CHA002 and TY2001. Panel (b): the first EOF mode of the Hadley circulation among the six experiments excluding TY2001; this is the same as **Figure-8**(b), but for DJF.

DR2003
CHA0001
CHA0005
CHA001
CHA003

TY2001

Summary

- Global climate simulation using MRI-AGCM + WW3 coupled model (wave-dependent roughness)
- The spatial pattern of drag coefficient climatology
  - In wave steepness dependent roughness experiment
    - Swell dominance
  - Wave age dependent roughness experiment
    - wind direction stationarity
  - Wind climatology difference is 15% (lower latitudes)
- Impacts on precipitation (10~20%)
  - Hadley circulation
    - (JJA) The impacts of precipitation and Hadley circulation are similar between wave-coupled experiments and wind-dependent roughness experiment
    - (DJF) Impacts of wave steepness (swell) dependent roughness on atmospheric circulation is different when compared with wind or wave age (wind-sea) dependent roughness.

Paper) Shimura T., N. Mori, T. Takemi and R.Mizuta (2017) Journal of Geophysical Research-Oceans, 122, pp.1995-2011.

end

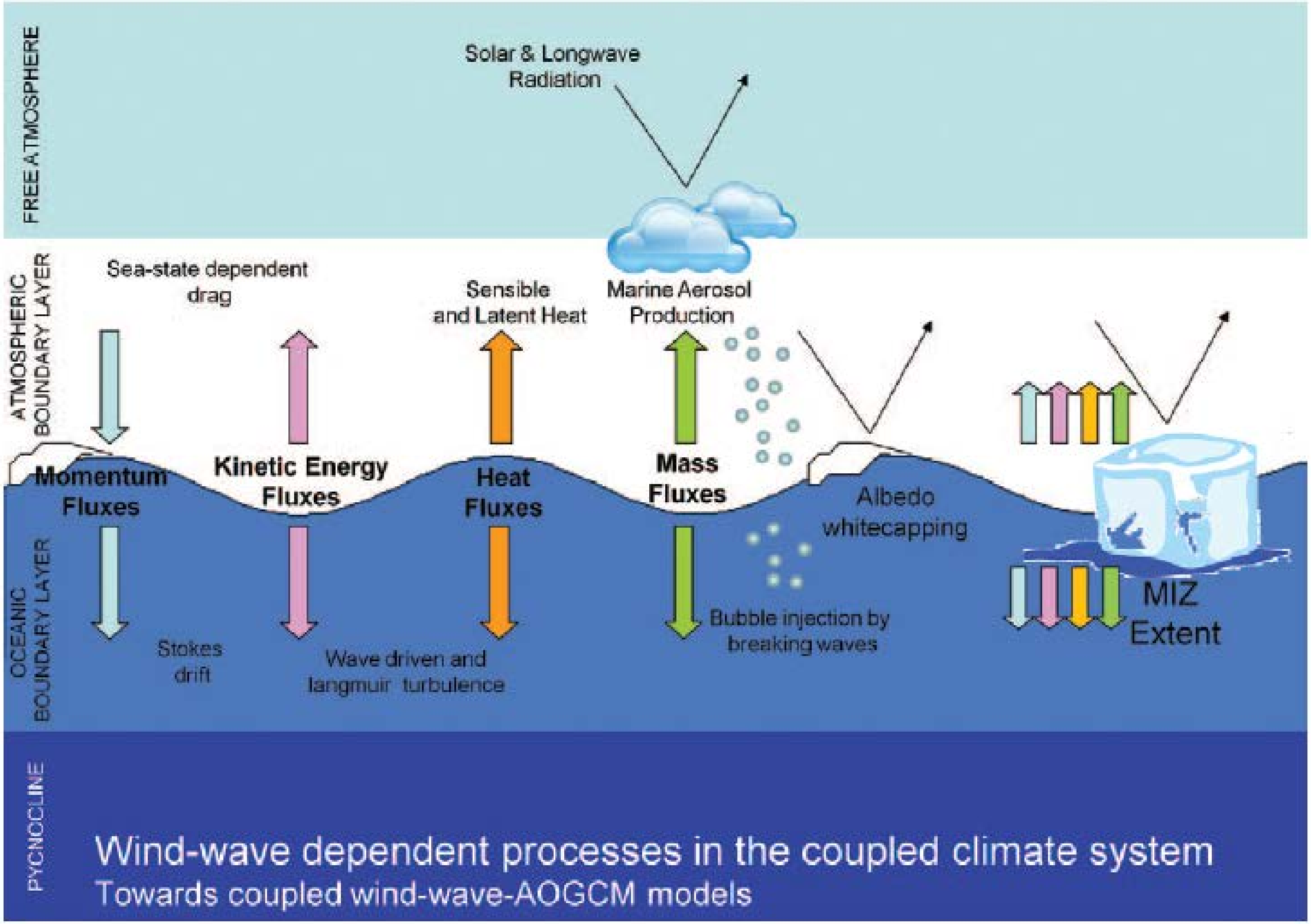


FIG. 1. A schematic view of the influence of waves on air–sea exchanges.

Cavaleri et al. (2012, BAMS)

Ocean wave dependent momentum roughness length

Wave steepness dependent
(Taylor and Yelland, 2001)

$$\frac{z_{0m}}{H_s} = A_1 \left(\frac{H_s}{L_p}\right)^{B_1}$$

Hs: Significant wave height
Lp: Peak wave length
A1=1200, B1=4.5

Wave age dependent
(Drennan et al., 2003)

$$\frac{z_{0m}}{H_s} = A_2 \left(\frac{u_*}{c_p}\right)^{B_2}$$

Hs: Significant wave height
Cp: Wind-sea peak wave phase speed
A2=3.35, B2=3.4

- Toba3/2law

$$\frac{gH_s^{eq}}{u_*^2} = \alpha_t \left(\frac{gT_s^{eq}}{u_*}\right)^{3/2}$$

- Deviation from equilibrium

$$H_s = a_h H_s^{eq}$$

$$L_p = a_l L_p^{eq}$$

- Significant period -> peak

$$T_p^{eq} = C_t T_s^{eq}$$

- Deep water condition

$$z_{0m} = A_1 (2\pi)^{\frac{B_1+3}{2}} C_t^{\frac{3(B1+1)}{2}} \alpha_t^{B_1+1} \frac{a_h^{B_1+1}}{a_l^{B_1}} \left(\frac{u_*}{c_p^{eq}}\right)^{\frac{B_1-3}{2}} \cdot \frac{u_*^2}{g} = \alpha_{ty2001} \cdot \frac{u_*^2}{g}$$

$$z_{0m} = A_2 (2\pi)^{3/2} C_t^{3/2} \alpha_t a_h \left(\frac{u_*}{c_p^{eq}}\right)^{B_2-3/2} \cdot \frac{u_*^2}{g} = \alpha_{dr2003} \cdot \frac{u_*^2}{g}$$

$$\alpha_{ty2001} = 0.177 \frac{a_h^{5.5}}{a_l^{4.5}} \left(\frac{u_*}{c_p^{eq}}\right)^{0.75} \qquad \alpha_{dr2003} = 3.029 a_h \left(\frac{u_*}{c_p^{eq}}\right)^{1.9}$$

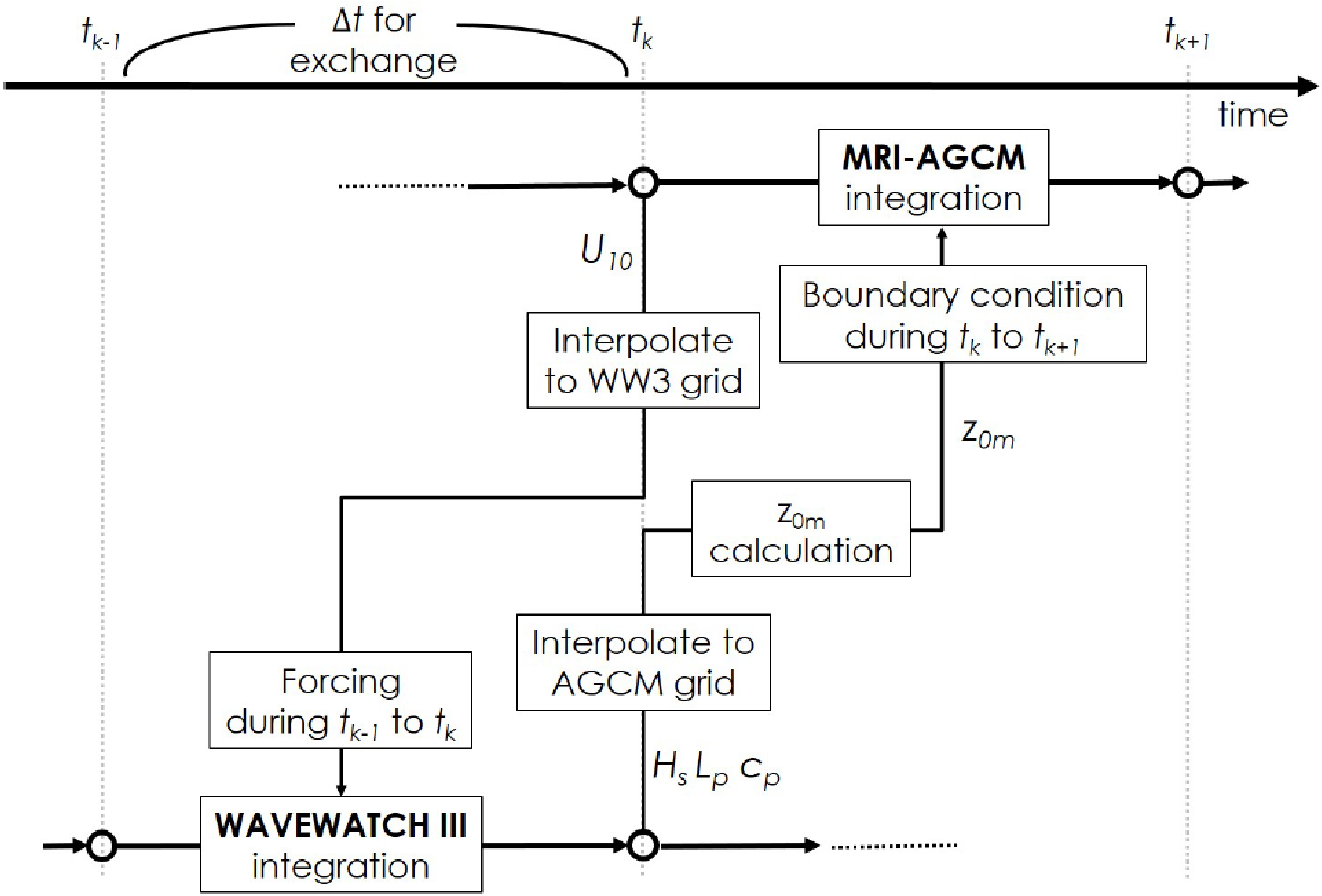
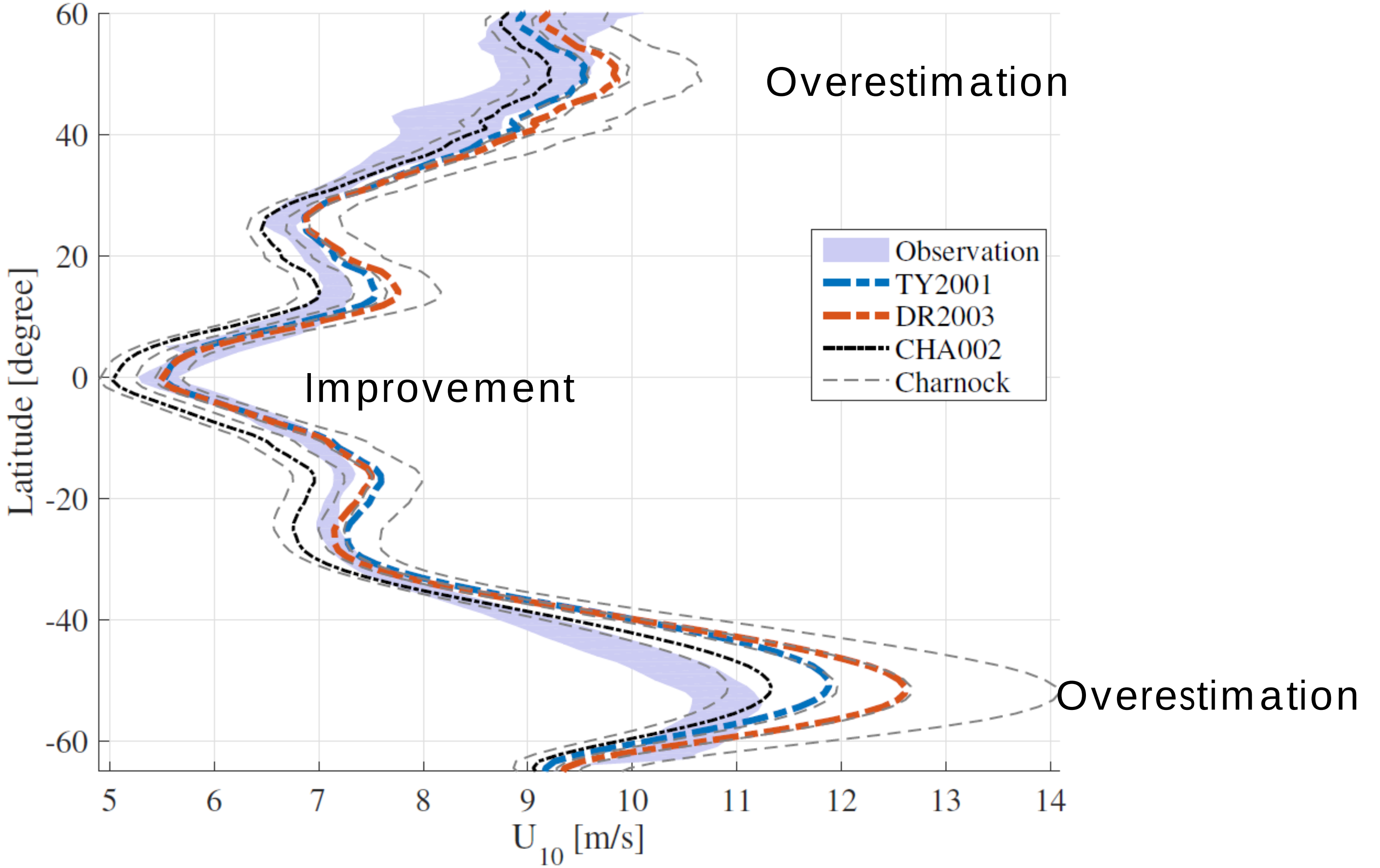


Figure 1. Schematic view of the coupling between MRI-AGCM and WAVEWATCH III.

Sea surface wind speed climatology
Comparison with satellite-based observations



Shimura et al. (2017)

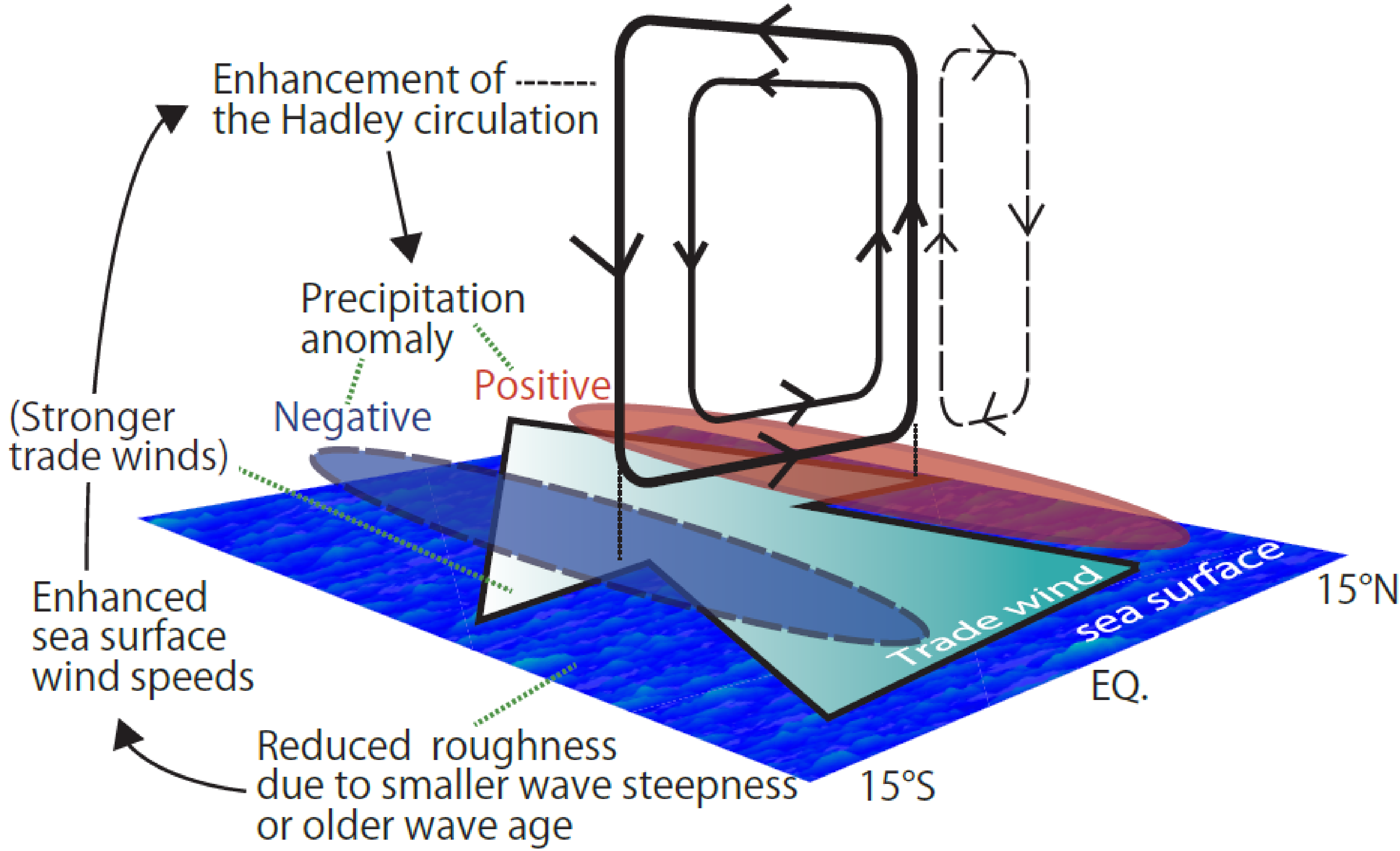


Figure 10. Overview of the atmospheric circulation responses to wave-dependent roughness in the boreal summer.