# Parameterization of a wave-dependent surface roughness: a step towards a fully coupled atmosphere-ocean-sea ice-wave system

**Elodie CHARLES  and Mark HEMER**

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WEALTH FROM OCEANS FLAGSHIP | CLIMATE & ATMOSPHERE THEME

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**Centre for Australian Weather and Climate Research**
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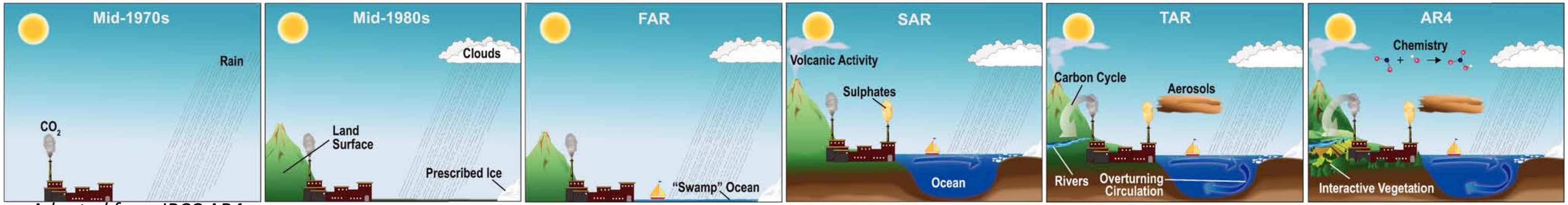
# Motivation

Basic science

Climate change

Development of Global Climate Models

Global Climate Models are getting higher degrees of details (Atmosphere GCM, Ocean GCM, Land surface, Sea Ice, Carbon cycle, Aerosols, Clouds...)

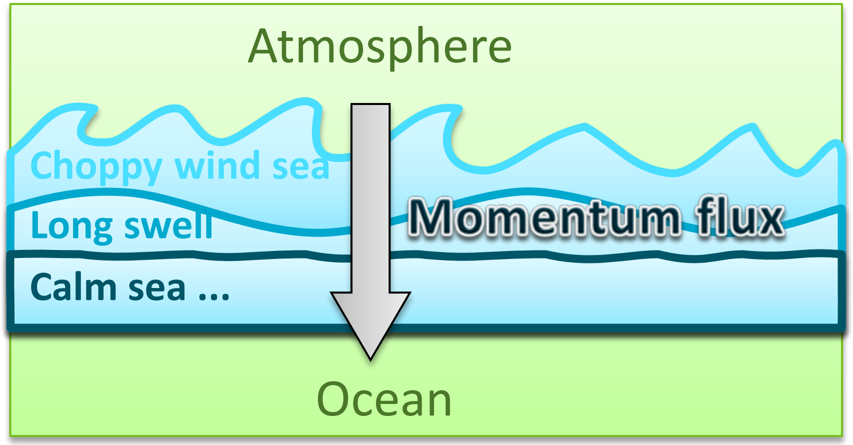


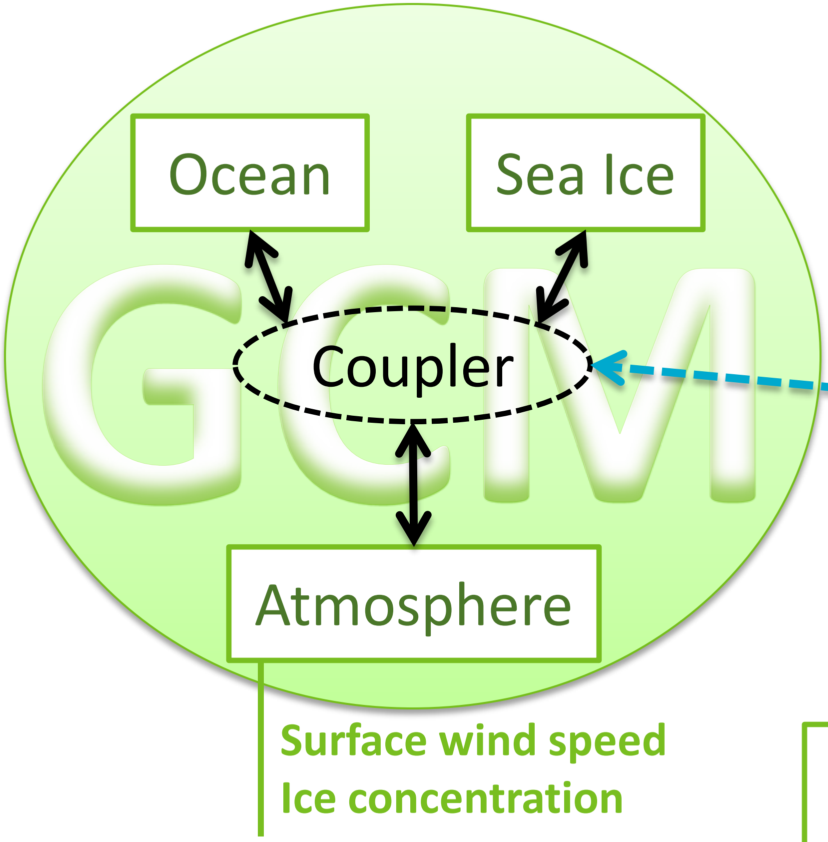
*Adapted from IPCC AR4*

**Wind-Waves** interact with main climate components and have an active role on momentum, heat, mass and energy fluxes

*Sullivan and McWilliams 2010, Cavaleri et al. 2012, Babanin et al. 2012*

# Methodology





Short term simulations (9 years) are run with 3 different wave-dependent roughness parameterizations and a control one

# Conclusions

- Preliminary results show that the roughness parameterization induces large differences in the atmospheric boundary layer and wave conditions:

| /Control | Z0m | MFlux | U10 | Hs |
|---|---|---|---|---|
| SCOR | ↘ | — | ↗ | ↗ |
| T&Y | ↗ | ↗ | ↘ | ↘ |
| Drennan | ↘ | ↘ | ↗ | ↗ |

❖ No agreement

❖ Is it significant ?
(9-year simulations)

❖ Which one is the best?

# Future work

- Running long-term simulations (100+ years) with present-day conditions
- Comparing the results with present-day climatology

# Scientific question

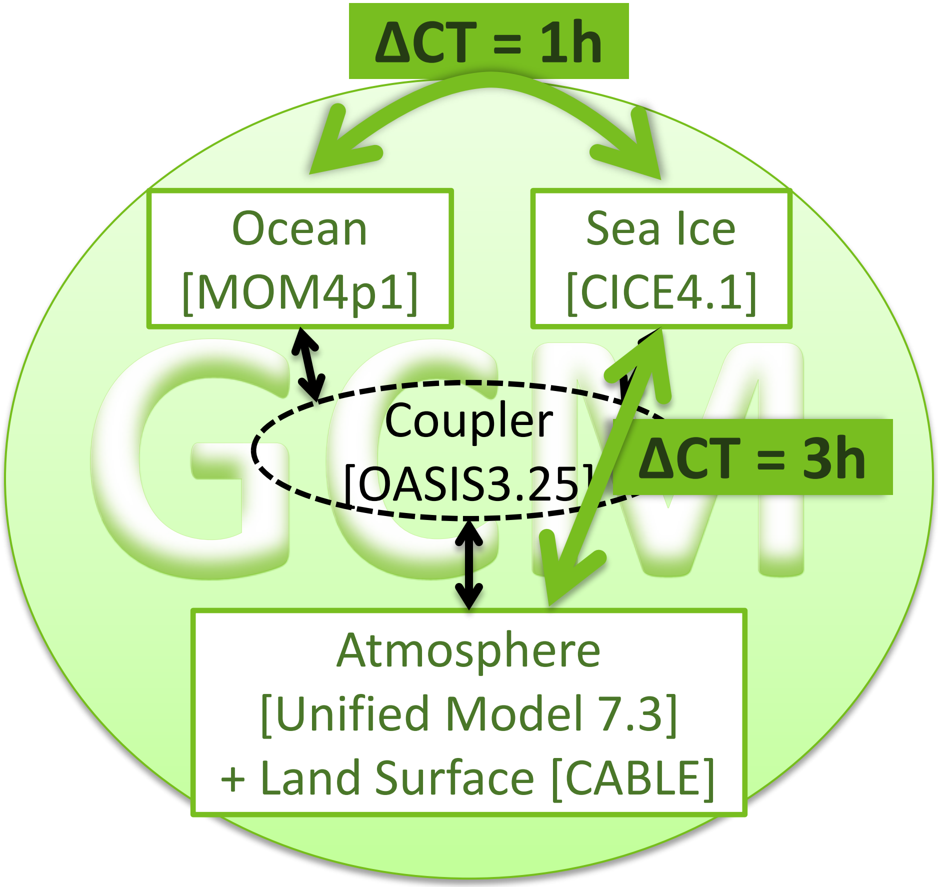
Does the adding of wave physics in a climate coupled system induce changes on long-term projections ?

# Outline

- Description of the coupling
- Roughness parameterization
- Short simulation design and results

# Existing coupled climate model ACCESS-CM

ACCESS = Australian Community Climate and Earth System Simulator



ΔCT = 1h

Ocean
[MOM4p1]

Sea Ice
[CICE4.1]

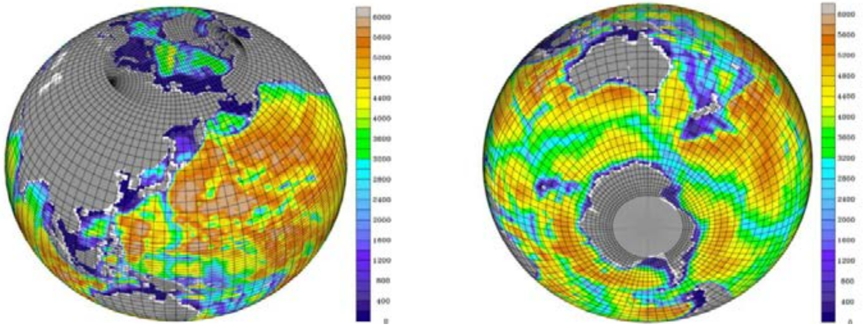
GCM

Coupler
[OASIS3.25]

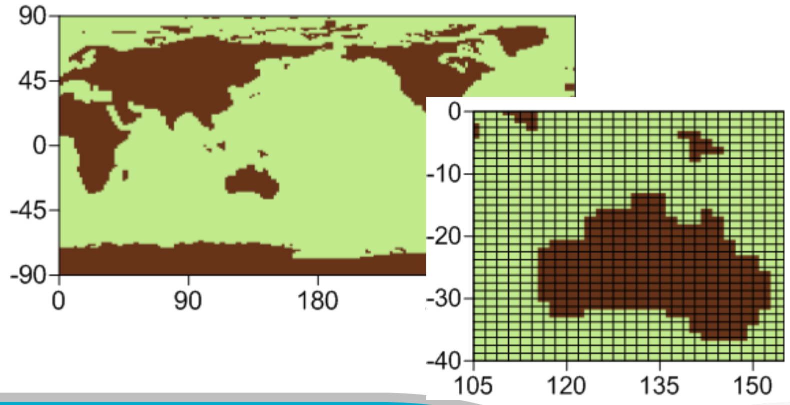
ΔCT = 3h

Atmosphere
[Unified Model 7.3]
+ Land Surface [CABLE]

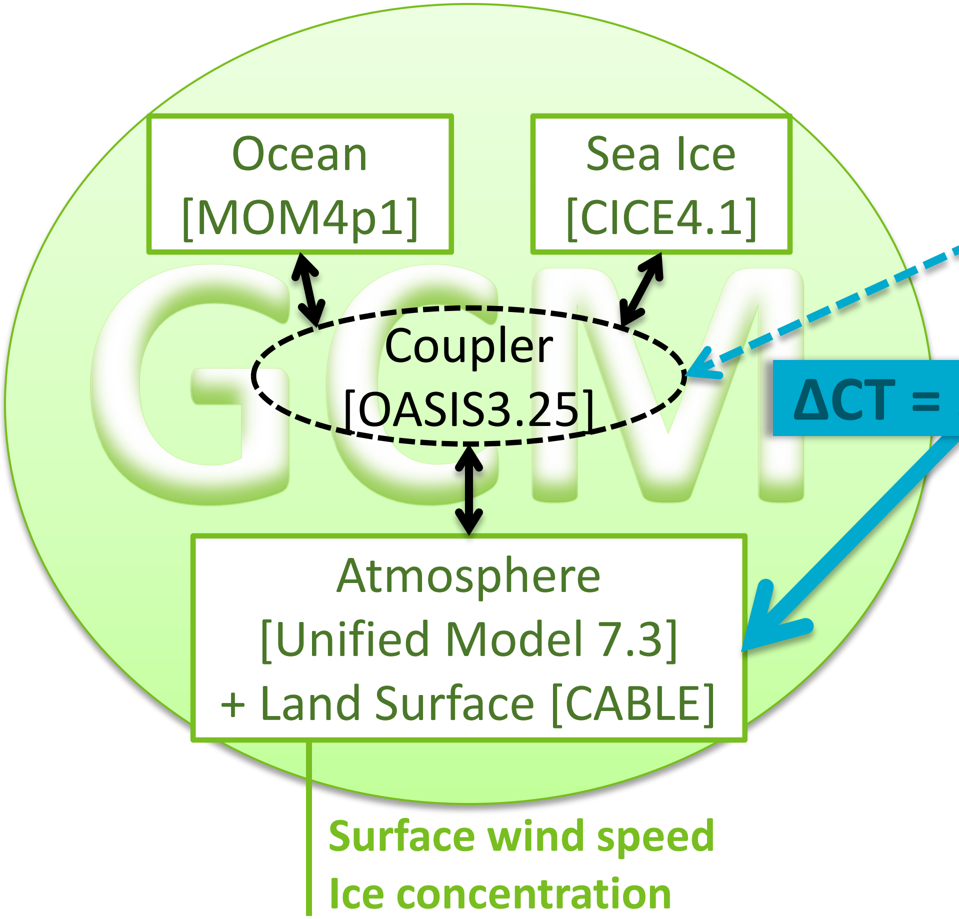
Tripolar grid: 20 to 110 km



Regular lat-lon grid:
1.875° long x 1.25° lat (nx= 192/ ny=144)



# Adding of the Wavewatch III wave model



GCM

Ocean
[MOM4p1]

Sea Ice
[CICE4.1]

Coupler
[OASIS3.25]

Atmosphere
[Unified Model 7.3]
+ Land Surface [CABLE]

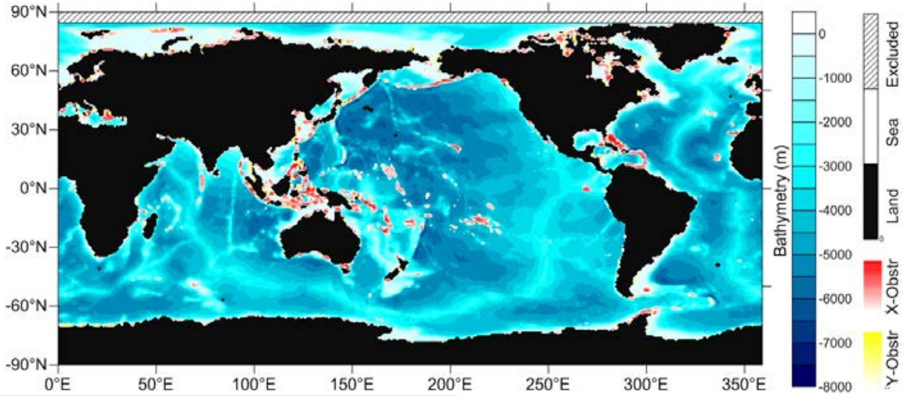
**Surface wind speed**
**Ice concentration**

**ΔCT = 30 min**

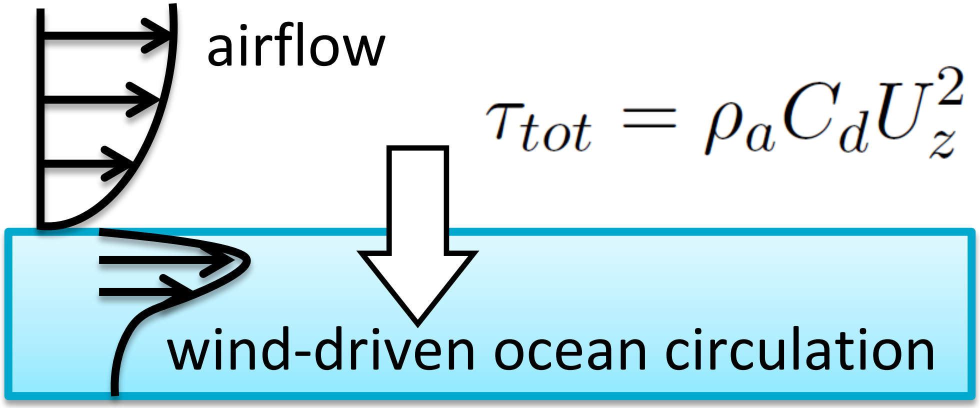
Wind-Waves
[WAVEWATCH III]

**Sea surface roughness**

Regular lat-lon grid (mask ≥85°N ; land ≥79°S)
ΔX=ΔY=1°;Nθ=24; Nfreq=32; ΔT=1800 sec



# Momentum roughness length in the AGCM



$$\tau_{tot} = \rho_a C_d U_z^2$$

Drag coefficient: $C_d = \left(\frac{u_*}{U_z}\right)^2 = \left(\frac{\kappa}{\Phi_m(L, z + z_{0_m}, z_{0_m})}\right)^2$

Momentum roughness length: $$z_{0_m} = \underbrace{\frac{0.11\nu}{u_*}}_{\text{Viscous term (in light winds and calm sea)}} + \underbrace{\frac{\alpha}{g} u_*^2}_{\text{Wave term (in stronger winds, most of the stress is supported by the wave-induced stress)}}$$

Charnock: $0.01 < \alpha < 0.02$

# A multitude of parameterizations of $z_{0wave}$

$$z_{0_m} = \frac{0.11\nu}{u_*} + z_{0_{wave}}$$

We test 4 different parameterizations of $Z_{0wave}$:

- CONTROL: variable Charnock, used in CMIP5 runs
- SCOR (Jones and Toba 2001), wave age dependent
- Taylor and Yelland (2001), wave steepness dependent
- Drennan et al. (2003), wave age and height dependent

Wave age: $\beta = C_p / u_*$

Wave steepness: $s = H_s / L_p$

Note: surface heat fluxes depend on $z_{0m}$ and hence depend on $z_{0wave}$

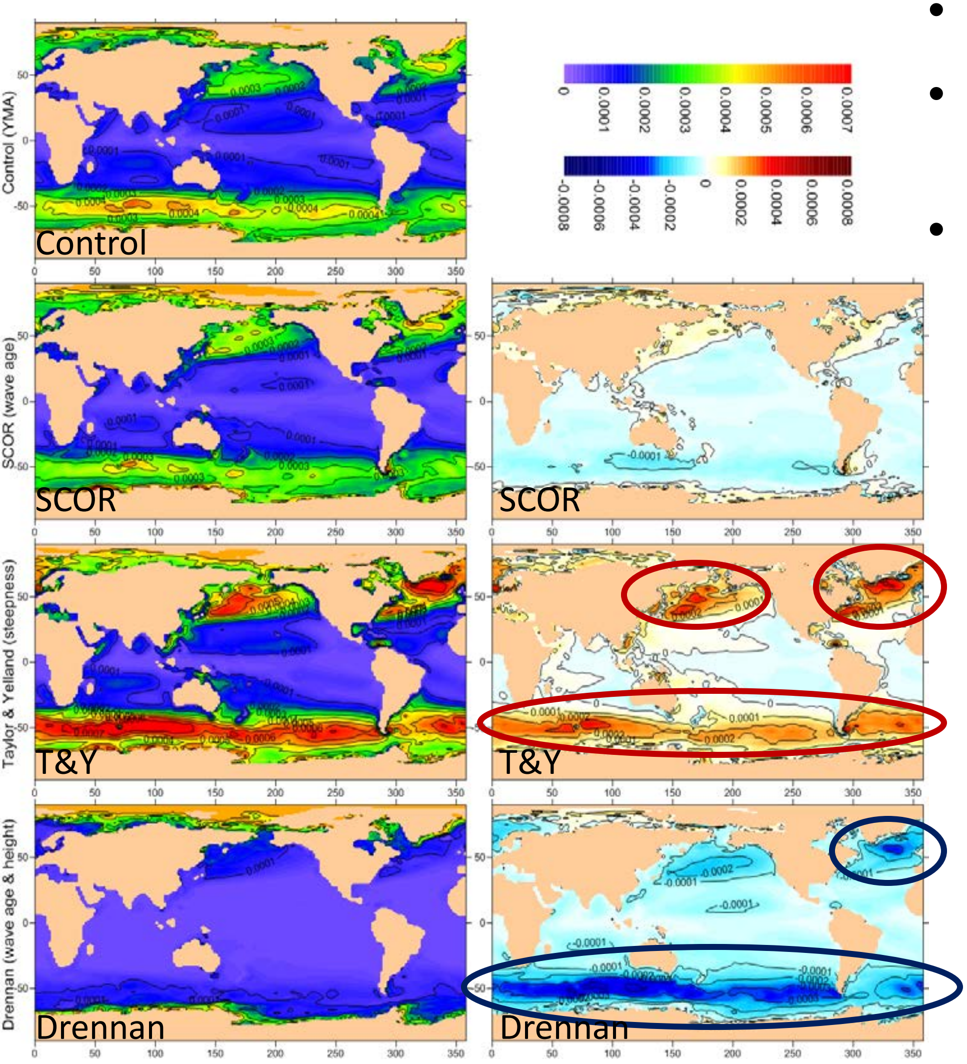
# Short simulations: details and limits

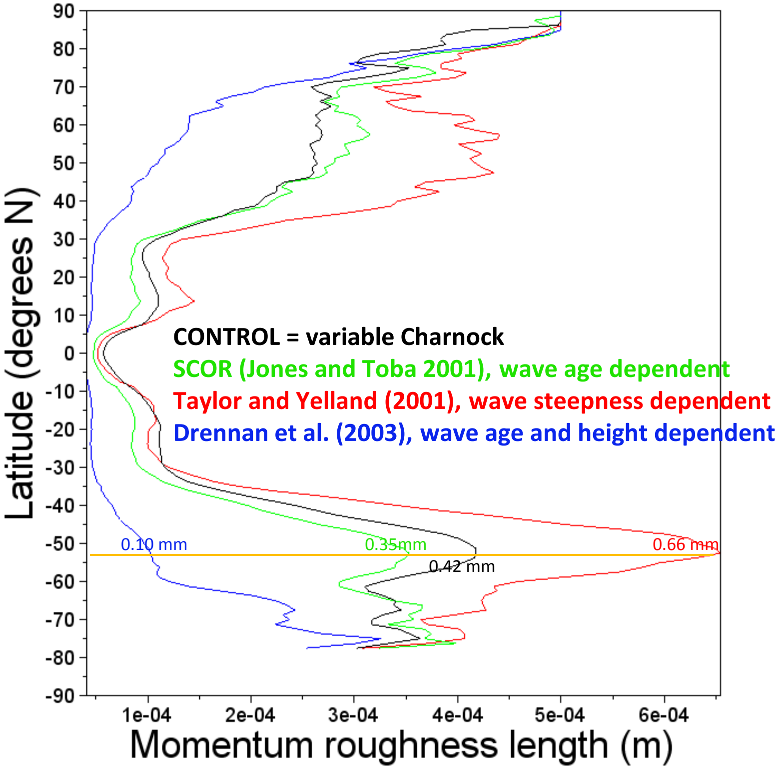
- Simulations with the ACCESS+WW3 system were carried out from January 0001 to August 0010
- System is initialized with pre-industrial conditions (1850)
- The GHG and aerosols rates are based on pre-industrial levels (1850) and kept constant throughout the simulation
- The first 6 months are removed for the “spin-up”*
- Statistics of atmospheric and wave parameters are calculated on a 9-year period*

* Usually for this kind of simulation, the spin-up and following run cover hundreds of years

# Momentum roughness length z0m (m)

- SCOR: light decrease compared to control
- T&Y: increase in NW Atlantic and Pacific, Southern Ocean (=wind generation zones)
- Drennan: large decrease in the Southern Ocean

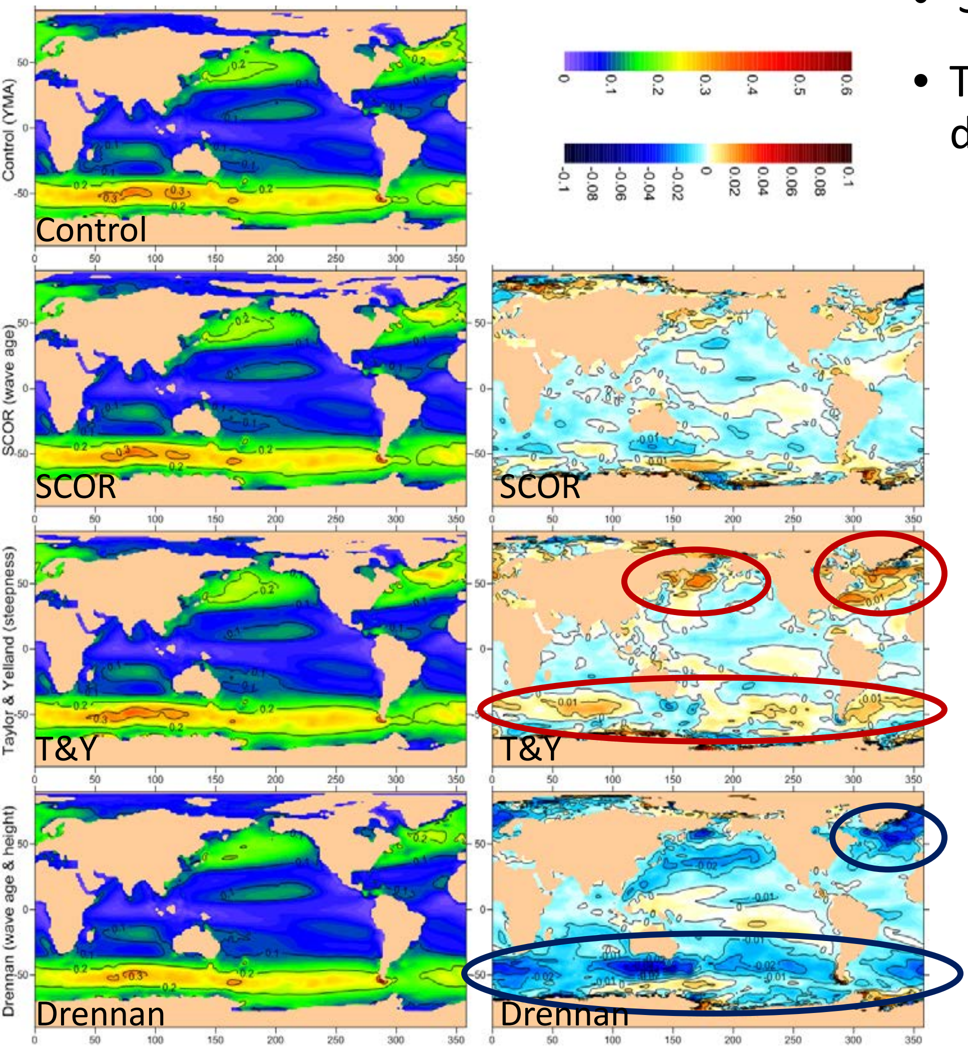


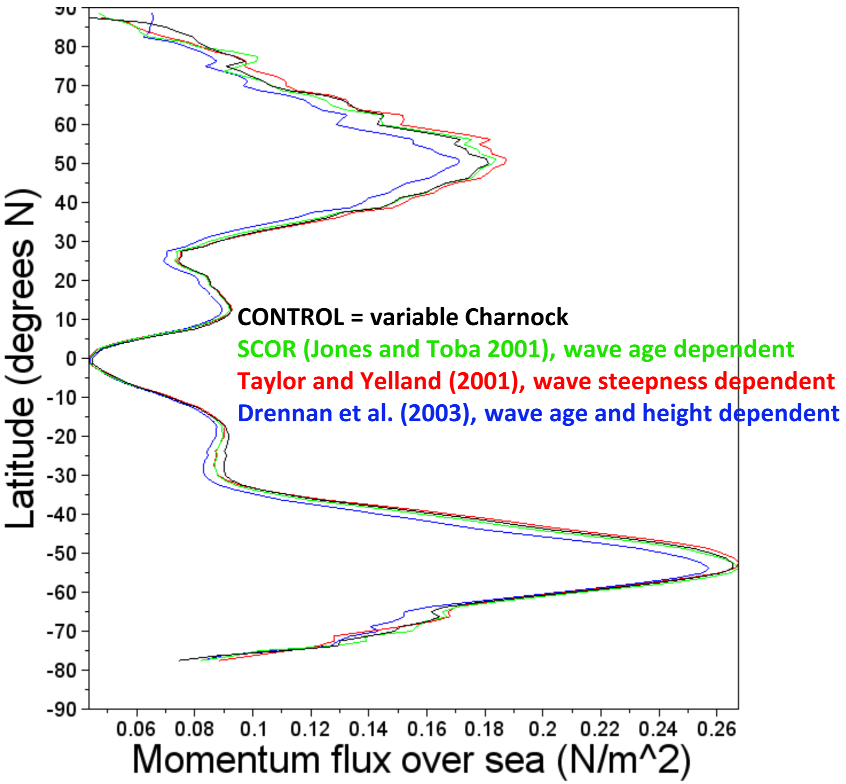


**CONTROL = variable Charnock**
**SCOR (Jones and Toba 2001), wave age dependent**
**Taylor and Yelland (2001), wave steepness dependent**
**Drennan et al. (2003), wave age and height dependent**

# Momentum flux (N/m2)

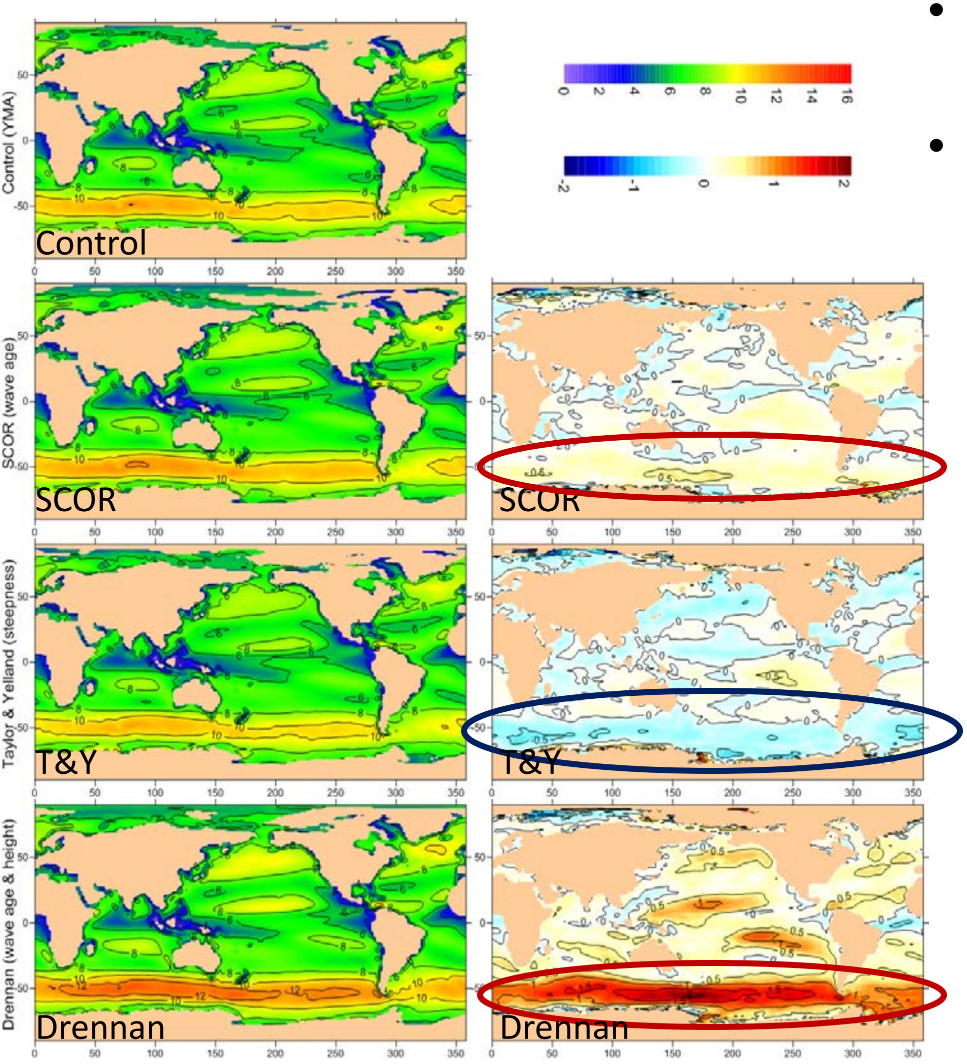
- SCOR: very similar to control
- T&Y and Drennan: same areas of increase or decrease as for z0m. However, smaller amplitude

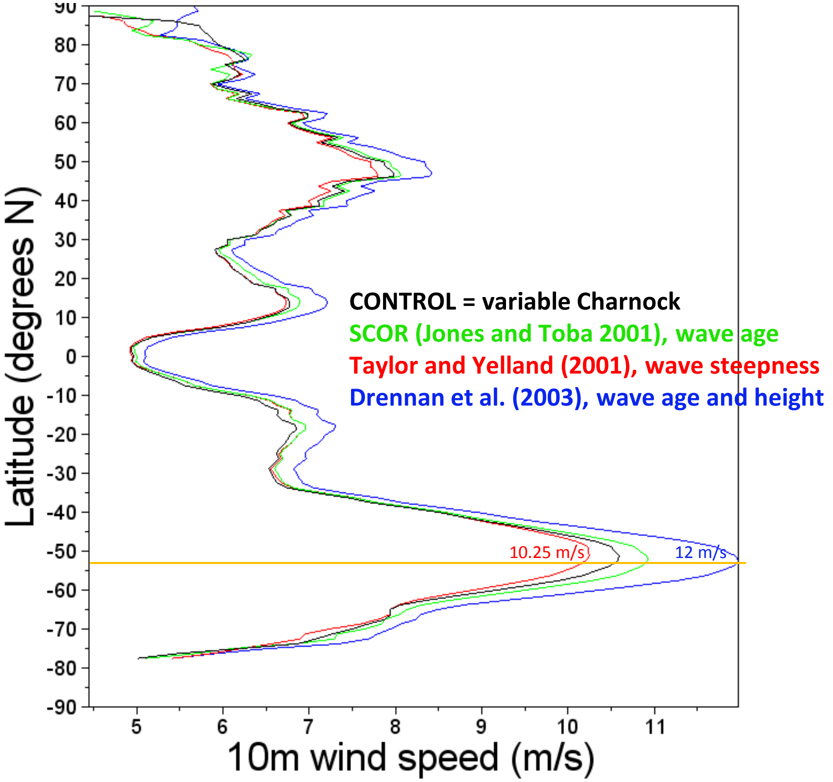




# 10-m wind speed U10 (m/s)

- SCOR & Drennan: an overall increase, with largest changes in the Southern Ocean
- T&Y: decrease in the Southern Ocean

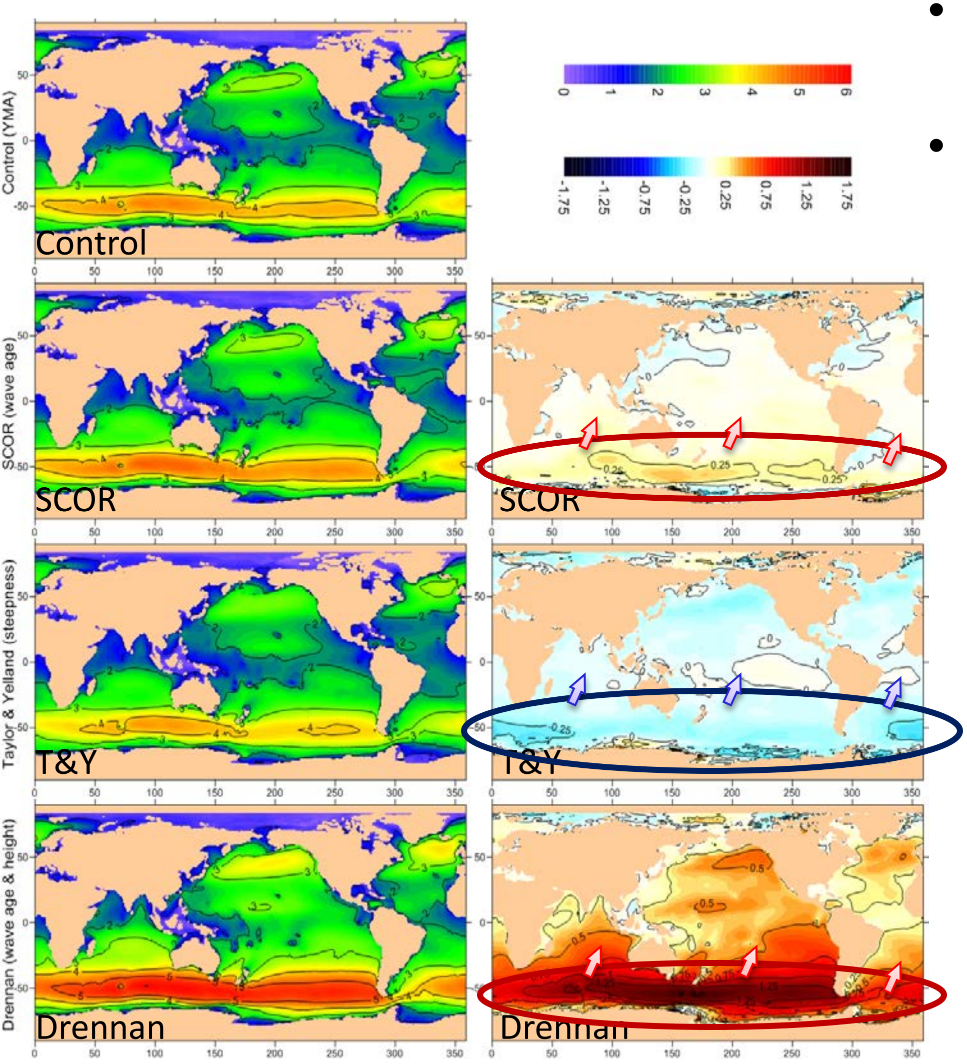


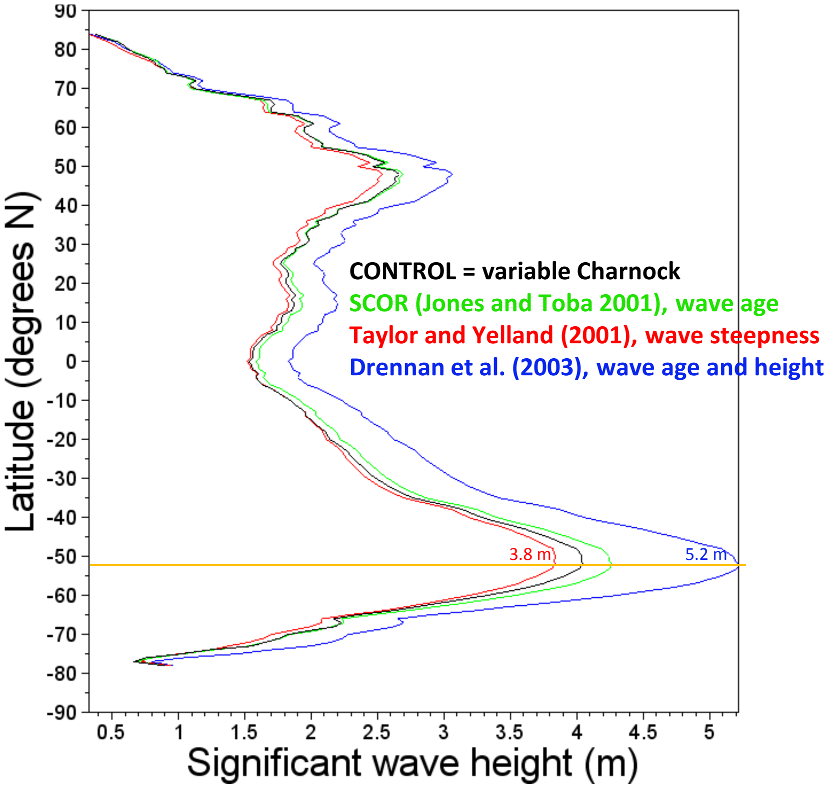


**CONTROL = variable Charnock**
**SCOR (Jones and Toba 2001), wave age**
**Taylor and Yelland (2001), wave steepness**
**Drennan et al. (2003), wave age and height**

# Significant wave height (m)

- Same changes as for the wind in wave generation areas
- Propagation of changes in swell-dominated areas (Indian Ocean, South Pacific, ...)





# Concluding remarks

- Preliminary results show that the roughness parameterization induces large differences in the atmospheric boundary layer and wave conditions:

| /Control | Z0m | MFlux | U10 | Hs |
|---|---|---|---|---|
| SCOR | ↘ | – | ↗ | ↗ |
| T&Y | ↗ | ↗ | ↘ | ↘ |
| Drennan | ↘ | ↘ | ↗ | ↗ |

❖ No agreement

❖ Is it significant ?
(9-year simulations)

❖ Which one is the best?

# Future work

- Running long-term simulations (100+ years) with present-day conditions
- Comparing the results with present-day climatology
- Looking at changes in the Oceanic Boundary Layer with more confidence

# Thank you

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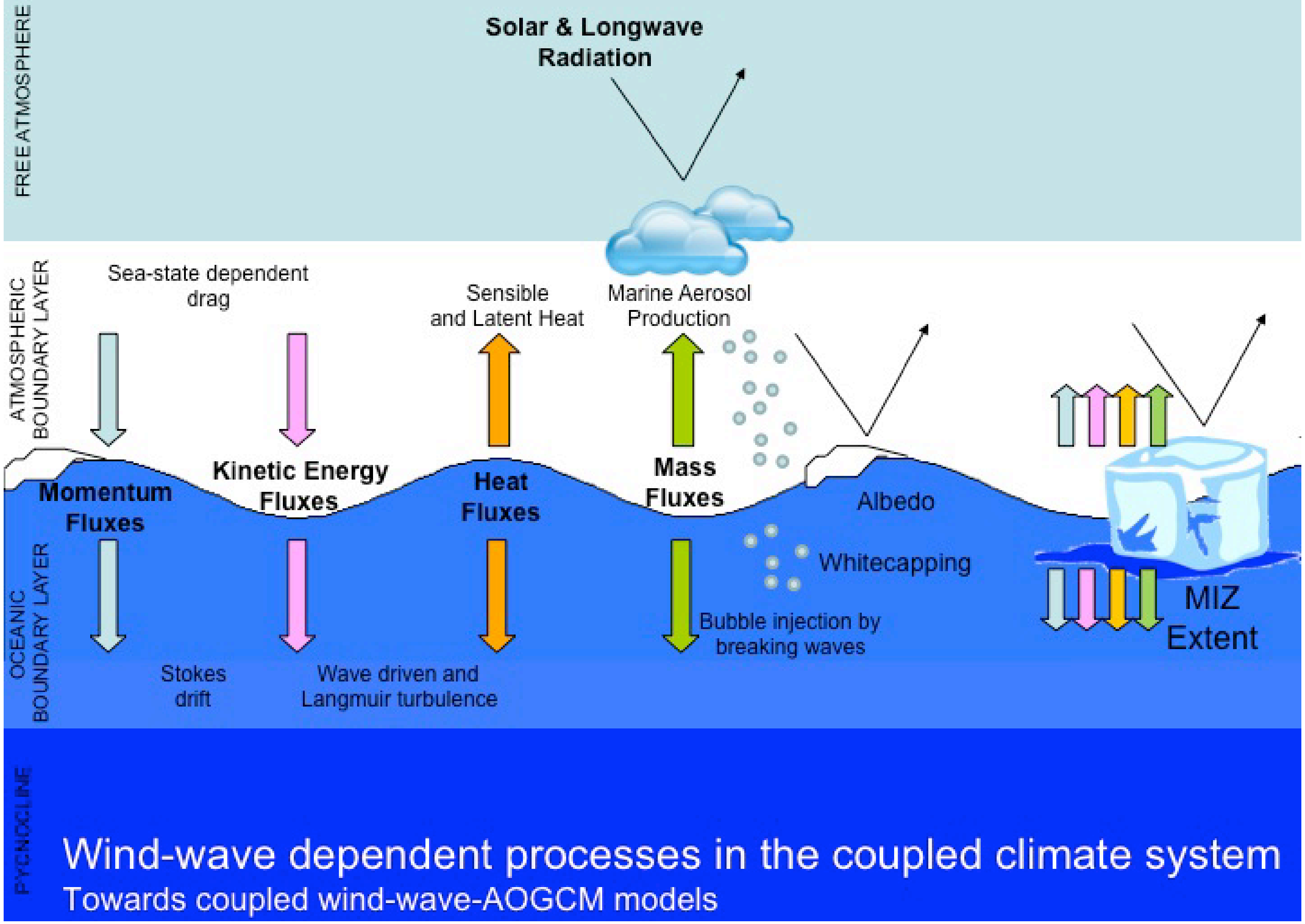
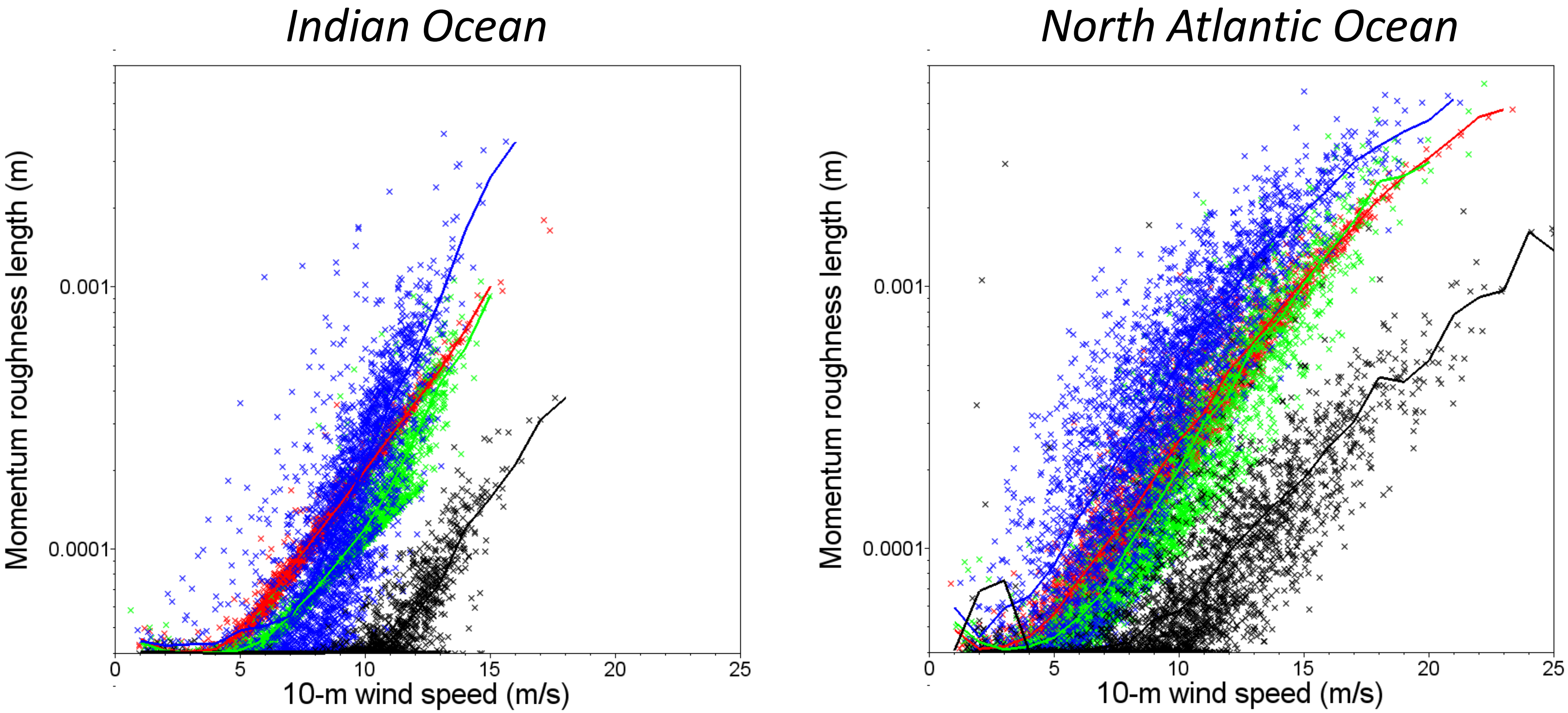
# Many interactions with ocean/atmosphere/ice



*Cavaleri, Fox-Kemper and Hemer, 2012: Wind-waves in the Coupled Climate System, BAMS*

# Roughness versus 10-m wind speed

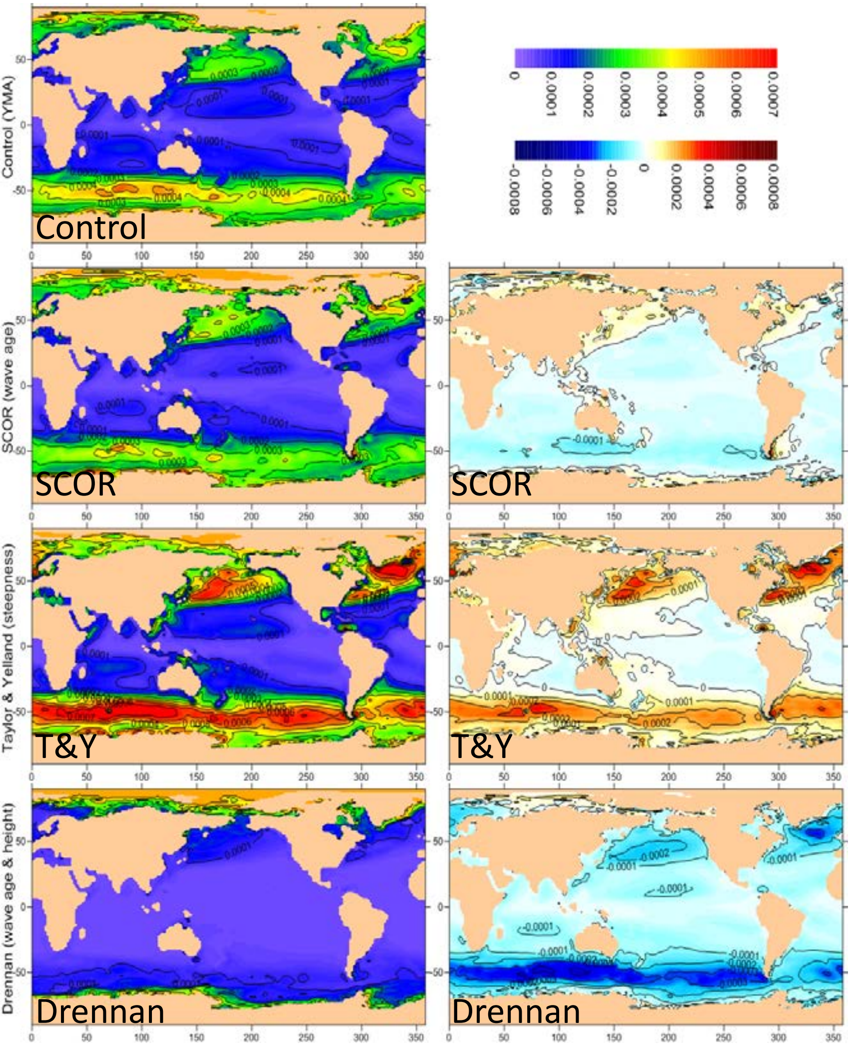


*Indian Ocean*

*North Atlantic Ocean*

*Plots of daily mean values of momentum roughness length versus 10-m wind speed at two locations: (left) in the Indian Ocean (78.75°E;-15°N) and (right) in the North Atlantic Ocean (330°E;50°N). Control (red), SCOR relationship (green), Taylor and Yelland (2001) (blue) and Drennan et al. (2003) (black) are plotted.*

# Momentum roughness length (m)



**CONTROL = variable Charnock**

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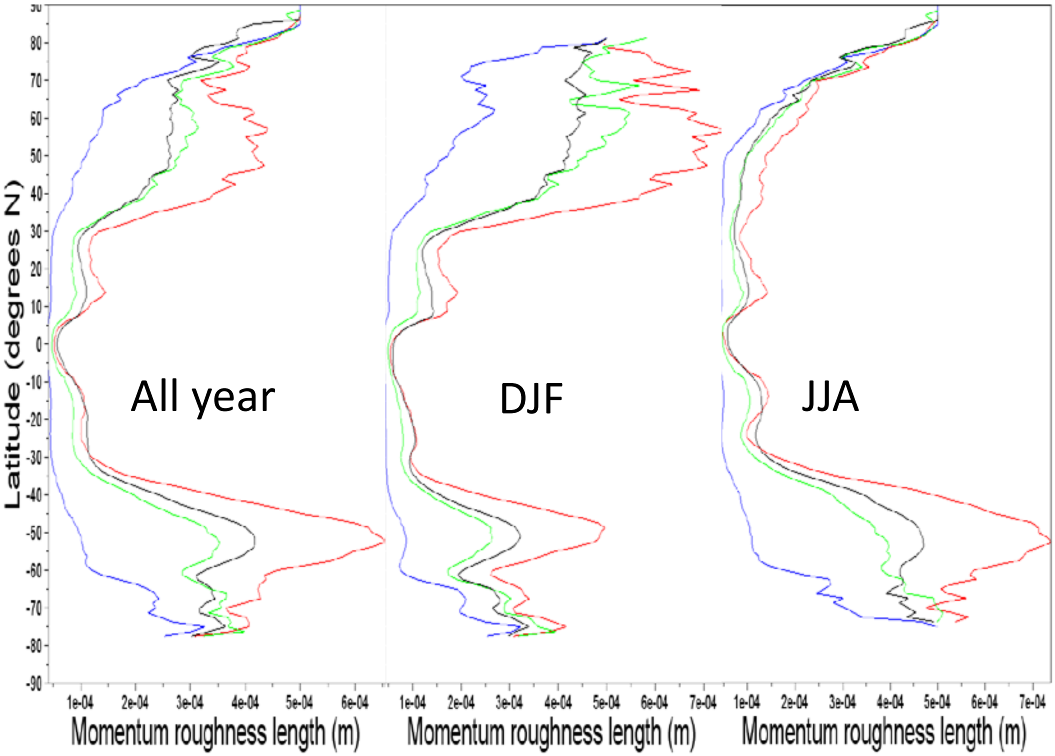

*Zonal means for all year, DJF and JJA. Control (black), SCOR relationship (green), Taylor and Yelland 2001 (red) and Drennan et al. 2003 (blue) are plotted.*

# 10-m zonal wind speed (m/s)

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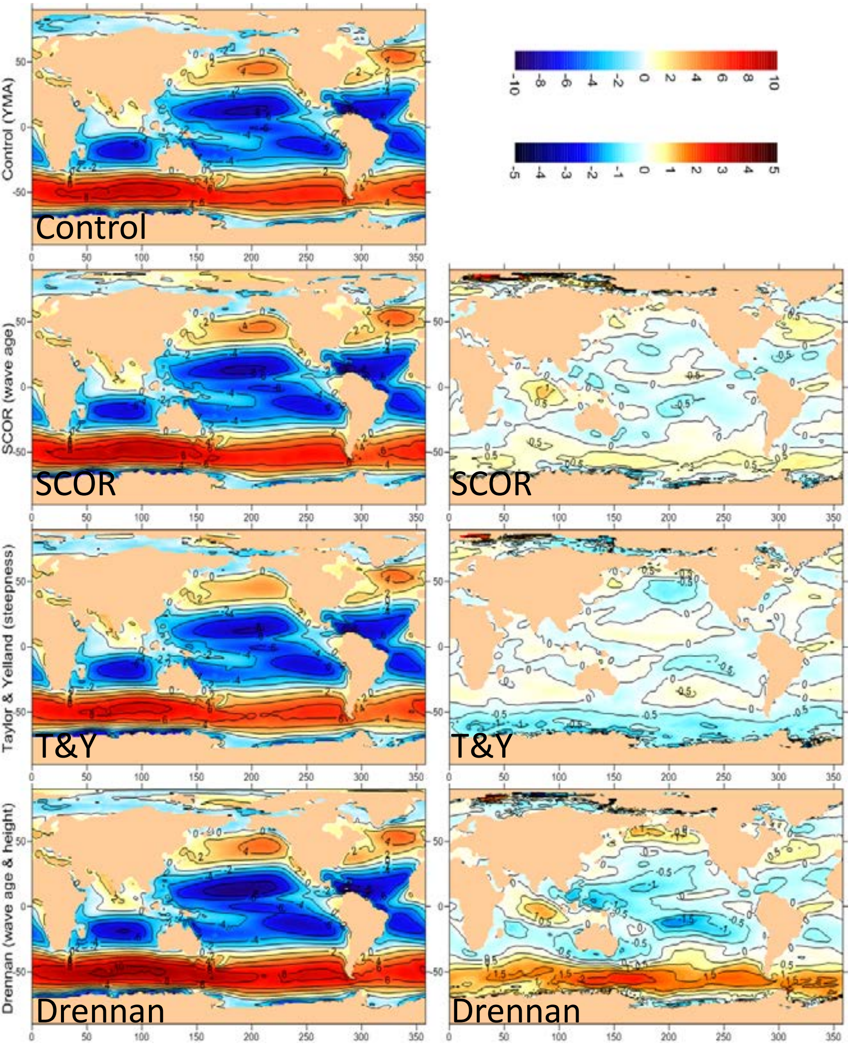

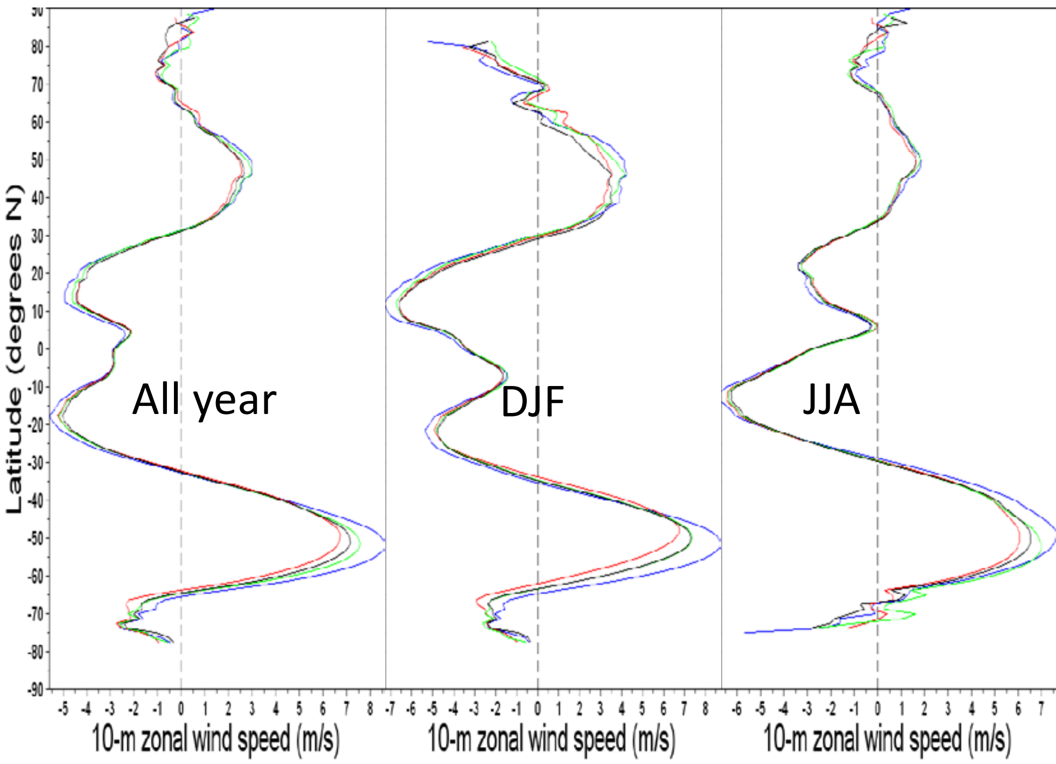

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# 10-m wind speed (m/s)

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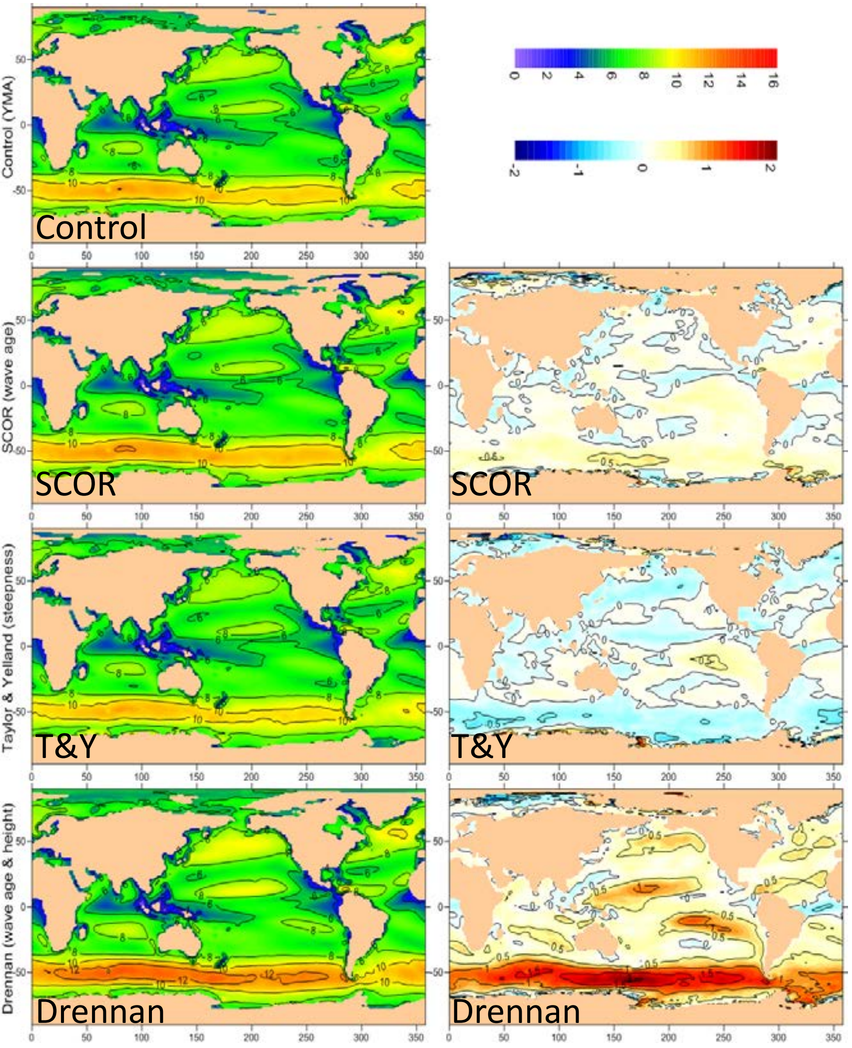
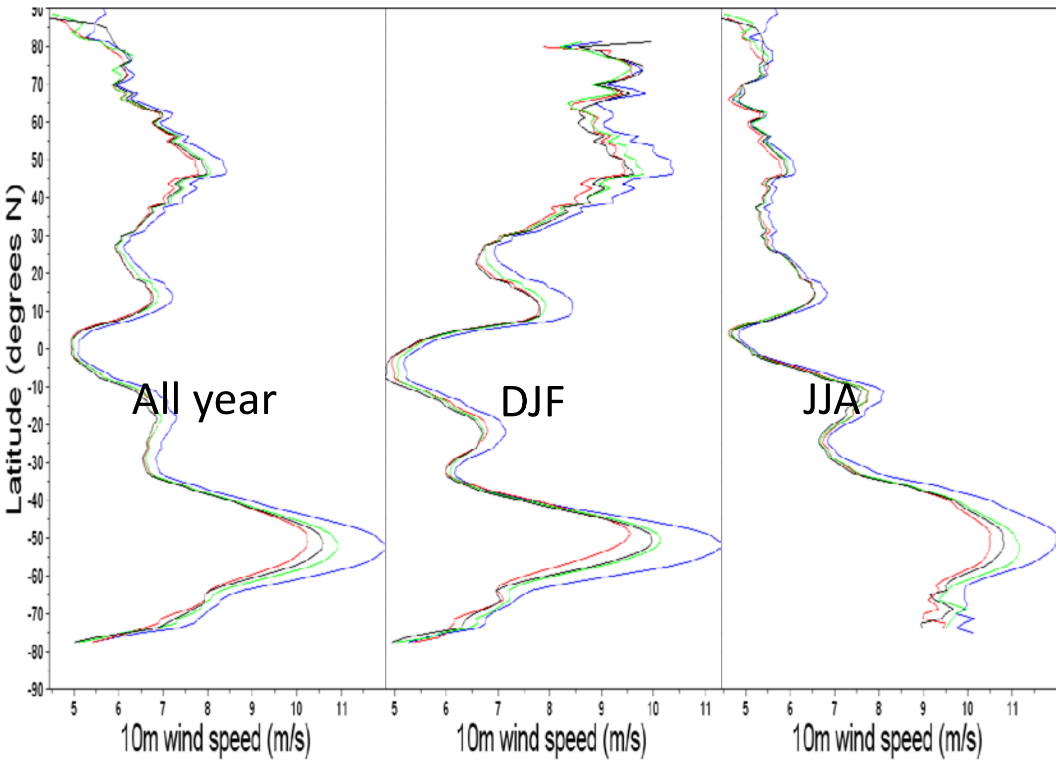
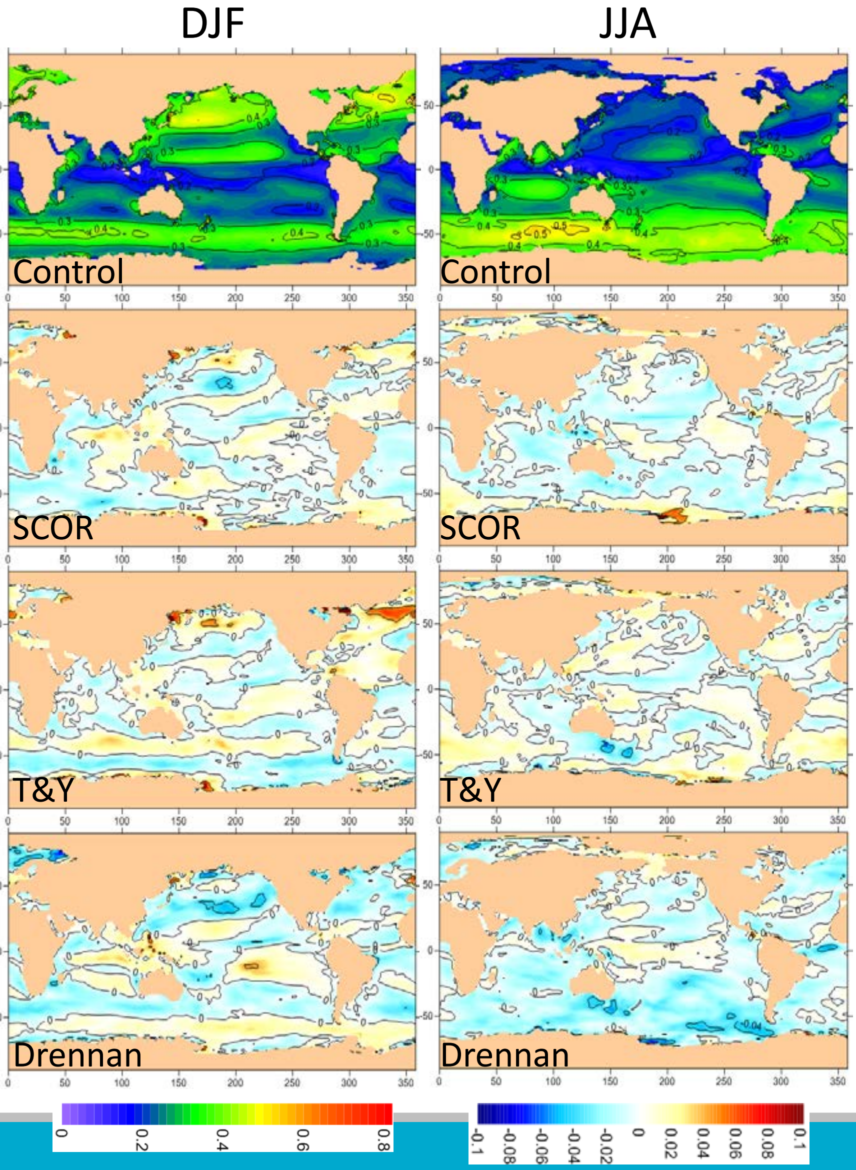




*Zonal means for all year, DJF and JJA. Control (black), SCOR relationship (green), Taylor and Yelland 2001 (red) and Drennan et al. 2003 (blue) are plotted.*

# Friction velocity (m/s)



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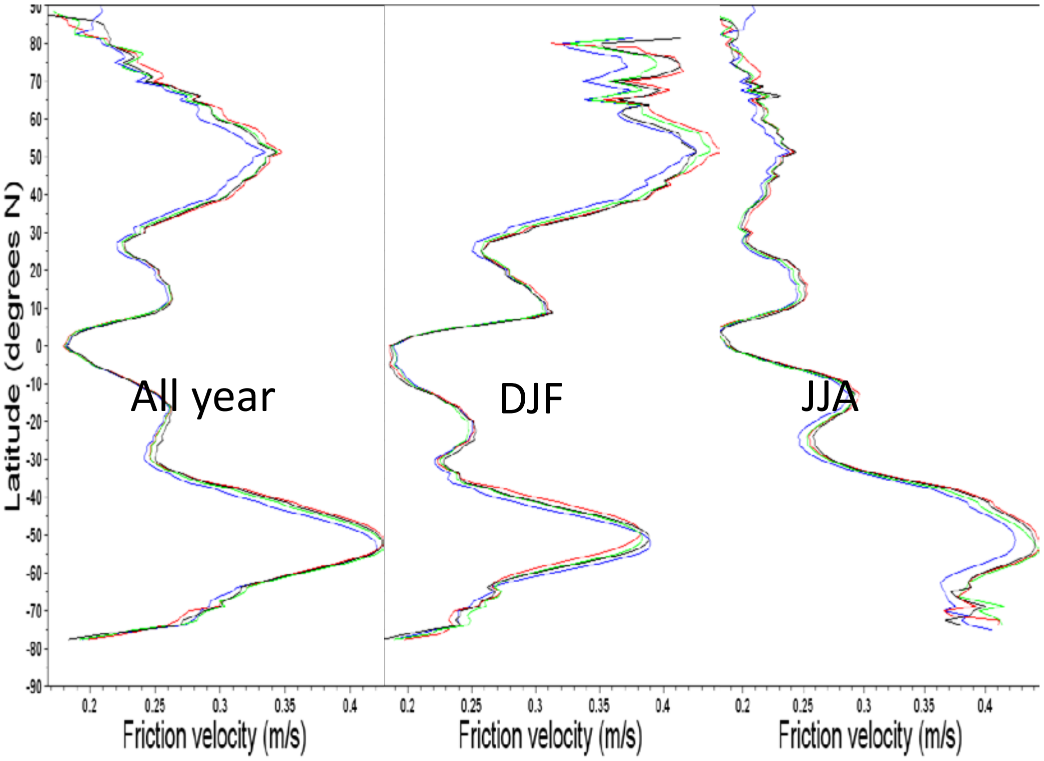

*Zonal means for all year, DJF and JJA. Control (black), SCOR relationship (green), Taylor and Yelland 2001 (red) and Drennan et al. 2003 (blue) are plotted.*

# Significant wave height (m)

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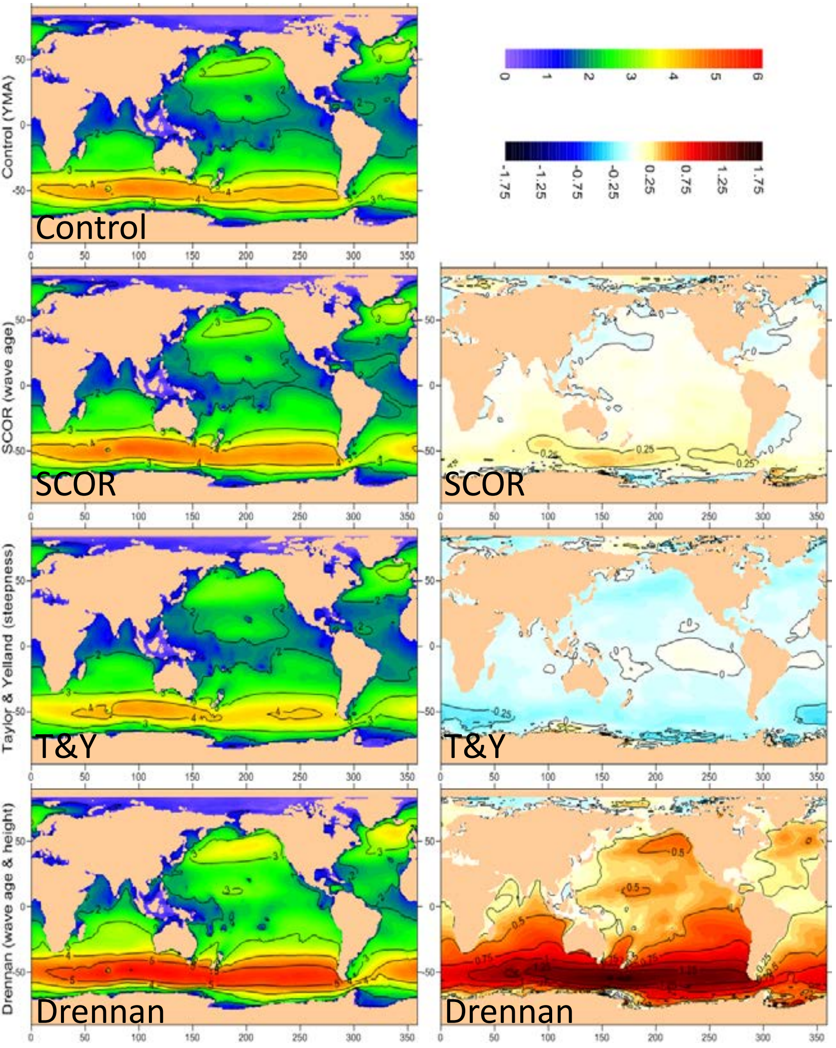
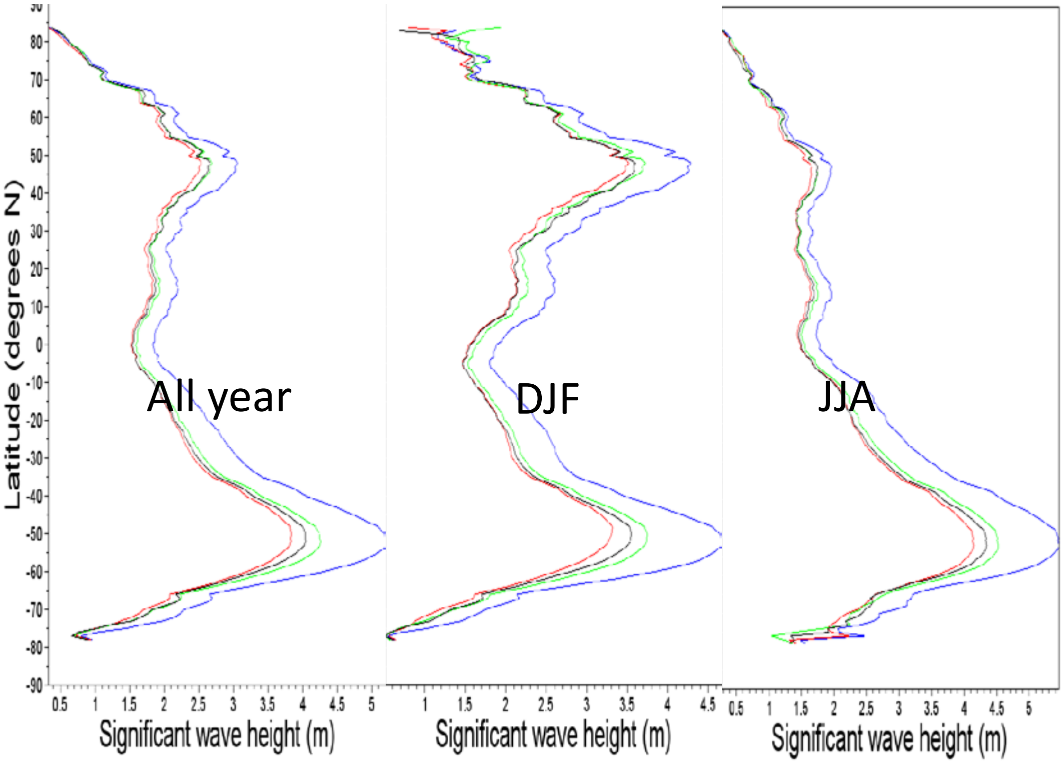




*Zonal means for all year, DJF and JJA. Control (black), SCOR relationship (green), Taylor and Yelland 2001 (red) and Drennan et al. 2003 (blue) are plotted.*

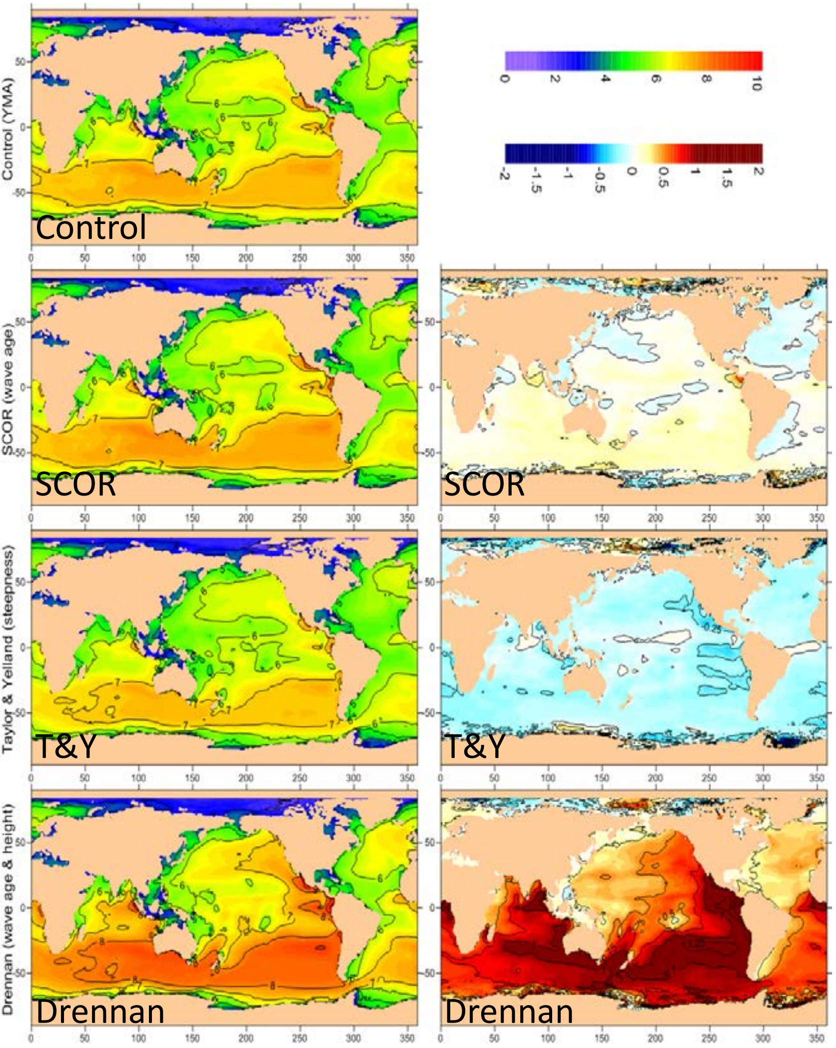
# Mean wave period t02 (s)

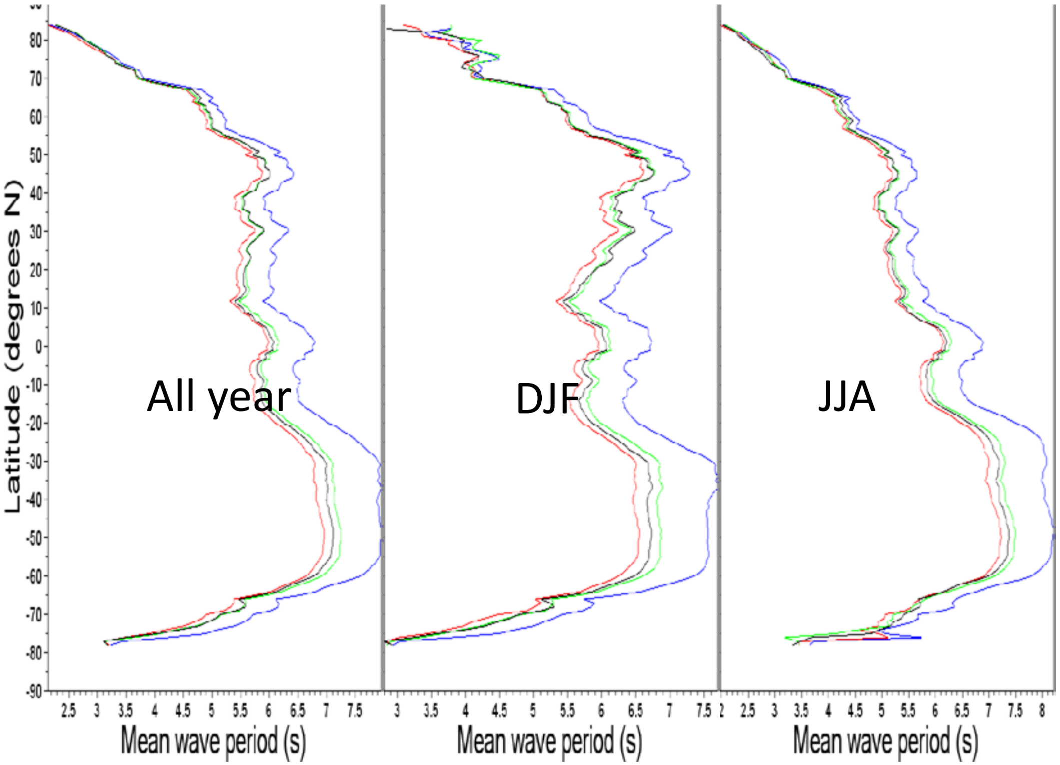
**CONTROL = variable Charnock**

**SCOR (Jones and Toba 2001), wave age dependent**

**Taylor and Yelland (2001), wave steepness dependent**

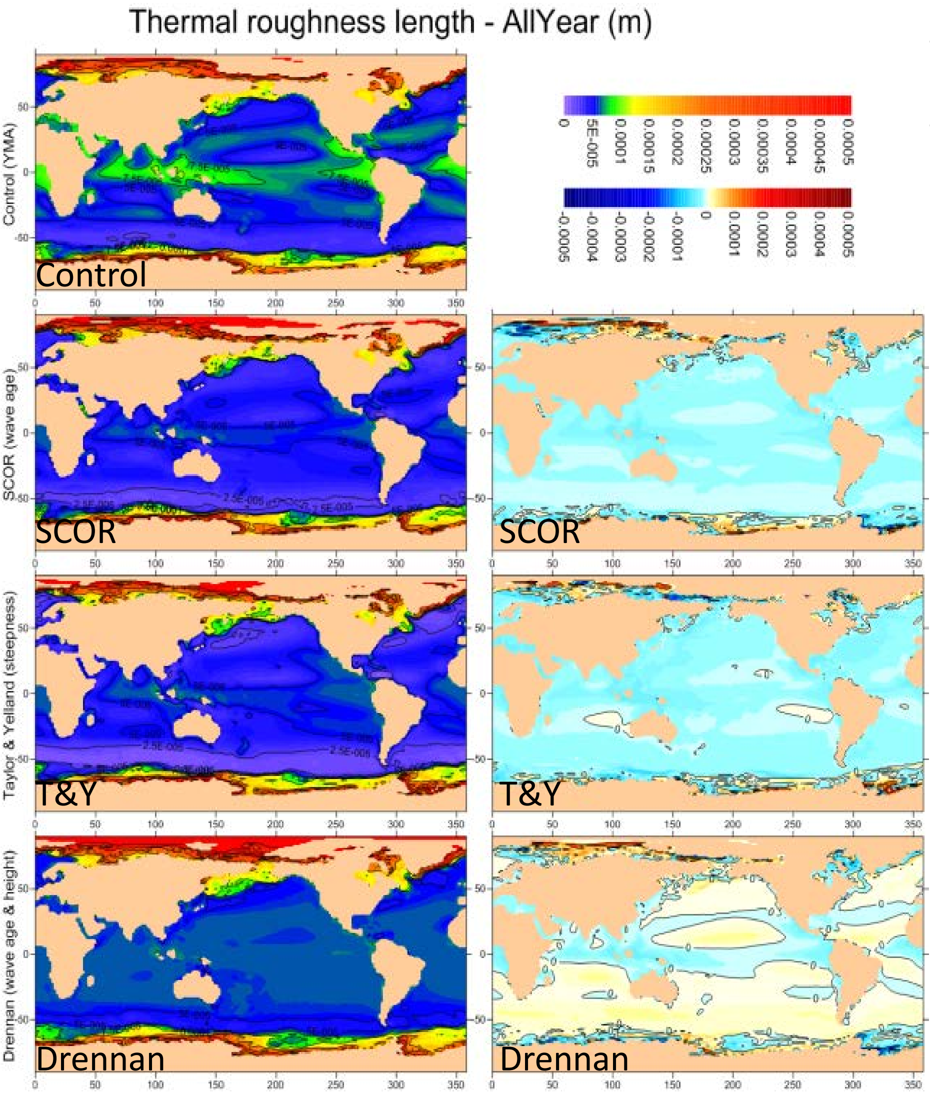
**Drennan et al. (2003), wave age and height dependent**



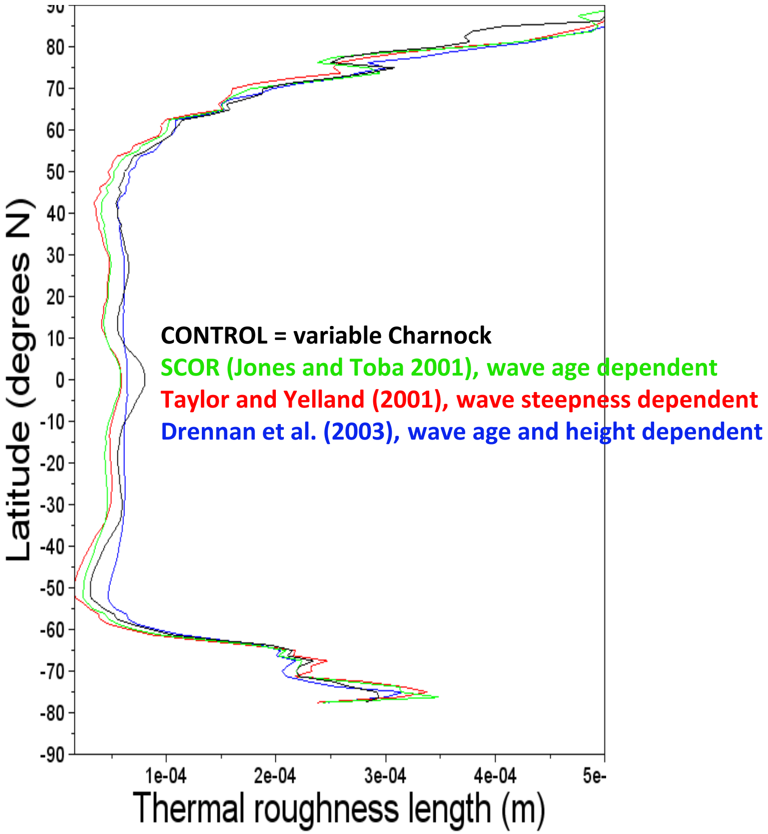


*Zonal means for all year, DJF and JJA. Control (black), SCOR relationship (green), Taylor and Yelland 2001 (red) and Drennan et al. 2003 (blue) are plotted.*

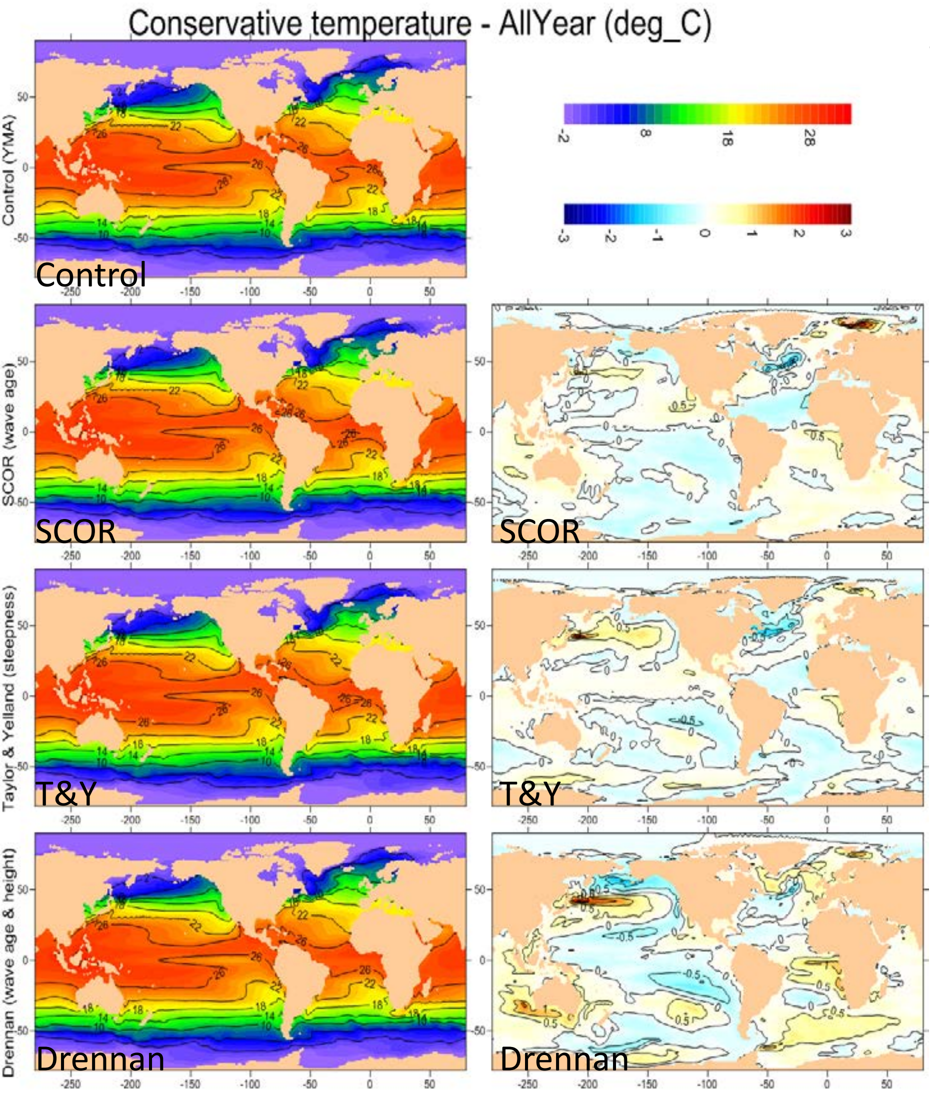
# Thermal roughness length (m)



- SCOR & T&Y: overall decrease
- Drennan: slight increase (except along the equator = smoothening of the values between 50N and 50S)



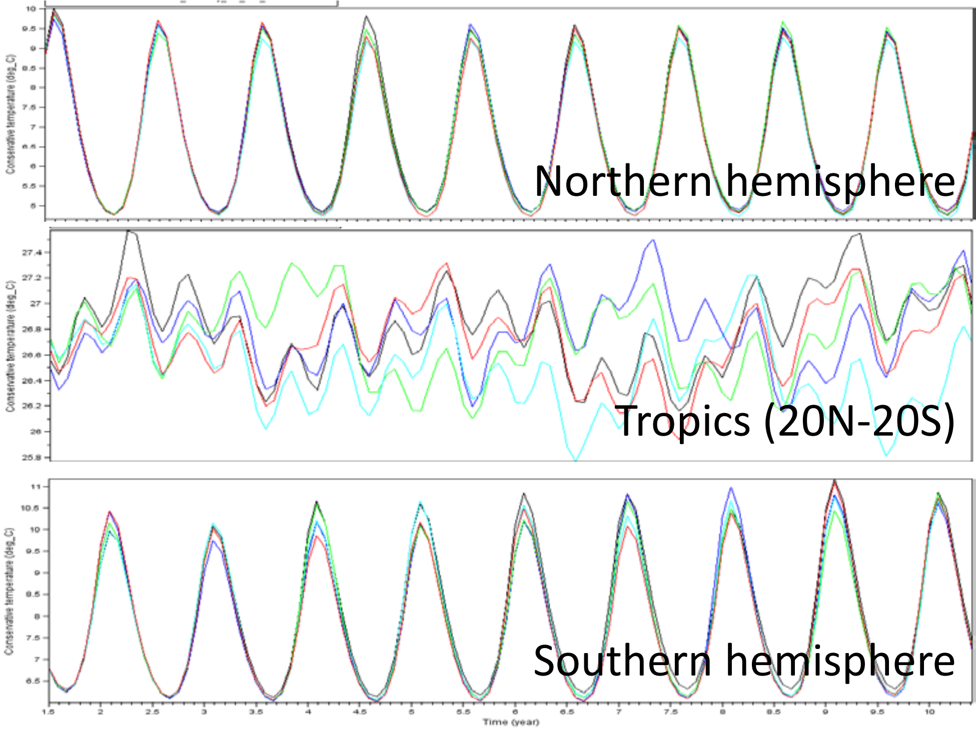
# Sea surface temperature (degree C)



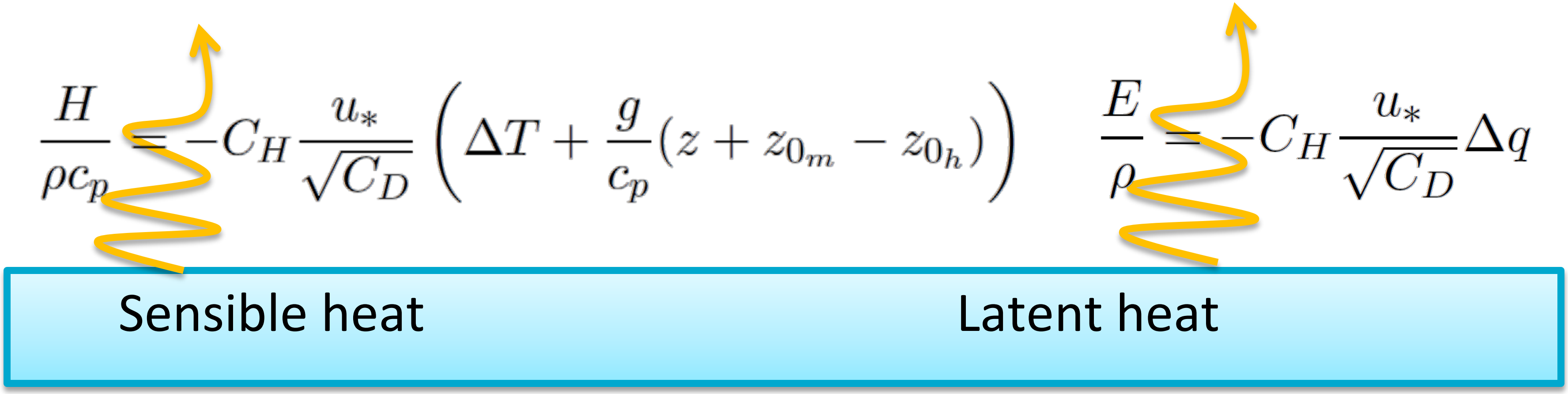
- Large interannual variability: too short time period & spin-up.

→ <u>Next step is to run long-term simulations</u>

**Z0WAV0: CONTROL = Yimin's variable Charnock parameterization**
**Z0WAV1: constant Charnock**
**Z0WAV2: SCOR (Jones and Toba 2001), wave age dependent**
**Z0WAV3: Taylor and Yelland (2001), wave steepness dependent**
**Z0WAV4: Drennan et al (2003), wave age and height dependent**



# About the surface turbulent heat fluxes



$$\frac{H}{\rho c_p} = -C_H \frac{u_*}{\sqrt{C_D}} \left( \Delta T + \frac{g}{c_p} (z + z_{0_m} - z_{0_h}) \right) \qquad \frac{E}{\rho} = -C_H \frac{u_*}{\sqrt{C_D}} \Delta q$$

Surface exchange coefficient:

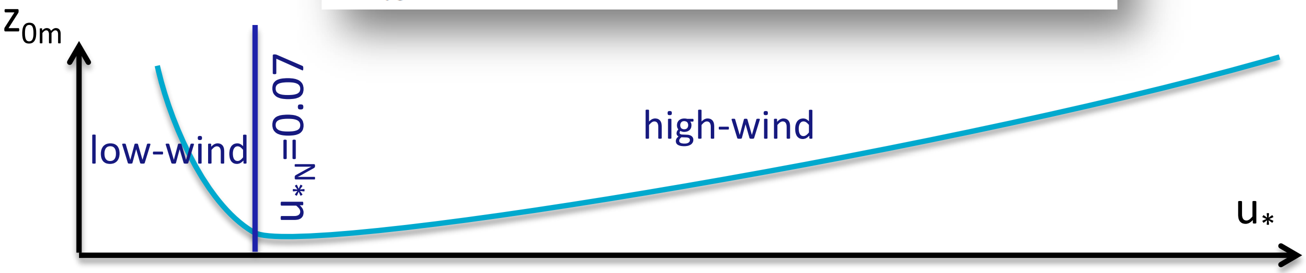
$$C_H = \frac{\kappa^2}{\Phi_m(L, z + z_{0_m}, z_{0_m}) \Phi_h(L, z + z_{0_m}, z_{0_h})}$$

Thermal roughness length over sea: $z_{0_h} = f(z_{0_m}, \ u_*)$

→ Surface heat fluxes depend on $z_{0m}$ and hence depend on $z_{0wave}$

# Calculation of $z_{0h}$ in Unified Model

$$z_{0_h} = f(z_{0_m},\ u_*) = f(z_{0_m},\ ?)$$



yes

**low-wind**

Wind conditions? $u_{*N} = \kappa \frac{U_z}{ln(z/z_{0_m})} \leq 0.07$

no

**high-wind**

$$z_{0_m} = \overset{\text{dominant term}}{\boxed{\frac{0.11\nu}{u_* + 10^{-5}}}} + \frac{\alpha}{g} u_*^2 \rightarrow u_{*L} = \frac{0.11\nu}{z_{0_m} - \frac{\alpha}{g} u_{*L}^2} - 10^{-5} \Leftrightarrow u_{*L} = f(u_{*L})$$

Fixed-point theorem: f has a unique solution and is convergent iff:

$$|f'(u_{*L})| < 1 \Leftrightarrow u_{*L} < \left[\frac{0.11\nu g}{2\alpha}\right]^{1/3}$$

yes

... iterations

$$z_{0_h} = \max\left(\frac{2.52 \times 10^{-6}}{u_{*L}}, \frac{2.56 \times 10^{-9}}{z_{0_m}}\right)$$

no

$$z_{0_h} = \frac{2.56 \times 10^{-9}}{z_{0_m}}$$

❖ The wave-dependent parameterization modifies *f* and *f’* (convergence criterion)

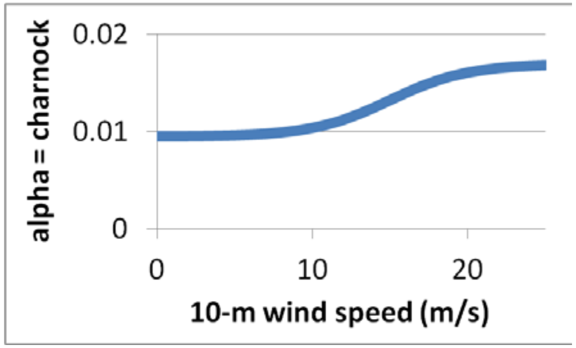
# Z0WAV0: Variable Charnock (YMA)

- This is the current parameterization in ACCESS. It does not depend on wave parameters. We use it as a control run.

- The coefficient α depends on the 10-m wind speed

$$\alpha = (\alpha^{\text{max}} - \alpha^{\text{min}}) \frac{\tanh\left[C^{\text{rate}}\left(U_{\text{10n}} - U_{\text{10n}}^{\text{mid}}\right)\right] + 1}{2} + \alpha^{\text{min}}$$

$$z0_m = \frac{0.11\nu}{u_*} + \frac{\alpha}{g} u_*^2$$



$$\beta = C_p/u_*$$

# Z0WAV2: SCOR / wave age

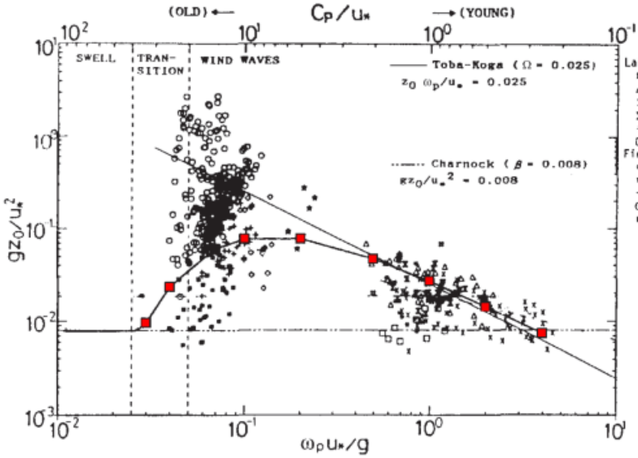
- Jones and Toba (2001) proposed a relation between the Charnock parameter and wave age, which shows that the nondimensional sea surface roughness first increases and then decreases with the increasing wave age:

$$\frac{z_{0_{wave}}g}{u_*^2} = \alpha(\beta) = \begin{cases} 0.03\beta\exp\{-0.14\beta\} & \approx 0.35 < \beta < 35 \\ 0.008 & \beta > 35 \end{cases}$$

$$z_{0_m} = \frac{0.11\nu}{u_*} + \begin{cases} 0.03\left(\frac{\beta}{g}\right)\exp\{-0.14\beta\}\,u_*^2 & \approx 0.35 < \beta < 35 \\ \frac{0.008}{g}u_*^2 & \beta > 35 \end{cases}$$

≈ Cp=gTp/2π (deep water assumption)

≈ β is calculated using u* calculated within WW3

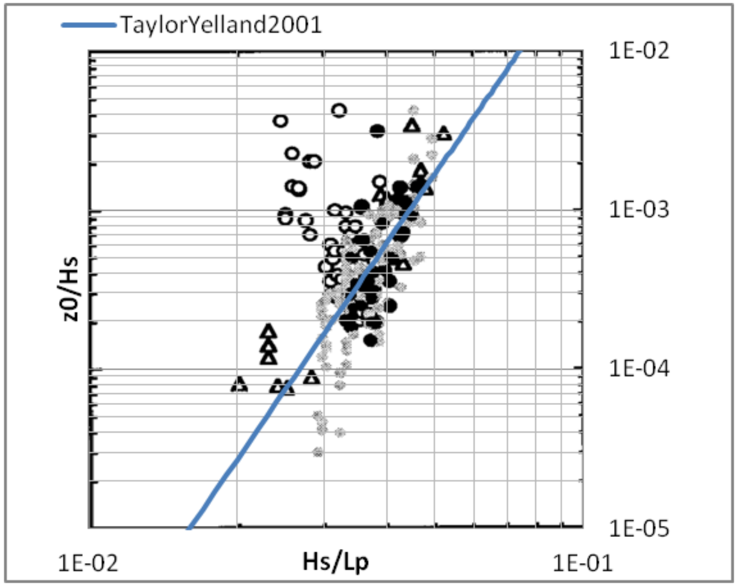


$$s = H_s/L_p$$

# Z0WAV3: Taylor and Yelland /wave steepness

$$\frac{z0_{wave}}{H_s} = a_1 \left(\frac{H_s}{L_p}\right)^{b_1} \quad (a_1 = 1200 \text{ and } b_1 = 4.5)$$

$$\boxed{z0_m = \frac{0.11\nu}{u_*} + a_1 H_s \left(\frac{H_s}{L_p}\right)^{b_1}}$$

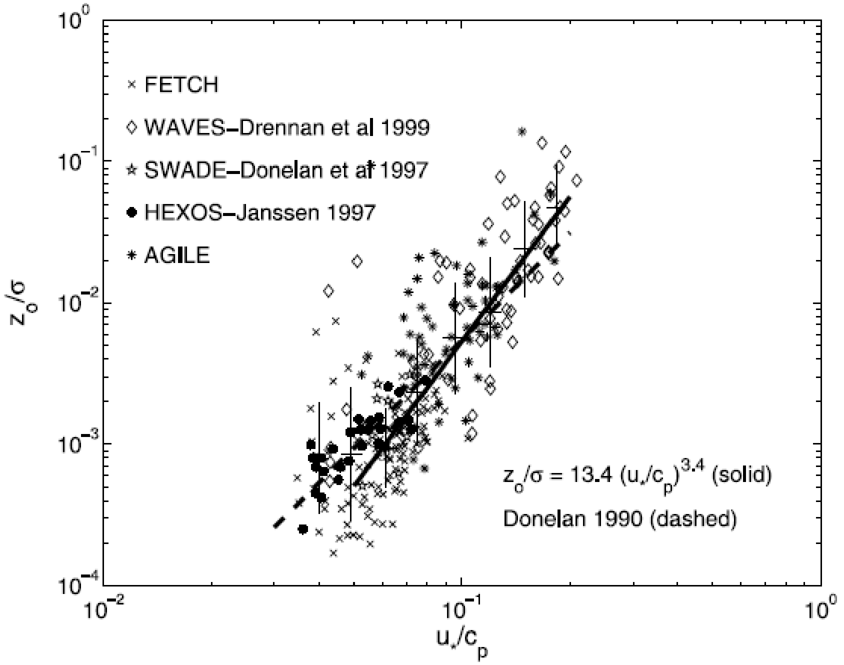


$$\beta = C_p/u_*$$

# Z0WAV4: Drennan et al. / wave age & height

$$\frac{z_{0wave}}{H_s} = a_2\left(\frac{u_*}{C_p}\right)^{b_2} \quad (a_2 = 3.35 \text{ and } b_2 = 3.4)$$

$$\boxed{z_{0_m} = \frac{0.11\nu}{u_*} + a_2 H_s\left(\frac{u_*}{C_p}\right)^{b_2}}$$



- Cp=gTp/2π (deep water assumption)

# Choice of the wave parameter to be sent to UM

- For every parameterization, the wave-coherent part of the momentum roughness length can be written as follow:

$$z0_{wave} = Au_*^B$$

$$\begin{array}{lll}
\mathrm{Z0WAV1}: & A = \alpha/g & B = 2 \\
\mathrm{Z0WAV2}: & A = \alpha(\beta)/g & B = 2 \\
\mathrm{Z0WAV3}: & A = a_1 H_s \left(H_s/L_p\right)^{b_1} & B = 0 \\
\mathrm{Z0WAV4}: & A = a_2 H_s/C_p^{b_2} & B = b_2
\end{array}$$

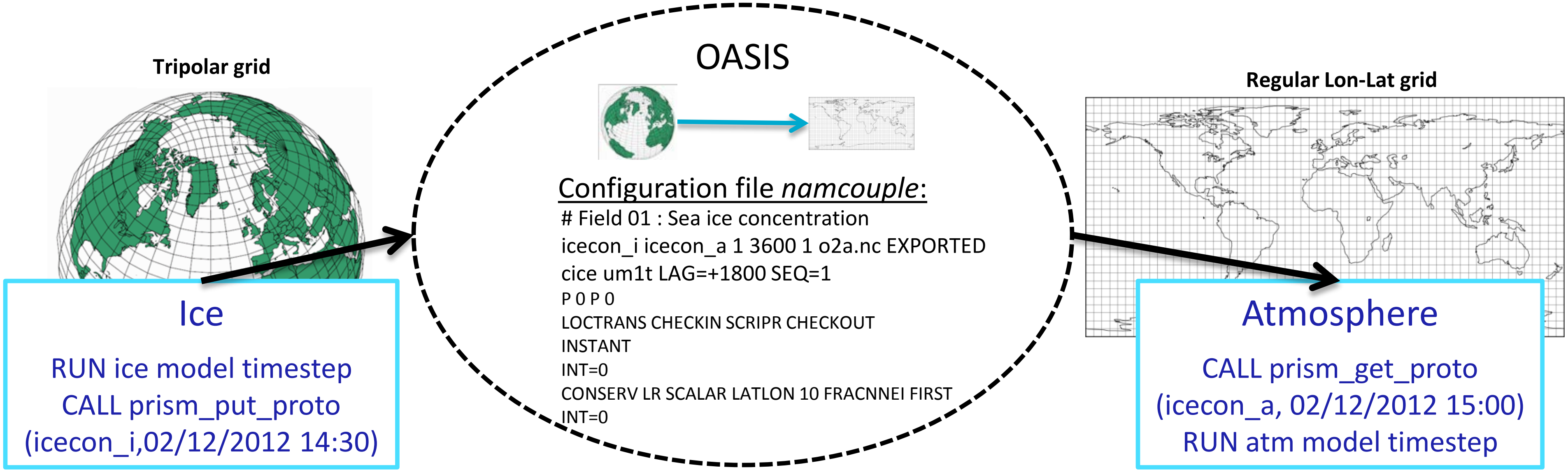
- The factor A is sent to the Unified Model and B is set at the beginning of the run in Unified Model input file

≈ Z0WAV2: β depends on u* but is calculated within WW3. The exponential part of the SCOR relation does not allow to factorize it.

# OASIS coupler

- Aim: interface to couple existing numerical General Circulation Models of the ocean and atmosphere
- At the runtime, it acts as a <u>separate executable</u>, which main function is to interpolate the coupling fields exchanged between the submodels and as a <u>communication library</u> linked to the submodels

*Example of sea ice concentration transfer from ice to atm model:*



**Ice**

RUN ice model timestep
CALL prism_put_proto
(icecon_i,02/12/2012 14:30)

Configuration file *namcouple*:

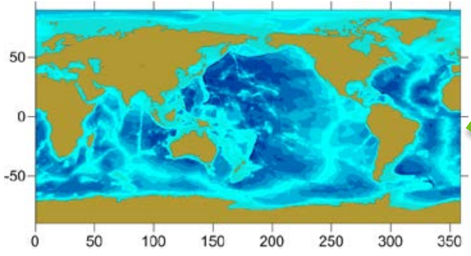
```
# Field 01 : Sea ice concentration
icecon_i icecon_a 1 3600 1 o2a.nc EXPORTED
cice um1t LAG=+1800 SEQ=1
P 0 P 0
LOCTRANS CHECKIN SCRIPR CHECKOUT
INSTANT
INT=0
CONSERV LR SCALAR LATLON 10 FRACNNEI FIRST
INT=0
```

**Atmosphere**

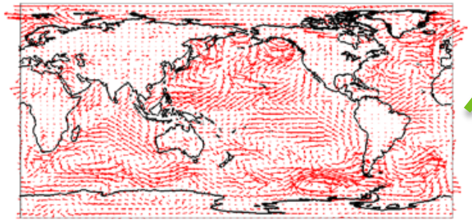
CALL prism_get_proto
(icecon_a, 02/12/2012 15:00)
RUN atm model timestep

# WAVEWATCH III wave model

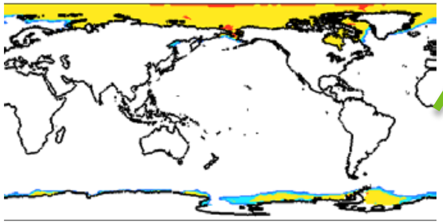
**Bathymetry**



**Wind fields**



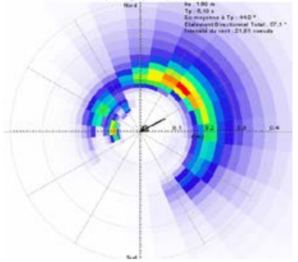
**Ice concentration**



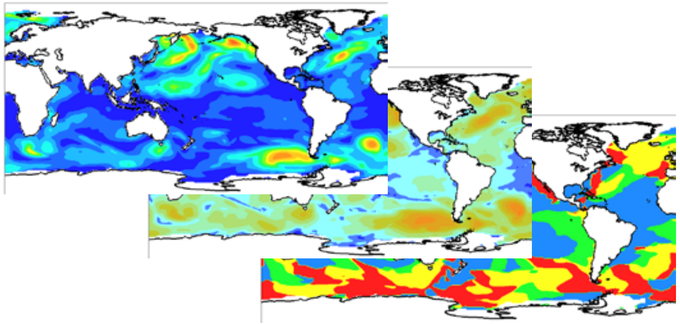
WAVEWATCH III

*Spectral model based on wave action balance equation*

**Wave spectrum F(f,θ)**



**Wave height, period, direction...**



**+ Other wave parameters: charnock, steepness, wave age, momentum/energy fluxes from waves to ocean/atm...**