PARAMETERIZATION OF A WAVE-DEPENDENT SURFACE ROUGHNESS: A STEP TOWARDS A FULLY COUPLED ATMOSPHERE-OCEAN-SEA ICE-WAVE SYSTEM

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1. INTRODUCTION

Wind-waves are located at the interface between the atmosphere and ocean and affect exchanges of momentum, heat, energy and mass between oceanic and atmospheric boundary layers (Sullivan and McWilliams 2010, Cavaleri et al. 2012, Babanin et al. 2012). In particular, waves play an active role in the transfer of momentum between atmosphere and ocean. In the atmospheric model, momentum flux is partly determined by the surface roughness length. It is usually calculated as a function of the surface wind speed (Charnock, 1955). However, previous studies have shown that the roughness is related to the sea state (defined by wave age, wave steepness and/or whitecapping induced spray) and that its estimation can be improved using a wave-dependent parameterization.

Several wave-dependent surface roughness parameterizations are available which fit a large range of meteorological and wave condition measurements, whether in the field or in the laboratory. In practice, the use of a wave dependent parameterization in climate models requires knowledge of the wave conditions at each timestep on the whole domain. This can be done by adding a wave model in the coupled climate model system.

The present study aims (1) to implement a wave model in a coupled climate model, and (2) to implement and test different wave-dependent surface roughness parameterizations.

The paper is organized as follows. Section 2 describes the climate and wave models used in this study and how they are coupled together, including the choice of the wave parameter to be returned. The results of short-term simulations using a wave-dependent surface roughness parameterization are presented in section 3. Finally, conclusions are drawn in section 4.

2. METHODOLOGY

This section describes the ACCESS coupled model and the technical coupling with the WAVEWATCH III wave model. It is followed by the choice of the wave-dependent surface roughness parameterizations and the experimental design used for this study.

2.1 THE COUPLED SYSTEM ACCESS-CM

The Australian Community Climate and Earth System Simulator coupled model (ACCESS-CM) has been developed at the Centre for Australian Weather and Climate Research (CAWCR), a partnership between CSIRO and the Bureau of Meteorology. It is built by coupling the UK Met Office atmospheric unified model (UM7.3), and a land surface component, to the ACCESS ocean model, which consists of the NOAA/GFDL ocean model MOM4p1 and the LANL sea-ice model CICE4.1, under the CERFACS OASIS3.25 coupling framework (see figure 1).

The version 1.3 of the ACCESS-CM is used in this study and includes the CSIRO Community Atmosphere Biosphere Land Exchange version 1.8 (CABLE1.8) as land surface component and new atmospheric physics (Bi et al. 2013).

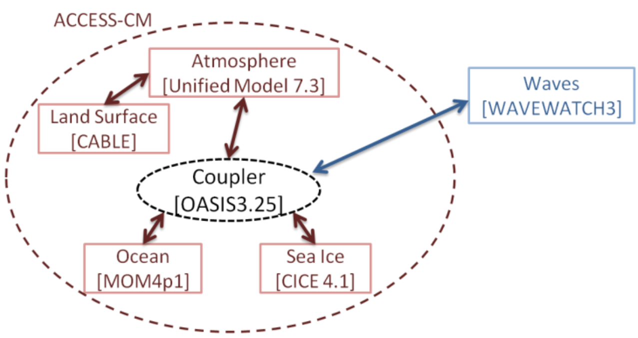

Figure 1: ACCESS-CM components and coupling framework. The coupling of the WAVEWATCH III model is carried out through the OASIS coupler.

The spatial resolution for the atmospheric component is 1.25° latitude by 1.875° longitude horizontally with 38 levels in the vertical. The oceanic and sea ice components share the same grid: 360 longitude by 300 latitude points with 50 vertical levels. A tripolar grid is used North of 65°N, a cosine dependent (Mercator) grid is used south of 30°S and a refinement of latitudinal spacing to 1/3° is applied between 10°S and 10°N.

The ocean and sea ice models exchange coupling fields at each timestep, that is 1 hour. The atmospheric model presents a shorter timestep (30 minutes) and receives/sends coupling fields through OASIS every 6 timesteps, that is 3 hours. All the coupling fields to be exchanged between the atmosphere and the ocean pass through the sea ice model.

2.2 IMPLEMENTATION OF THE WAVE MODEL WAVEWATCH III

The NOAA WAVEWATCH III wave model (WW3) is set up on a 1° by 1° regular longitude-latitude grid (masked above 85°N), using the GEBCO 1-min grid bathymetry. The spectral discretization is 24 directions by 32 frequencies and the global timestep is 30 minutes.

WW3 is then implemented in the existing ACCESS-CM system. It is considered as an additional submodel, using the OASIS coupler to pass the fields from / to the wave model. To generate, propagate and dissipate waves, the wave model requires regularly updated surface wind fields and ice concentration. These are provided by the atmospheric model at every timestep (30 minutes).

Wave parameters of interest for other submodels can be calculated within WW3 and sent through the coupler every 30 minutes or a multiple. In this study, we focus on the feedback of waves on the sea surface roughness. The wave parameters that can be used in the calculation of the sea surface roughness are identified in the next section. They are calculated and sent to the atmospheric model at every timestep.

2.3 MOMENTUM ROUGHNESS PARAMETERIZATIONS

In the Unified Model (Lock and Edwards, 2011), the momentum roughness length over the sea is calculated using a generalization of the Charnock (1955) formula to include low-wind conditions:

$$z_{0_m} = \frac{0.11\nu}{u_*} + \frac{\alpha}{g}\, u_*^2$$

With ν the kinematic viscosity, u* the friction velocity, α the Charnock coefficient (set to a constant value) and g the gravity acceleration.

In ACCESS1.3, a new expression of the Charnock coefficient was constructed to take into account its dependence on the surface wind speed (Sun et al., 2013, Ma et al., in prep.):

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

It is derived from Fairall et al. (2003) results: the Charnock coefficient (hence the surface roughness) presents an increase for wind speeds above U_{10n}=15 m/s. The contributions of ACCESS1.3 to the CMIP5 were carried out with this parameterization (Dix et al. 2013). In this study, simulations carried out with this non-wave dependent parameterization are considered as control.

The impact of the wave feedback is investigated by implementing three wave-dependent parameterizations of the surface roughness in the atmospheric model: the SCOR relationship issued from Jones and Toba (2001), the Taylor and Yelland (2001) and the Drennan et al. (2003) formulations. These parameterizations link the sea surface roughness to various wave parameters.

Jones and Toba (2001) proposed a relation between the Charnock parameter and the wave age ($\beta = C_p/u_*$, with C_p the phase speed), which shows that the non-dimensional sea surface roughness first increases and then decreases with the increasing wave age:

$$\frac{z_0 g}{u_*^2} = \alpha = \begin{cases} 0.03\,\beta\,\exp\{-0.14\beta\} & \approx 0.35 < \beta < 35 \\ 0.008 & \beta > 35 \end{cases}$$

Taylor and Yelland (2001) linked the surface roughness length, normalized by the significant wave height H_S, to the wave steepness ($s = H_S/L_p$, with L_p the wave length at spectral peak):

$$\frac{z_0}{H_S} = a_1\left(\frac{H_S}{L_p}\right)^{b_1} \qquad (a_1 = 1200 \text{ and } b_1 = 4.5)$$

Finally, Drennan et al. (2003) constructed a relation between the surface roughness length normalized by the significant wave height H_S and the wave age β:

$$\frac{z_0}{H_S} = a_2\left(\frac{u_*}{C_p}\right)^{b_2} \qquad (a_2 = 3.35 \text{ and } b_2 = 3.4)$$

For each wave-dependent parameterization, the wave part of z_{0m} ($= \alpha/g\, u_*^2$ in the original formulation) can be written as $z_{0m} = Au_*^B$, with A, a factor that varies with the wave conditions and the chosen parameterization and B, a factor that depends only on the chosen parameterization. The factor A is calculated in WW3 and sent to the atmospheric model every 30 minutes and the factor B is set as a constant at the beginning of the simulation.

In the UM, the thermal roughness length over sea is inferred from the momentum roughness length and the friction velocity. Therefore, the changes in sea surface roughness will impact both momentum and heat fluxes.

2.4 SHORT-TERM SIMULATIONS: EXPERIMENTAL DESIGN

The four different surface roughness parameterizations described in the previous section are tested in the ACCESS-CM+WW3 coupled system.

In climate modeling, the spin-up and following run usually cover hundreds of years. The simulations presented here cover 9.5 years and their goal is to give a rough estimate of the differences between the non-wave and wave dependent parameterizations. Longer term simulations will be carried out in a near future to assess those differences with more confidence.

The experimental framework for these short-term simulations involves initialization using pre-industrial conditions (year 1850), a 6-month spin-up, followed by a 9-year run. Standard CMIP5 preindustrial (circa 1850) prescriptions are used for the greenhouse gas and aerosol emissions and are kept constant during the whole simulation.

3. RESULTS

In this section, we investigate the differences between the different roughness parameterizations. Climatology is calculated for different fields, on the last 9 years of each simulation. The non-wave dependent parameterization is defined as the control climatology.

3.1 MOMENTUM ROUGHNESS LENGTH AND FLUXES

The momentum roughness length maps (see figure 2) highlight a large variation of response between the chosen parameterizations. The SCOR relationship gives values of similar magnitude to the control, though presenting some pattern variations: roughness length is smaller in the Southern Ocean and around the Equator and larger in the North West regions of the Pacific and Atlantic Oceans. Taylor and Yelland (2001) parameterization presents very high values of roughness length in the mid- to high-latitudes. In the Southern Ocean, the maximum annual average value reaches 0.9 mm that is 0.4 mm larger than in the control. Drennan et al. (2003) parameterization exhibits very low values of roughness length. Values around the 50°S latitude – where maximal values are found in other parameterizations – barely reach 0.15 mm.

As a result, we can notice similar patterns of differences for the momentum flux (see figure 3): larger roughness length induces larger momentum fluxes. The largest differences occur in the mid- to high-latitudes; however, the order of magnitude of those differences is not as large as for the roughness length. The SCOR relationship and the Taylor and Yelland (2001) parameterizations both exhibit an increase of momentum fluxes compared to the control in the North-West region of the Pacific and Atlantic oceans and in the Southern Ocean. The Drennan et al. (2003) parameterization exhibits a decrease in these same regions.

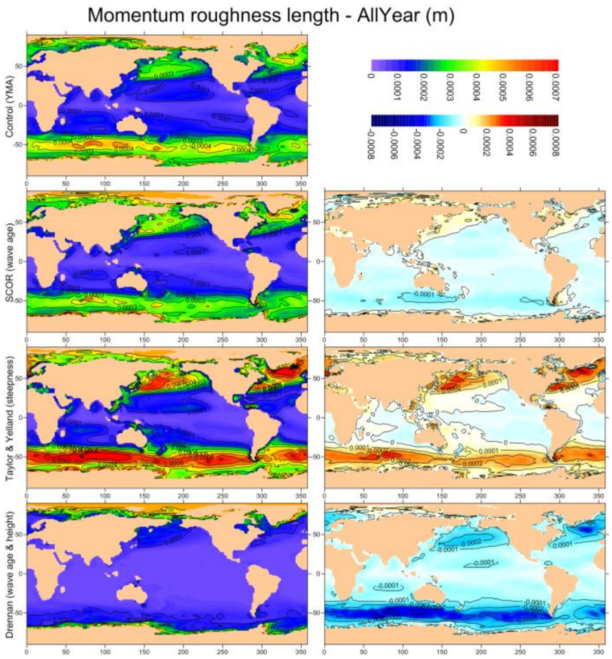

Figure 2: Annual momentum roughness length (m) over the ocean averaged over the 9-year simulations for four different sea surface roughness parameterizations (left column) and difference with the control (right column).

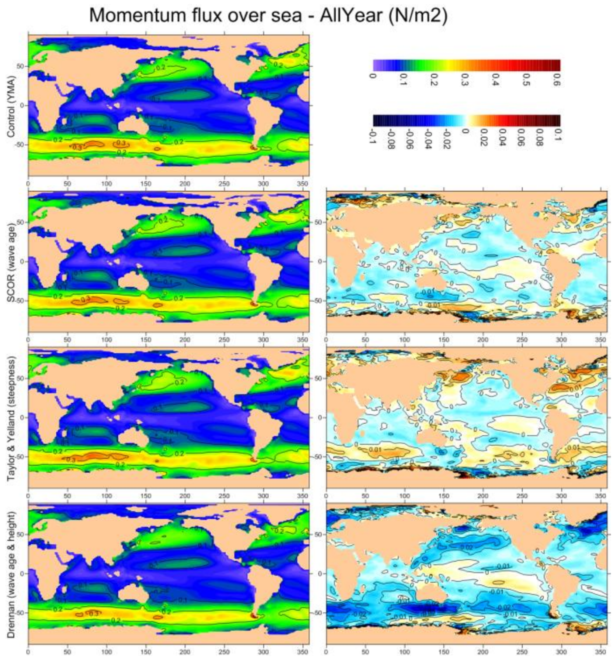

Figure 3: Annual momentum flux (N/m^2) over the ocean averaged over the 9-year simulations for four different sea surface roughness parameterizations (left column) and difference with the control (right column).

3.2 WIND CONDITIONS

As for the roughness length, the Taylor and Yelland (2001) and Drennan et al. (2003) parameterizations bound the results in terms of surface wind speed (see figure 4). The increase in roughness obtained with Taylor and Yelland (2001) in the Southern Ocean results in a decrease of annual mean wind speed of up to -0.6 m/s. The very low roughness values obtained with Drennan et al. (2003) result in an overall increase of the surface wind speed compared to the control, especially in the Southern Ocean (up to +2 m/s) and in the Central Pacific (up to +1.2 m/s). Finally, the SCOR relationship exhibits an increase of the 10-m wind speed in the Southern Ocean (up to +0.6 m/s) compared to the control.

3.3 WAVE CONDITIONS

The choice of the roughness parameterization impacts the significant wave height firstly in the wave generation areas. As they are generated by the surface wind, waves vary in accordance with the wind speed changes in these areas (see figure 5). The regions with smaller sea surface roughness and larger wind speed compared to the control – the Southern Ocean for both SCOR and Drennan et al. (2003) parameterizations and the North-West regions of the Pacific and Atlantic Oceans for the latter – present larger wave heights. In Taylor and Yelland (2001), the rougher sea surface in the mid- to high-latitudes results in smaller wave heights.

However, outside the generation areas, the wave changes do not necessarily follow the wind speed changes. The swell propagation towards the equator is particularly noticeable in Drennan et al. (2003): as the waves generated in the Southern Ocean propagate towards the Indian Ocean or the South Pacific, the pattern of increase also extends to these regions.

3.4 HEAT FLUXES AND SEA SURFACE TEMPERATURE

The thermal roughness length, used to calculate the heat fluxes between the atmosphere and the ocean, depends on the momentum roughness length. It is reduced with the SCOR relationship and the Taylor and Yelland (2001) parameterization compared to the control (not shown here). The Drennan et al. (2003) parameterization exhibits smaller values around the equator and slighlty larger values in other regions.

Then, the choice of the roughness parameterization has the potential to affect heat fluxes and sea surface temperature. However, the short spin-up used in this study does not allow assessing any changes in the ocean at this point.

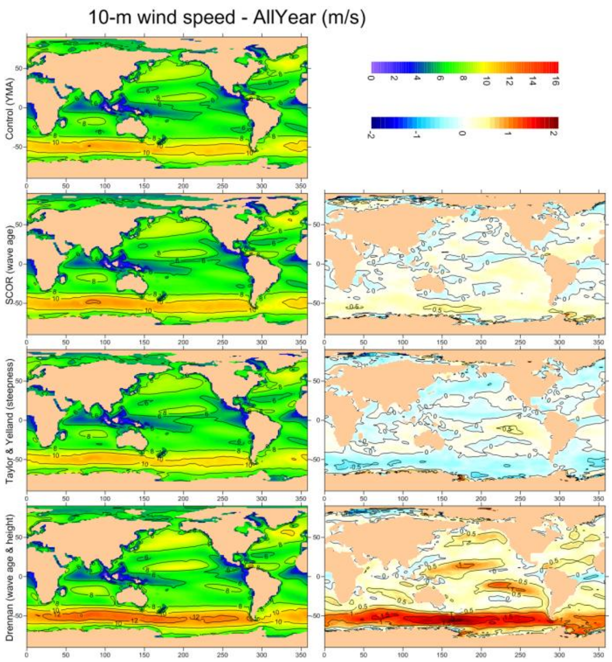

Figure 4: Annual 10-m wind speed (m/s) averaged over the 9-year simulations for four different sea surface roughness parameterizations (left column) and difference with the control (right column).

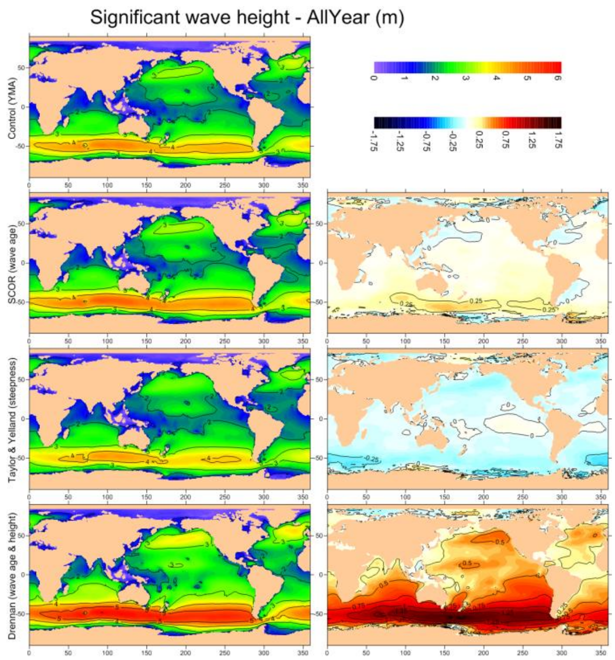

Figure 5: Annual significant wave height (m) averaged over the 9-year simulations for four different sea surface roughness parameterizations (left column) and difference with the control (right column).

4. DISCUSSION AND CONCLUSIONS

The short-term simulations analyzed in this study highlight that the choice of the surface roughness parameterization has a significant impact on the atmospheric boundary layer and wave conditions.

The three wave-dependent parameterizations that we tested give quite different results. In particular, the Drennan et al. (2003) parameterization exhibits large differences with the control for all analyzed parameters. The plots of roughness versus wind speed (see figure 6) underline the singularity of this parameterization. The Drennan et al. (2003) parameterization (black dots) systematically gives smaller values of roughness length for a given wind speed. The other parameterizations roughness values vary within a common range and exhibit slight variations, depending on the wave conditions (Indian Ocean is dominated by swell whereas the location in the North Atlantic is a wave generation area).

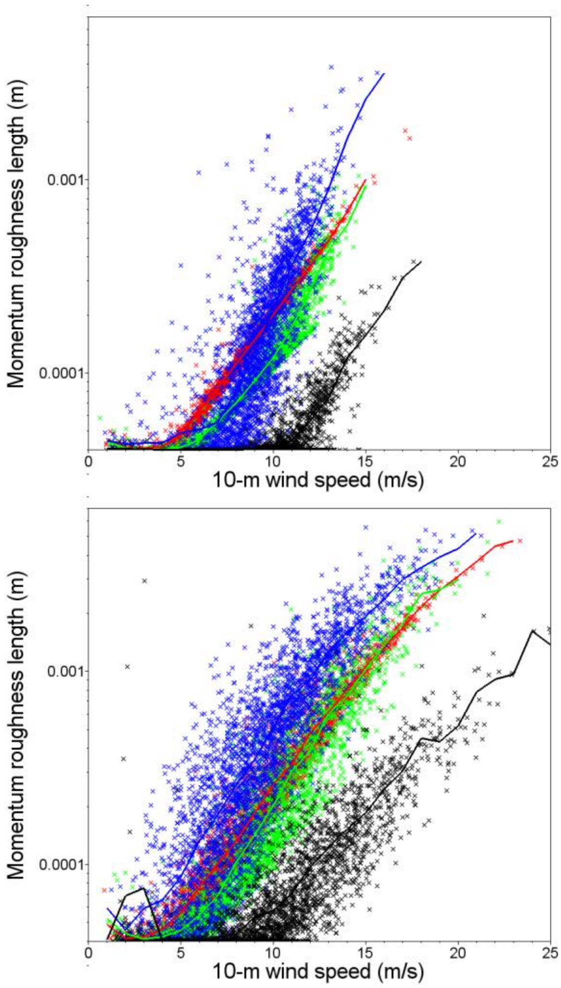

Figure 6: Plots of daily mean values of momentum roughness length versus 10-m wind speed at two locations: (top) in the Indian Ocean (78.75°E;-15°N) and (bottom) in the North Atlantic Ocean (330°E;50°N). Control (red), SCOR relationship (green), Taylor and Yelland (2001) (blue) and Drennan et al. (2003) (black) are plotted.

At this stage, it is difficult to determine which parameterization gives more realistic results. One of the motivations for implementing a wave model in a climate model is to reduce the biases in the Southern Ocean: in the atmospheric boundary layer, wind speeds simulated by models are generally larger than observed ones. From that perspective, the Taylor and Yelland (2001) parameterization would give an interesting reduction of the wind speed in this region. However, the choice of one parameterization requires a thorough analysis of the oceanic and atmospheric parameters globally, preferably comparable with observed climatology.

Long-term simulations with present day conditions will be carried out in a near future, allowing a deeper investigation of the changes highlighted in this paper, an analysis of the changes in the oceanic boundary layer and a comparison with present day climatology.

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REFERENCES

Babanin, A. V., M. Onorato, and F. Qiao (2012): Surface waves and wave-coupled effects in lower atmosphere and upper ocean. J. Geophys. Res., 117, C00J01, doi:10.1029/2012JC007932.

Bi, D., Dix, M., Marsland, S., O'Farrell, S., Rashid, H., Uotila, P., Hirst, A., Kowalczyk, E., Golebiewski, M., Sullivan, A., Yan, H., Hannah, N., Franklin, C., Sun, Z., Vohralik, P., Watterson, I., Zhou, X., Fiedler, R., Collier, M., Ma, Y., Noonan, J., Stevens, L., Uhe, P., Zhu, H., Griffies, S., Hill, R., Harris, C. and Puri, K. (2013): The ACCESS coupled model: description, control climate and evaluation. Aust. Met. Oceanogr. J., 63, 41-64.

Cavaleri, L., Fox-Kemper, B. and Hemer, M. (2012): Wind-Waves in the Coupled Climate System. Bull. Amer. Meteor. Soc., 93, 1651-1661.

Charnock, H. (1955): Wind stress on a water surface. Quart. J. Roy. Meteor. Soc., 81, 639-640.

Dix, M., Vohralik, P., Bi, D., Rashid, H., Marsland, S., O'Farrell, S., Uotila, P., Hirst, T., Kowalczyk, E., Sullivan, A., Yan, H., Franklin, C., Sun, Z., Watterson, I., Collier, M., Noonan, J., Rotstayn, L., Stevens, L., Uhe, P. and Puri, K. (2013): The ACCESS coupled model: documentation of core CMIP5 simulations and initial results. Aust. Met. Oceanogr. J., 63, 83-99.

Drennan, W. M., Graber, H. C., Hauser, D. and Quentin, C (2003): On the wave age dependence of wind stress over pure wind seas. Journal of Geophysical Research, 108(C3), 8062.

Fairall, C.W., E.F. Bradley, J.E. Hare, A.A. Grachev and J.B. Edson (2003): Bulk Parameterization of Air-Sea Fluxes: Updates and Verification for the COARE Algorithm. J. Climate, 16, 571-591.

Jones, I. S. F. and Toba, Y (2001): Wind Stress Over the Ocean. Cambridge, UK: Cambridge Univ. Press.

Lock, A. and Edwards, J (2011): The parameterization of boundary layer processes. UM Documentation Paper 24.

Ma, Y., Zhou, X., Bi, D., Sun, Z. and Hirst, A. (in prep.): Improved Air-Sea Flux Algorithms in an Ocean-Atmospheric Coupled Model for Projection of Global Ocean SST and its Tropical Pacific Variability.

Sullivan, P. P., McWilliams, J. C, 2010: Dynamics of Winds and Currents Coupled to Surface Waves. *Annu. Rev. Fluid Mech.*, *42*, 19-42.

Sun, Z., Franklin, C., Zhou, X., Ma, Y., Okely, P., Bi, D., Dix, M., Hirst, A., Shonk, J. and Puri, K. (2013): Modifications to atmospheric physical parameterisations aimed at improving SST simulations in the ACCESS coupled model. Aust. Met. Oceanogr. J., 63, 249-259.

Taylor, P. K. and Yelland, M. J (2001): The Dependence of Sea Surface Roughness on the Height and Steepness of the Waves. Journal of Physical Oceanography, 31, 572-590.