Estimates of the contribution of wind-waves in the coupled ocean-atmosphere climate system.

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ABSTRACT

It has been argued that surface wind waves make a non-trivial contribution in the coupled ocean-atmosphere climate system and that these wave dependent processes are large enough and sufficiently understood to warrant their inclusion in fully coupled ocean-atmosphere-ice general circulation models (AOGCMs). However to justify the extra computational overhead, some quantitative estimates of the contribution of waves to global budgets are required. Our study aims to provide initial quantification of two notable processes with recent parameterisations of these processes and realistic forcing: 1) the sea-state dependence of atmospheric drag, with its consequent influence on momentum, heat and moisture exchanges across the air-sea interface. We find seastate dependent parameterisations of drag at the sea-surface result in a range of up to 1PW of additional heat transfer to the ocean, which is within the bounds set by alternative wind-dependent parameterisations; and 2) the contribution of waves to mixing of the surface ocean. Here, we find wave driven forcing of 1-d mixing models applied globally results in approximately 1PW of additional heat uptake in the global ocean per year.

1. INTRODUCTION

The ocean is a critical component of the earth's climate system. The extent to which the ocean drives the atmospheric climate is dependent on the exchange of radiation, heat, mass, momentum, and freshwater across the air-sea interface. Many observational studies have shown that surface waves significantly modulate these exchanges, but our earth climate models are yet to consider the effects these have on simulations of our global climate. Presently, many of these processes are parameterized as a function of wind speed only. While this may be appropriate when winds and waves are in equilibrium, we are aware that swell dominates the global wave field (Semedo et al., 2011) and for some processes wind-dependent parameterisations may not be the most representative of the physical system. It has therefore been recently argued (e.g., Cavaleri et al., 2012) that the contribution of waves to surface exchange is now sufficiently understood, measured and predictable enough to warrant a more detailed representation in coupled ocean-atmosphere climate models. However quantitative estimates of the contribution of waves to global climate budgets, required to justify the extra computational overhead required of coupled wave-climate model, were left wanting.

A coupled wave-climate model could incorporate many processes. In the first instance, we concentrate on two processes, but will continue to expand the range of processes considered in future studies. The first wave modulated process considered, following the early work of ECMWF (e.g., Janssen and Viterbo, 1996) is the sea-state dependence on atmospheric drag and the consequent influence on momentum, heat and moisture exchange across the air-sea interface. The other process we consider is the contribution of waves to mixing of the surface ocean. In this paper, we present first-order estimates of the contribution of waves to the global heat budget via these processes. The paper is structured such that, following this introduction, section 2 focuses on the sea-state dependent drag parameterisations, section 3 focusses on wave driven mixing, and section 4 presents some concluding remarks.

2. SEA-STATE DEPENDENT DRAG

Air-sea fluxes of momentum, heat, freshwater and their components have been computed globally using CORE Normal Year Forcing and the monthly Hadley Centre sea Ice and SST data set version 1 (HadISST1) (following Large and Yeager, 2009).

Wave forcing is derived from a purpose run 1degree implementation of WaveWatchIII (Tolman, 2009; v.4.08, using Ardhuin et al., 2010 source terms) using the subgrid island blocking scheme of Tolman (2003), as modified by Chawla and Tolman (2007). The model was run on a 1 x 1 degree global (-79.5:79.5 x 0.5:359.5) grid, with the wave spectra discretised over 32 frequencies exponentially spaced from 0.0373 Hz to 1.1 Hz and 24 directions with a constant 15 degree directional resolution. The wave model uses a time and component variable time step, resulting in a global model output every 3600s.

The wave model was forced with CORE2 normal year winds (Large and Yeager, 2004) (to provide a self consistent dataset with the atmospheric forcings), and climatological annual cycle of sea-ice distribution (NSIDC update of Chapman and Walsh, 1991). Six-hourly CORE2 data was linearly interpolated to the WWIII resolutions. Integrated parameters were archived 6-hourly on the 1degree grid. Full 2-D wave-spectra, from which Stokes profile was calculated (see Section 3), were archived at 4 degree grid points at 6-hourly temporal resolution.

We investigate the sensitivity of the air-sea surface fluxes to three available sea-state dependent parameterisations of the transfer coefficient for drag. Those used are:

i) Wave age dependent (Oost et al., 2002)

$$z_o = (50/2\pi)\ \lambda_p\ (u_{*a}/c_p)^{4.5}$$

ii) Wave steepness dependent (Taylor and Yelland, 2001)

$$z_o = 1200\ H_S\ (H_S/\lambda_p)^{4.5}$$

iii) Wave induced stress dependent (Janssen and Viterbo, 1996)

$$z_o = \alpha\ (u_{*a}^2/g),\ \alpha = \beta(1 - (\tau_\omega/\tau))$$

all with an additional smooth flow limit term added. These roughness parameterisations are tested relative to the wind dependent parameterisations used in Large and Yeager (2009) and a constant Charnock parameter (coefficient, $\alpha = 0.01$). We repeat the calculations of Large and Yeager (2001), testing sensitivity of their results to alternative (sea-state dependent) parameterisations of roughness, and determine the relative global mean air-sea flux components for each drag parameterization. Figure 1 displays global maps of mean momentum flux bias relative to the momentum flux computed using parameterisations used by Large and Yeager (2004). Table 1 summarises calculations carried out in the study, presenting the global mean heat flux components (latent, sensible, short-wave radiative, long-wave radiative and total heat flux) for each parameterization of drag implemented. Which of these parameterisations is the most appropriate or best is not our aim. Our objective is to determine the sensitivity of annual global mean air-sea exchanges to sea-state dependent parameterisations of roughness.

The global heat and momentum budgets display large sensitivity to available parameterisations of drag. Global integration of the total heat flux (Table 1) indicates seastate dependent parameterisations result in up to 0.65 PW of additional heat transfer to the ocean (relative to the CORE estimates which use the wind speed dependent parameterization defined in Large and Yeager, 2004). Relative to other wind-speed dependent parameterisations of drag (e.g., constant Charnock parameter), sea-state dependent parameterisations imply up to 2.32 PW of additional heat storage in the global ocean. This suggests the supposed contribution of additional heat via consideration of wave dependent drag is of similar magnitude to the uncertainty which surround estimates based on alternative wind dependent parameterisations of drag.

3. WAVE-DRIVEN SURFACE OCEAN MIXING

The parameterizations of upper ocean mixing used in the current generation of climate models are forced by air-sea fluxes of momentum, heat and salt with no dependence on surface waves. These models typically have large errors of both signs in boundary layer thickness (Belcher et al., 2012) and, in particular, consistently predict overly shallow boundary layers in the Southern ocean (e.g., Sallee et al., 2013). It seems likely that these errors are due to inaccurate representations of vertical mixing processes and lateral restratification processes that thin the boundary layer (Fox-Kemper et al., 2011).

Three wave driven mechanisms have been proposed capable of mixing the surface ocean. The injection of turbulence into the surface ocean due to breaking waves, which is capable of mixing to depths of order of the wave height (Craig and Banner, 1994), Langmuir mixing, which is capable of mixing to depths of order 100m (e.g., Thorpe, 2004), and mixing driven by non-breaking waves as proposed by Bababin and Haus (2009). In this study, we consider only the contribution of wave (Stokes drift) driven Langmuir mixing to the surface ocean mixed layer.

One-dimensional mixed layer simulations were carried out globally, using CORE normal year atmospheric forcing. The mixed-layer model implemented was the second moment closure model of Harcourt (2012) which deviates from the Mellor-Yamada 2.5 parameterizations due to inclusion of the Craik-Leibovich (CL) vortex force. Differences include additional forcing terms in the equilibrium model, or algebraic closure, that underpins stability functions relating turbulence velocity and length scales to eddy viscosities and diffusivities. Furthermore, a component of the momentum flux is directed down the gradient of Stokes shear. These modifications offer a more detailed prognosis of the effects of Langmuir turbulence beyond additional production of turbulent kinetic energy (TKE) terms introduced by d'Allessio et al (1998) or Kantha and Clayson (2004) because they account for the different mixing impacts of shear and CL production into the different components of TKE.

A year-long independent depth-time simulation was run at 4 degree intervals (latitude and longitude) across the global ocean. Each simulation was initialized near the summer solstice (approximately mid-June in the northern hemsiphere, and approximately mid-December in the southern hemisphere). Initial salinity and temperature profiles were derived from the over 700,000 Argo profiles taken during the years 1992-2010 (Gould et al., 2004). The summer solstice profile used for initialization was taken as an Argo profile we consider to be the most representative of the Argo profiles which occurred within +-40 days of the solstice and 4 degrees of each gridpoint. The most representative cast was the one that had the maximum correlation with the ensemble average of the collection of profiles in this window. Actual casts were used as initial profiles instead of averages, because averages had too much smoothing, which made for weak stratification and unrealistic levels of mixing.

The mixing model was forced using CORE normal year atmospheric forcing (Large and Yeager, 2004), with self evolving sea-surface temperature. Stokes spectra forcing was derived from the CORE normal year forced global 1 degree model described above, where spectral data was archived at 4 degree intervals – defining the locations at which Argo profiles were collected and mixing model simulations were undertaken.

The mixing model was integrated over a full annual cycle, with and without surface wave forcing. The effects of waves were determined as the difference between the two simulations, assessed after 6 months (near winter solstice, assumed near to the end of the mixing season) and 12 months (at completion of the annual cycle)

By comparing identical calculations with and without wave forcing, the effect of waves is isolated. Wave forcing has little effect at tropical or subtropical latitudes, but increases simulated boundary layer depths at high latitudes by 15-20% on average. This supports arguments of Belcher et al. (2012) that the effects of waves in enhancing boundary layer turbulence varies geographically and may explain some climate model biases in mixed layer depth. The contribution of surface wave generated turbulence within these models is unlikely to be properly included without consideration of the geographical variations in surface waves. In a changing climate, the distributions of both wind and waves, and perhaps their relative importance in driving mixing, is likely to change (Hemer et al., 2013).

Wave driven forcing of these mixing models leads to an approximate 25% increase in mixed layer depth in the extra-tropical storm belts, which is greater during the winter mixing season. Expressed as a surface heat flux, this is equivalent to up to $10Wm^{-2}$, or an additional heat uptake of 1.0 PW to the global ocean over one year.

4. CONCLUDING REMARKS

This study provides quantitative estimates of the non-trivial contribution of waves in the coupled climate system. We find that both parameterization of sea-state dependent drag and of wave driven Langmuir mixing have contributions to the global heat budget of the same order of magnitude as (and potentially provide a mechanism to improve) current biases in AOGCMs.

However, the approach taken for this study is a simplification which overlooks the feedback processes in the coupled system which might exist. Several groups have now commenced coupling of wave models to coupled climate models (e.g., Charles and Hemer, this volume; Qiao et al., 2013) to determine the contribution of the wave driven processes in the coupled system. Recent work has also demonstrated potentially significant effects of waves on submesoscale and mesoscale motions (McWilliams & Fox-Kemper, 2013).

To communicate the importance of waves in the climate system, there is a need for the waves community to present the magnitude of the contribution of waves in terms of interest to climate researchers - via the global heat budget. Waves modulate many other exchanges in the coupled system which we have not yet considered. We will continue to resolve quantitative estimates of the relative contribution of waves by these processes within the climate system. The simplistic approaches presented here offer some advantage to resolving the relative magnitude of different processes before the ultimate development of coupled wave-climate models.

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Table 1. Mean annual heat flux components associated with alternative parameterisations of sea-surface drag.

Flux	Large and Yeager, 2004	Charnock	Oost et al., 2002	Taylor and Yelland, 2002	Janssen and Viterbo, 1996
Sensible Heat Flux, Q_h	-12.8	-13.4	-12.9	-12.7	-13.4
Short-wave radiative heat flux, Q_s	178.4*	178.4*	178.4*	178.4*	178.4*
Long-wave radiative heat flux, Q_l	-53.9	-53.9	-53.9	-53.9	-53.9
Latent heat flux, Q_e	-107.4	-112.0	-106.5	-105.3	-111.9
Total heat flux, Q_a	4.3	-1.0	4.9	6.4	-0.8
Integrated additional heat storage	1.35 PW	-0.32 PW	1.34 PW	2.00 PW	-0.26 PW

*No consideration of whitecapping contribution

Figures

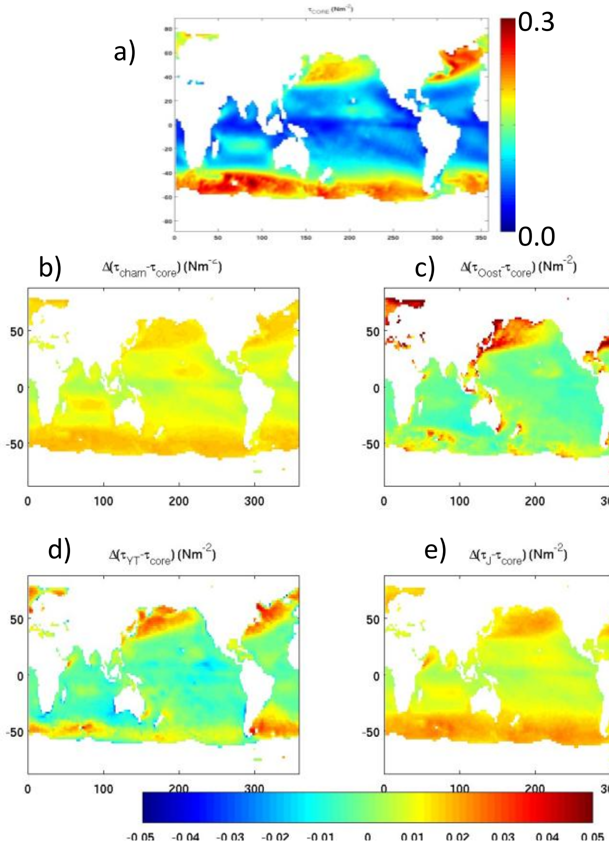

Figure 1

Figure 1. a) Mean annual mean CORE normal year momentum flux using the Large and Yeager drag parameterization (Nm^{-2}). b-e) Mean annual momentum flux bias (Nm^{-2}), relative to a), when using b) Charnock; c) Oost et al., 2002; d) Taylor and Yelland, 2001; and e) Janssen and Viterbo, 1996 parameterisations of drag.

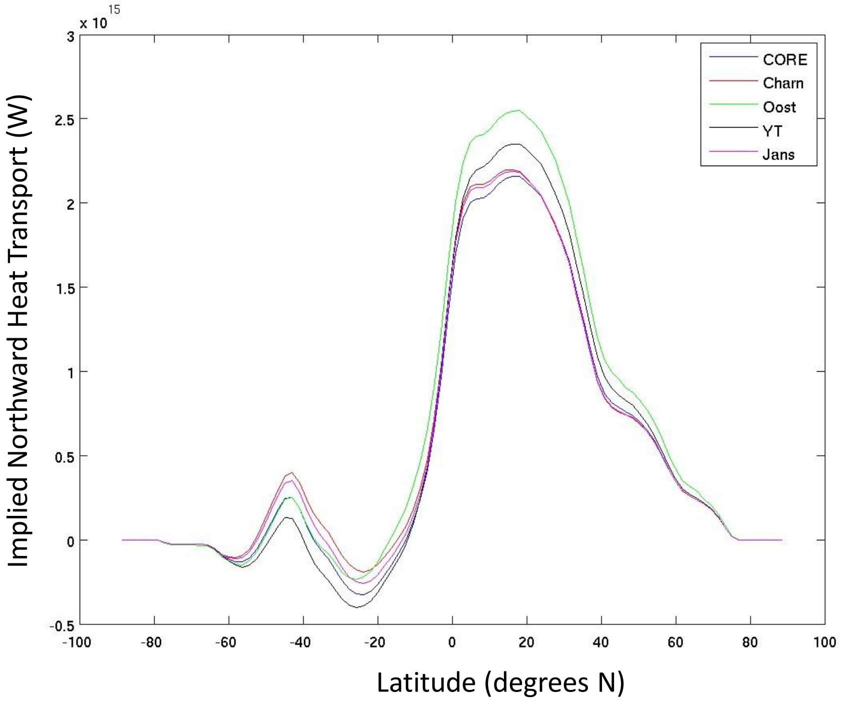

Figure 2

Figure 2. Implied northward heat transport (in W) given alternate parameterisations of drag. CORE uses Large and Yeager parameterisations, ‘Charn’ uses constant Charnock parameter, ‘Oost’ uses Oost et al., 2002, ‘YT’ uses Taylor and Yelland, 2001, and ‘Jans’ uses Janssen and Viterbo, 1997. Each calculation assumes a uniformly distributed storage (or bias) across the global ocean. The magnitude of this storage term is given in Table 1.

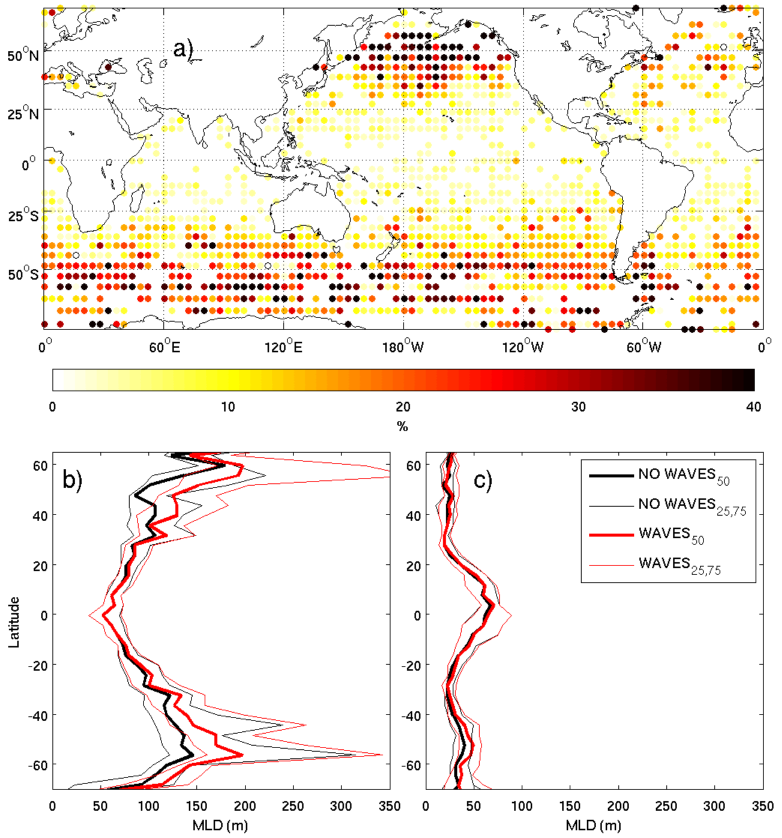

Figure 3

Figure 3. Contribution of wave driven mixing following annual integration of 1-D mixed-layer model using the second moment closure model of Harcourt (2012). A) Percentage increase in mixed layer depth with introduction of Langmuir mixing ~ 180 days after summer solstice (i.e., January snapshot in northern hemisphere and June snapshot in southern hemisphere). B) zonal mean mixed layer depth (MLD) ~180 days after summer solstice (~end of mixing season); c) zonal mean mixed layer depth at end of annual cycle.