A coupled atmosphere-ocean wave system for understanding air-sea fluxes

W. Perrie\textsuperscript{1} & Y. Zhang\textsuperscript{2}
\textsuperscript{1}Ocean Sciences Div., Maritimes Region, Fisheries & Oceans Canada
Bedford Institute of Oceanography, Canada
\textsuperscript{2}Dept. of Atmospheric Sciences, Nanjing University, PR China

Abstract

Our model for atmosphere-ocean wave coupled dynamics consists of the NCAR RegCM2 climate model and the WAM ocean wave model. Our domain of implementation is the North Atlantic. Coupling of atmospheric and surface ocean dynamics is achieved by the HEXOS sea-state dependent roughness. No explicit sea-state dependent thermal mechanism such as sea spray is considered. Our time-scales for simulations range from synoptic to seasonal. Results are compared with data collected during LSDCE (Labrador Sea Deep Convection Experiment).

1 Introduction

The study of climate dynamics and climate change requires an understanding of the exchanges of momentum, heat and water vapor at the air-sea interface. This is important for simulations and climate modelling on all time-scales, particularly for coupled atmosphere-ocean climate models. In the case of global coupled atmosphere-ocean general circulation models (GCM), it has often been necessary to apply flux corrections to resolve the climate drift problem. However, these models normally parameterize complicated air-sea interactions by simple bulk formulations, ignoring the ocean surface waves and detailed boundary layer interactions. Because air-sea fluxes of heat and momentum have a detailed linkage to sea-state, we suggest that it is therefore important to consider ocean surface waves, in simulations of the coupled atmosphere-ocean system.
In this paper, we construct a model system for coupled atmosphere-ocean dynamics for the North Atlantic, consisting of the NCAR Regional Climate Model RegCM, and the WAM ocean wave model. Coupling between these two models is achieved through the wave age (WA) dependent roughness of Smith et al. [1],

\[ Z_0 = 0.48 \times \left( \frac{C_p}{u_*} \right)^{-1} \frac{u_*^2}{g} \]  

where \( u_* \) is the friction velocity, \( g \) the acceleration due to gravity, \( u_*/C_p \) or alternately, \( U_{10}/C_p \), in terms of the 10m neutral wind speed, \( U_{10} \), where \( C_p \) is the phase speed at the peak of the wave spectrum. This represents a generalization of the traditional Charnock [2] relation,

\[ Z_0 = \alpha_c \frac{u_*^2}{g} \]  

where \( \alpha_c \) is the Charnock parameter, originally set to 0.011. It is well known that the Chanock relation corresponds to old or mature wind-sea. In the limit as waves become more mature, inverse wave age \( u_*^2/C_p \) decreases: for \( u_*^2/C_p > 26 \), the HEXOS \( Z_0 \) is less than that of the Charnock \( Z_0 \) of eqn (2), assuming 0.0185 for the Charnock parameter \( \alpha_c \), as suggested by Wu [3].

In this paper we are concerned with the impact that momentum coupling can have on atmospheric-ocean wave models. Model results are compared with field data collected during the Labrador Sea Deep Convection Experiment (LSDCE) [4], for both synoptic and seasonal time-scales. No similar sea-state dependent relation is available for heat and water vapor fluxes. The interplay of momentum and heat fluxes, between atmosphere and ocean surface wave models has been the subject of a number of studies using numerical models (Weber et al. [5]; Doyle [6]; Janssen and Viterbo [7]; Lionello et al. [8]; Desjardins et al. [9]; Lalbeharry et al. [10]). We note that Desjardins et al. [9] suggest that the effects of atmosphere-ocean coupling tend to be quite local and not actually located in active storm regions. They found small beneficial effects of coupling for surface parameters and they suggest that while the synoptic-scale aspects of the storm were only weakly affected, the impact for longer time-scales may be stronger.

2 Model description

The atmospheric model used in this study is RegCM of Giorgi et al. [11] [12]. It is a limited-area model similar to the Penn state-NCAR Mesoscale Model version 4.0 (MM4). It is hydrostatic and compressible and based on primitive equations, with a terrain-following \( \sigma \)-vertical coordinate, defined as \( \sigma = (p - p_1)/(p_2 - p_1) \), where \( p \) is pressure, \( p_1 \) is pressure at the uppermost model level and \( p_2 \) is the
surface pressure. We used 11 vertical σ levels with σ= 1.0, 0.99, 0.97, 0.93 and 0.85 for the lowest five levels. The model includes a state-of-the-art surface physics package, namely the Biosphere-Atmosphere Transfer Scheme (BATS), with an explicit planetary boundary model, detailed simulation of atmospheric radiation and a Kuo-type cumulus parameterization. Time-dependent sea surface temperatures are specified by interpolating weekly mean AVHRR (Advanced Very High Resolution Radiometer) values, from http://podaac.jpl.nasa.gov/mcsst.

Initialization of RegCM model prognostic variables (u, v, T, q, pS and TS) occurs at each horizontal model grid point and (except the surface pressure, pS and surface temperature, TS) at each model level. On the lateral boundaries of the domain, the model prognostic variables are forced prognostically, by using the reanalysis data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR), interpolated linearly to the model grid at 6-hourly intervals. The study domain covers the Canadian East coast, the Labrador Sea and the North Atlantic Ocean and is centered at 55°W, 55°N, with a 4500x4000km² size and a horizontal gridpoint spacing of 50km, for the period from 1 February - 30 March, 1997.

Ocean waves are simulated via the WAM model of Komen et al. [13]. This model gives the spectral energy density for surface gravity waves in deep water $E(f, \theta)$ as they evolve in space and time according to the relation

$$\frac{\partial E(f, \theta)}{\partial t} + \mathbf{C}_g \cdot \nabla E(f, \theta) = \varphi_{in} + \varphi_{ds} + \varphi_{nl}$$

where $\varphi_{in}$ is the spectral energy input by the wind, $\varphi_{ds}$ is the dissipation due to wave-breaking and white-cap formation, and $\varphi_{nl}$ is the nonlinear transfer of spectral energy due to wave-wave interactions. Parameterizations for $\varphi_{in}$, $\varphi_{ds}$ and $\varphi_{nl}$ are given in Komen et al. [13]. The WAM implementation represents $E(f, \theta)$ by 54 frequencies, ranging from 0.0417725 to 0.65268 Hz, and 12 directions, at every grid point. The spatial resolution of the wave model domain is 75°W-30°W and 37°N-65°N, on a 0.5° spatial grid.

The WA coupling mechanism uses the HEXOS sea surface roughness of eqn (1), relating $Z_o$ to wave age. The coupling scheme was developed to allow data communication between the two models. Because RegCM and WAM have time steps of 150s and 1200s respectively, the time step for data communication is 1200s. Thus, after eight RegCM model time steps, the winds are passed to WAM from RegCM, and associated variables are passed from WAM to RegCM. An iterative relaxation is included to achieve an equilibrium state among winds, waves and $Z_o$ at each gridpoint. This keeps $u*$ and $Z_o$ consistent in both RegCM and in WAM. By comparison, studies such as Desjardins et al. [9] have been concerned to pass $U_{10}$ from the atmospheric model to the wave model, implying that atmospheric model values for $u*$ and $Z_o$ can differ from those of WAM. In uncoupled mode, RegCM provides the winds to WAM as driving fields. There is no passage of data back to RegCM, however.
3. Synoptic time-scales

Synoptic storms occurring during LSDCE (Labrador Sea Deep Convection Experiment) can be represented by the time-series for significant wave heights, $H_S$, measured at buoys off Eastern Canada. $H_S$ time-series are shown in Figure 1, partially representing the LSDCE data, in comparison with coupled and uncoupled model estimates.

![Wave Height Time-Series](image.png)

Figure 1: Observed $H_S$ at buoy 44138, (—), at the peak of a storm crossing the NW Atlantic at 0800 UTC on March 8, 1997 compared to coupled (higher dashed line) and uncoupled models (lower dashed line), at 44.258°N Latitude and 53.623°W Longitude. Units are meters.

This shows that $H_S$ estimates from the uncoupled model seriously under-predict measurements at the buoy. Coupled model $H_S$ estimates are an improvement.
Figure 2: Sea level pressure from the coupled model, at the peak of the March 8 storm. Contour intervals are 5 hPa units.

The highest $H_S$ values occur at mid-day on March 8. To investigate this storm in detail, we consider the atmospheric and wave fields. Figure 2 gives the sea level pressure for the coupled model. The coupled model generates an enhanced deepening, by about 4 mb, compared to the uncoupled model. The uncoupled model is about 3 mb deeper than the coupled model just to the north of the low pressure minimum. This gives a dipole structure that implies a slight variation in storm trajectory speed. Far away from the storm centre, the pressure differences are negligible, as demanded by the NCEP boundary conditions. Associated wind field differences also show that the coupled model experiences higher winds at the storm centre. Slightly to the west and southwest of the storm, the uncoupled model has comparatively stronger winds, following the dipole structure of pressure fields. The wind dipole variation is about 40%, at most.
Coupled model contours for significant wave heights $H_S$ are shown in Figure 3, showing a high $H_S$ centre east of Newfoundland, in association with the March 8 storm. In effect, the coupled model $H_S$ estimates can exceed uncoupled model $H_S$ estimates by as much as 3.5m, or ~60%, near the storm centre.

4. Seasonal time-scales

To identify the impact of coupling dynamics on seasonal time-scales, we consider several boundary layer fields, for example, the mean temperature fields, winds, waves, pressure and precipitation. The differences between coupled and uncoupled models temperature values, at 1000mb, are slightly negative, over the open ocean, with very small biases. This implies that the WA coupling formulation slightly weakens the low pressure system on seasonal time-scales, over the ocean. Further analysis shows that the coupled model provides a slight systematic improvement, compared to the uncoupled model, with respect to the NCEP/NCAR reanalysis data. For wind fields, there is a negative bias around 45°-55°N and a positive bias near the Icelandic low. Thus, as a result of WA coupling, wind speeds seem to increase, to some extent, near the atmospheric active centre, and to decrease in the other regions. The maximum wind speed variation is small, ~10%, comparing coupled and uncoupled models.

In terms of the ocean wave climate, significant wave heights from the coupled model, as well as the difference fields between the coupled and uncoupled models, averaged for the LSDCE period in 1997 February-March, are considered.
The maximum differences in $H_S$ occur close to the dominant atmospheric centre i.e. the Icelandic low, at long fetches from the North American coast, in association with strong wind fields. Moreover, $H_S$ from the coupled model exceeds $H_S$ from the uncoupled model by as much as 1.4m, in qualitative agreement with TOPEX-Poseidon altimeter data.

5. Conclusions

To assess whether the coupling of ocean waves to the atmosphere can improve simulations of synoptic marine storms as well as climate simulations on time-scales of months/seasons, we constructed a coupled atmosphere-ocean wave model system using the NCAR regional climate model (RegCM) and the WAM ocean wave model. Coupling was via the WA parameterization for sea surface roughness of Smith et al. [1]. The model was used to investigate ocean-atmosphere interactions during the Labrador Sea Deep Convection Experiment (LSDCE). For synoptic storms, we show that the atmosphere-wave coupling has impact on boundary layer fields. For example, sea surface pressure near the storm centre is decreased by ~4mb, whereas the 1000mb temperature has ~1.5°C increase, compared to the uncoupled model. Moreover, coupled model wave heights are enhanced, in qualitative agreement with synoptic and seasonal time-scale observations.

Acknowledgements

This study was funded by the Panel on Energy Research and Development (PERD) of Canada under Project #23116. We are very grateful for the use of the NCAR regional climate model, RegCM, the NCEP/NCAR reanalysis data, and AVHRR sea surface temperature data. Yaocun Zhang is on leave from the Department of Atmospheric Sciences at Nanjing University, PRC.

References

Coastal Engineering VI


