WAVE-ATMOSPHERE-OCEAN MODELLING OF RECENT STORMS

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1. INTRODUCTION

This is a paper about waves. We consider the impacts of coupling the atmosphere and ocean on estimates of the wave spectra. Two air-sea coupling processes are considered. In one, we consider the effects of sea spray and related air-sea processes. This follows the approach of Andreas and Emanuel (2001) and Bao et al. (2000). In the second, an atmospheric model is coupled to an ocean circulation model. The dynamical coupling between the atmosphere and the ocean is effected through fluxes at the air-sea interface. The heat fluxes provide positive feed-backs within the system, tending to energize the atmosphere and intensify synoptic storms, whereas momentum fluxes provide negative feed-backs, resulting in atmospheric de-intensification of synoptic storms. These processes have impacts on ocean surface waves.

This study focuses on simulations of extra-tropical storms, specifically Bonnie, Earl and Danielle and similar storms, in 1998 and later years. These storms typically have their genesis in the tropics, pass along the US seaboard and move northeast, often crossing Atlantic Canada in the neighbourhood of Scotian Shelf and the Grand Banks. Verification of wave model estimates will ultimately consist of comparisons with available buoy data from these areas, as well as available remotely sensed satellite and aircraft data.

2. MODELS

We discuss two sets of wave forecast model results: those involving impacts of sea spray-atmospheric model coupling, and those involving atmosphere-ocean circulation model coupling.

2.1 *Wave Model*

The basin-scale wave model implemented in this study is the operational NCEP (National Center for Environmental Prediction; Washington, USA) model, WaveWatch3 (WW3) on an intermediate-resolution (0.5^o) domain. WW3 is available at http://polar.wwb.noaa.gov/waves and has features including:

a). Refraction and straining of wave field due to temporal and spatial variations of the mean water depth and mean current (tides, surges…).
b). New formulations for wind input, wave-wave interactions, white-capping dissipation.
c). Longitude-latitude grid, and flexible increments in each direction.
d). Source terms are integrated in time using dynamically adjusted time-stepping, adapting to conditions of rapid spectral changes.
e). Outputs such as significant wave height, Hs, mean wave direction, $<\theta>$, peak wave period, Tp, etc., at selected locations, along arbitrary satellite tracks.

2.2 Atmosphere – Sea Spray Model

The atmospheric component for this study is the MC2 model from the Meteorological Service of Canada (MSC) described at http://www.cmc.ec.gc.ca/rpn/modcom/index2.html. This is the mesoscale compressible community model, of Bergeron et al. (1994). It has been well-tested for simulations related to storms. MC2 is a modern state-of-the-art full-elastic nonhydrostatic model solving the full Euler equations on a limited-area Cartesian domain with time-dependent nesting of lateral boundary conditions given by the large-scale model. It uses semi-Lagranigan advection and a semi-implicit time differencing dynamical scheme.

Our concern is microphysical modelling of air-sea processes, namely sea spray, related to heat and moisture transfer during severe storm conditions. Sea spray droplets in the range 1 to 500 μm are important for this process. However, the transfers of latent and sensible heat related to these droplets are decoupled – the sensible heat exchange occurs about three orders of magnitude faster than the latent heat transfer. The ambient humidity has very little effect on the temperature scale and the sea surface temperature T_S has no effect on the radius time-scale because the droplet is at its equilibrium temperature T_{EQ} during most of its evaporation. These facts and related arguments of Andreas and Emanuel (2001) imply that sea spray can accomplish a net air-sea enthalpy transfer. Following Andreas and DeCosmo (2002), total air-sea latent and sensible heat fluxes are represented,

$$H_{L,T} = H_L + \alpha \overline{Q}_L \tag{1}$$

$$H_{s,T} = H_s + \beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \tag{2}$$

where H_s and H_L are the bulk aerodynamic estimates, $\overline{Q}_S$ and $\overline{Q}_L$ are 'nominal' values for spray sensible and latent heat fluxes, and α, β and γ are constants used to tune $\overline{Q}_S$ and $\overline{Q}_L$ to HEXOS data, respectively, 4.3, 6.5 and 3.8. Details of the computation of $\overline{Q}_S$ and $\overline{Q}_L$ are given in Andreas and DeCosmo (2002). Following Andreas and Emanuel (2001), the sea spray contributions to Equations (1)-(2) are given bulk formulae representations.

1.3 *Atmospheric-Ocean Model*

For consideration of N. Atlantic storms and the impacts of climate change on these storms, we also implemented a realistic regional climate model. This is the Canadian regional climate model (CRCM) of Caya and Laprise (1998). CRCM is a state-of-the-art regional atmospheric climate model, consisting of the same semi-Lagrangian semi-implicit marching scheme (SISL) as was implemented for MC2. Thus time-steps can be almost 10 times longer than apply for an Eulerian scheme on the same spatial resolution.

CRCM was coupled to the Princeton ocean model (POM). This model is widely used and well supported (http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/). This is a primitive equation ocean model representing the basic physical processes important for this coupling study. It is driven by fluxes of mass, momentum and moisture (P-E), and in turn it provides SST (sea surface temperature) to pass back to the atmospheric model. It uses sigma vertical coordinates. The ocean thermal stratification is based on the observed seasonal-mean climate, adjusted so the SST matches the control run, without altering the vertical temperature gradients. For uncoupled experiments, the SSTs are held fixed, for each simulation.

1.4 Model Set-up and Coupling

Atmospheric models CRCM and MC2 are implemented on 30km and 35km resolution grids for the NW Atlantic, respectively. WW3 is implemented at a similar resolution on a somewhat larger domain. POM is implemented at $1/6^o$ resolution. As yet, the atmospheric wind fields are used to drive WW3 in a one-way coupling formulation. Progress on two-way coupling between WW3 and the atmospheric model will be described at the Workshop. This will involve the wave-induced stress formulations and roughness parameterizations from HEXOS, as in many recent studies.

3. CASE STUDY

Hurricane Earl (1998) is presented as an example case study. Hurricane Earl originated on 17 August from a tropical wave off of the west coast of Africa. This evolved into a weak surface cyclonic circulation as the system passed through the Lesser Antilles on August 23. The large Hurricane Bonnie, at that time located over the southwest North Atlantic, inhibited the upper-level outflow of Earl. Continuing through the Gulf of Mexico, the tropical wave became a tropical depression between Merida and Tampico, Mexico on

August 31. This developed into Tropical Storm Earl at about 930 km south-southwest of New Orleans and reached hurricane status on September 2. At that time it was 230 km south-southwest of New Orleans. Maximum winds reached 189 km/hr and minimum pressure of 850 mb were measured. Earl made landfall as a Category 1 hurricane near Panama City, Florida on September 3. While moving towards Georgia, the storm weakened quickly and became extra-tropical on September 3. It continued, crossing the Carolinas and intensifying over Atlantic Canada. By September 6, Earl crossed Newfoundland and by September 8 it was absorbed by a larger extra-tropical cyclone resulting from Hurricane Danielle.

4. DISCUSSION

4.1 Sea Spray

In Figure 1 we give minimum sea level pressure (SLP) from MC2 when sea spray is computed, compared to the case with no sea spray is computed, for Earl. This is compared with CMC (Canadian Meteorological Centre) analysis SLP for Earl. This plot shows that the maximum impact of sea spray on SLP is about 3mb near the peak of the storm's intensity, during its extra-tropical phase. Corresponding maximum differences in winds are about 7m/s.

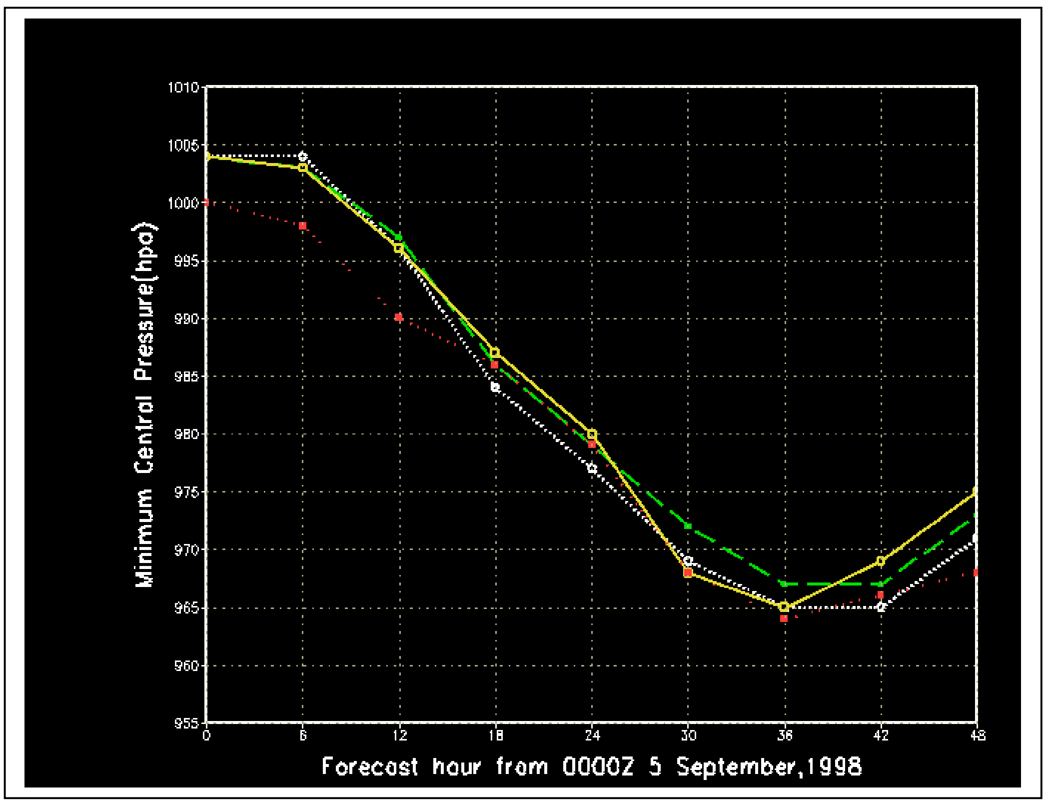

Figure 1. Minimum sea level pressure time series for Earl as it passes from the Carolinas to Labrador Sea crossing Newfoundland: solid line is CMC analysis; faint dotted line is the UNISYS analysis; dashed line is model simulation with no sea spray; bold dotted line is with sea spray.

4.2 Atmosphere-ocean

In Figure 2 we show SLP contours for the maximum impact of CRCM-POM coupling. We see a similar magnitude in variance between coupled and uncoupled simulations, as shown in Figure 1. This simulation

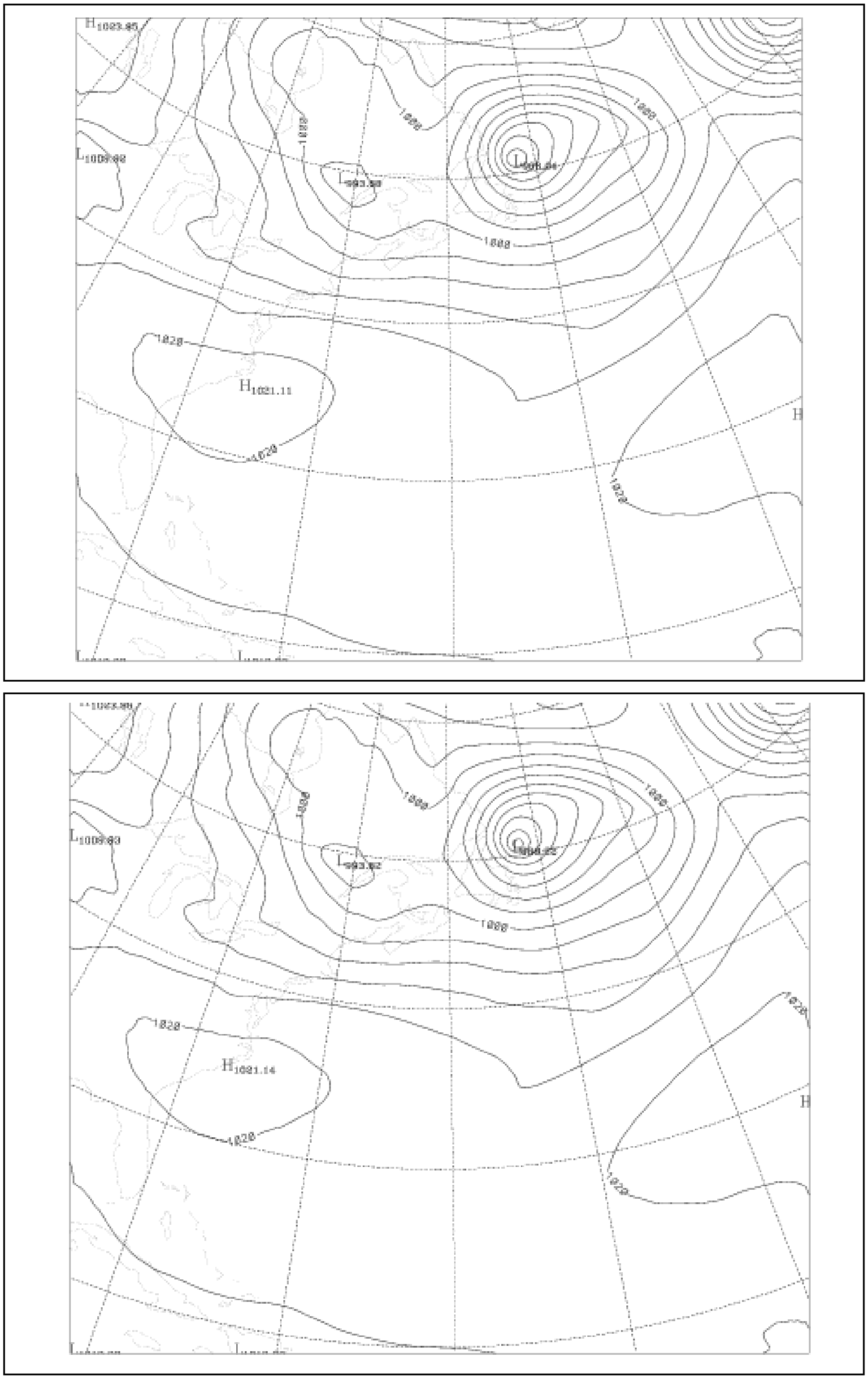

Figure 2. Comparison of CRCM-POM uncoupled (upper) and coupled (lower) simulations of extra-tropical storm Earl at the peak of the storm intensity after 2 days simulation. Minimum sea level pressure from analysis was 960mb, compared to 966mb for coupled and 968mb for uncoupled simulations.

was initiated as the storm passed over the Carolinas, just as it entered its extra-tropical phase. No bogussing was used in the initialization. Impacts on waves, for both sea spray and CRCM-POM coupling, will be presented at the Workshop.

5. CONCLUSIONS

A related paper by Jacob et al. (2002) suggests the importance of a skilled forecaster to accurately estimate wind fields. But this is hardly new – it has been a theme throughout these Workshops for many years. Our present study has explored two mechanisms related to this theme, because accurate wind fields are the reflection of accurate modelling of the atmospheric driving fields. We have tried to couple the atmosphere to the ocean surface via (1) explicit sea spray parameterization, and (2) coupling with an ocean circulation model. In the latter, passing heat, mass and momentum fluxes are used to drive an ocean circulation model, and SST is passed back to impact on the atmosphere model. We found that these mechanisms could each impact on the sea level pressures by 2-3mb for Earl. For stronger storms such as Bonnie, crossing warmer Gulf Stream waters near the Grand Banks the effects are larger. For Earl, the impact on wind fields is up to 7 m/s at peak storm intensity. This translates into about 3m variation in estimates for significant wave heights. This magnitude is similar to the impacts of two-way wave-atmosphere coupling studies for storms in the Grand Banks and Labrador Sea.

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