J10.4 THE ROLE OF EXTRATROPICAL STORMS IN AIR-SEA GAS TRANSFER

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1. INTRODUCTION

The natural carbon cycle has been disturbed by the rapid anthropogenic release of CO_2 from fossil fuel combustion, from land use practices and related activities. while roughly half the surplus CO_2 stays in the atmosphere, the other half is either sequestered in terrestrial biomass or in the oceanic carbonate system. A quantitative understanding of the exchange processes at the air-sea interface is related to transport and transformation in the surrounding boundary layers. In order to permit an accurate calculation of these air-sea exchanges, for estimates of regional and global fluxes, we need to ultimately establish their dependence on physical, biological, and chemical factors within the boundary layers and the horizontal and vertical processes. A number of studies are underway, or are planned, to look at climate simulation, as well as climate change scenario studies. Our objective is to examine the role of severe storms such as hurricanes to modify the release of CO_2 by mixing the upper ocean. In particular, we want to give an estimate of the variability in estimates for CO_2 release due to hurricane-type storms. Due to global warming, it has been suggested that warmer tropical and subtropical waters will enhance the frequencies and intensities of hurricanes and typhoons in the future (Knutson et al., 1998; Knutson and Tuleya, 1999; Walsh et al., 2000). If this is the case, enhanced upwelling and pumping of dissolved CO_2 in the surface water may lead to a positive feedback for global warming, because total CO_2 concentration is high in deeper water.

2. METHODOLOGY

We try to give estimates for the impacts of a hurricane on the air-sea CO_2 exchange, using two approaches. The usual representation of the air-sea CO_2 exchange rate is given by

$$Q = k_L s \Delta pCO_2 \tag{1}$$

where $\Delta pCO_2 = pCO_{2w} - pCO_{2a}$, with k_L the gas transfer velocity (m/s), and s the solubility of CO_2, following Weiss (1974). In one approach, the gas transfer velocity formula is expressed in terms of wind speed (Wanninkhof, 1992), for example the quadratic relation

$$k_L = 0.31 U_{10}^2 \left(S_c / 660\right)^{-1/2} \tag{2}$$

where S_c is the Schmidt number, and U_{10} the wind speed at 10m reference height. Units are m/s. As an alternative, Wanninkhof and McGillis (1999) suggest a cubic-wind relationship. In a second approach, a new formula for gas transfer velocity as a function of breaking-wave parameter R_B is implemented, as proposed recently by Zhao and Toba (2001),

$$k_L = 3.61 \times 10^{-7} R_B^{0.63} \tag{3}$$

and where the breaking-wave parameter R_B is expressed as

$$R_B = u_*^2 / u w_P \,. \tag{4}$$

Here, u_* is the friction velocity, u is the kinematic viscosity, and w_P, the wave spectral peak frequency. This is based on whitecap coverage and depends on only wind speed and sea-state, as described by R_B, which can be regarded as a Reynolds number to represent turbulence intensity of waves in the downward bursting boundary layer. Thus, R_B relates k_L to u_* and wave age.

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In the former case, k_L is estimated from the Wanninkhof wind-relation, and wind fields are generated from an atmosphere-ocean model. In the second approach, k_L is estimated from the Zhao-Toba wave-breaking parameter. Thus not only is u_* required, but to estimate wave age we also need to compute the spectral peak frequency, w_P, for wind-generated waves. This can be achieved by implementation of the NCEP operational wave model WaveWatch3 (WW3). Wind fields from the atmospheric model are used to drive the WW3 wave model. Alternately, we can also consider the impacts of sea spray on atmospheric model simulations, wind and wave fields and implicitly on the CO_2 exchange. This is achieved by implementing the sea spray parameterizations of Andreas and Decosmo (2002) within the atmospheric model. High winds in a hurricane can generate large amounts of sea spray, which can change the transfer of momentum, heat and moisture at the air-sea interface, with white-capping and wave-breaking.

3. MODELS

We discuss two sets of wave forecast model results: those involving 'two-way' coupled atmosphere-ocean models, and those where atmosphere-ocean models are 'one-way' coupled. Although we discuss atmosphere-sea spray coupling, no results are presented in this paper.

3.1 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) longitude-latitude grid, and flexible increments in each direction, and also (b) outputs such as significant wave height, Hs, mean wave direction, <θ>, peak wave period, Tp and peak frequency w_P.

3.2 Atmospheric-Ocean Model

To model N. Atlantic storms and the impacts of climate change, we have 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 is coupled to the Princeton ocean model (POM), with URL at (http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/). This is a primitive equation ocean model representing the basic important physical processes. 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. 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.

3.3 Atmosphere – Sea Spray Model

In a later study, and at the Conference, we will report results with sea spray coupling. In this approach, the atmospheric component is the MC2 (mesoscale compressible community). It has been well-tested for simulations related to storms. The model is available from the Meteorological Service of Canada (MSC) http://www.cmc.ec.gc.ca/rpn/modcom/index2.html. MC2 originates from a limited-area model developed by Robert et al. (1985). It is a state-of-the-art fully-elastic nonyhydrostatic 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 ultimately in microphysical modelling of air-sea processes, namely sea spray, bubbles and related to heat and moisture transfer during severe storm conditions. Sea spray transfers of latent and sensible heat related to 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 has no effect on the radius time-scale because the droplet is at its equilibrium temperature 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), the sea spray contributions can be given bulk formulae representations. Details are present by Li et al. (2002).

3.4 Model Set-up and Coupling

CRCM is implemented on a 35km resolution grid in the NW Atlantic, with WW3 on a similar resolution and larger domain. POM is implemented at $1/6^o$ resolution. Atmospheric wind fields are used to drive WW3, with wind fields input 6-hourly. Progress on two-way coupling between WW3 and the atmospheric models is underway, involving the wave-induced stress formulations.

4. CASE STUDY

We consider the impact of three 1998 hurricanes on air-sea CO_2 exchange. 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.

Danielle had a long track across the Atlantic. It originated from a tropical wave on 21 August and became a hurricane by 1200 UTC 25 August over middle tropical Atlantic. Danielle began to lose its tropical characteristics on 3 September, as its center passed about 200 nautical miles south of Cape Race, Newfoundland. It is estimated that Danielle became an extratropical storm with 65 knots wind speed by 0000 UTC 4 September. The storm moved eastward to east-northeastward across the north Atlantic for the next couple of days, with only slow weakening. Danielle became indistinct when it merged with Earl on 8 September.

For these three storms, we run the model from 0600 UTC 5 Sept, until 0000 UTC 8 Sept. providing 6-hourly outputs of wind and wave parameters. This is the operational standard.

5. IMPACTS ON CO_2 FLUX

While the impacts of hurricanes and typhoons are well documented, in terms of SST (sea surface temperature) and upper mixed layer (Ginis, 2002), impacts on air-sea exchanges of CO_2 are less well studied. Although we have extensive SST data, we have no *in situ* or remotely sensed CO_2 data specific to the storms, Earl, Bonnie and Danielle, for our domain of implementation. Thus, our calculations are based on relations suggested by Bates et al. (1998) and Kawahata et al. (2001). Bates et al. (1998) found that hurricane Felix in 1995 in the Sargasso Sea caused a cool wake of about 4^oC, persisting for 2-3 weeks, a decrease in seawater partial pressure of CO_2 by about 60 μatm. They estimated a peak net CO_2 efflux of ~+90 $mmol/m^{-2}$/day for Felix, and ~+10 $mmol//m^{-2}$/day for Luis and Marilyn. For hurricane John in the NE Pacific in 1994, Kawahata et al. (2001) estimated peak CO_2 absorbance of ~-4-22 $mmol/m^{-2}$/day, depending on wind estimates.

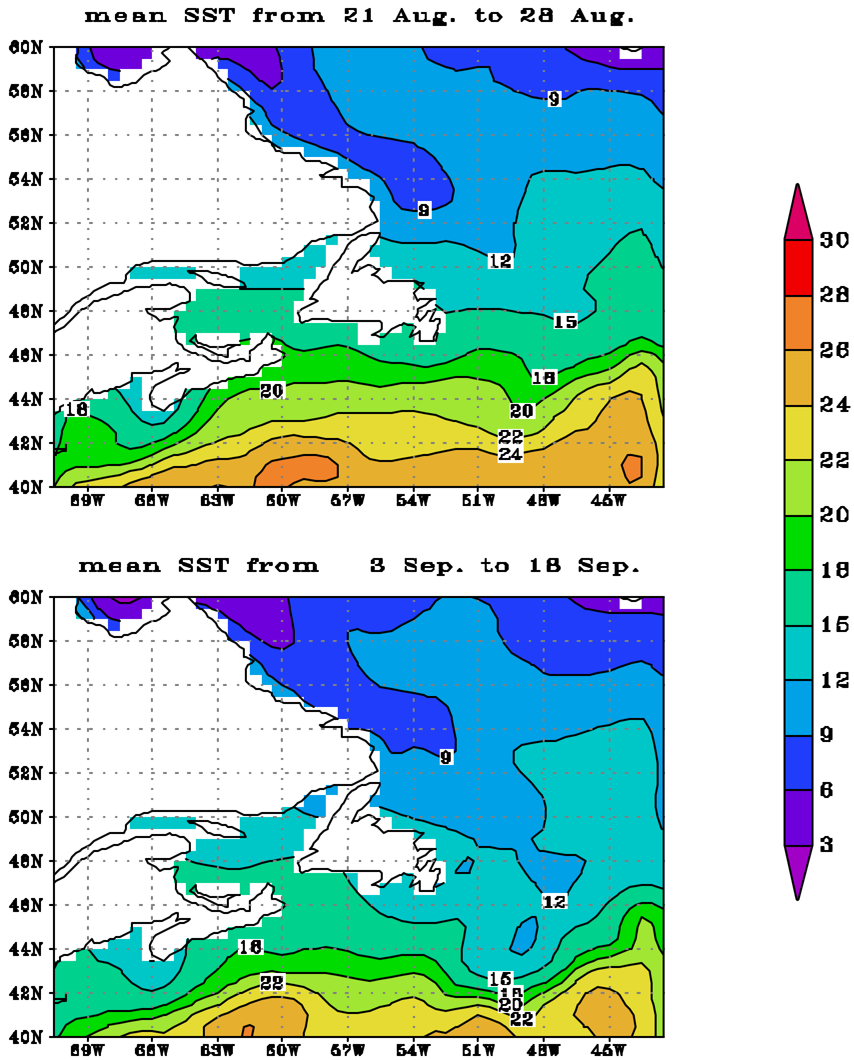

Figure 1. The impact of extra-tropical hurricanes in early September on SST, giving the mean SST for the weeks before (upper) and after (lower) these storms pass over the NW Atlantic.

The impact of Earl, Bonnie and Danielle on SST are shown by Figure 1, giving the mean SST for the weeks before and after these storms pass through the NW Atlantic. These are interpolations of AVHRR data, collected and processed at BIO (Fuentes-Yaco et al., 2002), smoothed to 0.5^o resolution. Figure 2 shows the corresponding SST difference, indicating a maximum temperature depression of as much as 6^{o}C on the Grand Banks. For seawater, a change in pCO_{2w}, the partial pressure of CO_2, may be estimated from Gordon and Jones (1973),

$$dpCO_{2w} / dT = 4.4\times10^{-2}(pCO_{2w}) - 4.6\times10^{-6}(pCO_{2w})^2 \qquad (6)$$

where dT is the temperature depression due to the hurricanes, and units are $m$atm ^{o}C^{-1}. Salinity is assumed to remain constant. We assume climatology for both background seawater pCO_{2w}, and the difference between seawater and air, $\Delta pCO_{2w} = pCO_{2w} - pCO_{2a}$, as given by Takahashi et al. (2001), for September. The latter is given in Figure 3, showing efflux south of the Grand Banks and absorbance to the north, interpolated to 0.5^o resolution. The corresponding impact of the three hurricanes on pCO_{2w}, is given in Figure 4, indicating a large decrease of about 80 $m$atm over the Grand Banks. This is in qualitative agreement with Bates et al. (1988). Although the hurricanes may cause a decrease in pCO_{2a}, we have no detailed measurements and we assume that atmospheric values remain about constant, as in the estimations of Kawahata et al. (2001). Note that Bates et al. (1998), assumed pCO_{2a} decreased by ~20 $m$atm in response to a transient 6% drop in atmospheric pressure (from ~1020 to 965 mbar).

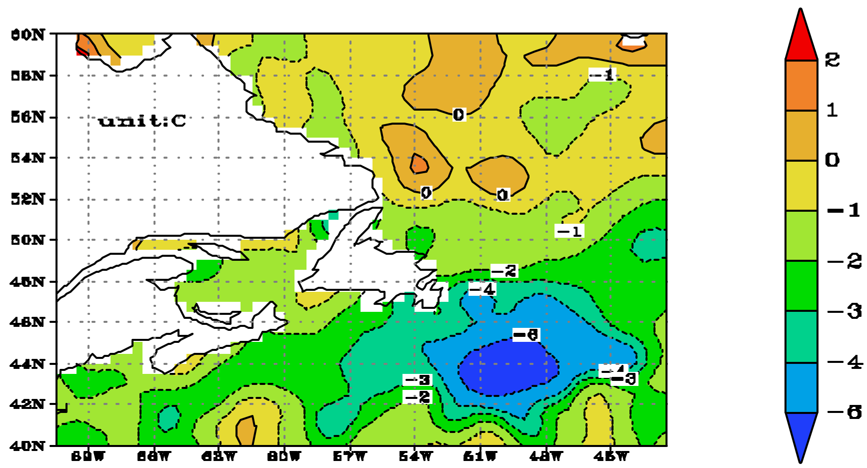

Figure 2. As in Figure 1, for SST difference, after minus before, the three extra-tropical hurricanes pass over the NW Atlantic.

To estimate the net air-sea CO_2 flux from Equation (1) we use the gas transfer velocity formulae of Equations (2)-(3). The gas transfer velocity k_L related to the Zhao-Toba wave-breaking parameter R_B in Equation (3), is given in Figure 5a, for 6:18 UTC on 6 September 1998. Corresponding results from the Wanninkhof (1992) wind relation in Equation (2) are given in Figure 5b. Here R_B is computed from wave age estimates from WW3. In both Figures 5a-b, the coupled CRCM-POM model is used to generate the wind fields. Results from the uncoupled CRCM model are given in Figures 6a-b. Figure 5-6 show a maximum variability on the order of ~20 cm/h, comparing Zhao-Toba wave-breaking and Winninkhof wind formulations. Comparing coupled CRCM-POM and uncoupled CRCM model results reveals a maximum variability on the order of ~40 cm/h.

We estimate the net air-sea CO_2 flux due to the three hurricanes in Figures 7a-b, for coupled and uncoupled modes of CRCM-POM, assuming the Zhao-Toba wave-breaking formulation for gas transfer velocity. Several distinctive features are evident, resulting in variability in how the storms were simulated. In the upper panel, results form the uncoupled CRCM imply that there are two centers of maximum absorbance: one in the Labrador Sea, and the other along the dominant NW Atlantic storm track. In the lower panel, for the coupled CRCM-POM scheme, giving a more realistic representation feedback of atmosphere-ocean feedback mechanisms, the maximum absorbance center is located along the dominant NW Atlantic storm track, and the Labrador Sea center is relatively less important. These results are of the same order of magnitude as those of Bates et al. (1998) and Kawahata et al. (2001). However, coupled CRCM-POM runs do not, thus far, consider that lower ocean levels have different concentrations of CO_2, and this may influence estimates for the impacts of storms on the air-sea gas fluxes.

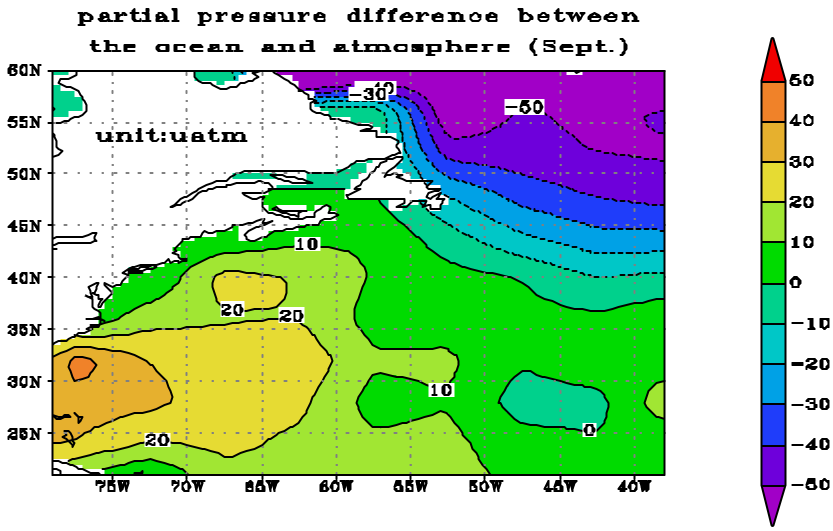

Figure 3. The difference between seawater and atmosphere, $\Delta pCO_{2w} = pCO_{2w} - pCO_{2a}$, as given by Takahashi et al. (2001), for September, interpolated to 0.5^{o} resolution.

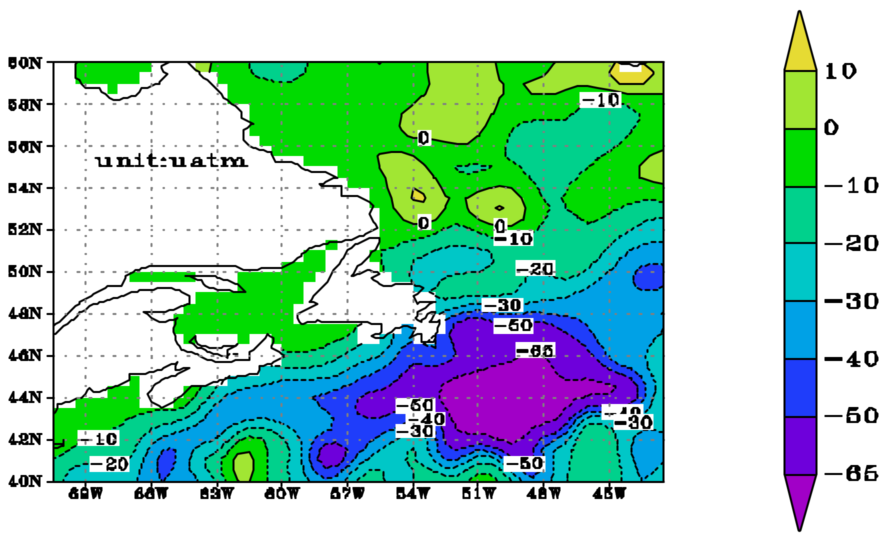

Figure 4. As in Figure 3, showing the decrease in pCO_{2w} due to three extra-tropical hurricanes.

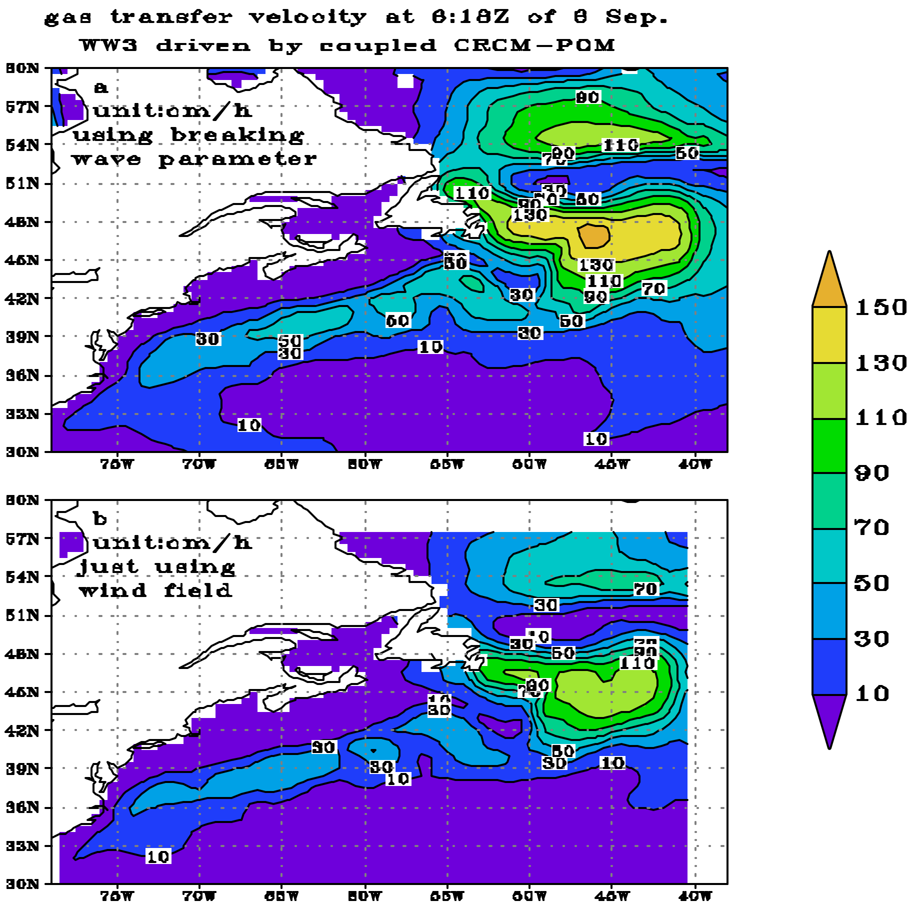

Figure 5. Gas transfer velocity k_L estimated from (a) the Zhao-Toba wave-breaking formulation (upper), and (b) the Wanninkhof wind-algorithm (lower). Wind fields are generated by the coupled CRCM-POM model and wave fields by WW3.

6. CONCLUSIONS

We have estimated the impact of extra-tropical hurricanes on air-sea CO_2 exchanges, using climatological fields as background fields. We found that there is absorbance in the northern part of our domain of implementation, and efflux in the southern part. Thus we can suggest that we found results consistent with both Kawahata et al. (2001) and Bates et al. (1998), who did calculations based on field estimates to suggest conditions where both absorbance and efflux could occur. They suggest that the impact of a few storms on the air-sea CO_2 exchange is a considerable fraction of the annual exchange. Although our study is preliminary, our magnitudes are similar to theirs. Extension of the model domain to Bermuda would allow access to extensive *in situ* data, and model–data comparisons. This would also be achieved by computation of satellite wind data and comparison with altimeter gas transfer estimates (Glower et al., 2000), which are in preparation. Computation of further storms may allow estimation of the season behaviour of air-sea CO_2 fluxes, based on our understanding of the climatology of extra-tropical hurricanes and intensifying storms. Limitations in these calculations are that the parameterizations for gas transfer velocity may not be valid for high wind speeds, i.e. in excess of 30 m/s. This is a concern for either the Zhao-Toba wave-breaking formulation or the Wanninkhof wind algorithm. Moreover partial pressures for CO_2 may not behave linearly under these more severe conditions, as the storm-center evolves.

Our experience was that the variability in air-sea parameters such as winds and waves, for example between coupled and uncoupled CRCM-POM runs, surpasses the variability implicit between Zhao-Toba wave-breaking or Wanninkhof-wind formulations for the gas transfer velocity. Moreover, coupled model Zhao-Toba simulations seem more realistic in the sense that maximum gas transfer velocities occur along the storm tracks.

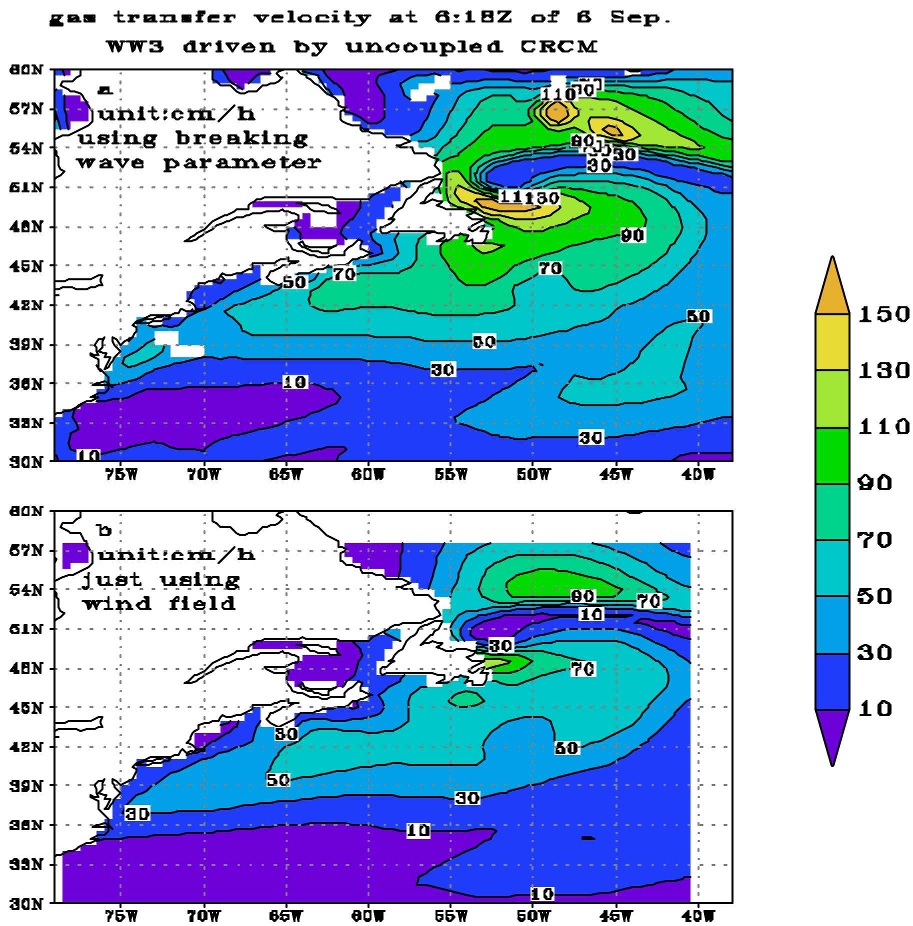

Figure 6. As in Figure 5, with winds given by the uncoupled CRCM-POM model.

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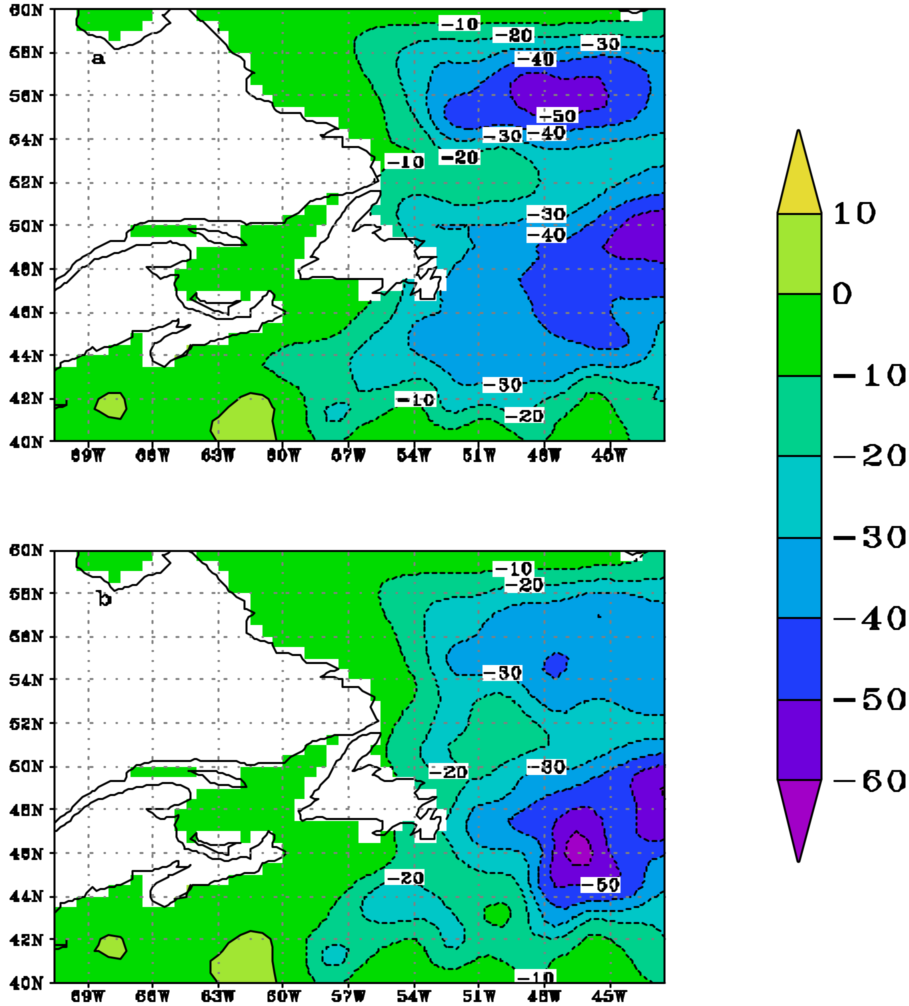

Figure 7. Net air-sea CO flux during hurricane Earl, estimated from the Zhao-Toba gas transfer velocity, with winds generated by the uncoupled CRCM-POM model (upper panel) and coupled CRCM-POM model (lower panel).