Hurricane impacts on air-sea CO_2 fluxes in subtropical North Atlantic

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1. Abstract

Hurricanes significantly influence surface ocean pCO_2 (pCO_2^{ocean}) and the air-sea CO_2 flux at short time scales, primarily at Bermuda (Bates et al. 1998a, Bates 2007). We use an ocean biogeochemical model to investigate causal mechanisms and to consider basin-wide impacts on interannual variability in air-sea CO_2 fluxes. Consistent with previous observations, we find that enhanced wind speeds dominate the hurricane's effect on the flux, driving CO_2 out of the ocean due to the negative air-sea gradient in pCO_2 ($pCO_2^{atm} < pCO_2^{ocean}$) that occurs in response to high sea surface temperatures (SSTs) during hurricane season (late summer / fall). Vertical mixing causes negative SST anomalies, which depresses pCO_2^{ocean}, but this is not sufficient to reverse the air-sea gradient. Though hurricanes drive local CO_2 efflux, we find no evidence for a relationship between year-to-year variability in hurricane frequency and year-to-year variability in air-sea CO_2 fluxes across the subtropical North Atlantic.

2. Introduction

The seasonal cycle of CO_2 exchange between the atmosphere and the subtropical North Atlantic Ocean is forced primarily by changes in the sea surface temperature (SST) due to seasonal heat fluxes (Bates 2007, Ullman et al. 2008, Takahashi et al. 2002). Mixed layer depth (MLD) cycling also causes seasonal changes in surface ocean pCO_2 (pCO_2^{ocean}), primarily through vertical supply of dissolved inorganic carbon (DIC). The rise in pCO_2^{ocean} during the northern hemisphere summer brings it above the atmospheric pCO_2 and leads to an efflux of carbon dioxide to the atmosphere (Bates et al. 1998b).

The high wind speeds characteristic of hurricanes and tropical storms cause a rapid release of CO_2 from the ocean due to the negative summertime gradient in pCO_2 (i.e $pCO_2^{atm} < pCO_2^{ocean}$). A deepening of the MLD also occurs with hurricane passage, causing a decrease in the SST of about 2-3˚C (Bates et al. 1998a, Perrie et al. 2004). Despite the sometimes-large decrease in pCO_2^{ocean} due to reduced SSTs, pCO_2^{ocean} remains higher than pCO_2^{atm}, so the wind speed enhancement causes a strong CO_2 efflux (Bates et al. 1998a).

Though this local effect has been clearly illustrated, the role of hurricanes and tropical storms play in the annual air-sea exchange of CO_2 in the subtropics is not entirely clear. Following on work of Bates et al. (1998a), who estimated a global flux up to 0.51 PgC/yr due to hurricanes, Bates (2007) estimates a global flux of 0.04-0.08 PgC/yr due to hurricanes. However, these fluxes could be simply a short-term enhancement of the summer/fall outgassing. Perhaps these fluxes would have occurred anyway, albeit more gradually, without the hurricane presence, over the summer/fall degassing period.

Using an ocean biogeochemical model, we evaluate the effects of hurricanes on the air-sea carbon dioxide exchange and surface ocean biogeochemistry. We first evaluate the CO_2 flux and biogeochemical responses to hurricanes at Bermuda during the year 1995. We then expand this investigation across the subtropical North Atlantic (25-40N) and over the years 1992-2006 to ask whether or not there is a relationship between hurricane frequency and net annual air-sea CO_2 fluxes.

3. Model

As described in Bennington et al. (2008) and Ullman et al. (2008), the MIT Ocean General Circulation Model (Marshall et al., 1997a,b) is regionally configured for the North Atlantic between 20˚S and 81.5˚N, with a horizontal resolution of 0.5˚ latitude and 0.5˚ longitude. The model has 23 vertical levels with a resolution of 10 m thickness at the surface increasing to 500m thickness for depths greater than 2200m. A sponge layer is included along regional boundaries. The model is forced with daily fields from the NCEP/NCAR Reanalysis I (Kalnay et al., 1996) for 1992-2006 and SSTs are relaxed (2 week timescale) to 1992-2006 satellite-based estimates (Reynolds et al., 2007).

The biogeochemical model includes carbonate chemistry (Follows et al., 2006) and nutrient cycling using an ecosystem model of intermediate complexity (Dutkiewicz et al. (2005) that models a pelagic ecosystem with one zooplankton class and two phytoplankton classes: diatoms and “small” phytoplankton (Bennington et al. 2008, Dutkiewicz et al. 2005). Atmospheric pCO_2 is from Mauna Loa observations (Keeling et al., 2001) and includes the seasonal cycle. The flux of carbon dioxide between the ocean and atmosphere is parameterized following Wanninkhof (1992). We define a positive flux as one directed out of the ocean.

After an 81-year physical spin up, the biogeochemical model was initialized with GLODAP (Key et al., 2004; Lee et al., 2006) DIC and ALK climatology, World Ocean Atlas 2005 (Garcia et al., 2005a, 2005b) nutrients and oxygen, low values of phytoplankton and zooplankton, and atmospheric pCO_2 fixed at 356 ppm (roughly the 1992 level). The biogeochemical model was integrated for 70 additional years to eliminate drift before the 1992-2006 simulation began.

4. Results

4a. Local CO_2 flux response to 1995 hurricanes at Bermuda

How well does the NCEP/NCAR Reanalysis used to force the model capture the hurricanes of 1995? Of the three storms, Hurricane Felix passed closest to Bermuda, occurring on August 14-15. Figure 1a demonstrates a peak in the wind speed on this day, indicating that the presence of Felix was replicated in the model. There was also a low-pressure center (not shown), with the lowest pressure on August 15th 1995 at 988.4 mb. The presence of Luis (September 8-9) and Marilyn (September 18-19) are also notable in the wind speeds.

The model responds to hurricane passage with increased mixed layer depths (MLD) of 5-20m (Figure 1b). In comparison to the available data, modeled MLDs are reasonable across both the seasonal cycle and during the hurricane season. Increased mixing causes SSTs (Figure 1c) to drop dramatically during the passage of each hurricane, rebounding slowly in the following weeks, consistent with observations (Bates et al. 1998a). pCO_2^{ocean} decreases with the passage of the hurricanes (Figure 1d). In order to better understand this drop in pCO_2^{ocean}, it is split into temperature and non-temperature components (Takahashi et al. 2002). With this split, is clear that SST depression drives the drop in pCO_2^{ocean} (Figure 1d). With Felix, there is a small decrease in pCO_2^{ocean} due to non-temperature causes. Despite the SST-driven drop, pCO_2^{ocean} is still significantly above the pCO_2 of the atmosphere (pCO_2^{atm}). Thus, the windspeed enhancement drives large positive (to the atmosphere) anomalies in CO_2 flux (Figure 1e) on short timescales coincident with the dramatic spikes in wind speed.

The magnitudes of modeled CO_2 fluxes during the 1995 hurricanes are similar to those described in Bates et al. (1998a) for Luis and Marilyn, but substantially less for Felix. This is due in part to the modeling being forced with daily winds, which do not capture the full intensity of a hurricane. For example, Felix has maximum sustained winds of 40-45 m/s (Bates et al. 1998a), while the daily maximum from NCEP/NCAR Reanalysis is only 14.5 m/s (Figure 1a). Modeled CO_2 fluxes during the two days of Felix, Luis, and Marilyn were 32, 18, and 15 (total 65) mmol/m^2, respectively, out of a total summer / fall efflux of 349 mmol/m^2 (a sum of all days with flux from ocean to atmosphere in Figure 1d). Bates et al. (1998a) used observations to calculate fluxes of 108, 21, and 18 (total 145) mmol/m^2, and estimate a total summertime efflux of 331 mmol/m^2. Because the model overestimates surface ocean pCO_2 in summer and fall (due to excessive nutrient limitation and associated underestimation of the biological productivity (Bennington et al. 2008)) and thus overestimates the total efflux in this period, the percentage of the total summertime efflux of carbon dioxide caused by the three hurricanes was 19% for the model, compared to 44% for Bates' model.

4b. Hurricane impacts on the surface ocean biogeochemistry

Profiles of phosphate (PO_4) and DIC, as well as MLDs, for one-day prior to and one-day post hurricane passage are presented in Figure 2. Vertical mixing driven by the storms does not penetrate into the nutricline, and thus there is not a substantial input of nutrients to the surface ocean to stimulates a biological response, consistent with Bates et al. (1998a). However, there have been satellite observations of enhanced surface ocean chlorophyll in the wake of a hurricane, something this model does not capture (not shown). Processes not represented in this model, such as atmospheric deposition of new nitrogen, (N. Bates, personal communication,

2008) may be responsible for the chlorophyll observations. Changes in the deeper (>50m) profiles of both phosphate and DIC suggest upward heaving of the seasonal thermocline in response to the hurricane.

DIC profiles are also show in Figure 2. The surface DIC response to the hurricane is not consistent from storm to storm. There is a large decrease in surface DIC with Felix, and moderate increases during Luis and Marilyn. These findings are further explored using an analysis of the model tendency terms, which allows the parsing of the mechanisms modifying surface ocean DIC. Figure 3 demonstrates the tendency terms for the 2 days of each hurricane event (in units of mmol/m^2 to facilitate comparisons with air-sea fluxes). As seen in the profiles in Figure 2, there is a strong loss of DIC from the surface ocean during Felix and moderate gains during Luis and Marilyn. For Felix, the loss of DIC is due primarily to an enormous input of freshwater that dilutes surface concentrations (Figure 3). This dilution overpowers DIC gains due to vertical mixing. For Luis, the small loss of DIC is due to freshwater loss and a net loss due to horizontal advection and mixing. For Marilyn, the DIC loss is driven by both vertical and horizontal advection and mixing. The varying behaviors of the horizontal and vertical terms may be the resultant effect of strong oscillations in surface-ocean vertical velocities in the near-surface ocean during hurricanes (Perrie et al. 2004). In all cases, there is a net loss of DIC due to the air-sea flux, but in no case is this the dominant term in the surface ocean DIC budget.

4c. Basin-wide impact on carbon dioxide flux

In this section, we use the model to determine if the effects of this increased CO$_2$ flux with hurricane passage extended beyond the days surrounding the presence of the hurricane, and beyond the small region near Bermuda. Bates et al. (1998a) suggest that the year-to-year differences in hurricane frequency and intensity might be an important mechanism for controlling interannual variability in air-sea CO_2 exchange at the global scale (0.04-0.51 PgC/yr), though Bates (2007) revises this estimate to be substantially lower (0.04-0.08 PgC/yr). If the relationship suggested by Bates et al. (1998a) extends to the larger scale, it would be expected that an increase in the number of hurricanes would increase the total CO_2 efflux from the ocean throughout the year; in other words, one would expect that the carbon sink in the North Atlantic may fluctuate from year to year, decreasing when the hurricane frequency is greater and increasing when there are fewer hurricanes.

Data from National Hurricane Center (NHC) was compiled to locate hurricanes and tropical storms that passed north of 25N in the North Atlantic from 1992 to 2006. The number of hurricanes per year is displayed in Figure 4a. The apparent increasing trend is not well defined by a linear trend, with an r^2 value of 0.36 ($p<0.05$). However the net North Atlantic CO_2 sink for 25-40N is increasing with a steady, significant trend ($r^2=0.66$, $p<0.01$, Figure 4b), due in large part to the anthropogenically-driven increase in $pCO_2^{atmosphere}$ (Ullman et al. 2008).

Figure 4c compares the local flux occurring along the track of the hurricane (“along-track”) CO_2 flux during hurricanes and tropical storms and the number of hurricanes. The trend is reasonably well defined by a linear relationship ($r^2=0.56$, $p<0.01$), as expected from the above analysis of 1995 hurricanes at Bermuda. The overall flux of CO_2 at the locations of hurricanes increases with the number of hurricanes that occur per season. The fact that we considered only hurricane and tropical storm number suggests that it is not necessary to describe variation in hurricane and tropical storm size and strength to capture the first-order effect of hurricanes on local CO_2 fluxes.

If we now consider the CO_2 flux across the basin between 25N-40N, we find there is not a statistically significant relationship between the number of hurricanes and the annual carbon flux to the ocean ($r^2=0.25$, $p<0.1$, Figure 4d). In other words, the model suggests that variation in the number of North Atlantic hurricanes and tropical storms does not have a clear relationship to the magnitude of the CO_2 sink in the subtropical North Atlantic. This finding is contrary to the suggestion of Bates et al. (1998a) and Bates (2007). It suggests that the large local fluxes occurring during a hurricane do not drive a significant additional efflux of CO_2 from the ocean, but instead only temporarily enhance the process of summer / fall outgassing already underway.

5. Summary

The model successfully captures observed seasonal patterns of MLD, SST and pCO_2 variations at Bermuda (Bates 2007), and also captures, to a large degree, the effects of hurricane passage (Bates et al. 1998a) on these quantities. Reduced pCO_2 in the wake of the 1995 hurricanes is mostly due to the drop in SST occurring with increased mixing that supplies cool subsurface waters to the surface. Changes in DIC have little impact on surface ocean pCO_2, and the changes that do occur are driven physically, not biologically. Nutrient supply to the surface with vertical mixing is weak because the mixing enhancement by the storm does not reach into the nutricline. Physical influences on surface DIC are from freshwater, vertical and horizontal advection and mixing, and the air-sea flux. In each of the three hurricanes of 1995, a different set of mechanisms drives short-term changes in surface DIC, but in no case does the air-sea flux dominate.

The model suggests that at the scale of the whole subtropical North Atlantic, 25-40N, the frequency of hurricanes and tropical storms does not cause significant variability in the net carbon sink from 1992-2006.

Acknowledgements

We thank Stephanie Dutkiewicz for fruitful collaboration on model development and analysis; Nick Bates for comments on the manuscript; and Dierk Polzin for assistance with the figures. We thank NASA for funding (CARBON/04-0300-0228).

References

Bates, N. R. , A. H. Knap, and A. F. Michaels, (1998a), Contribution of Hurricanes to Local and Global Estimates of Air-Sea Exchange of CO_2. *Nature* 395.6697: 58-61.

Bates, N. R., T. Takahashi, D.W. Chipman, and A. H. Knap (1998b), Variability of pCO_2 on Diel to Seasonal Timescales in the Sargasso Sea near Bermuda. *J. Geophys. Res.* 103 (C8): 15567-85.

Bates, N. R. (2007) Interannual Variability of the Oceanic CO_2 Sink in the Subtropical Gyre of the North Atlantic Ocean over the Last 2 Decades. *J. Geophys. Res.,* 112, C09013, doi: 10.1029/2006GC003759.

Bennington, V, G.A. McKinley, S. Dutkiewicz, D. Ullman (2008) What does chlorophyll variability tell us about export and CO_2 flux variability?, *Global Biogeochem. Cycles, in revision.*

Boyer, T. P., Levitus, S., Garcia, H. E., Locamini, R. A., Stephens, C., and J. Antonov, (2004), Objective analyses of annual, seasonal, and monthly temperature and salinity for the world ocean on a 0.25 degrees grid, *Int. J. Climatol*., 25(7), 931–945.

Dutkiewicz, S., M. J. Follows, and P. Parekh (2005), Interactions of the iron and phosphorus cycles: A three-dimensional model study, *Global Biogeochem. Cycles,* 19, GB1021, doi:10.1029/2004GB002342.

Garcia, H. E., R. A. Locarnini, T. P. Boyer, and J. I. Antonov, (2006a), World Ocean Atlas 2005, Volume 4: Nutrients (phosphate, nitrate, silicate). S. Levitus, Ed. NOAA Atlas NESDIS 64, U.S. Government Printing Office, Washington, D.C., 396 pp.

Garcia, H. E., R. A. Locarnini, T. P. Boyer, and J. I. Antonov, (2006b), World Ocean Atlas 2005, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation. S. Levitus, Ed. NOAA Atlas NESDIS 63, U.S. Government Printing Office, Washington, 6

D.C., 342 pp.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, 77 (3), 437–471.

Keeling, C. D. et al., (2001), Exchanges of atmospheric CO_2 and $^{13}CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000. I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages.

Key, R.M., et al. (2004), A global ocean carbon climatology: Results from GLODAP. *Global Biogeochem. Cycles*, 18, GB4031

Lee, K., L. T. Tong, F. J. Millero, C. L. Sabine, A. G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof, R. A. Feely, and R. M. Key, (2006), Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. *Geophys Res. Lett.* 33, L19605, doi:10.1029/2006GL027207.

Perrie, W., W. Zhang, X. Ren, Z. Long and J. Hare (2004), The Role of Midlatitude Storms on Air-Sea Exchange of CO_2. *Geophys Res. Lett.* 31, L09306, doi:10.1029/2003GL019212.

Takahashi, T., et al. (2002), Global sea-air CO2 flux based on climatological surface ocean pCO2, and seasonal biological and temperature effects, *Deep-Sea Res. II, 49*, 1601-1622.

Wanninkhof, R. (1992), Relationship between wind speed and gas exchange over the ocean, *J. Geophys Research*, 97, C5, 7373-7382.

Weiss, R.F. (1974), Carbon dioxide in water and seawater: The solubility of a nonideal gas, *Mar. Chem.*, 2, 203-215.

Ullman, D., G.A. McKinley, V. Bennington and S. Dutkiewicz, (2008), North Atlantic carbon cycle response to climate variability, *in preparation*.

Figure Captions:

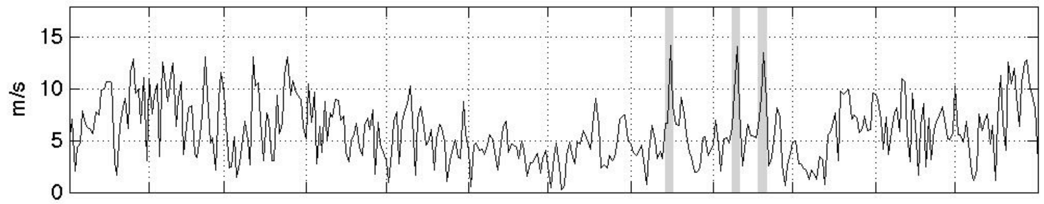
Figure 1. Modeled and observed variables at Bermuda (31N, 64W) from 1 January 1995 through 31 December 1995. SST and pCO_2 data of Bates (2007), and MLD's calculated from CTD profiles (downloaded from http://bats.bios.edu/) indicated with an asterisk. Hurricanes Felix, Luis, and Marilyn are denoted by the gray bars, beginning one day before closest approach to Bermuda and ending one day after: (a) NCEP reanalysis 10-meter wind speeds, (b) MLD, (c) SST, (d) pCO_2 (thin solid), pCO_2-T (thick dash), pCO_2-nontT (thick solid), and Mauna Loa pCO_2^{atm} (red dash), used to force the model.

Figure 2. Profiles of (top) phosphate and (bottom) DIC concentration from the model. Dashed lines are from a day before the hurricanes passed Bermuda, solid lines from a day after. On the phosphate profiles, the depth of the modeled MLDs the day before (triangle) and the day after (square) the hurricane are also indicated.

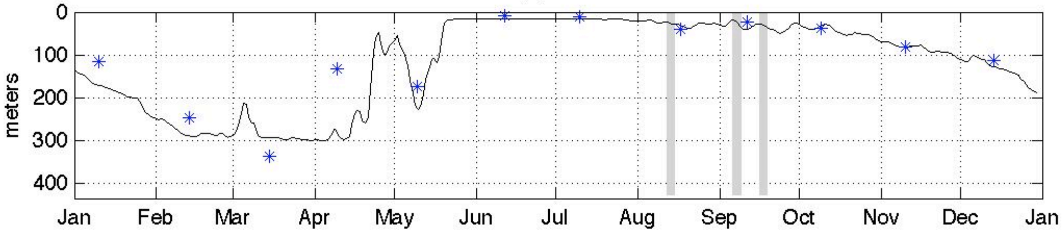
Figure 3. Model DIC tendency terms, 0-10m, integrated over the 2 days of each hurricane.

Figure 4. Scatter plots of year, hurricane frequency and modeled CO_2 fluxes, as well as best-fit lines when a linear trend is able to reasonably define the relationship. (a) Hurricane frequency (NHC data) versus year, (b) annual flux (25-40N) per year, (c) sum of the daily fluxes along hurricane tracks (NHC data) versus number of hurricanes, (d) annual flux versus hurricane frequency.

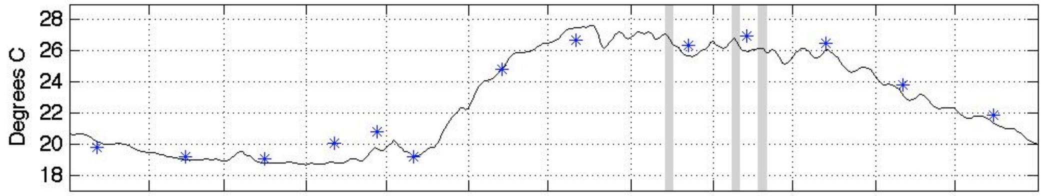
(a) Windspeed at 10 meters



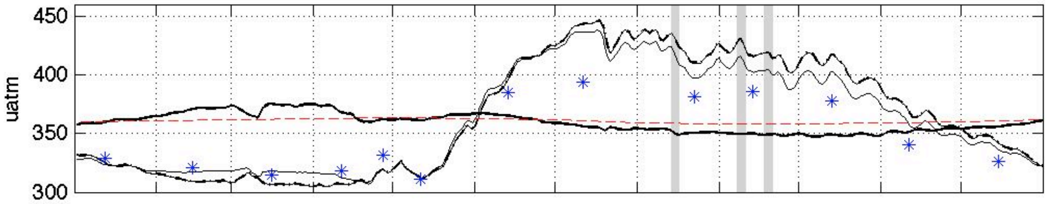
(b) MLD



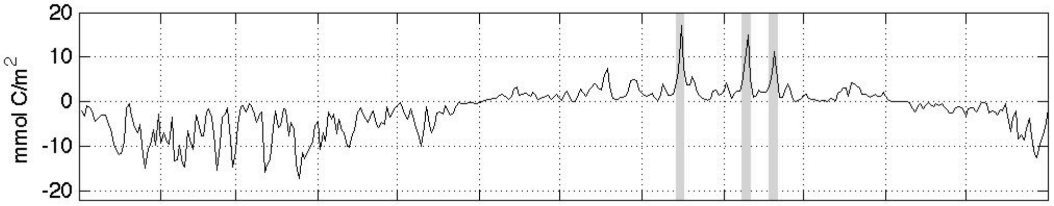
(c) SST



(d) pCO$_2$



(e) CO$_2$ flux



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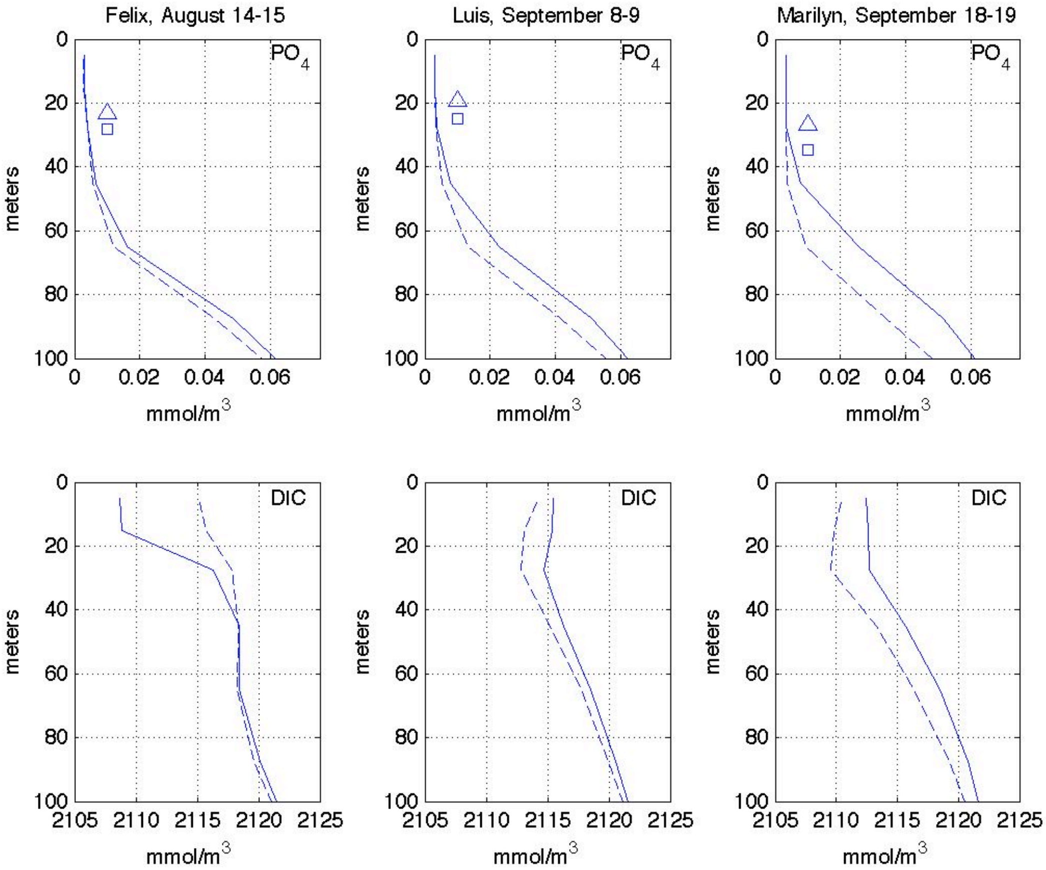

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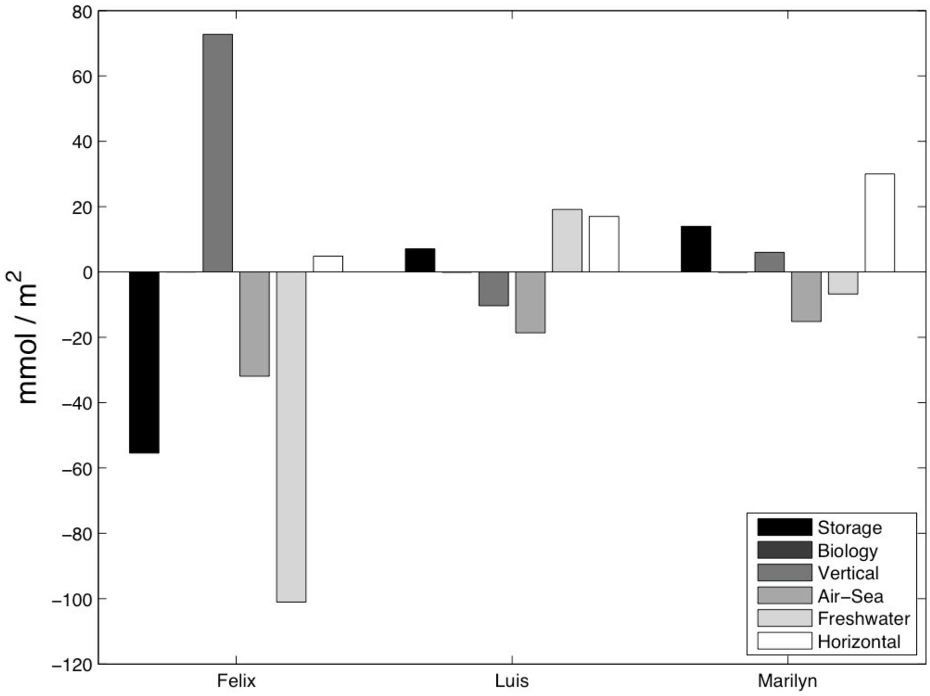

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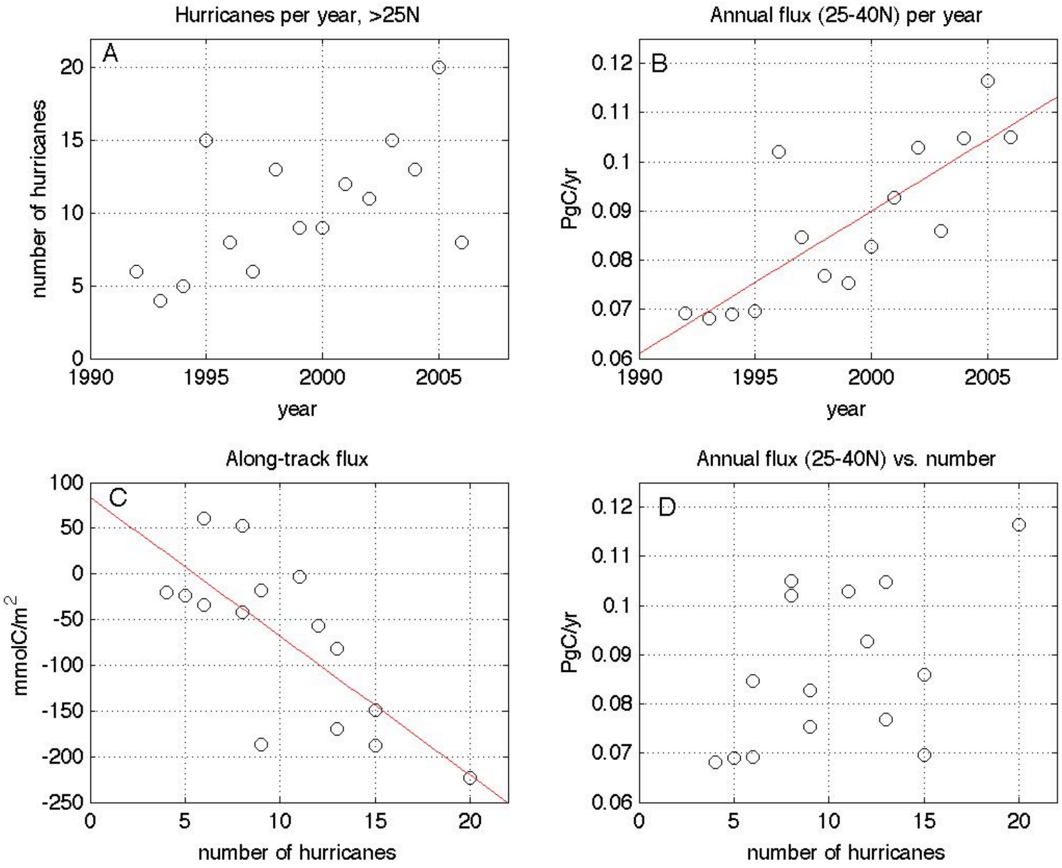

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