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

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1. Abstract

Observations at Bermuda and in the Caribbean Sea indicate that hurricanes significantly influence surface ocean pCO_2 (pCO_2^{ocean}) and the air-sea CO_2 flux at short time scales (Bates et al. 1998a, Bates 2007, d'Asaro and McNeil 2007, Wanninkhof et al. 2007). We use a North Atlantic regional 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 depress pCO_2^{ocean} but are 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 (Takahashi et al. 2002, Bates 2007, Ullman et al. 2008). 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) and nutrients which fuel biological productivity. During the northern hemisphere summer, pCO_2^{ocean} rises above atmospheric pCO_2 and thus 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, d'Asaro and McNeil 2007, Wanninkhof et al. 2007). 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, d'Asaro and McNeil 2007, Wanninkhof et al. 2007).

Though this local effect has been clearly illustrated, the role that hurricanes and tropical storms play in the annual air-sea exchange of CO_2 in the subtropics is not entirely clear. Following the work of Bates et al. [1998a], who estimated a net 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 simply be a short-term enhancement of the summer/fall outgassing; perhaps they would have occurred anyway, albeit more gradually, without the presence of a hurricane.

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 by Bennington et al. [2008] and Ullman et al. [2008], the MIT Ocean General Circulation Model (Marshall et al. 1997) 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 10m 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 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 (Dutkiewicz et al. 2005, Bennington et al. 2008). Atmospheric pCO_2 data 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. 2005) nutrients, 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, coming nearest to the island on August 14-15. Figure 1a demonstrates a peak in the wind speed on these days, 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 increases in 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 the components driven by temperature changes (pCO_2-T) and by non-temperature effects (pCO_2-nonT), i.e. DIC, Alkalinity and salinity variations (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. Analysis of the surface DIC budget (Section 4b and Supplementary text) indicates this drop is due to dilution by large freshwater inputs from the hurricane. Despite the SST-driven drop, pCO_2^{ocean} is still significantly above the pCO_2 of the atmosphere (pCO_2^{atm}). Thus, the wind speed enhancement drives large, coincident CO_2 efflux anomalies (Figure 1e). In the days or weeks following the hurricane passage, there is a depression in the CO_2 flux, coincident with the lowered SST and pCO_2^{ocean} , which is consistent with the observations of Wanninkhof et al. [2007].

The magnitudes of modeled CO_2 fluxes during the 1995 hurricanes are similar to those described by Bates et al. [1998a] for Luis and Marilyn, but substantially less for Felix. This is due in part to the model being forced with daily winds, which do not capture the full intensity of a hurricane. For example, Felix had maximum sustained winds of 40-45 m/s (Bates et al. 1998a), with maximum wind speeds at Bermuda of 26.2 m/s (Bates 2007), while the daily maximum from NCEP/NCAR Reanalysis at Bermuda is only 14.5 m/s (Figure 1a). NCEP maximum wind speeds for Luis (14.1 m/s) and Marilyn (13.5 m/s) were closer to those observed at Bermuda (19.1 m/s, 19.5 m/s, respectively). 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 underestimates the hurricane fluxes and 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' data analysis.

We show above that though the daily wind forcing used for this model does not grossly underestimate hurricane winds at Bermuda, these winds do cause model-estimated hurricane-driven CO_2 fluxes to be substantially too small. The quadratic dependence of gas exchange on wind speed following the Wanninkhof [1992] parameterization we use is a primary reason (Wanninkhof et al. 2007). Averaging of observations in both time and space in the creation of the daily NCEP Reanalysis product contributes to these muted wind speeds. A model with greater horizontal and temporal resolution would certainly improve our representation of the surface ocean response to hurricanes. However, we are not aware of forcing data that offers higher spatial and temporal resolution and that is also available for a sufficient number of years to simulate the interannual changes of central interest to this study – for example, QuickScat satellite winds are only available from 1999 to present. Thus, for the purpose of this study, we have illustrated that the model is able to capture, to a reasonable degree, the observed surface ocean response to all three 1995 hurricanes near Bermuda. This indicates that it is a reasonable tool for further consideration of the biogeochemical response to hurricanes at Bermuda (section 4b) and for addressing the question of whether or not interannual variability in hurricane activity drives interannual variability in basin-averaged CO_2 fluxes (section 4c).

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, along with monthly data profiles from BATS. PO_4 profiles indicate that the model nutricline sits slightly too high in the water column in August, but is more reasonable in September. There is no change in surface PO_4 with hurricane passage. The vertical gradient of DIC is too weak in the model compared to data, which is consistent with low productivity and high summer pCO_2^{ocean} as discussed above.

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. Model analysis (see Supplementary material) indicates that DIC loss during Felix is due to freshwater inputs and thus dilution of DIC. During Luis and Marilyn, the net DIC gain is due to vertical and horizontal advection and mixing, as well as net evaporation. For none of the three hurricanes is a net loss of DIC due to the air-sea flux a dominant term in the surface ocean DIC budget. Changes in the deeper (>50m) profiles of both PO_4 and DIC suggest upward heaving of the seasonal thermocline in response to the hurricane.

The before and after profiles at Bermuda indicate that, in this model, 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 to stimulate a biological response, consistent with the work of 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. Mixing of the subsurface chlorophyll maximum to the surface is a likely reason for this feature. The model's inability to capture this is due, at least in part, to the model's low overall biological productivity in the subtropical gyre and associated weak subsurface chlorophyll maximum. Additionally, model horizontal resolution is too coarse to capture the mesoscale and submesoscale processes that can drive strong local upwelling and mixing (Fox-Kemper et al. 2008).

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, 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 3a. 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 ($r^2=0.65$, $p<0.01$, Figure 3b), due primarily to the anthropogenically-driven increase in $pCO_2^{atmosphere}$ (Ullman et al. 2008).

Figure 3c compares the annual sum of the local CO_2 flux occurring along the path of the hurricane or tropical storm ("along-track") to the number of hurricanes. The trend is reasonably well defined by a linear relationship ($r^2=0.56$, $p<0.1$), as expected from the above analysis of three hurricanes from 1995 at Bermuda. Locally, CO_2 flux increases with the number of hurricanes. 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 25-40N, we find there is not a statistically significant relationship between the number of hurricanes and the annual carbon flux to the ocean ($r^2=0.23$, $p<0.1$, Figure 3d). 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 that is already underway. This ongoing seasonal outgassing can be clearly seen in Figure 1d,e.

5. Summary

In this paper, we study the impact of hurricanes on the carbon cycle of the subtropical North Atlantic using an ocean biogeochemical model that successfully captures observed seasonal patterns of MLD, SST and pCO_2 variations at Bermuda and also captures, to a large degree, the effects of hurricane passage on these quantities. Reduced pCO_2 in the wake of three 1995 hurricanes is mostly due to the drop in SST that occurs with increased mixing, which supplies cool subsurface waters to the surface. Though the high winds associated with the storms cause an intense, temporary efflux of CO_2, this drop in SST and corresponding reduced pCO_2 in the wake of the storms likely compensate for the enhanced flux during the storms. Nutrient supply to the surface with vertical mixing is weak because the mixing enhancement by the storm does not reach into the nutricline. Changes in DIC have little impact on surface ocean pCO_2, and the changes that do occur are driven physically, not biologically. The model suggests that, at the scale of the whole subtropical North Atlantic, 25-40N, the frequency of hurricanes and tropical storms is not associated with significant changes in the net annual carbon sink from 1992-2006.

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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., et al., (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.

D'Asaro, E. D., and C. McNeil (2007), Air-sea gas exchange at extreme winds speeds measured by autonomous oceanographic floats, J. Marine systems, 66, 92-109.

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.

Fox-Kemper, B., R. Ferrari, and R. Hallberg (2008) Parameterization of mixed layer eddies. I: Theory and Diagnosis, *J. Phys. Oceanogr*. 38, 1145-1165.

Garcia, H. E., R. A. Locarnini, T. P. Boyer, and J. I. Antonov, (2006), 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.

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 pp.

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

Lee, K., et al. (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.

Marshall, J.C., C. Hill, L. Perelman, and A. Adcroft (1997), Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling, *J. Geophys. Res.*, *102*, 5733–5752.

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 CO_2 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.

Wanninkhof, R., A. Olsen, and J. Triñanes (2007), Air-sea CO_2 fluxes in the Caribbean Sea from 2002-2004, *J. Mar. Syst.,* 66, 272-284.

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

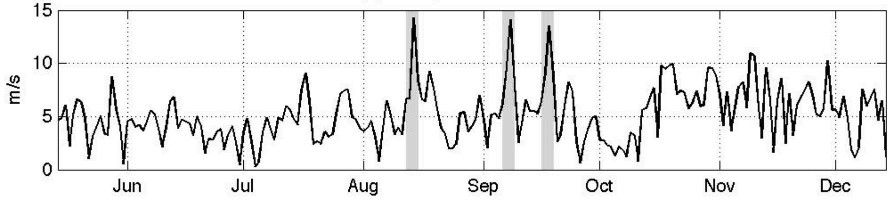
Figure Captions:

Figure 1. Modeled and observed variables at Bermuda (31N, 64W) from 15 May 1995 through 15 December 1995. SST and pCO_2 data from Bates [2007], and MLDs calculated from CTD profiles (downloaded from http://bats.bios.edu/) indicated with blue asterisks. 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) Total pCO_2 (thin solid bold black), pCO_2-T (thin red), pCO_2-nontT (dashed red), and Mauna Loa pCO_2^{atm} (thin black), used to force the model.

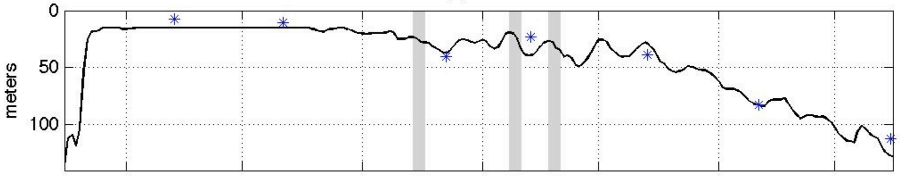
Figure 2. Profiles of (top) phosphate and (bottom) DIC concentrations from the model. Dashed lines are from a day before the hurricanes passed Bermuda, solid lines from a day after. On the phosphate profiles, the depth of the modeled MLDs the day before (triangle) and the day after (square) the hurricane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

Figure 3. Scatter plots of year, hurricane and tropical storm (TS) 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 and tropical storm frequency (NHC data) versus year, (b) annual flux (25-40N, including the Gulf of Mexico and Caribbean) per year, (c) sum of the daily fluxes along hurricane and tropical storm tracks (NHC data) versus number of hurricanes and tropical storms, (d) annual flux versus hurricane and tropical storm frequency.

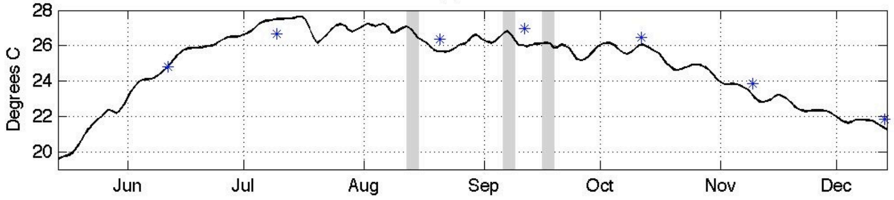
(a) Windspeed at 10 meters



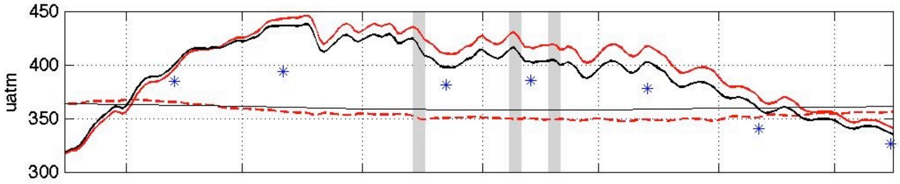
(b) MLD



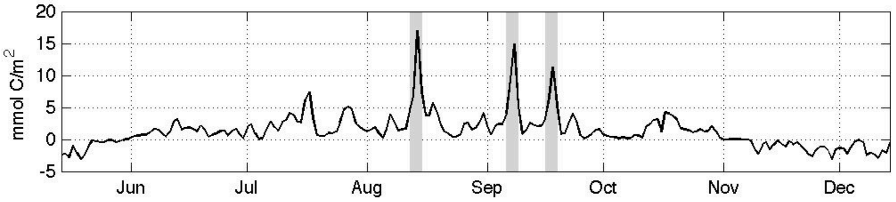
(c) SST



(d) pCO_2



(e) CO_2 flux



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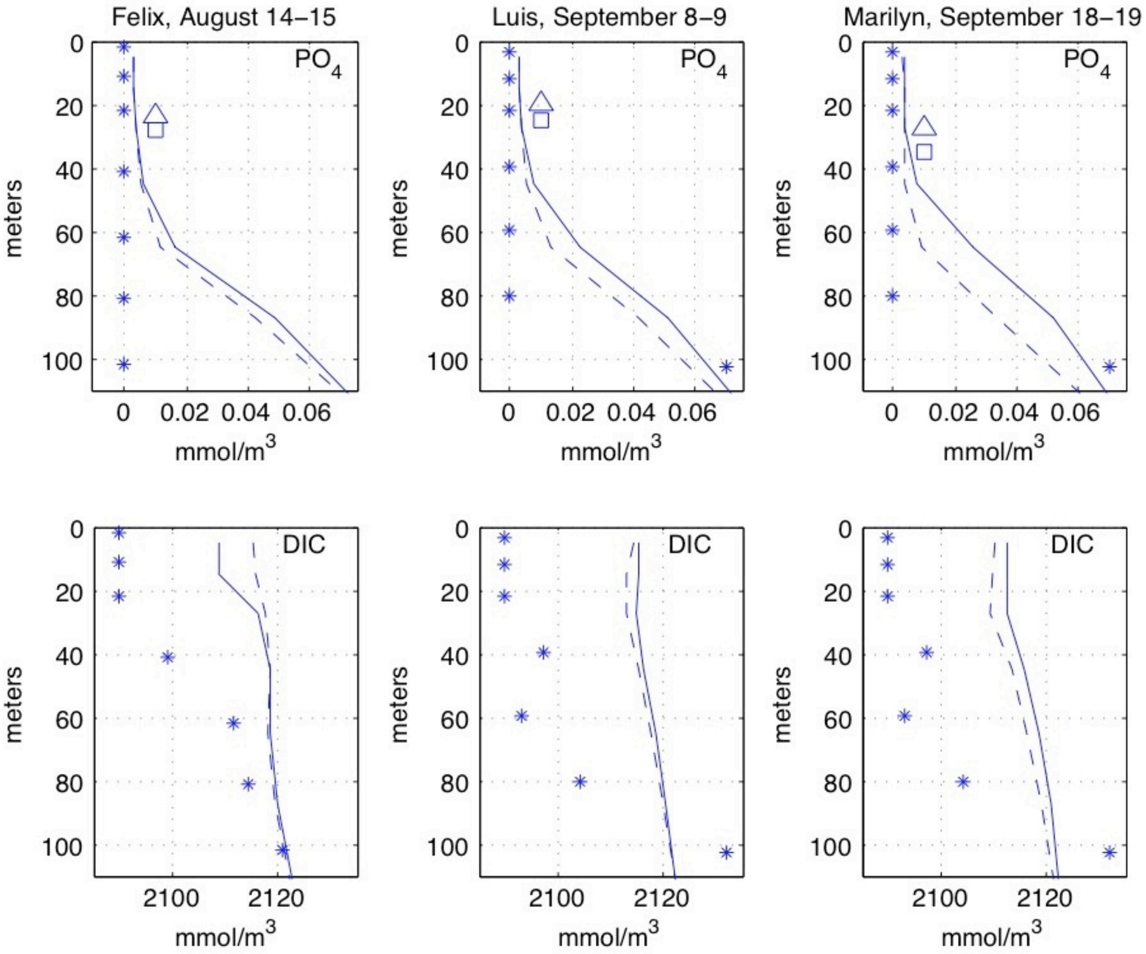

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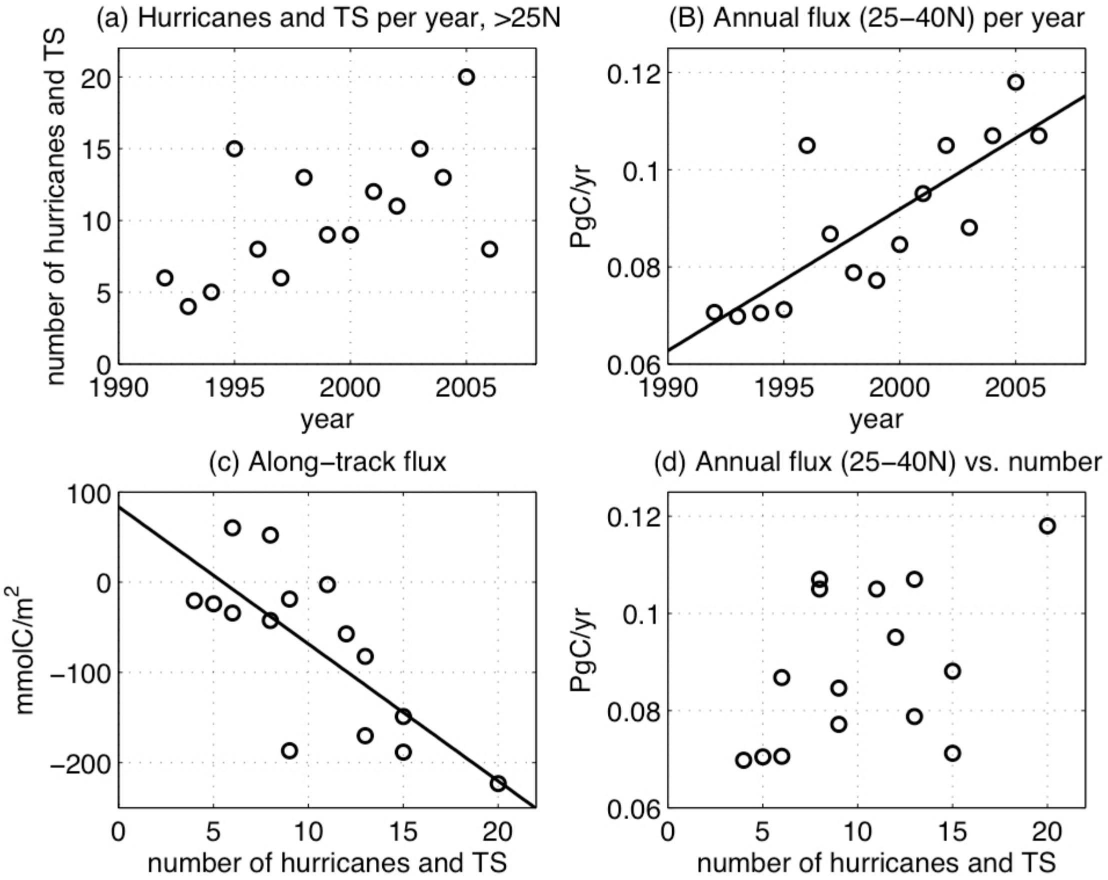

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