GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L07606, doi:10.1029/2009GL037553, 2009

Do hurricanes cause significant interannual variability in the air-sea CO_2 flux of the subtropical North Atlantic?

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Received 30 January 2009; accepted 9 March 2009; published 10 April 2009.

[1] Observations at Bermuda and in the Caribbean Sea indicate that hurricanes influence surface ocean pCO_2 (pCO_2^{ocean}) and air-sea CO_2 fluxes at short time scales. We use a regional version of the MIT ocean general circulation model to study impacts on interannual variability in air-sea CO_2 fluxes in the North Atlantic subtropical gyre (25–40N). Consistent with observations, 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 warm sea surface temperatures (SSTs) during hurricane season. With a storm, vertical mixing causes negative SST anomalies that depress pCO_2^{ocean}, but not enough to reverse the gradient. Though hurricanes drive a substantial local CO_2 efflux, we find no evidence for a relationship between year-to-year variability in hurricane frequency and variability in basin-integrated air-sea CO_2 fluxes across the subtropical North Atlantic. **Citation:** Koch, J., G. A. McKinley, V. Bennington, and D. Ullman (2009), Do hurricanes cause significant interannual variability in the air-sea CO_2 flux of the subtropical North Atlantic?, *Geophys. Res. Lett.*, *36*, L07606, doi:10.1029/2009GL037553.

1. Introduction

[2] 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, hereinafter referred to as B07; D. Ullman et al., North Atlantic carbon cycle response to climate variability, submitted to *Global Biogeochemical Cycles,* 2009]. During the summer, pCO_2^{ocean} rises above atmospheric pCO_2 and thus leads to an efflux of carbon dioxide to the atmosphere. 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.*, 1998, hereinafter referred to as B98; *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 [B98; *D'Asaro and McNeil*, 2007; *Wanninkhof et al.*, 2007].

[3] Though their local effects have been clearly illustrated, the role that hurricanes play in the annual air-sea exchange of CO_2 in the subtropics is not entirely clear. Following the work of B98 who estimated a net global flux up to 0.51 PgC/yr due to hurricanes, B07 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. Would the flux have occurred anyway, albeit more gradually, without hurricanes? In this paper, we consider the impacts of hurricanes on surface ocean biogeochemistry near Bermuda and on the interannual variability in air-sea CO_2 fluxes in the subtropical North Atlantic from 25–40N using an ocean biogeochemical model.

2. Model

[4] As described by *Bennington et al.* [2009] chlorophyll variability tell us about export and CO_2 flux and D. Ullman et al. (submitted manuscript, 2009), 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. Relaxation to hydrographic and biogeochemical tracers occurs along regional boundaries. The model is forced with daily winds, radiative and non-radiative fluxes from the NCEP/NCAR Reanalysis I [*Kalnay et al.*, 1996] for 1992–2006 and SSTs are relaxed (2 week timescale) to satellite-based estimates [*Reynolds et al.*, 2007]. Photosynthetic available radiation (PAR) incident at the sea surface is estimated as 40% of the shortwave radiation [*Frouin and Pinker*, 1995], and is attenuated in the water column by chlorophyll and water. After an 81-year physical spin up, the biogeochemical model was initialized with climatological DIC, alkalinity and nutrients, low values of phytoplankton and zooplankton, and atmospheric pCO_2 fixed at 356 μatm (1992 Mauna Loa mean), and was run for 70 years. For the main run, atmospheric pCO_2 data is interpolated from monthly Mauna Loa observations [*Keeling et al.*, 2001] and is adjusted for local surface atmospheric pressure. The biogeochemical model includes carbonate chemistry and nutrient cycling using an ecosystem model of intermediate complexity [*Dutkiewicz et al.*, 2005]. The flux of carbon dioxide between the ocean and atmosphere is parameterized following *Wanninkhof* [1992], shown by *McNeil and D'Asaro* [2007] to be appropriate when considering hurricanes. We define a positive flux to be out of the ocean.

3. Results

3.1. Local CO_2 Flux Response to 1995 Hurricanes at Bermuda

[5] For comparison to B98 we begin by asking: How well does the NCEP/NCAR Reanalysis capture the hurricanes of 1995? Of the three storms, Hurricane Felix passed closest

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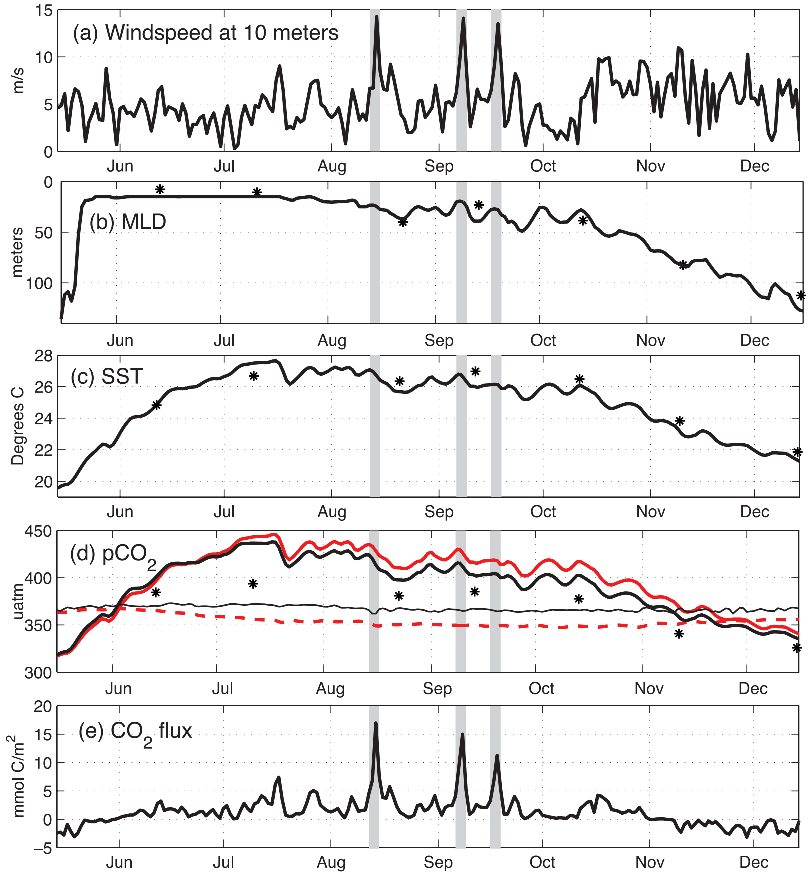

Figure 1. Modeled and observed variables at Bermuda (31N, 64W) from 15 May 1995 through 15 December 1995. SST and pCO_2 data from B07 and MLDs calculated from CTD profiles (downloaded from http://bats.bios.edu/) indicated with asterisks. Hurricanes Felix, Luis, and Marilyn are denoted by the gray bars, 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 pCO_2^{atm} (thin black), and (e) air-sea CO_2 flux, positive to the atmosphere.

to Bermuda, coming nearest 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 Reanalysis. There was 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.

[6] In comparison to the data, modeled MLDs are reasonable across both the seasonal cycle and during the hurricane season. The model responds to hurricane passage with increases in mixed layer depths (MLD) of 5–20m (Figure 1b). Increased mixing causes SSTs (Figure 1c) to drop during the passage of each hurricane, rebounding slowly in the following weeks (B98). 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) [*Takahashi et al.*, 2002] (see Text S1 in the auxiliary material).[1] With this split, is clear that SST depression drives the drop in pCO_2^{ocean} (Figure 1d). With Felix, there is also a small decrease in pCO_2^{ocean} due to non-temperature causes. Analysis of the surface DIC budget (section 3.2 and Text S1) a dilution by large freshwater inputs, an effect that will also lower SSS and thus pCO_2. 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 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} [*Wanninkhof et al.*, 2007].

[7] The magnitudes of modeled CO_2 fluxes during the 1995 hurricanes are similar to those described by B98 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 fully capture a hurricane's intensity. For example, Felix had maximum sustained winds of 40–45 m/s (B98), with maximum wind speeds at Bermuda of 26.2 m/s (B07), 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

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL037553.

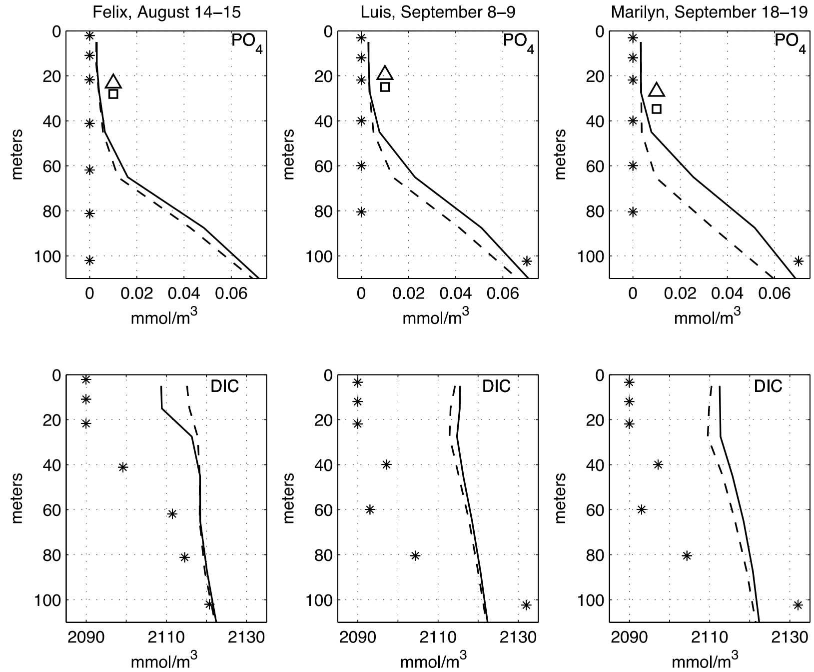

Figure 2. Profiles of (top) phosphate and (bottom) DIC concentrations from the model. Dashed lines are from a day before the hurricanes passed Bermuda, and solid lines are from a day after. On the phosphate profiles, the depth of the modeled MLDs the day before (triangle) and the day after (square) the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

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). B98 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 [*Bennington et al.*, 2009], and thus slightly 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% estimated by B98.

[8] Though the daily winds forcing the model do 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, but forcing data with appropriate resolution is a not available for long enough to allow simulation of the interannual changes of central interest to this study – for example, QuickScat satellite winds are only available from 1999. Thus, for the purpose of this study, we conclude that the model is able to reasonably capture the surface ocean response to all three 1995 hurricanes near Bermuda, and thus is a reasonable tool for study of the local biogeochemical response to hurricanes (section 3.2) and variability in basin-averaged CO_2 fluxes (sections 3.3 and 3.4).

3.2. Hurricane Impacts on the Surface Ocean Biogeochemistry

[9] Modeled phosphate (PO_4) and DIC profiles, and MLDs for one day prior to and one day post hurricane passage are presented in Figure 2, along with monthly data profiles from BATS. The model nutricline sits slightly too high in the water column, surface DIC is too high, and the DIC vertical gradient is too weak, all consistent with low productivity and high summer pCO_2^{ocean} as discussed above (see also Text S1), and may be due to a lack of subsurface to surface nutrient transfer in unresolved mesoscale eddies [*Ledwell et al.*, 2008]. These problems with the model mean state do likely degrade the representation of the biogeochemical response to hurricanes.

[10] The modeled 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. Detailed model analysis (see Text S1 and Figure S1) 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 (Figure 2).

[11] Consistent with B98, storm-induced mixing in the model does not penetrate into the nutricline, bring nutrients to the surface, and stimulate a biological response. However, there have been satellite observations of enhanced surface

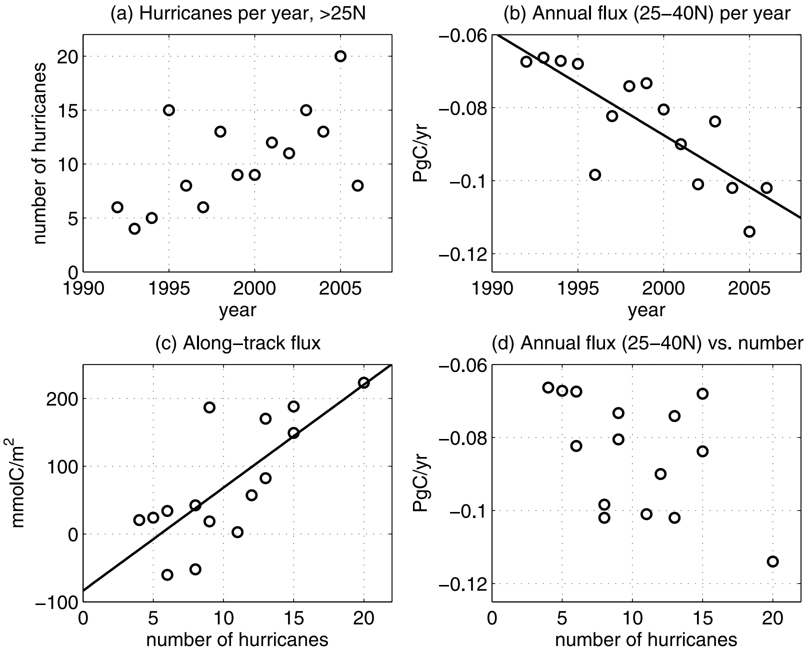

Figure 3. Scatterplots of year, hurricane, and tropical storm (TS) frequency and modeled CO_2 fluxes, as well as best-fit lines when a linear trend is able to reasonably define the relationship. (a) Hurricane and tropical storm frequency (NHC data) versus year, (b) annual flux (25–40N, including the 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, and (d) basin-integrated annual flux versus hurricane and tropical storm frequency.

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 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.

3.3. Basin-Wide Impact on Carbon Dioxide Flux

[12] In this section, we use our North Atlantic model to test the basin-scale extrapolations by B98 and B07. They conclude 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 globally between 40S and 40N. Neither our study nor theirs considers impacts north of 40N, where hurricanes may drive enhanced carbon uptake due to the reversed air-sea pCO_2 gradient in summer. Furthermore, we focus on the subtropical region, 25–40N.

[13] 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^{atm} (Ullman et al., submitted manuscript, 2009). 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 efflux increases with the number of hurricanes. The fact that we consider only storm number suggests that it is not necessary to describe variation in storm size and strength to capture the first-order effects on local CO_2 fluxes.

[14] If we now consider the basin-integrated CO_2 flux between 25–40N, we find there is not a statistically significant relationship between the number of hurricanes and the basin-integrated, annual 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 net CO_2 sink across the subtropical North Atlantic. This finding is contrary to the suggestion of B98 and B07. 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.

3.4. Are Model Errors Likely to Impact Our Conclusions?

[15] This model underestimates the magnitude of the local surface ocean carbon cycle response to hurricanes, largely because of the use of daily-mean winds and the one-half degree resolution. The model also overestimates the summertime air-sea gradient in pCO_2. These two effects partially counteract each other in the calculation of the flux, but the result remains an underestimate (section 3.1). Could these model flaws modify our conclusion that there is a negligible impact of hurricanes on interannual variability in the

subtropical CO_2 sink? To test this, we consider the modeled maximum annual along-track flux for all hurricanes (223 mmol C/m^2, Figure 3c) and assume it is an underestimate by more than a factor of 2; thus we will use 500 mmol C/m^2 in our calculation. Note that this is more than 3 times the flux due to all 1995 hurricanes (145 mmol C/m^2) estimated by B98. If we assume this annual flux applies over all of a canonical 250km diameter hurricane, the largest size used by B98, the total flux is 2.95×10^{-4} PgC/yr, only 0.26–0.44% of the annual net carbon flux estimate for the years 1992–2006 (−0.066 to −0.114 PgC/yr, Figure 3b) for the subtropical North Atlantic from 25–40N. If we add to this tropical force winds extending to 750km and causing a flux of 150 mmolC/m^2, the total flux is 1.00×10^{-3} PgC/yr, or 0.87–1.5% of the total annual sink. We conclude that even if the model was able to more accurately simulate the local impact of hurricanes, we would still not find them to have a significant impact on year-to-year variability in the subtropical North Atlantic carbon sink.

[16] Our findings are in contrast to previous works, particularly B98, which we attribute in part to the methodology used in their basin-scale extrapolation. They use very large hurricane-driven fluxes, values that are generally much larger (by 100 times or more) than those estimated from observations at Bermuda (see Text S1). Our modeled maximum annual hurricane-driven flux across the North Atlantic (25–40N, 223 mmol C/m^2) is only 3.4 times the maximum modeled annual flux at Bermuda (65 mmol C/m^2, 1995, section 3.1).

4. Summary

[17] We have evaluated 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 reasonable 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.

[18] **Acknowledgments.** We thank S. Dutkiewicz for collaboration on model development and analysis, N. Bates for data and commentary, R. Wanninkhof and an anonymous reviewer for insightful comments, the many scientists and technicians at the BATS, and NASA for funding (CARBON/04-0300-0228).

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