

Observations of Air-Sea Exchange of N₂ and O₂ during the passage of Hurricane Gustav in the Gulf of Mexico during 2008

Craig L. McNeil¹, Eric A. D'Asaro^{1,2}, and Jeffrey A. Nystuen^{1,3}

¹ *Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98115, USA, E-mail: cmcneil@apl.washington.edu*

² *Department of Oceanography, University of Washington, Seattle, WA, US
E-mail: dasaro@apl.washington.edu*

³ *E-mail: nystuen@apl.washington.edu*

Abstract. A lack of understanding of air-sea exchange processes at hurricane force winds makes it difficult to quantitatively evaluate the impact of tropical cyclones on regional and global carbon budgets and their potential for feedback on climate change. Following on from our prior work in H. Frances in 2004 (D'Asaro and McNeil, 2007), three gas sensing floats were deployed in H. Gustav, Gulf of Mexico, during September 2008 to measure air-sea fluxes of N₂ and O₂. Maximum winds during H. Gustav were approximately 44 m s⁻¹. Upper ocean dissolved N₂ and O₂ saturation levels increased to approximately 110%, similar to levels observed during H. Frances. The similarities of both data sets confirm the qualitative conclusions of our prior work, most notably, that large net counter gradient air-sea fluxes of N₂ and O₂ occur at hurricane force winds as a result of deep bubble injection.

Key Words: Hurricanes, bubbles, gas flux

1. Introduction

Significant uncertainty exists regarding the role of tropical cyclones in the global carbon cycle and especially their potential importance in climate change via feedback mechanisms. Tropical cyclones are assumed to mostly release CO₂ from the ocean back to the atmosphere during their passage since they mostly occur over regions of the ocean that, during the time hurricanes and typhoons occur, are supersaturated in CO₂. Estimates of net CO₂ release to the atmosphere during the hurricane passage are highly uncertain (Bates *et al.* 1998; Bates, 2002; Perrie *et al.* 2004; Koch *et al.* 2009). In the cold wake of a hurricane (D'Asaro *et al.* 2007), seasonal CO₂ fluxes may be locally suppressed due to the lower seawater pCO₂. This effect may partially compensate for the enhanced CO₂ efflux during the passage of a hurricane (Wanninkhof *et al.* 2007). In addition, hurricanes can

produce phytoplankton blooms in their wake (Babin *et al.* 2004; Seunghyun *et al.* 2007). The combination of air-sea gas exchange during and after the hurricane, plus any post-hurricane induced biological bloom, can be expected to determine the regional ‘carbon footprint’ of a hurricane. Our work has focused on measuring air-sea gas exchange rates at hurricane force winds with the goal of reducing uncertainty in air-sea gas flux estimates.

Since we cannot measure CO₂ exchange rates directly under hurricane force winds due to lack of suitable instrumentation, we instead infer gas exchange rates using measurement based estimates of N₂ and O₂ fluxes. Bubble mediated gas exchange formulations are used to scale the N₂ and O₂ derived exchange rates to those appropriate for use in CO₂ flux calculations (*e.g.*, Vagle *et al.* 2010). We previously described a wind speed based parameterization of air-sea exchange rates appropriate for hurricane force winds based on measurements obtained during H. Frances (D’Asaro and McNeil, 2007, henceforth DM-07; McNeil and D’Asaro, 2007; henceforth MD-07). Prior to that study there were no measurements of air-sea gas transfer rates at wind speeds above approximately 25 m s⁻¹ (hurricane force winds are defined by winds in excess of 32 m s⁻¹). The purpose of this paper is to present a brief overview of a new dissolved gas dataset collected during H. Gustav. We can only present here qualitative comparisons with the H. Frances data set (see Table 2 of DM-07). A quantitative comparison of both data sets, and one that tests the gas flux model and wind speed parameterizations developed for H. Frances, will be described in a follow-on paper.

2. Experimental overview

New measurements were collected in Hurricane Gustav, Gulf of Mexico, during September 2008 using GasFloats similar to those used in the prior H. Frances study (see Figure 1 of DM-07). Four float packages (#50–53) were air-deployed in the vicinity of 28 °N and 89 °W. The floats were deployed northwest of H. Gustav, which was advancing toward the floats from the southeast. A summary of the deployments is presented in Table 1. Float #50 was fully functional and provided high resolution O₂ and N₂ measurements. High frequency O₂ measurements are required to make O₂ covariance flux estimates and therefore only possible for Floats #50 and #53. Also, Float #53 only measured O₂ (the crystal of the GTD’s pressure sensor probably broke on impact). Float #52’s deployment package malfunctioned, so no scientifically useful data was obtained. Float #51 was eventually lost at sea during the passage of a second hurricane. Fortunately, however, this loss occurred after it had transmitted a low resolution subset of the H. Gustav data by Iridium satellite. Float #50 was deployed in the forward right hand quadrant of the hurricane and therefore should have

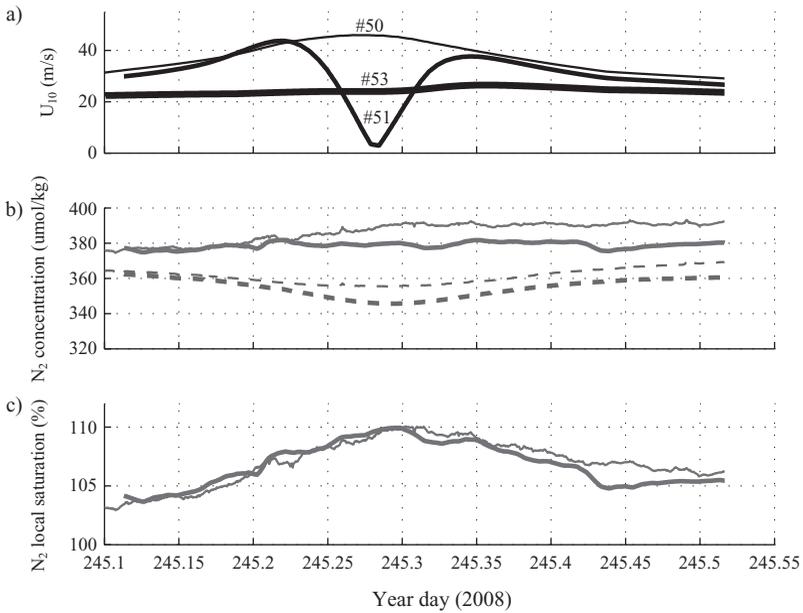


Figure 1 Dissolved N_2 measurements made during H. Gustav, showing: a) 10 m height wind speed estimates (black), and b) mixed layer dissolved N_2 concentrations (red) and local equilibrium concentrations based on gas solubility (dashed blue), and c) mixed layer dissolved N_2 saturation levels expressed with respect to local barometric pressure, calculated from the ratio of the concentrations in panel b. In each panel, data are shown for three floats: Float #50 (thin lines), Float #51 (medium lines), and Float#53 (thick lines). Note that Float #51 passed through the eye of the hurricane so the wind speed decreased to near zero. There are no N_2 measurements for Float #53 due to sensor malfunction.

experienced similar conditions as those floats deployed in the prior H. Frances study. A novelty is that Float #51 passed directly through the eye of the hurricane.

An important addition to the H. Gustav data set, that was not available for H. Frances, is ambient noise recordings (ANR). All floats deployed in H. Gustav were equipped with ANR instrumentation. We plan to analyze these data to estimate wave breaking rates. These estimates will then be compared to gas flux estimates.

Winds and atmospheric pressure were estimated using the H*WINDS analysis system (Powell *et al.* 1998).

3. Results and discussion

3.1 Overview of H. Gustav data

Figures 1 and 2 provide an overview of the dissolved N_2 and O_2 measurements obtained during H. Gustav. These measurements were made when the floats were

Table 1 Summary notes on the deployment of four floats into Hurricane Gustav in 2008. Low resolution (column 4) refers to sub-sampled data retrieved by satellite communications only, high resolution refers to a complete data set retrieved from ship-recovered floats. Covariance O₂ flux estimates are only available for high resolution datasets. Maximum 10 m height wind speeds in units of m s⁻¹ are also shown (column 5).

Float	N ₂	O ₂	Res.	U ₁₀	Deployment location
#50	Yes	Yes	High	45	Forward right quadrant of the hurricane, similar to H. Frances deployments.
#51	Yes	Yes	Low	41	Passed through eye of hurricane, but eventually lost at sea during second storm.
#52	—	—	—	—	Did not survive air deployment.
#53	No	Yes	High	15	Edge of the hurricane.

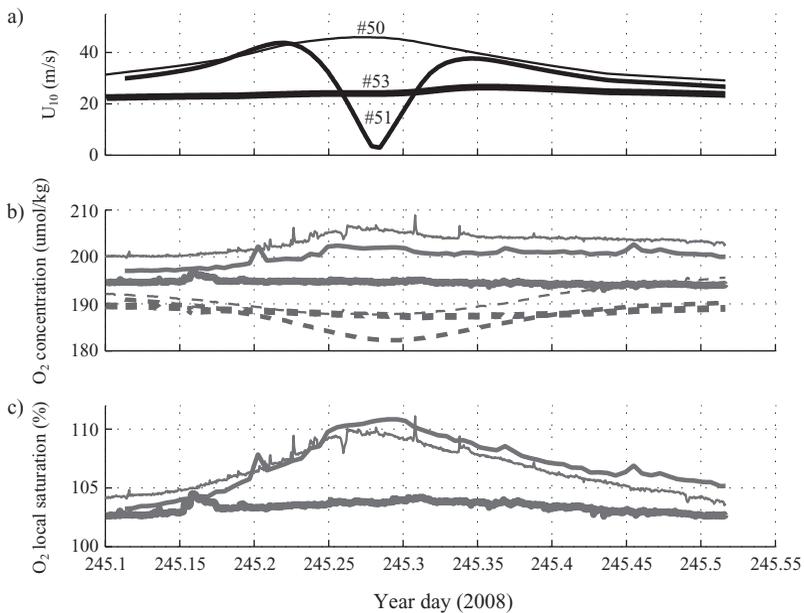


Figure 2 Dissolved O₂ measurements made during H. Gustav. See Figure 1 for description of line types.

freely drifting in the mixed layer during the passage of the hurricane. Maximum winds were approximately 45 m s⁻¹ at Float #50 (Figure 1a, and column 5 of Table 1). Central pressure of the hurricane was approximately 968.5 mbar. Note that for Float #51, the wind speed dropped to near zero in the eye of the hurricane (Figure 1a). Maximum local dissolved gas saturation levels at Floats #50 and #51 were approximately 110 % (Figures 1c and 2c). These saturation levels account for local air pressure fluctuations. Float #53 was located on the edge of the hurricane

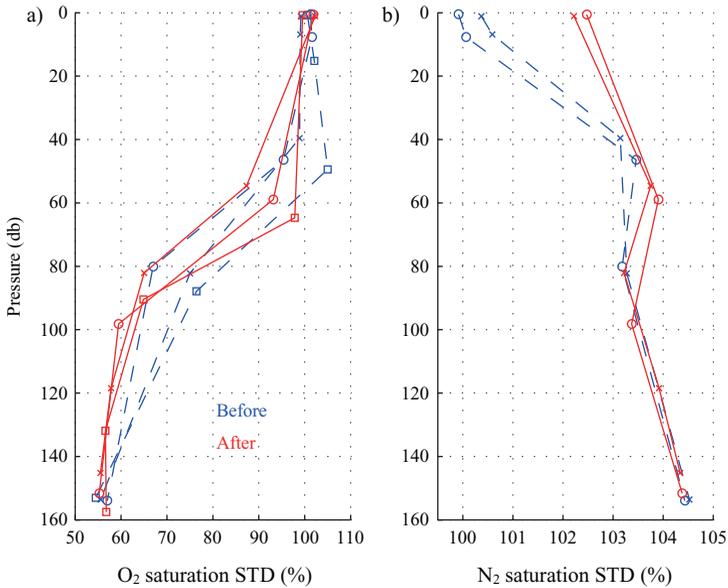


Figure 3 Vertical profiles of dissolved O₂ (left panel) and N₂ (right panel) saturation levels, expressed with respect to one standard atmosphere of moist tropospheric air (STD), obtained before (dashed blue) and after (red) the passage of H. Gustav for Float # 50 (circles), Float #51 (crosses), and Float #53 (squares).

(column 6 of Table 1), received much lower winds, and O₂ levels rose to only approximately 104% (Figure 2c).

Profiles of dissolved gas saturation levels before and after the passage of the hurricane are presented in Figure 3. Since these saturation levels are expressed with respect to 1 standard atmosphere of moist tropospheric air, variations in atmospheric pressure, which are of no consequence to variability in pycnocline gas levels, are excluded. Pre-hurricane dissolved O₂ saturation levels decreased from $101 \pm 2\%$ near the sea surface to $73 \pm 7\%$ at approximately 84 m depth (Figure 3a). Some pre-hurricane profiles also show subsurface O₂ supersaturation (e.g., Float #53). Dissolved O₂ is a biologically active gas hence pre-hurricane profiles reflect a strong biologically induced profile. Pre-hurricane dissolved N₂ measurements show a slight increase from $100.2 \pm 0.4\%$ near the sea surface to $103.25 \pm 0.1\%$ at approximately 82 m depth (Figure 3b). Dissolved N₂ is a biologically inactive gas hence saturation levels are mostly determined by heating and mixing. Net biological consumption of O₂ in the pycnocline at depths greater than approximately 70 m is evident from the large drop in O₂ saturation levels and relatively constant N₂ saturation levels. Post-hurricane near surface N₂ saturation levels were higher, by approximately 2.5%, than pre-hurricane levels (Figure 3b),

consistent with input of N₂ by dissolving bubbles during the hurricane. Negligible changes in near surface O₂ saturation levels were detected (Figure 3a). These observations are consistent with mixing of deeper waters with low dissolved O₂, but relatively constant N₂, during the hurricane.

Elaborate pre- and post-cruise calibrations of the float O₂ sensors were performed in Puget Sound (WA, USA) to ensure high accuracy in the dissolved gas measurements. Those data showed an absolute accuracy in dissolved O₂ measurement of $\pm 2 \text{ } \mu\text{mol kg}^{-1}$, or approximately $\pm 0.5\%$ in saturation level. During H. Gustav the deepest measurements of O₂ and N₂ saturation levels were made at $150 \pm 10 \text{ m}$ depth and remained constant. This is because the influence of the hurricane was not felt at those depths. The four deepest N₂ measurements, made by Float's #50 and #53, at depths ranging from 145 m to 154 m varied by less than 0.2 % in saturation level. The fact that deep N₂ saturation levels measured using different floats were consistent to within $\pm 0.2 \%$ saturation provides additional *in situ* evidence of the high quality of these gas measurements.

3.2 Comparison to H. Frances data

Measurements from the forward right hand quadrants of H. Gustav (2008) and H. Frances (2004) are plotted for comparison in Figure 4. The measurements from H. Gustav were made using Float #50. Wind speeds during H. Frances were larger than those during H. Gustav, by approximately 10 m s^{-1} (Figure 4a). During both hurricanes the local saturation levels of N₂ and O₂ in the ocean surface layer peaked at approximately 110% (Figure 4b). This occurs despite significant entrainment of waters with generally lower, in the case of O₂, or approximately equal, in the case of N₂, gas levels. Local gas saturation levels quickly increased as the storm approached the floats and slowly decreased as the storm moved away from the floats (Figure 4b). During both hurricanes the maximum gas saturation levels appear to lag the maximum winds, more so in H. Frances than H. Gustav, noticeably for N₂ in both hurricanes and O₂ in H. Frances, but poorly resolved for O₂ in H. Gustav (Figure 4b). Both data sets are qualitatively similar.

As seen from Figure 2 of DM-07, during the passage of H. Frances the maximum observed penetration depth of nearly neutrally buoyant Floats #21 and #22 was approximately 75 m. Although float penetration depth is an important indicator of the depth of large scale mixing, it tells us much less about the maximum depth of influence of smaller scale diffusive mixing in the pycnocline below this layer as seen by comparing the mixed layer depth estimates in H. Frances (magenta/yellow lines in Figure 2 of DM-7) with the float penetration depth (red/blue lines in Figure 2 of DM-07). The maximum depth of penetration of Float #50 during H. Gustav was 32 m, considerably less than that during H. Frances. This observation indicates that mixing during H. Gustav was shallower

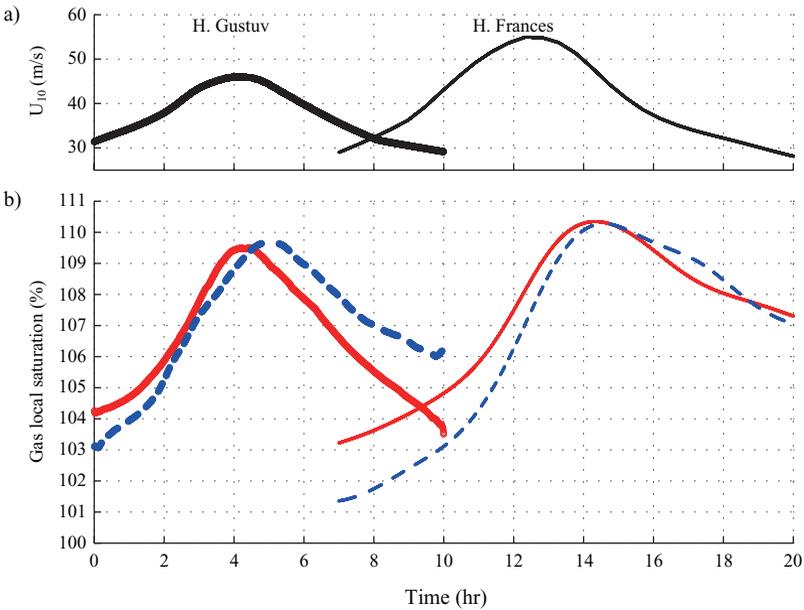


Figure 4 Comparison of data from the forward right quadrants of H. Gustav (heavy shading), made using Float #50, and H. Frances (light shading) showing: (a) wind speed (black lines), and (b) local saturation levels of dissolved N_2 (dashed blue lines) and O_2 (red lines).

that during H. Frances. An inspection of pre- and post-storm temperature and salinity profiles made during H. Gustav supports this interpretation. Active mixing within the pycnocline seems to extend to a depth of no more than 80 m depth in H. Gustav, but exceeded 110 m in H. Frances (magenta line, Figure 2 of DM-07). We suspect that shallower mixed layer depths during H. Gustav may have partially compensated for expected smaller gas fluxes, since wind speeds were lower, with the net result that measured changes in gas saturation levels during both hurricanes was similar. Why peak gas saturation levels lag peak winds is a more complicated question which we hope to answer after completing a detailed analysis of mixing during H. Gustav. We do note, however, that this feature of the H. Gustav data does not directly imply that the peak gas fluxes lead peak winds, as was assumed during the H. Frances study (MD-07).

4. Conclusions and outlook

We have presented a brief overview of a new high quality dissolved gas data set obtained during the passage of Hurricane Gustav in the Gulf of Mexico during 2008. Qualitatively, the new data set shows the same general features of the original H. Frances data set described in DM-07 and MD-07. Similarity of data

from H. Gustav (Float #50) and H. Frances (Floats #21 and #22) supports the qualitative conclusions of DM-07 and MD-07, namely: 1) at hurricane force winds, fluxes of N₂ and O₂ are into the ocean and therefore 'counter-gradient' at the highest winds speeds; and, 2) deep bubble injection is the dominant mechanism for exchange of N₂ and O₂ between the atmosphere and ocean at hurricane force winds.

Our next task in the analysis of H. Gustav data is to perform a careful error analysis of the budget derived net air-sea gas fluxes, and then compare the budget derived O₂ fluxes with the Float #50 derived O₂ co-variance fluxes. We will then use the budget derived fluxes from H. Gustav to perform an independent test of the gas flux model presented in MD-07. Our overall goal, however, is to improve existing parameterizations of gas flux at high to extreme wind speeds by incorporating wind and wave effects into the model formulations. Prior results from H. Frances indicated that gas fluxes were larger during rising winds than during falling winds, since peak gas fluxes led peak winds by approximately 100 minutes (MD-07). This result remains uncertain due to uncertainty in timing of the wind speed estimates. We plan to test the hypothesis that wave effects can cause a hysteresis in gas flux versus wind speed using ANR derived estimates of wave breaking rates during H. Gustav.

Acknowledgements

This work was supported by the National Science Foundation under grants OCE 0549887 and 0834340. McNeil is Vice President and co-owner of Pro-Oceanus Systems, Inc., the manufacturer of the GTD's used in this study.

References

- Babin, S.M., J.A. Carton, T.D. Dickey, J.D. Wiggert (2004), Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert, *J. Geophys. Res.*, 109:C03043, doi:10.29/2003JC001938.
- Bates, N.R. (2002), Interannual variability in the global ocean uptake of CO₂, *Geophys. Res. Lett.*, 29(5), 1059. doi:10.1029/2001GL013571.
- Bates, N.R., A. H. Knap, and A. F. Michaels (1998), Contribution of hurricanes to local and global estimates of air-sea exchanges of CO₂, *Nature*, 395, 58-61.
- D'Asaro, E.A., and C.L. McNeil (2007), Air-sea gas exchange at extreme wind speeds, *J. Marine Sys.*, 66(1-4), 92-109.
- D'Asaro, E. A., T. B. Sanford, P. P. Niiler, and E. J. Terrill (2007), Cold wake of Hurricane Frances, *Geophys. Res. Lett.*, 34, L15609, doi:10.1029/2007GL030160.
- Koch, J., G. A. McKinley, V. Bennington, and D. Ullman (2009), Do hurricanes cause significant interannual variability in the air-sea CO₂ flux of the subtropical North Atlantic?, *Geophys. Res. Lett.*, 36, L07606, doi:10.1029/2009GL037553.
- McNeil, C.L., and E.A. D'Asaro (2007), Parameterization of air-sea gas fluxes at extreme wind speeds, *J. Marine Sys.*, 66(1-4), 110-121.

- Perrie, W., W. Zhang, X. Ren, Z. Long, and J. Hare (2004), The role of midlatitude storms on air-sea exchange of CO₂, *Geophys. Res. Lett.*, 31, L09306, doi: 10.1029/2003GL019212.
- Powell, M.D., S.H. Houston, L.R. Amat Jr., and N. Morisseau-Leroy (1998), The HRD real-time hurricane wind analysis system, *J. Wind Eng. Ind. Aerodyn.*, 53-64.
- Seunghyun, S., T. Platt, C. Fuentes-Yaco, H. Bouman, E. Devred, Y. Wu, and S. Sathyendranath (2007), Possible biogeochemical response to the passage of Hurricane Fabian observed by satellites, *J. Plankton Res.*, 29, 687-697, doi:10.1093/plankt/fbm050.
- Vagle, S., C. McNeil, and N. Steiner (2010), Upper ocean bubble measurements from the NE Pacific and estimates of their role in air-sea gas transfer of the weakly soluble gases nitrogen and oxygen, *J. Geophys. Res.*, 115, C12054, doi:10.1029/2009JC005990.
- Wanninkhof, R., A. Olsen, and J. Trinanes (2007), Air-sea CO₂ fluxes in the Caribbean Sea from 2002-2004, *J. Mar. Sys.*, 66(1-4), 272-284.