# Toward Eddy Covariance $CO_2$ Flux Measurement Capability on an Ocean Buoy


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## Introduction

Direct air-sea $CO_2$ flux measurements using eddy covariance (EC) can be used to evaluate and improve ocean-atmosphere gas exchange parameterizations (e.g.,Wanninkhof and McGillis 1999; Butterworth and Miller 2016, Fig 1). While EC $CO_2$ fluxes from research vessels have improved over the last 20 years, existing data sets are of limited duration, and significant technical challenges remain, such as air flow distortion about ships (Fig 2).

An alternative is to use moored platforms such as ocean buoys that could enable longer deployments and are less affected by flow distortion (e.g., Weller et al. (2012) and Ocean Observing Initiative (OOI) buoys). For $CO_2$, major hurdles in buoy-based EC flux measurements include sea spray effects on gas analyzer performance, significant power limitations, and motion sensitivity of commercially available InfraRed Gas Analyzers (IRGAs) (McGillis et al. 2001).

A collaboration between SUNY Albany, the University of New Hampshire, and Campbell Scientific Inc. (CSI) aims to develop a robust, low-power EC air-sea $CO_2$ flux measurement system that can be deployed on buoys.

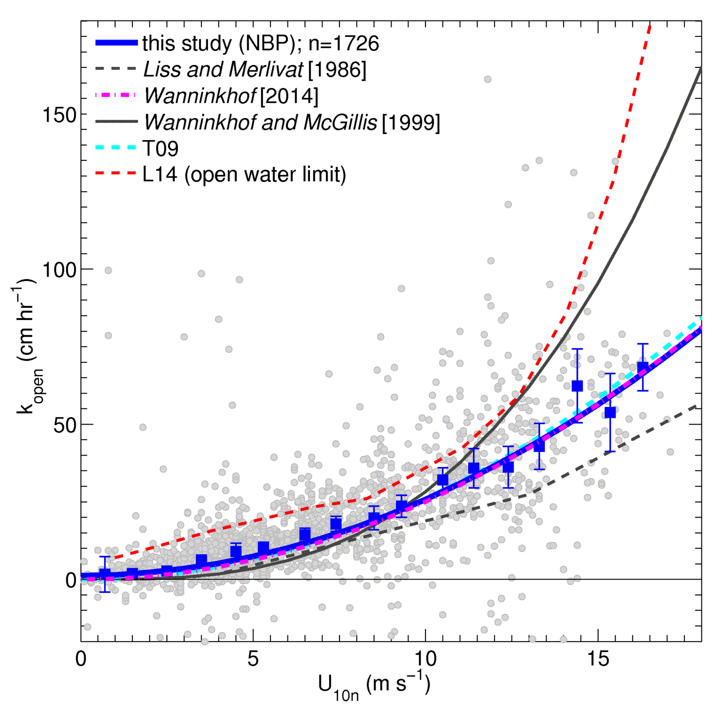



**Figure 1.** Gas transfer velocity versus neutral 10-m wind speed ($U_{10n}$) measured from *Nathaniel B. Palmer*, along with existing parameterizations.

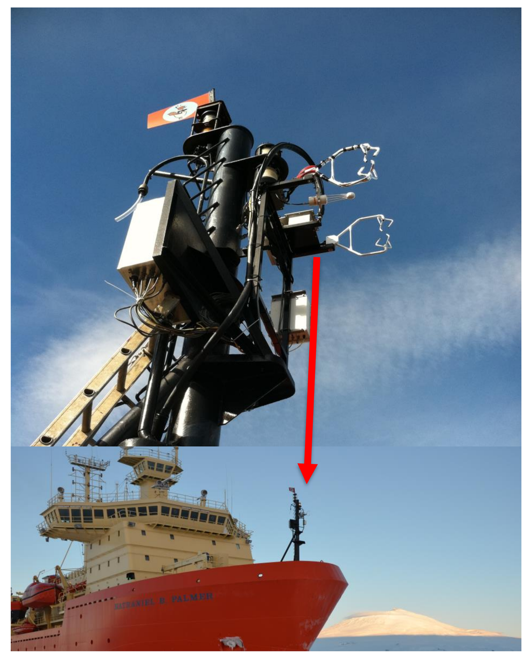


**Figure 2.** Eddy covariance flux system deployed by Butterworth and Miller (2016) aboard the U.S. research vessel Nathaniel B. Palmer.

## Air-Sea $CO_2$ Exchange

In models, $CO_2$ flux ($F_c$) is expressed using a bulk formula (1), where $\Delta pCO_2$ is the difference in $CO_2$ partial pressure between the bulk surface and the atmosphere, s is the solubility of $CO_2$ in seawater, and k is the gas transfer velocity. Generally, the gas transfer velocity depends on turbulence on both sides of the air water interface. For a low solubility gas like $CO_2$, the process is mostly water side controlled. Physical processes that affect k_ $CO_2$ include wind stress, ocean surface waves and roughness, mechanically generated bubbles and spray from breaking waves.

Bulk $CO_2$ flux : $F_c = ks\Delta pCO_2$ (1)

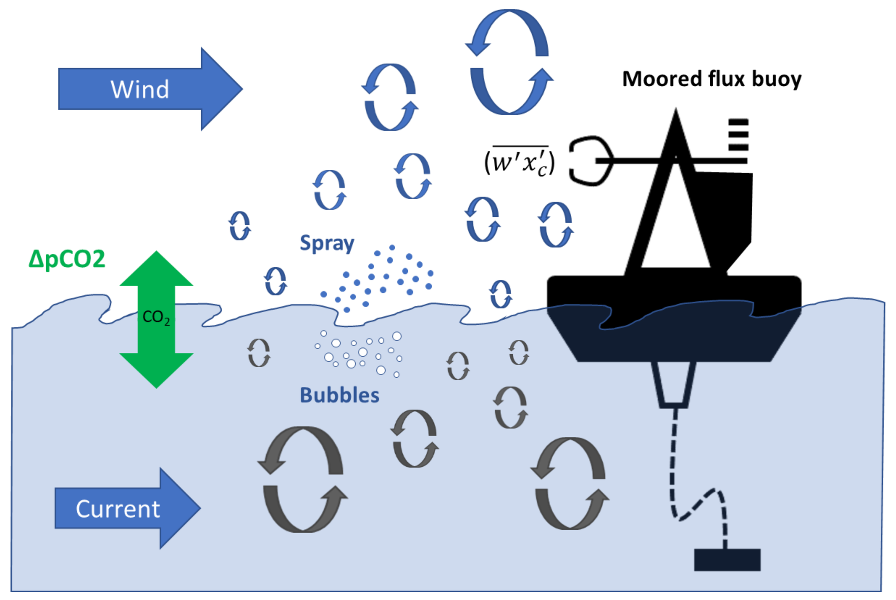



**Figure 3.** A schematic showing processes that contribute to $CO_2$ Flux at an air-sea interface, as measured using the eddy covariance method on a buoy.

## Methods

### Eddy Covariance

| | | |
|---|---|---|
| Momentum | $\tau = \overline{\rho_a}\,\overline{u'w'}$ | (2) |
| Latent heat | $H_L = \overline{\rho_a}\, L_v\, \overline{w'q'}$ | (3) |
| Sensible heat | $H_s = \overline{\rho_a}\, c_p \overline{w'T'}$ | (4) |
| $CO_2$ Flux | $F_c = \overline{\rho_a}\, \overline{w'x_c'}$ | (5) |

- Vertical turbulent fluxes proportional to covariance between vertical wind velocity and quantity of interest
- high-frequency measurements (10-20 Hz)
- 10-20 minute flux period
- EC measurements of $F_c$ can be combined with measurements of $\Delta pCO_2$ to determine k (equations 1 and 5)

Where $\rho_a$ is the density of air; $L_v$ is the latent heat of vaporization; q is specific humidity, primes represent fluctuations about the mean over the flux period; u and w are their respective wind components; T is air temperature measured by the sonic anemometer; and $x_c'$ represents fluctuations of the partial pressure of $CO_2$.

### Buoy-based approach

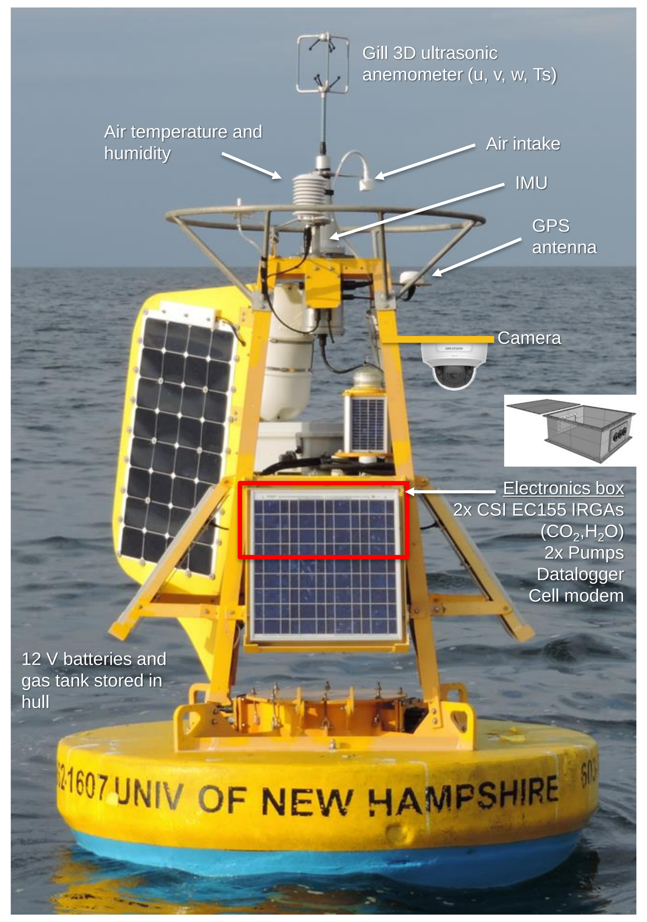



**Figure 4.** UNH 2-m diameter discus buoy.

1. closed path IRGA (McGillis et al. 2001)
2. sample air stream drying (Miller et al. 2010)
3. Motion correction of wind vector (Edson et al., 1998)

| Measurement | Manufacturer | Instrument |
|---|---|---|
| U, V, W, $T_s$ | Gill Instruments | R3-50 |
| Air temperature Relative humidity | Rotronic | MET - MP101A-T7 |
| $CO_2$ mixing ratio $H_2O$ mixing ratio | Campbell Scientific Inc. | EC155 |
| Motion | Microstrain | 3DM-GX5-45 |
| Visible images | Hikvision | DS-2CD2783G1-IZS |

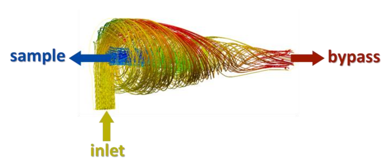



**Figure 5.** Streamline of air in the Vortex inlet developed by CSI (Ma et al. 2017). Yellow indicates homogenized intake air, red indicates dirty air, and blue indicates clean air destined for the IRGA sample cell.

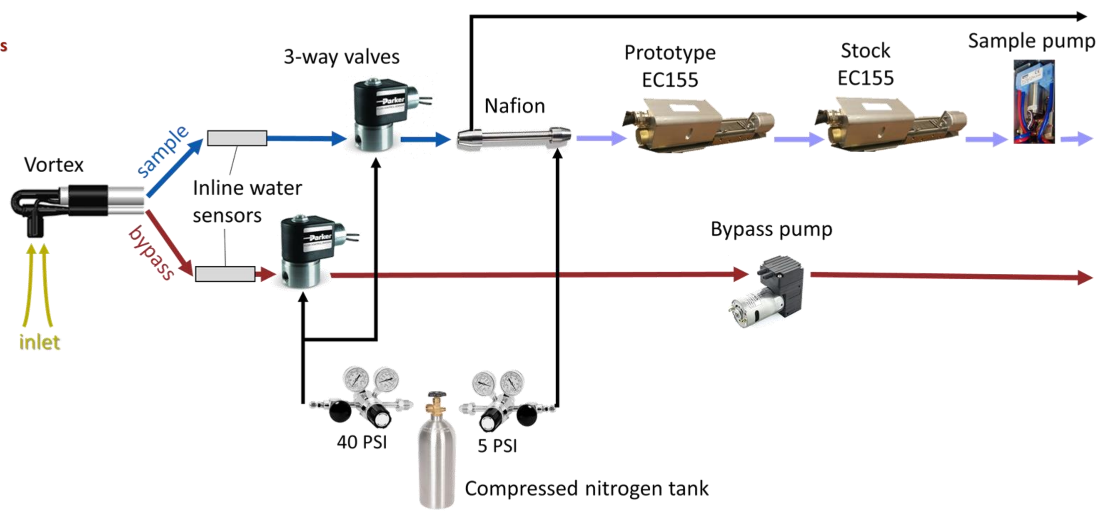



**Figure 6.** An air intake water rejection system to protect closed-path IRGA (based on Butterworth and Miller, 2016).

### Reducing IRGA Motion Sensitivity

In collaboration with CSI, an EC155 gas analyzer was modified (both hardware and software) to reduce sensitivity to motion. The prototype (proto) analyzer was tested in the lab alongside a stock unit. The sensitivity to motion was reduced by roughly a factor 3-5.

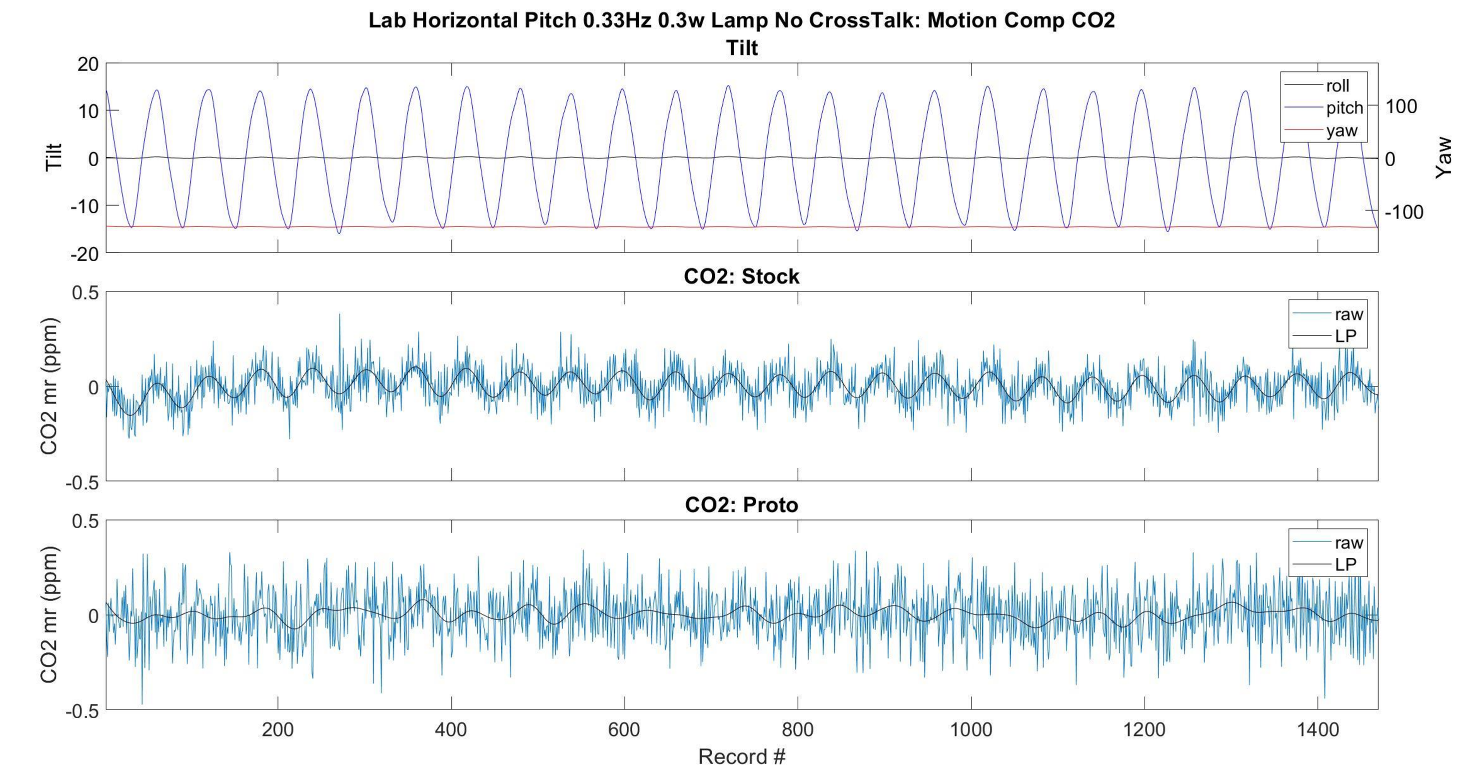



**Figure 7**. Example time series of manually-induced motion of a test platform, and $CO_2$ signals recorded by a stock and a prototype EC155 gas analyzer

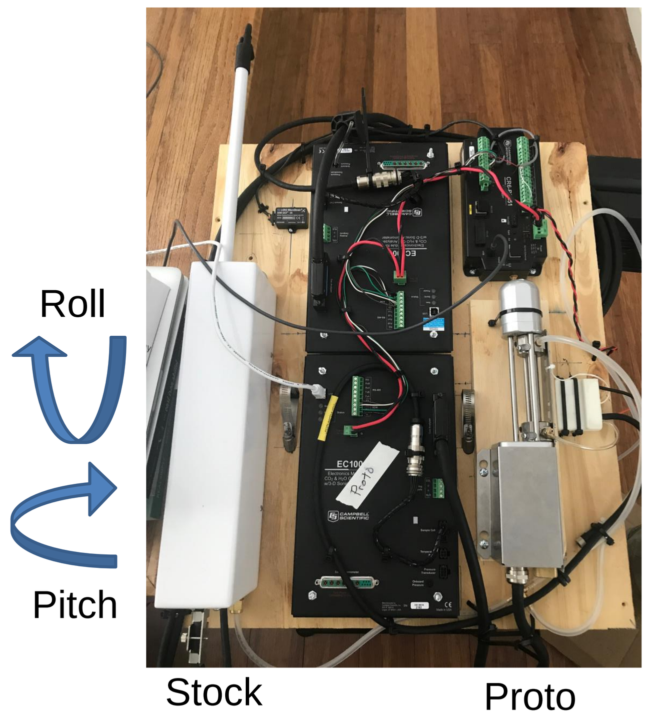



**Figure 8**. Test platform for motion testing of stock and prototype EC155 IRGA.

## Testing

### UNH Dive Tank

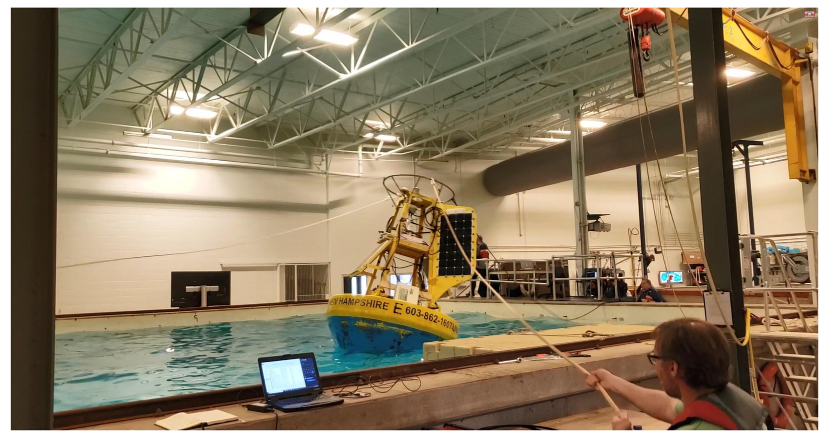


**Figure 9.** A 20 x 12 x 6 m tank was used to test and characterize motion sensitivity of the stock and prototype IRGAs. Motion was induced using ropes tied to buoy's top rail.

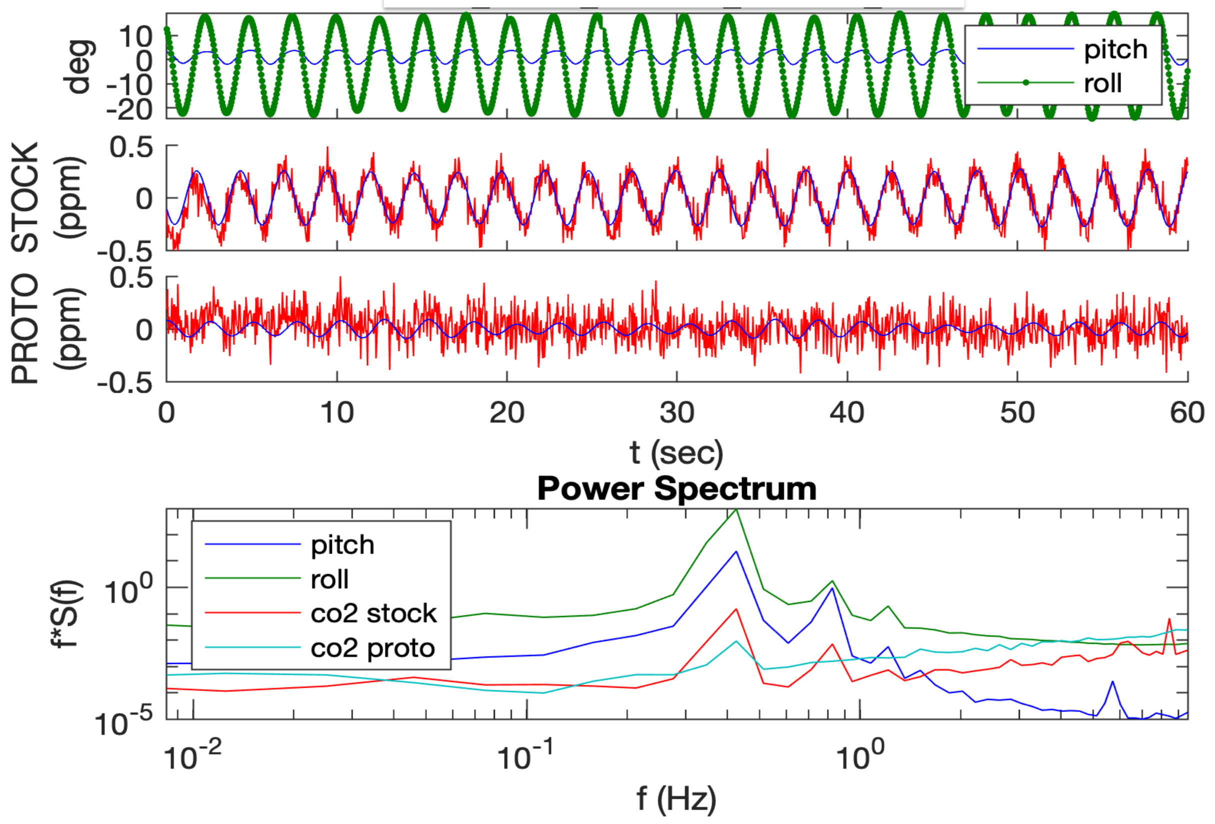
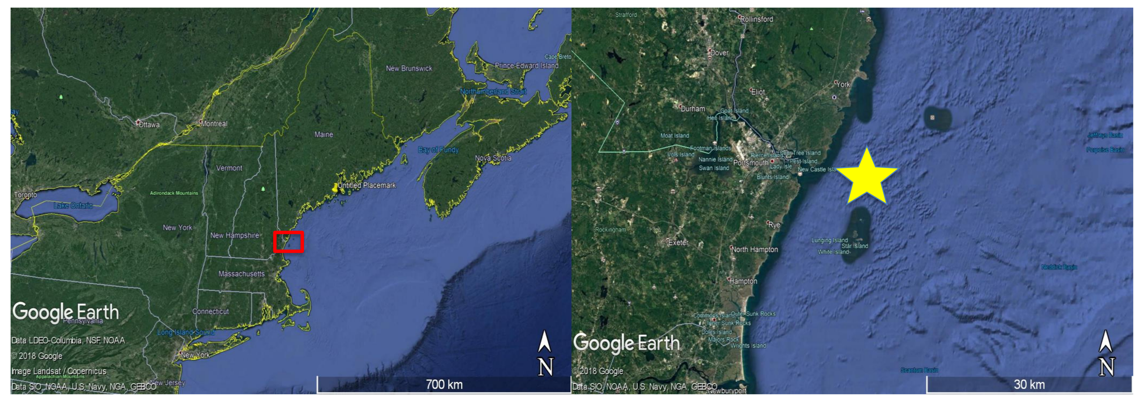



**Figure 10.** Time series and spectra $CO_2$ from preliminary tank test showing reduced sensitivity of prototype IRGA to buoy motion.

### Field Deployment (Spring 2020)

**Figure 11.** The flux buoy will be moored ~10 miles offshore in the Gulf of Maine. The yellow star indicates the approximate location of flux buoy mooring.





### Acknowledgements

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