

Air-Sea Gas Exchange at Extreme Wind Speeds

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Talk overview

- **Science**

High wind air-sea gas flux and its importance for the global C cycle

- **Methods**

O₂/N₂ gas sensing floats

- **Results**

Hurricane Frances deployment

- **Conclusions**

Science

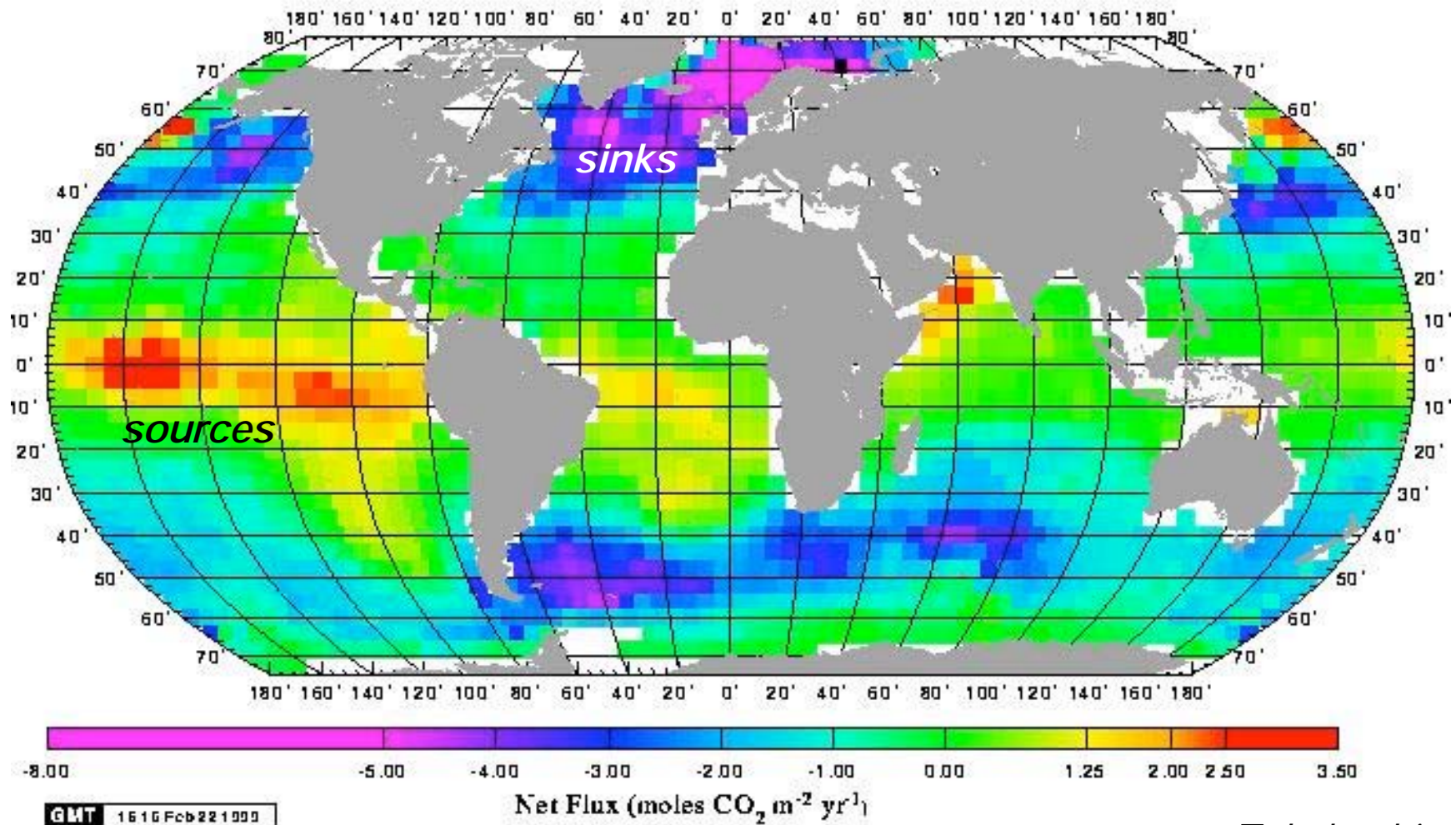
Constraining the global carbon cycle:

- We know that a significant fraction of the CO₂ released to the atmosphere by the burning of fossil fuels is taken up by the oceans
- Known oceanic CO₂ uptake rate of 2.2 ± 0.5 PgC yr⁻¹ from:
 - indirect estimates: C isotope ratios, O₂/N₂/CO₂ ratios between the ocean, terrestrial biosphere and atmosphere
 - direct estimates: interpolation over seasonal cycle and regionally over the globe of measured $\Delta p\text{CO}_2$ and flux laws:

$$F = K_T \Delta S \Delta p\text{CO}_2 \quad \text{with} \quad K_T \sim f(U_{10}, S_c, S)$$

$$F = K_T (Sc/660)^{1/2} S_{-pCO_2} \text{ with } K_T \text{ by W-92}$$

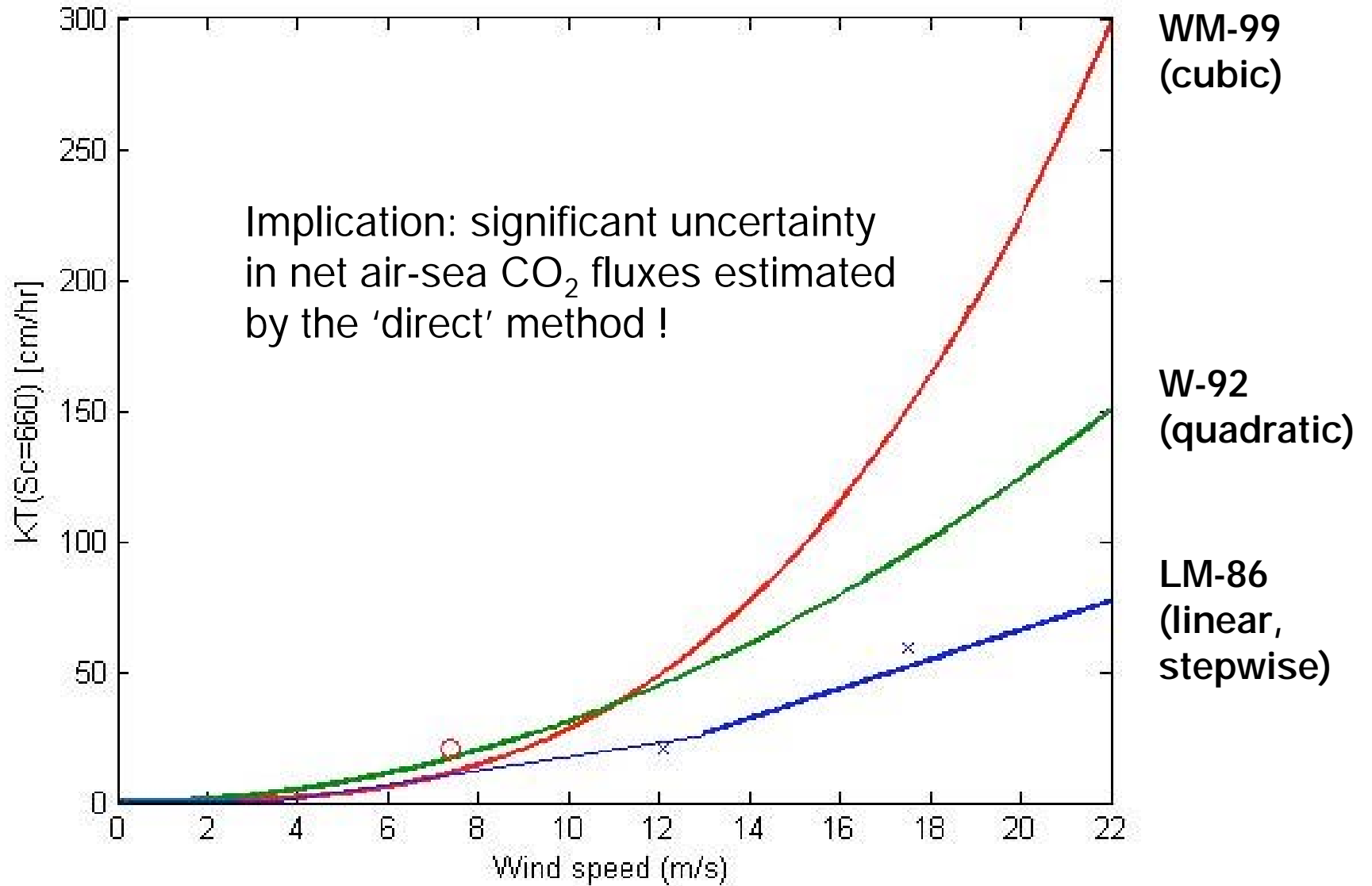
Annual flux per sq. meter (W-92 gas exchange) full 1995 corr.



Takahashi et al.

Note: the net flux is a small percent of the gross flux

Question 1: What is $K_T \sim f(U_{10})$ for $U_{10} < 22 \text{ m s}^{-1}$?



Direct estimates of global air-sea CO₂ flux vary:

LM-86 ~ 1.1 PgC yr⁻¹

W-92 ~ 2.2 PgC yr⁻¹ (similar to indirect constraints)

WM-99 ~ 3.3 PgC yr⁻¹

Conclusion: Large uncertainties. Better constraints on K_T will lead to better constraints on the direct estimates.

Further, accurate *predictions* of air-sea CO₂ fluxes in future global climates requires better *understanding* of the processes.

Question 2 : How much CO₂ is exchanged between the atmosphere and ocean during hurricanes?



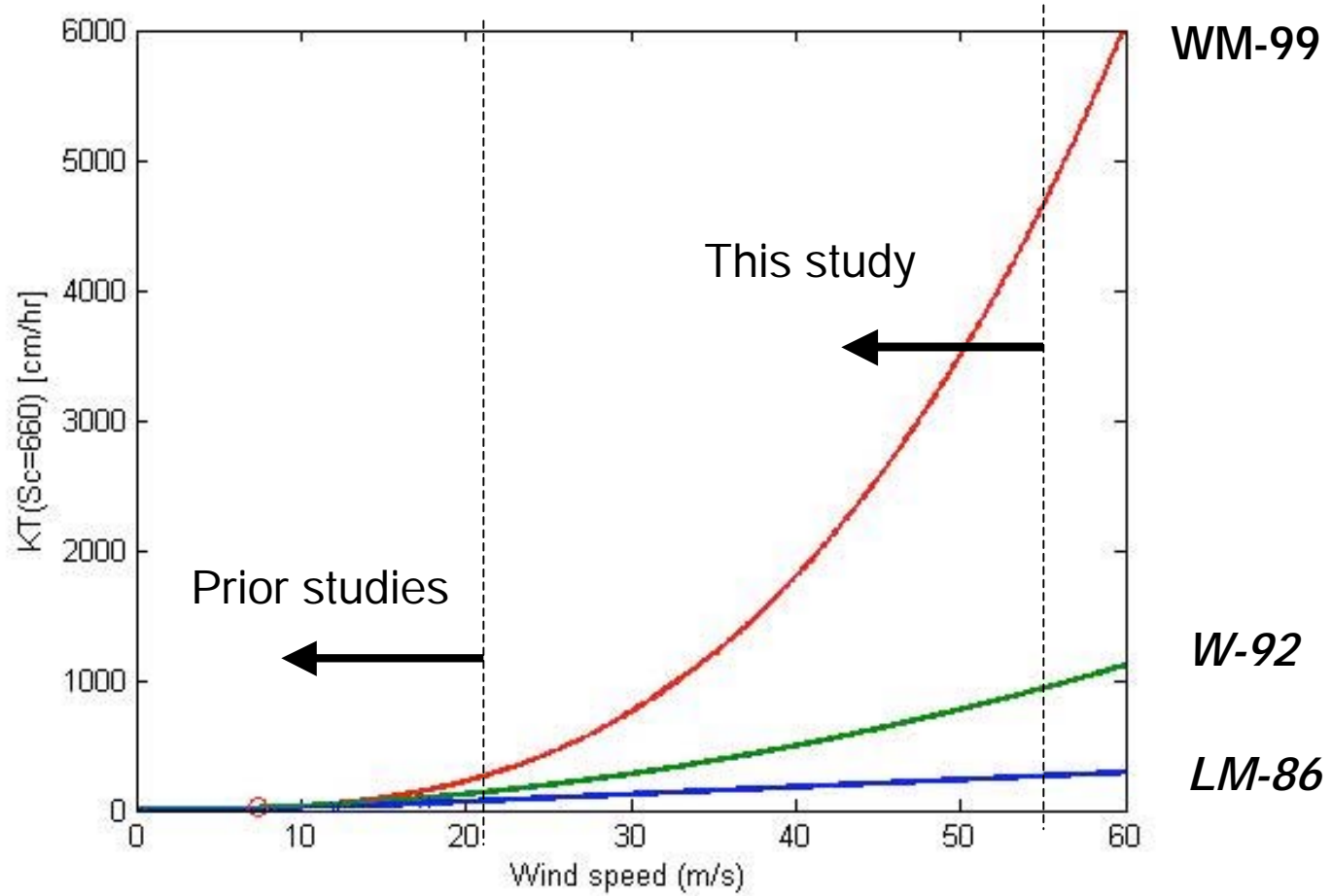
Bates et al. (1998, 2002) hypothesized that hurricanes release enough CO₂ back to the atmosphere for hurricanes to be considered important in the global carbon cycle.

Difficult to measure the CO₂ deficit because $p\text{CO}_2$ is a small component of total DIC.



Methods

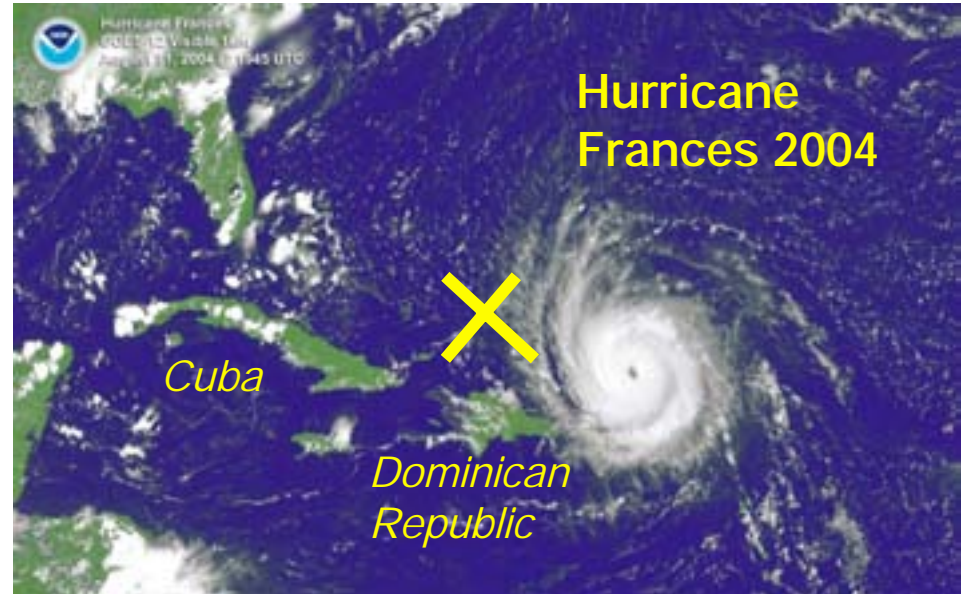
- * constrain $K_T \sim f(U_{10})$ by measuring fluxes of O_2 and N_2 at extreme winds, then scale to CO_2



* floats measuring O₂ and N₂



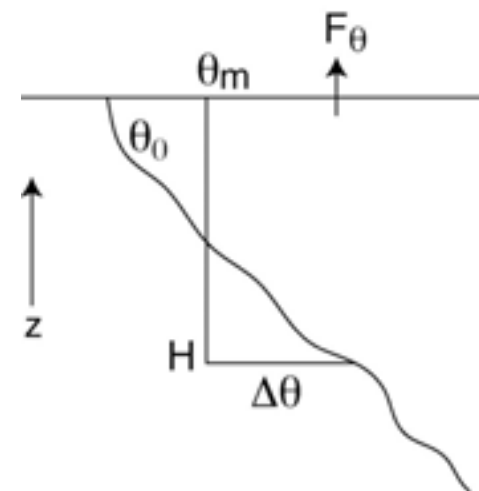
* air-drop



* *direct O₂ covariance fluxes*

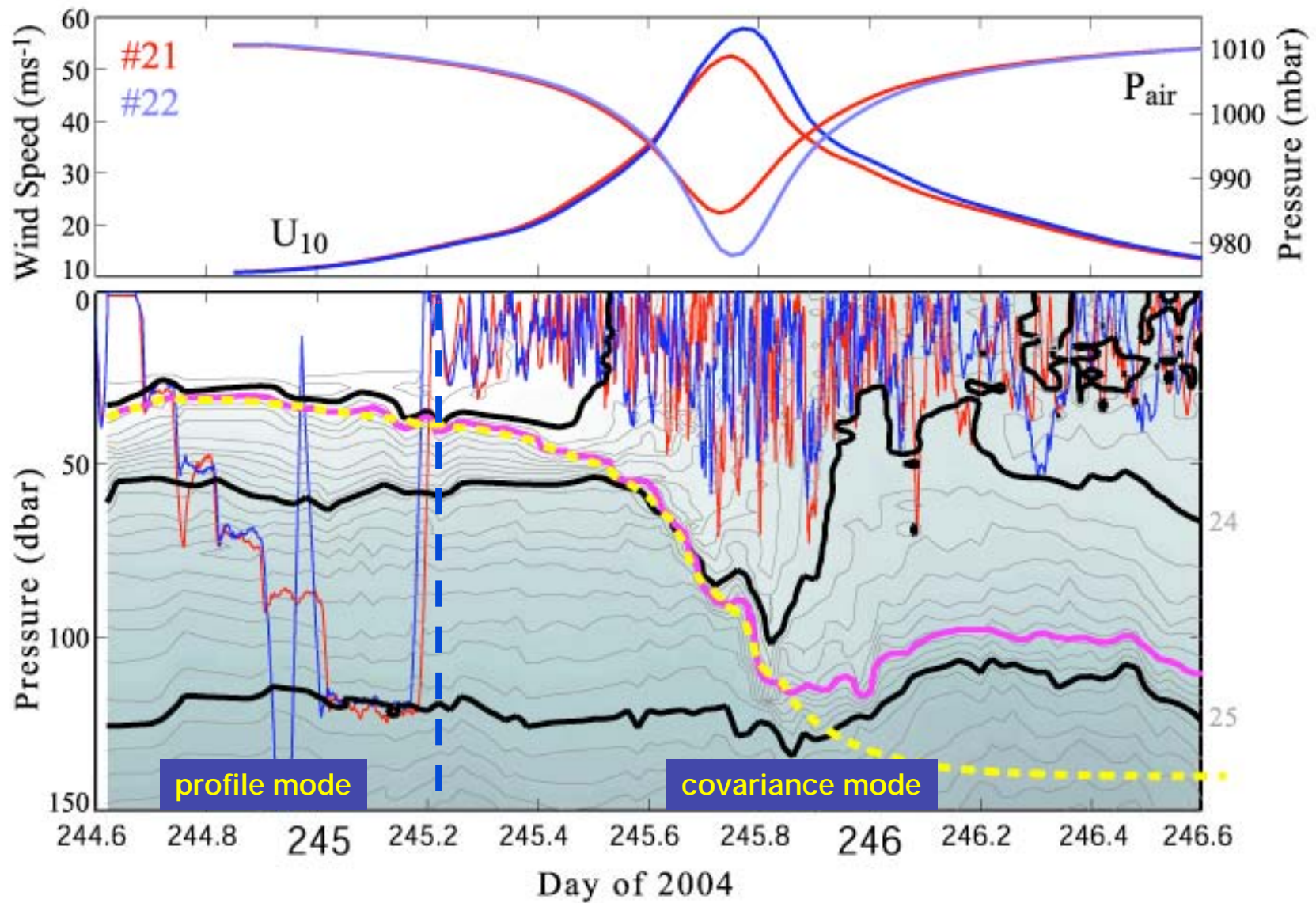
$$F = \langle w O_2' \rangle$$

* mixed layer gas budgets



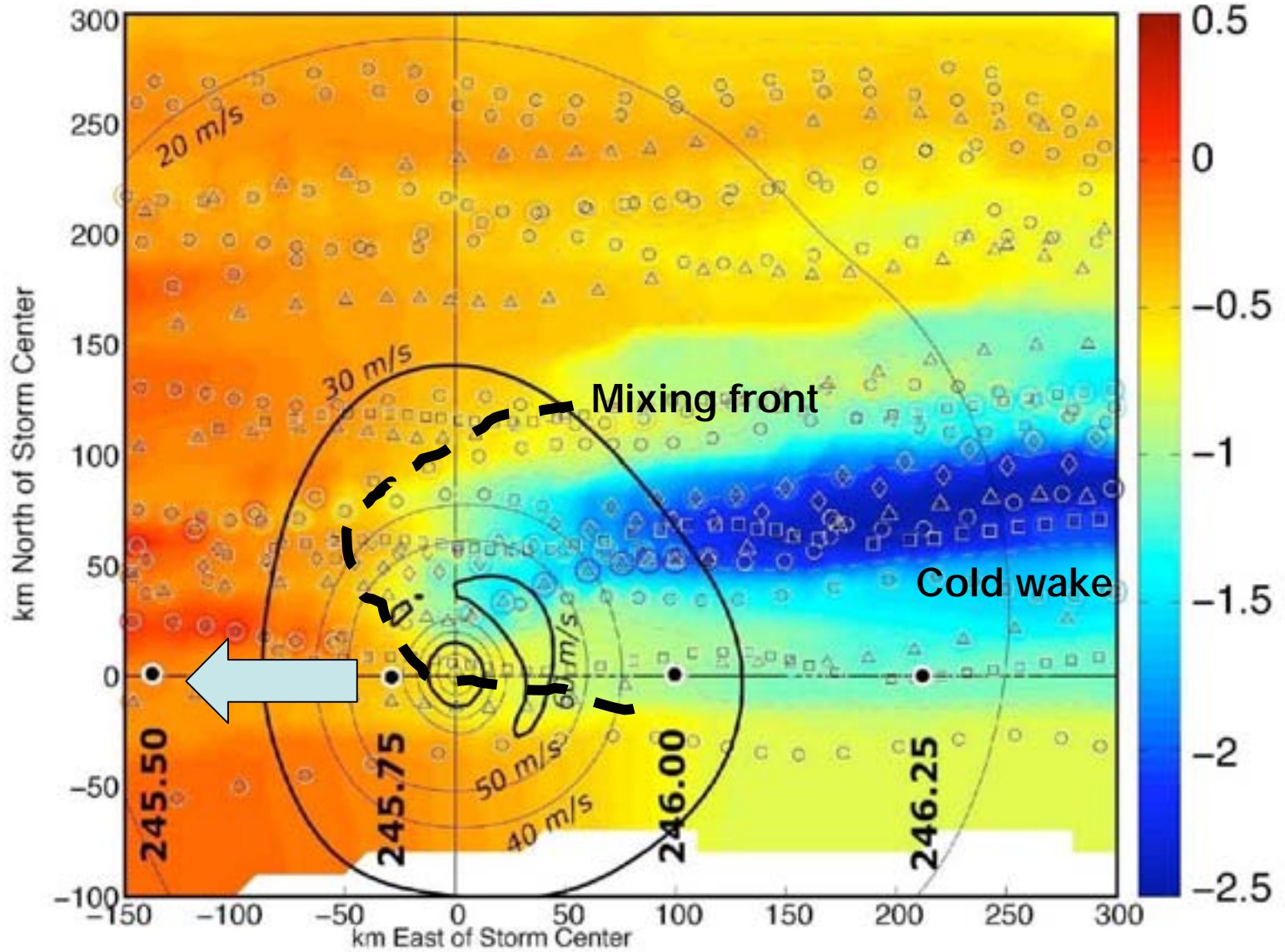
need pre/post profiles

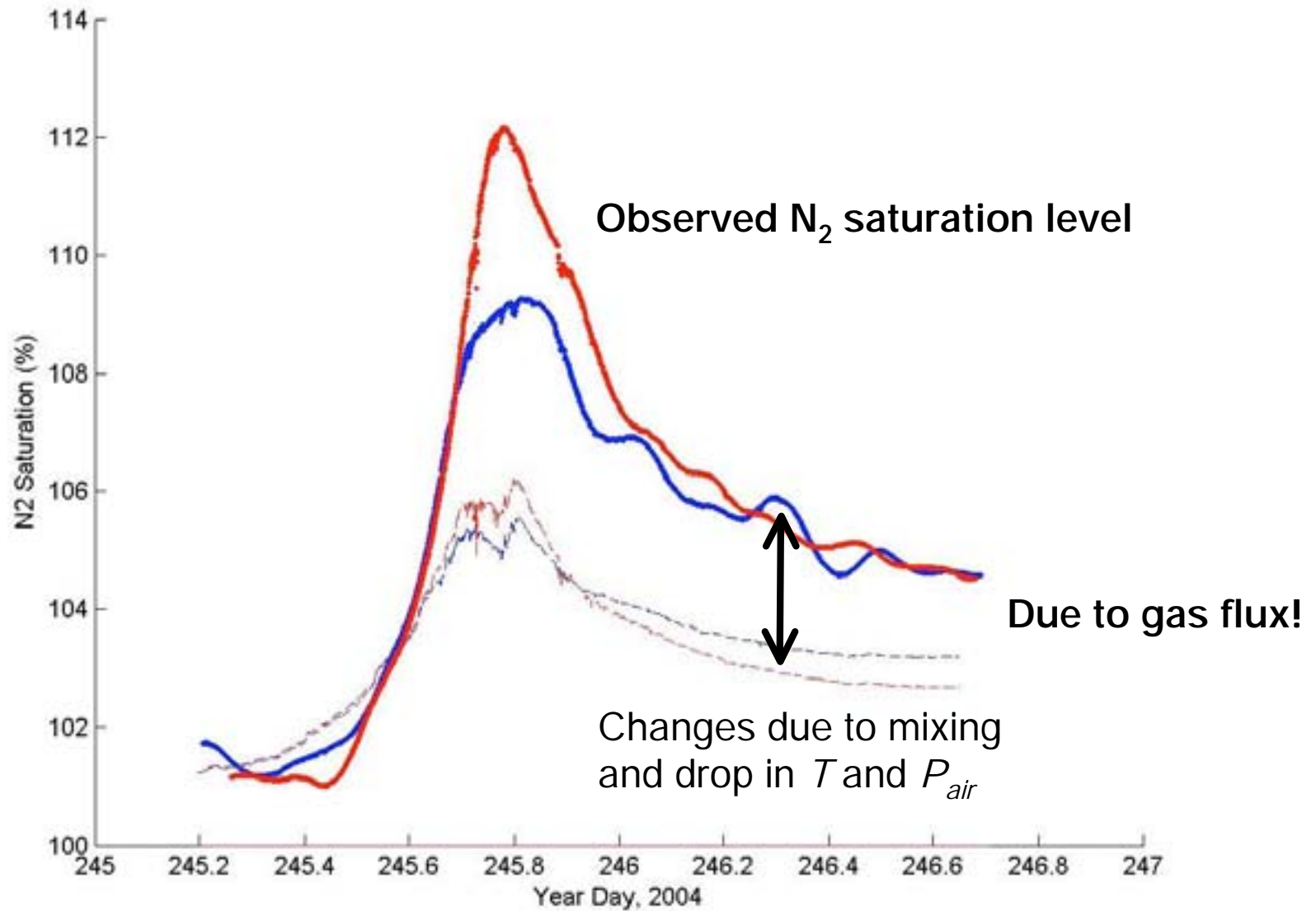
Results

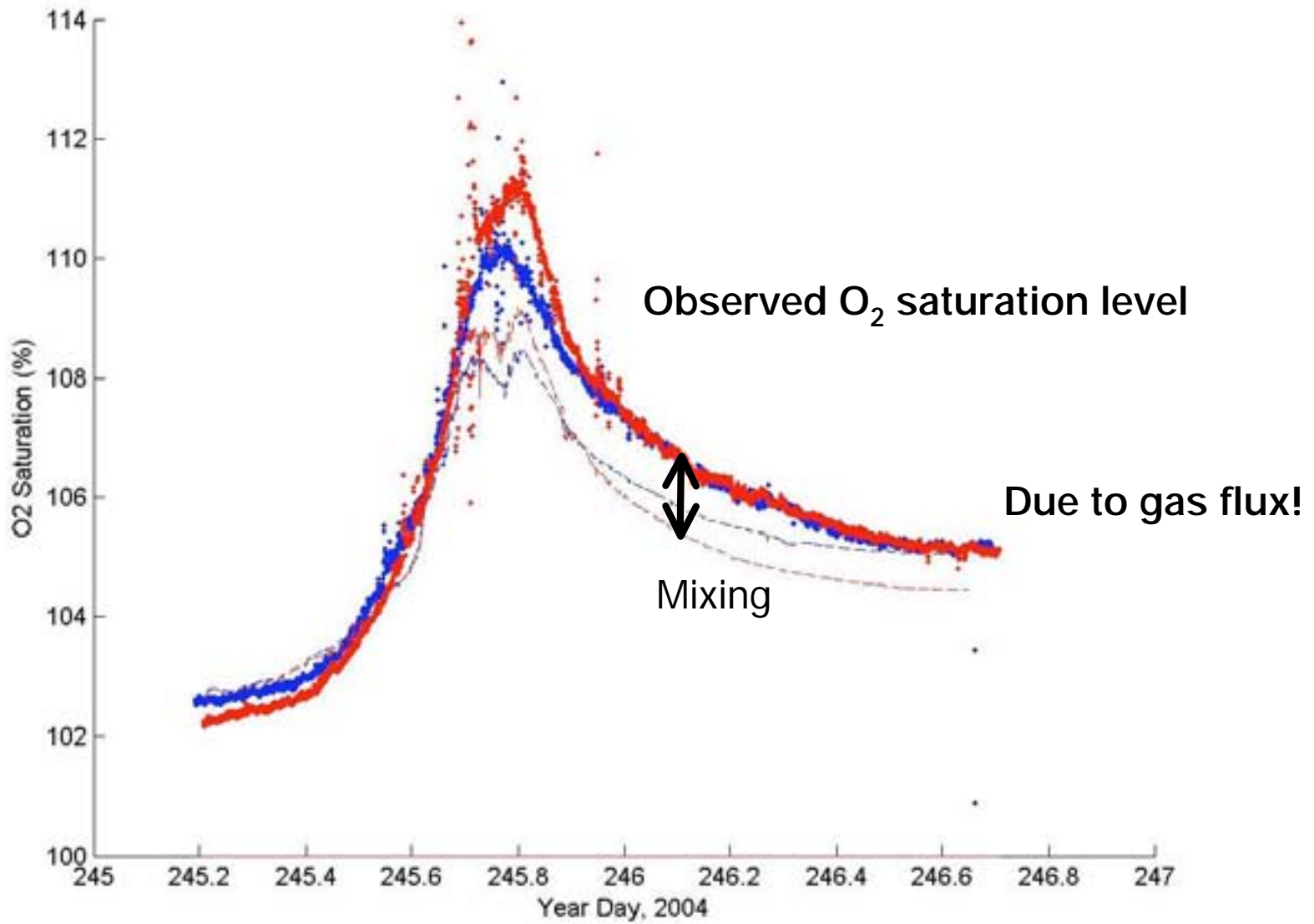


Sea Surface Temperature

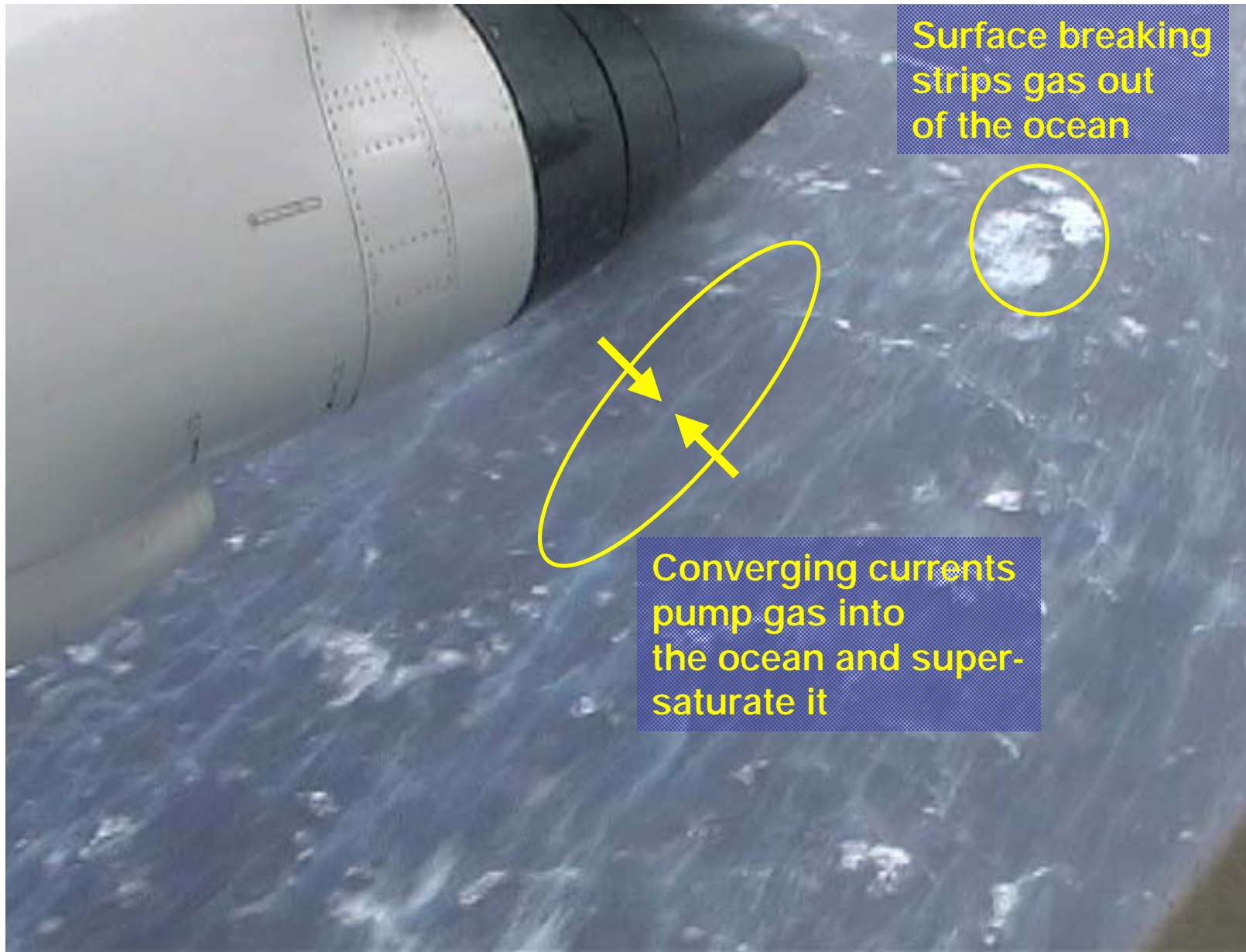
T (°C)







The ocean surface during a hurricane

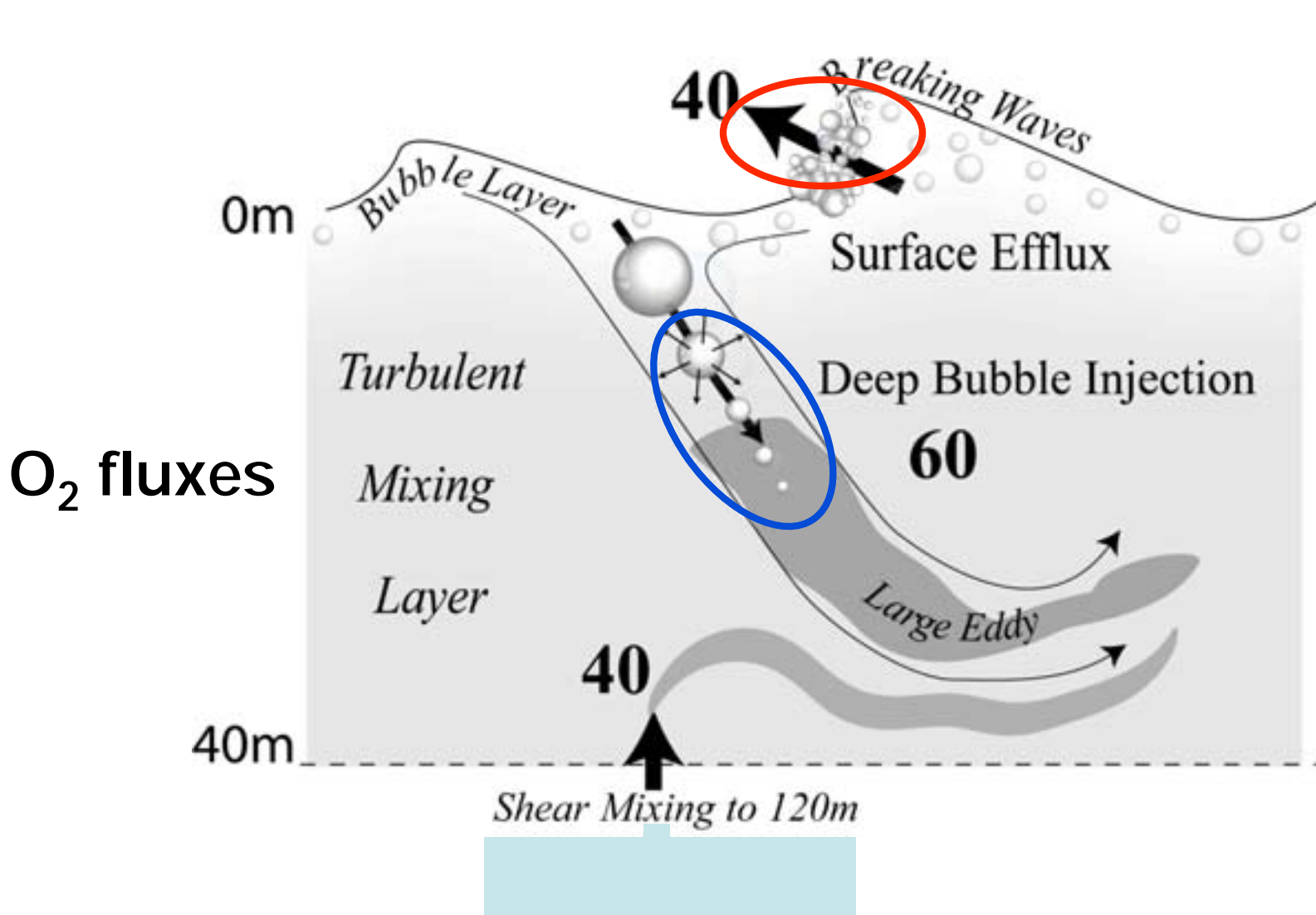


Eric Uhlhorn (NOAA) during Hurricane Fabian

Competing processes

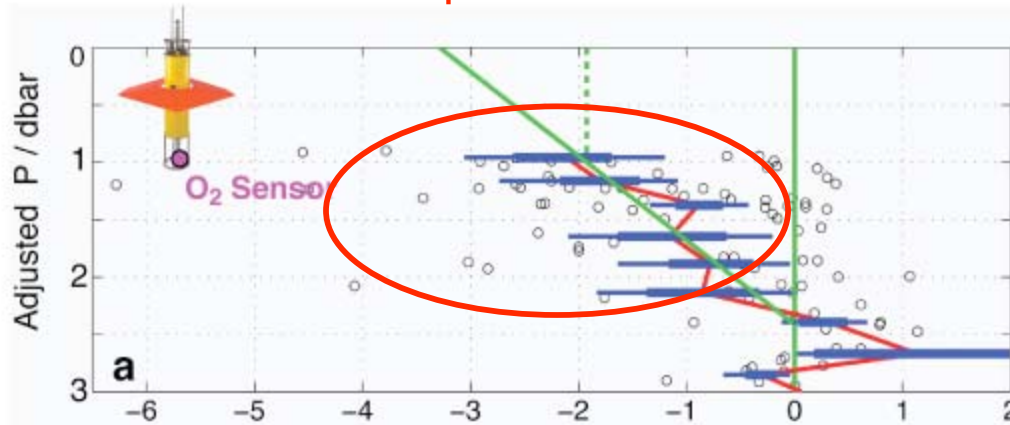
shallow efflux by breaking waves and interfacial turbulence

deep influx by bubble injection

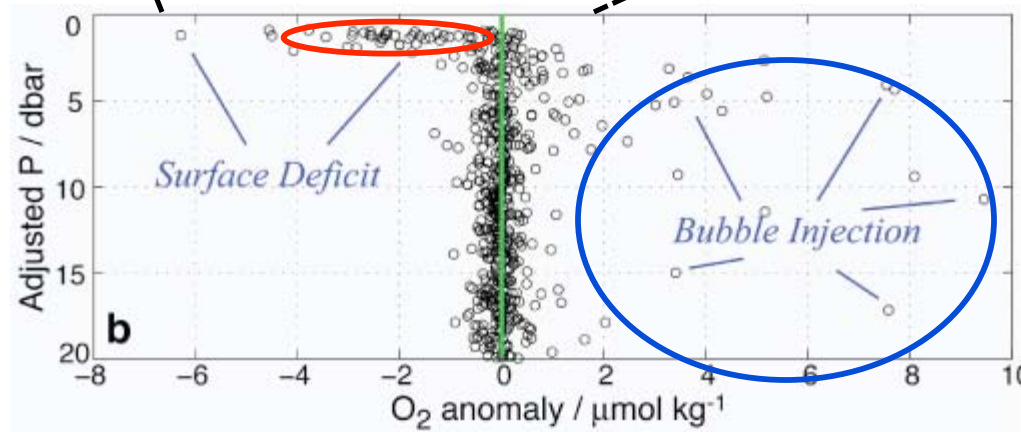


Shallow efflux removes O_2 from super-saturated ocean

0-3 m



0-20 m



Deep influx adds O_2 to super-saturate the ocean

Wind speed dependence of both processes?

Assume power law, $a + b(U_{10})^N$

shallow efflux by breaking waves
and interfacial turbulence

deep influx by
bubble injection

$$1) \quad K_T(S_c=N_2) \cdot S \cdot -\rho N_2$$

$$-N_2 \cdot F_{air}$$

$$2) \quad K_T(S_c=O_2) \cdot S \cdot -\rho O_2$$

$$-O_2 \cdot F_{air}$$

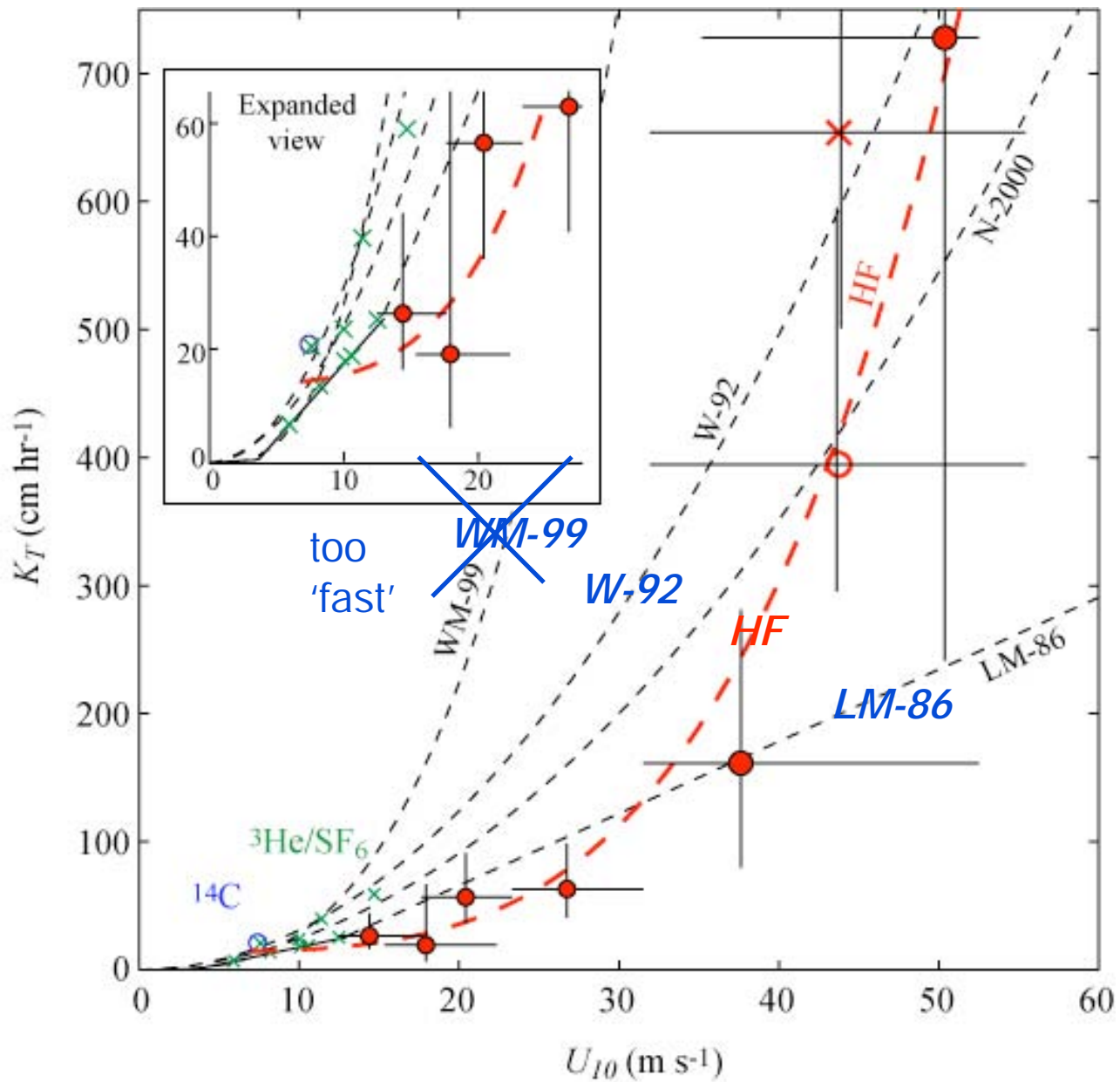
2 equations with 2 unknowns. Empirical fits to data:

$$N = 3.7 \pm 1.3$$

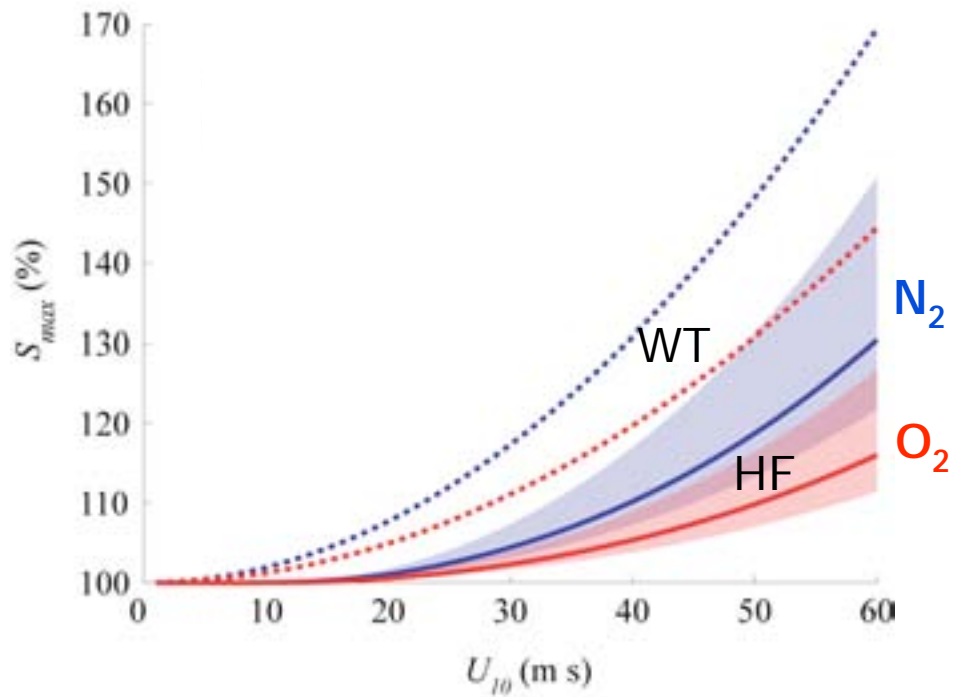
$$N = 6.35 \pm 0.1$$

Note: Peak in gas fluxes occurs 100 minutes *before* peak in the winds.
Possible evidence that wave breaking is not a simple function of U_{10} alone.

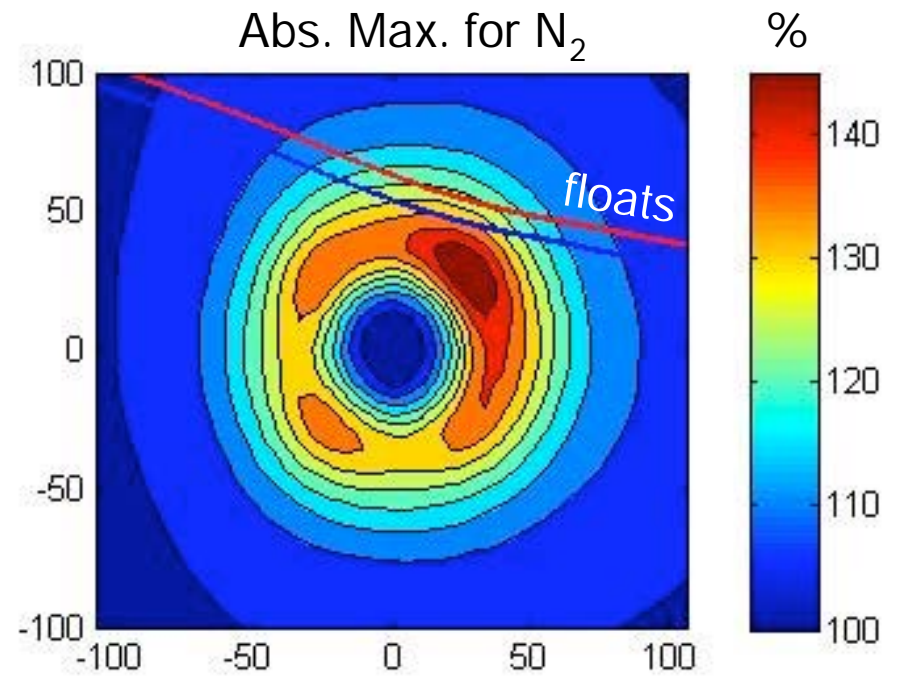
Calculated air-sea gas 'transfer velocity' K_T



Predictions for a 'stalled' hurricane (steady-state solutions)



WT – Woolf and Thorpe (1991)
HF – Hurricane Frances (2006 papers)



Implications for CO₂ fluxes?

Observed maximum flux of 200 $\mu\text{mol}(\text{air})\cdot\text{m}^2\cdot\text{s}^{-1}$ into ocean.

(*i.e.*, 1200 bubbles of 1 mm diameter enter ocean per second and completely dissolve).

The CO₂ in these bubbles is equivalent to 0.26 $\text{mmol}(\text{CO}_2)\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, but this is <2% of the expected CO₂ efflux during a typical hurricane (Bates *et al.*, 1998, 2002; Perrie *et al.*, 2004).

Conclusion 1

Analysis of the Hurricane Frances data indicates that the best estimates* of K_T at hurricane force winds lie somewhere between LM-86 and W-92.

*Data exclude the WM-99 relationship at hurricane force winds.

Conclusion 2

A new regime of air-sea gas transfer exists at wind speeds* in excess of 35 m s^{-1} . In this regime, the air-to-sea transfer rate of weakly soluble gases is dominated by complete bubble dissolution ('injection') of mm size bubbles. These deeply injected bubbles increase saturation levels. Breaking waves and the bubbly layer at the sea surface help counteract this processes by releasing gases back to the atmosphere, thereby partially relieving the dissolved gas buildup in the mixed layer.

* Complications with rising and falling winds (*ie.*, the 'delay'), to be investigated further.

Conclusion 3

The net influx of CO₂ to the ocean during a hurricane by bubble 'injection' will be small compared to the expected* net CO₂ efflux at the sea surface.

*WM-99 relationship will over-predict the CO₂ efflux (see Conclusion 1).

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