The Shiphikers Guide to the North Atlantic
VOS Liverpool (UK) - Halifax (CAN)

DON`T PANIC

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The answer to the **Ultimate Question of Life, the Universe and Everything** lies (partly) in CO_2 in the world oceans. Since the industrial revolution approximately 40-50% of the emitted CO_2 has been taken up by the oceans (Sabine et al. 2004). They are today a contemporary sink for ~30% of the annual anthropogenic CO_2 emissions (Le Quéré et al., 2013).

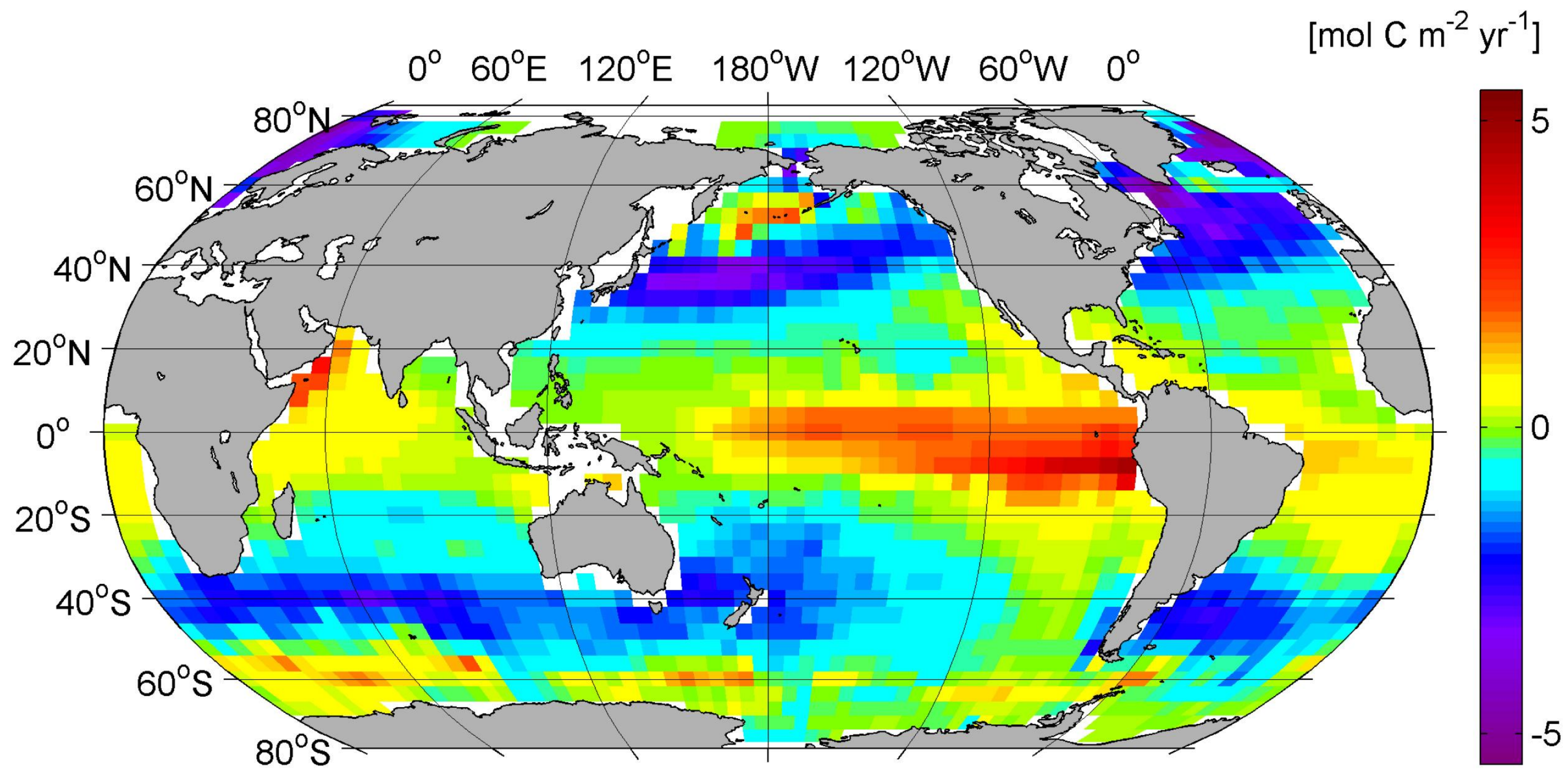

Figure 1. Sea–air CO_2 flux for reference year 2000. Negative values mean net oceanic CO_2 uptake. (from Park et al. 2010)

② How to obtain measurements in the world oceans?

... from voluntary observing ships (VOS) and research cruises. Ocean data is collected automatically from vessels and ships which travel in the normal course of their business. Weather observations are conducted by the crew. From time to time a scientist is needed on board to calibrate the system and take discrete samples.

Figure 2. ConRo vessel Atlantic Companion. One of the largest Container and Roll On Roll Of Cargo ships, traveling on a regular basis between Europe and North America.

③ SOCAT version 2

The Surface Ocean CO_2 Atlas (SOCAT, Sabine et al. 2013) contains 6.3 million quality controlled surface CO_2 data.

The number of values has largely increased since the middle of the nineties, when more and more VOS participated in various campaigns (Fig. 3).

The spatial density of CO_2 values in the North Atlantic is the highest in the SOCAT data set, three times larger, than in the North Pacific and doubled compared to the Southern Ocean (Fig. 4).

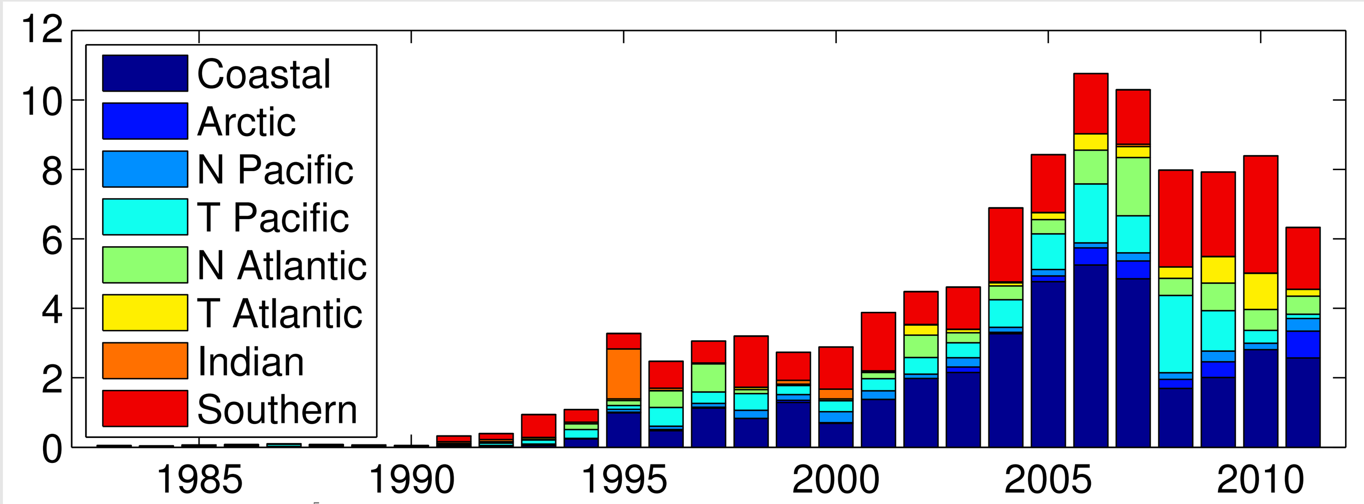

Figure 3. Number (x 10^5) of surface water fCO_2 values per region per year, SOCAT version 2. (from Bakker et al. 2014)

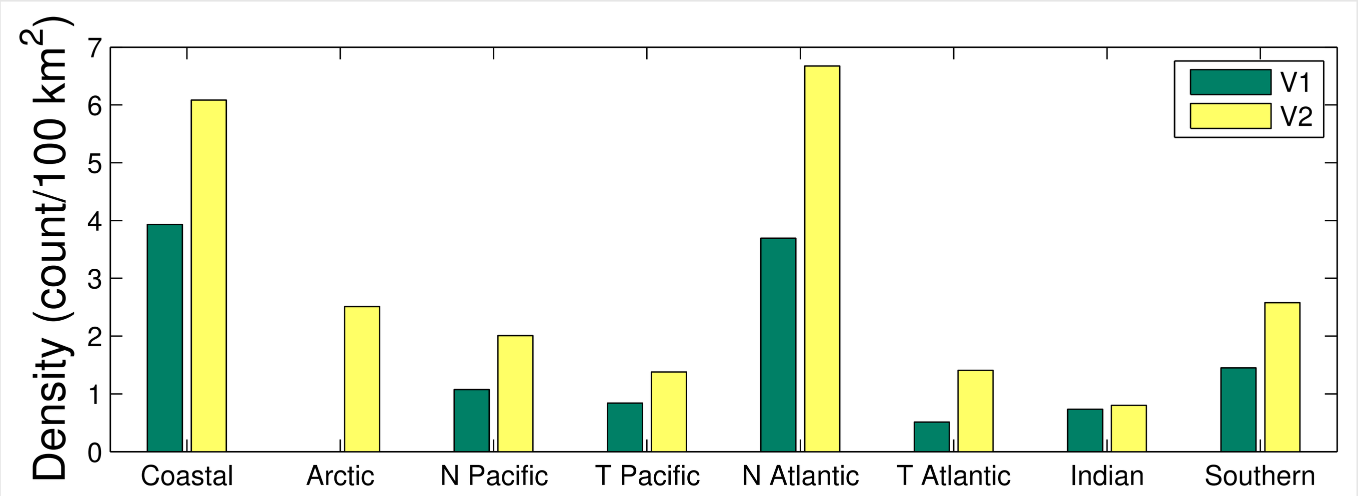

Figure 4. Density of surface water fCO_2 values per region for SOCAT versions 1 (V1) and 2 (V2). (from Bakker et

④ On the Trail of Richard Greatbatch: Liverpool (UK) → Halifax (Canada)

"Shiphiker" on board Atlantic Companion (Fig. 2) from 24th until 31th of May 2008.

Tasks: Take discrete samples, which are bottled/filtered and conserved (Fig. 7).

Figure 5. Atlantic Companion at Port of Liverpool (Seaforth Dock), 24th of May 2008.

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Figure 6. Sundogs (parhelia) at Halifax Harbour seen from Atlantic Companion, 31th of May 2008.

Continuously measured:
atmospheric pressure, in water: temperature, salinity, pCO_2, CO_2 isotopy, O_2 concentration, every 3 hours: air pCO_2
Discrete samples: nutrients + water isotopes every 3 hours, every 6 hours: CO_2, chlorophyll, dissolved and particulate nitrogen + carbon, CO_2 + O_2 isotopes

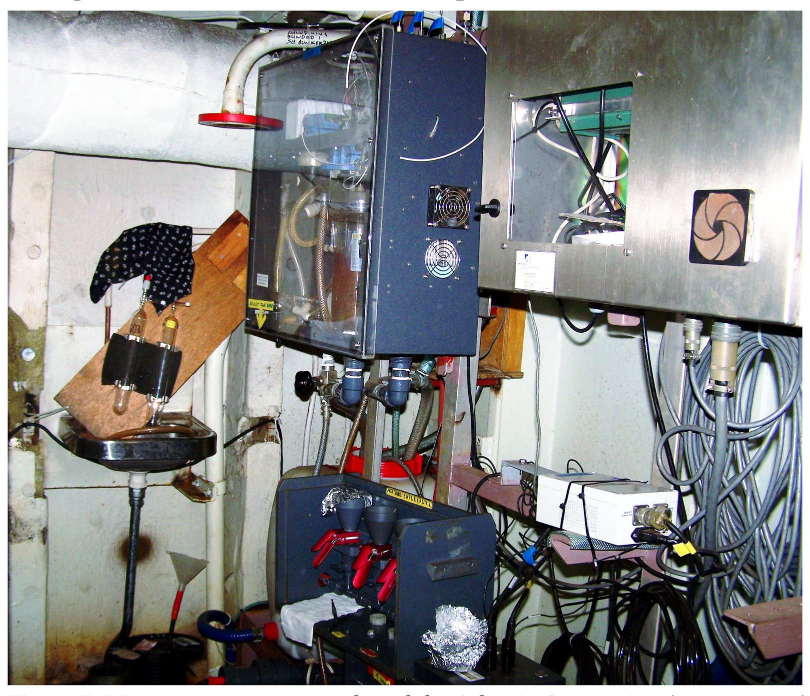

Figure 7. Measuring apparatus on board the Atlantic Companion (engine room).

⑤ On the Trail of Richard Greatbatch: NAO vs. CO_2 flux

The relation of the North Atlantic Oscillation (NAO) and CO_2 air-sea flux has been described in Thomas et al. 2008, with Richard as a co-author. Variations in NAO lead to changes in **ocean surface circulation** and surface water **thermodynamic properties**, via air-sea heat and freshwater fluxes, biological fluxes, lateral transport and vertical mixing, which impacts CO_2 uptake rates into the ocean.

DIC: Dissolved Inorganic Carbon
SST: Sea Surface Temperature
SSS: Sea Surface Salinity

DIC ⇧ → CO_2 uptake ⇩
SST ⇧ → CO_2 uptake ⇩
SSS ⇧ → CO_2 uptake ⇩

Main water masses in North Atlantic:
• relative cold, fresh and high-DIC polar waters
• relative warm, saline and low-DIC subtropical waters

Model results

With the help of model simulations Thomas et al. 2008 showed that at lag zero CO_2 uptake of the ocean increases in the western subpolar gyre (Fig. 8). This is primarily due to a lower SST origin from a larger southward velocity of the Labrador Current. At a lag of 2-4 years (NAO leads) the CO_2 uptake decreases in the eastern North Atlantic (Fig. 8), which can be traced back to the enhanced surface circulation under positive NAO resulting in an enhanced transport of warm and saline subtropical water into the subpolar gyre and a corresponding transport time across the Atlantic basin.

Observational results

There are significant correlations between observed NAO and fCO_2 (fugacity of CO_2) in SOCAT v2, despite an inhomogeneous spatial and temporal distribution of fCO_2.
Air-sea CO_2 flux has not been computed, instead measured fCO_2 is used. There is a tendency for CO_2 uptake in the ocean, when fCO_2 is low (and vice versa).
During positive NAO phases fCO_2 increases in the Labrador Sea and decreases in the eastern subtropical gyre (Fig. 9a). With a lag of 3 years (transport time of surface anomalies) there is a significant positive correlation in the eastern North Atlantic (Fig. 9b).

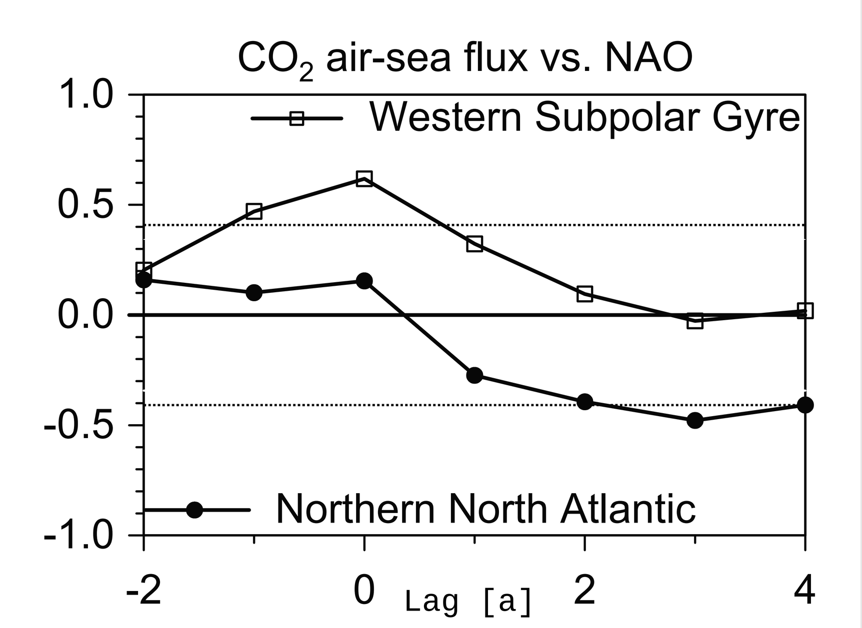

Figure 8. Correlation between CO_2 air-sea fluxes and NAO for two regions: western subpolar gyre (45°N - 60°N, west of 30°W) and northern North Atlantic (north of 60°N). Dotted lines denote 95% significance level. (from Thomas et al. 2008)

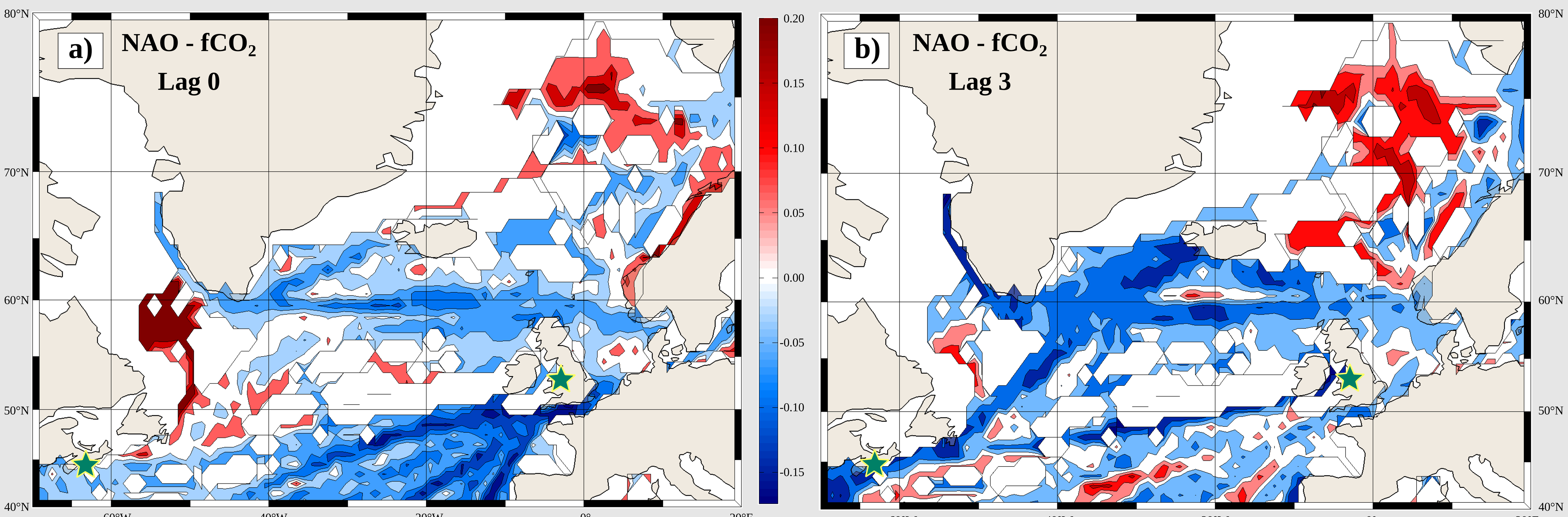

Figure 9. Correlation of NAO index and fCO_2 for the extended wintertime season October - March. a) at lead time 0, b) NAO leads by 3 years. Significant values ($p < 0.10$) > +0.15, < -0.15. Data: 1970-2011, SOCAT version 2 (Sabine et al. 2013). NAO from Jones et al. 1997. Green stars denote Liverpool (UK) and Halifax (Canada). Note that fCO_2 does not equal to an air-sea CO_2 flux.

⑥ Conclusion

- World oceans are a large sink for atmospheric CO_2
- Voluntary Observing Ships conduct measurements automatically while on business course

Model results:
  - positive correlation of NAO and CO_2 air-sea flux in western subpolar gyre
  - negative correlation with a lag of 2-4 years in the northern North Atlantic

Observations: significant correlations between NAO and fCO_2 in SOCAT v2

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