Verifying the consolidated theory of atmosphere-ocean CO_2 fluxes and the importance of the skin: First comparison between bulk and eddy covariance measurements

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Importance of the ocean

Global carbon budgets
The global land sink of carbon cannot be measured.

Ocean carbon sink provides a powerful constraint for identifying the land carbon sink.

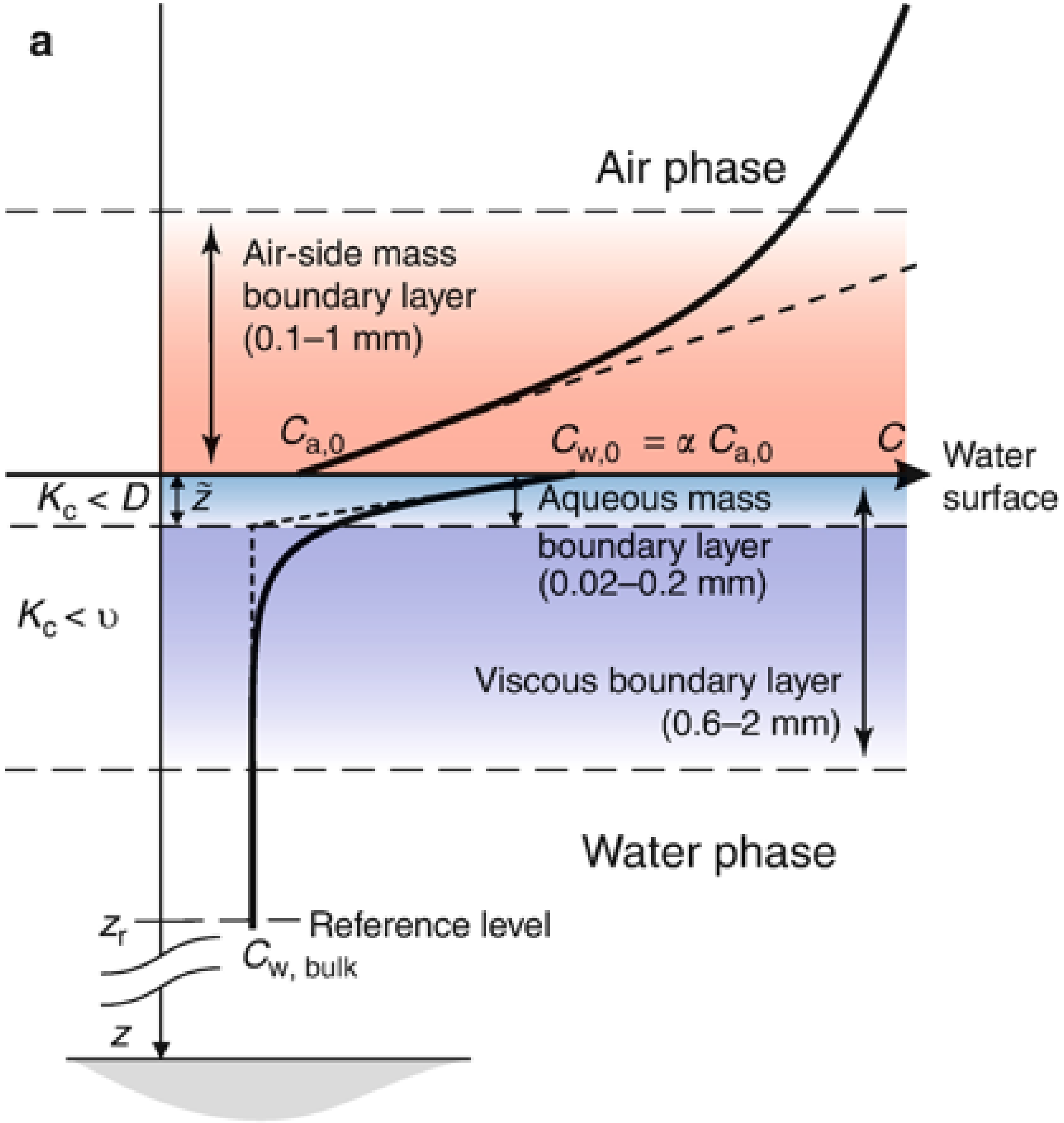
Food security and conservation
Monitoring the ocean sink also identifies regions and ecosystems at risk.

Accurate estimates of CO_2 absorption provide a powerful constraint on carbon budgets and are needed to inform policies to motivate societal shifts towards reducing carbon emissions.

GLOBAL CARBON project

WWF

Exchange across the air-sea interface



Source: Transfer across the air-sea surface, (2013), *Springer*.

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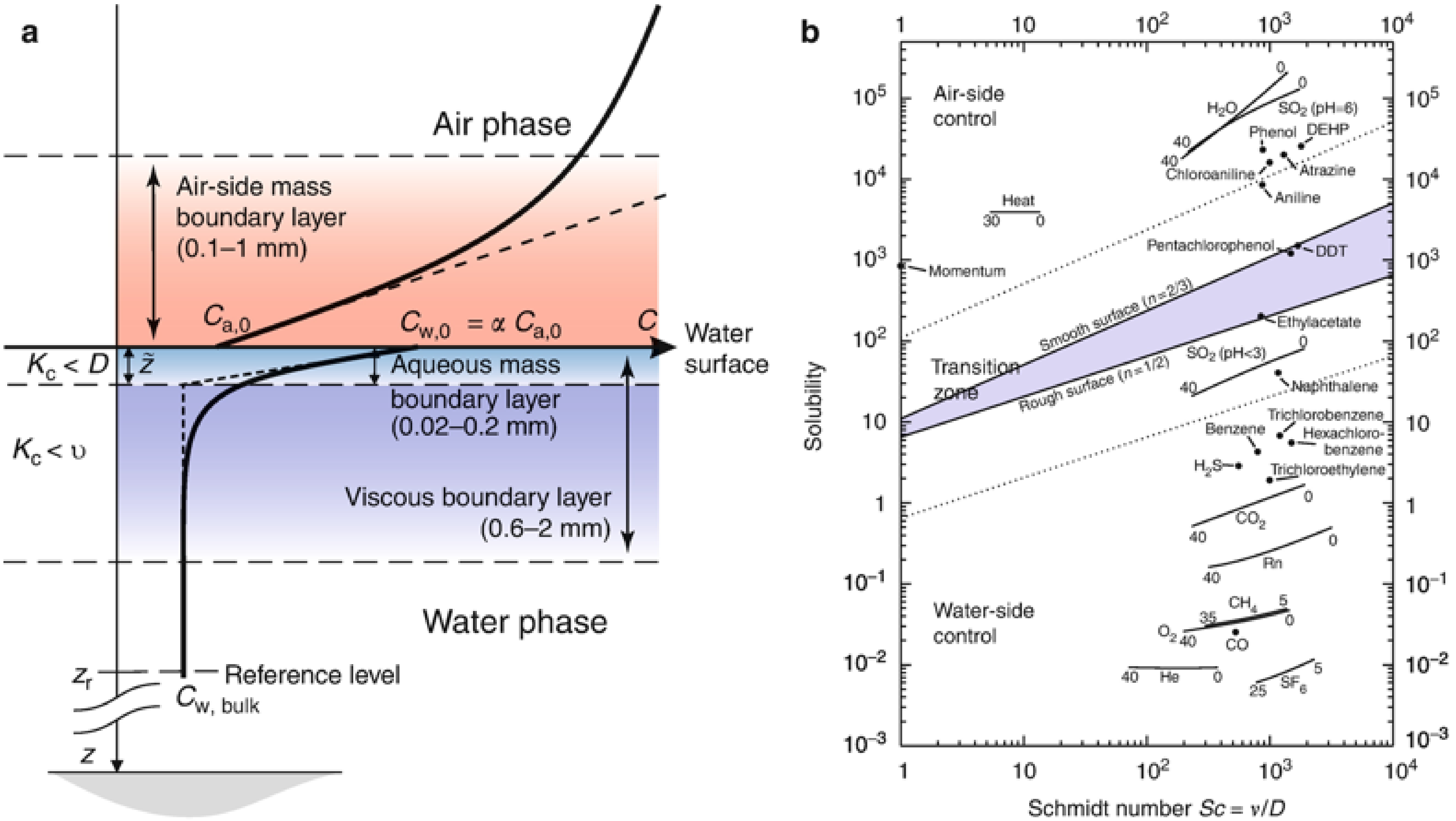

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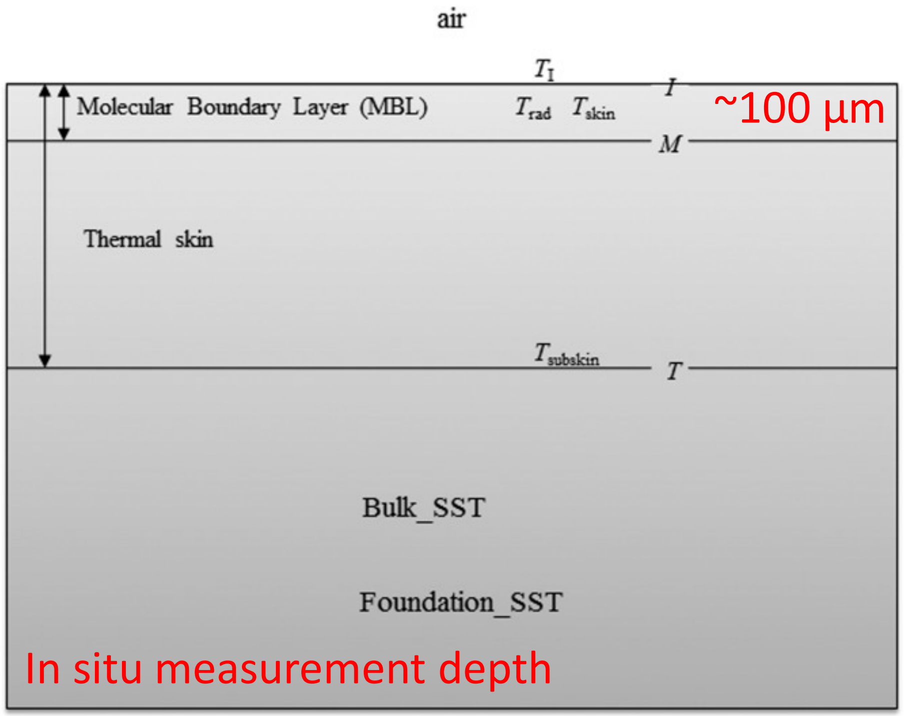
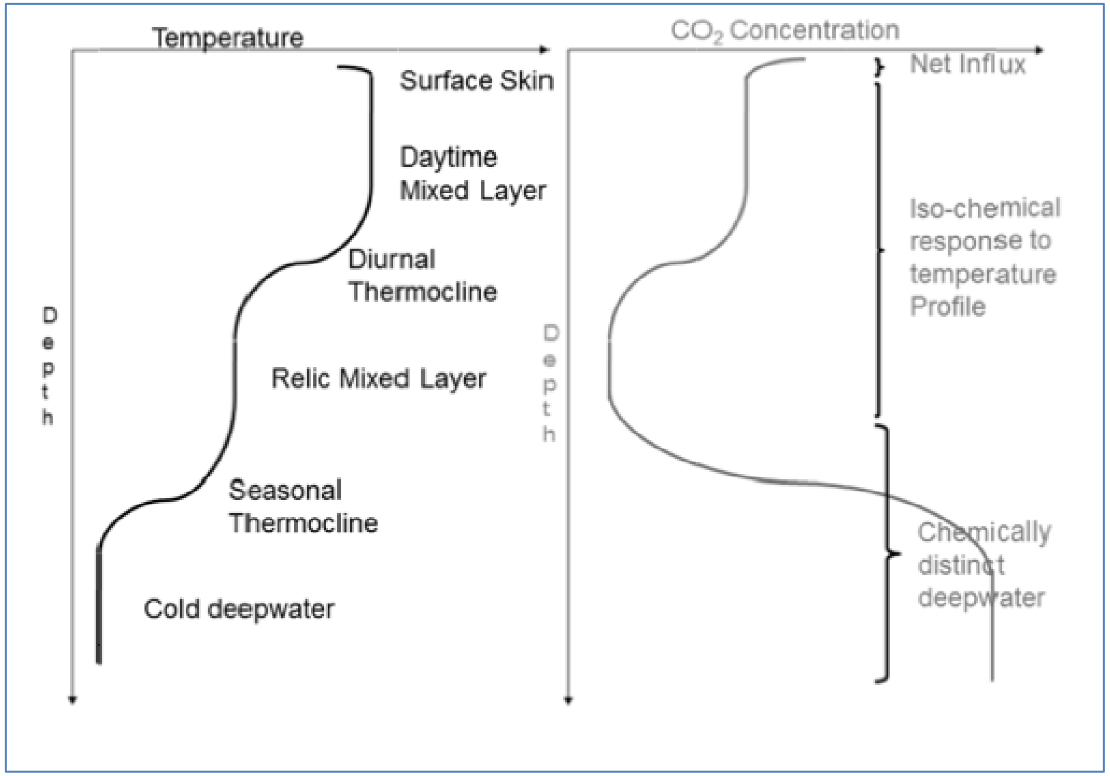
Consolidated methods for temperature and salinity handling within gas flux calculations



Source: Woolf *et al.,* (2016)



Woolf, D. K., *et al.*, (2016) On the calculation of air-sea fluxes of CO_2 in the presence of temperature and salinity gradients, *JGR.*

Goddijn-Murphy, L. *et al.*, (2015) The OceanFlux Greenhouse Gases methodology for deriving a sea surface climatology of CO_2 fugacity in support of air–sea gas flux studies. *Ocean Science*.

Consolidated methods for temperature and salinity handling within gas flux calculations

Quantified the thermal influences on calculation of air-sea gas fluxes:

Table 1. Thermal Effects on the Calculation of Air-Sea Gas Fluxes (Carbon Dioxide and Other Poorly Soluble Gases), Notation, and the Significance of Each

Origin of Effect	Subsection and Scaling	Scaling Parameter	Approximate Scaling Factor (CO_2)	Effect on Unreactive, Ideal Gases
Vapor pressure and nonideality	Section 2.1, Φ_1	C_I	−0.2%/K	Similar, but smaller effect related to nonideality vanishes
Solubility	Section 2.2, Φ_2	C_I	−2.5%/K	Variable, but typically most important
Carbonate chemistry	Section 2.3, Φ_3	C_M	1.5%/K	Not applicable
Schmidt number	Section 2.4, Φ_4	$C_I - C_M$	2.5%/K	Variable, but typically significant

Clarified a misconception

$$F = k\alpha_W(fCO_{2W} - fCO_{2A})$$

≠

Reduced accuracy

$$F = k(\alpha_W fCO_{2W} - \alpha_S fCO_{2A}),$$

More accurate calculation

Woolf, D. K., *et al.*, (2016) On the calculation of air-sea fluxes of CO_2 in the presence of temperature and salinity gradients, *JGR.*

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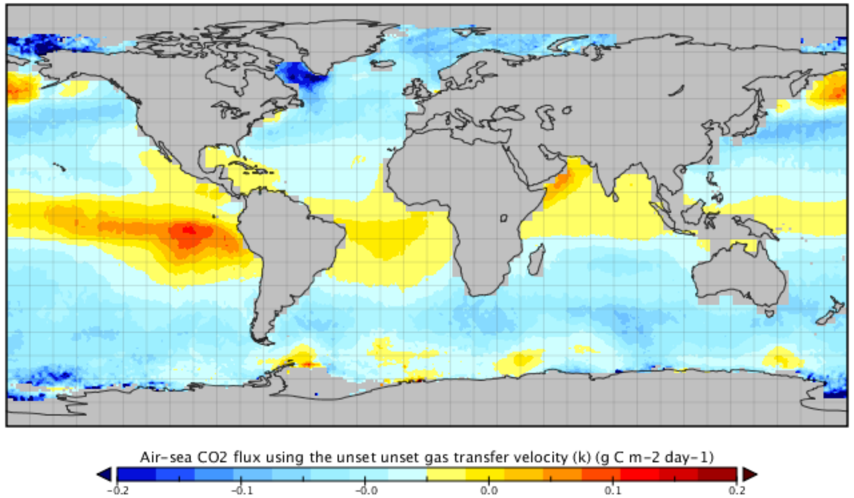
Open source FluxEngine air-sea gas flux toolbox (Python)

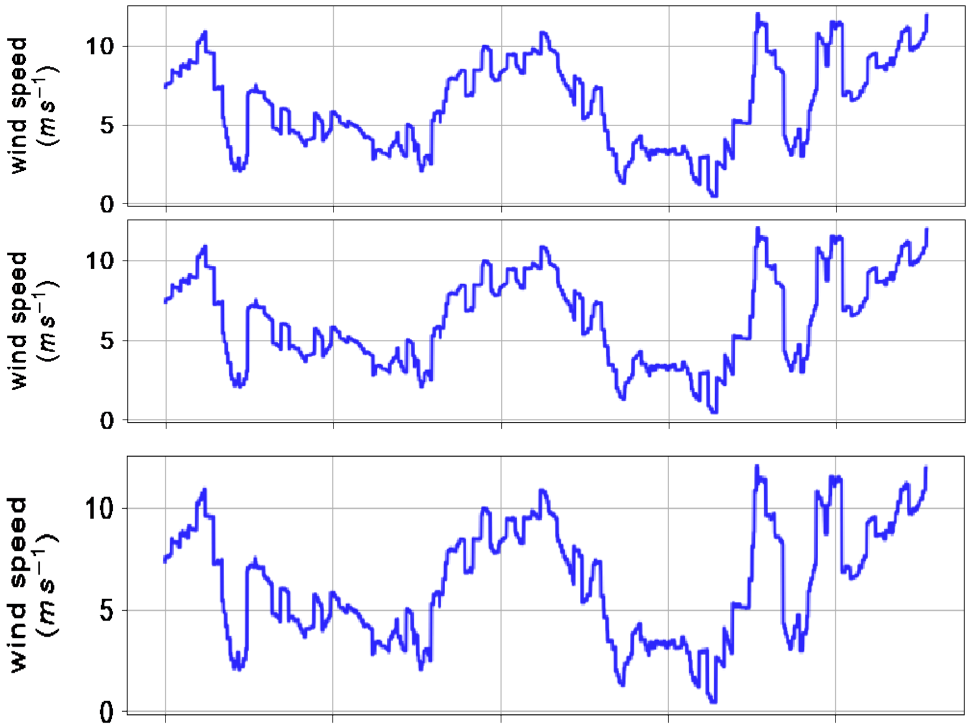
https://github.com/oceanflux-ghg/FluxEngine

Toolbox developed for community use:

- Open source license and Python library.
- Net flux tool with traceable land/ocean/basin templates.
- User configurable calculation.
- Extensively verified and version controlled.
- **Interactive tutorials**, used in IOCCP training school.
- So far used within 13 journal papers,



Example global mean daily flux output

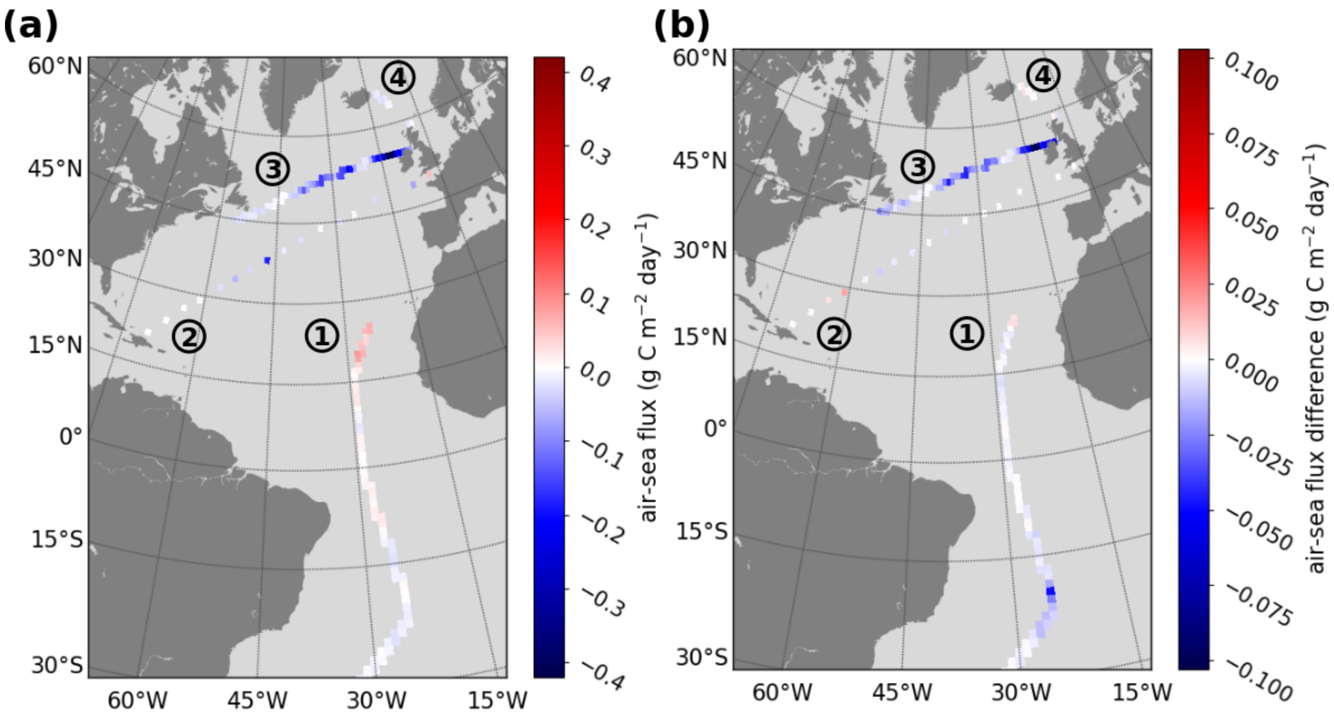


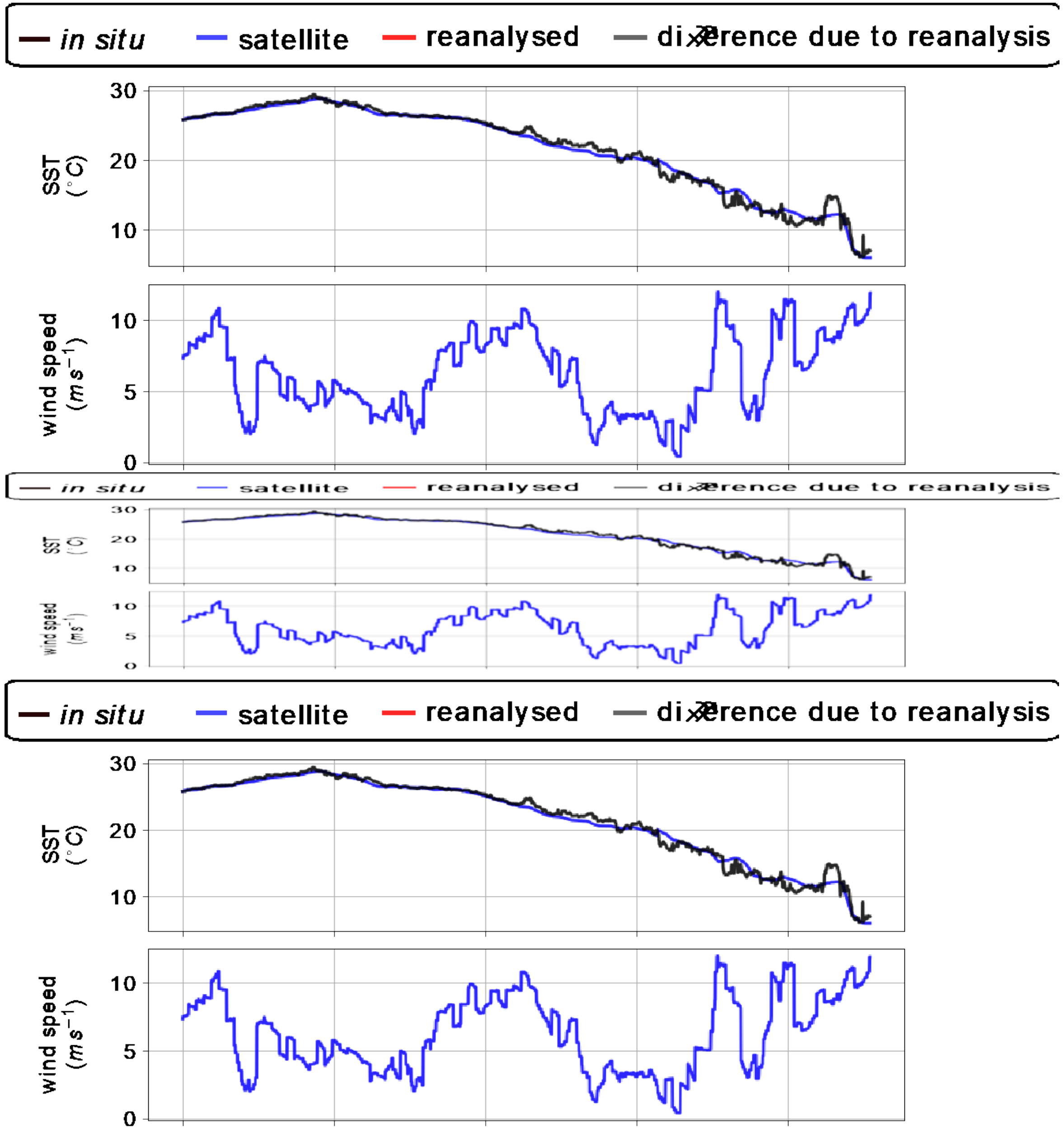
Example analysis of in situ cruise data

Shutler, J. D. *et al.*, (2016) Flux Engine: A flexible processing system for calculating air-sea carbon dioxide gas fluxes and climatologies, *Journal of Atmospheric and Oceanic Technology.*

Holding, T., *et al.,* (2019), The FluxEngine air-sea gas flux toolbox: simplified interface and extensions for *in situ* analyses and multiple poorly soluble gases, *Ocean Sciences*.

Consolidated methods - Impact of mishandling temperature for an *in-situ* research cruise

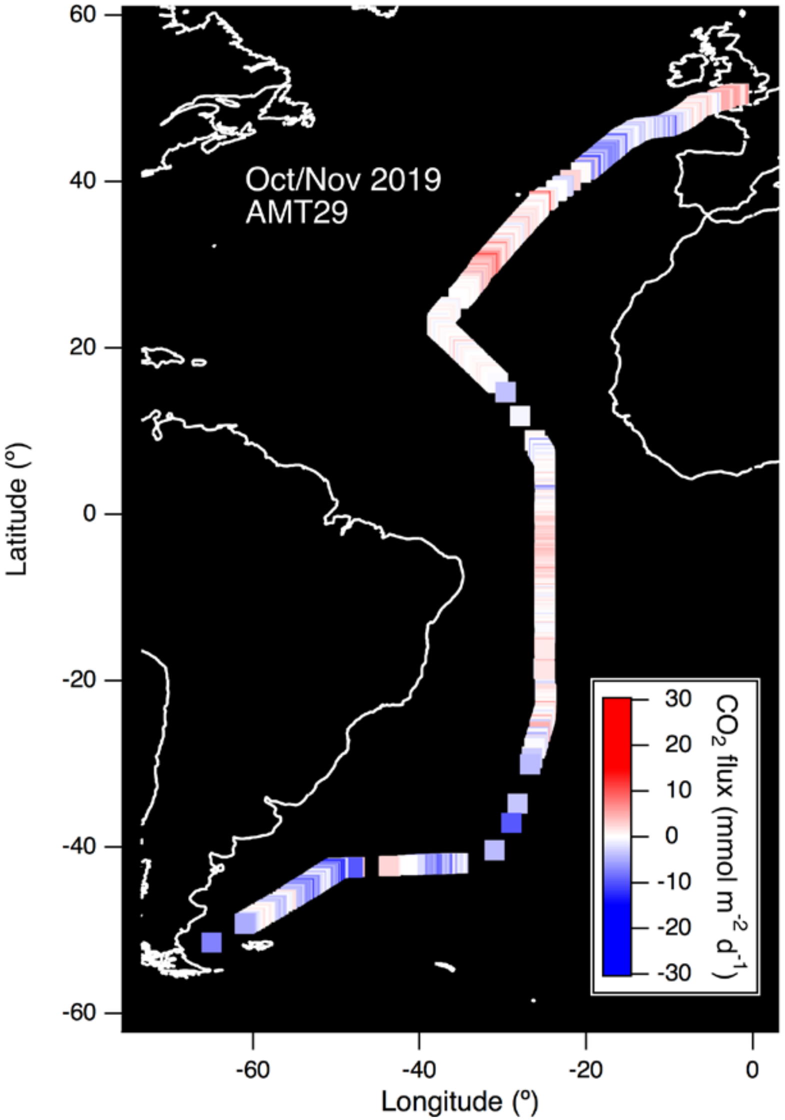


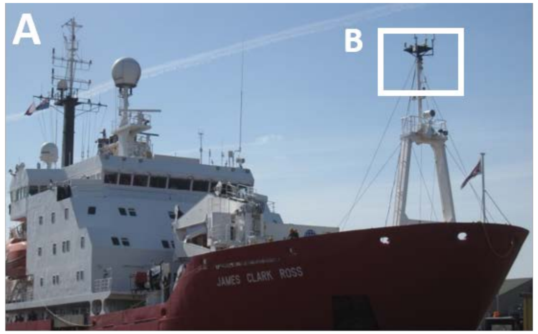


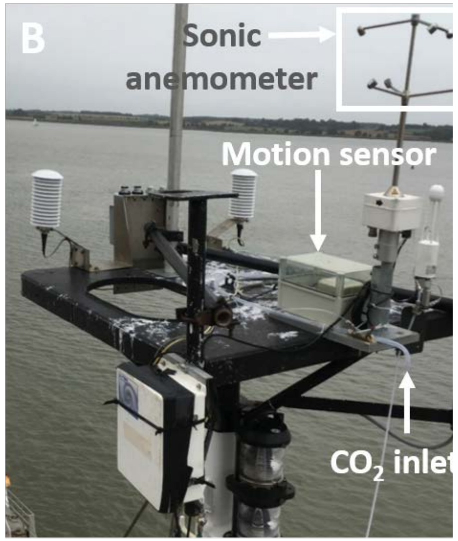
Holding, T., et al., (2019), The FluxEngine air-sea gas flux toolbox: simplified interface and extensions for *in situ* analyses and multiple poorly soluble gases, *Ocean Sciences*.

RINGO Readiness of ICOS

ESA OceanSatFlux – simultaneous in situ bulk and eddy covariance measurements, including SST skin

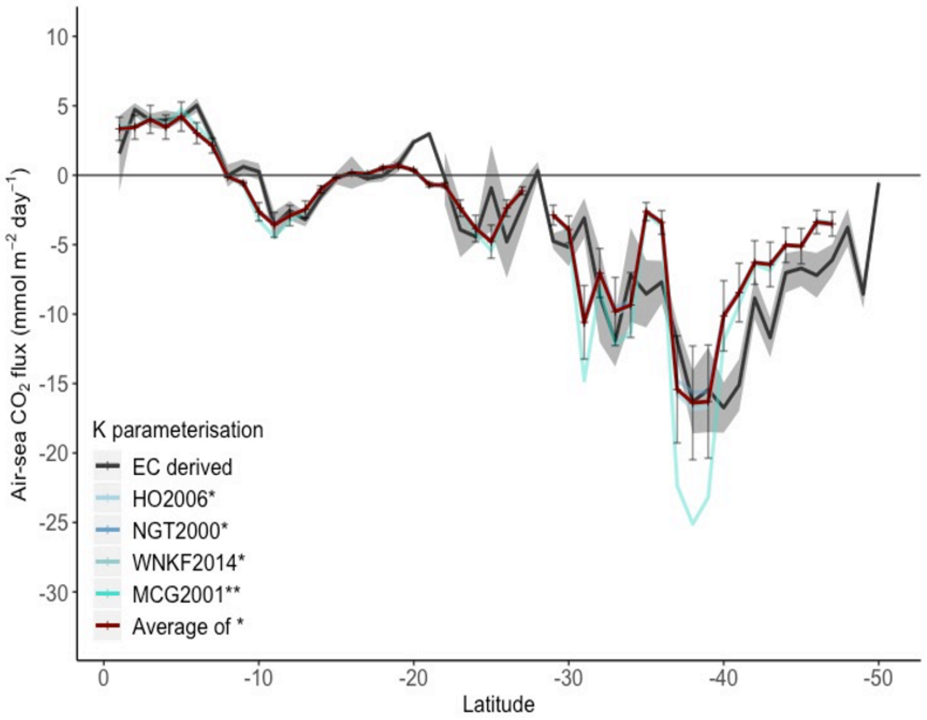






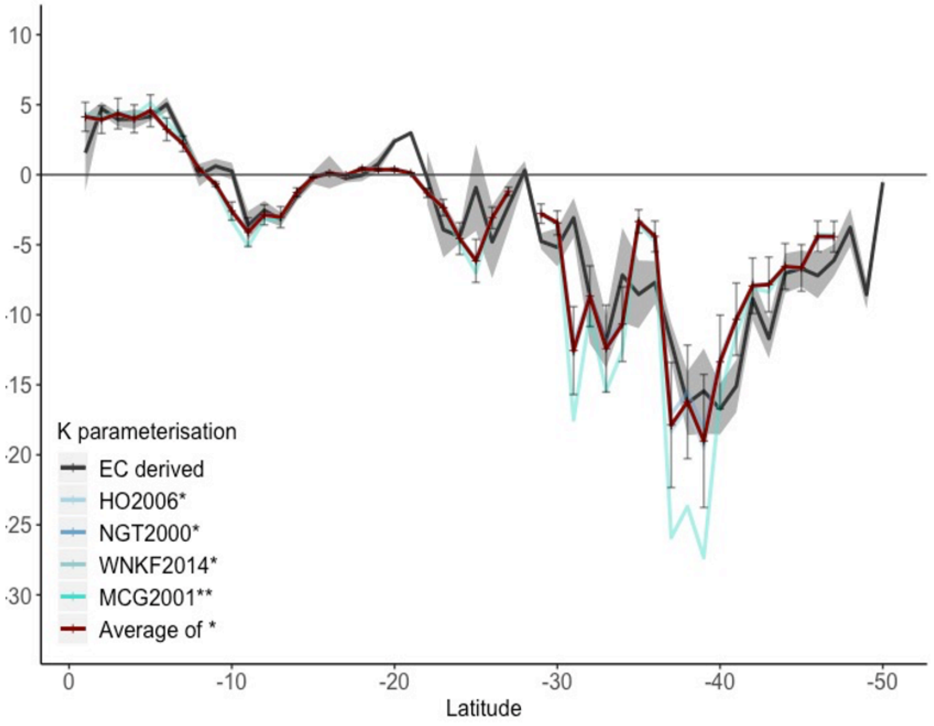
Direct bulk fluxes versus indirect eddy covariance

Well used low accuracy calculation using SST at depth



K parameterization used	Net air-sea CO_2 flux (mmol m² d⁻¹)	Mean K_{CO2}	Difference from EC net flux (mmol m² d⁻¹)		Difference from EC derived K_{CO2}	
			Net	RMSD	Net	RMSD
EC	-3.74±0.81	22.96±1.61	-	-	-	-
HO2006*	-3.30±0.76	20.01±1.37	-0.49	2.78	3.07	9.68
NGT2000*	-3.18±0.72	19.44±1.29	-0.61	2.73	3.71	9.49
WNKF2014*	-3.27±0.73	19.81±1.35	-0.52	2.79	3.28	9.68
MCG2001**	-4.06±0.96	23.33±1.98	0.26	3.73	-0.49	12.07
Combined mean of *	-3.25±0.72	19.75±1.36	-0.54	2.76	3.35	9.61
Combined mean of * and **	-3.45±0.78	20.65±1.52	-0.33	2.89	2.39	9.96

High accuracy calculation using SSTskin at SST at depth



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-3.92±0.86	18.79±1.35	0.12	2.72	4.93	11.81
-3.79±0.81	18.27±1.23	-0.007	2.55	5.48	11.73
-3.88±0.84	18.59±1.32	0.08	2.70	5.12	11.86
-4.76±1.07	21.88±1.89	0.97	4.18	1.73	13.27
-3.86±0.83	18.55±1.34	0.06	2.65	5.18	11.81
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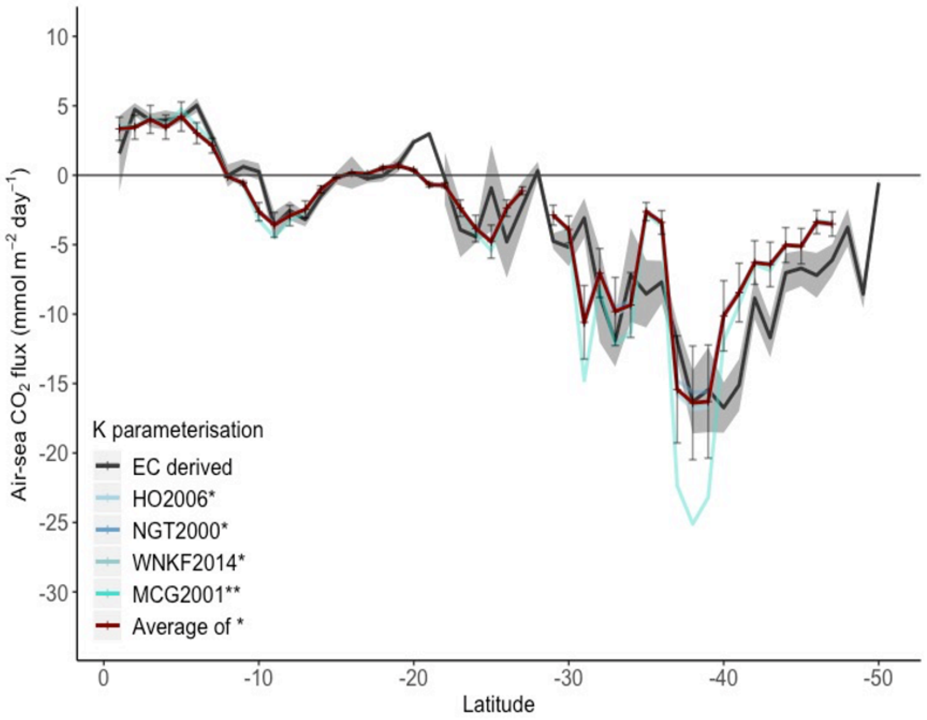

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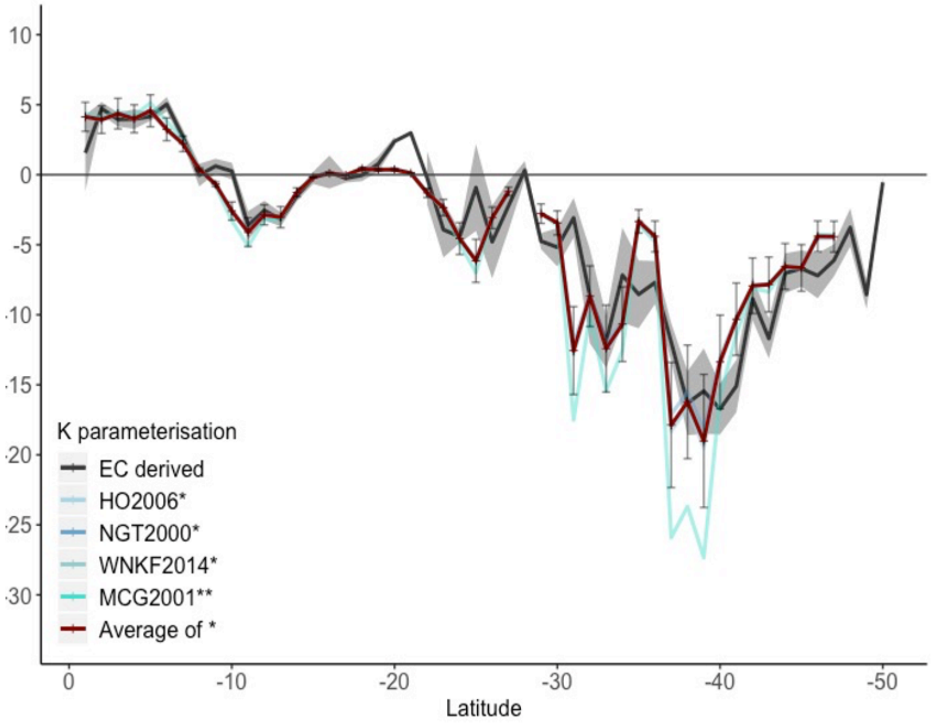

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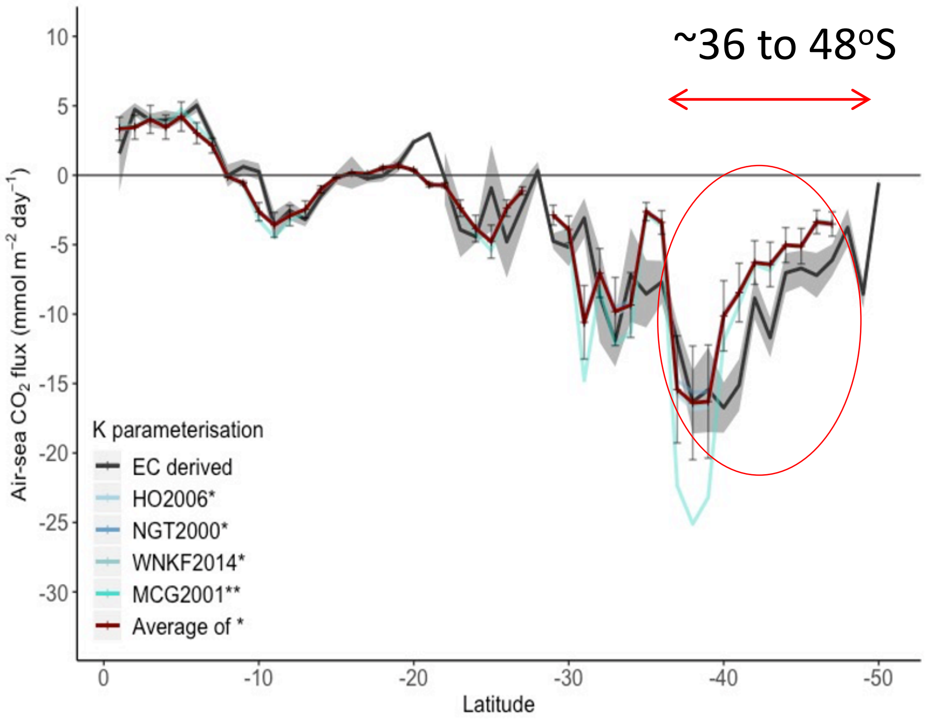

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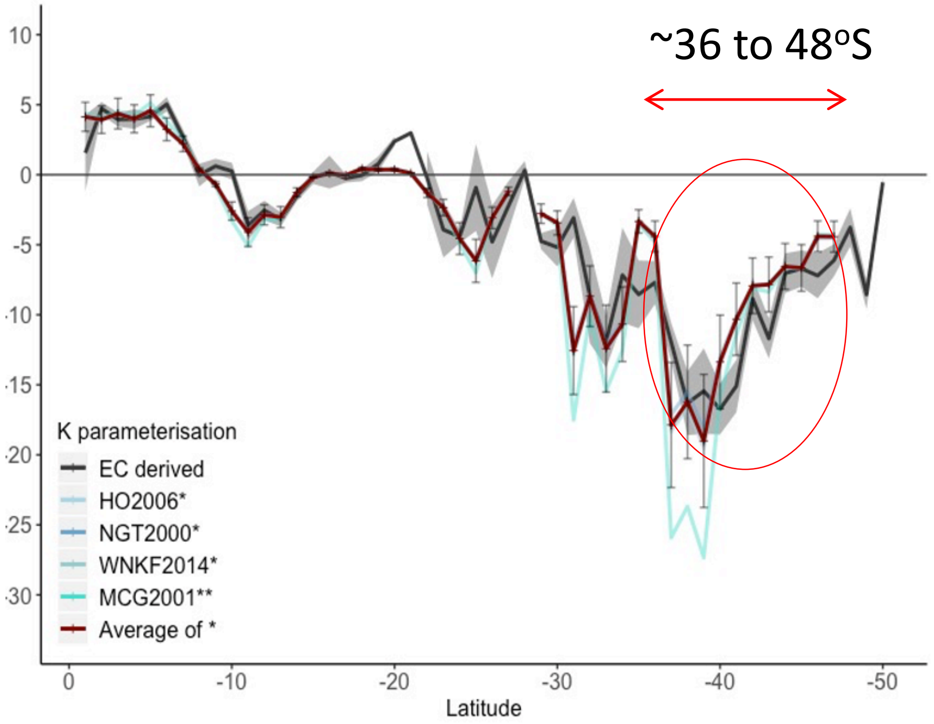

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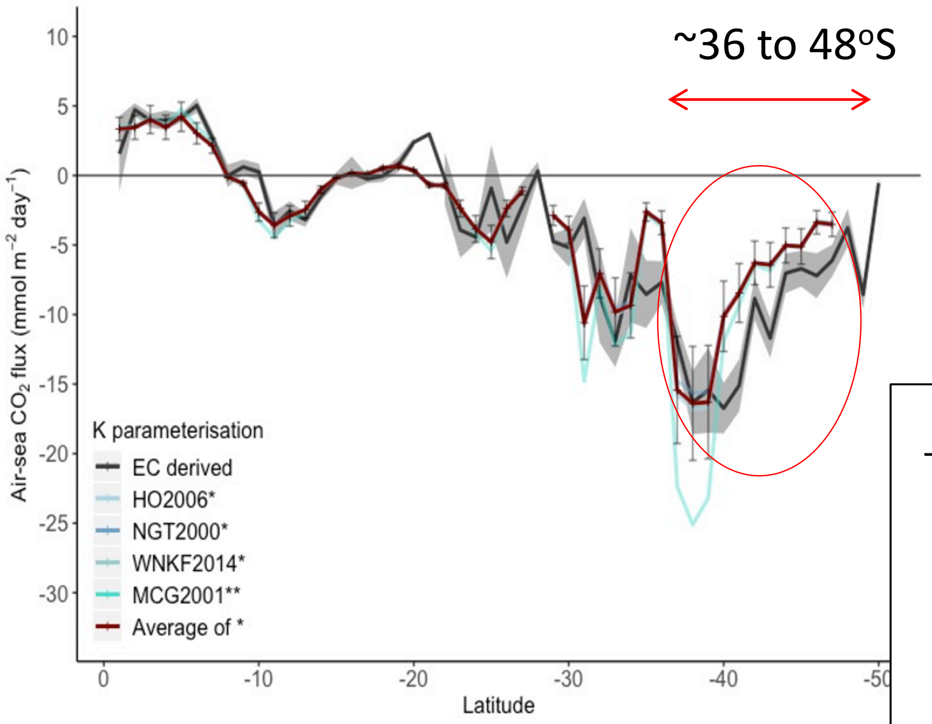

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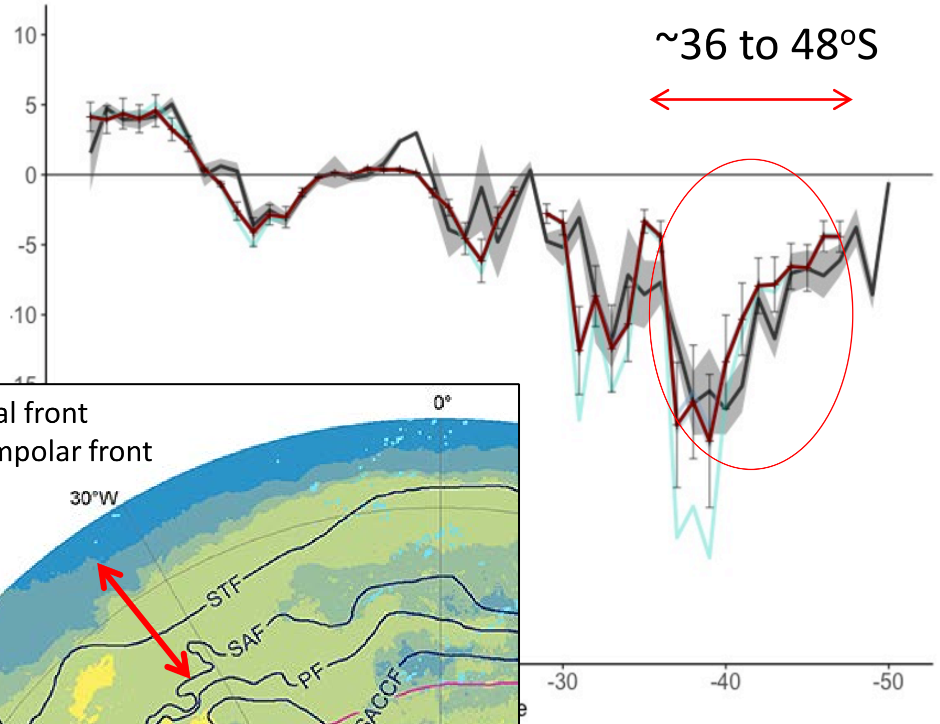

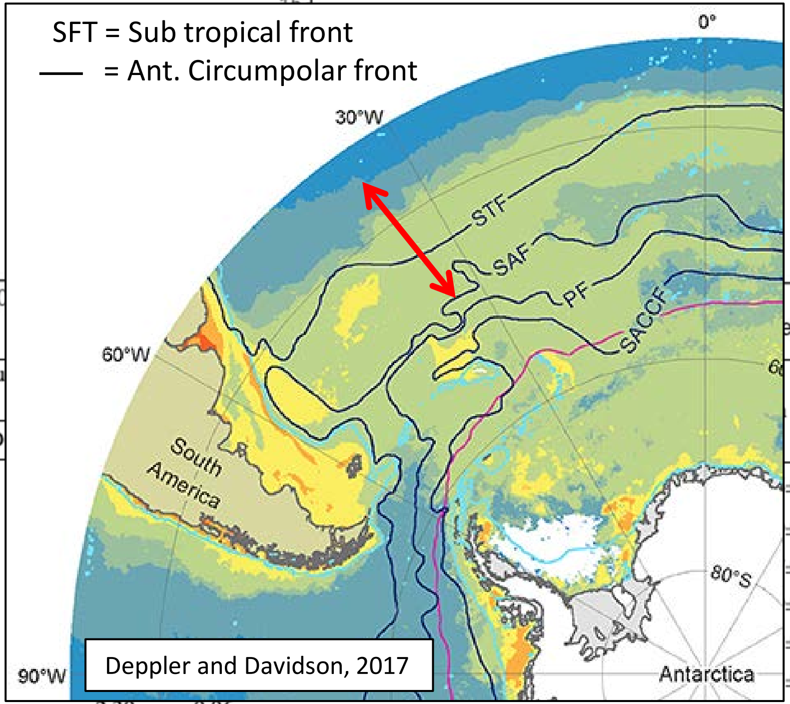

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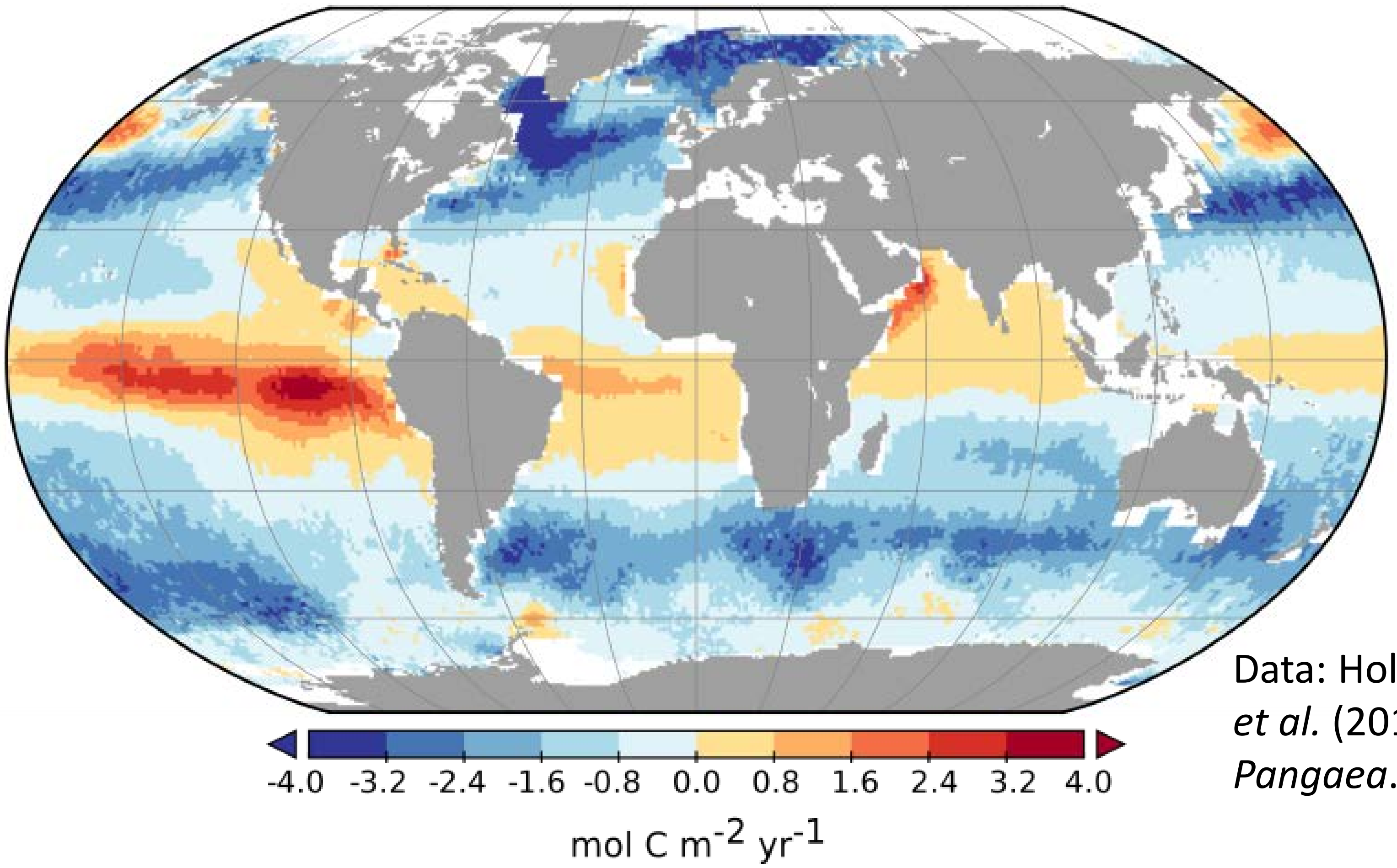
Global implications of consolidated methods for temperature and salinity handling within gas flux calculations

Results
Oceanic sink is at least 0.37 to 0.44 PgC larger than previously thought (Shutler *et al.*, 2019).

Global ocean sink value for 2010 is:
3 ± 0.6 PgC (Woolf *et al.*, 2019).



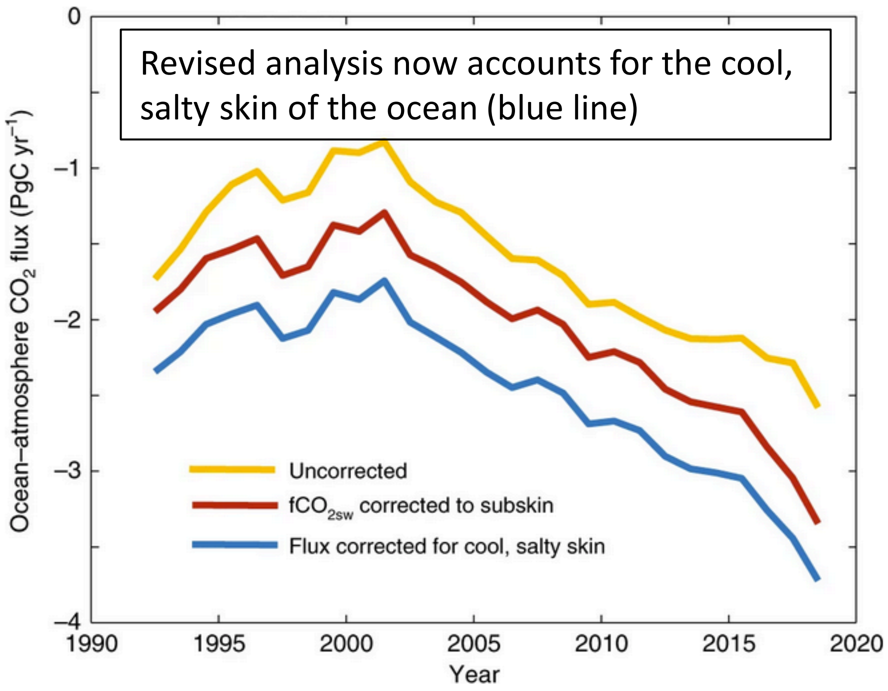
Data: Holding *et al.* (2019), *Pangaea*.

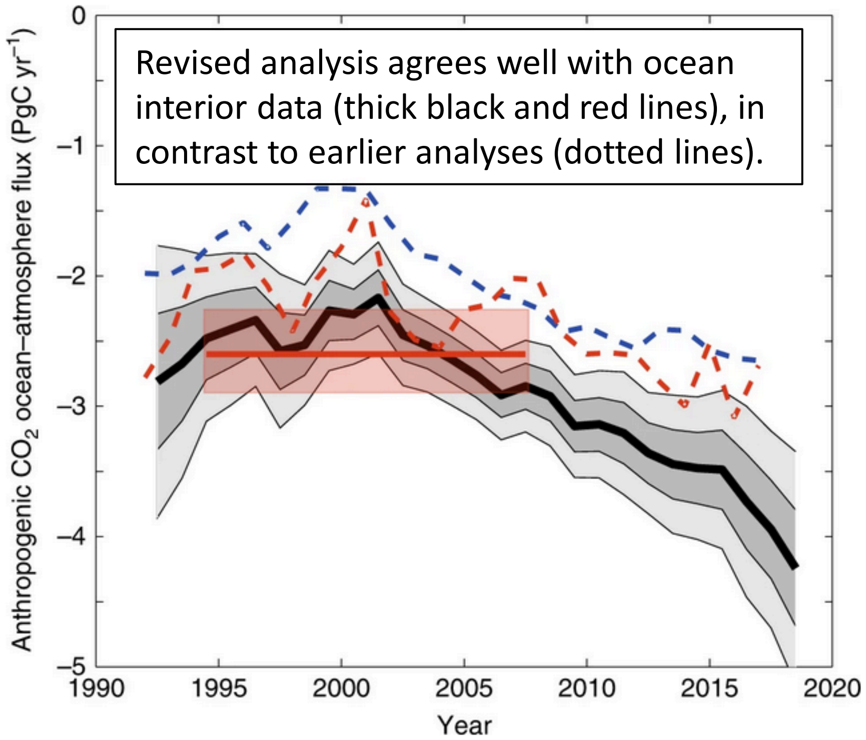
Shutler, J. D., *et al*. (2019) Satellites will address critical science priorities for quantifying ocean carbon, *Frontiers in Ecology and Environment*. doi: 10.1002/fee.2129

Woolf, D. K., *et al.* (2019) Key uncertainties in recent air-sea CO_2 flux, *Global Biogeochemical cycles,* doi: 10.1029/2018GB006041

Global implications of consolidated methods for temperature and salinity handling within gas flux calculations

- Ocean sink is much larger than most ocean carbon models suggest.
- **The annual difference in ocean uptake can amount to ~10% of annual global fossil fuel emissions**.
- Result agrees well with an independent synthesis of interior ocean hydrography data.
- Analysis supports the revision of land to ocean riverine flux to around 0.5 Pg C yr^{-1}.
- Work suggests that some revision of the global carbon budget is now required.





Watson, A., Schuster U., Shutler, J. D., *et al*., (2020) Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory. *Nature Communications*, https://doi.org/10.1038/s41467-020-18203-3

Conclusions

OceanSatFlux

Inter-comparison between direct and indirect air-sea CO_2 flux measurement techniques to:

- evaluate the theory of the impact of vertical temperature gradients on air-sea CO_2 exchange.
- advance uncertainty analyses within air-sea exchange studies (bulk and eddy covariance).

Using simultaneous SST skin measurements, underway and eddy covariance measurements.

The study:

- Confirmed that the consolidated theory appears correct.
- Found the largest impact within oceanic boundaries where SST vertical profiles are more variable (eg due to mixing and productivity).

Accurate SST measurements and their depth are essential for accurately measuring air-sea CO_2 fluxes. Ignoring vertical temperature gradients results in a systematic underestimate of the oceanic CO_2 sink.

Global implications for the ocean carbon sink, land to ocean riverine sink, quantifying the land carbon sink, global carbon and thus advice for reducing emissions.

esa amt4oceansatflux

Exeter PI for fluxes, Ian Ashton, i.g.c.ashton@exeter.ac.uk; presented by Jamie Shutler, j.d.shutler@exeter.ac.uk

Example 3: Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory

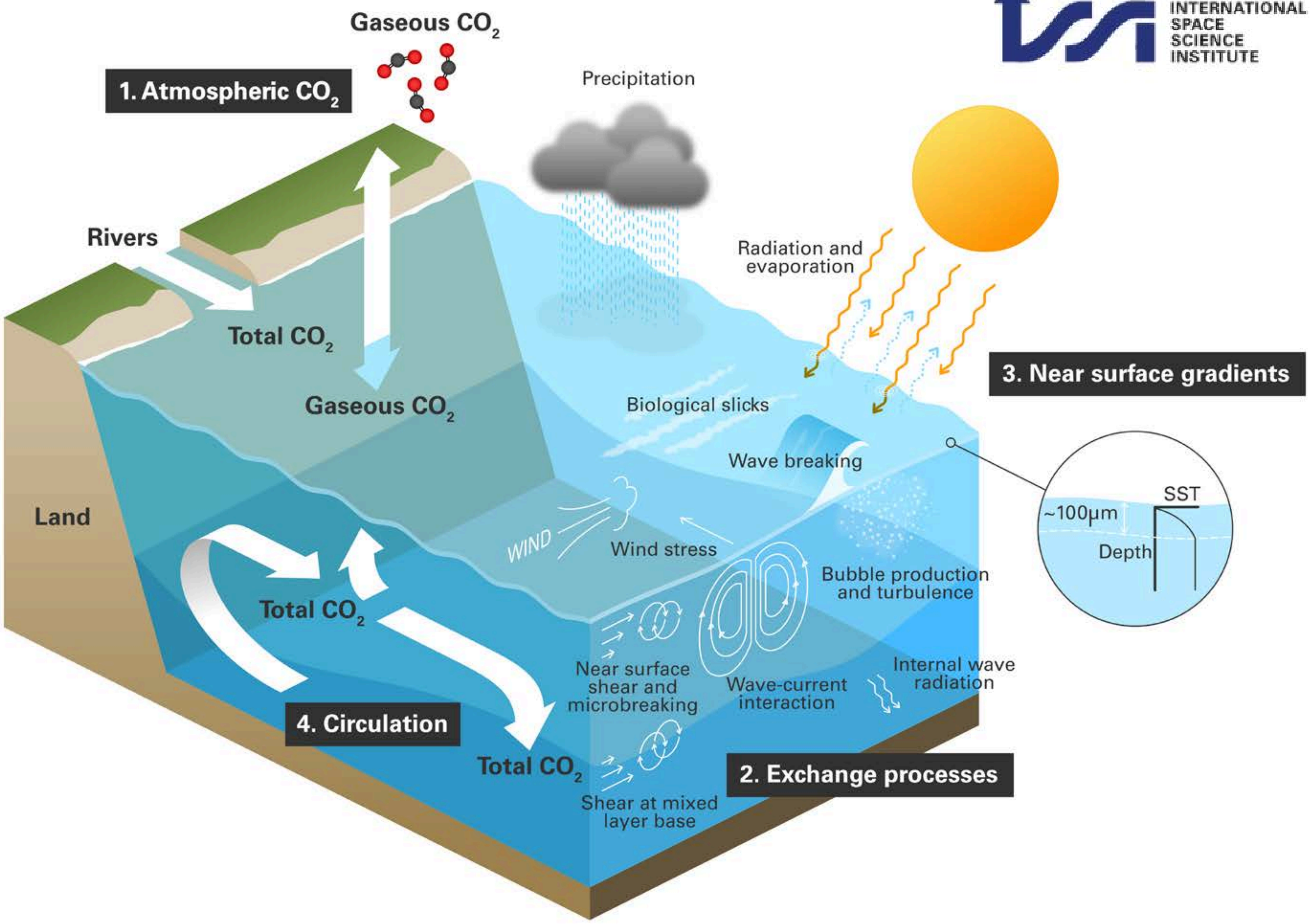
Mail Online

World's oceans soak up 900 million tonnes of CO2 a year MORE than previously thought — the amount emitted by 2.2 billion petrol cars

- Previous models did not account for temperature differences at different depths
- This alters how much carbon is soaked up by the water in total
- Researchers believe the world's oceans actually soak up far more carbon, equivalent to ten per cent of global fossil fuel emissions

Watson, A., Schuster U., Shutler, J. D., *et al.*, (2020) Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory. *Nature Communications*, https://doi.org/10.1038/s41467-020-18203-3

But satellite observations offer much more!



Simplified view of interactions, exchange and circulation of CO_2 within the ocean, identifying where satellite Earth observation is likely to play a leading role in expanding understanding and capability.

Shutler, J. D., Wanninkhof, R., Nightingale, P. D., Woolf, D. K., Bakker, D. C. E., Watson, A., Ashton, I., Holding, T., Chapron, B., Quilfen, Y., Fairall, C., Schuster, U., Nakajima, M., Donlon, C. J., (2019) Satellites will address critical science priorities for quantifying ocean carbon, *Frontiers in Ecology and Environment*. doi: 10.1002/fee.2129