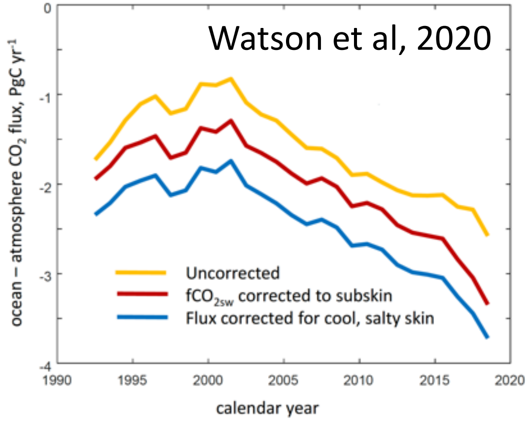
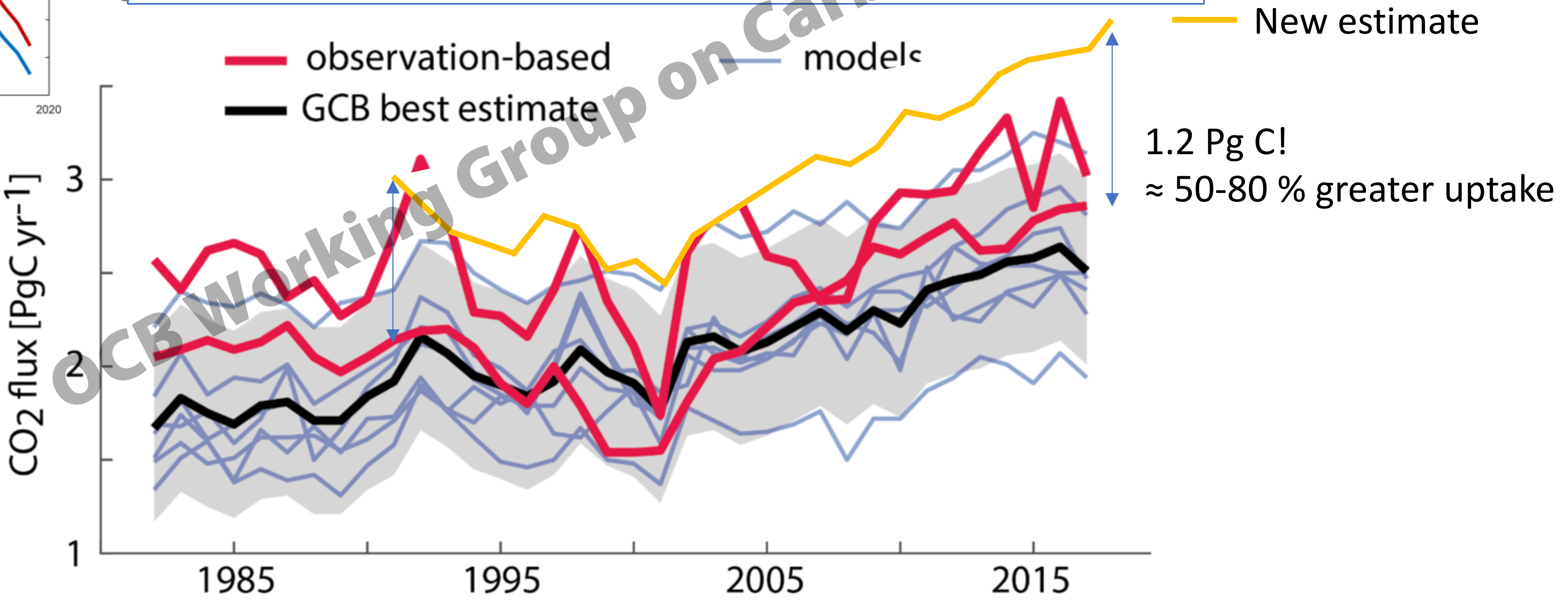
Gas Exchange Uncertainties

Working group member
Rik Wanninkhof, NOAA/AOML, Miami



Including chemical and thermal gradients in the surface boundary (≈ 100 micron) could increase the ΔpCO_2 by ≈ 6 µatm and thereby the air-sea flux by 1.2 Pg C [Watson, Woolf, Shutler et al.)



Its not who is right or wrong- but rather that there are unresolved issues.

Air-sea CO_2 fluxes

Direct Flux measurements : F = w'c'

are challenging:

- Experimental
- Need large concentration gradient ($\Delta pCO_2 \approx 40$ µatm)
- Use to understand the forcing of transfer
- Interpolating Flux on large scales very tricky

Bulk Formulation: a physical and an operational definition

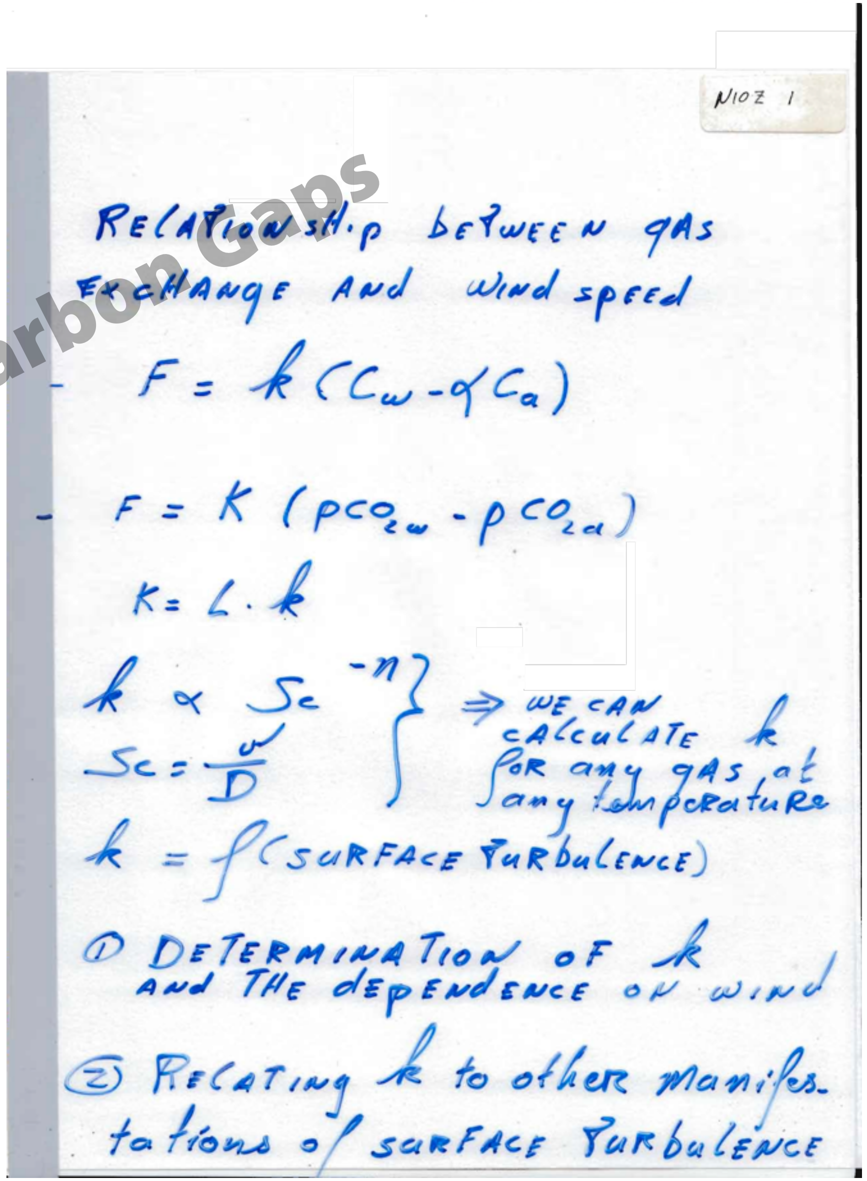
$F = k\,(C_w - K_o C_a)$

$K_o C_a$ = C_0 right at the interface

C_w = right below the mass (diffusive) boundary layer retarding the flux

$F = k\,K_o\,(pCO_{2w} - pCO_{2a})$

Measurement in bulk phases (air ≈ 10-m; water ≈ 1-m)



NIOZ 1

Relationship between gas exchange and wind speed

$F = k\,(C_w - \alpha C_a)$

$F = K\,(pCO_{2w} - pCO_{2a})$

$K = L \cdot k$

$k \propto Sc^{-n}$

$Sc = \nu / D$

⇒ we can calculate k for any gas at any temperature

$k = f$(surface turbulence)

① Determination of k and the dependence on wind

② Relating k to other manifestations of surface turbulence

Responsive to SOLAS themes:

- Theme 1. Greenhouse gases in the ocean (Tish, Greg Cutter)
- Theme 2. Air-sea interface and fluxes of mass and energy (Rachel/Penny, Haus, Potter)
- Theme 3. Atmospheric deposition and ocean biogeochemistry (Kate/Yuan/Bill Landing/Santiago/Greg Cutter)
- Theme 4. Interconnections between aerosols, clouds, and marine ecosystems (Cassie/Nicholas/Santiago)
- Theme 5. Ocean biogeochemical controls on atmospheric chemistry (Dave)

Workshop report chapter:

Air-sea exchange (Ho lead, Bell, Stanley, Potter pull together)

- Uncertainties and biases in CO_2 flux calculations (Palter, Cai)
- Medium (5-15 m s^{-1}) wind speed regimes (Emerson, Bell,Laxague)
- High (>15 m s^{-1}) wind speed regimes (Vlahos, Ortiz-Suslow, Stanley,Laxague, Haus, Potter)
- Coastal regimes (Ho, Najjar, Ortiz-Suslow)
- Sea spray aerosol fluxes (Henry, Allie?)
- Impact of sea ice on air-sea fluxes of gases and aerosols (Matrai, Schultz)

Ocean-Atmosphere Interactions

Bulk Flux equation for sea-air CO_2 exchange

OCB Working Group: Filling the gaps in observation-based estimates of air–sea carbon fluxes

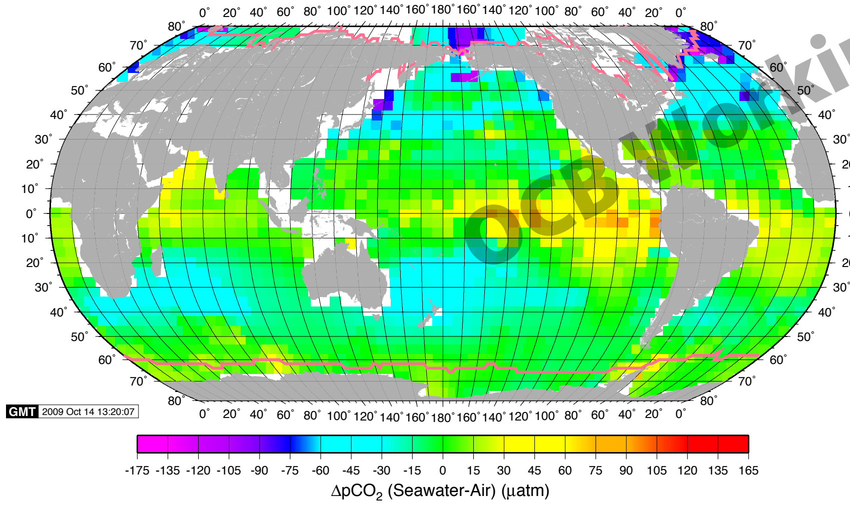
$$F = k \quad K_o \Delta pCO_2$$

Thermodynamic Forcing | Kinetic forcing | Flux

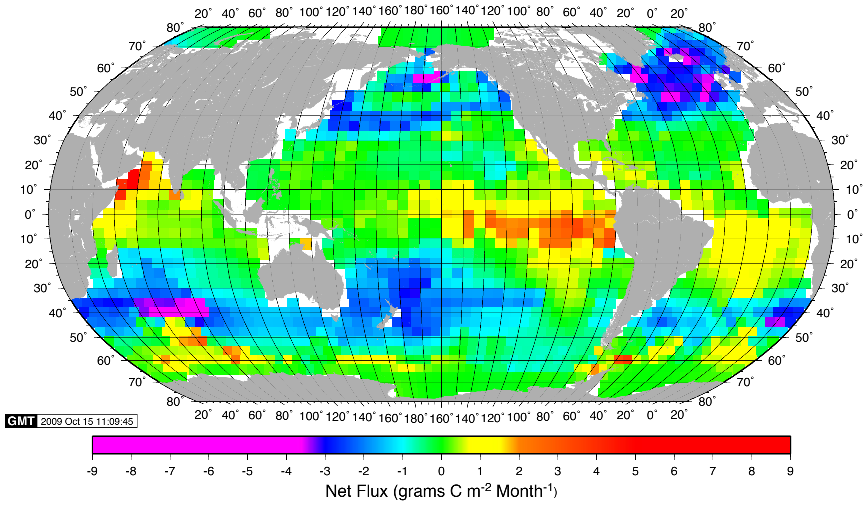
ΔpCO_2

$k = f(U_{10})$

ΔpCO_2 (Seawater-Air) (Rev Oct 09) for June 2000



MONTHLY Flux for June 2000 [Rev Oct 09] NCEP II Wind, 3,040K (U^2 wind, Γ=.26)



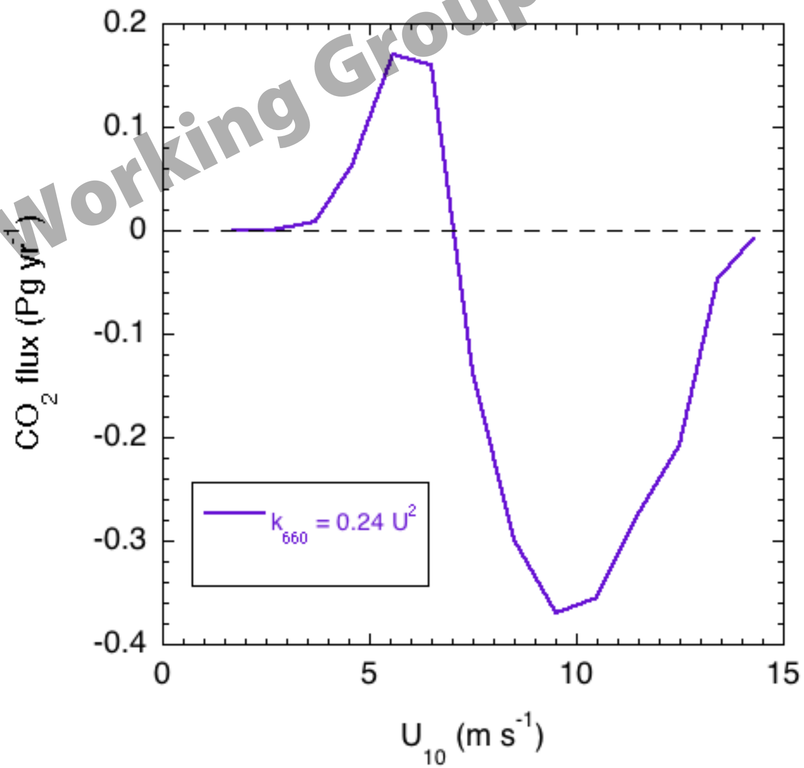
Concentration gradient → Fluxes

Wanninkhof, Gaps WG May, 2020

The importance of sea –air gas transfer in carbon cycle research

Global *net* Sea-Air CO_2 flux with wind- k parameterization = -1.38 Pg C yr^{-1}
Global *net* Sea-Air CO_2 flux with globally average k everywhere (global average winds) = -0.3 Pg C yr^{-1}

There is a correlation between areas of out/in gassing and low/high winds



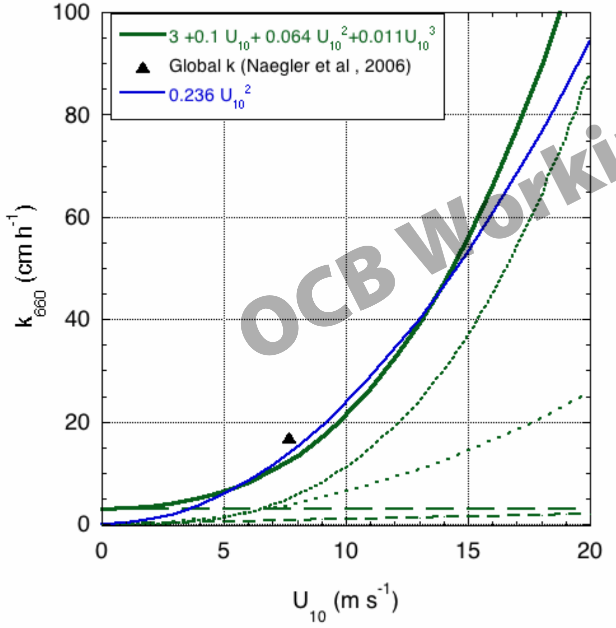
Wanninkhof et al., 2009

Reconciliation of current knowledge into a simple relationship

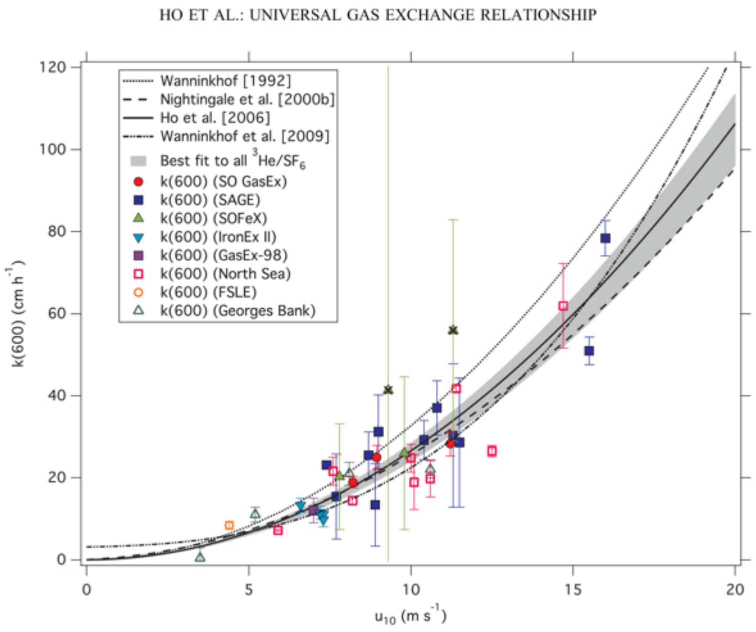
The hybrid model: What if all processes play a role?

1. Chemical enhancement and non-wind induced turbulence : Constant
2. Transfer across rigid wall: U
3. Wind stress: U^2
4. Energy dissipation/bubbles: U^3

k_{660}= 3 + 0.1 <U> + 0.26 $<U^2>$ + 0.011 $<U^3>$ ≈ k_{660}= 0.24$<U^2>$ for 4-15 m s^{-1} ± 20 %



(Wanninkhof et al., 2009)



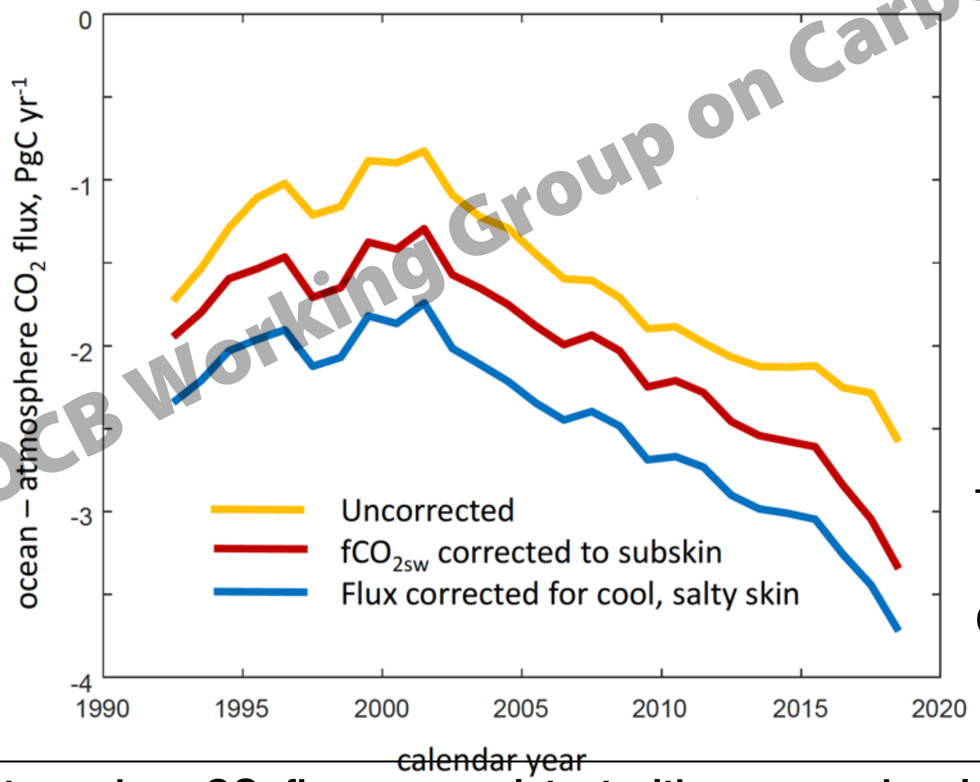
[Until we have a better knowledge of other factors and these factors can be measured globally], a quadratic dependency seems to work

Now what is the fuss?

Earth's radiation and water balance dictates a "cool and salty skin"

Having an accurate ΔpCO_2 is critical (at all scales)

- $\Delta\Delta pCO_2$ of 1 µatm ≈ 0.25 Pg C
- ΔpCO_2 is small ≈ -50- 50 µatm   global mean ≈<8 µatm
- pCO_2 is very temperature dependent (≈ 4 % ̊C $^{-1}$)



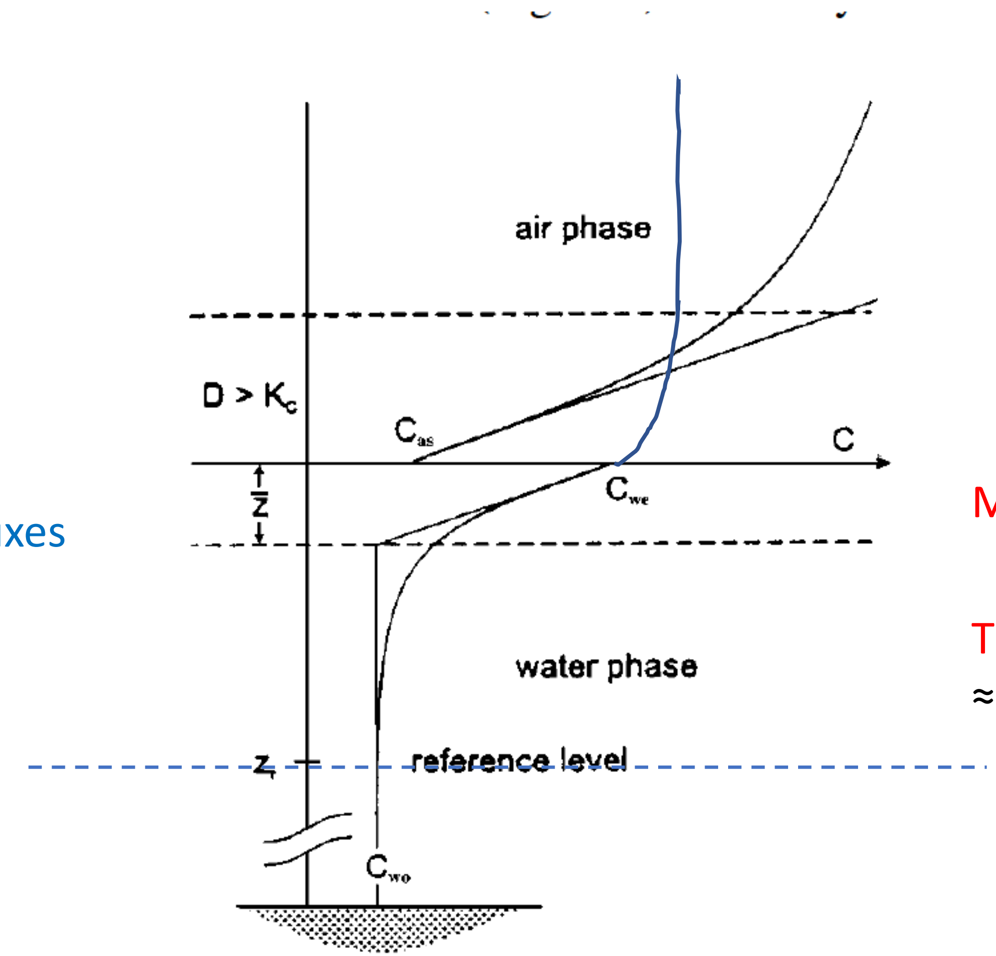
Thermal ≈ 0.7 Pg C

Chemical ≈ 0.4 Pg C

Larger estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory
Andrew J Watson, Ute Schuster, Jamie. D Shutler, Thomas Holding, Ian G. C. Ashton, Peter Landschützer David K. Woolf, Lonneke Goddijn-Murphy

Mass and thermal boundary layers

Sensible and latent heat fluxes
Cause a cool salty skin
(ΔT = 0.2 ̊C and ΔS =0.1)



Mass boundary layer

Thermal boundary Layer
≈5-10 times the mass boundary layer

-Where is the gas transfer impeded?
-What are the conditions across the relevant boundary layer

What do we use for concentration gradient to get air-sea CO_2 flux ?

$$F = k\,(K_{0w}\, pCO_{2w} - K_{0s}\, pCO_{2a})$$

$$[CO_2]_{aq,0} = K_0\,(T_s, S_s)\; pCO_{2a}$$

$$[CO_2]_{aq,d} = pCO_{2w} * ??????$$

Questions:

- What is the appropriate concentration gradient?
- What is the $[CO_2]$ at different locations though the mass and thermal boundary layers

Challenges:

- Very difficult to verify this issue and to address problem [on small scales]
- k and ΔpCO_2 determined independently [cannot do direct flux measurement and bulk flux estimate at same time]
- Adjusting k based on operational definition using bulk phases cannot be done simply as its ΔpCO_2 that drives the flux

Approaches:

- LES modeling could offer some insights
- Global mass balances could offer constraints.

OCB Working Group: Filling the gaps in observation-based estimates of air–sea carbon fluxes

Fate of anthropogenic CO_2 emissions (2007–2016)

Sources = Sinks

9.4 Pg C /yr
88%

12%
1.3 Pg C /yr

4.7 Pg C /yr
44%

28%
3.0 Pg C /yr

33 %? 22%
2.4 Pg C /yr
3.6 Pg C /yr**??**

Yellow: Estimates presented here

How well do we really know the carbon uptake by the ocean?

Budget Imbalance:
(the difference between estimated sources & sinks)

6%
0.6 Pg C /yr

- 6 % ?????

Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2017; Global Carbon Budget 2017

SOCONET, SOCAT, ICOS-OTC, ISOOS

(Wanninkhof, 8 min)

OCB Working Group: Filling the gaps in observation-based estimates of air–sea carbon fluxes

Providing an operational foundation for sustained surface operations from a diverse community – Bottom up efforts

ISOOS/OASIS: Integrated Surface Ocean Observing system: A "Big Idea" from Ocean Obs-19 for a sustained surface ocean observing system of all physical, chemical, and biological parameters
The Decade of Ocean Science for Sustainable Development;
GOOS The Science We Need For The Ocean We Want]
Step one: Observing Air-Sea Interaction Strategy (OASIS), SCOR WG

SOCAT: Collate, "homogenize" and higher level quality control of surface pCO_2 data; advocate for Best practices; assess overall quality of datasets
((± 2 µatm (A,B); ± 5 µatm (C,D); > ± 5µatm (E))
Good data ingestion tools
Aspirations: other surface water measurements; water column

SOCONET: Surface CO_2 reference network – Sustain and improve surface water CO_2 measurement good enough for air-sea CO_2 flux determinations (± 2 µatm water; 0.2 ppm air)
Regional network: ICOS-OTC: Integrated carbon observing system-Ocean Thematic Center A European Infrastructure project.
OTC lead Richard Sanders- looking at ways to sustain (fund) global networks

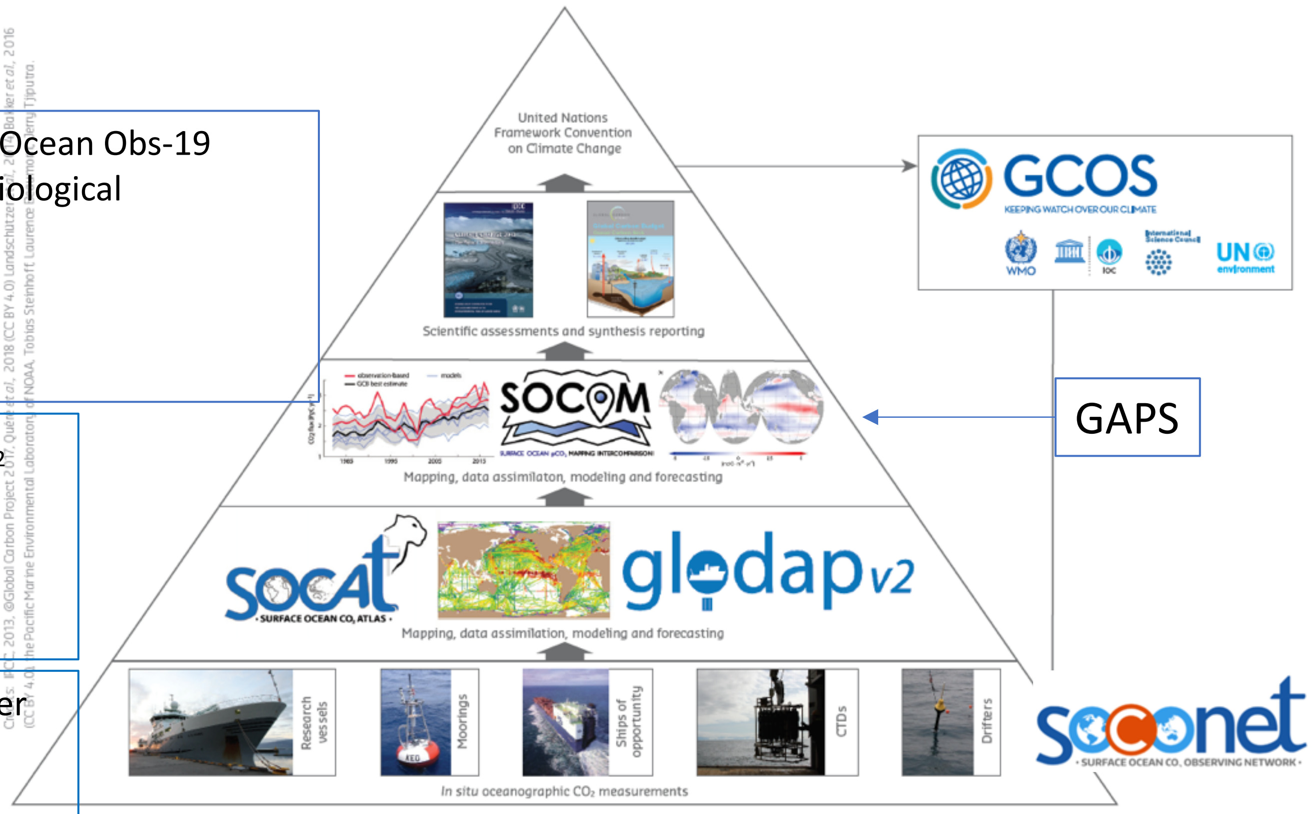


Figure 2.2. The value chain that connects *in situ* oceanographic measurements of carbonate chemistry variables to climate negotiations.