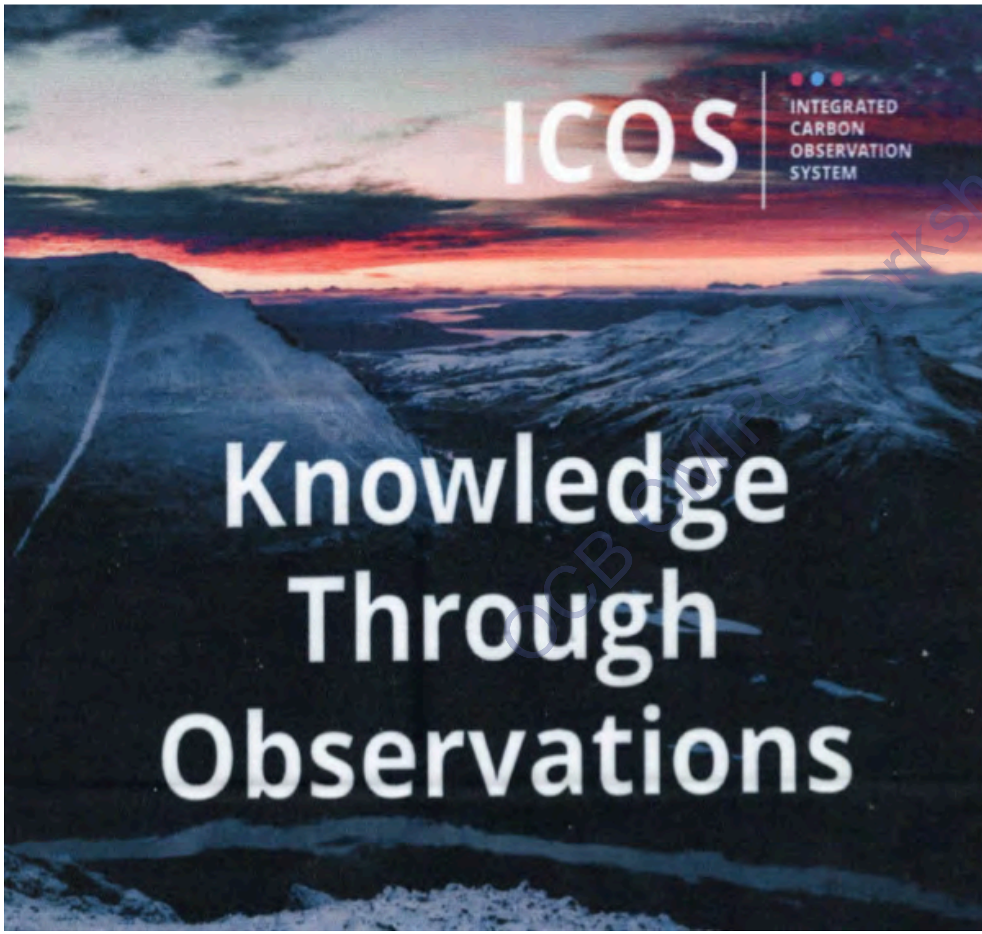
# How (well) do models calculate air-sea fluxes?

Rik Wanninkhof (NOAA/AOML)




OCB ocean carbon uptake in CMIP6 models synthesis and intercomparison workshop. Washington DC, Dec 8 & 9, 2018

# How (well) do models calculate air-sea fluxes?

## Bulk Flux formulation

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

<u>Topics:</u>

1) How well are we doing estimating global fluxes?
2) Sustained efforts to observe $pCO_{2w}$ (and $pCO_{2air}$)
3) Better $XCO_{2a}$ estimates
4) Possible biases in $pCO_{2w}$
5) What about k?
6) Can the models reproduce the observations? (suggested comparison)



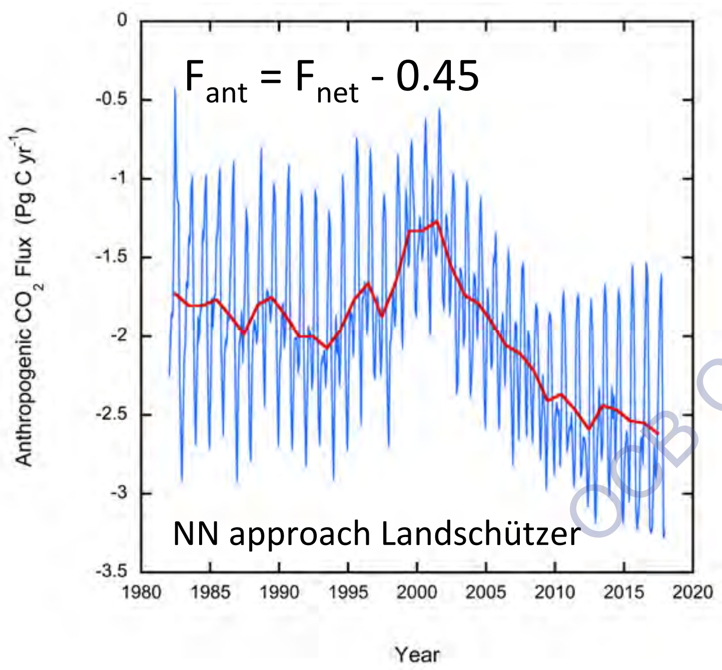
*"For gas exchange, model groups only need to change the value of the gas transfer coefficient, the formulations and coefficients for Schmidt numbers, and the atmospheric gas histories."* Orr et al. 2017

# How well are we doing estimating global fluxes?

## Anthropogenic Flux estimate

Air-Sea $CO_2$ fluxes

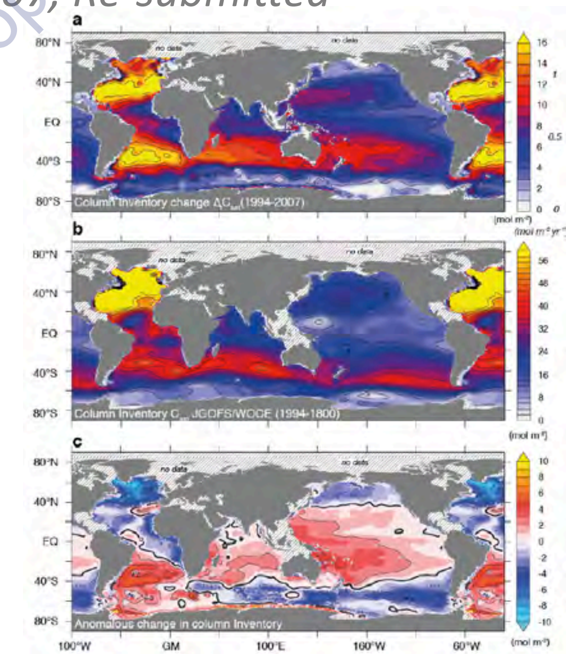
*State of the climate report, 2018*




Average 1994-2007 = **1.68**± 0.25 **Pg C yr $^{-1}$**

Inventory Gruber et al. submitted

*The oceanic sink for anthropogenic $CO_2$ from 1994 to 2007, Re-submitted*

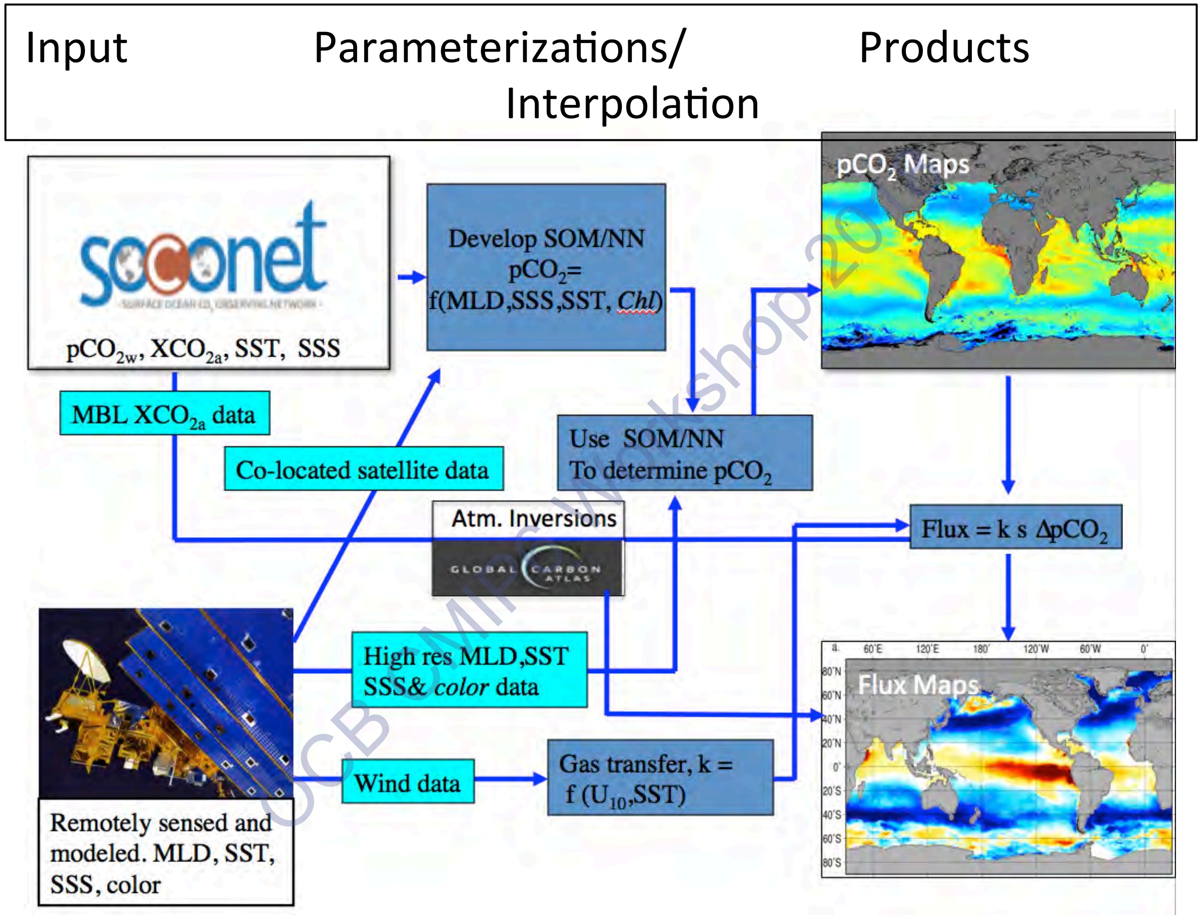


Average uptake rate of **2.5**±0.3 **Pg C yr$^{-1}$**
30±4 % of the global anthropogenic $CO_2$

- Air–sea $CO_2$ flux and change in inventory estimates need to be reconciled

# The Blurring of the observational-modeling divide

*The flux estimates require more than in situ observations*

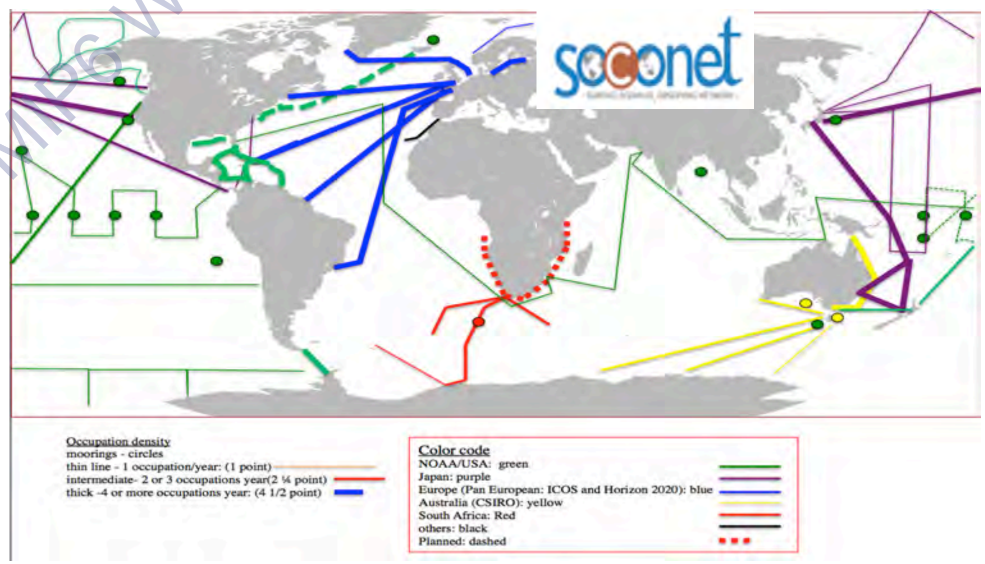



In Situ Obs.
Remotely sensed Obs/
Models

- ➢ A concerted effort is required to produce and validate flux maps

# Surface $CO_2$ observational efforts, $pCO_{2w}$, $XCO_{2a}$

- NOAA Research supports the largest sustained measurement campaign of surface water $pCO_2$ from ships, moorings, and ASVs
- Coordination in Europe starting under ICOS
- Strong sustained efforts in Japan and Australia
- Collated in two annually updated/overlapping datasets LDEO & SOCAT (≈ 1 M data points per year; lag ≈ 2 years)
- Effort to improve Best Practices for global operations:
  Surface Ocean Carbon Observing Network (SOCONET)
  Efforts to: -track,
  -speed-up,
  -improve,
  -harmonize,
  at acquisition phase



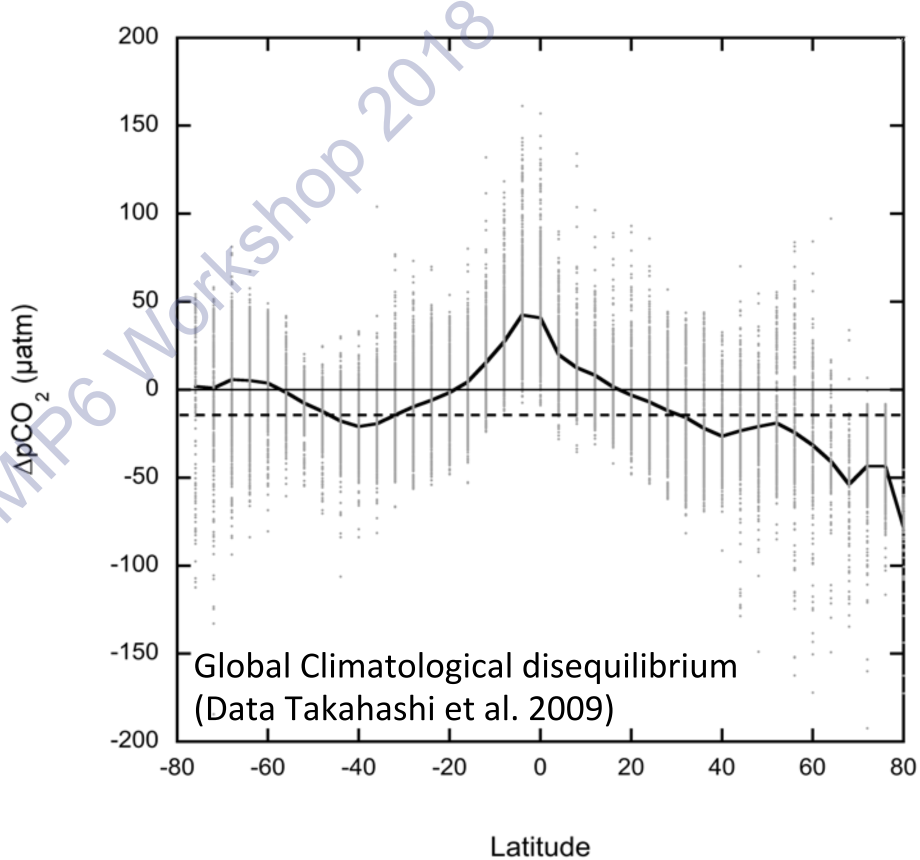

- Sustained efforts and resources are required to maintain the global "data pipeline"
- Need a new paradigm in funding

# Accuracies of the input parameters to obtain fluxes to 0.2 Pg C

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

k ≈ 20 %
s ≈ 5%
$pCO_{2w}$ ≈ 2 µatm (0.5 %)
$XCO_{2a}$ ≈ 0.2 ppm (0.05 %)

Global average air-sea disequilibrium ≈10 µatm "the 1:1:0.2 rule"

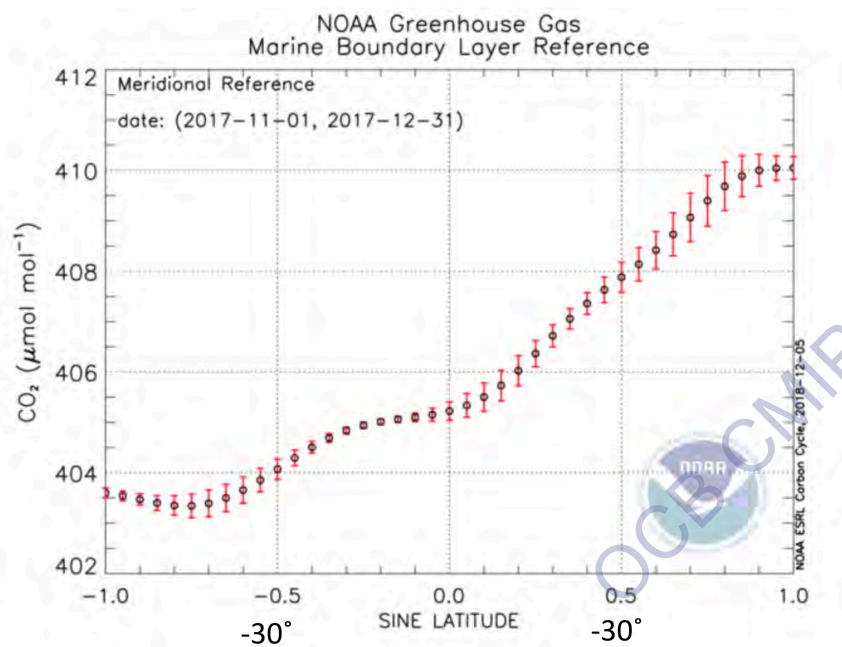


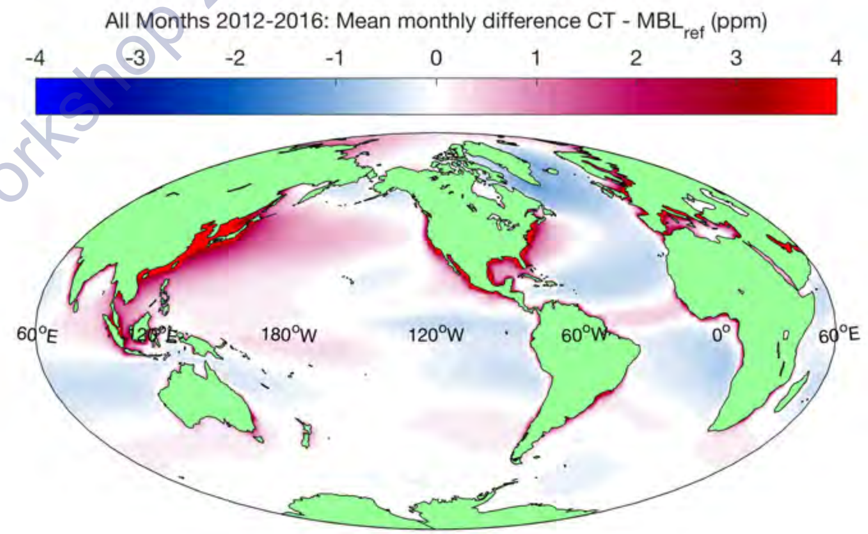



- Observational biases and biases in calculations are major issues

# Improvements in the input parameters, $pCO_{2a}$

$$pCO_{2a} = (P - p_{h2o})\, XCO_{2a}$$




Munro& Sweeney, NOAA/GMD



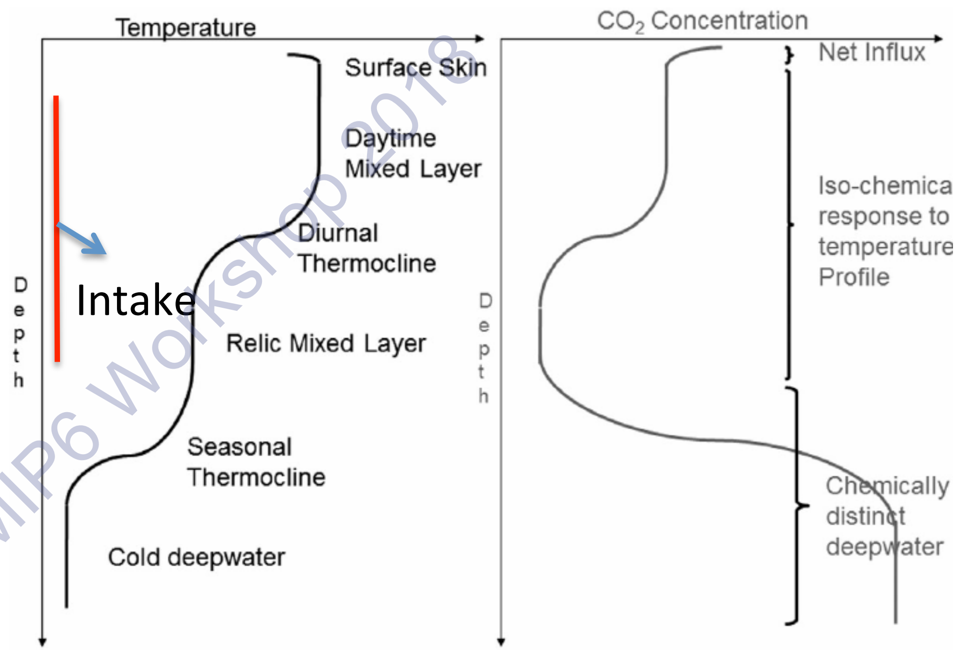
➢ Recommendation: Use a 3-dimensional (position, time) field

# Improvements in the input parameters, $pCO_{2w}$

## Surface temperature correction

Near-surface gradients:

- Cool skin ≈ 0.2 ˚C lower than bulk T
- Skin T is measured from satellites
- Impact ≈0.2-0.6 Pg C




AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2015JC011427

**On the calculation of air-sea fluxes of $CO_2$ in the presence of temperature and salinity gradients**

D. K. Woolf[1], P. E. Land[2], J. D. Shutler[3], L. M. Goddijn-Murphy[4], and C. J. Donlon[5]

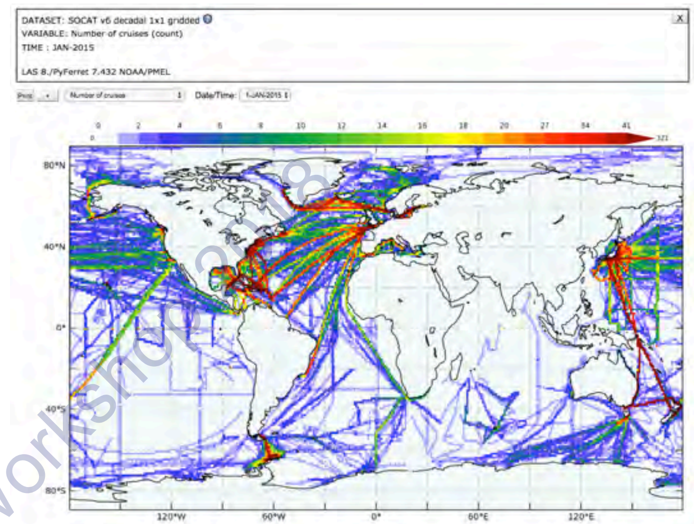
Key Points:

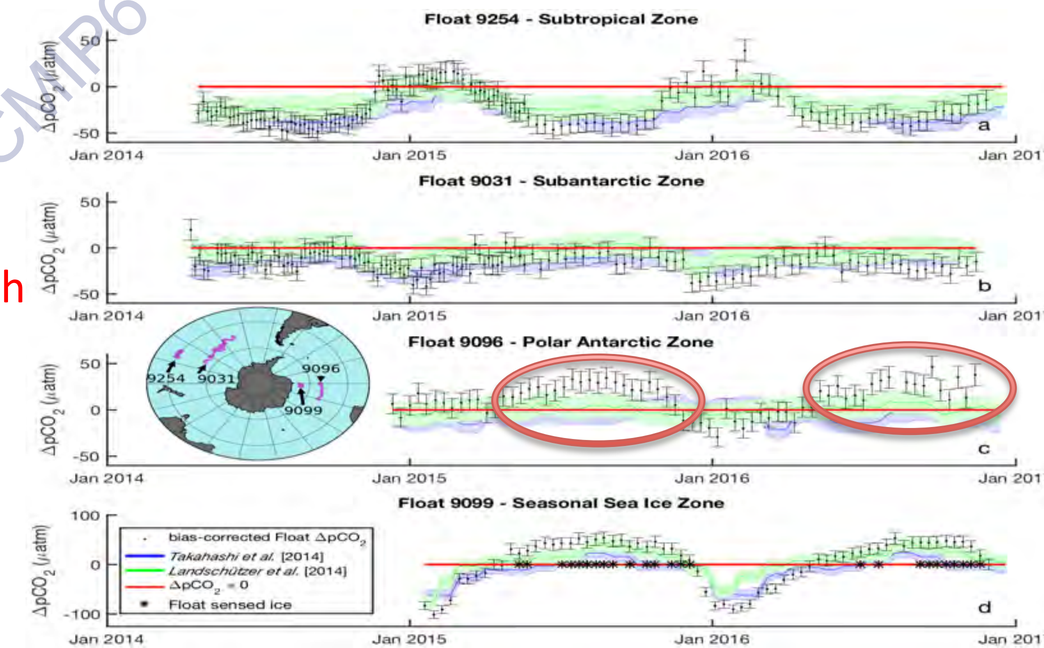
- The effect on calculated $CO_2$ fluxes of a cool skin on the sea surface is large and ubiquitous

- Recommendation: Correct all $pCO_{2w}$ values to skin temperature

# Improvements in the input parameters, $pCO_{2w}$
# Interpolation errors

Data sparsity and possible biases lead to large Interpolation errors



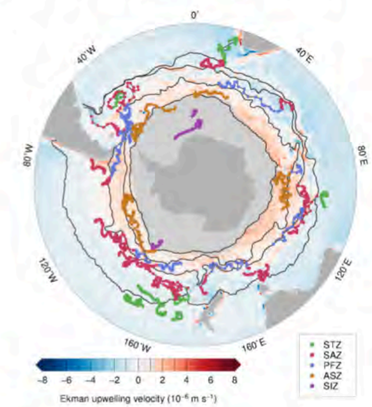

1. Get more targeted observations in missing seasons and regions through (directed) "smart sampling"
   - ➢ NN/SOM approaches
   - ➢ Biogeographical Provinces
   - ➢ Autonomous Surface Vehicles
2. Improve interpolation approaches

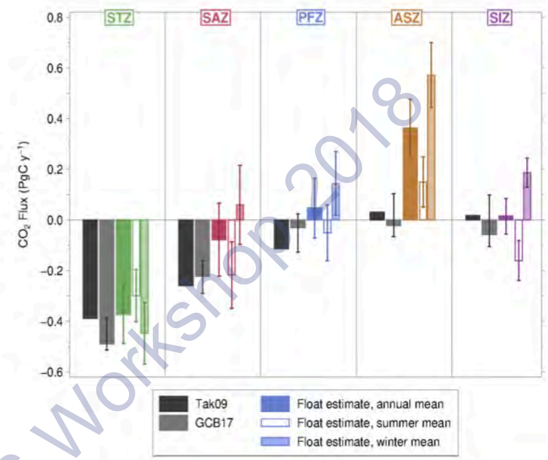
# Improvements in the input parameters, $pCO_{2w}$

## Biases in observations

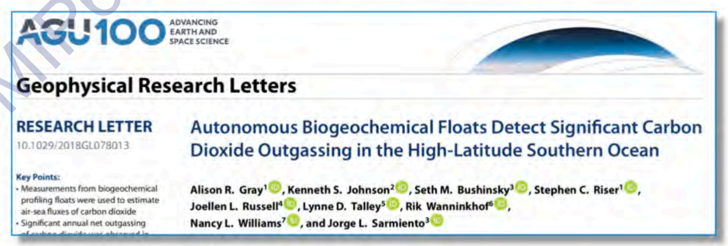
lower precision measurements/estimates are bias prone.

### Air-sea carbon flux from floats




In the high-latitude ASZ, monthly mean float-based fluxes diverge substantially from ship-based fluxes. The floats exhibit much stronger outgassing in the autumn and winter and much less uptake in the summer.


AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL078013

Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean

Alison R. Gray[1], Kenneth S. Johnson[2], Seth M. Bushinsky[3], Stephen C. Riser[1], Joellen L. Russell[4], Lynne D. Talley[5], Rik Wanninkhof[6], Nancy L. Williams[7], and Jorge L. Sarmiento[3]

Key Points:
- Measurements from biogeochemical profiling floats were used to estimate air-sea fluxes of carbon dioxide
- Significant annual net outgassing

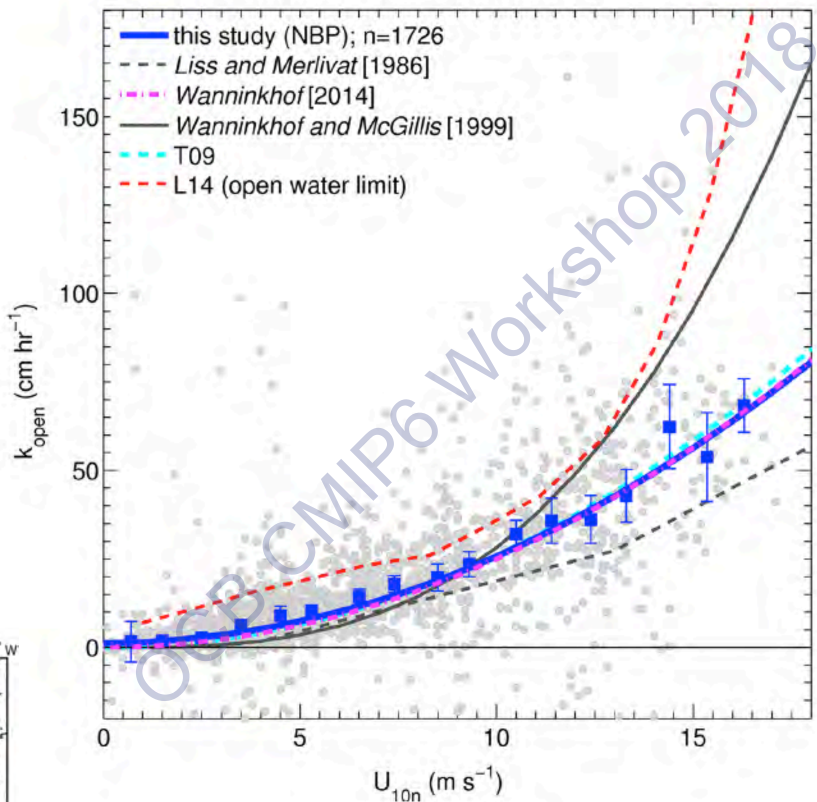
"Although the 0.36 Pg C yr$^{-1}$ difference in the ASZ stands out, the float-based estimates are higher than the ship-based fluxes in almost all regions. On average, the float-based estimates were 3.6±3.4µatm higher than the ship-based $pCO_2$"
Gray et al, (2018 )

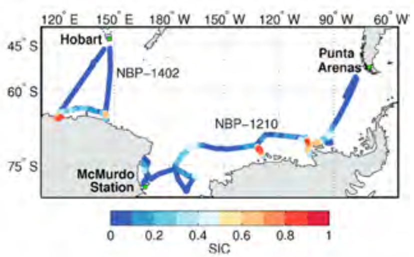
- ➢ Fully characterize all sensors and calculations
- ➢ Be sure measurement/estimate is "fit for purpose"

# Improvements in the input parameters, k

$k_{660} = 0.251 \langle u^2 \rangle$

Functionality seems to "work" and overall agreement with (good) direct flux measurements




**Geophysical Research Letters**

**RESEARCH LETTER**
10.1002/2016GL069581

**Key Points:**
- First unattended eddy covariance $CO_2$ fluxes in Southern Ocean and Antarctic marginal ice zone
- Quadratic dependence of open ocean gas transfer velocity on wind speed

## Air-sea exchange of carbon dioxide in the Southern Ocean and Antarctic marginal ice zone

**Brian J. Butterworth**[1] **and Scott D. Miller**[1]

[1]Atmospheric Sciences Research Center, State University of New York at Albany, Albany, New York, USA

# Improvements in the input parameters, k

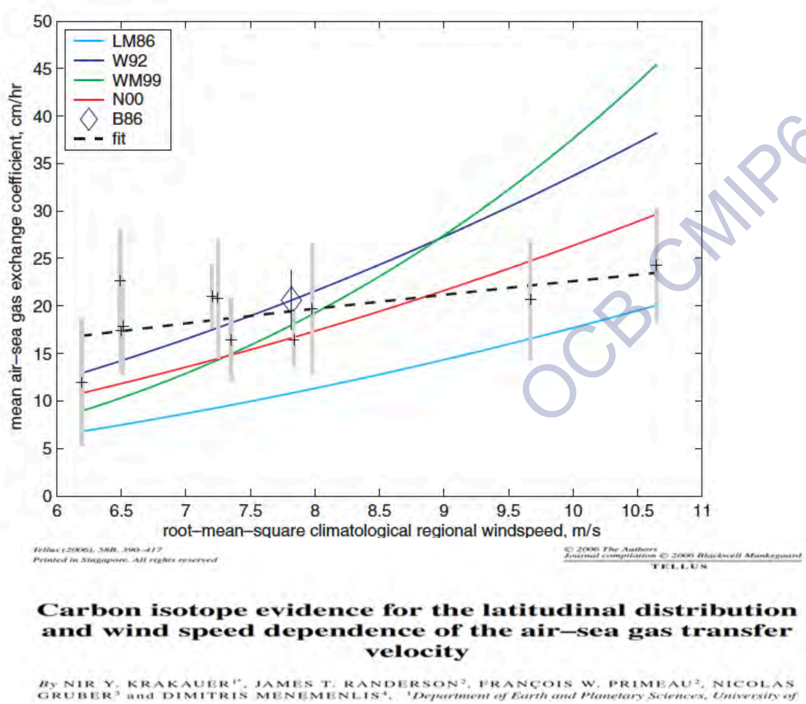
$k_{660} = 0.251 \langle u^2 \rangle$

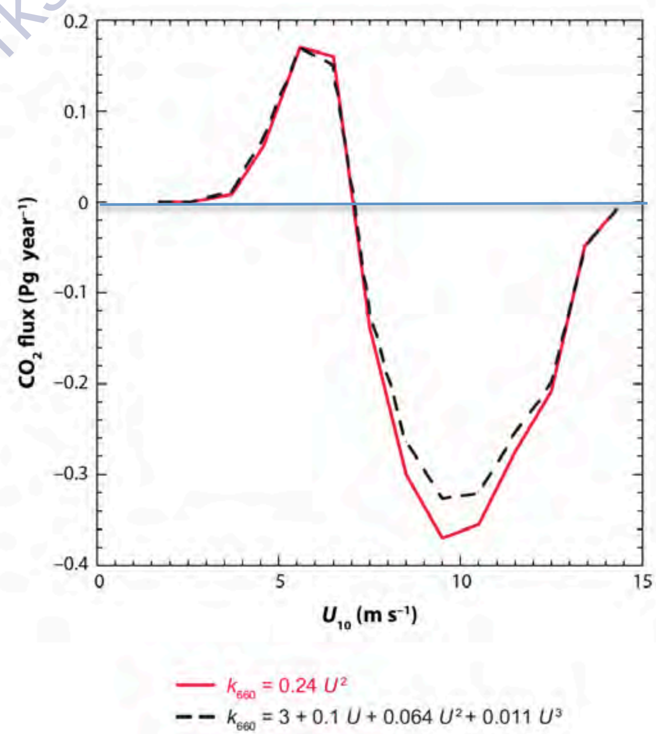
Relationship is based on fitting a parameterization with wind to match global $^{14}C$ inventory

Not an unique solution:

"*Results support a linear or lower increase of gas transfer velocity with wind speed in the global ocean (best-fit exponent: 0.5 ± 0.4; global mean rate: 20 ± 3 cm hr$^{-1}$ at a Schmidt number of 660)*" Krakauer et al., 2006





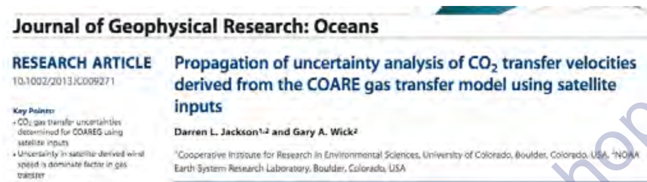



# Improvements in the input parameters, wind

$$k_{660} = 0.251 \langle u^2 \rangle$$

"Uncertainty in [satellite] derived wind speed is the dominant uncertainty in k "

Jackson and Wick, 2014


Journal of Geophysical Research: Oceans

RESEARCH ARTICLE
10.1002/2013JC009271

Key Points:
- $CO_2$ gas transfer uncertainties determined for COAREG using satellite inputs
- Uncertainty in satellite derived wind speed is dominate factor in gas transfer

**Propagation of uncertainty analysis of $CO_2$ transfer velocities derived from the COARE gas transfer model using satellite inputs**

Darren L. Jackson[1,2] and Gary A. Wick[2]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA, [2]NOAA Earth System Research Laboratory, Boulder, Colorado, USA

Significance differences in global wind products:

Wind products:

- CCMP
- ECWMF
- NCEP
- Coastal wind product- problems/ land/see breeze
- Satellite estimates [(passive/active) radiometry]

Notably, NCEP-2 and some coastal wind products are  quite different

- $k_{660} = 0.251 \langle u^2 \rangle$ is "tuned" to CCMP (6-hr, ¼˚) resolution

# Improvements in the input parameters, k

More sophisticated approaches related to boundary layer turbulence and bubble enhancements

[15] The parameterization relies on matching of the water and air flux expressions (both of which are expressed in terms of molecular and turbulent components), in addition to attending to the details of the molecular layer transfer on the water side. The final expression is quite general, and can be applied to any gas:

$$Fs = \frac{A_{sol} u_{*a} \Delta px}{\sqrt{\rho w/\rho a}\left[hwS_{cw}^{1/2} + \ln(zw/\delta w)/\kappa\right] + \alpha\left[haS_{ca}^{1/2} + C_d^{1/2} - 5 + \ln(S_{ca})/(2\kappa)\right]}, \quad (3)$$

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, C08S11, doi:10.1029/2003JC001831, 2004

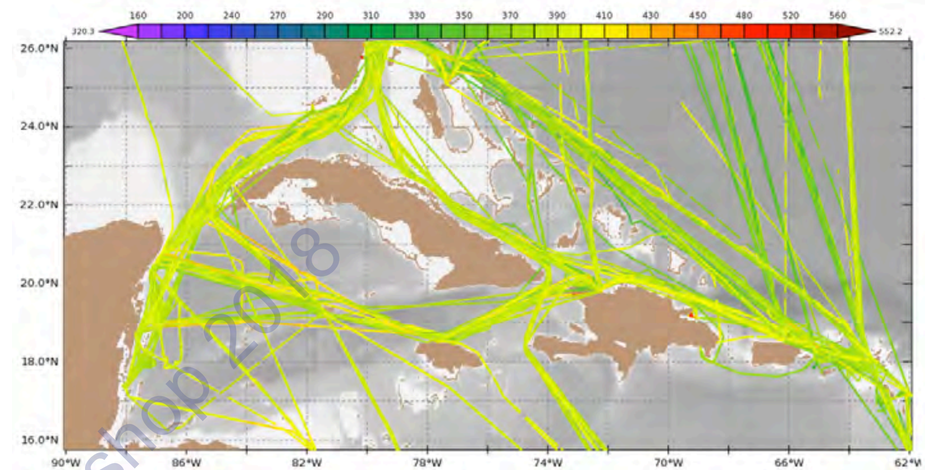
**Evaluation of the National Oceanic and Atmospheric Administration/ Coupled-Ocean Atmospheric Response Experiment (NOAA/COARE) air-sea gas transfer parameterization using GasEx data**

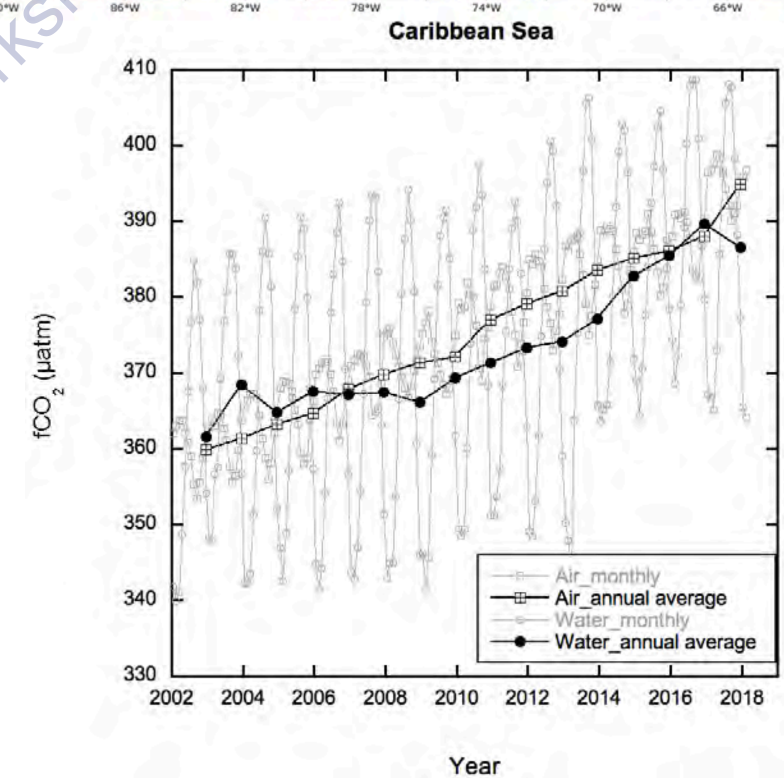
Jeffrey E. Hare,[1,2] Christopher W. Fairall,[3] Wade R. McGillis,[4] James B. Edson,[4]
Brian Ward,[4] and Rik Wanninkhof[5]

- Use Ocean Model Intercomparison Project (OMIP) to asses dependency and/ or other (physically based) algorithms (COARE-G)

# Comparison with regional time series

Weekly time series from 2002-2018
500 cruises




Trend 2002-2018:
Air: 2.2 µatm $yr^{-1}$
Water: 1.7 µatm $yr^{-1}$

- Can models reproduce the observations?

# Take home messages

- There is a mismatch between fluxes and inventories of 0.8 Pg C $yr^{-1}$
- Check if models reproduce seasonal and interannual variability
- Use models in diagnostic mode to address issues with k parameterization
- Easy “fixes” in models:
  - Use improved MBL-$XCO_2$ product
  - Correct for skin temperature
  - Consistent use of wind products