Air-Sea CO₂ Fluxes, the Indian Ocean, and SOLAS

Land, Air, Water Carbon Cycle
Results using a decade of remotely sensed SST and winds combined with ($\partial pCO_{2SW}/\partial SST$) relationships

Produced by Joaquin Trinanes, NOAA Coastwatch, and Rik Wanninkhof, NOAA/AOML/OCD

Climatology: Takahashi et al 2002

Method: Lee et al, 1998; Park et al, 2006; Cosca et al. 2003
Structure

- International SOLAS is Sponsored by SCOR, IGBP, and WCRP
- IGBP Core Project
- Part of the Earth System Science Partnership
Goals of SOLAS

To achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and of how this coupled system affects and is affected by climate, weather, and environmental change.

• FOCUS 1 – Biogeochemical Interactions and Feedbacks Between Ocean and Atmosphere (Fate, feedback and transport of reactive gases Atmospheric/Ocean coupling).


• FOCUS 3 – Air-Sea Flux of CO₂ and Other Long-Lived Radiatively Active Gases (Carbon dioxide and methane and ....N₂O)
SOLAS Scientific Steering Committee
Chair: Peter Liss
17 members

Science Plan and Implementation Strategy

WORKING GROUPS

Focus 1: Biogeochemical Processes
Focus 2: Physical Exchange Processes
Focus 3: Exchange of Greenhouse Gases
Model and Data Management Group

SOLAS SCIENTISTS

www.solas-int.org
SOLAS FOCUS-2

[Diagram showing various environmental and oceanographic processes involving carbon dioxide exchange, wave breaking, Langmuir circulations, aerosols, visible and UV radiation, infrared radiation, wave stress, evaporation, precipitation, DMS flux, near surface shear and microbreaking, and internal wave radiation.]
Some Historical Laboratory Estimates of Gas Exchange

\[ F_{a/w} = k [\Delta C]_{\text{air-water}} \]

- Merlivat and Memery (1983)
- Jaehne et al. (1985)
- Broecker et al. (1978), Siems (1980)
- Wanninkhof and Bliven (1991)
- Wanninkhof et al. (1991)
- Ledwell (1982)
- Wanninkhof and Bliven (1991)
- CO₂ Profiles at NASA WALLOPS
Micrometeorological Approaches

Profile Method or K-theory

\[-u_*^2 = \frac{\tau}{\rho}, \quad -u_* t_* = \frac{H_s}{\rho C_p}, \quad -u_* q_* = \frac{H_l}{\rho \lambda}\]

variables are given by Monin-Obhukov similarity theory

\[
\frac{\kappa z}{u_*} \frac{\partial \bar{u}}{\partial z} = \phi_m ; \quad \frac{\kappa z}{t_*} \frac{\partial \bar{t}}{\partial z} = \phi_i ; \quad \frac{\kappa z}{q_*} \frac{\partial \bar{q}}{\partial z} = \phi_q
\]

\[
\phi_m = (1 - \alpha \zeta)^{-\beta} \quad \text{for } \zeta < 0 \quad \text{unstable boundary layer}
\]

\[
\phi_m = (1 + \gamma \zeta) \quad \text{for } \zeta > 0 \quad \text{stable boundary layer}
\]

\[
\phi_t = \phi_q = \phi_m^2 \quad \text{for } \zeta < 0 ; \quad \phi_i = \phi_q = \phi_m \quad \text{for } \zeta > 0
\]

A GUIDE TO MAKING CLIMATE QUALITY METEOROLOGICAL AND FLUX MEASUREMENTS AT SEA, Bradley and Fairall, 2006
Micrometeorological Approaches

Direct Covariance or Eddy Correlation

\[
\frac{\partial c}{\partial t} + \vec{\nabla}_h c \cdot \vec{U}_h = - \frac{\partial (- D_c \partial c / \partial z + \langle w' c' \rangle)}{\partial z} + Q_c \quad \frac{\partial c}{\partial z} = - \frac{\langle w' c' \rangle}{u_* \kappa_z} \Phi_c \left( \frac{z}{L} \right)
\]

- **Momentum**: \( \tau = - \rho w u = \rho u_*^2 = \rho C_D \left( U_a - U_s \right)^2 \) \( \kappa_z \frac{\partial U}{\partial z} = \varphi_M(\zeta) \)
- **Sensible**: \( H = \rho c_p \overline{w \theta} = - \rho c_p u_* \theta_* = \rho c_p U C_H \left( T_s - T_a \right) \) \( \kappa_z \frac{\partial T}{\theta_* \partial z} = \varphi_H(\zeta) \)
- **Latent**: \( E = \rho L_E \overline{w q} = - \rho L_E u_* q_* = \rho L_E U C_E \left( Q_s - Q_a \right) \) \( \kappa_z \frac{\partial Q}{q_* \partial z} = \varphi_Q(\zeta) \)
- **Gas** \( F = \overline{w c} = - u_* c_* = U C_G \left( C_w - C_a \right) = k \Delta C \) \( \kappa_z \frac{\partial C}{c_* \partial z} = \varphi_G(\zeta) \)

Direct covariance \hspace{1cm} \text{bulk methods}

K-theory profiles
NOAA ship Ronald H. Brown included underway pCO$_2$ systems; micrometeorological fluxes and means; aspirated temperature, water-vapor, and carbon dioxide; and radiometric measurements providing heat fluxes and sea surface skin temperatures.

ASIS (air-sea interaction spar buoy) provided the centroid for the Lagrangian experiment. Both meteorological and oceanic measurements were performed on the autonomous platform.

SPIP (surface processes instrument platform) episodic deployments included profiles of windspeed, temperature, water-vapor, carbon dioxide in addition to subsurface measurements.
Floating Laboratory Instrument Platform (FLIP) too big for shallow water
Naturally Occurring Variability

\[ \sigma = 0.278 \text{ g/kg} \]

\[ \sigma = 0.085 \text{ g/kg} \]
Atmospheric CO₂ Boundary Layer

Turbulent Transfer - DC

\[ \langle w'c' \rangle = \frac{\langle u'w' \rangle^{1/2}}{\phi_c(\xi)} \kappa \frac{\partial c}{\partial z} \]

K-theory
Global Surface Ocean Carbon Dioxide

December

Seawater $\text{pCO}_2$ (uatm) at SST
Meteorological Approaches

![Graph showing data points and lines representing various meteorological approaches, with labels for each dataset such as GasEx-98 direct covariance, GasEx-98 dual tracer, Nightingale et al. 2000, GasEx-2001 direct covariance, Liss-Merlivat 1986, Wanninkhof 1992, McGillis et al. 2001, and GasEx-2001. The graph plots k660 (cm/hr) against U10N (m/s).]
\[
\frac{dF}{dT} = k \frac{\partial (C_s - C_w)}{\partial T} + (C_s - C_w) \frac{\partial k}{\partial T}
\]
US/NL/UK Collaboration at the Army Field Research Facility – Kitty Hawk, North Carolina
Air-Water Flux Tower

3.5 km offshore; Cabled Data and Power; 18-meter water depth; 20-meter height. Coupled air-water BL.
Surface Processes Instrument Platform (SPIP) and R/V Catch the Joy
Compass-Float for Autonomous Surface Measurements
River Surface Turbulent Kinetic Energy (TKE) Dissipation

Hudson River Estuary

TKE (W/kg)

Tidal Velocity (m/s)

Wind Speed (m/s)

$1 \times 10^5$ $1.5 \times 10^5$
including interior shallow, tidal, stratified effects
wave frequency versus wavenumber
Bock and Hara, 1993

surface films, waves and turbulence

clean

 surfactants
The Role of Surface Films

\[ \text{FLUX}_{\text{air-water}} = k [\Delta C]_{\text{air-water}} \]
Solubility, waves, mass diffusivity are particular for CO₂

**Figure.** The transfer velocity of carbon dioxide and dimethyl sulphide versus wind speed, based on the models of Woolf (1997, 2005). Direct transfer is shown by the dashed lines; CO₂ and DMS direct transfer are in a ratio of 1.3:1. Total (direct + bubble-mediated) transfer is shown by the full lines; CO₂ and DMS bubble-mediated transfer are in a ratio of 6:1. The set of curves represent the range of values that results from different wave development; each curve corresponds to a particular fetch.
Seawater spume, jet drops, and films drops evaporate. The adjustment in the carbonate system increase the droplets pCO₂ and is a source for atmospheric CO₂ if the drops are deposited back to the sea surface. (Dickson, Veron, Fairall, de Leeuw, Andreas, Banner)
Quantifying the correct CO₂ Flux

- Proxy techniques not measuring CO₂
- Other gases
- Heat
- Laboratory tanks
- Mass balances and quantifying inputs
- Tracers
- Wind
- Momentum
- Turbulence

- Schmidt No.
- Solubility
- Surfactants
- Variable, non-steady, winds
- Waves, microscale, fetch
- Bubbles
- Spray
- Waves
- Deposition
- Rain
- Chemical Enhancement
- Biology
- Carbonic Anyhydrase
- Neustons
- Ice
Existing and planned NOAA pCO$_2$ moorings are designed to build on the OceanSITES reference flux sites.
THE END

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