

Gaining insight into the interannual variability of air-sea CO₂ fluxes using satellite observation

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Method: We compute the contribution of thermodynamics, physical mixing and marine biological export production to the interannual variability of CO₂ (δFCO_2) using satellite observations from:

$$\delta FCO_2 = \delta FCO_2 [\text{thermodynamics}] + \delta FCO_2 [\text{mixing}] + \delta FCO_2 [\text{biology}]$$

$$\delta FCO_2 [\text{thermodynamics}] = kg \cdot \partial pCO_2 / \partial T \cdot \delta T$$

$$\delta FCO_2 [\text{mixing}] = kg \cdot \partial pCO_2 / \partial DIC \cdot \partial DIC / \partial z \cdot \delta MLD$$

$$\delta FCO_2 [\text{biology}] = PP \cdot \epsilon \text{ratio}$$

where kg is the wind speed dependant gas exchange coefficient, pCO_2 is the partial pressure of CO₂ in the ocean, T is temperature, DIC is dissolved inorganic carbon, MLD the mixed layer depth, PP the primary production and ϵ ratio the fraction of PP that is exported below the mixed layer. We estimate these terms poleward of 15°, for each month where satellite observations of SST (sea surface temperature), SSH (sea surface height) and chl a are available, according to the formulation described in Table 1. We then interpolate the anomalies in space to account for missing data.

Table 1: Formulation and data

Term	Formulation	Data
$\partial pCO_2 / \partial T$	4% per °C	Takahashi et al., 1993
kg	Wanninkhof (1992) based on daily wind speed	ERS satellite
$\partial DIC / \partial z$	Derivative computed around the winter MLD	Goyet et al., 2000
$\partial pCO_2 / \partial DIC$	Sarmiento and Gruber based on DIC and alkalinity	Goyet et al., 2000
MLD	Shallowest depth where $\rho - \rho_0 < 0.125$ kg/L	World Ocean Atlas 1994
δMLD	See details below	TOPEX/Poseidon SSH
PP	Behrenfeld and Falkowski (1997)	SeaWiFS chl a and T
ϵ ratio	Laws et al. 2000	PP and T

The δMLD is computed by assuming that interannual variations in sea surface height (SSH) are caused by changes in heat content following $\delta \text{Heat} = \rho_0 / \alpha \cdot \delta \text{SSH}$, where ρ_0 is the heat capacity and α is the thermal expansion. δT as a function of depth is estimated by assuming δHeat takes the same form as the seasonal penetration of heat in the ocean. The new MLD is then calculated using the formulation above. Our method assumes that the interannual variability in currents have a small impact on SSH compared to that in heat content when integrating over large regions (1000 km) and for variations of a year or longer.

Table 2: Satellite data used.

Term	Coverage	Data
SST	1x1 degree, 1982-today	Reynolds et al., 1994
Chlorophyll a	0.7x0.7 degree, Sept 1997-today	SeaWiFS, Hooker and McClain 2000
SSH	1x1.5 degree, Oct 1992-today	CNES, Cabanes et al., 2000
SSH	4x1.5 degree, Oct 1992-today	NOAA, Cheney et al., 1994
Wind speed	1x1 degree, Jan 1992-today	ERS

Abstract: While estimates of interannual air-sea CO₂ flux variability in the tropics tend to converge, the role of the mid and high-latitude oceans is poorly understood. Most of the interannual variability in air-sea CO₂ flux at these latitudes is caused by variations in ocean mixing and associated entrainment, in biological export production, in warming or cooling of surface waters, and in gas exchange velocity. Each of these processes leaves a signature that has been observed by satellite for at least five years. We present a first attempt to quantify these processes and their contribution to air-sea CO₂ flux variability in the extra-tropics.

Results:

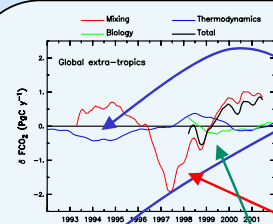


Figure 1: Interannual variability of the sea-air CO₂ flux (PgC/y) estimated using satellite observations for the extra-tropics (poleward of 15°). Negative values represent a flux anomaly from the atmosphere to the ocean.

SST variations of ± 0.3 °C drive δFCO_2 of ± 0.5 PgC/y. δFCO_2 is from the atmosphere to the ocean when SSTs are cold.

From SSH variations of ± 2 cm we estimate variations in MLD of ± 10 -15 m at high latitude, which drive δFCO_2 of ± 1.5 PgC/y. According to our assumptions, high SSH reflects an increased heat content and thus stratification of the ocean surface. The estimation of the MLD variability and the associated carbon entrainment is the most uncertain part of our analysis.

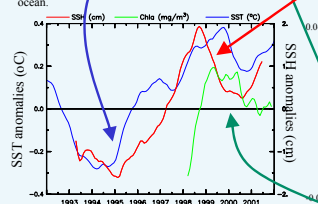


Figure 2: Interannual variability of observed SST (°C), SSH (cm) and chl a (mg/m³) averaged over the extra-tropics (poleward of 15°).

From chl a variations of ± 0.04 mg/m³ we estimate δFCO_2 of ± 0.3 PgC/y. The variability in primary production is ± 1.5 PgC/y, and the ϵ ratio is 0.3 on average over the extra-tropics. CO₂ flux anomaly is from the atmosphere to the ocean when the chl a anomalies are high.

High latitudes dominate the variability in δFCO_2

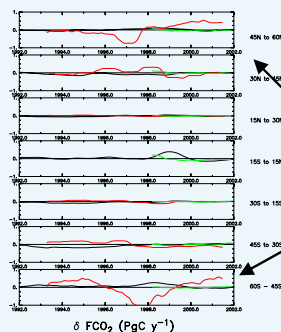


Figure 3: Zonal mean of the different processes.

Discussion:

What controls the variability in air-sea CO₂ flux in the extra-tropics? The primary source of variability is that associated with the entrainment of carbon from the intermediate ocean by physical mixing. Variability caused by the direct impact of warming or cooling are generally in the opposite direction, counteracting roughly 1/4 to 1/2 of the variability caused by ocean mixing. Variability in marine export production are the same order of magnitude than the thermodynamic variations, but do not show correlations with the other processes over large scales.

What is the uncertainty? For this preliminary analysis, the uncertainty is at least as large as the variability itself. Our method needs to be validated before the amplitude of our estimated variations can be trusted at all. Our estimate of the MLD variations and of the carbon entrainment is particularly critical for this study and most difficult to assess.

How does this compare to the equatorial Pacific? In this preliminary analysis, variations are of the order of ± 0.5 PgC/y when integrated over an entire hemisphere. This is of the same order of magnitude as the observed variations caused by El Niño events in the equatorial Pacific (Feely et al., 1999).

Why is the Southern Ocean so variable? First the ocean area between 30° and 65° is twice as large in the south than in the north. Second a large part of the variations in the north and sub-tropical Pacific cancel each other (see figure 3). Fourth, the gradient of carbon with depth ($\partial DIC / \partial z$) in the ocean is steeper in the south compared to the north Atlantic. Finally, $\partial pCO_2 / \partial DIC$ is larger. Although there is a large uncertainty in our current estimate, the pre-dominance of the Southern Ocean appears to be robust.

What role for marine biology? The short-term impact of changes in export production is very small. However, two-third of the vertical gradient in DIC ($\partial DIC / \partial z$) is controlled by the biological pump. Models that estimate the impact of climate change on CO₂ fluxes must predict accurate vertical gradients to estimate the impact of physical mixing.

What are our main assumptions? (1) that the interannual variability in currents, water fluxes and alkalinity are small when integrated over large region (1000 km or more) and (2) that missing values can be interpolated after the anomalies are computed.

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