Optimal network design to detect spatial patterns and variability of ocean carbon sources and sinks from underway surface pCO_2 measurements

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1. PROJECT SUMMARY

In agreement with the Intergovernmental Panel on Climate Change (IPCC), the *Second Report on the Adequacy of the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC)* concludes that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. One continuing aspect of the effort to redress the identified deficiency has been to expand the surface ocean pCO_2 measurement program in order to quantify our understanding of the seasonal and interannnual variability of air-sea CO_2 fluxes in the world oceans. While there is a reasonably good understanding of the major sources and sinks of CO_2 based on the sea surface pCO_2 climatology developed by Takahashi et al. (2002), the motivation for this study is to produce the optimal global pCO_2 sampling network design to provide a region-by-region estimate of the sampling required to quantify fluxes of CO_2 to the nearest 0.1 Pg C/year (Figure 1), updating and expanding the preliminary effort of Sweeney et al. (2002). The Surface Ocean CO_2 Atlas Project (SOCAT) has decided to standardize all measurements to fCO_2 (IOCCP Report #9) and we have done the same, using the methods described in Dickson and Goyet (1994) from the measured sea surface temperature and pressure.

2. ACCOMPLISHMENTS

1) We have processed the Takahashi pCO_2 dataset with over **4 million** measurements and calculated fCO_2 at the reported sea surface temperature (SST) and sea level pressure (SLP) values from those data. The atmospheric data comes from the GlobalView xCO_2 dataset interpolated to the latitude and time of each individual measurement. These xCO_2 values were then converted at the same SST and SLP into fCO_2 values for the atmosphere. The atmospheric value was subtracted from the oceanic value to determine the $DfCO_2$. The annual mean fluxes were calculated using the observed "long term mean" wind speeds from NCEP, and the observed sea surface temperature and salinity from the World Ocean Atlas (2001, Conkwright et al.) according to the formulas in Wanninkhof (1992). We have reanalyzed our results using the new gas-transfer velocity from Sweeney et al. (2006). This has resulted in a 33% reduction in the calculated fluxes, leading to a substantial increase in the target accuracy necessary to estimate each region to within 0.1 Pg. (Figure 1, Table 1).

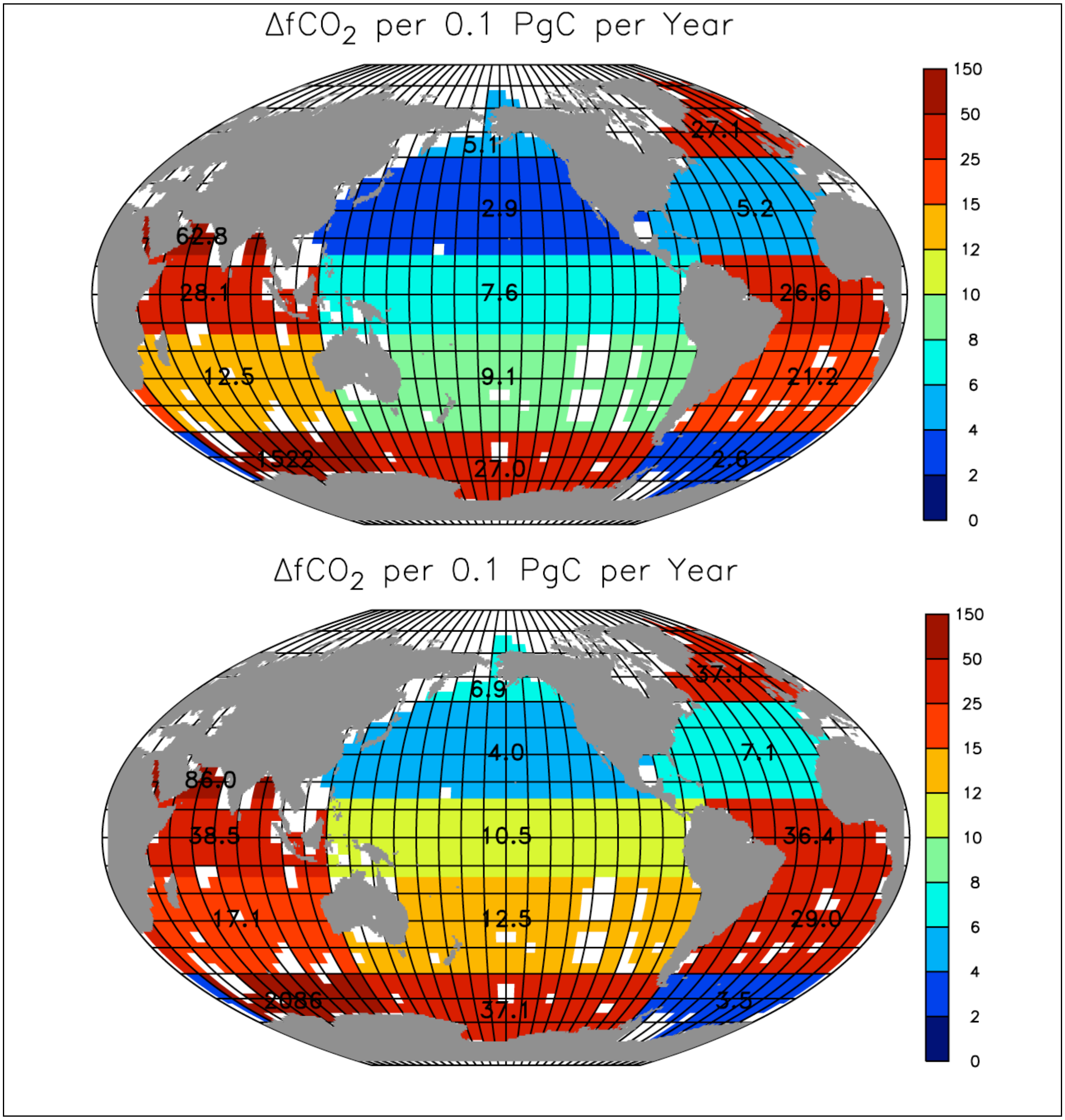

Figure 1. Target DfCO$_2$ to estimate a regional CO_2 flux within ± 0.1Pg-C/yr for the major oceanic regions. Fluxes in the top panel use the Wanninkhof 1992 wind speed/gas exchange relationship, while those in the lower panel use the Bomb-^{14}C derived relationship from Sweeney et al. (2006) that is 30% lower, resulting in larger tolerances to achieve the desired ±0.1 Pg accuracy.

Table 1. Mean annual sea-air fCO_2 difference, annual flux and the sea-air fCO_2 required for 0.1 Pg C flux. All the values are from the assembled fCO_2 database. The long-term mean wind speed data from NCEP and the wind speed dependence of gas transfer coefficient of Wanninkhof (1992) have been used.

Ocean Regions	Ocean Area (10^6 km^2)	Average $DfCO_2$ (matm)	Annual Flux (PgC/yr)	$DfCO_2$ per 0.1 PgC/yr uptake
Polar North Atlantic	9.3	-31.8	-0.12	27.1
Temperate North Atlantic	28.0	-10.7	-0.21	5.2
Equatorial Atlantic	19.1	17.4	0.07	26.6
Temperate South Atlantic	26.2	-15.2	-0.07	21.2
Polar South Atlantic	12.2	-0.1	< 0.01	2.6
Polar North Pacific	5.3	2.1	0.04	5.1
Temperate North Pacific	46.8	-12.5	-0.43	2.9
Equatorial Pacific	54.8	29.9	0.39	7.6
Temperate South Pacific	48.4	-16.6	-0.18	9.1
Polar South Pacific	22.9	3.4	0.01	27.0
Temperate North Indian	4.6	30.2	0.05	62.8
Equatorial Indian	21.6	17.9	0.06	28.1
Temperate South Indian	28.9	-24.6	-0.20	12.5
Polar South Indian	9.0	3.0	<< 0.01	1522
Global Oceans	337.1	-2.9	-0.6	0.5

Table 2. Mean annual sea-air fCO_2 difference, annual flux and the sea-air fCO_2 required for 0.1 Pg C flux. As in Table 1, but using the wind speed dependence of gas transfer coefficient of Sweeney et al. (2006).

Ocean Regions	Ocean Area (10^6 km^2)	Average $DfCO_2$ (matm)	Annual Flux (PgC/yr)	$DfCO_2$ per 0.1 PgC/yr uptake
Polar North Atlantic	9.3	-31.8	-0.09	37.1
Temperate North Atlantic	28.0	-10.7	-0.15	7.1
Equatorial Atlantic	19.1	17.4	0.05	36.4
Temperate South Atlantic	26.2	-15.2	-0.05	29.0
Polar South Atlantic	12.2	-0.1	-0.03	3.5
Polar North Pacific	5.3	2.1	0.03	6.9
Temperate North Pacific	46.8	-12.5	-0.31	4.0
Equatorial Pacific	54.8	29.9	0.29	10.5
Temperate South Pacific	48.4	-16.6	-0.13	12.5
Polar South Pacific	22.9	3.4	0.01	37.1
Temperate North Indian	4.6	30.2	0.04	86.0
Equatorial Indian	21.6	17.9	0.05	38.5
Temperate South Indian	28.9	-24.6	-0.14	17.1
Polar South Indian	9.0	3.0	<< 0.01	2086
Global Oceans	337.1	-2.9	-0.29	0.6

2) We have quantified the variability in surface pCO_2 (Figure 2) and determined which times in the annual cycle surface pCO_2 and associated air-sea fluxes are most variable and therefore need more sampling and/or sampling at a specific time of year (Figure 3). Comparing both panels, there are regions with highly variable fCO_2 and a low net flux (such as in and around the Ross Sea) as well as regions with fairly low air/sea variability but significant flux (downstream from the Agulhas Retroflection for example)

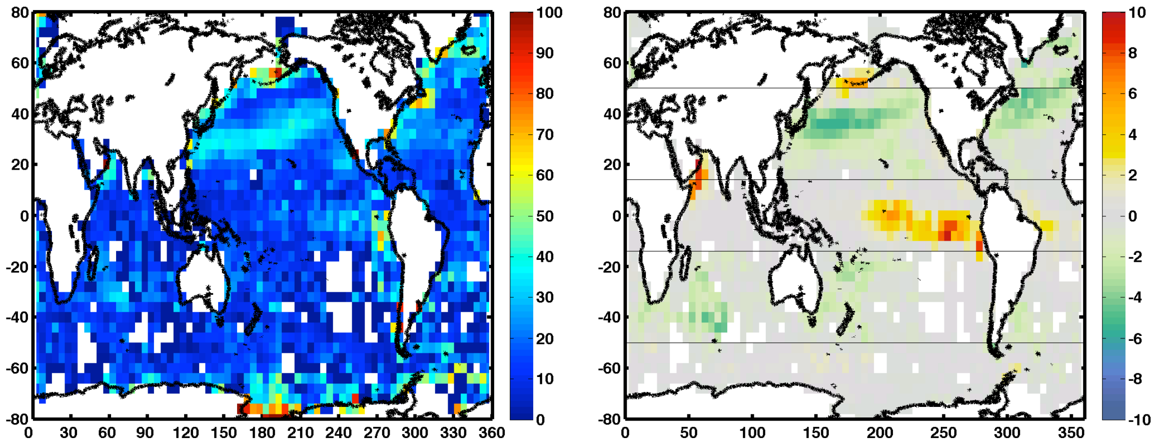

Figure 2. (left) The standard deviation of the monthly mean $DfCO_2$ for each bin indicates the amplitude of the annual cycle there; (right) Annual flux (in Tg, 10^{12} g) from available measurements -- the large expanse of gray indicates large undersampled areas, representing a large fraction of the assumed air/sea carbon flux. The net flux in this panel is 0.43 Pg into the ocean.

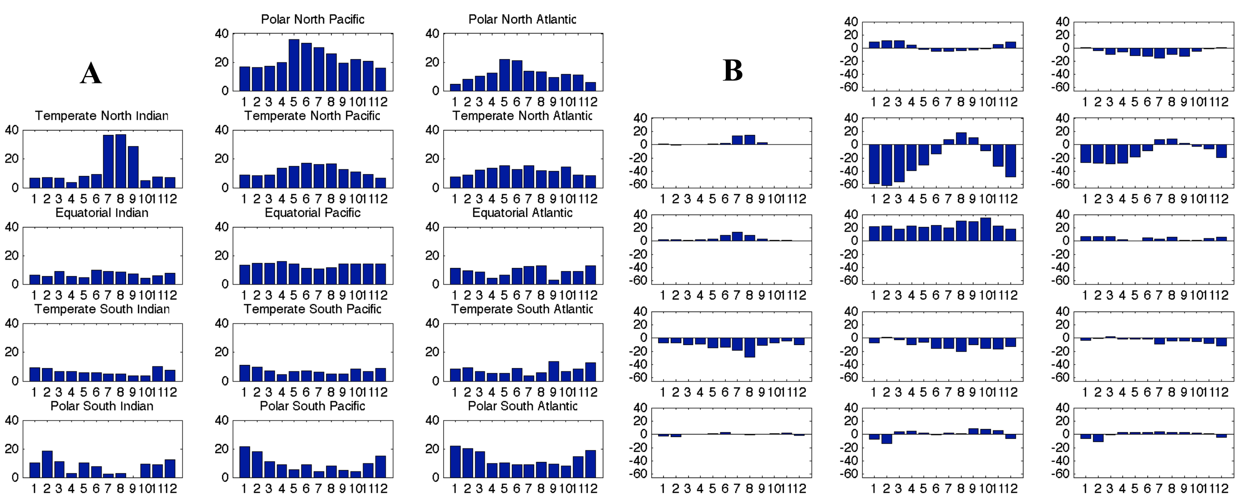

Figure 3. A) The monthly standard deviation of $DfCO_2$ for each region; B) The monthly flux (in Tg) from each region, positive is out of the ocean. Note the more pronounced seasonal cycle in the poleward boxes, and the generally larger variance in the Pacific sector.

3) A spatial *decorrelation length scale* analysis of the database was performed. This analysis uses a simple approach to resampling a series of data that assumes that a *linear interpolation* of the data set represents the true data set. The interpolated data is then resampled by the INDEX at regular intervals. The subsampled data (equal number of samples away from each other) is then linearly interpolated and resampled at the original sampling resolution from which a comparison

is made. This routine is meant to estimate the sample spacing needed to get a standard deviation within 5% of the range in the original data.

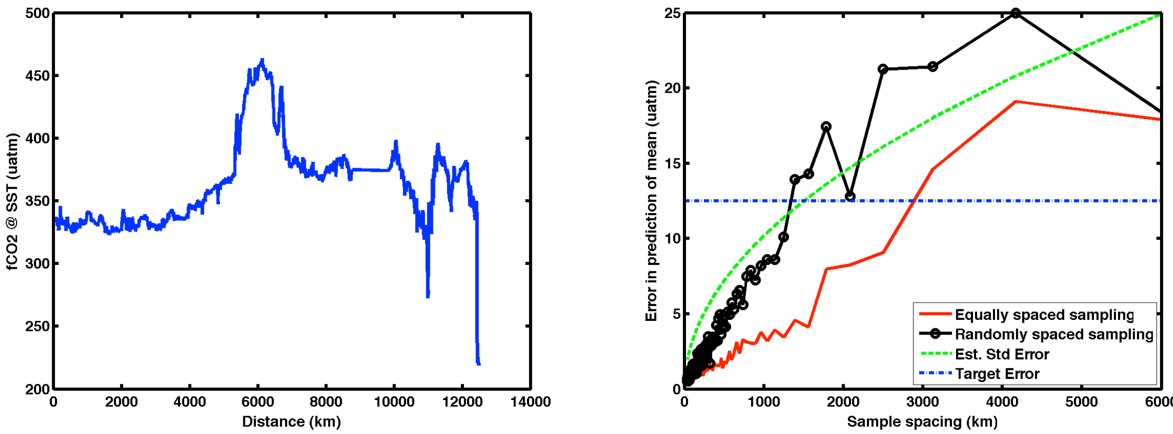

Figure 4. (left) The measured fCO_2 for one of the cruises in the database (0304 from New Zealand to Alaska); (right) the decorrelation length-scale analysis for this cruise. In (b) the standard error in the mean is indicated in green, sampling with equal space-intervals in red, sampling with randomly spaced intervals in black with circles, and the blue line indicates the target ΔfCO_2 needed to estimate the flux of CO_2 to the nearest ±0.1 Pg of C/yr in the temperate South Pacific. The calculated length scale in this example is about 3000km.

As an example, a cruise track (0304) is presented, along with the results that the method provides for estimating the observed variability within the data based on regularly spaced samples. For this cruise, randomly spaced subsamples at ~1200km and regularly spaced subsamples at ~3000km approximate the observed variability in the data to with the 5% necessary, in order to estimate the total air-sea flux for this region to within ±0.1 Pg.

The analysis of the length scales in the assembled dataset on the 4° by 5° grid is presented as Figure 5. One essential caveat to the length and time scale analysis is that wind speeds are highly variable and using wind speeds averaged over months will bias the calculated gas exchange coefficient. The figure below represents a maximum spacing applicable to wind speeds averaged over months rather than those averaged over a shorter time (hourly) period.

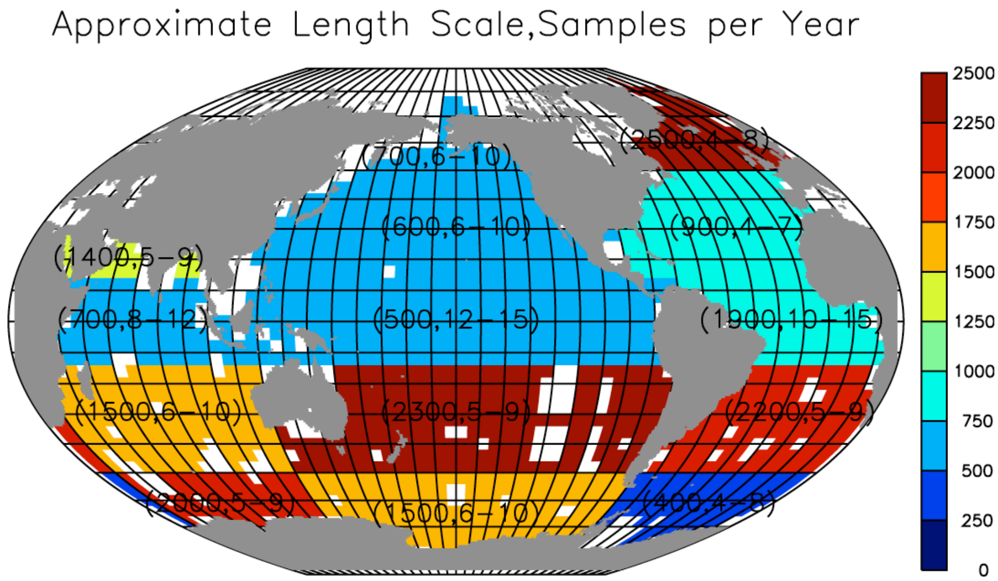

Figure 5. Calculated length-scale and frequency per year for regularly spaced measurements necessary to capture the observed variability in order to estimate the total regional flux of CO_2 to within ±0.1 Pg.

4) The temporal *decorrelation length scale* analysis of the database uses the same routine as for the spatial decorrelation. Each of the bins is treated as an undersampled time series. All measurements in a given bin were sorted according to the Julian day and the routine determines the number of measurements per year necessary to estimate the total regional flux within 5%. In general, the number of samples required in each region is between 4 and 15. Comparing these results to those presented by Sweeney et al. shows good agreement.

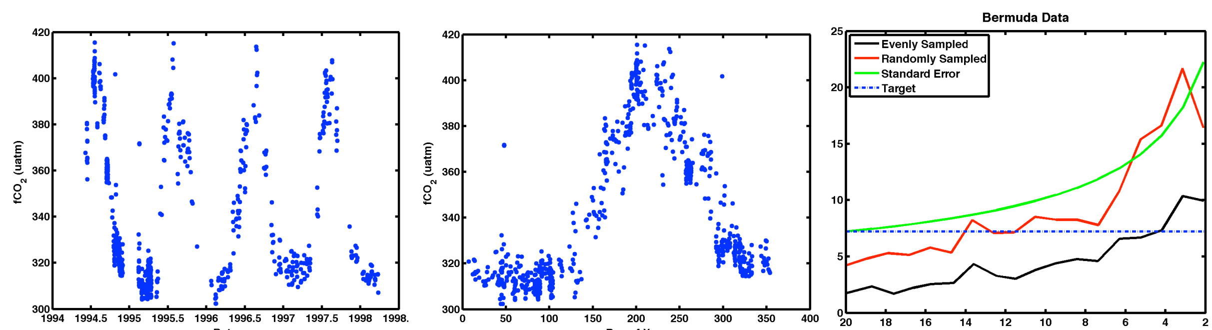

Figure 6. (left) The measured fCO_2 from the Bermuda Biological Research Station; (center) the same measurements as a function of day of year; (right) the decorrelation time-scale analysis for these data. On the right, the standard error in the mean is indicated in green, sampling with equal space-intervals in red, sampling with randomly spaced intervals in black with circles, and the blue line indicates the target ΔfCO_2 needed to estimate the flux of CO_2 to the nearest ±0.1 Pg of C/yr in the temperate North Atlantic. The calculated number of observations per year is ~4 for regularly spaced measurements and 12-15 for irregularly spaced measurements.