Appendix E

Errors in the Sea-Air CO$_2$ Flux Due to Time-Space Ocean Sampling Strategies for Sea-Air pCO$_2$ Difference

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E.1 Objective

One of the means for estimating CO$_2$ flux across the sea surface is to measure the sea-air pCO$_2$ difference (ΔpCO$_2$) and multiply this quantity with the CO$_2$ gas transfer coefficient that may be estimated using a measurable parameter such as wind speed and surface roughness. Therefore, it is important to understand how the estimated CO$_2$ flux across the sea surface may be affected by time-space sampling frequencies of surface water pCO$_2$ measurements over the global oceans. In our previous report presented at the Boulder Workshop (Sweeney *et al.*, 2002), we analyzed the time-space variability of several surface water pCO$_2$ data sets (which contain high-frequency variability components) obtained at fixed stations as well as along long transects over various oceanic regimes. The results of the analysis have led to the conclusion that, to obtain a precision of ±0.1 Pg C/yr over the temperate regions of the North Pacific and North Atlantic, the surface water pCO$_2$ over these areas must be sampled 7 to 10 times a year with evenly spaced measurements ranging from 200 km to 2,000 km apart (or 2° to 20° apart). Further, for a given number of measurements, sampling schedules with equally spaced time and space intervals are more effective than randomly spaced schedules. To test the validity of the analysis, we have assumed a known distribution of ΔpCO$_2$ over the global oceans and sampled it with various space-time intervals. The global and regional CO$_2$ flux values have been computed under different sampling schedules and compared with the original values. The results should represent a more realistic test for various sampling strategies. In this report, we summarize the findings of our study.

E.2 Method

For this purpose, the climatological mean monthly distributions of sea-air pCO$_2$ difference (ΔpCO$_2$) that have been obtained by the interpolation method of Takahashi *et al.* (1997) for the global oceans with $4° \times 5°$ resolution have been used as an *ocean* to be sampled. These monthly maps have been constructed using about 700,000 measurements for surface water pCO$_2$ for non-El Niño conditions. In constructing these monthly distributions, measurements were binned into $4° \times 5°$ pixels and averaged over a month. Hence, our ocean smoothes out any high-frequency variation of ΔpCO$_2$ in time and space, and accordingly our tests apply primarily to the sampling schedule for large-scale features (greater than 4° in the meridian, greater than 5° in the zonal direction, and greater than 1 month in time).

We sampled this ocean along meridional and zonal transects with varying spacing and with different time intervals. This simulates surface water pCO2 measurements made aboard transoceanic ships of opportunity. The sea-air CO_2 flux values have been computed for the global and regional oceanic areas using ΔpCO_2 values obtained under various time-space sampling schemes. Throughout this study, the effect of wind speed on the sea-air CO_2 gas transfer coefficient formulated by Wanninkhof (Eq. 1, 1992) and the NCEP 40-year mean monthly wind field have been used for the calculation of the net CO_2 flux. Table E-1 shows the CO_2 flux values computed when the ocean was sampled along N-S transects that are 5°, 10°, and 25° apart in the E-W direction. Since the data pixels are 5° wide in the E-W direction, this is the finest resolution that can be obtained for the data set. ΔpCO_2 values were read for each pixel along all N-S transects during a given month as though all measurements were made in a single month. The number of evenly spaced sampling periods in a year (i.e., 12, 6, and 3) is shown in the third column from the left, indicating that the samples were collected once every month, once every other month, and once every 4 months. A set of ΔpCO_2 values collected for the respective sampling schedule was interpolated in space and time using the 2-dimensional diffusion-advection transport equation according to the procedures described by Takahashi *et al.* (1995) and Takahashi *et al.* (1997). A monthly distribution of ΔpCO_2 in each of 12 months representing a sampling scheme has been computed and the corresponding net CO_2 flux distribution has been obtained. These flux values have been summed to a year for each oceanic region and are listed in Table D-1.

E.3 Results

E.3.1 Meridional transects

The first three rows in Table E-1 show the results of sampling along N-S transects every 5° apart, that is, all pixels have been sampled at evenly spaced time intervals. The first row shows a special case, in which daily ΔpCO_2 values in each 4° × 5° (400 km × 500–200 km) pixel using an objective interpolation based changes in mean monthly flow fields as specified in the Princeton GCM (Toggweiler *et al.*, 1989). This interpolation scheme preserves some high-frequency time variability, which would not be present in the monthly mean values. The daily flux values have been computed using the daily samples, and compared with the results (listed in row 2) obtained using monthly mean values for each pixel. They are found to be consistent within 0.01 Pg C/yr, indicating that the daily ΔpCO_2 variability does not significantly change the mean flux estimates in any ocean basin. For the subsequent calculations of the CO_2 flux, we use monthly mean ΔpCO_2 values. The flux values obtained for monthly sampling are found to be similar to those obtained for six samplings a year (i.e., every other month). The

Table E-1: Global and regional sea-air CO_2 fluxes computed on the basis of sampling along evenly spaced meridional transects.

Transects/Time	**Transect Spacing (degrees)**	**Temporal Spacing (No./yr even space)**	**Global Ocean Flux (Pg C/yr)**	**Temperate N. Pacific >14°N (Pg C/yr)**	**Eq. Pacific 14°N–14°S (Pg C/yr)**	**Northern N. Atlantic >50°N (Pg C/yr)**	**Temperate N. Atlantic 14°N–50°N (Pg C/yr)**	**Eq. Atlantic 14°N–14°S (Pg C/yr)**
Meridional*	5	365	−2.45	−0.65	+0.73	−0.50	−0.32	+0.19
Meridional*	5	12	−2.44	−0.64	+0.73	−0.51	−0.32	+0.19
Meridional	5	6	−2.37	−0.60	+0.71	−0.51	−0.30	+0.17
Meridional	10	12	−2.09	−0.51	+0.58	−0.44	−0.26	+0.15
Meridional	10	6	−1.95	−0.47	+0.54	−0.43	−0.23	+0.13
Meridional (Jan/May/Sept)	10	3	−1.72	−0.37	+0.52	−0.43	−0.19	+0.12
(Feb/June/Oct)	10	3	−1.81	−0.42	+0.50	−0.40	−0.21	+0.13
(March/July/Nov)	10	3	−1.81	−0.42	+0.45	−0.37	−0.20	+0.12
(Apr/Aug/Dec)	10	3	−1.84	−0.40	+0.47	−0.43	−0.20	+0.13
Meridional	25	12	−1.19	−0.26	+0.36	−0.27	−0.14	+0.11

*All pixels are sampled throughout the year.

latter are smaller than the former by no more than 0.04 Pg C/yr in regional fluxes (temperate North Pacific). A reduction of the sampling frequency from monthly to every other month does not significantly alter the annual flux in the regional and global scales.

An increase of spacing between N-S transects to 10° (or 1,000 km near the equator) causes some reductions in the CO_2 flux. Compared to the global flux of –2.45 Pg C/yr for the full-sample case, the global flux computed for 10° intervals is reduced by about 0.35 Pg C/yr when each transect is sampled 12 times a year, and by 0.5 Pg C/yr when each transect is sampled 6 times a year. The fluxes for the northern and temperate North Atlantic regions obtained for the 10° spacing with 12 monthly sampling are within 0.1 Pg C/yr, and those for the North Pacific region are within 0.15 Pg C/yr of the full sampling flux. If these regions are sampled 3 times a year at evenly spaced intervals (i.e., January/May/September, February/June/October, March/July/November or April/August/December), the data yield fluxes within 0.1 Pg C/yr of the flux values by full sampling. This suggests that, for the North Atlantic Ocean (including high-latitude, temperate, and equatorial areas), a precision of 0.1 Pg C/yr may be attainable with N-S transects 10° apart (1,000 km near the equator and 400 km at high latitudes) with a repeat frequency of 3 or 4 times a year. On the other hand, the North Pacific requires N-S transects more closely spaced than 10°, also with a repeat frequency of 3 or 4 times. This may be due to the fact that the fronts running E-W in the Pacific exhibit more pronounced changes in ΔpCO_2. The timing of the sampling does not appear to be critical as long as they are more or less evenly spaced. Further, the flux values are relatively insensitive to temporal frequency of sampling, whereas they are more sensitive to spatial intervals. This suggests that transect sampling aboard transoceanic ships may yield more effective data sets than those obtainable via time-continuous observations made at fixed locations using moored buoys.

The last row of Table E-1 shows the flux values obtained for N-S transects 25° apart (2,500 km near the equator). This spacing yields flux values nearly 50% of the reference values, and hence is not acceptable. With this coarse spacing, major oceanographic features are missed.

E.3.2 Zonal Transects

The flux values are computed using ΔpCO_2 values read along various E-W zonal transects for each month and are summarized in Table E-2. The first row lists the full-sampling reference values, to which other values are to be compared. Zonal transects 8° (800 km) apart yield smaller uptake fluxes by 0.1 Pg C/yr in the Atlantic and 0.17 Pg C/yr in the Pacific. The flux values obtained for transects 12° (1,200 km) and 16° (1,600 km) apart drop off significantly. For a given transect spacing, N-S transects appear to yield better flux values than E-W transects. This may be due to the fact that meridional gradients of surface water pCO_2 are generally much steeper than zonal gradients. Hence, N-S transects tend to cut across major steep gradients and thus are able to document the major oceanic features.

Table E-2: Global and regional sea-air CO_2 fluxes computed on the basis of sampling along evenly spaced zonal transects and along a grid of evenly spaced meridional and zonal transects.

Transects/Time	**Transect Spacing (degrees)**	**Temporal Spacing (No./yr even space)**	**Global Ocean Flux (Pg C/yr)**	**Temperate N. Pacific >14°N (Pg C/yr)**	**Eq. Pacific 14°N–14°S (Pg C/yr)**	**Northern N. Atlantic >50°N (Pg C/yr)**	**Temperate N. Atlantic 14°N–50°N (Pg C/yr)**	**Eq. Atlantic 14°N–14°S (Pg C/yr)**
Meridional*	5	12	−2.44	−0.64	+0.73	−0.51	−0.32	+0.19
Zonal only	8	12	−1.83	−0.47	+0.56	−0.40	−0.24	+0.15
Zonal only	12	12	−1.69	−0.42	+0.48	−0.28	−0.23	+0.12
Zonal only	16	12	−1.07	−0.27	+0.35	−0.21	−0.13	+0.10
Meridional + Zonal	10 × 12	12	−2.29	−0.57	+0.66	−0.47	−0.30	+0.17
Meridional + Zonal Feb/June/Oct	10 × 12	3	−2.10	−0.50	+0.59	−0.45	−0.25	+0.16

*All pixels are sampled throughout the year.

Listed in Table E-2 are the flux values obtained by a combination of E-W and N-S transects for two sampling intervals, 12 times and 3 times a year, respectively. As expected, these grid sampling schemes yield flux values significantly better than the meridional or zonal transects alone.

E.4 Conclusion

Various surface water pCO_2 sampling strategies have been tested using the climatological mean monthly distributions of ΔpCO_2. To simulate trans-oceanic observations of surface water pCO_2, the climatological ΔpCO_2 field was sampled along evenly spaced N-S or E-W transects at various time intervals. Global and regional CO_2 flux values have been computed using the numerical scheme of Takahashi *et al.* (1995, 1997) for space-time interpolation of ΔpCO_2, the Wanninkhof (1992) formulation of wind speed dependence of gas transfer coefficient, and the NCEP 40-year mean monthly wind speed. We have found that, for the North Atlantic Ocean (including high-latitude, temperate, and equatorial areas), a precision of 0.1 Pg C/yr may be attainable with N-S transects 10° (1,000–400 km) apart with a repeat frequency of 3 or 4 times a year. On the other hand, the North Pacific requires N-S transects more closely spaced than 10°, also with a repeat frequency of 3 or 4 times annually. Greater spacing causes significantly smaller ocean CO_2 flux. For a given number of ocean transects, N-S transects appear to yield better flux values than E-W transects. Decreasing the sampling from 12 to 3 months of the year at equal intervals does not seem to have an effect on CO_2 flux estimates. This would suggest that, given the spatial distribution needed, ocean transect sampling aboard transoceanic ships may be a more effective means than the time-continuous observations that can be made at fixed locations using moored buoys.

While it is clear that taking data that has been binned into $4° \times 5°$ areas and 1-month time blocks over the last 30 years adds considerable smoothing to the data, the results of this study support those using actual transects and time series that used measurements taken at much higher resolution (1–2 orders of magnitude) (Sweeney *et al.*, 2000). For the North Pacific, Sweeney *et al.* (2000) suggest that samples should be taken every 200–600 km while in the North Atlantic samples could be taken as little as every 2,000 km. Time-series stations analyzed by Sweeney *et al.* (2002) suggest a slight increase in sampling frequency that may be due to scarcity of data in some seasons in parts of the North Pacific and North Atlantic. Despite this discrepancy it is clear that short-term variability (< monthly) has little effect on the annual averages.

E.5 References

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