Development of the CO₂ latitude gradient in recent decades

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Abstract. Because 90% of the CO₂ from fossil fuel combustion is emitted in the Northern Hemisphere, annual mean atmospheric CO₂ mixing ratios are higher at middle and high northern latitudes than in the Southern Hemisphere. The observed CO₂ latitude gradient varies inter-annually and has generally increased as fossil fuel CO₂ emissions have increased. Back extrapolation of the measured CO₂ latitude gradient to zero fossil fuel emissions gives a latitude gradient with the Northern Hemisphere lower than the Southern. A linear regression of Mauna Loa minus South Pole annual mean differences versus fossil fuel emissions for 1958 through 1996 gives a slope of 0.5 $\mu\text{mol mol}^{-1}$ (abbreviated as ppm CO₂) (Gt C)⁻¹ ($\sigma = 0.03$) and an intercept (at zero fossil fuel emissions) of -0.8 ppm ($\sigma = 0.2$). Shorter data records yield similar results with larger uncertainties. We argue that this extrapolated gradient does not represent preindustrial conditions but is more correctly viewed as a decadal average gradient due to natural sources and sinks that underlie the anthropogenic perturbation. We interpret the extrapolated gradient as evidence for a contemporary Northern Hemisphere sink that has been proposed on the basis of other measurement and model approaches. The slopes (ppm CO₂ per gigaton of C from fossil fuel burning) calculated from sufficiently long records tend to agree with model calculations based on fossil fuel emissions, suggesting that any trend in the Northern Hemisphere sink, during the period of the measurements, has been small relative to the trend in fossil fuel emissions.

1. Introduction

Although the long-term rate of increase of atmospheric CO₂ is essentially the same in both hemispheres (~ 1.4 ppm yr⁻¹ during 1981-1992 [Conway *et al.*, 1994]), annual mean mixing ratios are higher in the Northern Hemisphere. The annual mean Barrow, Alaska-South Pole difference is currently ~ 4 ppm. This difference is maintained because $\sim 90\%$ of fossil fuel CO₂ emissions occur in the Northern Hemisphere [Marland *et al.*, 1994], and interhemispheric mixing occurs on a timescale of 1-1.5 years [Law *et al.*, 1996]. Keeling *et al.* [1989] have shown that the north-south difference is increasing because of increasing anthropogenic emissions in the Northern Hemisphere. If the measured difference between Mauna Loa and the South Pole is extrapolated to zero fossil fuel emissions, CO₂ concentrations in the Northern Hemisphere are lower than in the Southern Hemisphere. Keeling *et al.* [1989] proposed that such an extrapolation reveals the preindustrial surface CO₂ latitude gradient, and they hypothesized that it was caused by vigorous uptake of CO₂ in the North Atlantic Ocean balanced by loss from the southern oceans.

These ideas were given a different interpretation by Taylor and Orr [1997]. Adopting Keeling *et al.*'s [1989] hypothesis that the extrapolation to zero fossil fuel emissions represents the preindustrial CO₂ gradient at the Earth's surface, they attributed the lower annual mean Northern Hemisphere CO₂ concentrations

to covariance between seasonal variations in atmospheric mixing and a seasonal terrestrial biosphere which acts as a source during the winter and a sink during the summer. Since the preindustrial biospheric source and sink are presumed to be annually balanced, no net annual mean sink is implied at middle to high latitudes in the Northern Hemisphere. Translated to today's conditions, Taylor and Orr [1997] asserted that no significant terrestrial sink at midlatitudes is necessary to explain the relatively small observed north-south gradient [Tans *et al.*, 1990] because, in their view, a balanced biosphere would already counteract the fossil fuel imposed gradient.

There is general agreement among atmospheric modelers that the covariance between transport and sources/sinks constitutes an important aspect of the CO₂ latitudinal gradient. In a recent intercomparison of atmospheric transport models [Law *et al.*, 1996], results were presented for simulations in which all models used the same seasonal source/sink pattern for an annually balanced terrestrial biosphere. The model results fell into three groups. One group, including all models with an explicit formulation for the planetary boundary layer, obtained a surface interhemispheric gradient about half as strong and of the same sign as that produced by fossil fuel burning. Denning *et al.* [1995] demonstrated that this was mostly because of the seasonal difference of vertical mixing processes: Respiratory CO₂ is trapped near the surface during winter, while the summer CO₂ drawdown is mixed into a much greater volume of the atmospheric column during summer. This phenomenon is commonly referred to as the seasonal atmospheric rectifier effect. A second group of models produced a very slight positive or no significant gradient. One model [Taylor, 1989] resulted in a significantly negative gradient, with the Southern Hemisphere

surface having a higher concentration than the northern, opposite to the result of *Denning et al.* [1995].

In this paper we reexamine the trend in the CO₂ latitude gradient in recent decades and offer a new interpretation of the extrapolation to zero fossil fuels. Using several long CO₂ measurement records and fossil fuel emission data, we have extrapolated the latitude gradient to zero fossil fuel emissions. In agreement with *Keeling et al.* [1989], we find that over the past several decades, in the absence of fossil fuel emissions, the oceans and biosphere would have produced a gradient with less CO₂ in the Northern Hemisphere relative to the South Pole. What does this tell us about CO₂ sources and sinks?

2. Data

In this analysis we use annual mean atmospheric CO₂ mixing ratios obtained from flask samples collected at the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) sampling sites at Barrow, Alaska (BRW); Mould Bay, Canada (MBC); Station M (STM); Niwot Ridge, Colorado (NWR); Terceira Island, Azores (AZR); Key Biscayne, Florida (KEY); Mauna Loa and Cape Kumukahi, Hawaii (MLO and KUM); Guam (GMI); Ascension Island (ASC); American Samoa (SMO); and the South Pole (SPO); these mixing ratios cover the time periods indicated in Table 1. These sites were chosen because their measurement records are long and mostly continuous. Shorter and discontinuous records are insufficient for performing meaningful regressions. The NOAA CMDL air sampling network and measurements are described in *Conway et al.* [1994 and references therein], and the data are available for electronic transfer via ftp from the CMDL server (ftp.cmdl.noaa.gov). Annual mean atmospheric CO₂ mixing ratios measured at Mauna Loa (in situ) and the South Pole (flasks) from 1958 to 1996 by the Scripps Institution of Oceanography (SIO) [*Keeling et al.*, 1994] are also used. The global annual CO₂ emission data for fossil fuel combustion and cement production through 1996 are from *Marland et al.* [1994] and subsequent updates. The 1997 value is a preliminary estimate (T. Boden, personal communication, 1999).

3. Results

Annual mean CO₂ mixing ratios relative to the South Pole are plotted as a function of fossil fuel CO₂ emissions for Mauna Loa in situ data (1958-1996) and Barrow (1976-1997) and Ascension Island (1980-1997) flask data in Figure 1. The solid lines are linear regressions to the data. Similar regressions have been calculated for each record, and the slopes, intercepts, and uncertainties (1 σ from *Bevington* [1969]) are summarized in Table 1.

Although there is significant correlation between the latitude gradient and fossil fuel emissions for all sites, it is clear from Figure 1 and Table 1 that the slopes and intercepts determined from the shorter NOAA CMDL flask records are much less certain than those determined from the 39 year SIO Mauna Loa and South Pole records. The results from the relatively short flask records must be viewed with caution because the rate of fossil fuel combustion only increased from 4.9 to ~6.7 Gt C year⁻¹ from 1976 to 1997. It is encouraging, however, to note the relatively good agreement between the independent (except for calibration) 39 and 22 year SIO and NOAA CMDL records at MLO: The slopes and intercepts agree to within 1 σ uncertainties. We have also performed a regression on the 1976-1996 subset of the SIO MLO record. The slope and intercept still agree with the flask and in situ records to within 1 σ , while the uncertainties are larger and are similar to those obtained from the shorter flask records. Another encouraging result is the good agreement of the slope and intercept between KUM (sea level) and MLO (3400 m), which are both on the island of Hawaii.

The slopes and their 1 σ uncertainties are plotted versus latitude in Figure 2. It is interesting to note that the largest slopes (~1.0 ppm CO₂ (Gt C)⁻¹) are observed at middle and high northern latitudes. This is consistent with the increase in fossil fuel emissions having occurred primarily at midlatitudes of the Northern Hemisphere. Note also that a significant negative slope is observed at ASC (Figure 1), indicating that as fossil fuel emissions increase, the difference between ASC and SPO is decreasing.

The intercepts and 1 σ uncertainties from Table 1 are plotted in Figure 3. The average station minus South Pole differences

Table 1. Summary of Linear Regression Results

Site	Type	Time Period	Slope, ppm CO ₂ (Gt C) ⁻¹	σ_{slope}	Intercept ppm	σ_{int}
MBC	Flask	1981-1996	1.05	0.24	-2.4	1.4
BRW	Flask	1976-1997	0.76	0.20	-0.8	1.2
STM	Flask	1981-1997	0.76	0.18	-1.6	1.1
NWR	Flask	1976-1997	0.91	0.19	-2.7	1.1
AZR	Flask	1980-1988 1995-1997	0.58	0.39	-0.9	2.2
KEY	Flask	1976-1997	0.48	0.16	0.6	0.9
MLO	Flask	1976-1997	0.56	0.10	-1.2	0.6
MLO	In situ	1958-1996	0.51	0.03	-0.8	0.2
MLO	In situ	1976-1996	0.44	0.12	-0.4	0.7
KUM	Flask	1977-1997	0.58	0.12	-1.0	0.7
GMI	Flask	1980-1997	0.39	0.19	0.3	1.1
ASC	Flask	1980-1997	-0.30	0.12	3.1	0.7
SMO	Flask	1976-1997	0.19	0.11	-0.1	0.6

Figure 1. Annual mean CO₂ differences from the South Pole plotted against global fossil fuel emissions for Mauna Loa (squares), Barrow (circles), and Ascension Island (triangles). The solid lines are linear regressions fitted to the data. The time periods for each site and the slopes, intercepts, and their uncertainties are given in Table 1.

and their standard errors for the 1981-1984 and 1994-1997 NOAA CMDL data are plotted for comparison. The measured gradients clearly show the increase relative to the South Pole over the past two decades. The gradient extrapolated to zero fossil fuel emissions (intercepts) is dramatically different from the observed gradients. The minimum in the extrapolated gradient is -2.7 ppm at NWR. At higher latitudes (STM, BRW, and MBC) the surface CO₂ is 1-2 ppm lower than at the South Pole, and at MLO and KUM, CO₂ is ~1 ppm lower than at SPO. For KEY, GMI, and SMO the gradient is slightly positive or zero. Extrapolation of the negative slope for ASC results in a CO₂ value 3.1 ppm higher than SPO, with a relatively small statistical uncertainty. As was noted with the slopes, there is good agreement among the intercepts for the MLO (flask), MLO (in situ), and KUM (flask) records.

4. Discussion

It is clear from the scatter of the data in Figure 1 and the uncertainties of the slopes in Table 1 that there is significant interannual variability in the CO₂ latitude gradient. Most of this variability is not random or due to measurement error but reflects regional variations in marine and terrestrial CO₂ sources and

Figure 2. The slopes from linear regressions of annual means minus South Pole differences versus fossil fuel (ff) emissions plotted as a function of latitude. The error bar represents $\pm 1 \sigma$. The MLO value from the Climate Monitoring and Diagnostics Laboratory (CMDL) flask data is represented by an open square to distinguish it from KUM. The star represents the MLO slope from the Scripps Institution of Oceanography (SIO) (1958-1996) record.

Figure 3. The CO₂ latitude gradient (relative to the South Pole) for 1981-1984 (solid squares) and 1994-1997 (solid circles) and extrapolated to zero fossil fuel emissions (solid triangles, the intercepts from Table 1). Again, the CMDL MLO value is represented by the open circle, square, and triangle, and the SIO (1958-1996) MLO value is represented by a star.

sinks [Conway *et al.*, 1994] as well interannual variations in atmospheric transport. For sites with long enough records, however, a significant trend underlies the interannual variability [Keeling *et al.*, 1989]. In our current analysis of the data the slopes represent the trend in the latitude gradient averaged over the period of the measurements, and the uncertainties and significance of the slopes and intercepts are determined by and reflect the interannual variability. In this work we emphasize the trend in the gradient specifically to address the interpretation of Keeling *et al.* [1989].

There is good agreement among modeled surface CO₂ latitude gradients determined from transport models that are driven exclusively by the same fossil fuel emissions pattern [Law *et al.*, 1996]. The average maximum latitude gradient for the 12 models is ~5 ppm CO₂ for fossil fuel emissions of 5.3 Gt C (~0.94 ppm CO₂ (Gt C)⁻¹). Observations of other tracers without marked seasonal variations in their emissions, such as CFCs and ⁸⁵Kr, have been used in many cases to tune this particular aspect of the models. The slopes determined from atmospheric measurements, plotted in Figure 2 as ppm per gigaton of C, compare remarkably well with the model results for fossil fuel emissions. Excluding two models on the high end, the majority of models give zonal

means of ~0.75 ppm CO₂ (Gt C)⁻¹ at the high northern latitudes and ~0.85 ppm CO₂ (Gt C)⁻¹ at midlatitudes. The observed slopes at midlatitudes (Table 1) tend to be somewhat lower than the zonal means possibly because regions of strong fossil fuel emissions (on continents) have traditionally been avoided by the sampling network strategy. The agreement between the observations and models suggests that a middle or high latitude northern sink (oceanic or terrestrial) has exhibited little or no trend during the last two (or, in the case of the MLO in situ data, four) decades. Any trend in the northern sink would exert a major influence on the observed slopes of the north-south gradient versus fossil fuel emissions. The increase in annual fossil fuel emissions from 1976 to 1997 was 1.8 Gt C. A hypothetical trend in an annual terrestrial sink of 0.5 Gt C over that period would increase or decrease the slopes by ~28%, depending somewhat on the season toward which the trend in the sink is weighted. Therefore, if we hypothesize a significant trend in the sink, the model transport of the fossil fuel signal would be inconsistent with the observed slopes. This argument is most applicable to sinks (or sources) at middle and high latitudes. The surface CO₂ latitude gradient is less sensitive to tropical sources because of strong vertical mixing that dilutes the signal.

The above discussion illustrates that by comparing the observed latitudinal CO₂ gradient as a function of fossil fuel emissions (Figure 1) with model results one may recover information about the spatial pattern of other (possibly changing) sources and sinks during the period of the observations. The hypothesis of Keeling *et al.* [1989] that a preindustrial latitude gradient is recovered in this extrapolation procedure is an enormous and very uncertain leap. This would require that any changes in sources and sinks at middle and high latitudes, other than fossil fuels, were either zero or proportional to fossil fuel emissions in space and time. In fact, we know that land use changes have contributed to the anthropogenic perturbation of the carbon cycle and that these changes have varied differently over space and time than fossil fuel emissions. The CO₂ source due to land use changes in tropical and extratropical latitudes [Houghton and Hackler, 1995] is plotted with the fossil fuel source in Figure 4.

We propose that extrapolating to zero fossil fuel emissions is not the same as extrapolating back to preindustrial times. Rather, it reveals the contemporary gradient, averaged over the period of the measurements, underlying the measured fossil fuel perturbed gradient. If we can trust the modeled fossil fuel CO₂ gradient sufficiently, we can extract information about decadal trends in marine and terrestrial processes at middle and high latitudes. We find that in the absence of fossil fuel emissions the contemporary gradient is negative in the midlatitudes of the Northern Hemisphere and positive in the southern tropical Atlantic Ocean (ASC), while the majority of chemical transport models predict that an annually balanced biosphere (no net flux) would give rise to a positive latitude gradient because of the rectifier effect [Denning *et al.*, 1995; Law *et al.*, 1996]. The discrepancy between this positive gradient and our extrapolated negative gradient is consistent with a large Northern Hemisphere sink. As pointed out by Denning *et al.* [1995], this sink would have to be stronger than that proposed by Tans *et al.* [1990]. Estimating the magnitude of the Northern Hemisphere sink is uncertain, in part because the modeled latitude gradient depends so strongly on the

rectifier effect. To improve these estimates, it is of crucial importance to measure vertical profiles of CO₂ and other species in different seasons, especially at continental midlatitudes in the Northern Hemisphere, to understand and quantify the rectifier effect better. Other approaches to quantifying the Northern Hemisphere sink on various timescales include estimating the marine sink based on decadal measurements of *p*CO₂ [Takahashi *et al.*, 1997], estimating the terrestrial CO₂ sink based on measurements of ¹³C of CO₂ since 1990 [Ciais *et al.*, 1995a, b], and measuring the O₂/N₂ latitudinal gradient [Keeling *et al.*, 1996], also during the 1990s. These results are consistent with our interpretation of the extrapolated latitude gradient and also suggest that a large portion of the Northern Hemisphere sink is terrestrial.

While the negative extrapolated latitude gradient in the Northern Hemisphere is consistent with a large sink, the positive gradient observed at ASC suggests the influence of, at least, a regional CO₂ source, which may have exhibited a decadal trend. The only other two tropical sites with records long enough to support this regression analysis (GMI and SMO) gave intercepts not significantly different from zero. Although ASC is one of the shorter records included in this study, we have a high degree of confidence in the measurements themselves, and the slope and intercept are statistically significant. Thus, while the ASC result may appear anomalous, we will take it at face value and consider two possible sources.

A comparison of the CO and CO₂ data from the air samples collected at ASC has shown a possible influence at ASC of biomass burning in Africa during August-October [Novelli *et al.*, 1992]. It has also been shown that elevated O₃ over the South Atlantic is due to biomass burning in both Africa and South America [Thompson *et al.*, 1996]. However, we are not aware of a significant downward trend in biomass burning. A marine origin for this feature is also possible because there is a large region upwind of ASC with CO₂ partial pressures in the surface waters typically 20-40 μ atm higher than the atmosphere. Again, there are not enough data to determine a decadal trend in *p*CO₂ (T. Takahashi, personal communication, 1998). Measurements do show that sea surface temperatures in this region were $\sim$ 1°C below normal during the El Niño years 1982, 1992, and 1997, which could have weakened the oceanic CO₂ source (T. Takahashi, personal communication, 1998), but we do not observe anomalies in the atmospheric ASC minus SPO CO₂ differences for these years. Thus, while the ASC minus SPO versus fossil fuel slope and intercept are significant, we are unable to explain the underlying process.

5. Conclusions

The CO₂ latitude gradient is a complicated function of sources, sinks, and atmospheric transport. A simple regression analysis of long atmospheric CO₂ records reveals a long-term trend in the magnitude of the gradient related to the trend in fossil fuel emissions. The regression slopes are consistent with three-dimensional model results for fossil fuel only runs, suggesting that trends in other sources and sinks during the past several decades were small relative to the trend in fossil fuel emissions. The regression intercepts, at zero fossil fuel emissions, confirm previous results showing lower CO₂ mixing ratios in the Northern Hemisphere than in the Southern Hemisphere.

Figure 4. CO₂ emissions (gigatons C per year) from global fossil fuel use (solid line, left-hand scale), land use changes in tropical regions (dashed line, expanded right-hand scale), and land use changes in northern temperate and high-latitude regions (dotted line, expanded right-hand scale).

This "negative gradient," underlying the fossil fuel perturbation, is consistent with the existence of a middle to high-latitude Northern Hemisphere carbon sink that has been proposed based on other lines of evidence.

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