FINAL REPORT

Study of the Role of Terrestrial Processes in the Carbon Cycle Based on Measurements of the Abundance and Isotopic Composition of Atmospheric CO_2

This is the final report for Grant DE-FG02-07ER64362 to PI Ralph Keeling which provided approximately 2 2/3 years of support, from Sept. 15, 2007 to September 14, 2011, including a no-cost extension. This grant, together with continuing grants from the National Science Foundation and additional new funding from BP, provided the core support for the Scripps CO_2 program over the grant period. A proposal to continue this work has been funded by DOE.

OBJECTIVES AND APPROACH:

The main objective of this project was to continue research to develop carbon cycle relationships related to the land biosphere based on remote measurements of atmospheric CO_2 concentration and its isotopic ratios $^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{14}C/^{12}C$. The project continued time-series observations of atmospheric carbon dioxide and isotopic composition begun by Charles D. Keeling at remote sites, including Mauna Loa, the South Pole, and eight other sites. Using models of varying complexity, the concentration and isotopic measurements were used to study long-term change in the interhemispheric gradients in CO_2 and $^{13}C/^{12}C$ to assess the magnitude and evolution of the northern terrestrial carbon sink, to study the increase in amplitude of the seasonal cycle of CO_2, to use isotopic data to refine constraints on large scale changes in isotopic fractionation which may be related to changes in stomatal conductance, and to motivate improvements in terrestrial carbon cycle models. The original proposal called for a continuation of the new time series of ^{14}C measurements but subsequent descoping to meet budgetary constraints required termination of measurements in 2007. Later, when funding permits, we plan to measure ^{14}C in CO_2 saved in glass ampoules.

OPERATIONAL ACTIVITIES:

Remote Sampling

The most extensive activity under this grant has been the continuation of time-series measurements of the concentration and $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotopic ratios of atmospheric carbon dioxide CO_2 at an array of remote sites, extending from Alaska to the South Pole. At all stations, samples of air are collected in 5-liter glass flasks and returned to our instrument laboratory for analysis. At Mauna Loa Observatory, Hawaii, and at La Jolla, CO_2 concentration is also measured continuously with on-site analyzers. Flask sampling frequency is once per week except at the three southernmost stations, where it is approximately half as often or less: Raoul I. in the Kermadec Islands, Baring Head, New Zealand, and the South Pole. Samples were also collected in collaboration with Seoul National University, South Korea, and El Centro de Investigacion Cientifica y de Education Superior de Ensenada (CICESE) of Baja California. The stations are, respectively: Cheju-Do Island near Korea (1990 to present) and on the coast of Mexico near La Paz (1997 to present). The Korean effort provides Seoul National University with intercomparisons with our data, but does not furnish an especially useful data set for our program. The second effort, however, has furnished data to be added to that of our present station array.

Discontinued Sampling in Vegetated Areas
Owing to budget constraints, at the outset of this funding period, we discontinued the long-term program to study gas exchange in vegetated areas which involved collecting and analyzing air samples over the diurnal cycle in mid-summer, starting in 1987 at two forest sites: Hamilton, Montana in the United States and Rock Lake in Alberta, Canada. We hope to re-initiate this program in the future in order to extend and interpret the 20-year time series of measurements.

Archiving of CO_2
Under this grant we have continued to archive CO_2 samples in glass ampoules from flasks collected at the remote sites.

CAPACITY BUILDING:

New Postdoc Recruited
In September 2008, a new postdoc (Lisa Welp) was recruited to help to write up results for publication. Lisa has been supported largely by other funding sources but is doing work on data collected by this program. Her recruitment addresses the challenge that members of this effort with most experience in scientific writing (the PI and Steve Piper in the Specialist series) are only able to dedicate a small fraction of their time to paper writing pertinent to this project, given competing needs such as support for ongoing measurement and data quality issues.

CALIBRATION AND INSTRUMENTATION ACTIVITIES:

The instrumentation setup at Mauna Loa was modified to incorporate a rack for supporting the calibration tanks that allows the tanks to be stored horizontally. This reduces a potential source of artifacts involving thermal and gravimetric fractionation in the tanks, which may cause small offsets between the CO_2 content of the air delivered from the tank relative air in the tank.

During this funding period, the lab space used by the project was consolidated under a mandate to provide new lab space for a (successful) faculty recruitment effort at Scripps. This consolidation involved a considerable effort by many of the people working this project. The consolidation was completed by the fall of 2008. The experience since then suggests that the retained space is indeed adequate for the primary operational aspects of the program, with some impact, however, on the ability to engage in instrument development.

Progress was made in transitioning to a new CO_2 analyzer for the primary gas calibration work and flask analyses at Scripps. This progress includes the preparation of a new analysis rack, consisting of a Siemens CO_2 analyzer, gas delivery lines, switching manifolds, regulators, and a box system for supporting calibration tanks horizontally. The new system has been built but has not been fully tested. The plan is to carry out intercomparisons on calibration tanks in parallel with the older (original) APC system that has been in use (with improvements) since the 1950s. This system will be interfaced with a system for delivering air from flasks, thus allowing the older system to be fully decommissioned.

Also during this funding period, there was ongoing construction of a new rack for extracting the CO_2 from flasks into sealed glass ampoules for subsequent isotopic analysis. Routine usage of this new rack commenced in winter 2009, which greatly increases the lab's extraction capability. The rack, however, is still not fully automated, requiring user intervention at steps controlling the liquid nitrogen delivery. Thus more work to fully automate the rack is still ongoing, although not urgently required.

In the first year, a possible problem emerged with the extraction system for carbon isotopes, as revealed through sequential offsets in isotopic values. This problem was quickly diagnosed as resulting from exposure of small portion of the CO_2 sample to elastomeric vacuum tubing. The problem was easily avoided by a slight modification to how the extraction rack was operated. The impact of the artifact on previously collected data is expected to be small but is still under investigation.

Also during this funding period work was done to address the stability of the manometric calibration for the CO_2 concentration measurements. It was determined that the glass "plenums" used to calibrate the Scripps manometer system (the basis of the Scripps calibration scale) decreased in volume very slightly over time since they were brought into use in 1970. This has implications for the manometric scale on which the Scripps CO_2 records are based. We developed a new data processing system for the manometric calibration which allows for drifting plenum volumes and which allows the history of the manometric determinations of primary reference gases to be easily recomputed with different assumptions regarding plenum drift, etc. This new data system has been used to prepare manometric tank histories to be compared against the histories on the most recent SIO scale. This comparison will form the basis for a new manometric scale. Large changes are not expected and the scale is expected to be in close agreement with the independent scale issued by NOAA.

INTERPRETATIONAL ACTIVITIES AND FINDINGS:

Global Trends in CO_2

Measurements of CO_2 and $^{13}C/^{12}C$ at stations in our network provide the basis for analysis of regional and global variations of atmospheric CO_2 (Figures 1 and 2). The time derivative of the average of our two longest records, at Mauna Loa and the South Pole, is shown in Figure 3. Atmospheric CO_2 and $^{13}C/^{12}C$ continue to vary in close concert with each other and in synchrony with the Southern Oscillation Index, up through the end of of the record. The pattern shows that the land biosphere continues to be the main cause of variations of atmospheric CO_2 on the El Nino time scales. An interesting recent development is that the rate of change curves for CO_2 and $^{13}C/^{12}C$ have separated and remained separate consistently since early 2005. It is possible that this signals a change in balance of oceanic and terrestrial biospheric net CO_2 fluxes, with the net global oceanic sink decreasing while the biospheric sink increases, but it is equally or more likely that it reflects a large increase in isotopic discrimination associated with photosynthesis in response to recent climatic conditions. Persistent changes in atmospheric circulation might also play a role in this phenomenon. Careful modeling is required to sort this out.

With considerable media attention, members of the carbon community have recently called attention to the potential for large carbon-climate feedbacks, whereby warming caused by rising greenhouse gases may feedback to cause additional CO_2 releases, fueling a feedback loop that may amplify global warming. This possibility was reflected, e.g. in the press release by Chris Field at the AAAS meeting (Stanford University News, 2009, http://news-service.stanford.edu/news/2009/february18/aaas-field-global-warming-ipcc-021809.html): "Without decisive action, global warming in the 21st century is likely to accelerate at a much faster pace and cause more environmental damage than predicted". This viewpoint largely draws on the Canadell et al (2007) study suggesting that CO_2 has risen over the past couple decades at a rate faster than expected from the models used by the Intergovernmental Panel on Climate Change, even after accounting for actual (high) rates of fossil-fuel burning. Canadell et al drew a connection between this behavior and the potential for "stronger-than-expected and sooner-than-expected climate forcing", thereby touching on the possibility that large carbon-climate feedbacks may be starting to kick in.

Certainly, recent increases in measured CO_2 have been large. The increase at Mauna Loa was once again very high in 2009, surpassing 2 ppm, for the 6th highest annual increase in the record (in order starting with the highest: 1998: 2.77 ppm, 2005: 2.51, 2002: 2.49, 1987: 2.38, 2003: 2.25, 2009: 2.23). However, in our view, the claim that CO_2 is rising more rapidly than expected is not well founded. Our view is expressed in the manuscript "Climate effects on atmospheric carbon dioxide over the past century" (Rafelski et al. 2009). In this article, we compare the observed rise in CO_2 with the rise expected from simple box models of the sort used in this community for 30 or more years. Building on prior work of C.D. Keeling et al. (1995) the comparison highlights the need for a source/sink term that varies in concert with global land temperature on decadal time scales in the sense of a positive feedback. We show, however, that the effect is tied to carbon releases from reservoirs with rapid (2-5 year) turnover times and as such represents an insignificant as a positive feedback on rising CO_2.

The analysis doesn't rule out the possibility of stronger feedbacks tied to longer-lived pools of carbon, such as arctic tundra, but concludes that it is difficult (really impossible) to resolve any such an effect from the global records. The difficulty arises because releases from long-term pools would be masked by uncertainty in other slowly varying processes, such as land-use emissions and any CO_2 fertilization effect. We show that models depicting the “classic” land and ocean sink behavior (tied to rising CO_2) but which also include weak decadal land temperature effect are able to account for the rise from 1958 to the present with high fidelity (see Figure 4). We also show that the decadal land temperatures effect is almost certainly closely tied to the same processes that cause CO_2 to vary on the shorter El Niño time scale. In sum, we show that the CO_2 rise to date is in concordant with simple models of the sort developed 30 years ago without strong feedbacks.

The message for future CO_2 buildup the message is mixed. The expected rise is already fast enough, given the high rates of fossil-fuel burning, to cause serious concerns regarding global warming without invoking the possibility of large future carbon-climate feedbacks. At the same time, the possibility of large future carbon-climate feedbacks is neither supported nor ruled out by global trends to date.

Evolution of the Interhemispheric Gradient in Atmospheric CO_2

We published in 2011 a manuscript on the evolution of the interhemispheric gradients of atmospheric CO_2 and $\delta^{13}C$ (CD Keeling et al., 2011). This study involved a concerted effort by the PI and Stephen Piper, a Specialist with the project, to complete a manuscript initiated by CD Keeling. The manuscript addresses the finding, first reported in Keeling et al (1989) and Tans et al (Tans et al., 1990) that the interhemispheric gradient was considerably smaller than expected from fossil-fuel burning alone, suggesting the existence of a northern terrestrial sink or a highly asymmetric oceanic exchanges of CO_2.

In our analysis, we have used observations of atmospheric CO_2 at our network of stations augmented by data in the 1950s and 1960s from ships and ice floes. We rely on the remarkable proportionality between increases in fossil fuel emissions and atmospheric CO_2 in recent years, disregarding short-term variations, to partition the observations by regression analysis between a stationary or natural component and one that evolves with fossil fuel emissions. We have performed a similar regression analysis with records of $^{13}C/^{12}C$ at these sites to further ascribe variations in observations to land biospheric or oceanic fluxes. We have performed regional inverse model calculations using the atmospheric transport model TM2 to estimate the magnitude of natural and time-evolving sources and sinks of CO_2.

The analysis reasserts the point made in Keeling et al (1989) that the smaller-than-expected interhemispheric gradient is substantially caused by asymmetry in natural ocean carbon transports and that the oceans play a larger role in the southward transport of carbon than suggested by recent models or studies of ocean pCO2. Ocean models, inversion studies, and pCO_2 data have limitations in the Southern Ocean, raising the possibility that these approaches cannot yet reliably resolve a critical component of the CO_2 system, involving natural CO_2 releases around Antarctica balanced by widespread oceanic uptake to the north. By relying on $\delta^{13}C$ data, this study avoids this limitation. The implications for the northern land sink are complex, depending on uncertainties in atmospheric transport and puzzling discrepancies between ice-floe CO_2 data from the 1950s and data from Barrow, Alaska in the 1960s.

Radiocarbon measurements

A significant achievement in this funding period was the completion of the Ph.D. thesis of Heather Graven entitled "Advancing the use of radiocarbon in studies of global and regional carbon cycling with high precision measurements of ^{14}C in CO_2 from the Scripps CO_2 Program" (Graven, 2008). This project involved a close collaboration with Tom Guilderson of LLNL under previous funding to improve the capability for making high precision radiocarbon measurements and to apply this capability to measure archived CO_2 samples from the Scripps CO_2 program, thus producing long-term high quality time series at the Scripps sites. The resulting data are included in Figure 2. Results from all sites show an irregular seasonal cycle and a long-term decreasing trend. The results, which comprise the most comprehensive large-scale dataset for ^{14}C variability, are qualitatively similar but more precise than most previous observations. The data contain useful constraints on ocean circulation, gas exchange, and fossil-fuel burning. Heather's thesis is available at http://bluemoon.ucsd.edu/publications/heather/thesisHG_050708.pdf

Heather (as a post-doc at ETH-Zurich and Scripps) prepared a manuscript describing and analyzing the 15-year trend in radiocarbon from samples collected in La Jolla, and also prepared a second manuscript describing the shorter records from additional stations. These manuscripts are in press in the *Journal of Geophysical Research* (Graven et al., 2011a, 2011b). The manuscripts present previously unpublished observations of radiocarbon from flasks collected for the Scripps CO_2 program and discuss the variation in terms of known influences, such as fossil-fuel burning, and natural CO_2 exchanges with the oceans, atmosphere, and stratosphere. The datasets expand significantly on the landmark time series maintained by Ingeborg Levin and colleagues from the University of Heidelberg. Among the new features revealed are a shift in the gradient in radiocarbon due to land and ocean exchanges, and strong interannual variability, evidently tied mostly to variations in stratospheric-tropospheric exchange.

Regional radiocarbon measurements

As an offshoot of her thesis project to measure radiocarbon in atmospheric CO_2, Heather Graven also participated in an effort to assess the feasibility of using radiocarbon to determine regional fossil-fuel emissions. This work involved airborne sample collections (for radiocarbon analysis) as well as in situ airborne measurements of CO_2 and CO concentrations, and relied on partial support from this grant for extractions and isotopic analyses and extractions. A manuscript from this project, published in *Tellus*, demonstrates the feasibility of using radiocarbon to distinguish land biospheric and fossil-fuel contributions to the nocturnal CO_2 buildup (Graven et al., 2009).

Isotope Studies

Lisa Welp, a postdoc in the group, led a study of the interannual variability in the oxygen isotopic composition of CO_2, taking advantage of the Scripps $\delta^{18}O$ records, the longest of their kind. These isotopic measurements were made in three different labs (Mook lab in Groningen until 1991, Wahlen lab at SIO 1991-2001, and Keeling lab at SIO, 2001-present). The emphasis has been to understand the cause of evident global variations in $^{18}O/^{16}O$ on interannual time scales. The study presents the discovery of a major feature of the world hydrological cycle, involving modulation of the isotopic composition of tropical leaf and soilwater associated with El Niño events and its transport into the CO_2 system, as shown in Figure 5. This discovery opens the door to novel applications of measurements of the ^{18}O isotopes of CO_2 to constrain rates of gross primary production, stomatal conductance, and water-use efficiency. This study was published in Nature in 2011 (Welp et al., 2011)

Trends in Seasonal Cycle Amplitude

We have reanalyzed the seasonal cycle of atmospheric CO_2 for four of our stations in the Northern Hemisphere, Point Barrow (71°N), Alert (82°N), La Jolla (32°N), and Mauna Loa (20°N). The seasonal cycle at these stations is of particular interest because it is produced almost entirely by land plants and soil bacteria and is reflective of biospheric activity over large regions.

In a previous analysis, Keeling et al. (1996) showed that the amplitude of the seasonal cycle at Point Barrow increased dramatically, by almost 40%, from 1960 to 1994. The cycle at Alert increased similarly to that at Point Barrow from 1985 to 1994 suggesting that the changes at these two stations are representative of large-scale Arctic air masses. The change at Mauna Loa, much farther south, was smaller, about 20%, but also increasing.

Keeling et al. (1996) showed that these changes were paralleled by changes in average land temperatures of the zones in which they occur, suggesting that changing temperature increased plant carbon cycling to produce larger seasonal release and/or uptake by land plants and soil. Coincidentally, the drawdown of CO_2 in the spring at all stations advanced by 5-7 days.

In our new analysis, as shown in Figure 6, the seasonal amplitude at Point Barrow continued its increase to 2008. Over the last 7 years, the amplitude increased rapidly to record highs in 2007 and 2008. The phase of the cycle has continued to move earlier, occurring 5 days earlier in 2008 than in the 1960s. Changes at Alert have continued similarly to those at Point Barrow and to zonal land temperature changes. Measurements at Ocean Station Papa (STP) at 50°N were recently resumed in 2007 by Chris Sabine, Steve Emerson and others after a long layoff beginning in 1982. The seasonal amplitude in the recent measurements indicates a smaller increase than at Barrow or Alert but larger than Mauna Loa (Figure 6).

La Jolla is located in heavily populated Southern California on the northern outskirts of San Diego and while sampling is performed only during periods of steady onshore winds the seasonal amplitude time series displays higher variability than other locations in our sampling network. At La Jolla, since the 1950s, the amplitude has increased more than 60%, more than at any of our other stations (Figure 6). This increase might be explained in part by long term shifts in local coastal wind patterns. It is unlikely to be explained by variations in local emissions because of the care taken to sample only under background or near background conditions.

Steve Piper led a study focused on changes in the seasonal amplitude at Mauna Loa (manuscript in preparation) that are in marked contrast to changes at Barrow, Alert, La Jolla and Station Papa. The seasonal amplitude at Mauna Loa has not continued increasing along with a continued increase in the zonal land temperature (Figure 6). With 14 more years of record, it is now clear that quasi-decadal variability rather than a long-term trend is the dominant characteristic of the record at Mauna Loa. The study shows that the dominant features in the amplitude change are closely tied to the Pacific Decadal Oscillation, a dominant mode of climate variability over the Pacific region, modulating drought and atmospheric transports in the region. After correcting for the PDO influence, it is found there is little residual trend in the record. The lack of a strong amplitude trend at Mauna Loa is in stark contrast to the record from Barrow Alaska, which shows marked increases over the same 50-year time scale.

Arctic Trends

Postdoc Lisa Welp led a project involving the PI and Steve Piper, and collaborations with Prabir Patra (JAMSTEC – Japan) and Ramakrishna Nemani (NASA-AMES) combining CO_2 data, inverse modeling, and satellite remote sensing data of vegetation to resolve changes in Arctic and boreal carbon balance over the past 22 years. The emphasis is on trying to understand the competing influences of the ongoing (and rapid) warming at high northern latitudes on arctic and boreal photosynthesis and respiration. The analysis separately considers changes in the zone from 50 to 60°N and the zone north of 60°N. Summer CO_2 uptake increased in both zones from 1986 to 2007. However, the >60°N zone, which includes most of the tundra biome, had no significant long-term trend in annual CO_2 uptake, with increased July uptake offset by autumn release. The 50-60°N zone, in contrast, showed a trend towards increasing annual CO_2 uptake of an extra 13 Tg C yr^{-1} from 1986 to 2007 with net uptake extending from the summer into the fall. Overall, the analysis suggests that warming at high northern latitudes has caused a small net CO_2 uptake, without (so far) triggering any large releases.

Comparative Study of the Interannual Changes of Atmospheric CO_2 Produced by Biospheric Models

The original proposal called for employing biospheric models LPJ, IBIS, NCAR-CN/BGC and Nemani PEM in a comparative study of interannual variations of atmospheric CO_2, with particular focus on the seasonal cycle. Chris Kucharik (IBIS) of University of Wisconsin had to pull out owing to new funding constraints and Peter Thornton (NCAR) took a new position at Oak Ridge which required a change in his focus. The other three collaborators, Martin Heimann (TM3 model), Wolfgang Cramer (LPJ), and Dr. Rama Nemani (PEM, BGC, meteorological inputs) remain committed to the project. In addition, Dr. Rama Nemani and colleagues at NASA-AMES have produced simulations with the models that might be used for this project. However, during the grant period, we ultimately focused on seasonal and gradient work that involved more fundamental interpretation of our CO_2 and $^{13}C/^{12}C$ observations. We are pursuing the work with biospheric models under a renewal grant.

Water use efficiency

An additional project, as described in the proposal, to analyze the long-term trends in the $^{13}C/^{12}C$ ratio of atmospheric CO_2 to constrain changes in water-use efficiency of land plants, progressed only slowly over the grant period owing to priority given by the PI to other projects. We plan to pursue this study with later funding.

DELIVERABLES

Project Web Page

A group website (http://scrippsco2.ucsd.edu) serves as the primary outlet for data and graphical materials from the program. The target audience includes students, the public at large, the media, and the scientific community. This web site, which was recently developed, and was maintained and further developed under support from this grant, displays updated high-quality plots of the Mauna Loa record and other "classic" plots from the program. The site also includes tabulated data available for download and discussion of the major program elements and their significance. The site continues to be refined and updated in response to user suggestions.

We continue also to submit our data to CDIAC.

Publications

Graven, H. D. 2008. Advancing the use of radiocarbon in studies of global and regional carbon cycling with high precision measurements of ^{14}C in CO_2 from the Scripps CO_2 Program. Ph.D.,University of California, San Diego, La Jolla.

Graven, H. D., B. B. Stephens, T. P. Guilderson, T. L. Campos, D.S. Schimel, J. E. Campbell, and R. F. Keeling, 2009: Vertical profiles of biospheric and fossil fuel-derived CO_2 and fossil fuel CO_2: CO ratios from airborne measurements of $\Delta^{14}C$, CO_2 and CO above Colorado, USA, *Tellus B*, 61(3), 536-546.

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Graven, H.D., T.P. Guilderson and R.F. Keeling, 2011b: Observations of radiocarbon in CO_2 at seven global sampling sites in the Scripps flask network: Analysis of spatial gradients and seasonal cycles*, J. Geophys. Res.,* doi:10.1029/2011JD016535, in press.

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Piper, S.C., R.F. Keeling, P. Patra, and L.R. Welp, 2011, Interannual variations in the seasonal cycle of atmospheric CO_2 at Mauna Loa, Hawaii. In preparation for submission to *Geophysical Research Letters.*

Rafelski, L.E., S.C. Piper and R.F. Keeling, 2009: Climate effects on atmospheric carbon dioxide over the last century. *Tellus Series B-Chemical and Physical Meteorology*, **61**, 718-731.

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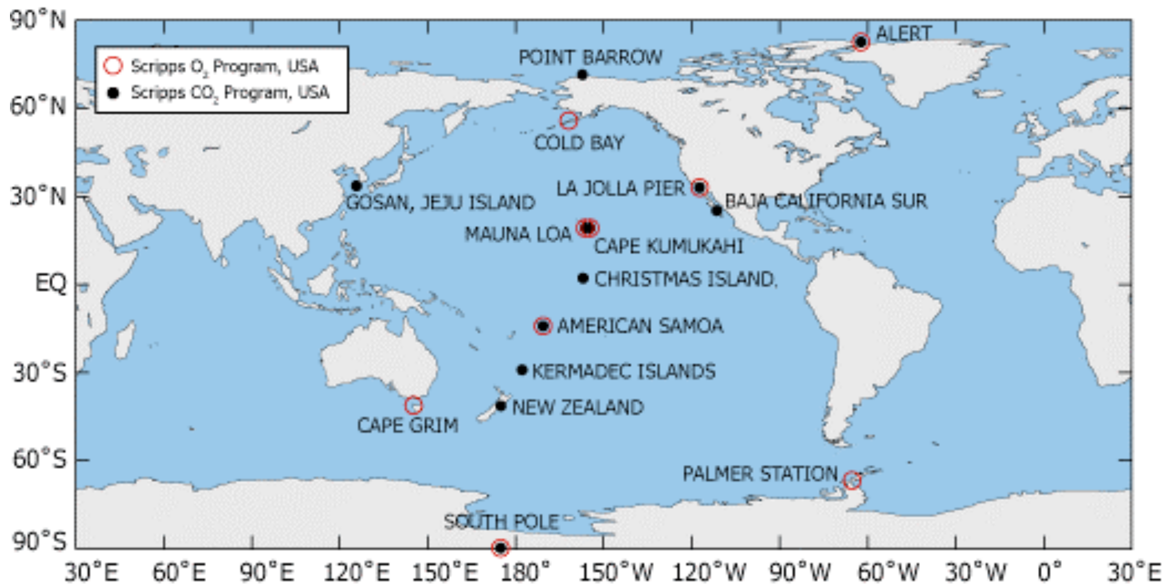

Figure 1. Scripps flask sampling networks. Solid black circles, CO_2 program (solid black circles); O_2 program (open red circles).

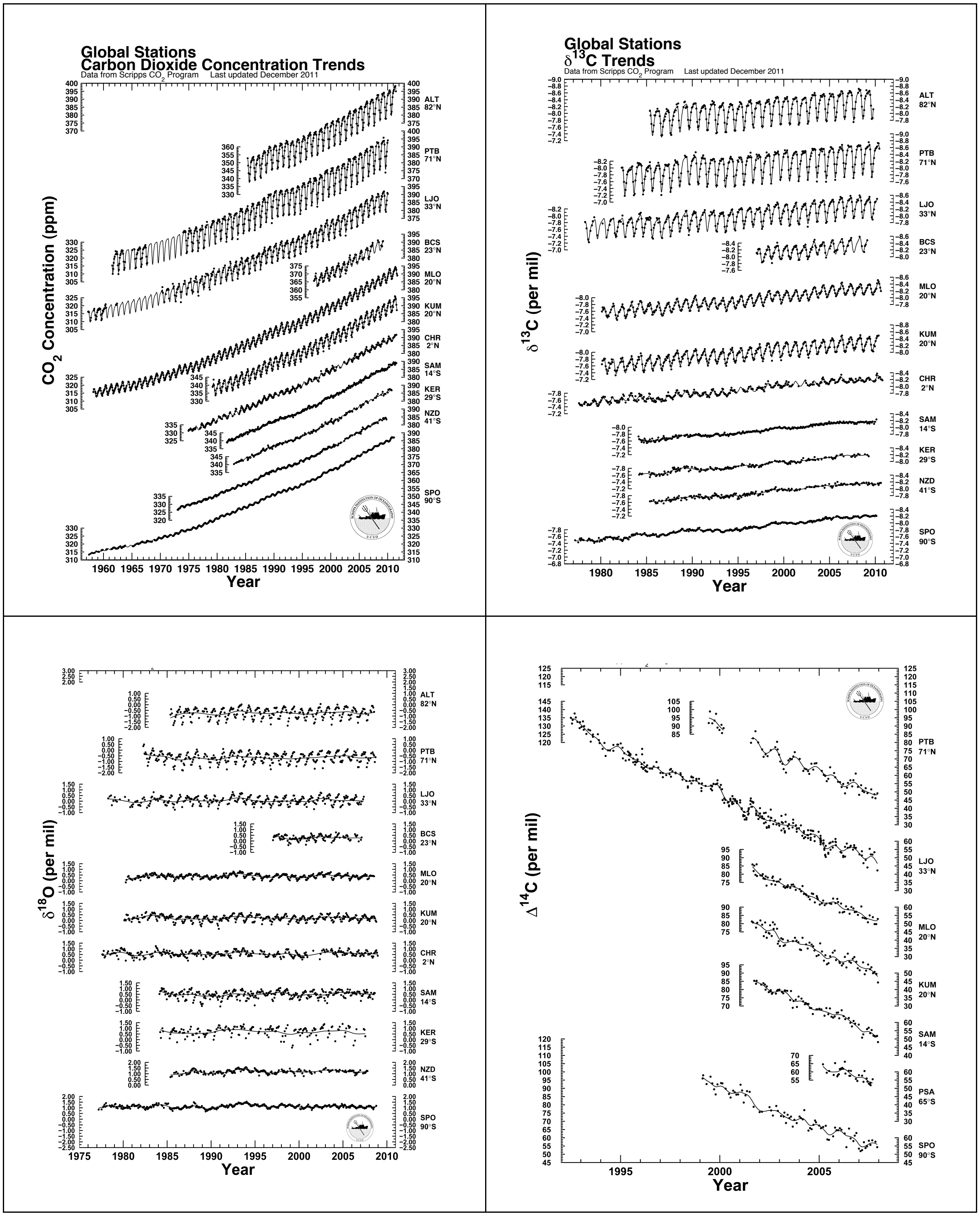

Figure 2. Measurements of the concentration and isotopic abundances ($\delta^{13}C$. $\delta^{18}O$. $\Delta^{14}C$) of CO_2 from flasks collected for the Scripps CO_2 program, Alert Canada (ALT), Point Barrow, Alaska (PTB), La Jolla, California (LJO), Baja California Sur (BCS), Mauna Loa (MLO) and Cape Kumukahi (KUM), Hawaii, Christmas Island (CHR), American Samoa (SAM), Kermadec Island (KER), Baring Head, New Zealand (NZD), and South Pole (SPO).

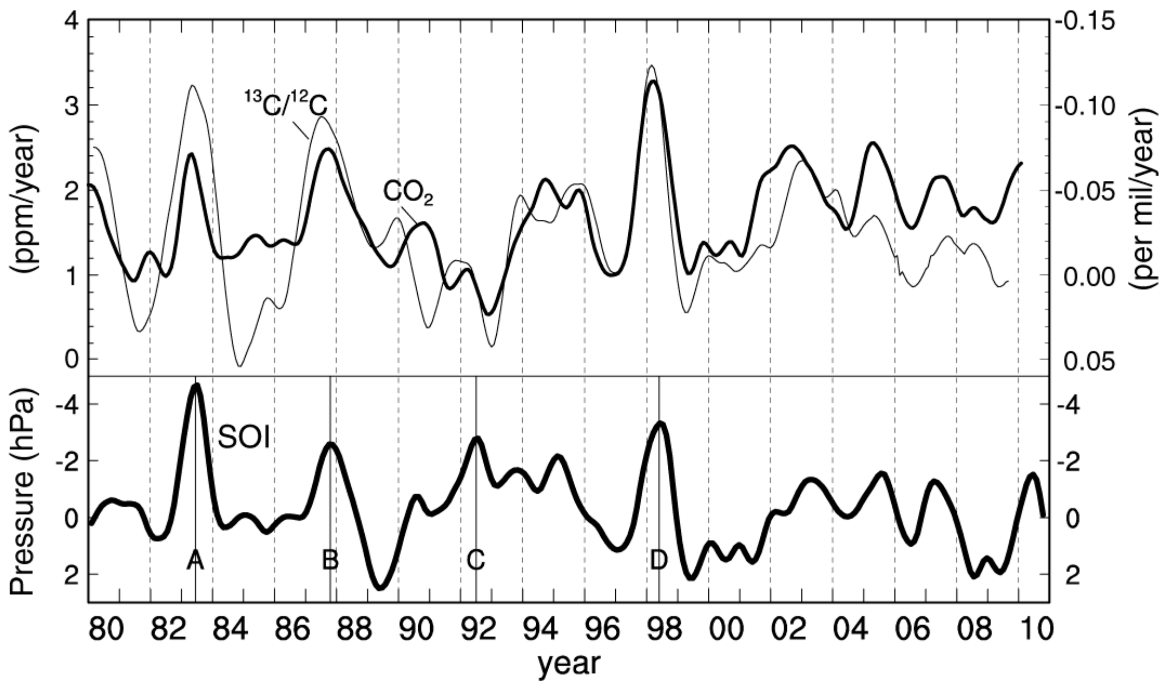

Figure 3. Rates of change of atmospheric CO_2 concentration, in ppm (thick line), and $\delta^{13}C$, in per mil (thin line), averaged from records at Mauna Loa and the South Pole to serve as a global proxy. For comparison, the Southern Oscillation Index (SOI) is shown, calculated as the difference of atmospheric pressure at Darwin, Australia and Tahiti. The SOI is shown inverted and lagged 6 months. Vertical lines labeled "A", "B", "C", and "D" indicate times of minima in the Southern Oscillation index lagged by 6 months.

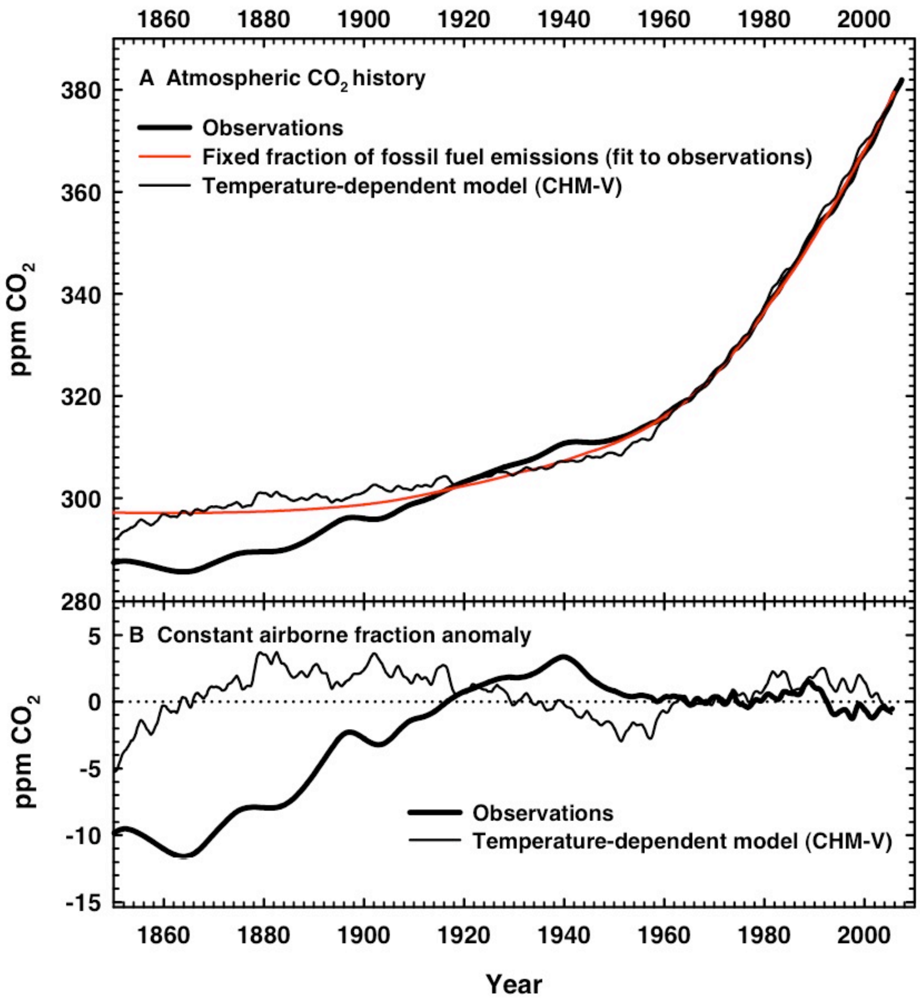

Figure 4. Comparison of observed and modeled trends in atmospheric CO_2 since 1860. A. Observed trend (solid black line) from combining the *in situ* Mauna Loa and South Pole records (after 1958) with the Antarctic ice core record (Meure et al., 2006) (before 1958). The red curve is a fit to the observed trend since 1958 which assumes a constant fraction of fossil-fuel emissions have remained airborne. The thin black curve is a model of the rise which accounts for ocean and land uptake driven by rising CO_2, and the response of short-term land reservoirs to warming via a temperature-dependent respiration. B. Observed and modeled trends expressed as deviations from a constant air-borne fraction. The model can be seen to account very well for the overall CO_2 rise from 1958 to the present. Although the modeled CO_2 is slightly above the observations for a period from ~1992 to 2004, the two curves converge again near the end of the record. The model accounts less well for the changes before 1958. The analysis suggests the possibility, not previously noted, of a ~2 ppm offset between the ice core and *in situ* records in 1958. From Rafelski et al. (2009).

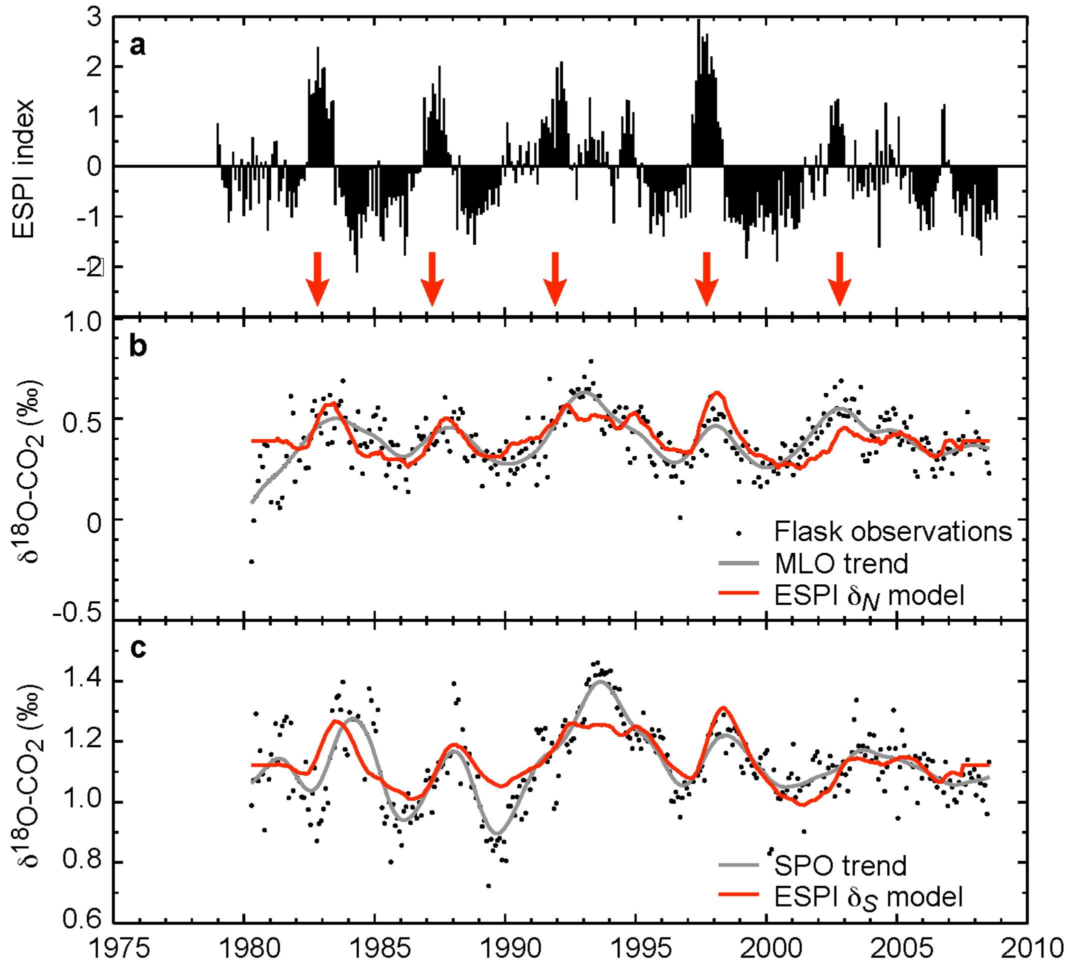

Figure 5. (a) The El Niño/Southern Oscillation Precipitation Index (ESPI), a measure of the large-scale rainfall anomalies associated with El Niño events (Curtis and Adler, 2000). Red arrows denote El Niño events. **(b)** Seasonally-detrended $\delta^{18}O$ of CO_2 from flasks collected at Mauna Loa Observatory (points), with smoothed curve to flask data (grey line) and two-box model driven by EPSI index (red line). **(c)** Same for South Pole. The two-box model has been fit simultaneously to both data sets, with one box representing the northern hemisphere (MLO) and the other the South Pole (SPO).

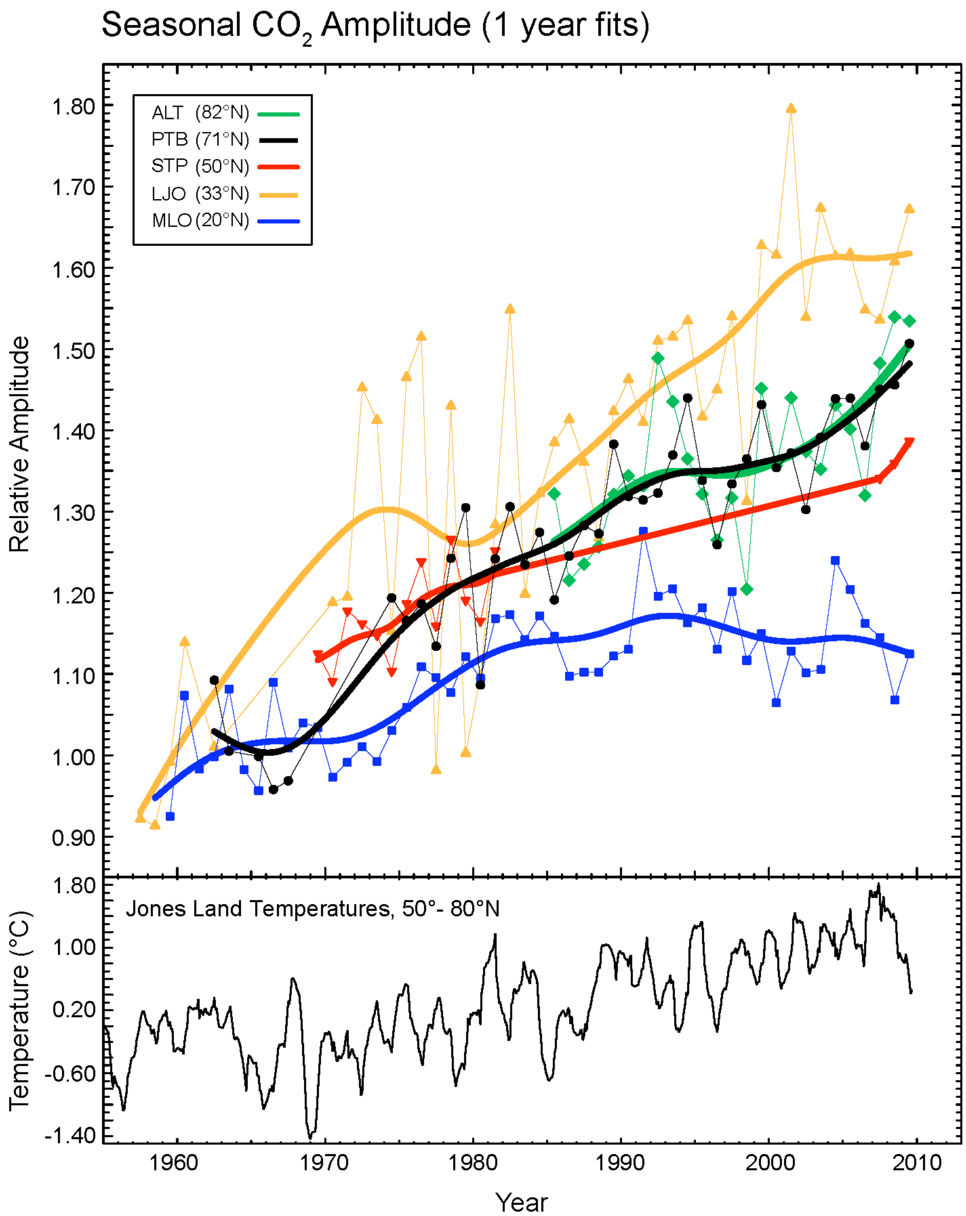

Figure 6. Amplitude of the seasonal cycle in atmospheric CO_2 at northern hemisphere stations. Amplitudes at Barrow (PTB) and La Jolla (LJO) are normalized based on the early years 1957-1962 of the records. Amplitudes at Station Papa (STP) in the Alaskan Gyre and Alert Station are normalized to the overlap with Barrow in their respective early years. Points show amplitudes estimated on an annual basis. Bold curves are stiff spline fits to the annual data. Bottom panel: Land surface temperatures, 12-month running averages of Jones record (Brohan et al., 2006).