Measurements and modeling of CO_2 concentration and isotopes to improve process-level understanding of Arctic and boreal carbon cycling"

Final Report.

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PROJECT GOALS

The major goal of this project was to improve understanding of processes that control the exchanges of CO_2 between the atmosphere and the land biosphere on decadal and longer time scales. The approach involves measuring the changes in atmospheric CO_2 concentration and the isotopes of CO_2 ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) at background stations and uses these and other datasets to challenge and improve numerical models of the earth system. The project particularly emphasized the use of these data to improve understanding of changes occurring in boreal and arctic ecosystems over the past 50 years and to seek from these data improved understanding of large-scale processes impacting carbon cycling, such as the responses to warming, CO_2 fertilization, and disturbance. The project also led to advances in the understanding of changes in water-use efficiency of land ecosystems globally based on trends in $^{13}C/^{12}C$.

The core element of this project was providing partial support for continuing measurements of CO_2 concentrations and isotopes from the Scripps CO_2 program, initiated by C. D. Keeling in the 1960s. The measurements included analysis of flasks collected at an array of ten stations distributed from the Arctic to the Antarctic. The project also supported modeling studies and interpretive work to help understand the origins of the large ~50% increase in the amplitude of the atmospheric CO_2 cycle detected at high northern latitudes between 1960 and present and to understand the long-term trend in carbon $^{13}C/^{12}C$ of CO_2. The seasonal cycle work was advanced through collaborations with colleagues at MPI Jena and Imperial College.

ACCOMPLISHMENTS

A. Measurement activities

A detailed description of measurement activities in Years 1 and 2 was provided in the annual reports for these years. This information will not be repeated for this final report, but for completeness we describe in similar detail activities over the past (final) year. As previously, activities generally continued smoothly, but with several challenges.

In July, 2017, Dr. Steve Piper retired and engineer Adam Cox took over management of the flask program. Fortunately, Dr. Piper will be working 1 or 2 days a week which should help Mr. Cox as he becomes more comfortable with operations of the flask program.

At Christmas Island, flask sampling continued to be problematic. Long-time collaborator Kim Andersen visited the island in April-May 2016 and located and trained a new observer Bwebwentau Raiati. According to Kim, Mr. Raiati has been the person in charge of the island's Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) fallout testing center and does a good job there. Kim sampled air using the NOAA automatic sampling system and apparently Mr. Raiati obtained samples through Oct 2016, but due to problems with Scripps flask inventory and supply, Scripps samples were only obtained in Nov-Dec 2016. Owing to substantial problems with cargo planes and ships those flasks have not been received. Currently, the Scripps record does not include any CO_2 measurements at Christmas Island after January 2016. We have recently received communication that we will be receiving the new 2016 samples soon.

Flask sampling at Raoul Island has remained problematic because winds from the appropriate clean ocean sector have become quite rare according to our observers. In May, 2017, onsite park ranger Paul Rennie was replaced by senior ranger Irene Middleton. Ms Middleton worked for the New Zealand National Institute of Water and Atmosphere (NIWA) for a few years and thus has research experience that may help to improve sampling at the island.

At Samoa, the number of samples rejected for poor quality increased substantially in 2016 and 2017. Two flasks are sampled quickly in succession at each sampling event. A large difference between the 2 flasks of the pair (more than 0.4 ppm) indicates problems in sampling or handling of flasks during transport or analysis. We have not identified the specific causes of problems in this recent period.

B. Data synthesis/modelling activities:

Accomplishments related to the seasonal cycle.

As described in Year 2 report, the PI collaborated with colleagues in MPI Jena on a modelling study of seasonal cycles in CO_2:

Forkel, M., N. Carvalhais, C. Rödenbeck, R. Keeling, M. Heimann, K. Thonicke, S. Zaehle and M. Reichstein (2016). "Enhanced seasonal CO2 exchange caused by amplified plant productivity in northern ecosystems." Science 351(6274): 696-699.

The Forkel et al. study simulated amplitude increases using the LPJmL dynamic global vegetation model and the TM3 atmospheric transport model. This study is significant because LPJml is first model that has been able to simulate increases in the seasonal amplitude as large as those reported by Graven et al. (2013). The ecosystem component of this model was heavily tuned to match empirical data, including FLUXNET data, but not to match satellite greening and seasonal amplitude trends. The model nevertheless reasonably well simulates trends in greening and amplitude since 1980. The model attributes the amplitude trend to a combination of direct warming influences on ecosystem function and an indirect effect via vegetation dynamics on ecosystem structure. The most important inferred structural change is a shift increase in forest cover at the expense of herbaceous cover.

The PI was also an indirect contributor to

Thomas, R. T. et al., (2016). Increased light-use efficiency in northern terrestrial ecosystems indicated by CO2 and greening observations. Geophysical Research Letters, 43(21), 11339-11349. doi:10.1002/2016gl070710

This study uses the Multi-scale Synthesis and Terrestrial Model Intercomparison Project - MsTMIP (http://nacp.ornl.gov/MsTMIP.shtml) to examine the basis for changes in the seasonal CO_2 amplitude and vegetative greenness over the past decades. This work importantly shows that, although nearly all models capture the greening trends reasonably well, they do not capture the increase in CO_2 amplitude. This leads to the suggestion that increased vegetation light-use efficiency (LUE) has contributed to the seasonal amplitude increase and that a mechanism not capture by the models is responsible for this LUE increase.

A third activity related to understanding trends in the seasonal amplitude and supported by this project involves an ongoing collaboration with Christian Roedenbeck of MPI Jena to carry out inverse modelling. This project uses a novel approach, in which the land-atmosphere fluxes are represented by a cyclo-stationary seasonal cycle and annual-mean fluxes (both perhaps with slowly-varying long-term trends), plus fluxes that vary on shorter time scales with which are based on a fixed scaling with land surface temperature. The method optimizes these regional scale factors, the mean cycles, and long-term source/sinks, based on atmospheric CO_2 observations. The method appears to be remarkably robust in the face of even very sparse atmospheric CO_2 data, thus allowing the method to be extended back to the 1960s, when CO_2 coverage was limited. This temperature-based approach supersedes the method described in the original proposal for using a prior model and inverting on differences. A first paper describing the method and applying it to data since 1980 has been drafted. The next step will be to apply it to inverse modelling of the early 1958-1980 period. A major activity of this grant in support of this project involved continued preparation of the early 1960's data, in support of the early inverse modelling.

Accomplishments related to isotopic trends.

The atmospheric isotopic measurements supported the publication:

Keeling, R. F., Graven, H. D., Welp, L. R., Resplandy, L., Bi, J., Piper, S. C., . . . Meijer, H. A. (2017). Atmospheric evidence for a global secular increase in carbon isotopic discrimination of land photosynthesis. Proceedings of the National Academy of Sciences, 114(39), 10361-10366.

This paper reported on the long-term records of $^{13}C/^{12}C$ changes supported by this program. The paper showed that these measurements can be used to quantify specific ecological changes on land, involving the effect of rising CO_2 on water-use efficiency. The water-use efficiency is effectively the amount of water a plant needs to support photosynthesis. As CO_2 rises, plants usually become more water efficient, because they can afford to close their stomata and still support photosynthesis, while losing less water through the stomata. This study quantifies this effect globally, showing that the water-use efficiency has increased effectively in proportion to the amount of CO_2 in air, corresponding to a ~40% increase from pre-industrial times to present. This is a major change in the functioning of our planet's land ecosystems.

This work received notable press coverage (Washington Post, Sept 14, 2017): https://www.washingtonpost.com/news/energy-environment/wp/2017/09/14/some-good-news-about-global-warming-for-once-plants-are-speeding-up-their-use-of-carbon/?utm_term=.b27713a0d505

This project also supported an ongoing collaboration with Lisa Welp and Heather Graven to quantify changes in leaf-level water-use efficiency of arctic/boreal ecosystems using long-term records of CO_2 concentration and isotopic composition at the high northern latitudes from Barrow and Alert stations. This study exploits the ability to resolve the isotopic composition of

CO_2 withdrawn during the growing season over large expanses of the northern hemisphere using the long-term records of $\delta^{13}C$ with CO_2 from the Scripps CO_2 program. A manuscript describing these results, led by Welp, is in preparation.

PRODUCTS AND DISSEMINATION

The primary products of this project to date are the observed changes in CO_2 concentration and isotopic composition. These data are made available on the project website: ScrippsCO2.ucsd.edu. The work supported the following publications described above:

PARTICIPANTS AND COLLABORATING ORGANIZATIONS

1. Name: Prof. Ralph Keeling
2. Project Role: PI
3. Nearest person month worked: 1
4. Contribution to Project: Prof. Keeling has directed the overall project
5. Funding Support: UC California
6. Collaborated with individual in foreign country: Yes
7. Country(ies) of foreign collaborator: Germany, UK
8. Travelled to foreign country: No

1. Name: Dr. Steve Piper
2. Project Role: Specialist
3. Nearest person month worked: 6
4. Contribution to Project: coordinated flask shipments, CO2 analyses, related data workup
5. Funding Support: This project
6. Collaborated with individual in foreign country: Yes
7. Country(ies) of foreign collaborator: Kiribati, New Zealand, Canada
8. Travelled to foreign country: No

1. Name: Alane Bollenbacher
2. Project Role: Staff Research Associated, retired and returned to active duty
3. Nearest person month worked: 0
4. Contribution to Project: Isotope analyses and data workup
5. Funding Support: This project
6. Collaborated with individual in foreign country: No

1. Name: Sara Afshar
2. Project Role: Specialist
3. Nearest person month worked: 0
4. Contribution to Project: coordinated flask shipments, CO2 analyses, related data workup 5. 5. Funding Support: This project
6. Collaborated with individual in foreign country: No

1. Name: Stephen Walker
2. Project Role: Programmer analyst
3. Nearest person month worked: 2

4. Contribution to Project: software support of data reduction and graphics
5. Funding Support: This project
6. Collaborated with individual in foreign country: No

1. Name: Lynne Merchant
2. Project Role: Programmer analyst
3. Nearest person month worked: 1
4. Contribution to Project: data dissemination/ website support
5. Funding Support: This project
6. Collaborated with individual in foreign country: No

1. Name: Bill Paplawsky
2. Project Role: Development Engineer
3. Nearest person month worked: 2
4. Contribution to Project: instrumentation support
5. Funding Support: This project
6. Collaborated with individual in foreign country: No

Other collaborators;
Martin Heimann, Markus Reichstein, MPI Jena
Heather Graven, Imperial College, London
Lisa Welp, Purdue University
KR Kim, Korea National University

IMPACTS:

a. Impact on principle discipline. This project contributes to understanding land carbon cycling through quantifying sink magnitudes, and identifying trends in large-scale metabolic rates. This insight is relevant for improving process level modeling of land ecosystems.

b. Impact on other disciplines: By contributing fundamental insights into how land biospheric processes are changing over time, this project also has impacts on forestry, hydrology, and agriculture. Also, the global nature of the atmospheric observations have impacts also atmospheric science and oceanography.

c. Impact on development of human resources: This project contributes to the career development of students at several collaborative institutions (Jena, Princeton) by motivating modelling studies of land biospheric processes and providing education on carbon processes. The project also contributes to career development of several junior professors: Lisa Welp and Heather Graven, who were previously postdocs under the PI. The data provided by this project, including both flask data and the in situ Mauna Loa record, enables countless projects of students and researchers around the world. The Mauna Loa record is a major teaching resources.

d. Impact on physical, institution, and information resources that form infrastructure: The project helps sustain and improve the Scripps CO_2 program, initiated by CD Keeling in the 1950s, and carried on under the PI. This program contributes widely-sought information resources involving changing CO2 concentrations and isotopic composition in background air. It also sustains and improves measurement capabilities, thus advancing and supporting world-wide CO_2 measurement efforts. The program supports related research efforts at Scripps and elsewhere, including measurements in seawater by Prof. Dickson at Scripps, and measurements in ice-cores by Prof Severinghaus. The capabilities are also relevant for other activities, including ongoing measurement efforts at tracking regional CO_2 emissions, such as the NIST-funded Los Angeles Megacities project. The project helps sustain a facility at Scripps for preparing calibrated gas mixtures in real air that supports measurement efforts elsewhere.

e. What is the impact on technology transfer? Nothing to report

f. What is the impact on society beyond science and technology? The project has broad social impacts via dissemination of background CO_2 data, which serves as a major basis for communicating aspects of global change to an ever more curious public. The PI is a frequent presenter of public lectures on climate change and carbon cycling, with credentials that are sustained by this program.

g. What dollar amount of the award's budget is being spent in foreign countries? < 1% for sampling fees in Kiribati.

CHANGES/PROBLEMS: Nothing additional to report.