Interview with Britton Stephens

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“The amount of knowledge about our earth and the climate system that has been gained from sustained measurements of atmospheric CO_2 and other gases is immeasurable, yet these programmes are required to justify themselves as hypothesis-driven experiments every 3 years to funding agencies with oscillating budgets and priorities.”

Britton Stephens

Britton Stephens is a Scientist III in the Earth Observing Laboratory of the National Center for Atmospheric Research in Boulder (CO, USA). He received a bachelor's degree in earth and planetary sciences from Harvard in 1993 and a PhD in oceanography from the Scripps Institution of Oceanography in 1999. Before joining NCAR in 2002, he completed a post-doctoral fellowship with the National Oceanic and Atmospheric Administration's Carbon Cycle and Greenhouse Gases group. His research has focused on developing and deploying new instruments for tower, ship, and aircraft-based observations of atmospheric O_2 and CO_2, and on synthesizing data sets and models to elucidate global carbon cycle processes.

He maintains a network of CO_2 instruments in the US Rocky Mountains and an O_2 instrument on a ship in the Southern Ocean. His research contributions include a synthesis of airborne data that led to a major revision of model-based estimates of the global distribution of terrestrial CO_2 fluxes.

Britton Stephens speaks to Ruth Williamson, Commissioning Editor for *Carbon Management*, about promising state-of-the-art instruments for measuring atmospheric carbon cycle species, the challenges of conducting research on land, oceans and in the air, and important future directions for carbon cycle research.

Q You are a very active researcher in atmospheric carbon cycle observations. What aspects of climate research led you to specialize in this particular area?

A I spent a lot of time in the outdoors growing up, and loved tinkering with things to figure out how they worked, so building instruments to study earth sciences was a pretty natural fit. I had a great class in atmospheric chemistry in college, and although initially the atmosphere seemed invisible and abstract, I soon realized you could use it to learn about the forests and the oceans on very large scales. What also appealed to me initially was the tangible nature of the research – it was not something far off in the past or the future, or buried in a computer laboratory – you could actually learn something about the global carbon cycle and climate change by going out in the field and measuring what was happening right now.

After college, I got a job for the US Geological Survey, hiking around forests in New England (USA) and Manitoba (Canada) measuring soil CO_2 exchange, and as soon as I realized I could get paid to use my brain and spend time outside, I was hooked. The technical aspects of improving and developing new measurement techniques I also found rewarding. Since the late 1950s,

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progress in understanding the global carbon cycle has largely been driven by advances in observational techniques, and there are still a lot of fun challenges to tackle.

Q Much of your research has focused on new instruments for tower-, ship- and aircraft-based observations of atmospheric O_2 and CO_2. Throughout your career, what have been the most significant advances in atmospheric carbon cycle instrumentation?

A The most significant advances in terms of what we measure – first CO_2, then isotopes of CO_2, then O_2 – all predate my involvement, with the advances since then coming in terms of how we measure these species: on what platforms, with what temporal resolution and comparability and with how much or little effort. In the case of atmospheric CO_2, there has been a considerable contribution from the commercial sector, with the recent advancement by several companies of laser-based cavity-enhanced absorption spectroscopy techniques, which have revolutionized what is possible in terms of long-term measurement stability. As a result, we are currently seeing a dramatic increase in the number of field sites making continuous *in situ* atmospheric CO_2 measurements, as the effort required to make them has come down. There are still many ways biases can creep in, however, so as the field grows we have to ensure that new investigators benefit from the collective wisdom of everyone who has made errors in the past [1].

My contributions have primarily been in the area of surface and airborne atmospheric O_2 measurements. Measuring O_2 at the same time as CO_2 can tell us a lot about what processes are influencing CO_2, as fossil fuels, forests and the oceans all have related but differing impacts on O_2. I am proud of the instruments I have developed, in particular because O_2 is so hard to measure – the required precision is equivalent to detecting the addition of 1 O_2 molecule to 2.5 million molecules of air – but for that same reason, they have not yet seen widespread application.

Q Currently, what would you say are the most promising state-of-the-art instruments for measuring atmospheric carbon cycle species, and what upcoming instrumentation are you looking forward to working with?

A The new laser-based techniques are also being applied to a host of other relevant gases and isotope ratios with great potential for studying the primary anthropogenic GHGs (CO_2, CH_4 and N_2O), along with tracers indicative of key processes (e.g., CO, ^{13}C, ^{18}O) with robust easy-to-deploy instruments. The various flavours of laser techniques do not work similarly well for all species though, so if you want state-of-the-art precision for multiple gases, you still need a combination of instruments. However, progress in this regard is encouraging.

For tracking fossil fuel CO_2 directly, the holy grail for measurements would be an *in situ* radiocarbon (^{14}C isotope of CO_2) sensor, as fossil CO_2 is radiocarbon free. Such a measurement would allow direct verification of country-level fossil fuel emissions, detection of leaks from CO_2 sequestration sites and separation of human components in studies of natural carbon cycling. These measurements are hard because the background level of $^{14}CO_2$ is very low, at only 1 in 10^{12} molecules of CO_2. Currently, flasks of air must be collected, the CO_2 cryogenically isolated and converted to graphite and the graphite then run on an accelerator mass spectrometer, though several *in situ* methods are being pursued. For atmospheric O_2, I am looking forward to continuing work to make the existing methods more robust, so that these can be employed on more platforms and by more people.

Q You were one of the principal investigators on a 3-year global airborne survey of greenhouse and related gases that collected an unprecedented data set of species from the surface to the tropopause, and nearly pole to pole, in all seasons. What were the main outcomes of this research?

A The HIAPER Pole-to-Pole Observations (HIPPO) campaign was led by Steve Wofsy of Harvard (MA, USA) with key collaborators from the National Center for Atmospheric Research (NCAR; CO, USA), the National Oceanic and Atmospheric Administration (NOAA; CO, USA), Scripps Institution of Oceanography (CA, USA), Princeton University (NJ, USA) and the University of Miami (FL, USA). HIPPO used the NSF/NCAR Gulfstream V (GV) research aircraft (HIAPER) to collect an extensive and highly detailed data set of over 90 atmospheric species measured from the surface to 14 km, and from 87 N to 67 S, throughout the annual cycle. The field campaigns spanned 2009–2011, with a total of 434 flight hours and 787 measured profiles. All of the data have been made publicly available [2], and a large number of collaborative efforts with scientists not involved in the collection of the data are now underway.

The atmospheric CO_2 measurements dramatically captured the vertical and latitudinal distribution of CO_2 throughout the Northern Hemisphere on nine unique time slices. Heather Graven (then a post-doctorate researcher at Scripps Institution of Oceanography and now a lecturer at Imperial College London, UK) recently led a paper published in *Science* using HIPPO data to show that the seasonal exchange of CO_2 with northern terrestrial ecosystems has increased by over 50% over the past 50 years [3]. The atmospheric O_2

measurements made during HIPPO clearly reveal seasonal O_2 exchange with the Southern Ocean. The impact of this exchange throughout the Southern Hemisphere troposphere had not been observed before, and capturing both its vertical and horizontal extent provides a means to quantitatively assess estimates of Southern Ocean biogeochemical cycling, independent of atmospheric transport model errors. Measurements of black carbon, water vapour and selected reactive species have also been exploited in early publications, but the vast majority of the measured species have yet to be looked at in detail and I anticipate fruitful research on the HIPPO data set for years to come.

Q Were there any particular difficulties in coordinating such a large research project? If so, how were these overcome?

A The NSF/NCAR GV was brand new when HIPPO was proposed, and while global deployments were envisioned when it was procured, a campaign of the scope of HIPPO had not been attempted before. Each campaign consisted of flights over a 3-week period, from Boulder (CO, USA) to Anchorage (AK, USA), to near the North Pole and back, south across the Pacific to Christchurch (New Zealand), to 67 S and back, and then returning via various routes to Boulder. Staging of support crew and repair parts in the field as for typical airborne campaigns was not possible, so the flight, maintenance and science crew had to be largely self-sufficient.

For a while it seemed as if there was a HIPPO curse, as our planned flight route had to be revised on numerous occasions for natural disasters, including the Christchurch earthquakes, the Samoa tsunami, a volcanic ash cloud over the Southern Ocean and the Japan earthquake and tsunami, but this is probably inevitable when trying to sample in so many parts of the world at once. Also, for the scientists on board a single flight day – including several hours of pre-flight, 8-hours of focused flight activity, an hour of post-flight and many more hours of processing data – proved mentally and physically exhausting. Fortunately, the few maintenance or weather issues to cause delays generally happened to be somewhere with a nice beach, so crew morale remained high.

Q You have maintained a network of mountaintop CO_2 instruments in the US Rocky Mountains since 2005. Nearly a decade on, what important findings have been made from this network?

A The Regional Atmospheric Continuous CO_2 Network in the Rocky Mountains was born out of a collection of autonomous CO_2 sensors originally funded and built for a local-scale CO_2 study at the Niwot Ridge (CO, USA) field site. When this study completed, I saw an opportunity to contribute to the US and global networks of atmospheric CO_2 time-series stations by deploying them semi-permanently at mountain locations in Colorado, Utah and Arizona (USA). We have been successful at piecing together enough support since then to keep five stations going for almost 10 years. The data have been used by the NOAA CarbonTracker system since 2007, and in other global and North American model based flux estimations.

The reason for measuring CO_2 from mountaintops is that very tall communication towers do not exist in the US Mountain West. However, mountaintop measurements challenge current global atmospheric transport models that have coarse topography. One thing we learned was that the CarbonTracker model could not reconcile both the daytime flasks, which have been collected at Niwot Ridge since 1968, and our in situ measurements selected for clean night-time air conditions because the model thinks the site elevation is 1 km above ground. Thus, the utility of all CO_2 measurements in complex terrain will continue to grow as modelling systems and model resolution improves. The Hidden Peak site in Utah has proved to be a useful background site for a number of urban pollution studies in Salt Lake City.

Another Colorado site sits in the bottom of a valley in the Fraser Experimental Forest and records the pooling of forest-respired CO_2 every night. Fortuitously for science, but not for the forest, mountain pine beetles killed most of the trees in this valley soon after our measurements started. Dave Moore (University of Arizona; AZ, USA) and Nicole Trahan (University of Colorado; CO, USA) led a paper last year using the CO_2 data, field studies and satellite data to show that ecosystem respiration dramatically decreased after this disturbance, contrary to some expectations of a large respiration pulse from the newly dead organic matter [4].

Q At sea, you have developed and operate a continuous atmospheric O_2 and CO_2 instrument on a ship transiting the Southern Ocean between Chile and Antarctica. What have been the outcomes of this research?

A As a graduate student in 1998, I spent several weeks making atmospheric O_2 and CO_2 measurements from the ARSV L.M. Gould between Punta Arenas (Chile) and Palmer Station (Antarctica), and have always wanted to go back to extend this work. I finally did get around to writing several proposals and getting funding to do this. We built a new analyzer and in June of 2012 installed it for ongoing measurements on the Gould. It has been running well since, and we now have a 2-year detailed record of atmospheric O_2 directly over the Southern Ocean.

Preliminary results indicate that Southern Ocean O_2 and CO_2 air–sea fluxes are anti-correlated throughout the year, whereas many state-of-the-art ocean biogeochemistry models predict positive flux correlations for much of the time, suggestive of overestimated thermal forcing. I am collaborating with others to compare these measurements to a suite of models and to investigate what processes are responsible for the model–data differences. The *in situ* atmospheric O_2 measurements also show significant enhancements over areas of high biological productivity, such as along the Antarctic Peninsula in summer, and there is potential to use them to learn about local-scale biological processes.

Q Therefore, you have extensive field research experience on land, water and in the air. What would you say has been your biggest achievement in improving our ability to manage carbon?

A It is probably not a field measurement. Rather, I have also done a lot of work synthesizing the output from global carbon cycle models and comparing them to independent data sets to assess their validity. In a 2007 paper [5], I showed that systematic biases in representing vertical atmospheric transport was the dominant cause of variability among the atmospheric CO_2 inverse model estimates of global carbon cycling compiled by the TransCom3 study [6]. Specifically, these models could not distinguish northern extratropical from tropical carbon sinks, and independent aircraft data suggested that the models with weak uptake in the north and weak sources in the tropics were more accurate. This was important because much effort had already gone into trying to find a missing CO_2 sink in the northern extratropics, based on earlier model results, and because the lack of a strong source in the tropics where significant deforestation is occurring suggests that intact forests are a big sink, possibly as a result of CO_2 fertilization.

There had also been a friendly debate in the community about whether model biases or sparse observations were responsible for the large spread in inverse model results. It turns out there is no right answer to this question, but I hope that a lasting impact of this study is that the global carbon cycle research community remembers the importance of comparing posterior model concentrations to observations.

Q What are the challenges in synthesizing global carbon cycle data and models?

A While there are a number of technical obstacles, the biggest challenges are unfortunately cultural. In general, carbon cycle modellers and observationalists are not working closely enough together, such that the observations are not used to their fullest potential and model development is not as rapid as it might otherwise be. For people doing measurements, working across this cultural divide can ensure that their efforts result in observations that are amenable to use by existing models and useful for improving knowledge on larger scales; while for modellers, working across this divide can ensure that their efforts result in models that can be tested with existing data and that they can have input into what new measurements are undertaken.

The bad news is that with no effort the situation can actually get worse. Some of the new data assimilation techniques for atmospheric CO_2 do not automatically produce posterior concentration fields, and even for models that do, the most recent model intercomparison exercise [7] did not collect concentration fields. Thus, while atmospheric CO_2 inverse models continue to diverge by over 4 $PgCyr^{-1}$ on the difference between northern and tropical fluxes [7], we have actually taken a step backwards from the TransCom3 study in our ability to assess these differences in global carbon flux estimates against atmospheric data. The good news is that this can be fixed with just a little a bit of effort on both sides.

Q What do you feel is most important for improving the quality of field-based carbon monitoring research?

A Closer integration of models and data, and modellers and observationalists will certainly help. Clearly, funding and support for long-term atmospheric carbon cycle observations is also a major limitation. Outside of North America and Europe, there are large continental regions with very few carbon-cycle-relevant atmospheric observations. And even in the USA, which has historically led global carbon observing efforts, the NOAA carbon cycle group has experienced significant cuts, and recently the Scripps Institution of Oceanography CO_2 and O_2 programmes have come close to being shut down for lack of funding after 55 and 25 years, respectively. The amount of knowledge about our earth and the climate system that has been gained from sustained measurements of atmospheric CO_2 and other gases is immeasurable, yet these programmes are required to justify themselves as hypothesis-driven experiments every 3 years to funding agencies with oscillating budgets and priorities. If only a tiny fraction of the billions of dollars that are already exchanging hands each year trading carbon credits could be set aside for observations, the field would be on a much more sustainable footing.

Q What emerging research are you currently working on at the National Center for Atmospheric Research?

A My work analyzing the HIPPO and related data sets is currently focused on deriving quantitative estimates of seasonal CO_2 exchange by northern extratropical ecosystems. It turns out that we know this number a lot better than previously thought, and this should help to pin down other more uncertain aspects of the global carbon cycle. I am also working on updating my 2007 study comparing atmospheric CO_2 inverse models to aircraft data, by collaborating directly with interested modelling groups, to learn if atmospheric transport is still a limiting factor. In addition to my shipboard work in the Southern Ocean, I recently submitted a proposal in collaboration with Matt Long, an ocean biogeochemical model developer at NCAR, for an intensive airborne study of O_2 and CO_2 over the Southern Ocean. If funded, the flights would be in early 2016.

Q Is there a particular area of research you are interested in working in that you currently are not?

A I have followed with great interest the various proposals to mitigate climate change through atmospheric CO_2 removal. I think it is clear that negative emissions will be required to avoid the worst impacts of climate change, so the importance of examining these proposals in detail and working on new ideas will continue to grow.

Q What words of advice would you give a young field-based researcher beginning a career in carbon cycle observations?

A Avoid thinking of yourself as someone who just does measurements, and expand your methodological horizons early. Take a numerical methods course. Get a model of whatever you are interested in measuring and ask for help in setting it up and running it. Then spend as little time as possible staring at a computer screen, because you can.

Q Overall, how would you summarize the current status of carbon cycle research in improving our ability to manage carbon, and where you feel the field is advancing?

A We do not have the ability to measure CO_2 fluxes on the scale of a large mitigation project or a country with sufficient accuracy to verify emissions or offsets. Thus, if someone is selling carbon credits for a forestry project or for national emission reductions, the buyer simply has to trust that the offsets or reductions actually occurred. In the worst-case scenario, for all of the money exchanging hands in carbon markets, atmospheric CO_2 will continue to rise just as fast as it would have if no markets were set up. However, regional-scale atmospheric flux estimation techniques are improving, in particular with networks of new robust sensors and high-resolution atmospheric modelling. Important contributions are already being made in rejecting official CH_4 leakage estimates from gas fields as too low [8,9], which gives hope for similar checks for CO_2 sometime in the future.

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