PERSPECTIVE

Observing carbon cycle–climate feedbacks from space

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The impact of human emissions of carbon dioxide and methane on climate is an accepted central concern for current society. It is increasingly evident that atmospheric concentrations of carbon dioxide and methane are not simply a function of emissions but that there are myriad feedbacks forced by changes in climate that affect atmospheric concentrations. If these feedbacks change with changing climate, which is likely, then the effect of the human enterprise on climate will change. Quantifying, understanding, and articulating the feedbacks within the carbon–climate system at the process level are crucial if we are to employ Earth system models to inform effective mitigation regimes that would lead to a stable climate. Recent advances using space-based, more highly resolved measurements of carbon exchange and its component processes—photosynthesis, respiration, and biomass burning—suggest that remote sensing can add key spatial and process resolution to the existing in situ systems needed to provide enhanced understanding and advancements in Earth system models. Information about emissions and feedbacks from a long-term carbon–climate observing system is essential to better stewardship of the planet.

remote sensing | climate feedback | mitigation | ecosystems | Winston Churchill

The carbon cycle is the Earth's most fundamental biogeochemical cycle, yet much of it remains enigmatic; it is a reflection of a planet with life, and its relevance to life has long been apparent. It is quite remarkable and telling that human activity has significantly altered carbon cycling at the planetary scale. The atmospheric concentrations of CO_2 and CH_4 have dramatically exceeded their envelope of the last several million years. This increase is important in itself, and the increases of CO_2 and CH_4 shift the Earth's climate on time and space scales that are important to humans.

The perturbation of the carbon cycle by humans occurs first and foremost through the transfer of carbon from geological reservoirs (fossil fuels) into the active land–atmosphere–ocean system (1–3) and, secondarily, through the transfer of biotic carbon from forests, soils, and other terrestrial storage pools (e.g., industrial timber) into the atmosphere as well as through the additional production of greenhouse gases in managed and agricultural lands (4–6).

Fossil fuel emissions are known best from bottom–up estimates relying on national consumption and energy production statistics. While estimating the carbon released as CO_2 and CH_4 from land-cover and land-use change and animal husbandry remains challenging, it is becoming more certain, partly due to advances in remote sensing (7). Uncertainty of perturbation due to fossil fuel emission on the global carbon cycle will likely grow both in an absolute sense, as fluxes increase and their proportional uncertainty remains stable, and in a relative sense, as more emissions occur in nations or regions with inadequate or poorly developed reporting systems. The current uncertainty of flux estimates of the perturbation is evidenced, in part, by disagreements between top–down derived flux estimates (using atmospheric concentration measurements) and bottom–up inventory methods for both CO_2 and CH_4 (8–10). Quantifying the forcing (emissions) is, obviously, essential to the development of any effective policy frameworks and early evidence from a new satellite mission suggests that a mature

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space-based greenhouse gas observing system could aid in estimating national to regional emissions of fossil CO_2 (10, 11).

Concentrations, however, not only reflect emissions but also are substantially modulated by uptake by terrestrial and marine systems, which reduce atmospheric carbon accumulation by nearly 50%. What controls the quantitative rate of increase in the atmospheric fraction of human CO_2 and CH_4 emissions? Clearly, concentrations are a function of emissions; however, other processes, some of which may be climate dependent, are involved and are not yet well understood. If the balance of sources and sinks changes as a result of carbon–climate feedbacks, then climate forcing and the impact of human activities will change (12).

Understanding and ultimately predicting the stability of atmospheric CO_2 and CH_4 levels in the future are the key concerns that motivate this Perspective. Climate can affect large-scale release of CO_2 from the Earth system. For example, terrestrial tropical ecosystem feedbacks from the El Niño drove an ∼2-PgC increase in global CO_2 emissions in 2015 (13, 14). If emissions excursions such as this become more frequent or persistent in the future, agreed-upon mitigation commitments could become ineffective in meeting climate stabilization targets. Earth system models disagree wildly about the magnitude and frequency of carbon–climate feedback events, and data to this point have been astonishingly ineffective at reducing this uncertainty. Space-based observations provide the global coverage, spatial and temporal sampling, and suite of carbon cycle observations required to resolve net C fluxes into their component fluxes (photosynthesis, respiration, and biomass burning). These space-based data substantially reduce ambiguity about what is happening in the present and enable us to falsify models more effectively than previous datasets could, leading to more informed projections (15, 16).

Remarkably, Earth system processes have produced a relatively stable average proportion of anthropogenic emissions (from fossil fuel combustion, cement production, and land use) being retained in the atmosphere (17) (Fig. 1). The fact that this proportion has remained relatively constant at ∼0.5 over the last 50 y is both interesting and noteworthy. The ratio of the annual increase in atmospheric carbon dioxide to the emissions from anthropogenic sources is called the airborne fraction (AF) and, by definition, represents the proportion of human emissions that remains in the atmosphere—the human effect on the atmosphere and hence on climate.

Earth system models, which reproduce the AF in the present, fundamentally disagree at the process level and consequently disagree when simulating the future. Differences in model parameterizations and structures, despite seemingly similar behavior in the present, are reflected by significant differences when projecting the future. This is important: If the balance among the emissions and the uptake processes changes, then the airborne fraction will change, and, as a result, so will climate forcing (18). Climate-induced feedbacks on the carbon cycle and carbon-cycle feedbacks on climate have long been hypothesized (19). The concentration of CO_2 over the past decades shows substantial variability on interannual to decadal timescales, and the variation shows climate correlations suggesting the imprint of strong climate feedbacks (Fig. 2). However, the mechanisms through which carbon–climate feedbacks occur remain controversial, since few lines of evidence provide unambiguous conclusions about the nature and magnitude of the various effects.

The case for methane is even more complicated. Atmospheric CH_4 is currently at three times its preindustrial levels (15), which is clearly driven by anthropogenic emissions, but equally clearly, some of the change is because of carbon-cycle–climate feedbacks. Atmospheric CH_4 rose by about 1%/y in the 1970s and 1980s, plateaued in the 1990s, and resumed a steady rise after 2006 (20). Why did the plateau occur? These trends in atmospheric methane concentration are not understood (21). They may be due to changes in climate: increases in temperature, shifts in the precipitation patterns, changes to wetlands, or proliferations in the carbon availability to methanogens (22). Current data are insufficient to provide a definitive conclusion (21).

Speaking broadly but accurately, carbon science has been limited by data. Critical regional scales where climate variation produces globally significant carbon cycle fluxes have been all but impossible to observe directly. Since carbon exchange is the net of numerous component fluxes, attributing its variation to underlying mechanisms affecting one or another component have had to be

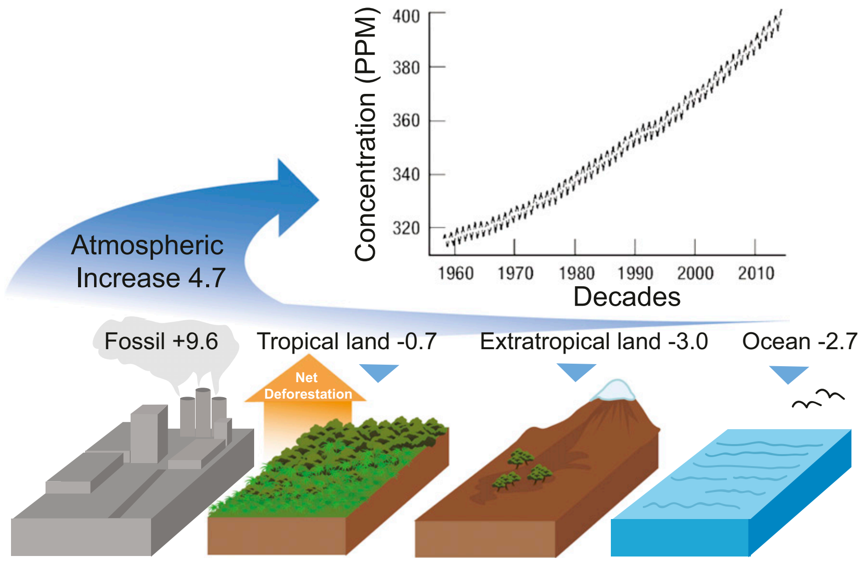

Fig. 1. Earth system feedbacks lead to sinks that absorb about half of anthropogenic emissions, with the remainder contributing to the atmospheric increase. Fluxes are from Le Quéré et al. (17) and partitioned consistent with Fig. 3. This budget is not balanced and includes a 0.6 Pg/y residual flux.

inferred indirectly. Recent work suggests satellite observations can fill the gap in the resolution of processes and regional scales. Research on feedbacks has focused almost exclusively on feedbacks via CO_2 (23); we likewise focus on CO_2 but return to CH_4 and methane–climate feedbacks later in this paper. We also note that there is still a relative scarcity of methane measurements from space—although this is rapidly changing with the launch of TROPOspheric Monitoring Instrument (TROPOMI) on Sentinel 5P (24). We focus primarily on emerging evidence from a variety of sources and argue that by using space-based measurements we can begin to observe the signatures—the time/space and process patterns of flux—of several long-hypothesized feedbacks.

Carbon–Climate Feedbacks in the Contemporary Era

Friedlingstein et al.'s (25) seminal paper outlined the current framework for studying the carbon–climate feedbacks for CO_2. Friedlingstein et al. (25) showed that for CO_2 the carbon–climate feedbacks can, at a high level, be described by the equation

$$g = -\alpha(\gamma_{land} + \gamma_{ocean})/(1 + \beta_{land} + \beta_{ocean}). \quad [1]$$

In this expression, α is the linear climate sensitivity in degrees K/ppm CO_2, the γs are the sensitivities of the land and ocean carbon exchange to climate, and the βs are the sensitivities of the land and ocean carbon exchange to increasing CO_2. By analogy to electrical systems, β and γ are the gain of the carbon–climate system or the extent to which increasing CO_2 affects the concentration of CO_2 directly through concentration and indirectly through climate. Models of the carbon–climate system include both γ and β feedbacks, but current parameterizations vary and produce a wide range of divergent results (25), the iconic Freidlingstein plot.

Current scientific understanding is that roughly 25% of the carbon emitted by anthropogenic sources is being sequestered in the oceans, largely as a result of β or concentration-gradient–driven exchange (26). Ocean models agree on global carbon inventories, but they diverge on the specific regions responsible, which means that apparent convergence of modeled future ocean uptake is not robust. The understanding of future changes to ocean circulation and biogeochemistry remains imperfect; this is understandable, given the myriad positive and negative feedbacks. However, there is an extensive array of physical and biochemical in-ocean tracers, which provide valuable large-scale constraints on the surface exchange of CO_2; such constraints are generally absent for the terrestrial system (27).

Terrestrial feedback effects remain uncertain. While experimental studies consistently show increases in plant growth rates under elevated CO_2 (β, termed CO_2 fertilization), the extrapolation

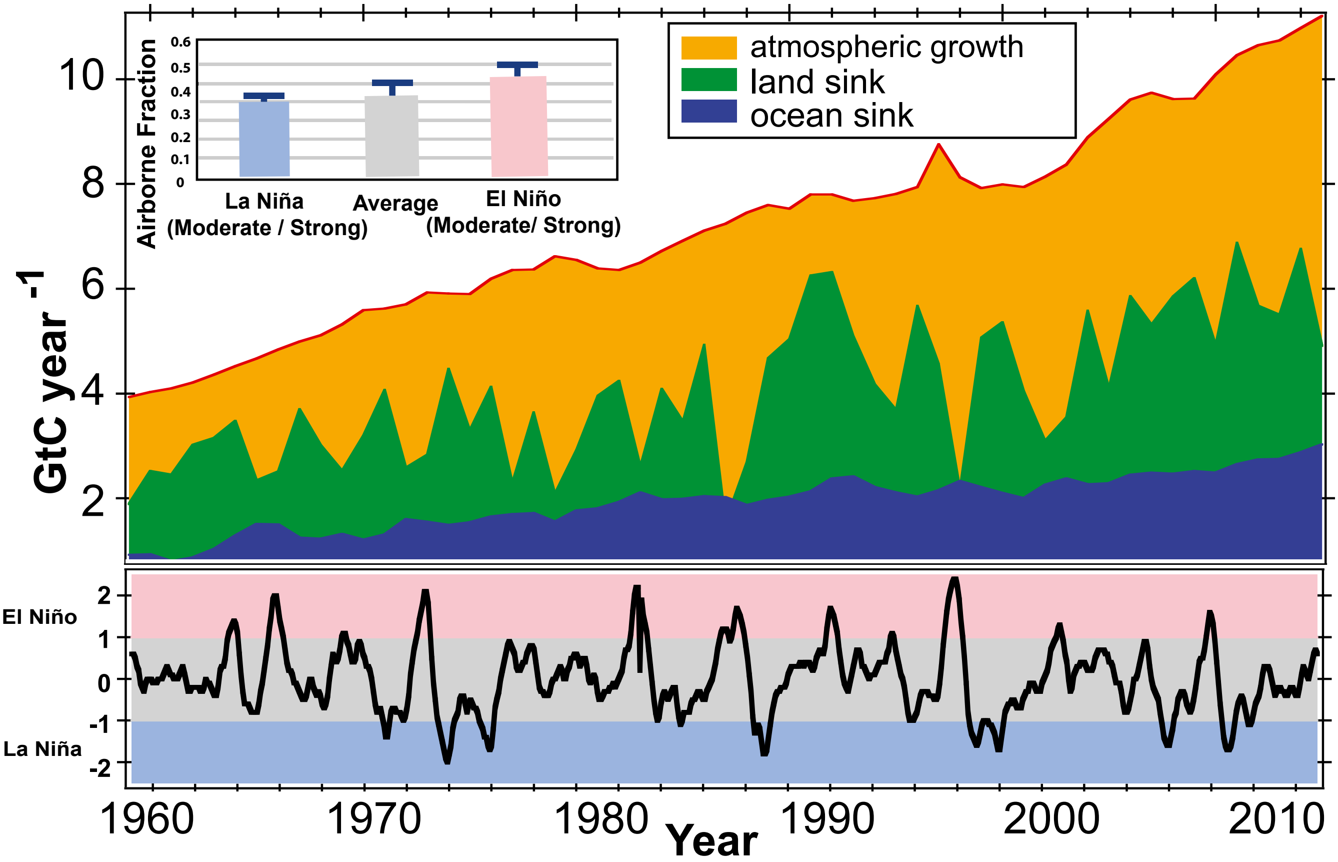

Fig. 2. The fate of fossil fuel over the 1959–2015 CO_2 record, the ENSO cycle, and the AF. Over the long term, atmospheric CO_2 increases relatively smoothly, but varies considerably from year to year, largely due to variable land uptake. Variability in the land uptake is correlated with the El Niño cycle (*Lower*) with more fossil fuel CO_2 remaining in the atmosphere during El Niño periods as a result of reduced land uptake and the opposite in La Niñas (AF *Inset*). Total anthropogenic emissions (including fossil fuel emissions and land use) are partitioned into their fate as atmospheric CO_2 growth (red), land sink (green), and ocean sink (blue). The AF is the ratio of the atmospheric CO_2 to the sum of all three terms. Data are from Le Quéré et al. (17). *Lower* shows the Oceanic ENSO index (68) and *Upper Inset* shows the AF [computed from Le Quéré et al. (17)] binned for the time period when the ENSO index is in the *Top* or *Bottom* shaded region (*Lower*), indicating moderate to strong El Niño or La Niña conditions.

of even the largest-scale experiments to ecosystem carbon storage is problematic and some ecologists have argued that the physiological response could be eliminated entirely by restrictions due to limitation by nutrients or micronutrients (28). However, there is recent evidence from the atmosphere that suggests increasing CO_2 enhances terrestrial carbon storage, leading to the continued increase in land uptake paralleling CO_2 concentrations (17, 29). Fig. 3 shows the carbon budgeting technique, called the "diver-down" method (29, 30). Fluxes in the plot are derived from assimilating either in situ data (for the pre-CO_2 satellite period) or satellite estimates of column-averaged concentrations of CO_2 (for the recent period) into atmospheric transport models (13).

In a diver-down analysis, the global carbon budget (31) is used as a constraint on the net land flux; assimilation of CO_2 data is used to partition the global net land flux between the tropics and the northern extratropics. In situ and inventory information can be used to estimate tropical land use flux, by estimating the sink needed to balance the net deforestation flux so that their difference (net deforestation − sink = estimated net flux) matches the observed net flux (29). Because the net tropical flux for 2010–2013 is small, ~0.2 PgC/y (Fig. 3), this suggests a sink balancing the estimated net deforestation (17) during this period, or about ~0.7 PgC/y, likely due to CO_2 "fertilization" or β. This uptake, which is smaller than the estimate of 1.4 PgC/y similarly derived for earlier decades, may reflect a saturating sink, growing nutrient limitation, or the influence of increasing climate stress.

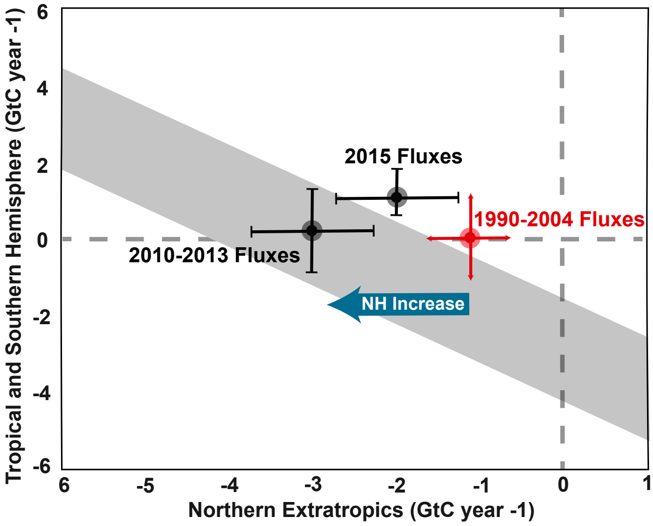

Fig. 3. Decadal increases in northern extratropical uptake and anomalous fluxes during the El Niño year of 2015. Shown is partitioning of the average and 2015 El Niño land sink between the northern extratropics and Southern Hemisphere (SH), 1990–2015. The sum of the northern extratropical and Southern Hemisphere and tropical, SH axis values equals the total land sink and can be compared with the residual land sink from the global budget (indicated by the diagonal band) calculated by the Global Carbon Project, in this case averaged for the years 2010–2016. Any combination of SH and Northern Hemisphere (NH) within the band (± uncertainty, the width of the band) satisfies the global carbon budget constraint. The constraint for the period 1990–2007 was quite different and is not the same as the 2010–2016 band. The average fluxes for the period 1990–2004 are from Schimel et al. (29). The blue arrow indicates the apparent large decadal increase in NH extratropical uptake from the earlier period to the present. The 2010–2013 results are from the Carbon Monitoring System-Flux system (49).

To try to tease apart β and γ feedbacks, Keenan et al. (32) exploited the fact that global warming over vegetated land notably slowed since the start of the 21st century (the so-called temperature pause). Atmospheric CO_2 concentrations continued to rise, and there was also slowing of the growth rate of atmospheric CO_2 between 2002 and 2014. This coincided with a period during which global temperature increases over vegetated land also slowed. This provided an opportunity to test the relative roles of some of the processes creating the enhancement of terrestrial carbon uptake and the consequent decline in the AF. Keenan et al. (32) concluded that the terrestrial sink was enhanced primarily by CO_2 fertilization (β feedback) and secondarily by a slowdown in temperature-driven ecosystem respiration (γ feedback).

Ballantyne et al. (33) both agree and disagree with Keenan et al. (32). Ballantyne et al. (33) find no evidence of increases in primary production during the "temperature pause," but rather attribute the decline in the AF solely to temperature-induced declines in ecosystem respiration (γ feedback). We note that during this temperature pause, and for two decades earlier, there was a pattern of increased terrestrial "greening," observed via trends in satellite vegetation indexes, in the northern extratropics. This increased greening is thought to be the result of a warming climate and increasing CO_2 (CO_2 fertilization), but this causality is not well established and significant debate continues (34–36).

Like the temperature pause, the strong 2015 El Niño provided another opportunity to probe the roles of different terrestrial processes in the carbon–climate feedback. The response of the carbon cycle as expressed by changes in atmospheric CO_2 concentrations during the El Niño has been evident since the early 1980s, and although early work attributed this response to the oceans (37), more recent work has shown that it is largely (38, 39), although not entirely, due to the land (40). Fig. 2 shows the significant year-to-year variation in uptake and release of carbon in the Earth system in proportion to total anthropogenic emissions. A simple analysis shows the effect of the variation on the AF. The average AF, binned by phases of the El Niño Southern Oscillation (ENSO) cycle, reveals a relationship between climate variability and the AF (Fig. 2, *Inset*).

El Niño years tend to be hot and dry in the tropics, while La Niña years tend to be cold and wet (41). While the decadal effect of the terrestrial biosphere is a sustained CO_2 sink, Fig. 2 illustrates the impact of γ. This simple histogram shows that the AF is high during El Niño years, relative to the long-term mean, due to carbon release from ecosystems, and low during La Niña years as a result of larger than usual terrestrial CO_2 uptake. As the tropical climate moves toward El Niño-like droughty conditions, tropical carbon uptake declines or transitions to net emission, while under La Niña conditions, carbon uptake increases.

The asymmetry in magnitude between the La Niña and the El Niño AFs (Fig. 2, *Inset*) is not unexpected, and it likely reflects two factors. First, the terrestrial climate anomalies between La Niña and the El Niño are not mirror images and affect different geographic regions (41–43) and biomes with very different characteristics. Second, terrestrial systems are slow-in/fast-out systems that accumulate carbon over decades at a pace limited by plant growth and soil carbon stabilization, but can lose carbon far more quickly due to wildfire and plant mortality. From this, one would expect a smaller carbon cycle response during La Niña/uptake conditions compared with El Niño/loss conditions of drought (and fire) (losses), as shown in Fig. 2, *Inset*.

Satellite Observations of Carbon–Climate Feedbacks

Satellite observations provide information about the carbon cycle in two ways. First, satellites observe column CO_2 (X_{CO2}) and provide dense sampling of CO_2 in areas of the world poorly observed by the surface observing network, which have been of particular importance in the tropics and have already led to scientific advances. The improvement in sampling has long been anticipated in the literature (44). Second, and less anticipated, satellites provide both the net flux of CO_2 and several of its key process-level fluxes. The ability to measure net fluxes comes from the serendipitous discovery that solar-induced fluorescence (SIF) can be observed, taking advantage of the oxygen-A band. The oxygen-A band is used on greenhouse gas satellites to determine optical path length through the atmosphere (45). SIF is directly correlated with terrestrial photosynthesis, so greenhouse gases satellites provide not only the net flux [net ecosystem exchange (NEE)] of CO_2 but also one of the gross fluxes [photosynthesis of gross primary production (GPP)]. Finally, satellite measurements of CO, a tracer for fossil and biomass burning, have long been available. The combination of X_{CO2}, SIF, and CO allows carbon fluxes to be analyzed in ways fundamentally different from earlier analyses of the surface network. Fossil fuel emission estimates can also be improved using multitracer approaches, including the use of CO and NO_2 (10). Below, we provides examples from recent work that demonstrate the scientific impact of both the density of observations and the availability of NEE, GPP, and biomass burning fluxes.

Inversions of atmospheric concentrations (or mixing ratios) of CO_2 to determine surface fluxes are hugely dependent upon relatively dense satellite observations; this is particularly true in the tropics where in situ measurements are very sparse (46). NASA's OCO-2 was launched just in time to observe the El Niño of 2015 in detail, but the Japanese GOSAT instrument (Table 1), launched in 2009, provided a baseline that could be used to quantify flux changes between years with climatological temperature and rainfall and the El Niño year. Satellite-constrained estimates show the El Niño effect varies regionally within the tropics (13).

Earlier analyses of the El Niño effect of the carbon cycle have, at best, quantified pan-tropical responses with considerable uncertainty about the role of the humid and semiarid tropics. Analyses in Liu et al. (13) exploiting the increased density of observations in the tropics showed that each tropical continent responded to drought conditions, but remarkably simultaneous estimates of CO_2 flux, biomass burning, and photosynthesis from space showed that each continent responded idiosyncratically. These flux differences between years are less sensitive to errors caused by transport or bias in the data, which tend to have some consistency over time (47).

Additional satellite data streams allow further decomposition of the net CO_2 flux into its component fluxes (13). There are now space-based observations of SIF (48), directly related to photosynthesis and hence GPP. Using SIF-derived estimates of GPP together with satellite inversions of X_{CO2} to infer the net terrestrial carbon flux (NEE) and estimates of biomass burning constrained by satellite-based concentrations of carbon monoxide (X_{CO}), the terrestrial carbon balance can be estimated from the equation:

$$\mathrm{NEE} - \mathrm{GPP} + \mathrm{BB} = R_{eco}, \qquad [2]$$

where NEE is the net carbon exchange, GPP is gross primary productivity, BB is biomass burning, and R_{eco} is ecosystem respiration, which can be estimated as the residual. By combining satellite measurements of X_{CO2}, SIF, and X_{CO}, the primary net and contributing gross fluxes of CO_2 can be estimated separately, which enhances the analysis of climate effects on ecosystem processes. In addition, assessing the consistency or contradictions between independent observations of component and net fluxes provides another way of assessing the likelihood of detecting systematic error in one or another of the measurements.

Table 1. Past, ongoing, and planned greenhouse gas missions 2002–2025

Mission (sponsoring agency)	CO_2	CH_4	Orbit	Start–finish
Past				
ENVISAT SCIAMACHY (ESA)	•	•	LEO	2002–2012
Ongoing				
GOSAT TANSO-FTS (JAXA-MOE-NIES)	•	•	LEO	2009–ongoing
OCO-2 (NASA)	•		LEO	2014–ongoing
TanSat ACGS (CAS-MOST-CMA)	•		LEO	2016–ongoing
Sentinel 5P TROPOMI (ESA)		•	LEO	2017–ongoing
Feng Yun 3D GAS (CMA-CNSA)	•	•	LEO	2017–ongoing
Planned				
Gaofen 5 GMI (CNSA)	•	•	LEO	2018–2026
GOSAT-2 TANSO FTS-2 (JAXA/MOE/NIES)	•	•	LEO	2018–2023
OCO-3 (NASA)	•		LEO-precessing (ISS)	2019–2022
MicroCarb (CNES-UKSA)	•		LEO	2020–2025
MERLIN (DLR-CNES)		•	LEO	2021–2024
MetOp-SG Sentinel 5 (Copernicus)	•	•	LEO	2021–2025
GeoCarb (NASA)	•	•	GEO	2022–2025

These missions use passive spectroscopic measurements of reflected sunlight as well as an active laser sensor (MERLIN), deployed in differing orbital vantage points (LEO, GEO, and on the ISS), and provide diverse measurements well out into the future, and require calibration and bias correction and intercalibration against each other. ESA, European Space Agency; CAS, Chinese Academy of Sciences; CMA, Chinese Meteorological Agency; CNSA, Chinese National Space Administration; CNES, Centre National d'Études Spatiales; DLR, Deutsches Zentrum für Luft-und Raumfahrt; GEO, geostationary orbit; ISS, International Space Station; JAXA, Japan Aerospace Exploration Agency; LEO, low Earth orbit; MOE, Ministry of the Environment, Japan; NASA, National Aeronautics and Space Administration; NIES, National Institute for Environmental Studies, Japan; UKSA, United Kingdom Space Agency.

The increased continental-scale resolution of flux and underlying processes (fire, respiration, photosynthesis) provided an entirely new level of detail about carbon cycle responses to climate, foreshadowing the potential of a mature space-based observing system. Focusing on the El Niño droughts of 2015, the increased resolution at subcontinental scales showed that carbon emissions overall increased in tropical forest regions (13) and not primarily in semiarid regions as may have occurred in previous droughts (43). The 2015 El Niño impacts on local climates differed in each tropical forest region, with high temperatures in tropical Africa but near-normal rainfall; whereas in Asia and tropical South America conditions were both hot and dry. The primary biogeochemical responses were revealed by the satellite's combination of spatial and process resolution and were different on each continent as well. All three continents showed release of CO_2, but fire dominated emissions in Asia, based on CO:CO_2 ratios (13). In Amazonia, SIF dropped, reflecting reduced photosynthesis, while in Africa, net carbon uptake declined, but without concomitant reductions in SIF or increases in CO, implying that R_{eco} increased (13).

The strong interannual correlation between tropical climate variability and CO_2 concentration anomalies has been used to provide a simple global constraint on carbon–climate feedbacks (23, 25). By assuming that CO_2 concentration variability reflects global mean tropical climate anomalies, interannual variability of global mean CO_2 concentration provides an observational constraint on carbon cycle model sensitivities to climate, reducing uncertainty about predicted future carbon–climate feedbacks (23). Satellite results show that each tropical continent's El Niño weather could be characterized as drought, but with varying changes to temperature and rainfall. The carbon cycle changes reflect regional extremes and ecological responses that may depend on region, rather than widespread, uniform tropical average changes.

Partitioning net carbon flux into its component fluxes can add insight to variations even at very large scales. The tropics dominated interannual variability in the growth rate of CO_2 over the 5 y previous to the 2015 El Niño (Fig. 4*A*). The longer X_{CO2} and SIF time series, recently published (49), shows that GPP (estimated from SIF) does not fully explain tropical net flux changes over the period 2010–2015 (Fig. 4*B*), as the increases estimated from SIF were only one-third as large as the variation in net exchange, while GPP did not explain extratropical exchange either (Fig. 4*C*). The importance of respiration and fire over GPP in terrestrial flux variability may be a general pattern and not specific to the 2015 tropical response.

While the satellite record is still too short to derive a formal, probabilistic measure of carbon–climate sensitivity, the initial studies described above suggest it will be a powerful tool. Importantly, satellite data do not require collapsing carbon–climate sensitivity into a one-dimensional metric but allow for regions such as the tropics and Arctic–Boreal zone to be assessed separately. In addition, in contrast to flux estimates from the in situ networks, satellite observations allow partitioning of the net CO_2 flux into its constituent process-level fluxes. Initial results suggest strong carbon flux correlations with climate and imply that positive carbon-cycle–climate feedbacks may be more prevalent than anticipated by modeling studies (50).

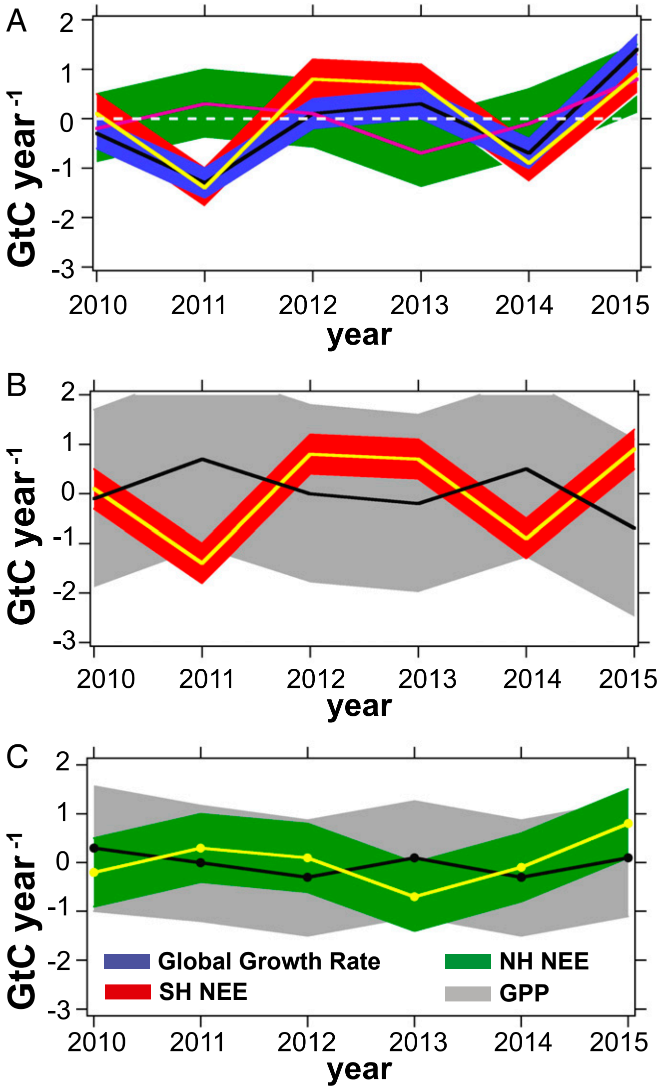

Fig. 4. Net carbon exchange and photosynthesis anomalies over the satellite record for southern and northern land areas. Photosynthesis does not fully explain variation in carbon exchange. (*A*) Tropical variability in NEE (red) dominates interannual variation in the global growth rate of atmospheric CO_2 (blue), with northern (NH) land (green) showing lower and uncorrelated variation. (*B*) Interannual variation in GPP does not explain tropical variability in NEE, suggesting strong roles for fire and/or respiration. (*C*) NH GPP remains relatively constant through the 2010–2015 period, while beginning in 2013, NEE declines by nearly 50%. By convention, +GPP indicates uptake, while −net flux (NEE) indicates uptake. Anomalies are calculated by subtracting the long-term mean to highlight interannual changes and reduce sensitivity to transport and data bias errors.

Methane–Climate Feedbacks

Determining the relative contributions of anthropogenic and Earth system drivers to the CH_4 trends has been challenging due to the uncertainties in all components of the methane budget (e.g., ref. 51) and the sparse observing network (e.g., refs. 52 and 53). Current and future satellite observations may allow progress (8) in resolving these different contributions to the methane budget. In particular, there is significant although not unequivocal evidence that tropical wetlands have played an important role in driving methane trends over the past two decades (e.g., refs. 52 and 54) as a result of their large contribution to the methane budget coupled to substantial variability in tropical precipitation. If true, this suggests significant sensitivity of wetland fluxes to climate, but testing this hypothesis is challenging given the substantial uncertainty in global wetland fluxes (Fig. 1). Fossil and agricultural sources may also have contributed to the methane trends (e.g., refs. 53 and 55), as have changes in the hydroxyl radical (OH) sink (56). A recent inverse model study (57) showed that the current global suborbital observation system for atmospheric methane (including isotopes) cannot unambiguously attribute methane trends to specific source sectors vs. removal by OH; sustained and improved measurements are essential. Continuing as well as new, spatially denser satellite measurements of CH_4 are likely to play an increasing role in understanding CH_4 (Table 1).

Observing System Challenges

To diagnose and quantify feedback processes, extremely valuable and observable geophysical quantities, CO_2 and CH_4 concentrations, can be used to estimate surface fluxes (58). Different processes and regions each present different challenges to obtaining sufficient density and duration of concentration measurements in time and space, reflecting seasonal cycles, cloud climatologies, interferences such as aerosol and albedo, and the sizes of characteristic concentration gradients. Long time series are needed to observe carbon–climate feedbacks as they emerge and to quantify the relationships between climate and anomalous fluxes, requiring a sustained observing system and the ability to intercalibrate successive sensors.

All of the known remote measurement techniques, whether using reflected sunlight or active laser illumination, are subject to bias errors, where the true signal is modified by other atmospheric and surface effects and these systematic errors may have regional variation. Systematic error may result from surface albedo, atmospheric aerosols and their height distribution, thin clouds, and other challenging but correctable effects (59). Active (LIDAR) greenhouse gas measurements may be less susceptible to these biases, but this has not yet been demonstrated in the field.

While today's greenhouse gas instruments were designed to meet standards for accuracy and precision determined by global-scale gradients of CO_2 and CH_4 (60), next-generation approaches will have to target regional and even subcontinental carbon-cycle processes. Systems including passive spectroscopy for wide coverage and active sensors capable of winter measurements for high latitudes, as well as constellations of satellites contributed by multiple spacefaring nations, are attractive intuitively, but calibration of each sensor against the others must be a part of an overall strategy, requiring maintenance and expansion of the in situ and Total Column Carbon Observing Network (TCCON) networks. There is also the emerging possibility of land-focused geostationary satellites such as GeoCarb (61). Global terrestrial coverage could be provided by three to four geostationary platforms (e.g., roughly 110°W, 70°W, 85°E, and perhaps on the prime meridian), but would not observe oceans and high latitudes.

Building an optimal (or reasonably optimal) carbon–climate observing system from the existing and planned sensors (Table 1), likely launched by at least seven space agencies, plus new investments in missions and technology yet to be made, requires careful analysis of the science and how it is affected by the variables measured by the observing system (X_{CO2}, X_{CH4}, CO, SIF, etc.) and their sampling in time and space, accuracy, and precision. The specific observing challenges (clouds, sunlight, observing mode, expected signal size, and bias error) must be incorporated into analysis tools. Once these factors are quantified, then the uncertainty of the derived flux estimate from simulated concentration (mixing ratios) measurements of CO_2 and CH_4 (X_{CO2} and X_{CH4}) can be estimated and quantified. Since massive investments are required for a global carbon observing system, and substantial sums have already been expended, our first author reminds us that Winston Churchill once said, "We have run out of money, now we must think."

With diverse and conflicting requirements and at any fixed cost, either carbon–climate feedback questions must be prioritized, leaving some regions and processes less adequately observed, or a constellation of instruments must be developed. The most cost-effective approach to this is not self-evident. Additionally, because of the mass balance constraint on fluxes (because the global budget is relatively well known), there is synergism between observing systems that produces added information; but realizing this requires addressing calibration and bias correction that depends on the robust network of surface concentration TCCON X_{CO2} (59) measurements.

The Way Forward

Thinking today, as in the Churchill quotation above, requires more than just cogitation; it now depends on computation as well. Carbon scientists, recognizing the challenge of a carbon and climate observing system, have long used simulation, sometimes borrowing a concept from meteorology—observing system simulation experiments (OSSEs)—to design optimal observing strategies. The first such study examining the carbon cycle was Rayner et al. (38), which focused on CO_2 and enhancing the surface observing network. That study identified one site in the Amazon as providing the largest marginal reduction in uncertainty. Carbon-cycle OSSEs begin by assuming or simulating a set of surface fluxes, the "truth" (often referred to as a 'nature run') to create a simulated global pattern of concentrations using an atmospheric transport model to translate fluxes into concentrations. Those concentrations are then translated into observations using a model of the proposed instrument and its interaction not only with CO_2 but also with factors that interfere with the observation, such as clouds, aerosols, surface albedo, and viewing geometry. The set of simulated observations is used to estimate fluxes, and the estimated fluxes are compared with the nature run.

OSSEs allow quantification of the uncertainty of the observing system. Since the release of Rayner et al.'s (38) original paper, OSSEs have played a significant role in the design of NASA's orbiting carbon observatory mission (60, 62), have aided NASA and the European Space Agency (ESA) in designing follow-up missions (63), and were critical to NASA's decision to select a geostationary (GEO) carbon observatory for X_{CO2} and X_{CH4}. Recent OSSE documents, for example, outline the advantages of persistent observations from GEO [potentially multiple observations per day compared with ∼1/mo for similar low-Earth orbiting (LEO) approaches] for resolving both small-scale biogeochemical and regional urban processes (2, 64). Other studies identify the need for winter measurements at high latitudes where low solar angles and short days limit the use of reflected sunlight spectroscopic measurements, and either airborne in situ or active remote sensing using laser measurements is required (63).

Planning greenhouse gas missions and their scientific exploitation is especially challenging as the actual retrieval, the vertically integrated amount of the gas in question, is, for the most part, not the quantity of scientific interest. Instead, the surface fluxes, deduced from the time–space patterns of concentration in combination with atmospheric transport, are the focus of research (44, 62). This requires advancing the capability for mission simulation and extending it to multiple tracers beyond the current state of the art; this is a scientific undertaking in and of itself, in the spirit of the very first OSSE study by Charney et al. (65) in 1969 as part of the Global Atmospheric Observing Program.

Conclusions

The carbon cycle, a focus of sustained research since the 1950s, contains a mystery that grows more and more perplexing over time. How does the mean AF of CO_2 remain so constant for such a sustained period of time, while at the same time varying so substantially year to year? We have no robust quantitative or predictive explanation for this or for the variation in the growth rate of CH_4; although models have been tuned to reproduce observed behaviors, these same models predict wildly varying greenhouse gas concentrations in the future.

The sparsity of data on carbon fluxes over regions corresponding to today's major climate anomalies (42, 66) has limited our ability to quantify the strength of carbon–climate system feedbacks, since the majority of the in situ observing effort is in the midlatitudes, while the potential feedbacks are largest at high and low latitudes where the majority of terrestrial carbon storage resides. Synthesis of existing observational studies, including new satellite results, demonstrates strong coupling between the carbon cycle and the climate system and, as records lengthen, should increasingly inform us about carbon-cycle feedbacks.

As Pierre Friedlingstein observed in a presentation at a March 2015 workshop (67), in situ networks alone have "no hope of being a strong constraint over carbon–climate feedbacks," while measurements of atmospheric concentrations of CO_2 and CH_4 from space have "clear potential to constrain carbon cycle feedback uncertainty." Phillipe Ciais, at that same workshop (67), amplified Friedlingstein's comment by noting that to quantify carbon–climate feedbacks, it was essential "to characterize carbon flux anomalies at the spatial scale of climate anomalies," scales which surface networks simply cannot resolve, but for which space-based methods are proving well suited (13). As satellite records lengthen the quality of data products improves; in addition, the coverage from multiple missions (Table 1) further increases the density of observations. As this happens, the utility of the satellite observations of NEE, GPP, ecosystem respiration, and biomass burning for constraining global and longer-term carbon–climate feedbacks will increase.

Satellite observations add a significant tool for capturing fluxes at crucial scales intermediate between the global and the local and allowing the observation of the processes that link climate anomalies and carbon fluxes that affect the global budget. Satellites not only add density of observations, but also deepen the ability of scientists to probe the carbon cycle by partitioning the net exchange of CO_2 into some of its key component gross fluxes. These component fluxes each respond to the environment independently and the apparent climate response of their sum, NEE, is difficult to attribute unambiguously to particular mechanisms. As a result, the suite of space-based measurements of net and component fluxes will provide additional insight into how climate affects the carbon cycle. Advancing these capabilities requires continued effort on the development of missions, the maturation of algorithms, calibration and validation procedures, and improved inverse and assimilation models, as well as the integration of multiple tracers of both Earth system and anthropogenic processes.

The challenge is of more than just scientific importance. Carbon–climate feedbacks influence future climate uncertainty and could confuse emission reduction targets. Proposed and agreed-to mitigations of emissions assume a relationship between emissions, concentrations, and, ultimately, climate, but perhaps as a result of model uncertainty, future changes to the AF have not been transparently integrated into negotiating frameworks. Carbon–climate feedbacks affect the emission–concentration–climate relationship and control the magnitude of reductions required to achieve any given temperature target (15). For example, 2015–2016 El Niño carbon-cycle carbon anomalies added nearly 30% to the annual growth rate of CO_2. That increase, sustained, would have major implications for mitigation. The anticipated global challenges and costs of mitigation are high enough that reducing carbon-cycle–climate feedback uncertainty will significantly aid in planning efficient and effective action and reduce surprises that could disrupt agreements.

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