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Chapter 2
Observing a Vulnerable Carbon Cycle

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2.1 Introduction

The carbon cycle and indeed the entire earth system are now inextricably linked with human activities (Global Carbon Project 2003; Steffen et al. 2004; Field and Raupach 2004), so that the 'carbon–climate–human system' constitutes a single, coupled entity in which interacting processes link all of its major components. Linking processes of primary significance include

1. The human drivers of energy consumption and land-use change, through increases in both population and per capita consumption
2. The role of human energy systems as sources of CO_2 and other greenhouse gases (GHGs)
3. Land-use change (deforestation, increases in agricultural and urban land use) and its consequences for both GHG emissions and resource (water, land, ecosystem) condition
4. Climate forcing by CO_2 and other GHGs, following from drivers 1, 2 and 3
5. The changing roles of the ocean and the terrestrial biosphere as sinks and sources of CO_2 and other GHGs, driven by the disequilibrium of the earth system through human activities
6. Impacts of climate change through declines in resource condition and human well-being
7. Attempts by human societies to reduce their impact on the global environment, for example, through reductions in GHG emissions to avoid 'dangerous climate change' (Schellnhuber et al. 2006)

Through the first six of these processes humankind is unintentionally influencing the earth system, while the seventh is an effort to manage global-scale human impacts on the earth system by mitigating their causes.

An integrated global carbon observation system (Ciais et al. 2004) is a contribution to monitoring the first six of the above processes, and bringing about the seventh. These underlying motivations lead to two broad goals for global carbon observations, respectively oriented towards understanding and management. The former goal is to provide increased understanding of the cycles of carbon and related entities (water, energy, nutrients) in the earth system, contributing to our ability to diagnose trends and to predict future evolution of the carbon–climate system over timescales of decades to centuries. The latter is to provide the global-scale observations of carbon fluxes and GHG emissions needed to manage the carbon cycle, through emissions reduction programmes based on incentive, regulatory or trading mechanisms. Between them, these two goals largely determine the necessary broad attributes of a global carbon observing system. A recent analysis (Raupach et al. 2005) identified seven main attributes for terrestrial carbon observation, which (with slight extension) provide a broad specification of attributes for a complete global carbon observing system. These seven are (1) scientific rigour; (2) global scope and consistency; (3) spatial resolution sufficient to resolve and monitor all important processes, especially carbon fluxes associated with human land use and energy systems; (4) temporal resolution sufficient to monitor variability in fluxes from weather to climate timescales; (5) integrated monitoring of all relevant entities [CO_2, CH_4, CO, volatile organic compounds (VOCs), black carbon, together with fluxes of water, nutrients and other entities relevant in modulating carbon fluxes]; (6) process discrimination (for instance, between anthropogenic and non-anthropogenic fluxes, and between contributions to net fluxes such as assimilation, autotrophic and heterotrophic respiration); and (7) quantification of uncertainty.

Here, we discuss the implications of carbon–climate vulnerabilities for the attributes of an integrated carbon observation system. By 'carbon–climate vulnerability' we mean a positive, disturbance-amplifying feedback between an aspect of the carbon cycle (a pool or flux) and physical climate, including atmosphere, oceans and the hydrological cycle. In particular, carbon–climate vulnerabilities are processes causing global warming through the enhanced greenhouse effect to be larger than it otherwise would be in their absence.

Two ways have been used recently to quantify carbon–climate vulnerability in the above sense. The first is a risk-assessment methodology (Gruber et al. 2004, henceforth G2004) involving heuristic, judgement-based estimates of the releases of carbon to the atmosphere from several terrestrial and oceanic pools under projected changes (to 2100) in temperature, ocean circulation and other physical climate properties. G2004 expressed the results of the assessment as ellipses on a plane with axes defined by the mass of carbon released and a qualitatively judged probability of release (with small releases having high probability and vice versa). This approach is a valuable beginning, but cannot properly quantify carbon–climate feedbacks by estimating the extent to which a carbon release is modified by the extra climate change induced by the release itself.

The second, much more quantitative approach is through the use of fully coupled carbon–climate models. Eleven such models were compared in the recent Coupled Climate–Carbon Cycle Model Intercomparison Project (C^4MIP) (Friedlingstein et al. 2006). The models included full physical climate, ocean carbon biogeochemistry responsive to temperature and atmospheric CO_2 and terrestrial carbon dynamics responsive to light, water, temperature and CO_2. All models were run from 1850 to 2100 under a prescribed emissions scenario (the IPCC SRES[1] A2 scenario; see later

[1] IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emissions Scenarios.

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for details). The results showed that coupling of the carbon cycle to climate through temperature-dependent processes led to increased atmospheric CO_2 in 2100 of 20–200 ppm (augmenting a CO_2 concentration of around 700 ppm, depending on the model) and an increase in predicted global temperature of 0.2–2 °C (augmenting an enhanced-greenhouse-induced warming of around 4 °C, likewise depending on the model). There were substantial differences among the ten models, stemming both from carbon cycle parameterisations (for instance, the temperature response of terrestrial heterotrophic respiration) and from the behaviour of modelled physical climate (for instance, the tendency of some of the models to dry out the Amazon as the model climate warms). As a means of studying carbon–climate vulnerabilities, fully coupled carbon–climate models are comprehensive, but they are laborious and difficult to parameterise because of model complexity. The extensive C^4MIP runs to date have focused on only a few of the potentially important feedback processes.

In this chapter, we analyse carbon–climate vulnerability and its implications for carbon cycle observations. The plan of the chapter (following this brief introductory section) is that Sect. 2.2 surveys the major feedbacks in the carbon–climate–human system at a general level, including forcing by and feedbacks on human actions. Section 2.3 focuses on carbon–climate feedbacks involving terrestrial processes, drawing from C^4MIP results and other sources. Attention is given to both CO_2 and CH_4. Section 2.4 proposes a perturbation-based approach using simple models for analysing carbon–climate vulnerabilities and illustrates the approach with a semi-quantitative evaluation of the response of permafrost carbon pools to global change. Finally, Sect. 2.5 discusses the implications of carbon vulnerability for integrated carbon observation.

2.2 Feedbacks and Vulnerabilities in the Carbon–Climate–Human System

The trajectories of climate and the carbon cycle are coupled by atmospheric composition. Of the linking groups of processes mentioned in Introduction, four are of central importance for feedbacks and vulnerabilities in the contemporary carbon–climate–human system. The first is enhanced radiative forcing by GHGs, CO_2 and CH_4 being the largest contributors. The other three correspond to the three major groups of fluxes in the atmospheric CO_2 and CH_4 budgets: emissions from human activities, ocean–atmosphere exchanges and land–atmosphere exchanges. Section 2.2.1 focuses on land–atmosphere exchanges in more detail, but before doing so, we examine all four groups of processes in general terms.

2.2.1 Radiative Forcing

The carbon cycle accounts for some, but not all, of the processes involved in the radiative forcing of climate. Total radiative forcing can be considered as the sum of

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three contributions: (1) from CO_2, (2) from non-CO_2 GHGs (mainly CH_4, halocarbons, N_2O, ozone) and (3) from non-gaseous mechanisms (mainly aerosols, albedo changes, solar variations). The first two are relatively well known (IPCC 2007): the current (2001–2005) radiative forcing from CO_2 is +1.66 ± 0.17 W m^{-2}, and the forcing from non-CO_2 GHGs is about +1.3 W m^{-2} (+0.48 from CH_4, +0.34 from halocarbons, +0.16 from N_2O and +0.30 from ozone). The third contribution, from aerosols, albedo changes and solar variations, is highly uncertain but is considered to be negative, current estimates being around −1.3 ± 1 W m^{-2} (IPCC 2007). The current net radiative forcing (+1.6 W m^{-2}, range +0.6 to +2.4) drives global warming (at about 0.016 °C y^{-1}over the period 1980–2005). Thus, current net radiative forcing is approximately equal to the radiative forcing from CO_2 alone, with other contributions approximately cancelling. This does not imply that *future* forcing will behave this way, because all three contributions to radiative forcing are dependent on emissions scenarios and also on future climate through climate feedbacks, so the three contributions will evolve differently under these influences. In summary, a carbon budget and a radiative forcing budget are different entities, but they share a large common term associated with rising atmospheric CO_2.

2.2.2 *Emissions from Human Activities*

The global balance of atmospheric CO_2, shown in Fig. 2.1, demonstrates that human activities are the overwhelmingly dominant contribution to the current disequilibrium of the global carbon cycle. Fossil-fuel emissions were about 7.2 ± 0.3 Pg C y^{-1} for the period 2000–2005, and increased at over 3% y^{-1} for 2000–2005 compared with 1% y^{-1} for 1990–1999 (Canadell et al. 2007a; Raupach et al. 2007). Emissions from land clearing have changed more slowly, averaging about 1.5 ± 0.5 Pg C y^{-1} (Canadell et al. 2007a).

The atmospheric CH_4 balance involves ten major source terms and three sink terms, and is discussed in more detail later. Of the current total source, about 2/3 is anthropogenic.

The four main groups of IPCC SRES scenarios (Nakicenovic et al. 2000) all involve major increases in CO_2 emissions over the period to 2100 (Table 2.1), ranging from 12 to 17 Pg C y^{-1} in 2050 and from 7 to 30 Pg C y^{-1} in 2100. Methane emissions are also projected to increase in most scenarios. From the present standpoint of vulnerability analysis, the important question is: are these emissions scenarios significantly dependent on climate itself, so that different emissions scenarios would result from different climate change scenarios? While climate is just one among the many economic, social and environmental factors influencing the scenarios, there are potential mechanisms for feedbacks on emissions scenarios from climate change. Examples include increased energy use to buffer against adverse effects of climate change (e.g. air conditioning), increased energy use to augment resources threatened by climate change (e.g. desalination to supplement water supplies) and increased military energy use brought on by climate-induced geopolitical instability.

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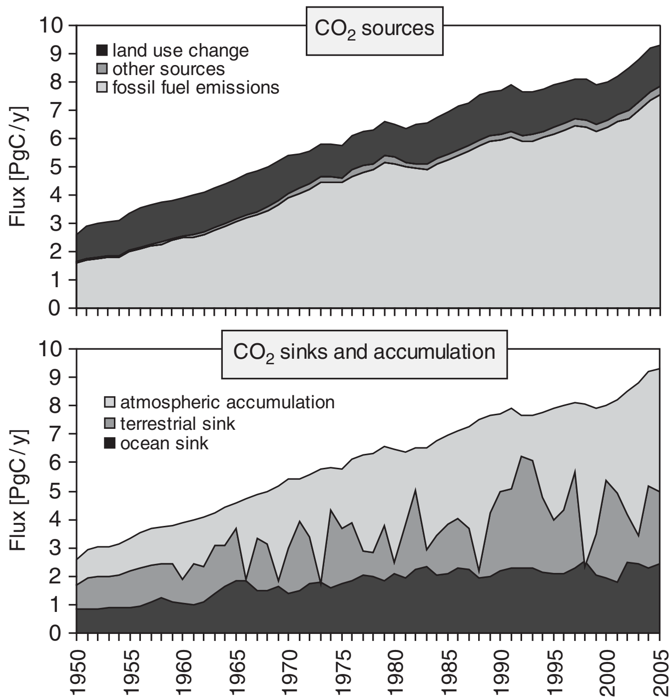

Fig. 2.1 The global carbon budget for the period 1950–2005, showing terms in the CO_2 mass balance: [atmospheric CO_2 accumulation] = [emission flux from fossil fuels] + [other industrial emissions] + [emissions from land-use change] – [flux to terrestrial sink] – [flux to ocean sink]. Data sources as in Canadell et al. (2007a), with atmospheric CO_2 change from ice core data (Law Dome, Antarctica; Etheridge et al. 1998b) before 1959 and direct measurements (Keeling and Whorf 2005) after 1959. Net terrestrial uptake is inferred by difference (total emissions less ocean uptake).

Table 2.1 Indicative fossil-fuel emissions of CO_2 under four major IPCC SRES emissions scenarios (Nakicenovic et al. 2000)

Scenario	Global-local orientation	Economic-environmental orientation	Fossil-fuel emission (PgC y^{-1}) in 2050	Fossil-fuel emission (PgC y^{-1}) in 2100
A1B	Global	Economic	17	15
A2	Regional	Economic	15	30
B1	Global	Environmental	11	15
B2	Regional	Environmental	12	7

There are three variants of the A1 (globalised, economically oriented) scenario: A1B (balanced), A1T (technologically innovative) and A1FI (fossil-fuel intensive), leading to very different emissions trajectories. Only the A1B scenario is used here

2.2.3 Ocean–Atmosphere Exchanges

The ocean is a major CO_2 sink, currently absorbing about 25% of fossil-fuel emissions (Fig. 2.1). This will continue over the next century according to C^4MIP carbon–

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climate models (Friedlingstein et al. 2006). There are several timescales for ocean–atmosphere exchanges related to different ocean carbon pools, but even the shortest is long enough for ocean uptake of CO_2 to be fairly smooth from year to year (Fig. 2.1). Several reviews (Jacobson et al. 2000; Steffen et al. 2004; Le Quere and Metzl 2004; Greenblatt and Sarmiento 2004) describe the processes involved, which include (1) *air–sea exchange* of CO_2, driven by the difference in CO_2 partial pressure (pCO_2) between atmosphere and ocean surface waters; (2) *buffering* between dissolved CO_2 and DIC (total inorganic carbon including CO_2, H_2CO_3, HCO_3^- and CO_3^{2-}), which means that only about 10% of the carbon crossing the air–sea interface contributes to aqueous pCO_2, with the rest appearing as other forms of DIC; (3) *the ocean circulation pump*, by which ocean circulations export carbon from surface to deep ocean waters and (4) *biological pumps*, by which soft-tissue and carbonate detritus from ocean biota in the surface layer export carbon to deep waters as they sink.

All of these processes are subject to climate feedbacks. G2004, in their risk-assessment-based analysis of carbon cycle vulnerabilities, identified six feedbacks. First, chemistry leads to a positive feedback because ocean pH falls as CO_2 is taken up, thereby altering the CO_2/DIC partition and reducing uptake. Second, temperature increases lead to a similar positive feedback through the CO_2/DIC partition. Third, changes in deep ocean circulation (mainly through increasing vertical stratification) increase ocean equilibration times, inducing a positive feedback through reduced uptake over timescales of 10–100 years since the mixing timescale becomes longer. Fourth, ocean circulation changes alter the equilibrium carbon distribution itself (in addition to changing the equilibration timescale), which when coupled with the biological pump leads to a negative feedback because upward transport of DIC from deep to surface waters is reduced but the downward biological pump is not. Fifth, the biological pump is subject to large influence by climate change, but uncertainties are so high that it is not yet possible to identify whether these influences add up to an overall positive or a negative feedback. Sixth, there is the possibility of release from the vast stores of methane hydrates in sediments under continental shelves (and in permafrost). Such a release would constitute a massive positive (heating) feedback on the climate system, but is rated by G2004 as a high-risk, low-probability scenario.

2.2.4 Land–Atmosphere Exchanges

Like the oceans, the terrestrial biosphere currently takes up about 25% of fossil-fuel emissions of CO_2, but unlike the ocean sink, the terrestrial CO_2 sink varies enormously from year to year (Fig. 2.1). Similarly, on longer (100 year) timescales, C^4MIP results suggest higher variability for the terrestrial than the ocean CO_2 sink, both in time and between individual models in C^4MIP. Land–atmosphere exchanges are also critical in the CH_4 budget. These issues are explored in more detail in Sect. 2.3.

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2.3 Vulnerabilities in Terrestrial Carbon Pools and Fluxes

The terrestrial carbon balance equates the net change in terrestrial-biospheric carbon to the sum of carbon fluxes into the terrestrial carbon pool. These fluxes include land–air gaseous exchanges, waterborne and airborne particulate transport, and product removal by humans. The focus here is on the first, which is the most significant for the global carbon budget (though the others can be important particularly for regional carbon budgets). Gaseous carbon exchange between terrestrial systems and the atmosphere occurs through fluxes of CO_2 and several other species including CH_4, VOCs and CO. The CO_2 exchange dominates the mass flux, but exchanges of other species have significant effects on radiative forcing. Here, we summarise the main processes leading to vulnerabilities in land–air exchanges of carbon as CO_2 and CH_4, since these two entities are the most important from both mass-flux and radiative forcing standpoints.

2.3.1 Vulnerabilities Associated with CO_2 Exchanges

Table 2.2 summarises the main processes affecting the net land-atmosphere flux of CO_2 in terrestrial systems. The table identifies three classes of driver for changes in

Table 2.2 Processes contributing to net land–atmosphere exchange of CO_2

	Process	Driver	Sign of land-to-air flux (+,–) =(source, sink)
a1	CO_2 fertilisation	*a*	–
a2	Nutrient constraints on CO_2 fertilisation	*a*	+
a3	Fertilisation by nitrogen deposition	*a*	–
a4	Effects of pollution (e.g. acid rain, ozone, etc.)	*a*	+
b1	Response of respiration to warming and moisture	*b*	+ (warming), ± (moisture)
b2	Response of NPP to warming and moisture	*b*	– (warming), ± (moisture)
b3	Radiation effects (e.g. direct/diffuse partition)	*b*	–
b4	Biome shifts	*b*	±
b5	Permafrost thawing	*b*	+
b6	Changes in wildfire regime	*b*	+ (rapid), – (slow)
b7	Changes in herbivore (e.g. insect) ecology	*b*, *c*	+
c1	Changes in managed fire regime	*c*	+ (rapid), – (slow)
c2	Managed reforestation and afforestation	*c*	–
c3	Unmanaged forest regrowth (after cropland abandonment)	*c*	–
c4	Woody encroachment/woody thickening	*c*	–
c5	Deforestation and land clearing (e.g. forest to savannah)	*c*	+
c6	Peatland and wetland drainage	*c*	+
c7	Agricultural practices	*c*	±

Drivers are (*a*, shaded grey) changes in atmospheric composition and chemistry; (*b*, unshaded) physical climate changes; (*c*, shaded grey) changes in land use and land management. The sign of the land-to-air CO_2 flux is the same as the sign of the climate warming feedback (a positive land-to-air flux increases the CO_2 radiative forcing)

NPP net primary production