Sustainability of Gaia: A Question of Balance

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1. Overview

With the mixed publicity in the media related to climate change, the scientifically credible, robust facts are often overshadowed by mixed, contradicting, or plainly wrong stories. This paper, therefore, dispels myths and lays the foundation behind the scientific evidence pertaining to the on-going changes in our climate and to our planet.

Atmospheric carbon dioxide is the most important of the radiative forcing components driving the ongoing change in climate (IPCC, 2007). The global increases in atmospheric carbon dioxide concentration are driven primarily by carbon dioxide release during fossil fuel combustion and land use change. On average, 40% of the carbon dioxide released by fossil fuel combustion stays in the atmosphere and the remainder is removed from the atmosphere by Earth's oceanic and terrestrial biosphere. Life on Earth, on land and in the oceans, offsets the impact of human modification of the global carbon cycle. Quantifying and projecting the removal of atmospheric carbon dioxide is critical to understanding how the Earth's climate will change and evolve over the next years, decades, and centuries. The Fourth Assessment Report (AR4) of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC, 2007) was the first to address the "Earth System" by including a coupled carbon cycle and climate.

Here are a few facts excerpted from the recent Fourth Assessment Report to help frame the importance of the global carbon cycle and the rise in atmospheric carbon dioxide concentration (from frequently asked question 7.1, IPCC, 2007):

> "The concentration of carbon dioxide is now 379 parts per million, very likely (>90% probability) much higher than any time at least 650 thousand years, during which atmospheric carbon dioxide remained between 180 and 330 parts per million. The current rate of increase in atmospheric carbon dioxide is very likely at least seven times faster than at any time during the two thousand years before the Industrial Era. Finally, the recent rate of change is dramatic and unprecedented; increases in atmospheric carbon dioxide never exceeded 30 ppm in 1000 years- yet now atmospheric carbon dioxide concentrations have risen by 30 ppm in the last 17 years."

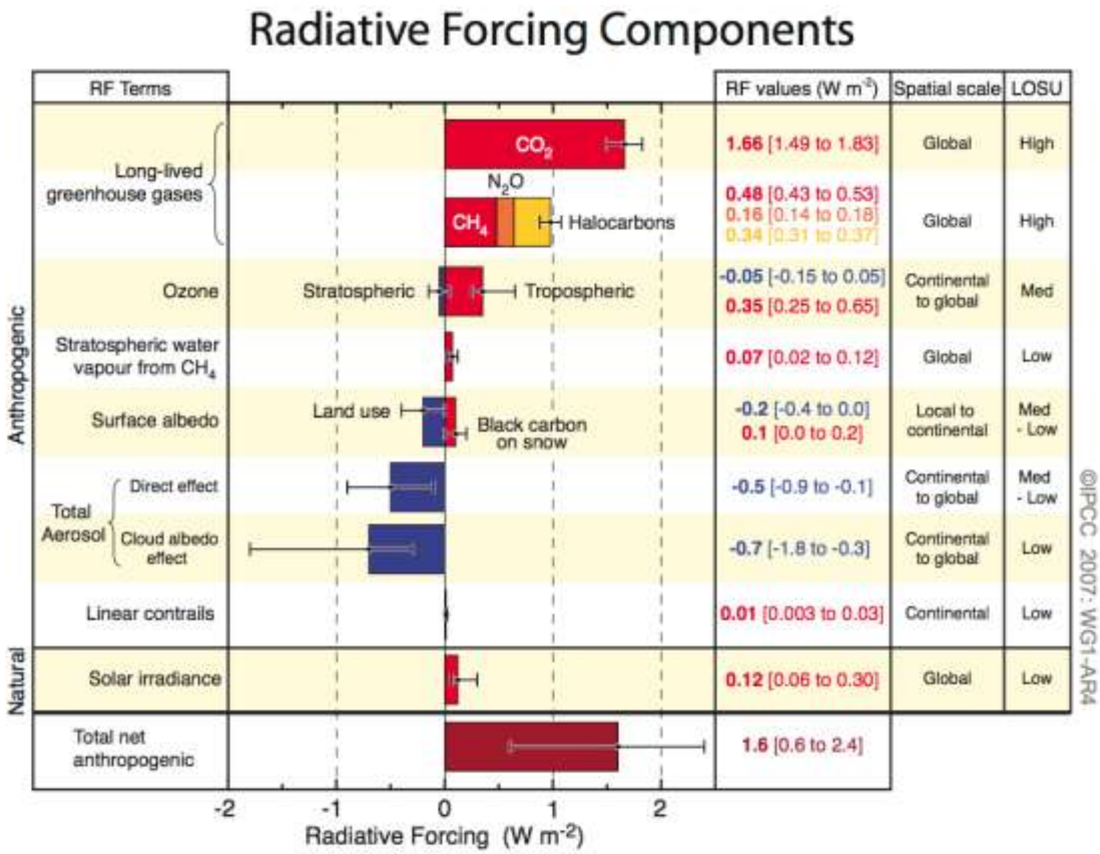

Figure 1. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide, (N_2O) and other important agents and mechanisms, together with the typical geographical extent parenthesis (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms and cannot be obtained by simple addition. Additional forcing factors (not included here) are considered to have a fairly low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. Source: IPCC (2007). An increase in radiation forcing of $2W/m^2$ is equal to an increase of global temperature of about 1K.

The natural carbon cycle is characterized by photosynthesis, respiration, decay, and sea-surface gas exchange lead to massive exchanges, sources and sinks, of carbon dioxide between the land and atmosphere (estimated at ~120 Gt-C per year) and the ocean and atmosphere (estimated at ~70 Gt-C per year) (Figure 1). The natural global carbon cycle under current climatic conditions is generally stable. In fact, the natural sinks for carbon with high fluctuations from year to year produce a small net uptake of carbon dioxide of approximately 3.3 Gt-C per year over the last 15 years, partially offsetting the human-caused emissions (Denman et al, 2007) (Figure 16). The ocean sink for CO_2 uptake is slightly smaller (2.2 Gt C per year) and better characterized than the land-based sink. Had these sinks not existed, atmospheric concentrations of CO_2 would have increased even more dramatically.

The rise in atmospheric dioxide concentration is driven by emissions of carbon dioxide from fossil fuel combustion and cement manufacturing is responsible for more than 75% of the increase in atmospheric carbon dioxide concentration. The remainder of the increase comes from land-use changes dominated by deforestation and associated biomass burning with contributions from changing agricultural practices. All these processes are caused by human activity. The natural carbon cycle cannot explain the observed atmospheric increase of 3.2-4.1 Gt-C in the form of carbon dioxide, per year over the last 25 years (one Gt-C equals 10^{15} grams of carbon, that is, 1 billion metric tons).

Further evidence of the human fingerprint on the carbon cycle comes from examining the character of carbon dioxide in the atmosphere, in particular the ratio of its heavy to light carbon atoms, which has changed in a way that can be attributed to addition of fossil fuel carbon. In addition, the ratio of oxygen to nitrogen in the atmosphere has declined as carbon dioxide has increased, as we expect when atmospheric oxygen becomes depleted by burning fossil fuels. A heavy form of carbon, the carbon-13 isotope, is less abundant in vegetation and in fossil fuels formed from vegetation from earlier geological times, and is more abundant in carbon in the oceans or in volcanic or geothermal emissions. The relative amount of the carbon-13 isotope in the atmosphere has been declining, suggesting that the added carbon comes from fossil fuels and vegetation. Carbon also has a rare radioactive isotope, carbon-14, which is present in atmospheric carbon dioxide but absent in fossil fuels. Prior to atmospheric testing of nuclear weapons, decreases in the relative amount of carbon-14 showed that fossil fuel carbon was being added to the atmosphere (Levin et al., 2007).

2. **The physics of the problem**

Questions of the kind 'Why do we know that the climate is changing?' And 'How do we know that the climate change is forced by humans?' are often legitimately asked.

We know that the climate is changing because we have multiple lines of evidence to affirm that the climate is warming. The globally averaged temperature has risen 0.75°C based on dozens of high quality records. The 152 scientists that contributed to the AR4 IPCC Working Group 1 report concluded that warming is unequivocal. The scientific community is now confident of the scientific conclusion because of the multiple lines of evidence (IPCC, 2007). Globally-averaged temperature is rising, the sea level is rising, and the Northern Hemisphere snow cover has declined. The record in high global average temperature for the 20th century is consistent with the coral record, the tree ring record, the borehole record, and the ice core record. All of these different ways of looking at the climate are now painting a consistent picture of a warmer globe. The increase of temperature, sea level, and changes in ecosystems constitute some of the measures attesting to the fact that the climate has changed while radiation forcing is an order of magnitude which cannot be measured by present-day sensors.

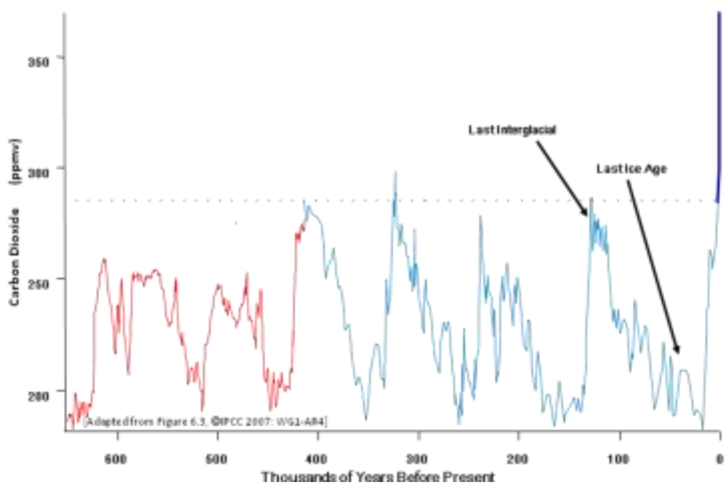

Figure 2. Atmospheric carbon dioxide mixing ratios for the 650,000 years before present together with the contemporary carbon dioxide mixing ratios. Source: IPCC (2007).

How do we know that the changes forced by humans? Carbon dioxide is causing the bulk of the radiative forcing (Figure 1). The current rise in atmospheric carbon is unprecedented in the last 650,000 years (Figure 2). This increase is a physical fact noted as early as Arrhenius (1896a, b). The question then is whether this has an effect on the climate or whether it is compensated or buffered by other processes. Some have suggested that the change in climate is driven by changes in the earth's orbital clock but these Milankovich cycles nearly compensates in the next thousands of years; others have suggested that the changes in our climate are driven by the amount of sunlight received by the Earth, an argument refuted by the fact that there is no trend in solar irradiance between 1978 and 2005 (Figure 3). The oft-discussed close relationship between solar activity and temperature has failed in the last twenty years when the earth temperature significantly increased (Theijl and Lassen, 2000).

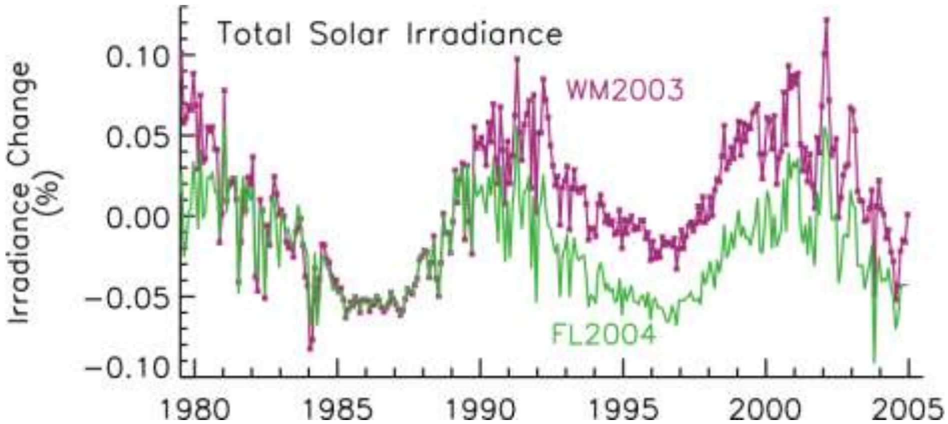

Figure 3. No observed trend total solar irradiance since 1978 based on spectral information, solar magnetic flux model rather than proxy data, and a re-evaluation of variations in Sun-like stars. Source: IPCC (2007).

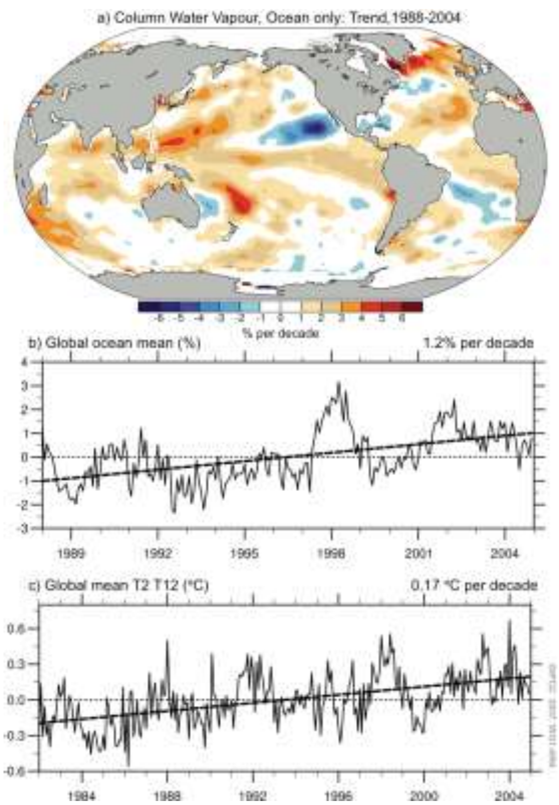

Figure 4. Column water vapor trends from 1988-2004 together with the associated trend in ocean temperature and global temperature Source: IPCC (2007).

Therefore, there is no recent increase in solar output to explain the recent rise in global mean temperature. Others argue that the water vapor feedback drives changes in climate. The trends in column water vapor argue that water vapor does not drive climate changes but rather responds to climate change as a major feedback that amplifies global climate change (Figure 4). Others argue that volcanic eruptions will offset the warming climate. But volcanoes cool the earth quickly along with the cooling effect i.e. within one to three years. If volcanic emissions can cool the earth, then greenhouse gases must warm the earth.

Others argue that some parts of the earth are cooling rather than warming. It is true that there are some areas that are experiencing cooling other areas are compensating by experiencing more warming. The global distribution of the warming and the resulting changes in precipitation are not uniform in time or space. When the temperature is averaged over the entire globe and over the last 200 years, the net result is a global mean increase in temperature of 0.75° C. Another significant line of evidence for humans driving climate change is that Climate System models are unable to reproduce the rise in global temperature, global land temperature, or global ocean temperature using natural forcing only (Figure 5). Climate System models that use all human plus natural radiative forcing are able to reproduce the observed increase in temperature with remarkable integrity.

Climate change is driven by perturbations to the energy balance of the Earth system. These perturbations are called "*climate forcings*" and have been the subject of considerable scientific interest as it relates both to our understanding of the Earth's history and help us project future change. Briefly state, a climate forcing is an energy imbalance imposed on the climate system either external or by human activities. Climate forcings can be classified as radiative (direct or indirect) or non radiative. *Direct radiative forcings* affect the radiative budget of the Earth directly; for example, added CO_2 absorbs and emits infrared radiation. Direct radiative forcing may be due to a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. *Indirect radiative* forcings create a radiative imbalance by first altering climate system components (e.g. precipitation efficiency of clouds), which then almost immediately lead to change in radiative fluxes. Examples include the effect of solar variability on stratospheric ozone and the modification of cloud properties by aerosols. *Nonradiative forcings* create an energy imbalance that does not involve radiation directly. An example is the increasing evapotranspiration flux resulting from agricultural irrigation, (Board on Atmospheric Sciences and Climate: BASC, 2005).

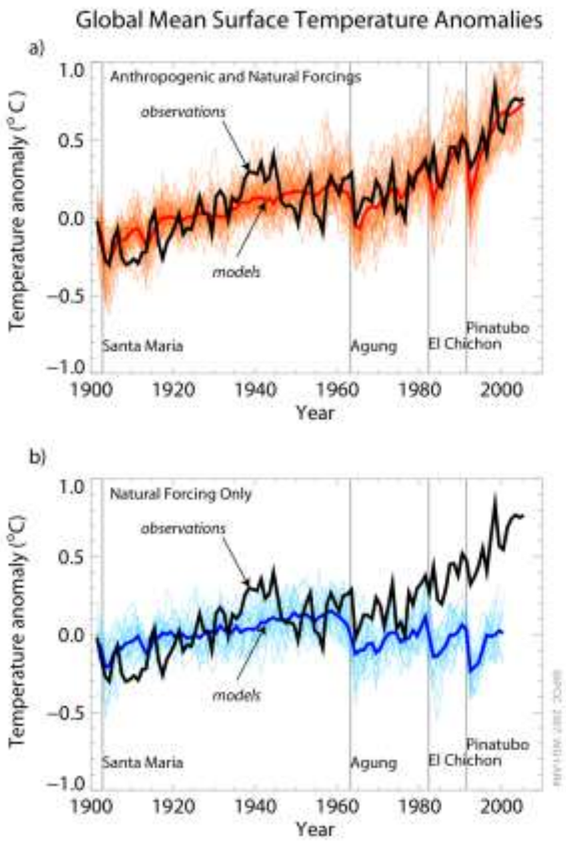

Figure 5. Climate System model ability to reproduce the observed temperature trend with natural forcing or natural plus anthropogenic forcing. Source: IPCC (2007).

Given the traditional focus of climatologists on temperature as well as the clear link between greenhouse gases and surface temperature, studies of long-term changes in climate have emphasized temperature as the primary index for climate change. The concept of "radiative forcing" provides a way to quantify and compare the contributions of different agents that affect surface temperature by modifying the balance between incoming and outgoing radiative energy fluxes (BASC, 2005). Radiative forcing is usually quantified as the rate of energy change per unit area of the globe as measured at the top of the atmosphere, and is expressed in units of "Watts per square meter". When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system (IPCC, 2007).

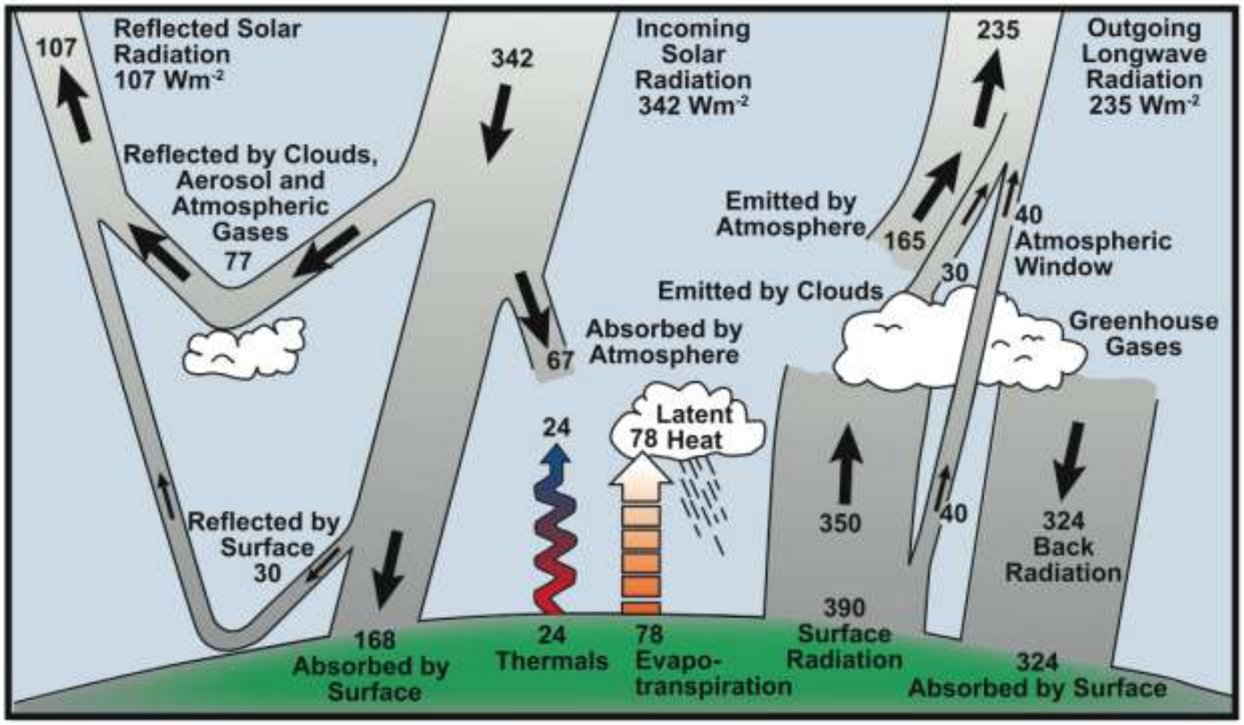

Figure 6. Energy budget for the atmospheric components of the climate system. Source: Kiehl and Trenbert (1997)

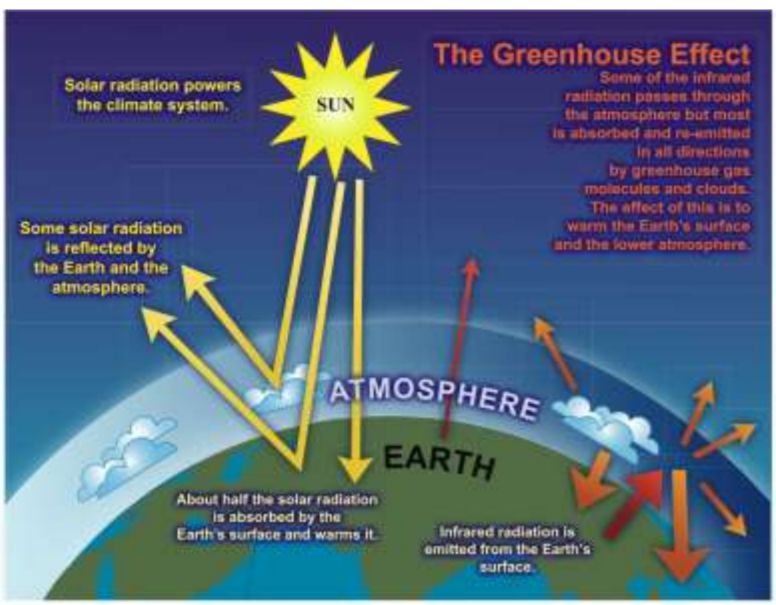

Figure 7. An idealized model of the natural greenhouse effect. Source: IPCC (2007).

The various physical processes that contribute to Earth's global annual mean energy budget are shown in Figure 6. The Earth receives a continuous influx of energy from the Sun.

About 69% of this energy is absorbed at the Earth's surface or by the atmosphere, while the rest is reflected back to space.

To balance the absorbed incoming energy, the Earth must radiate the same amount of energy back to space. Radiative forcing of climate by trace gases is commonly referred to as the "greenhouse effect." Solar radiation that passes through clouds and that is not reflected back to space strikes the Earth's surface (Figure 7). The longer wavelength (infrared) radiation created there is emitted, and then is absorbed by clouds and atmospheric greenhouse gases (GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a few others). Those constituents reradiate upwards and downwards, thereby heating the Earth's surface. Increasing concentrations of GHGs can cause more warming, and vice-versa, decreasing means less warming or even cooling. Human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the greenhouse effect, causing global warming.

3. **Anthropogenic emission growth rates**

Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (Figure 8). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture (IPCC, 2007). According to the Intergovernmental Panel on Climate Change, it is very likely that the increase in the combined radiative forcing from carbon dioxide, methane, and nitrous oxide has been at least six times faster between 1960 to 1999 than over any 40-year period during the two millennia prior to the year 1800.

Carbon dioxide is the most important anthropogenic greenhouse gas. Annual mean growth rate of atmospheric CO_2 was 2.2 ppm per year in 2007 (up from 1.8 ppm in 2006), and above the 2.0 ppm average for the period 2000-2007 (Global Carbon Project, 2008). The average annual mean growth rate for the previous 30 years was about 1.5 ppm per year. This increase is to a large extent expected given the much larger fossil fuel emissions during the same period. In 2007, the atmospheric CO_2 concentration was 383 ppm, approximately 37% above the concentration at the start of the Industrial Revolution (about 280 ppm in 1750). According to the

IPCC, the present concentration is the highest during the last 650,000 years and probably during the last 20 million years.

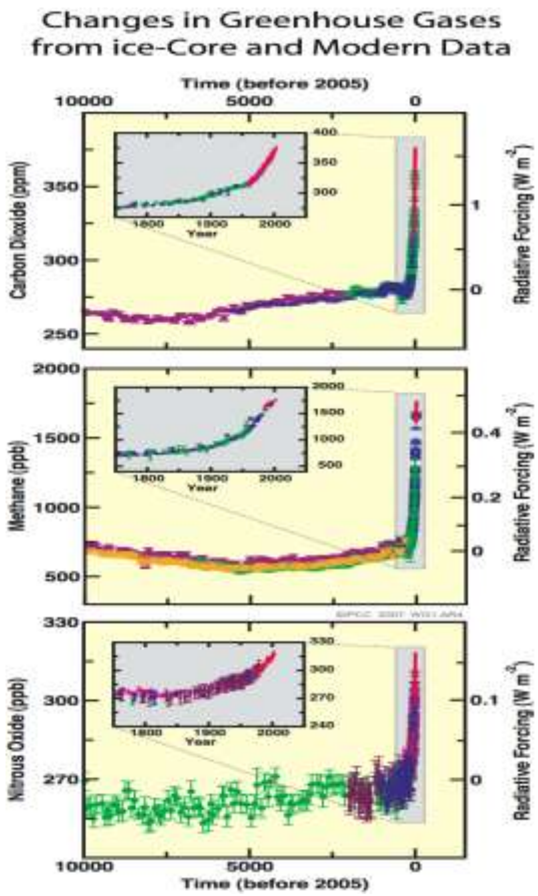

Figure 8. Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Source: Summary for Policymakers, IPCC (2007).

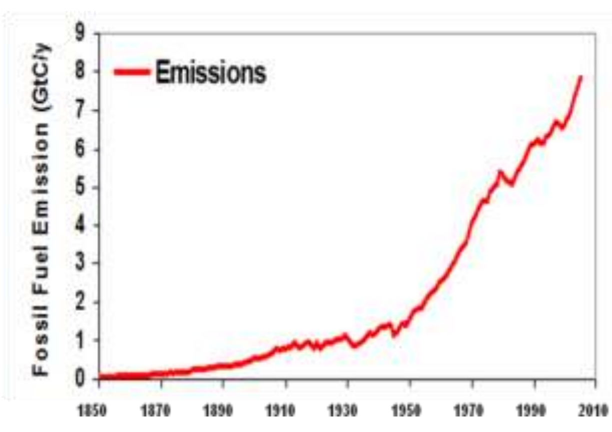

Figure 9. Observed global carbon emission from fossil fuel. Source: Global Carbon Project (2008), original from G. Marland, T.A. Boden, R.J. Andres, and J. Gregg at CDIAC

The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use, with land-use change, providing another significant but smaller contribution. Annual fossil fuel and cement emissions increased from from 6.2 PgC per year in 1990 to 8.5 PgC in 2007 (Figure 9), a 38% increase from the Kyoto reference year 1990. The growth rate of emissions was 3.5% per year for the period of 2000-2007, an almost fourfold increase from 0.9% per year in 1990-1999 (Global Carbon Project, 2008). The actual emissions growth rate for 2000-2007 exceeded the highest growth rate predicted i.e. a scenario initially thought to be needed if unlikely, for the decade 2000-2010 in the emissions scenarios of the Intergoverment Panel on Climate Change, Special Report on Emissions Scenarios (IPCC-SRES) (Global Carbon Project, 2008). This makes current trends in emissions higher than the worst imagined IPCC-SRES emission scenario.

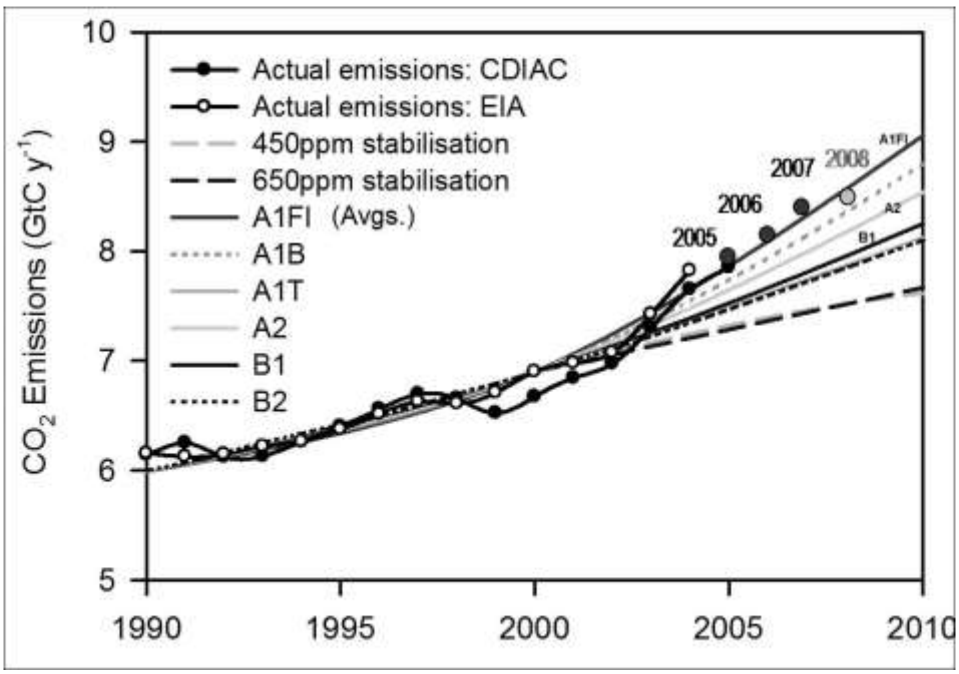

Figure 10. Observed global CO_2 emissions from both the EIA and global CDIAC data, compared with emission scenarios and stabilization trajectories. Dots indicate the revised and updated numbers for 2005, 2006, 2007, and 2008, respectively. Source: Global Carbon Project (2009), original from Raupach et al. (2007), PNAS.

Figure 10 compares observed global emissions with six Intergovernmental Panel on Climate Change (IPCC) emissions scenarios and also with stabilization trajectories describing emissions pathways for stabilization of atmospheric CO_2 at 450 and 650 ppm. Observed emissions were well outside the envelope of IPCC emissions scenarios in 2005 and 2006 with recent data (not presented here) for 2007 suggesting a further exacerbation of that trend. The actual emissions trajectory since 2000 was close to the highest-emission scenario in the envelope, A1FI. More importantly, the emissions growth rate since 2000 exceeded that for the A1FI scenario. Emissions since 2000 were also far above the mean stabilization trajectories for both 450 and 650 ppm.

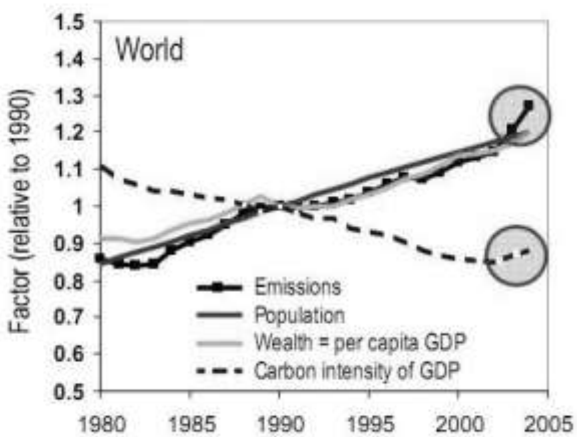

Figure 11. Factors in the Kaya identity as global averages. All quantities are normalized to 1 at 1990. Source: Global Carbon Project (2008), original from Raupach et al. (2007), PNAS.

A breakdown of emissions among sources (not shown here) shows that solid, liquid, and gas fuels contributed (for 2000–2004) ≈35%, 36%, and 20%, respectively, to global emissions. However, this distribution varied strongly among regions: solid (mainly coal) fuels made up a larger and more rapidly growing share of emissions in developing regions (the sum of China, India, developing countries, and least-developed countries) than in developed regions (U.S., EU, Japan, and developed countries), and the Former Soviet Union region had a much stronger reliance on gas than the world average (Raupach et al., 2007).

Since 2000, the strong global fossil fuel emissions growth has been driven not only by long-term increases in population and per-capita global gross domestic product (GDP) but also by a reversal of earlier declining trends in the energy intensity of GDP (ratio of global primary energy consumption to world GDP) and the carbon intensity of energy (the ratio of global CO_2 emission flux from fossil fuel combustion and industrial processes to global primary energy consumption) (Figure 11). Slightly increasing recent trends in carbon intensity occurred regardless of the level of economic development of countries across the world.

All IPCC emissions scenarios to 2100 suggest continuous decreases in both GDP and carbon intensity of energy (and therefore in carbon intensity of GDP) (Nakicenovic et al., 2000) so that the predicted rate of global emissions growth is less than the economic growth rate. Without these likely decreases, Edmonds et al. (2004) predict emissions over the coming century to be up to several times greater than current emissions. Figure 11 shows that the earlier decline in the energy intensity of GDP is now reversed. When the rapid emission growth recorded is juxtaposed against declining carbon intensity and its related corresponding impact on global warming, the reality is sombering

In recent years, the recent growth rate in emissions has been strongest in rapidly developing economies, particularly China, because of very strong economic growth coupled with post-2000 increases in the energy intensity of GDP and the carbon intensity of energy and therefore in carbon intensity of GDP. Developed nations have used two centuries of fossil-fuel emissions to achieve their present economic status, whereas developing nations are currently experiencing intensive development with a high-energy requirement, much of the demand being met by fossil fuels. Rothman (1998) explains that this may be largely the result of the relocation of energy-intensive activities from developed to developing countries with increasing globalization of the economy.

After decades of improvements, the carbon intensity of the global economy, the carbon emitted per unit of GDP, stalled during the period 2003-2005, a change reflecting China’s rapidly growing share in economic output and carbon emissions. However, since 2005 China’s energy intensity (which underpins carbon intensity) has decreased (improved) by 1.2% in 2006 and 3.7% in 2007 compared to 2005 levels (according to the National Energy Administration in China).

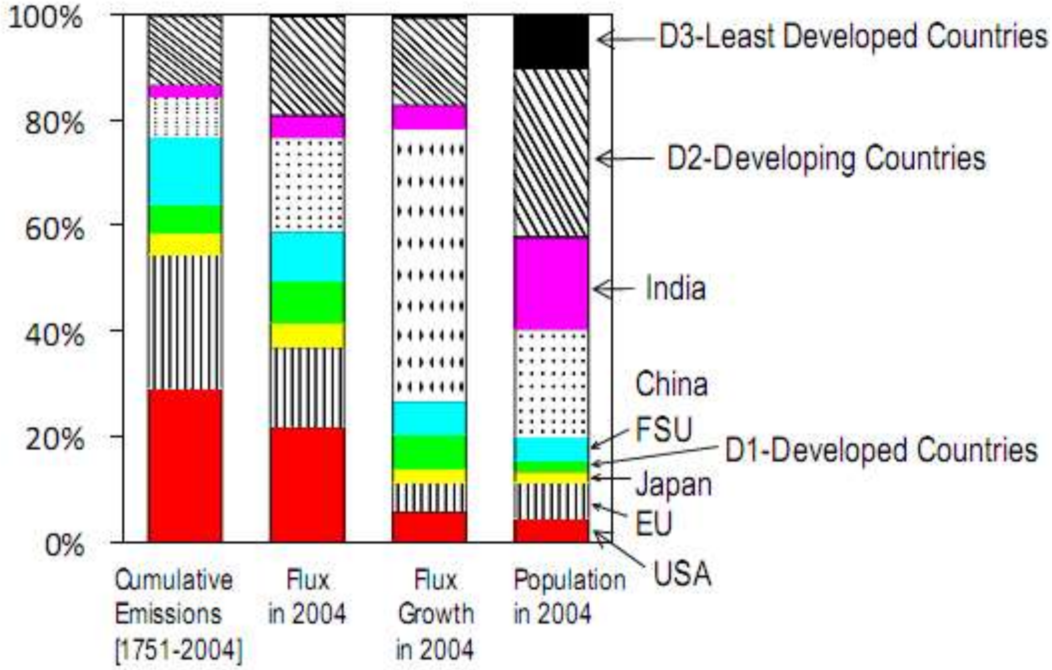

Figure 12. Relative contributions of nine regions to cumulative global emissions (1751–2004), current global emission flux (2004), global emissions growth rate (5 year smoothed for 2000–2004), and global population (2004). Source: Raupach et al. (2007), PNAS.

The biggest increase in emissions has taken place in developing countries, largely in China and India. China passed the U.S. in 2006 to become the largest CO_2 emitter (Global Carbon Project, 2008). India will soon overtake Russia to become the third largest emitter. Currently, more than half the global emissions come from less developed countries.

Seen from a different perspective, developing countries with 80% of the world's population has been emitting only 20% since 1751; the poorest countries in the world, with 800 million people, have contributed less than 1% of these cumulative emissions. A multi-decadal perspective on emissions is essential because of the long atmospheric residence time of CO_2. Figure 12 reflects the carbon burden shared by different regions around the planet.

4. Sources of emissions, including destruction of natural sinks

4.1 Emission from land-use change

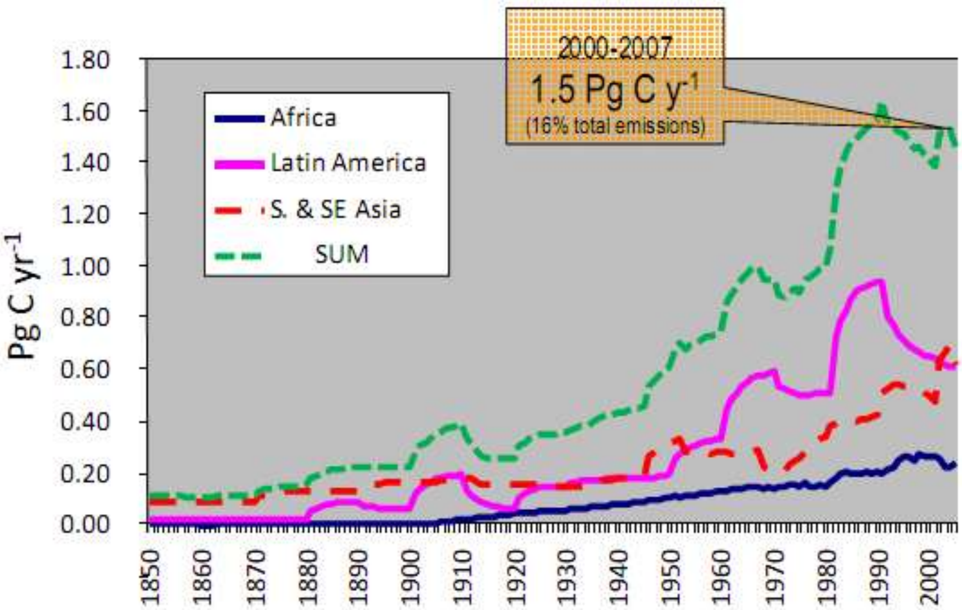

Figure 13. Historical emissions from land and use change. Source: Global Carbon Project (2008), original from R.A. Houghton, unpublished .

Prior to widespread fossil fuel use, humanity's largest effect on local climate is likely to have resulted from land use. Emissions due to land-use change (e.g. harvesting of forest products and clearing for agriculture) include the net flux of carbon between the terrestrial biosphere and the atmosphere resulting from deliberate changes in land cover and land use. Recently, land-use change has been responsible for an estimated net emission rate of 1.5 PgC per year to the atmosphere: This is largely the difference between CO_2 emissions from deforestation and CO_2 uptake by reforestation. Emissions for 2006 and 2007 were extrapolated from the previous 25-yr trend of 1.5 PgC per year. Land-use change emissions result almost exclusively from deforestation in tropical countries (approximately 41% from South and Central America, 43% from South and Southeast Asia, and 17% from Africa). An estimated 160 PgC was emitted to the atmosphere from land use change during the period 1850-2007 [1 Pg = 1 billion tons or 1000 x million tons] (Figure 13) (Global Carbon Project, 2008). Furthermore, more changes occur simultaneously when the surface undergoes land-use changes: the change in surface temperature is significant, and the destruction of peat lands induces the release of large amount of carbon into the atmosphere. These facts should be reflected upon in the light of coincident data on emission trends worldwide seen earlier AND in the light of the recent scientific facts presented below.

4.2 **Natural Sinks**

According to the Global Carbon Project (2008), natural land and ocean CO_2 sinks have removed 55% (or 4.9 PgC per year) of all CO_2 emitted from human activities during the period 2000-2007. This has been leading to the increased size of the natural sinks growing in proportion to increasing atmospheric CO_2. However, the efficiency of these sinks in removing CO_2 has decreased by 5% over the last 50 years, and will continue to do so in the future. That is, 50 years ago, for every ton of CO_2 emitted to the atmosphere, natural sinks removed 600 kg. Currently, the sinks are removing only 550 kg for every ton of CO_2 emitted, and this amount continues to fall.

4.3 **Natural Ocean CO_2 sinks**

According to Canadell (2007), the global oceanic CO_2 sink removed 25% of all CO_2 emissions for the period 2000-2007, equivalent to an average of 2.3 PgC per year. The size of the CO_2 sink in 2007 was similar to the figure obtained the previous year but lower by 0.1 PgC compared to its expected increase from atmospheric CO_2 growth owing to the presence of a *La Nina* event in the equatorial Pacific. The Canadell study shows that the Southern Ocean CO_2 sink was higher in 2007 compared to 2006, consistent with the relatively weak winds and the low Southern Annular Mode (a circumpolar pressure oscillation between Antarctica and southern mid-latitudes). An analysis of the long term trend of the ocean sink shows a slower growth than expected of the CO_2 sink over the last 20 years (Global Carbon Project, 2008).

4.4 **Natural land CO_2 sinks**

Terrestrial CO_2 sinks removed 29% of all anthropogenic emissions for the period 2000-2007, equivalent to an average of 2.6 PgC per year. Terrestrial ecosystems removed 2.9 PgC in 2007, down from 3.6 Pg in 2006, largely showing the high year-to-year variability of the sink. An analysis of the long-term trend of the terrestrial sink shows a growing size of the CO_2 sink over the last 50 years (Global Carbon Project, 2008).

5. Global Carbon balance

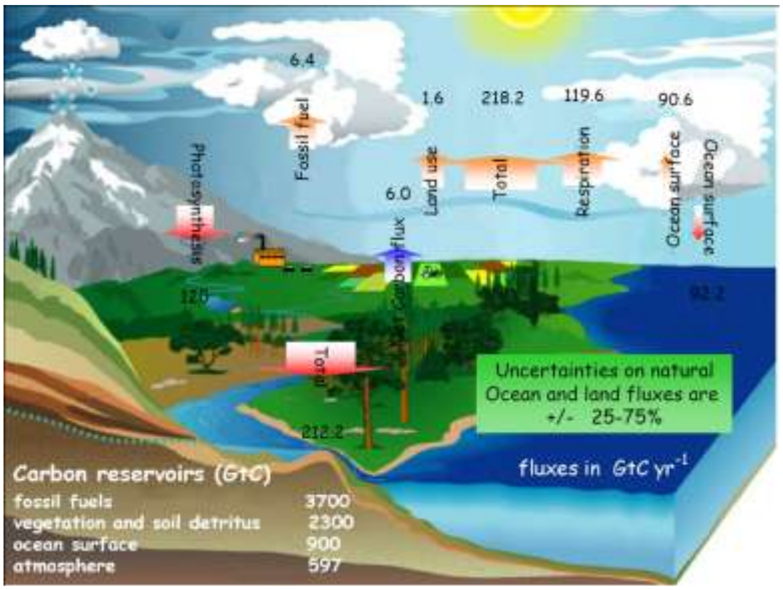

Figure 14. Global Carbon Cycle

This section examines the several pathways in the carbon cycle which are of particular importance. The main pathways to and from the atmosphere are diffusion into and out of the ocean, photosynthesis which consumes CO_2 from the atmosphere (an output from the atmosphere), respiration which produces CO_2, and the burning of fossil fuels and biomass which produces CO_2. The terrestrial sink is the net amount of CO_2 removed by the vegetation and by the ocean after the amount of CO_2 respired back to the atmosphere has been accounted for.

The annual increase in atmospheric CO_2 is substantially smaller than the increase in anthropogenic emissions, because natural sinks on land and in the ocean remove part of the anthropogenic CO_2. The sheer magnitude of the size of the land and oceanic CO_2 sinks, which combined, currently remove over half of all anthropogenic emissions thus providing a strong negative (stabilizing) feedback on the carbon-climate system (Gruber et al.,2004; Sabine et al., 2004). The CO_2 airborne fraction (the fraction of total emissions from fossil fuels and land-use change accumulating in the atmosphere) has averaged 0.43 since 1959, but has increased through that period at a rate of approximately 0.24% y^{-1} (Canadell et al., 2007) (Figure 14). The increase in the airborne fraction implies that carbon emissions have grown faster than CO_2 sinks on the land and oceans. Because land and oceans are in regions that are gaining and regions losing carbon, this trend could result from any or all of three scenarios: sink regions could have weakened, either absolutely or relative to growing emissions; source regions could have intensified; or sink regions could have transitioned to sources.

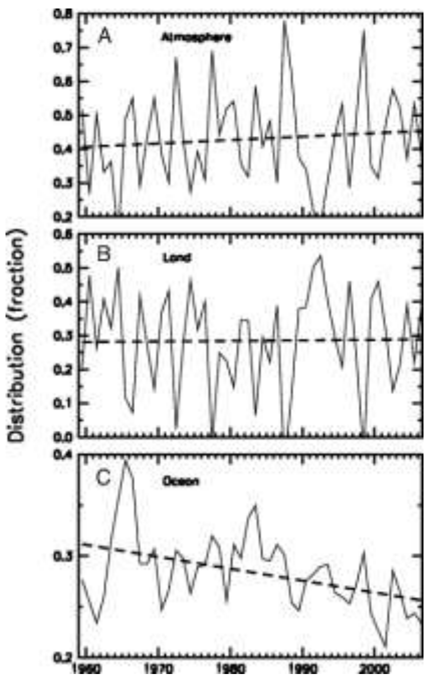

Figure 15. Fraction of the total emissions that remains in the atmosphere (*A*), the land biosphere (*B*), and the ocean (*C*). Source: Canadell J. G. et.al. (2007), PNAS.

Whereas both land and ocean sinks continue to accumulate carbon on average at ≈5.0 ± 0.6 PgC y^{-1} since 2000, large regional sinks have been weakening. In the Southern Ocean, the poleward displacement and intensification of westerly winds caused by human activities has enhanced the ventilation of carbon-rich waters normally isolated from the atmosphere at least since 1980, and contributed nearly half of the decrease in the ocean CO_2 uptake fraction estimated by the model (Le Quere et al., 2004) as shown in Figure 15*C*. On land, a number of major droughts in mid-latitude regions in 2002–2005 have contributed to the weakening of the growth rate of terrestrial carbon sinks in these regions (Angert et al., 2005; Breshears et al., 2005; Ciais et al., 2005; Knorr et al., 2005).

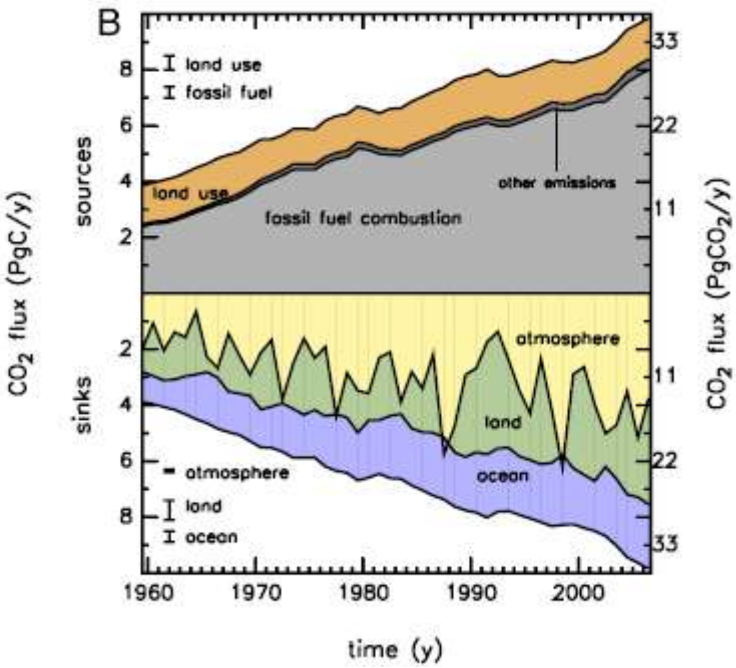

Figure 16. (*Upper*) CO_2 emissions to the atmosphere (sources) as the sum of fossil fuel combustion, land-use change, and other emissions, which are primarily from cement production. (*Lower*) The fate of the emitted CO_2, including the increase in atmospheric CO_2 plus the sinks of CO_2 on land and in the ocean. Flux is in Pg y^{-1} carbon (left axis) and Pg y^{-1} CO_2 (right axis). Source: Canadell J. G. et.al. (2007), PNAS.

These inter-decadal trends in atmospheric CO_2 concentration are created by two types of forcings: the drivers of anthropogenic emissions and those dictating the trends in land and ocean sinks (Figure 16). The CO_2 growth rate also varies strongly at inter-annual (1 to 10 y) time scales, through mainly biophysical mechanisms. Fluctuations in CO_2 growth rate correlate with the *El-Nino*-Southern-Oscillation (ENSO) climate mode (Keeling and Revelle, 1985; Keeling et al., 1995; Jones and Cox, 2005), because the terrestrial carbon balance in tropical regions is biased overestimating CO_2 fluxes during dry, warm *El-Ni ˜no* events (Zeng et al., 2005; Knorr et al., 2005). Volcanic events are also significant: the CO_2 growth rate decreased for several years after the eruption of Mt. Pinatubo in June 1991 (Jones et al., 2001), probably because of increased net carbon uptake by terrestrial ecosystems due to higher diffuse solar radiation (Gu et al., 2003) and cooler temperatures (Jones and Cox, 2001) caused by volcanic aerosols. This inter-annual variability in the CO_2 growth rate is important as it indicates mechanisms that govern the land and ocean CO_2 sinks and it can obscure longer-term trends in the CO_2 growth rate with strong variability at higher frequencies.

6. Model projections

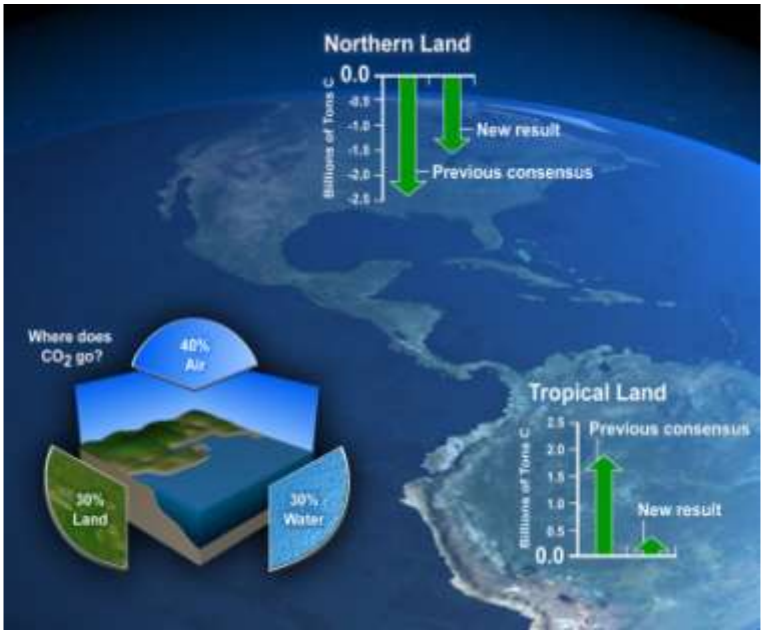

Figure 17. Summary of the key findings of Stephens et al. (2007). Percentages reflect the fate CO_2 emitted by fossil fuel consumption. Only ~40% remains in the atmosphere following emission, ~30% is taken up by land and the remainder is taken up by oceans.

For the past 45 years, oceans and land have absorbed an average of 45% of the carbon dioxide emitted by fossil fuel combustion with 55% remaining in the atmosphere to serve as a greenhouse gas (Denman et al., 2007). The gradient of atmospheric carbon dioxide between the Northern and southern Hemispheres strongly indicates that much of the fossil fuel CO_2 release has occurred in the Northern Hemisphere. Recent analyses based on observations and models (Canadell et al., 2007) conclude that the growth rate of global average atmospheric carbon dioxide for 2000-2006 was 1.93 ppm per year, an almost 30% increase over the 1990s average. Fossil fuel emissions now exceed all of the IPCC predicted of trajectories of fossil fuel emissions of CO_2 made a decade ago (Canadell et al., 2007).

Projections of the future carbon cycle suggest that carbon dioxide absorption by the biosphere will be reduced (Friedlingstein et al., 2006). Fung et al. (2005) show that the carbon sink strength varies with fossil fuel emission rate. As fossil fuel emissions increase, the capacity of the land and oceans to absorb the carbon dioxide emitted decreases. The overall result is the atmospheric carbon dioxide concentration emitted by fossil fuel that remains in the atmosphere, will increase in the future. A recent paper by Stephens et al. (2007) combined observations and model analyses to redefine the location of the "missing" terrestrial carbon sink. As explained by Richard Houghton, "Using only those models that accurately reproduced new observations of vertical CO_2 gradients, the new findings yielded terrestrial fluxes of carbon more consistent with northern mid-latitude observations (inventory-based estimates of a carbon uptake) and more consistent with physiological understanding (CO_2 fertilization in tropical regions)." The authors conclude that northern forests, including U.S. and Europe, are consuming much less CO_2 than previously thought and intact tropical forests are strong carbon sinks and offset carbon dioxide release from deforestation (Figure 17), solving the apparent missing sink enigma.

Our understanding of the carbon cycle remains incomplete. In model analyses, Sitch et al. (2007) conclude that the 2100 projected ozone concentrations could reduce the terrestrial carbon sink by as much as 40% for the time period 1901-2100. In addition, the carbon and the nitrogen cycles being intimately interrelated, the Hungate et al. (2003) study points out that there is insufficient nitrogen available on the globe today to sustain the carbon dioxide uptake predicted for 2100. Today's fossil fuel emissions of carbon dioxide exceeding even the worst case prediction made 10 years ago underscores the fact that our ability to predict the evolution of atmospheric carbon dioxide is limited. Our predictions of the future carbon dioxide concentrations appear to be overly conservative while we overestimate the strength of future carbon sinks.

7. Uncertainties in the estimates of terrestrial carbon sources and sinks

We have seen earlier how the speed, impact and severity of climatic changes are determined by the sum of the amount of greenhouse gases present and released in the atmosphere minus the amount sequestered by oceanic and by terrestrial sinks (Figure 15). Sink strengths are either constant or decreasing while the gap between the sinks and the sources has been increasing (IPCC, 2007, Table 7.1). The property of these sinks, their behaviour, and response to every rising ambient carbon dioxide concentrations are therefore the subject of much concern and the dynamics of these sinks needs to be examined more closely and better quantified to find out whether they have already reached their buffer limit.

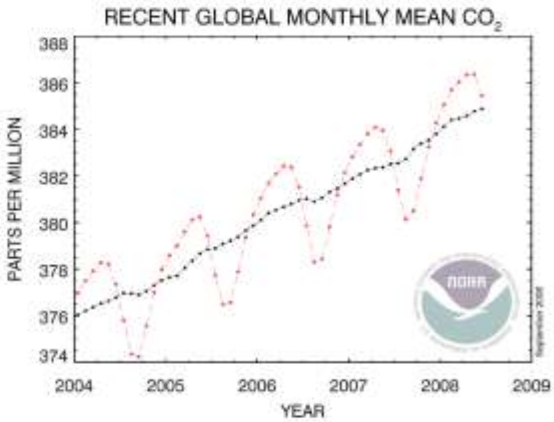

Figure 18. Recent monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. The last four complete years of the Mauna Loa CO_2 record plus the current year are shown. Source: NOAA ESRL Global Monitoring Division

As discussed above, the beginning of the Industrial Revolution in 1750 marked the beginning of a global mean atmospheric CO_2 concentration upward trend. Figure 18 shows the recent global monthly mean CO_2 concentration with its seasonal trend superimposed on the annual trend: it is also readily apparent that the signal of the concentration of CO_2 is systematically lower in the summer than in the winter in the northern hemisphere due to the stronger vegetation sink strength during that season.

Two sinks, the ocean and the ecosystems, exert a regulating factor of the carbon cycle of the Earth (Figure 18). Unfortunately, since the nineties, these sinks are either constant or are still decreasing and the gap between the sinks and the sources has been increasing (IPCC, 2007, Table 7.1). The dynamics of these sinks should be investigated to find out whether they have already reached their buffer limit. This information impacts the definition of the climate scenarios which need not only a forecast of the emissions but also of the related change of the natural buffers.

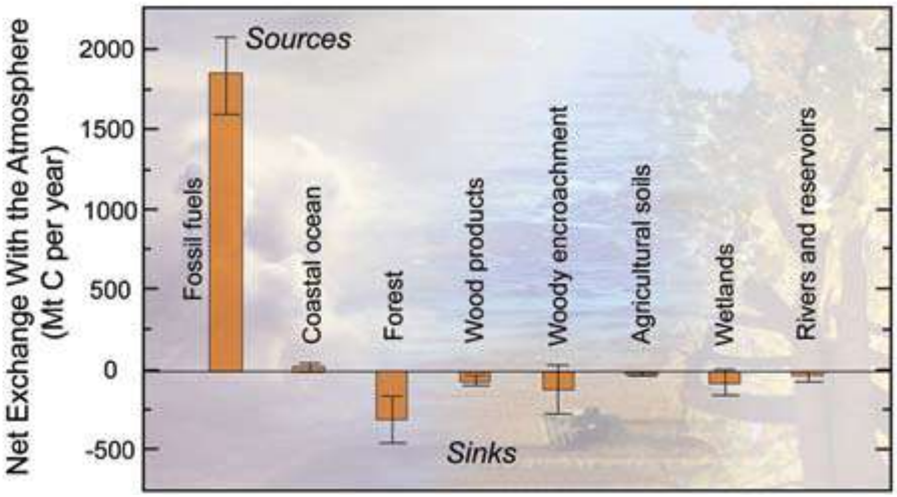

Figure 19. North American carbon sources and sinks (million tons of carbon per year) in 2003. Height of a bar indicates a best estimate for net carbon exchange between the atmosphere and the indicated element of the North American carbon budget. Sources add CO_2 to the atmosphere; sinks remove it. Error bars indicate the uncertainty in that estimate, and define the range of values that include the actual value with 95% certainty. Source: CCSP (2007).

Since oceanic sinks strength and size change relatively slowly, the discussion below is limited to that of terrestrial sinks. At present, approximately half of the emissions are taken up by terrestrial sinks, primarily by photosynthesis. These sinks exhibit much spatial and temporal variability on a daily timescale. This leads global estimates to have a large amount of uncertainty surrounding the magnitude of those carbon sinks (Figure 19). Plants grow, capturing carbon dioxide, respire at night releasing some of the CO_2 back to the atmosphere; the soil microbes respire carbon dioxide, adding further complexity to the carbon balance. Furthermore, woody encroachment of pastures and abandoned fields, particularly at low latitudes, occur within just a few years. Agricultural soils, and their manipulation in the form of tillage, no-tilth strategy, fertilizers, amount of water applied, all constitute further factors adding complexity to the quantification of terrestrial sinks. This is in addition to the importance of soil temperature on CO_2 emissions. In addition, the carbon sequestered undergoes a conversion into wood products. Land-use change, for instance, particularly in the Amazon forest, releases massive amount of carbon into the atmosphere, further modifying not only the carbon dioxide released, but also the ability of the terrestrial sinks to store carbon.

Figure 20. FLUXNET site DE-Bay (Waldstein-Weidenbrunnen, Bayreuth, Germany), Main tower for eddy-covariance and additional micrometeorological measurements.

Since the nineties, regional measuring networks of carbon dioxide fluxes worldwide make systematic regional and global analysis of observations from micrometeorological tower sites. The flux tower sites use the eddy-covariance method (Aubinet et al., 2000; Moncrieff et al., 1997) to measure the exchange of carbon dioxide (CO_2), water vapour, and energy between terrestrial ecosystems and the atmosphere. At present, over 500 tower sites (Figure 20) are operating on a long-term and continuous basis. Researchers also collect data characterizing site vegetation, soil, hydrologic, and meteorological characteristics at the tower sites.

The first dataset was produced in 2000 with 97 years of data from 38 European and North American sites. Recently, a new database consists of over 960 site-years of data from over 253 eddy-covariance measurement sites is available. Major efforts were made over the past two years to harmonize, standardize, and gap-fill the 'raw' 30-minute data records submitted by participants. The database also includes additional relevant information such as ecosystem respiration, climate and site characteristic information and gross primary productivity, (http://www.fluxdata.org/).

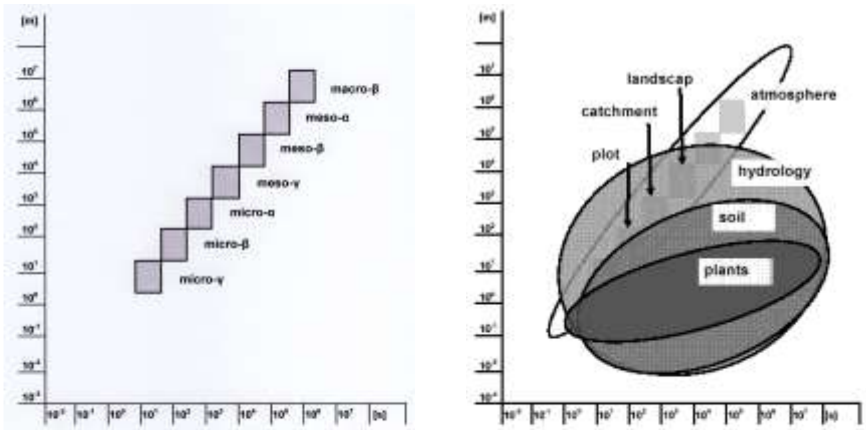

Figure 21. a) Scales of atmospheric processes according to Orlanski (1975); b) Atmospheric scales added by typical scales in hydrology (Blöschl and Sivapalan, 1995), in soils (Vogel and Roth, 2003) and in plant ecosystems (Schoonmaker, 1998), the Figure was adopted from Foken (2008b).

A reason for our limited knowledge of the exact magnitude of the terrestrial carbon sinks and their dynamics both in the present and future climate is a fundamental question. In contrast with other geophysical processes, meteorological processes have a clear time-space scaling (Beniston, 1998). The reason for this is the spectral organization of atmospheric processes, where relevant wavelengths (physical spatial dimensions) are related to distinct durations in time (frequencies). The principle of classification was formulated earlier by Orlanski (1975) (Figure 21a). While atmospheric processes are organized, hydrological processes, biogeochemical carbon processes in soils and plant ecosystems have smaller space scales (Figure 21b). This scaling principle is essential for measurements of atmospheric processes (Foken, 2008b). For instance, the carbon dioxide flux measurements are related to the microscale. An upscaling to larger scales is possible only with models.

Hydrological and ecological models must be coupled with atmospheric models to assess the impact of increased carbon dioxide emissions on terrestrial ecosystems. This, therefore, spurs the need to develop strategies aimed at transferring hydrological and ecosystem processes to the larger atmospheric space scale. Atmospheric models currently work with averaged soil and plant parameters and soil and plant models work with averaged atmospheric parameters. This has the consequence that atmospheric models do not work with the exact ecosystem structure. On the other hand, averaged atmospheric parameters are often linked to climatological drivers and not to the real driver, atmospheric turbulence. This linkage is achieved by applying the well-known and widely used Penman-Monteith-approach (Allen et al., 2004; Monteith, 1965). Due to similar simplifications and using the radiation as the main forcing parameter instead of wind velocity, models can be related to coarse local climatological features. Nevertheless, for many model efforts, there is no simple alternative available due to treatment of scales-dependent physical processes, but the uncertainties must be investigated and addressed. It can be assumed that, for modelling results desired at long timescales, both the challenge of reducing uncertainties in models and in measurements and a good characterization of the dynamics of terrestrial carbon sinks assume critical importance.

7.1 **Uncertainties of flux measurements**

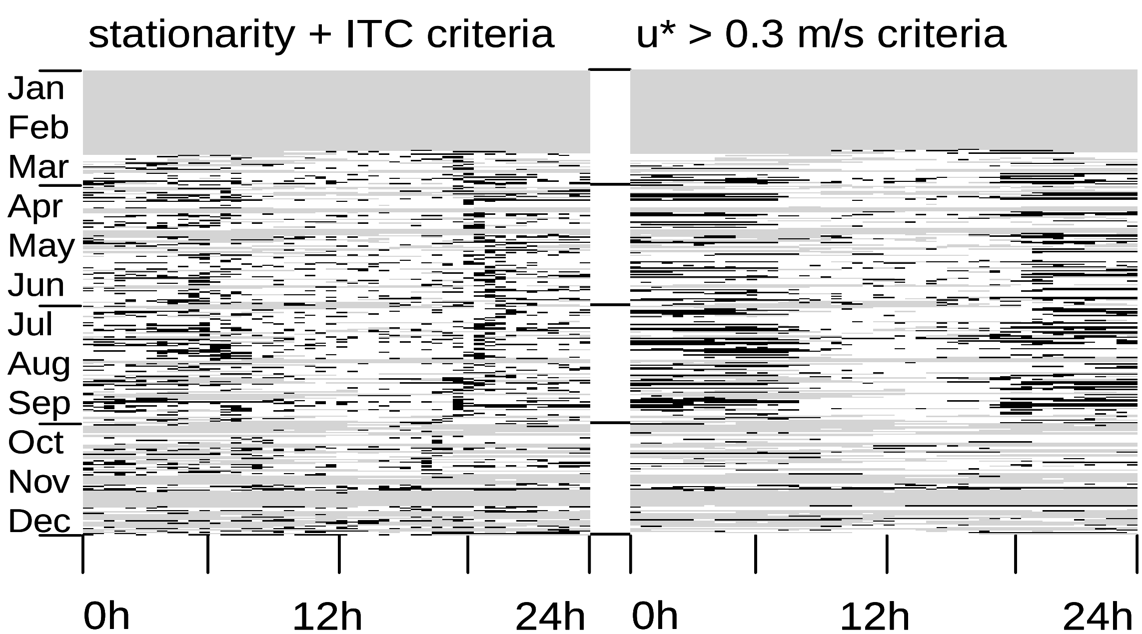

Figure 22. Result of different gap filling strategies (left: quality of flux data; right: friction velocity threshold) for the FLUXNET site DE-Bay (Waldstein, Weidenbrunnen) in the year 2003 (Ruppert et al., 2006a). Light grey are periods with missing data which are not gap filled and dark grey are gap filled data.

The eddy-covariance method used to determine the carbon-dioxide fluxes has been the standard method over the last two decades (Lee et al., 2004). The challenges in using this method generally relate mostly to factors influencing the efficiency of this method. First of all, the measuring method is restricted to a turbulent atmosphere, so calm, clear nights with little or no wind present a challenge for those interested in obtaining a robust value of the amount of carbon respired by vegetation in such conditions. The equations used in models also generally typically are limited to turbulent flow conditions, leaving out all exchange of carbon dioxide between the terrestrial ecosystems and the atmosphere at night, when most of the carbon dioxide is respired, despite the fact that approximately 40-60% of the carbon is exchanged during these conditions!

Therefore, in nighttime conditions, data obtained for measurement periods where the turbulence is small is generally replaced by proxi-data taken in turbulent conditions by a process referred to as 'gap filling'. This operation in the post-data collection phase of an experiment is performed alongside with missing data. The replacement of that data by 'gap-filled' data ranges approximately between 50 to 70 % of the year. The presently used gap-filling strategy is based on Goulden et al. (1996) and expanded by Falge et al. (2001a; 2001b). In calm conditions with light winds, 'real' field data is replaced by surrogate data when the windspeed falls below a certain threshold.

Another approach based on the data quality of eddy-covariance measurements (Foken et al., 2004) where only data are gap filled for a low data quality (Ruppert et al., 2006a); this method needs raw data and cannot be applied already to processed data. A comparison of both methods illustrates that the number of gap-filled data is nearly the same, with the difference that it is often other portions of the dataset which gap-filled (Figure 22). The benefit of the last method lies in that the presence of a higher number of available nighttime data available for the parameterization of respiration fluxes.

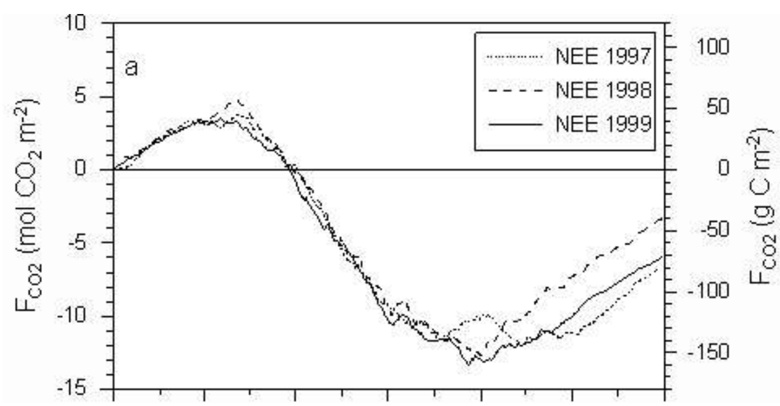

Figure 23. Annual net ecosystem exchange (NEE) in the years 1997 to 1999 for the FLUXNET site DE-Bay (Waldstein, Weidenbrunnen) according to Rebmann et al. (2001).

The gap-filling strategy has also a significant influence on the annual sum of the net ecosystem exchange (NEE). Characterized by a weak sink strength at sites (Figure 23), the annual uptake is of the order of the uncertainties of gap-filling methods i.e. ±25 g C m^{-2} $year^{-1}$ (Moffat et al., 2007).

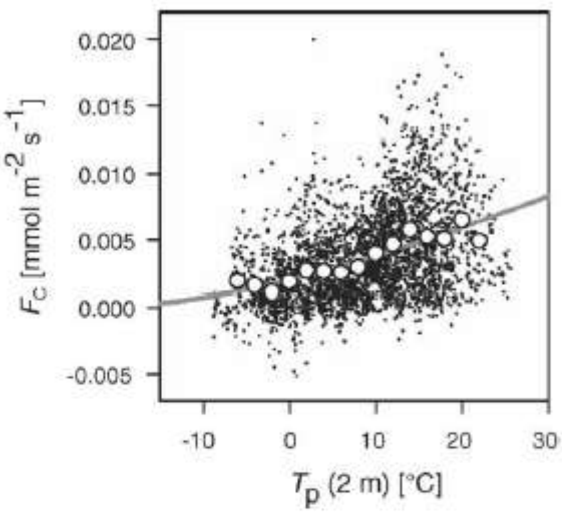

Figure 24: Regression line for the night time respiration as a function of the temperature for the FLUXNET site DE-Bay (Waldstein, Weidenbrunnen) in the year 2003 (Ruppert et al., 2006a)

Another method of filling gaps in data sets obtained in calm night time conditions consists in replacing the less-than-robust CO_2 rate respired by vegetation with the respiration rate obtained using a parameterization of the respiration the temperature (Lloyd and Taylor, 1994) and of the carbon uptake/assimilation depending on radiation (Michaelis and Menton, 1913).

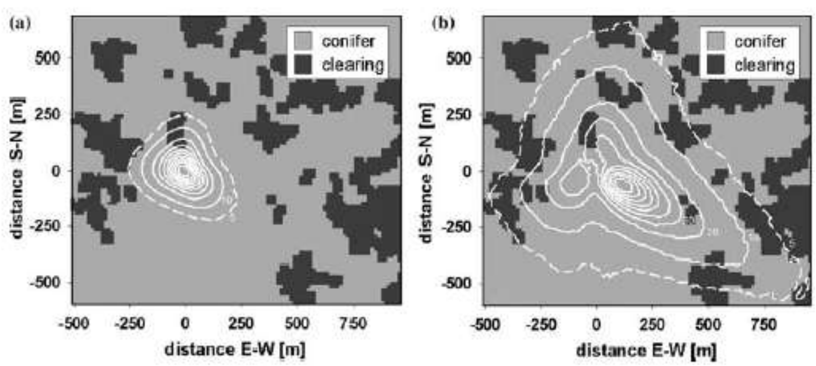

Figure 25: Footprint climatology for unstable (a) and stable (b) stratification for the for the FLUXNET site DE-Bay (Waldstein, Weidenbrunnen) according to Göckede et al. (2006). A three-dimensional weighting function is indicated by the white lines. Values are in percentages to the peak of the function, with solid lines ranging from 90% to 10%, and the dashed line as 5% of the maximum. Distances to the tower position are given in m, with the tower position located at (0, 0).

It stands to reason that, given the myriad of technical challenges facing experimentalists in assessing continuously the true net rate of carbon taken up and respired by terrestrial ecosystems, the robustness of proxi methods becomes inordinately important in the assessment of terrestrial carbon sinks.

As shown in Figure 24, the scatter in the data is high and the regression line is more or less a climatologically approach for the relation. The figure on carbon uptake is similar. While measured data bear a genuine relationship to the turbulent exchange process, the missing data replaced by data using semi-empirical methods represents only averages leaving out any relationship to physical processes. Uncertainties in the experimental data have also an influence on further model parameterizations (Papale et al., 2006).

In addition to the challenges inherent to a field data collection often riddled with sub-optimal data suitability, there are additional challenges to achieving robust terrestrial carbon sinks estimates.

Measured atmospheric flux data represent the exchange between the underlying surface upwind of the tower and a point measurement. In a typical experiment aiming at determining the sink strength of a particular ecosystem, the exchange of carbon dioxide between a particular domain and the measurement system is sought while being mindful that the region of influence to the CO_2 exchange is constantly changing with surface properties and atmospheric conditions. The contribution of the upwind underlying vegetation relative to a point measurement can be described by models referred to as 'footprint' models (Leclerc and Thurtell, 1990; Schuepp et al., 1990; Leclerc et al., 1997; Leclerc et al., 2003a; Leclerc et al., 2003b; Vesala et al., 2008; Vesala et al., 2004). A projection of the footprint on the underlying land use map shows (Figure 25) that the footprint also covers areas outside the domain: The problem then, is to interpret measured fluxes, which are often a mixture of the flux of the target area and other land use types contained within the footprint. Such footprint investigations (Göckede et al., 2008) were also used recently to identify footprint areas with low data quality to improve the measurement and analysis of terrestrial ecosystem carbon budget.

The flux structure in and above the canopy is also remarkably complex. Decoupling and counter gradients (Denmead and Bradley, 1985) do not only influence modelling methods but also the measurements. Often the forest trunk space is decoupled from the atmosphere except around midday when a good coupling can be found (Thomas and Foken, 2007). At other time of the day, often the respired carbon dioxide from the soil is taken up in the lower crown. Furthermore, the exchange between the trunk space and the atmosphere occurs by organized small-scale air motions which a duration of several tens of second. There are very effective in transporting CO_2. Their mean, time-averaged contribution to fluxes is about 20 % (Thomas and Foken, 2007) but for single periods, it can be as high as 80 % of the flux values (Bergström and Högström, 1989). The eddy-covariance method measures most of these coherent structures within an error of less than 5 %.

In addition to the challenges mentioned above, secondary circulations in the atmosphere boundary layer are present and arise from the heterogeneity in the landscape (Shen and Leclerc, 1994; Shen and Leclerc, 1995; Leclerc et al., 2003b; Inagaki et al., 2006; Kanda et al., 2004; Steinfeld et al., 2007). An analysis of such structures during the LITFASS-2003 experiment (Mengelkamp et al., 2006) have shown that the energy transport with such structures is in the order of the mission energy (Foken, 2008a). The structures cannot be easily measured with the eddy-covariance method because of their spatial scale extent and steady-state character. This issue is linked to measurements of carbon dioxide which are also transported by these secondary circulations.

7.2 **Emerging findings in determining carbon sources and sinks**

In talks and discussions related to the quantitative understanding of the measurements of the carbon dioxide exchanged between the surface and the atmosphere, the notion of the footprint, the measure of the spatial upwind surface extent influencing the measurements on a tower, almost always surfaces (Leclerc et al., 1990; Schuepp et al., 1990; Leclerc et al., 1997; Foken and Leclerc, 2004; Vesala et al., 2008). This is because these measurements need to be placed in the context of the site itself and its inherent intrinsic characteristics and the signature of each individual source/sink, each leaf, branch, soil area, litter over a envelope of varying proportions differs with time of day, height of measurements, the roughness of the vegetation and their individual weight varies with distance from the measurement system.

As already alluded, a myriad of factors contributes to make the interpretation of these measurements difficult. These can also include the advection of carbon dioxide, heat and water vapor in the case of terrestrial ecosystems, from a region normally well outside the scale of the flux tower measurements. These non-local contributions to the surface-atmosphere exchange at an unexpected far away location from its origin typically arise as a result of dissimilarities in the surface properties such as albedo, specific heat, surface roughness and other factors (Leclerc et al., 2003a; Sun et al., 1997). Real-world, oft-encountered examples include the innocuous presence of a large pond or lake upwind, the presence of a river in the middle of a forest, a clearing in the midst of an otherwise homogeneous forest stand (Leclerc et al., 2003a), a highway filled with cars at rush hour upwind of the tower flux measurements in a managed forest canopy (Leclerc (2008), personal communication).

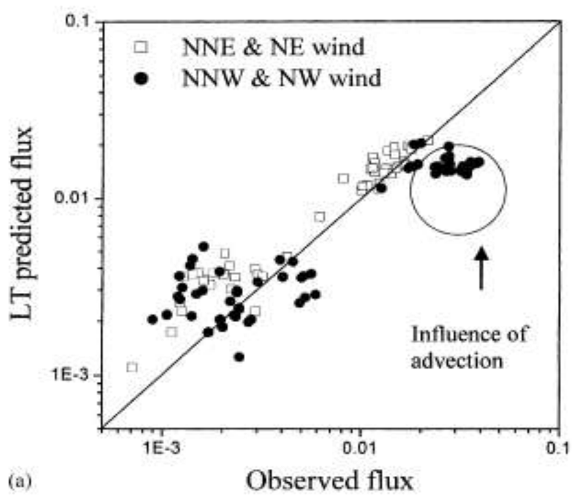

Figure 26. Footprint flux measurements in the roughness sublayer above the slash pine forest canopy AmeriFlux site versus modeled with the Lagrangian simulation. Source: Leclerc et al. (2003a).

It is the difference in temperature and to a lesser degree in moisture, between two adjoining but dissimilar surfaces that gives rise to circulations. Figure 26 illustrates the point. When measurements of the exchange of gases are made of a region where there is horizontal homogeneity over a very large distance upwind of the measurements, the modeled fluxes agree beautifully with the experimental data. However, when the wind direction originates from a region characterized by horizontal inhomogeneity and patchiness, the fluxes modeled have been shown to be off by as much as three hundreds of % (Leclerc et al., 2003a) and quite possibly more in other cases. This is an important result since flux instrumentation is typically not equipped to provide information separating the local/expected from the non-local contributions. The prescription for this lies in putting up several flux tower systems in a pre-determined triangular array or using an alternate method, often at high logistical costs. More concerted efforts are ongoing in this area so that measurements done with the eddy-covariance method can be relied upon in a wider range of surface conditions.

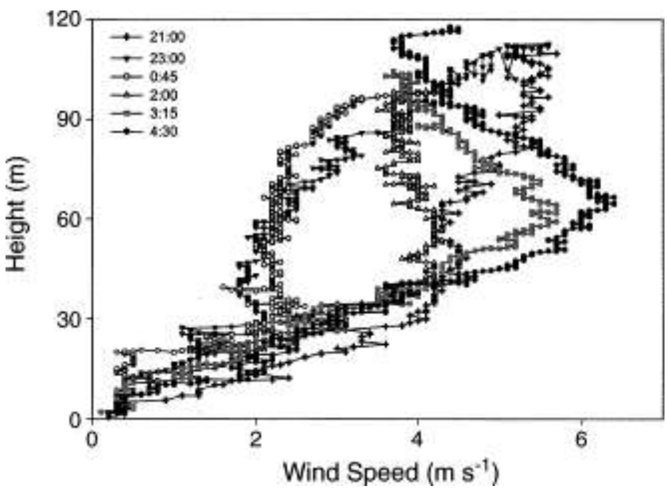

Figure 27. Wind speed profile during the nighttime. Source: Mathieu et al. (2005).

The challenge in correct measurements of the terrestrial carbon sink and their interpretation rapidly becomes compounded when attempts to quantify measurements are made during nocturnal conditions. Typically, the signal to noise ratio is small at night, and typically in a calm clear night, is very intermittent (Figure 27). The traditional wisdom suggests replacing periods where the winds are very small by data collected in windier conditions. Figure 28 shows a typical signal of a velocity time series and carbon dioxide. Measurements made at a point fail to reveal the bigger, three-dimensional picture of the factors responsible for the exchange processes: In this case, much of the transport in the most important events of the night originate from the upper portion of the nocturnal boundary layer or above, far above the flux sensor level, as is the case when an atmospheric low-level jet is present in the atmosphere at the time of measurements (Karipot et al., 2006; Karipot et al., 2008).

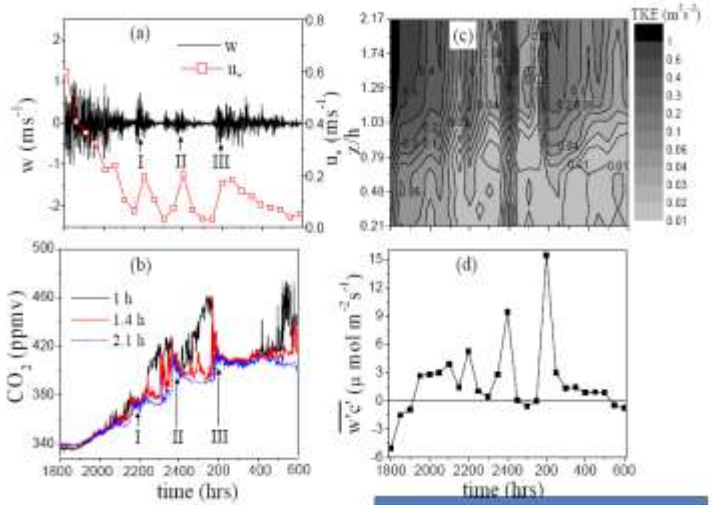

Figure 28. Time series of a) vertical velocity (w) and estimated friction velocity at 1.4 h, b) CO_2 concentration at 1 h, 1.4 h and 2.1 h, c) turbulent kinetic energy estimated using sonic anemometer measurements at thirteen levels within and above the canopy and d) CO_2 flux at 1.4h on June 25–26. w and CO_2 time series are re-sampled to 0.05 Hz to reduce cluttering. Periods marked as I, II and III correspond to the jet activity following calm conditions. Source: Karipot et al. (2006).

We can see in this Figure 29b that the concentration of carbon dioxide increases throughout the night to then suddenly and sharply decreases in three episodes. These episodes are brief but nonetheless constitute the dominant mechanism of carbon dioxide exchange between a forest canopy and the overlying atmosphere in calm nights. When the amount of turbulent kinetic energy is depicted as a function of time and height, sharp large turbulent kinetic energy values are present during those periods, right through the bottom of the canopy. It is those events that form the bulk of the CO_2 transfer from the vegetation to the atmosphere (Figure 28d) during a typical clear night. This is produced by a non-local phenomenon called the atmospheric nocturnal low-level jet which typically occurs at tens canopy heights away from the vegetation. The properties of the jet are linked with the surface transport in a manner that also varies throughout the night and from location to location. This is a novel finding suggesting that the link between the upper region of the nocturnal boundary layer is much stronger than we had previously anticipated adding further to the need of more investigations of this ‘teleconnection’.

8. Conclusions

New emerging climate models scenarios should include improved description of ecosystem sinks and concerted efforts must be made to embed more sophisticated ecosystem sink response. The feedback between the ecosystem response and the climate models has been shown recently to be more important than previously thought suggesting that more efforts be devoted to the inclusion of evolving vegetation and land-use patterns within these models. The inclusion of the coupling between hydrological, vegetation, carbon cycles linked to the nitrogen cycle might also contribute in improving our description of the impact of climatic changes in terrestrial ecosystems.

Already, a better understanding of carbon sequestration by ecosystems is already emerging as its fundamental role to help devise adaptation strategies in a changing climate is becoming increasingly clear. While more detailed experimental and modeling studies are likely to show additional uncertainties in carbon sequestration from vegetation and oceans, the size and influence of these uncertainties is likely to decrease. Regardless of the remaining uncertainties in our present climate-CO_2- global warming cycle knowledge, the management, use, and enjoyment of ecosystems need far more precise results. Increasingly, experiments are geared toward improving the evaluation of climate models, moving away from point measurements to spatially-integrated carbon flux measurements.

This paper has surveyed the question of balance between the amount of carbon naturally present in the atmosphere and the fraction captured by oceans and terrestrial vegetation. It has discussed the amount, rate and acceleration in the rate of actual carbon dioxide emissions pumped to the atmosphere worldwide and the trends governing those emissions both in the industrialized nations and in the developing nations. It has also surveyed the reasons underlying the massive increases in carbon dioxide emissions, leading to a planet that is warming up at a rate faster than even the most aggressive models have been predicting.

This paper has also reviewed the source of uncertainties in terrestrial sources and sinks strengths and sizes and the need for new improved methods to reduce these uncertainties. To reduce atmospheric carbon concentration, there must be an immediate and a sharp decrease of global carbon emissions. With that, the burden of cutting emissions rests on the biggest carbon polluters who are the richest.

From the evidence presented above eliminating all alternative explanations sometimes heard by detractors or by the public press on the causes of climate changes, it can be concluded that the sustainability of GAIA, our beautiful blue planet, is under an unparalleled assault in its history. Unless immediate remedial action is taken multilaterally to curb the emissions of greenhouse gases, it is likely to, in the words of James Lovelock, 'suffer a fever' that might kill the patient.

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