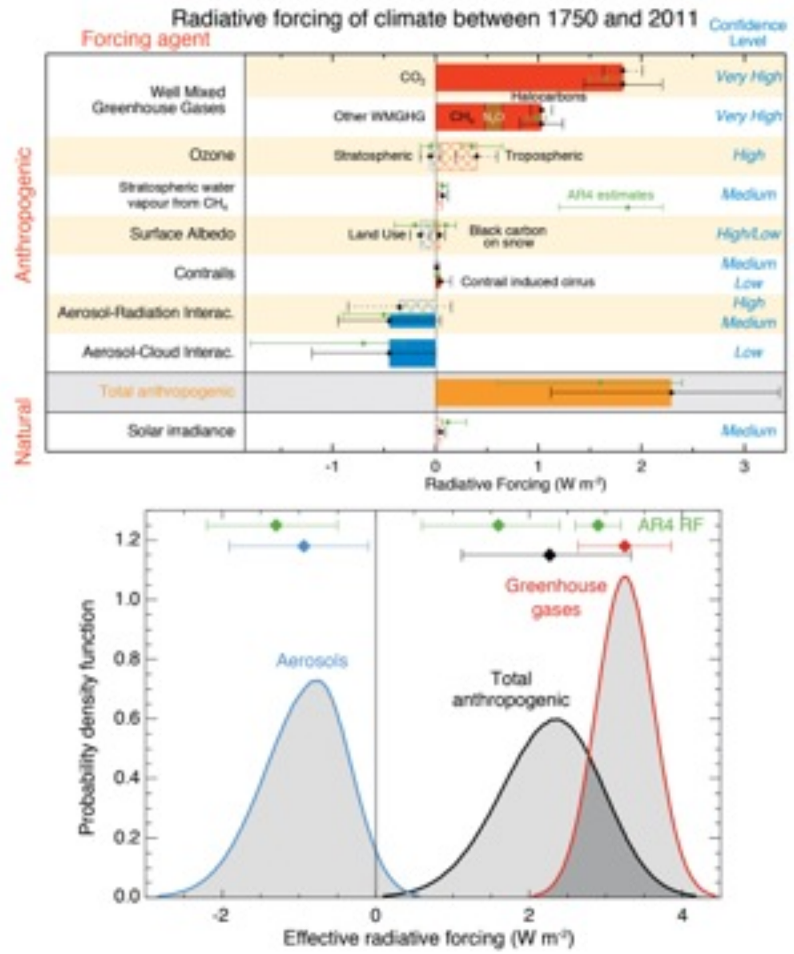
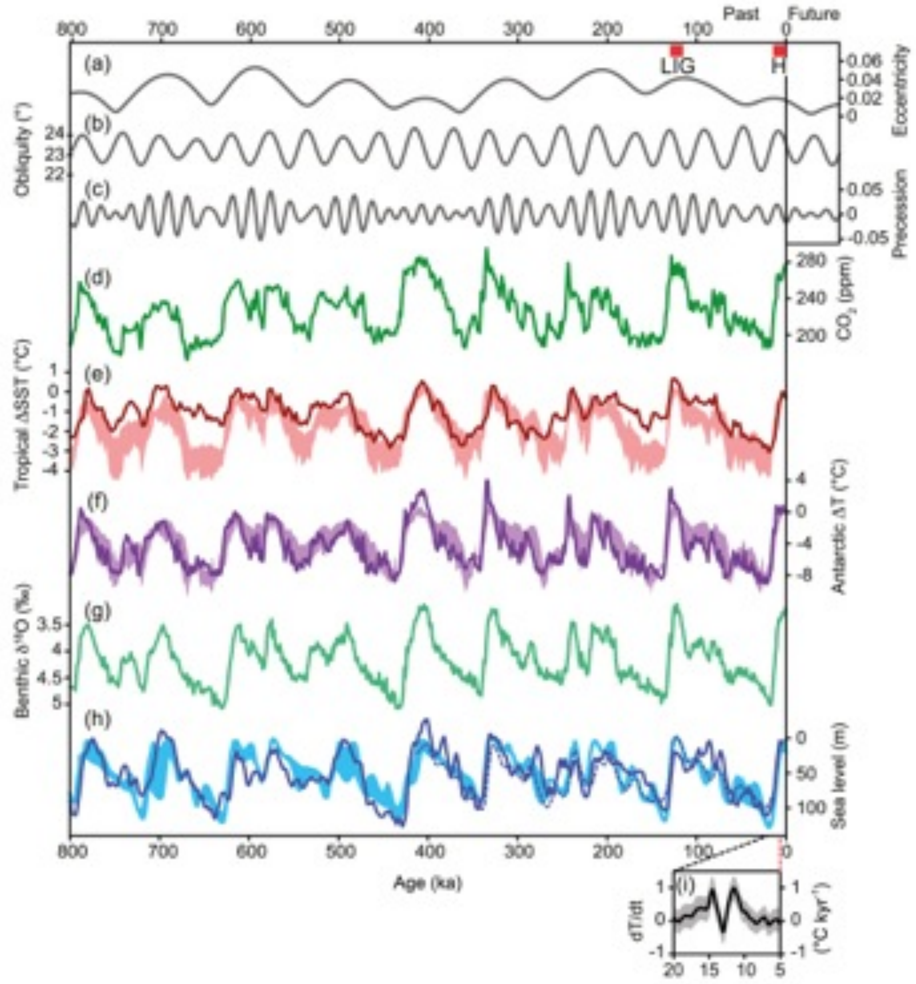
IPCC-AR5 Chapter 6:

Carbon

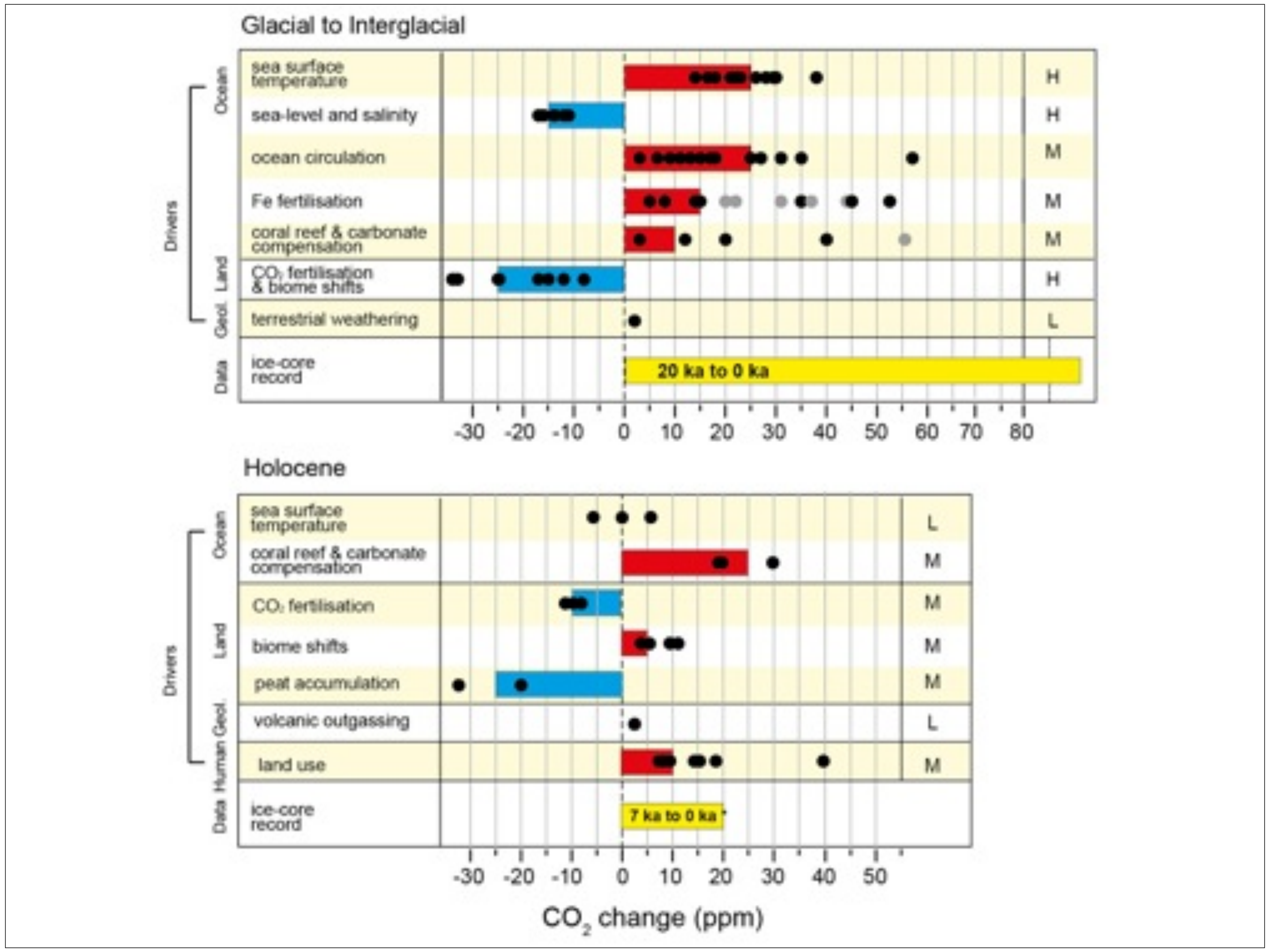
and Other Biogeochemical Cycles



CO2, CH4 and N2O are the biggest GHGs. Uncertainty in black carbon. (CFCs) They all have important biogeochemical cycles, which complicates things.



There is a “near-zero lag between the deglacial rise in CO2 and averaged deglacial Antarctic temperature. Previous studies estimating temperature lead of 800±600 years … probably overestimated.” “High-confidence that GHGs are an important feedback.”



Drivers of CO2 change during deglaciation.

Circles are model estimates, bars represent expert opinion.

Ocean warms, CO2 is less soluble.

Sea level rises, less salty, CO2 is more soluble.

Sea level rises, less alkaline, CO2 is more soluble.

Ocean was more stratified in glacial period, less upwelling. Limited role of ice-cap.

Glacial was much dustier, promoted productivity in current HNLC regions.

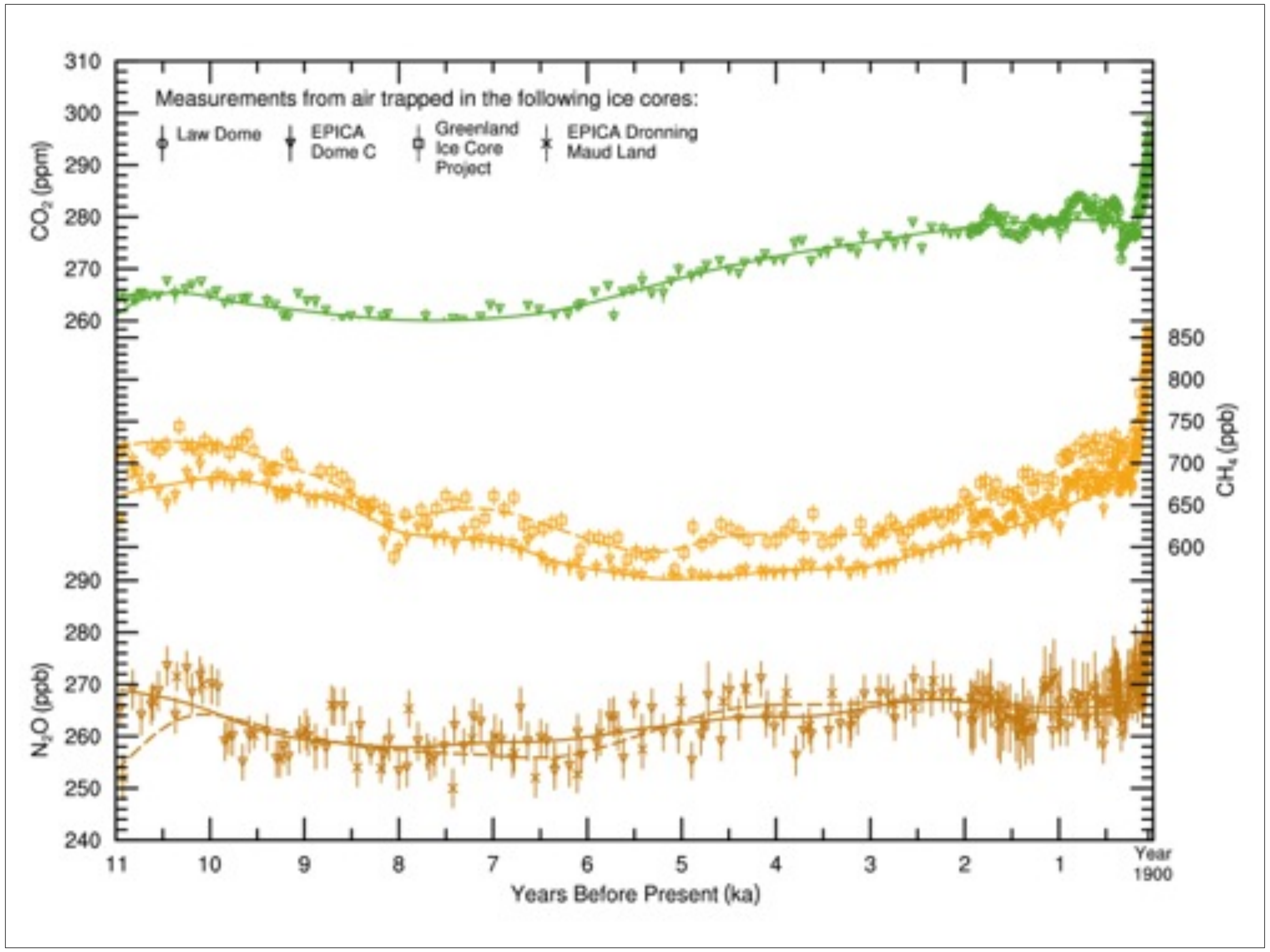
Calcium carbonate is more soluble at lower temp, warming increases CO2(aq).

Shift from deep-water deposition to shallow, more CaCO2, less HCO3, more CO2; similarly more coral.

del13C indicates Land storage of 300 PgC between 11-5 ka.

Volcanic CO2 emissions to the atmos between 12-7 ka were estimated to be two to six times higher than during the las millennium, of about 0.1 PgC/yr.

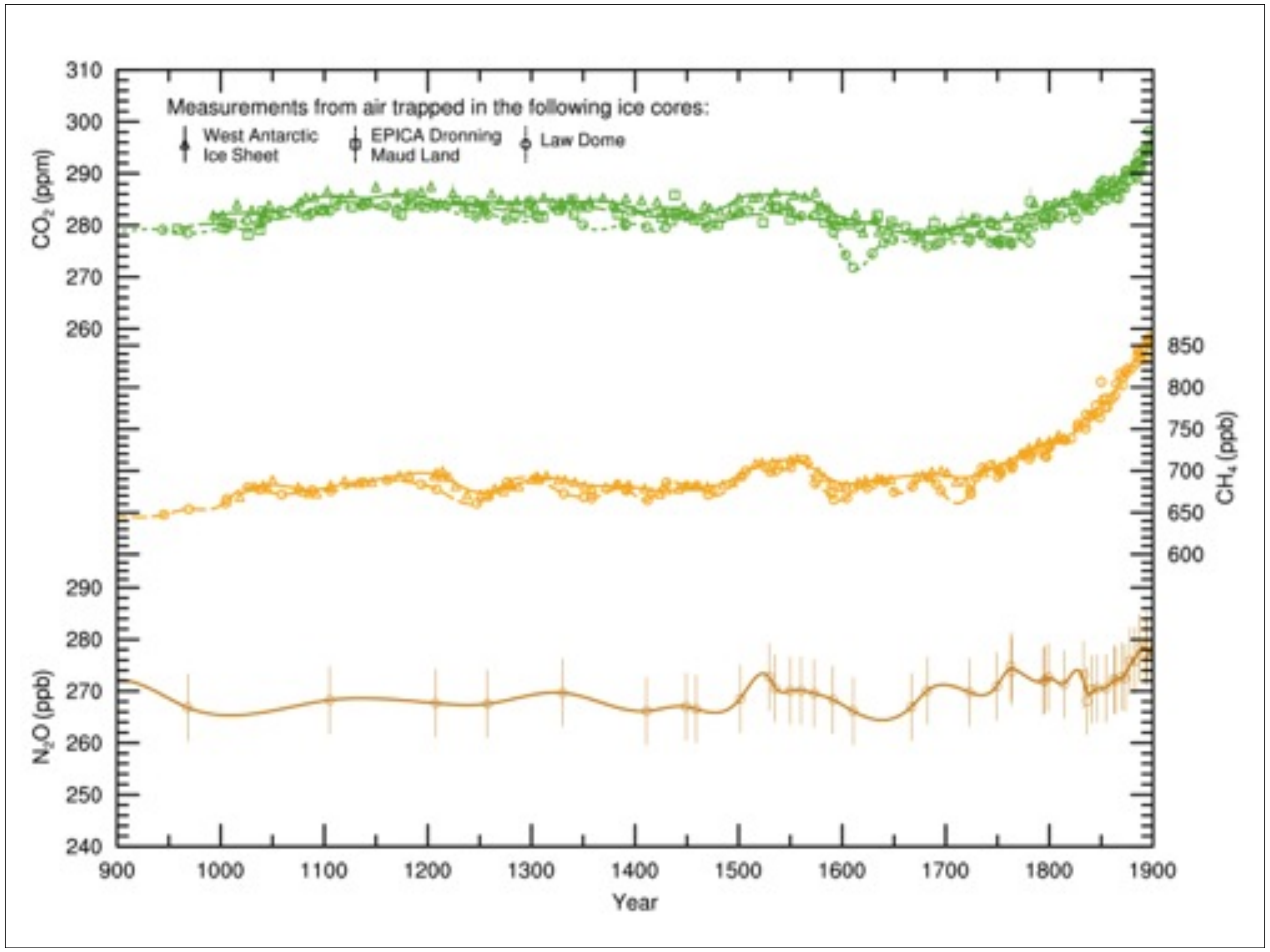
(Low confidence.)



Law Dome, EPICA Dome C an Dronning Maud Land - East Antarctic

20 ppm rise during pre-industrial era. Land use, and agriculture? Similar variation is seen in previous inter-glacieal. Still. (As likely as not human.)

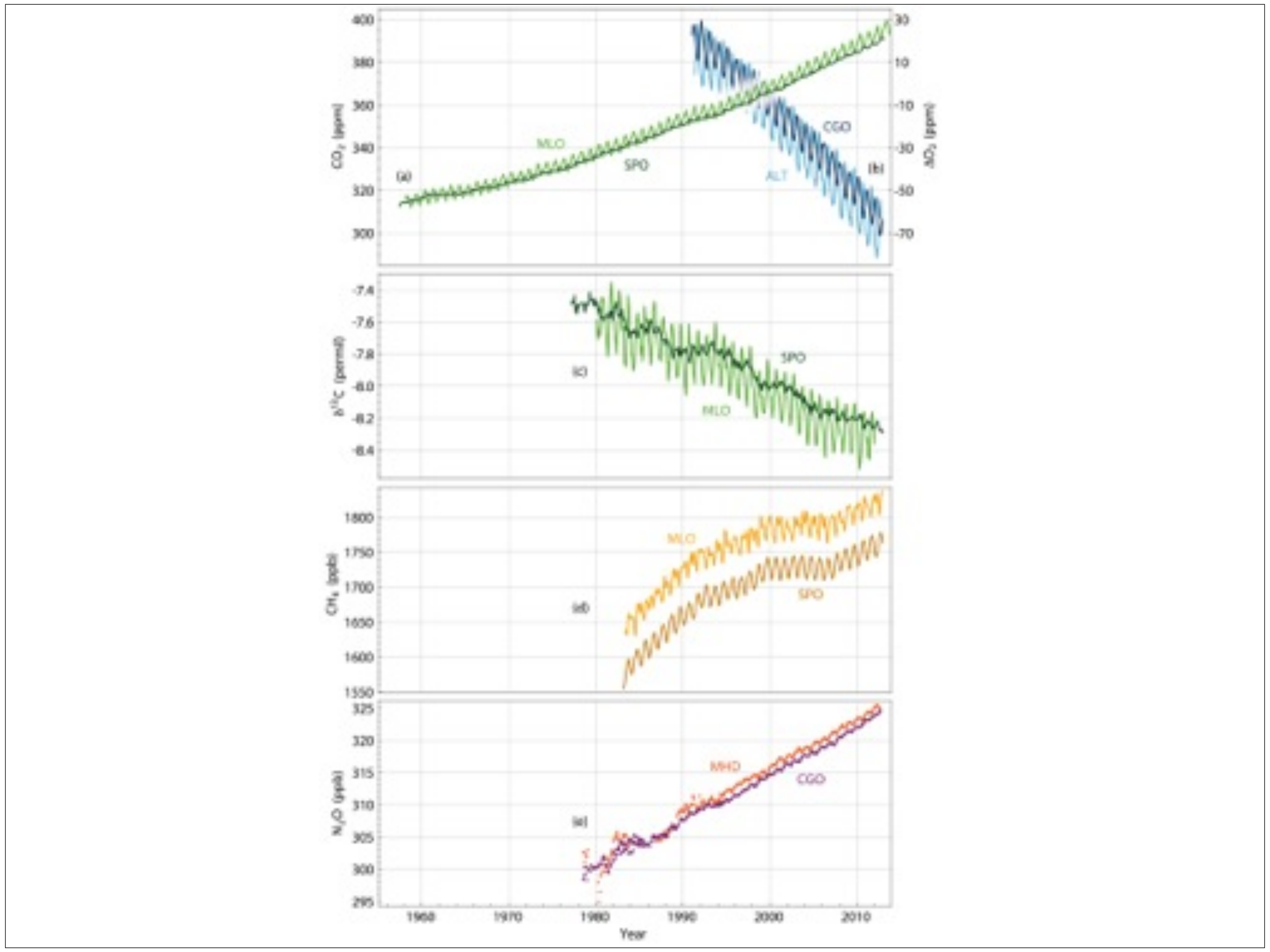
Rice domesticated 8-13 ka, rapid spread 3 ka.



1600? Maunder minimum or volcanic, cooling>uptake? Temp records disagree with each other. Might be depopulation of the Americans following European contact leading to forest regrowth.

Methane has high variability in natural and antropogenic sources. Rise begins before CO2.

Sodium nitrate mining in Chile in 1823. Haber 1913.

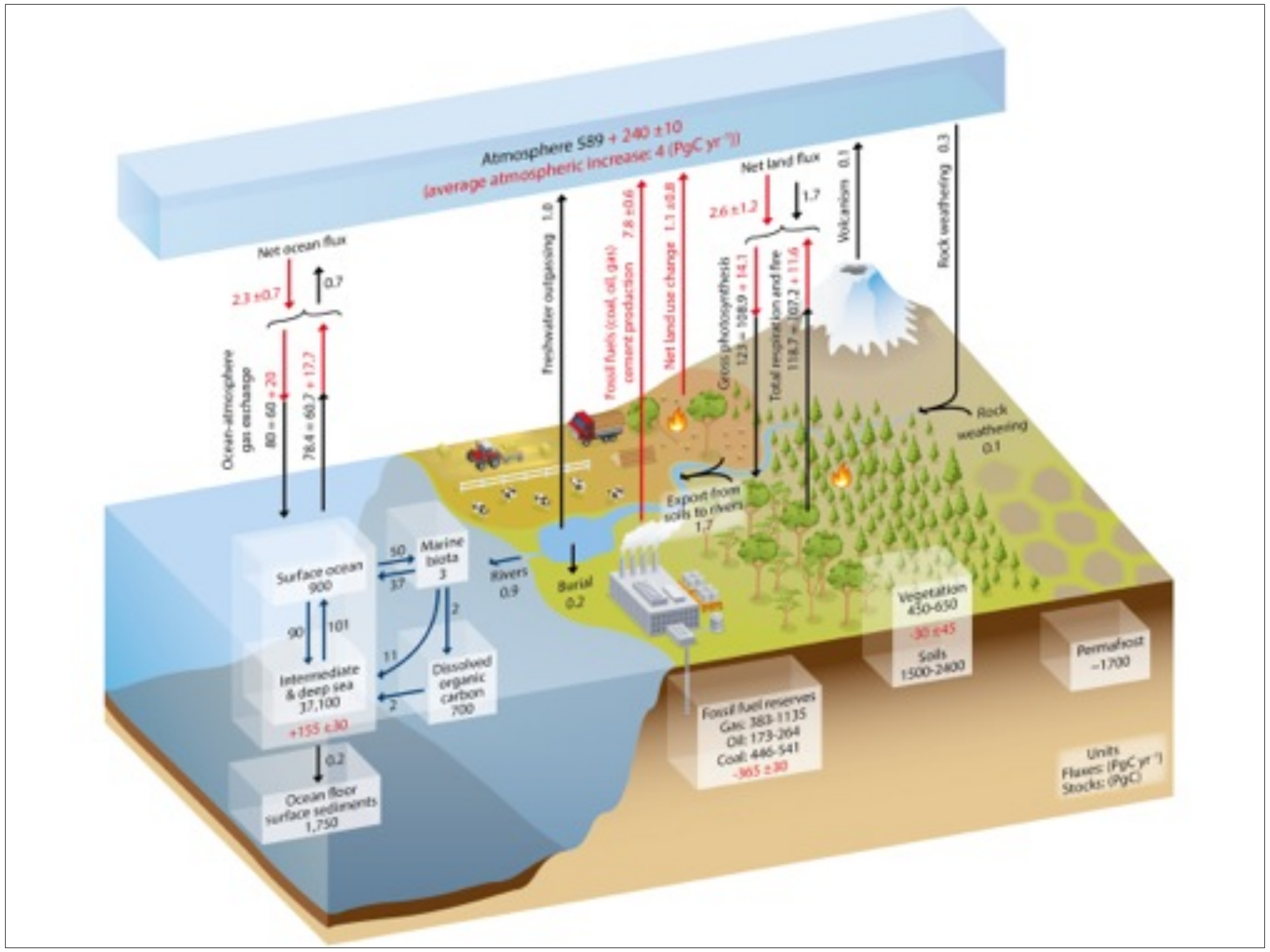


Seasonal cycles illustrate N.Hem land. CO2 increases causing O2 to decrease.

Hemispheric gradient of CO2 indicates anthropogenic impact; curves diverge, its growing. Fossil fuels were biogenic, more C12, lowers ratio over time.

Methane growth slowed or stopped, but now increasing again.

N2O, Ireland and Tazmania.



828 PgC in the atmosphere, 390.5 ppm in 2011.

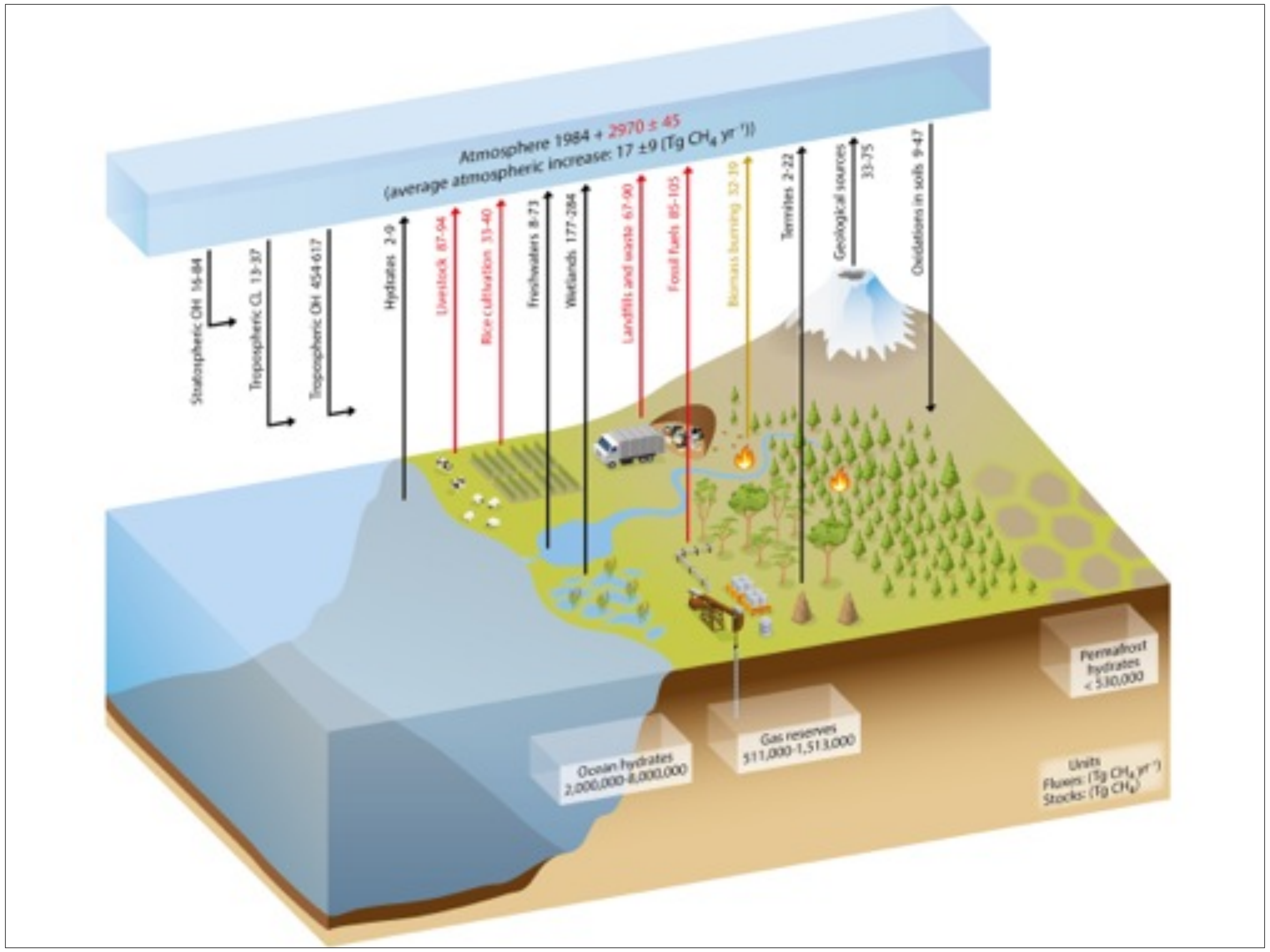
396.33 ppm in July 2014, up from 394.39 in 2013.

There are large stocks in soils, particularly wetland soils and in permafrost.

Balance of biologic fluxes on land? River export.

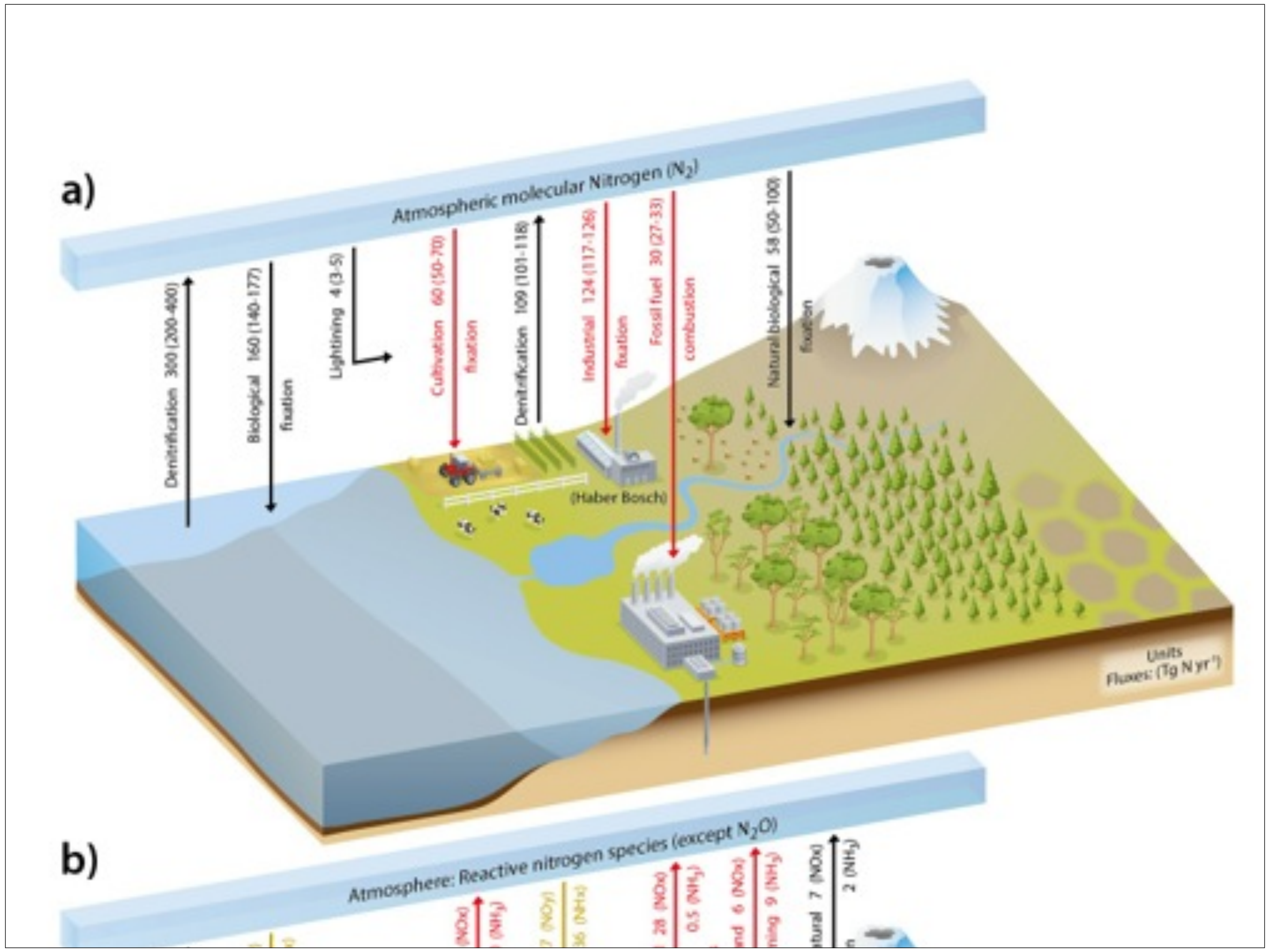
Oceans in balance. Solubility pump, biological pump, carbonate pump.

Long-term balance with the weathering of silicate rocks.



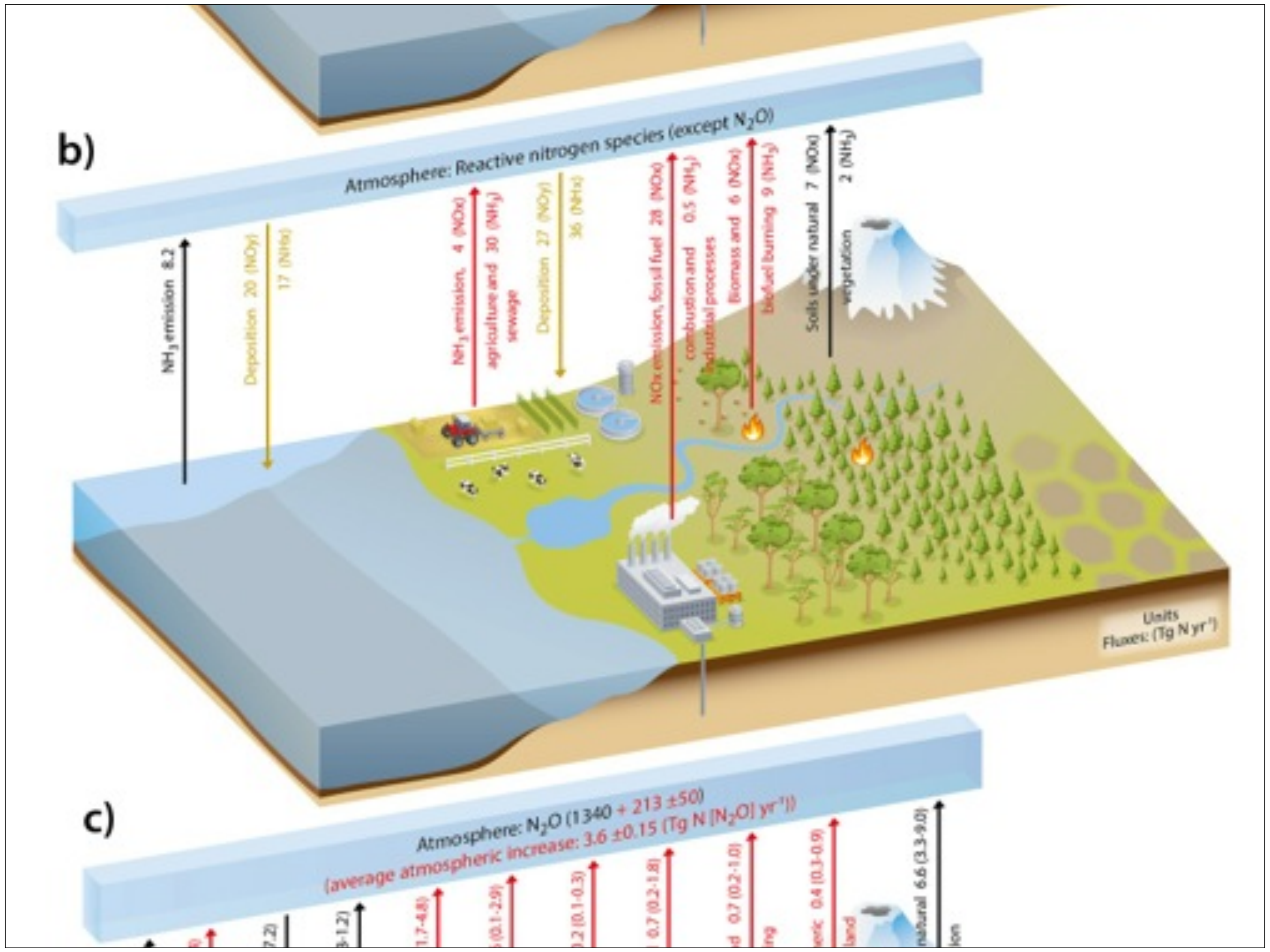
Wetland methanogenisis. Pyrogenic and geologic fluxes. Fossil fuel extraction. Hydrates. Archer 2007 corrected estimate in 2009, 1,600 - 2,000 PgC .

Destroyed by rxn with hydroxyl. Consumed in soils. Also reacts in strat to form water.

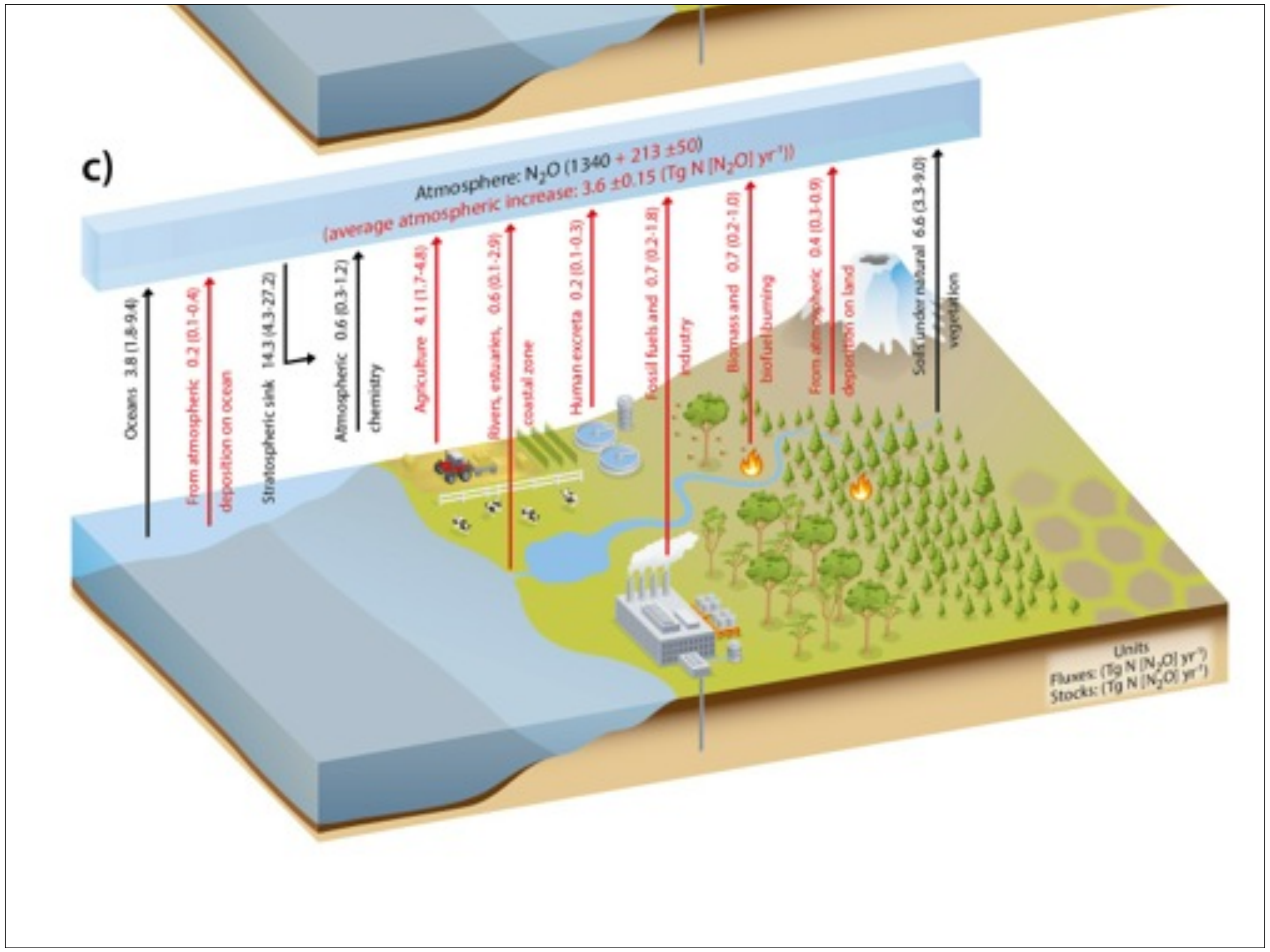


Twice as much fertilizer production as natural terrestrial fixation of nitrogen.

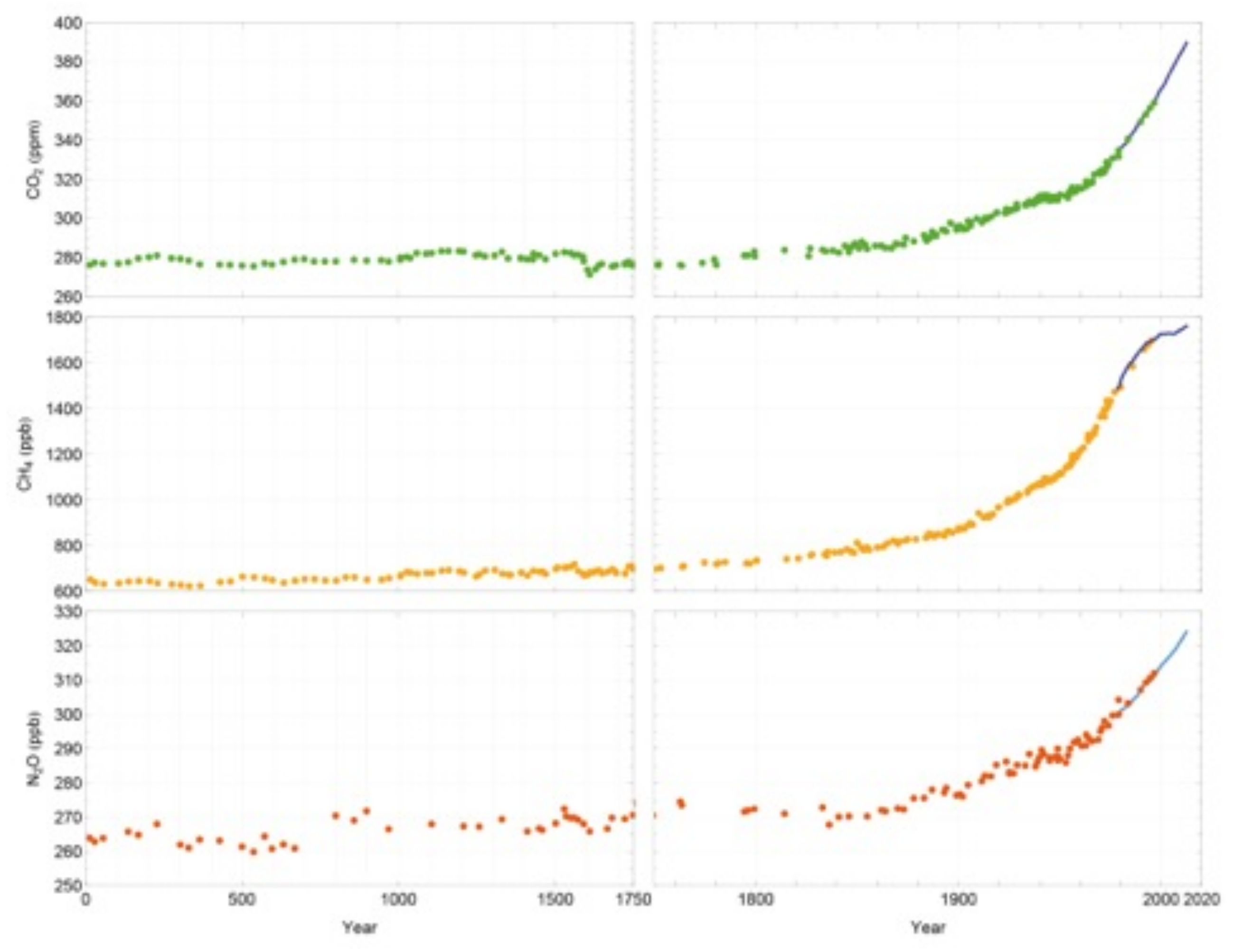
Mostly, it re-mineralizes.



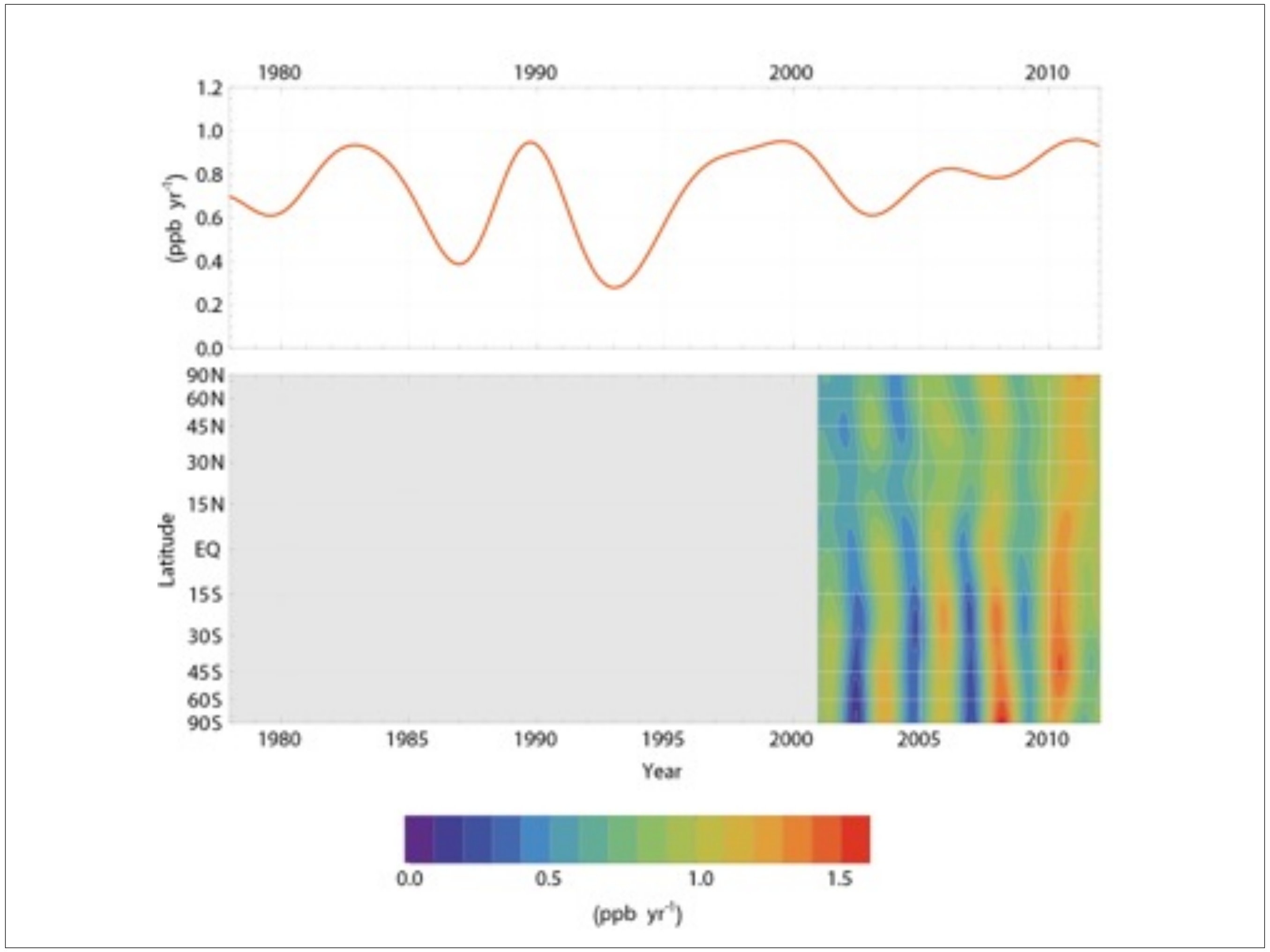
Some of it is reactive, problem for ozone.



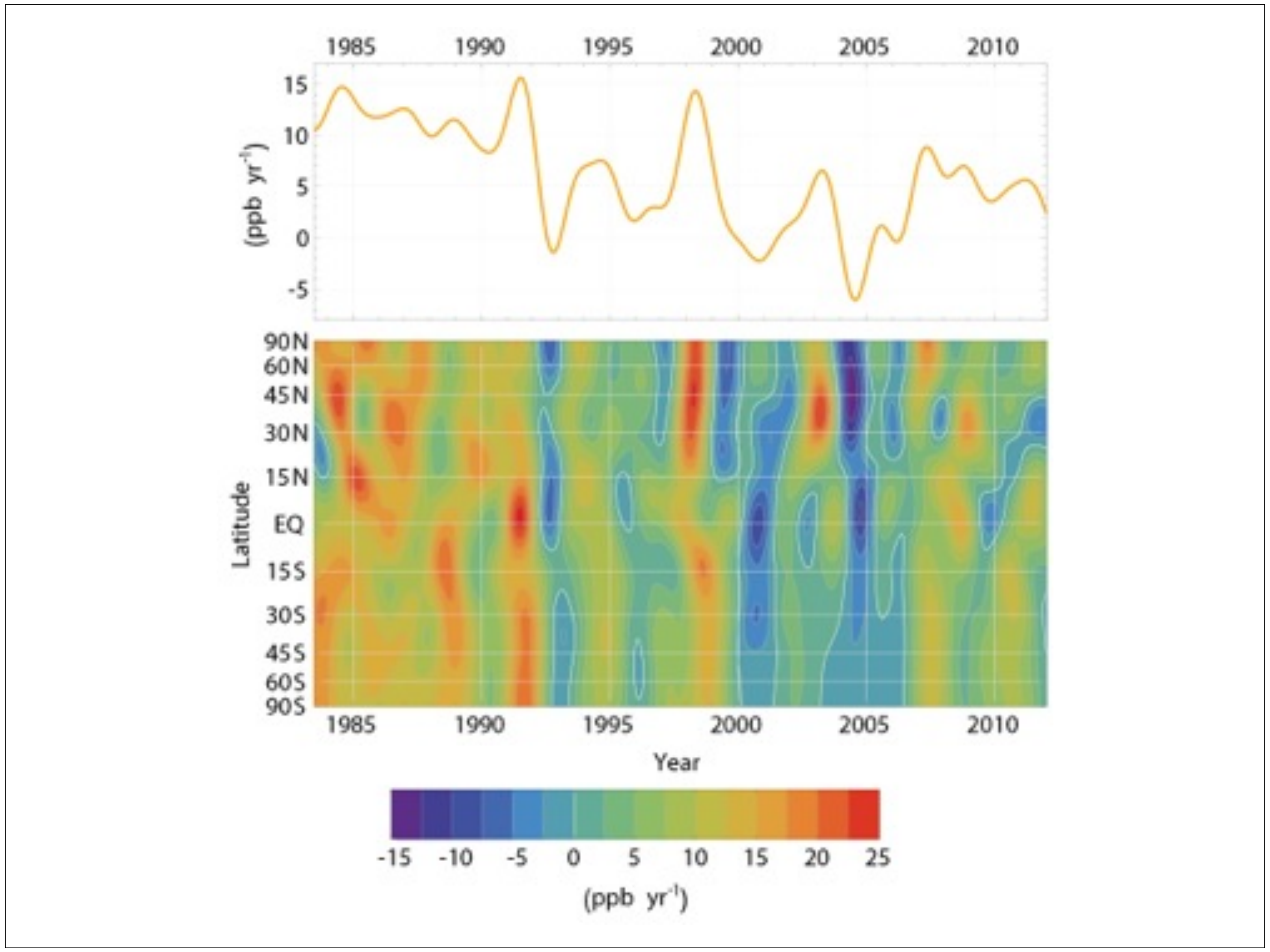
A little bit forms Nitrous Oxide.



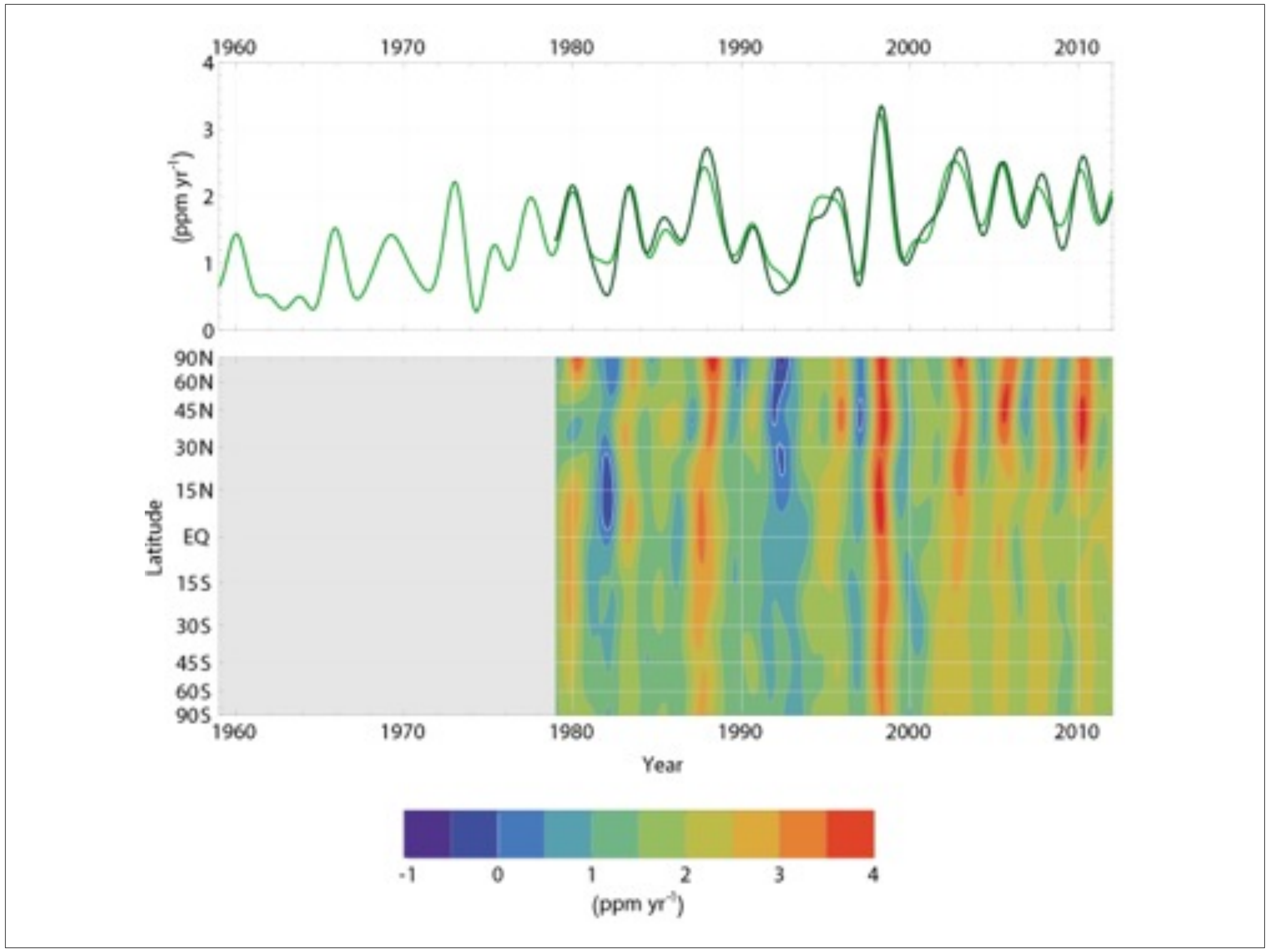
400
380
360
340
320
300
280
260
CO$_2$ (ppm)
1800
1600
1400
1200
1000
800
600
CH$_4$ (ppb)
330
320
310
300
290
280
270
260
250
N$_2$O (ppb)
0
500
1000
1500
1750
1800
1900
2000
2020
Year
Year



Food production is likely responsible for 80% of the increase in atmospheric N2O, via the application of fertilizers. Destroyed by rxn with O(1D), therefore of importance to strat. chemistry. (Is ozone depletion therefore why its growing faster in the S. Hem?)

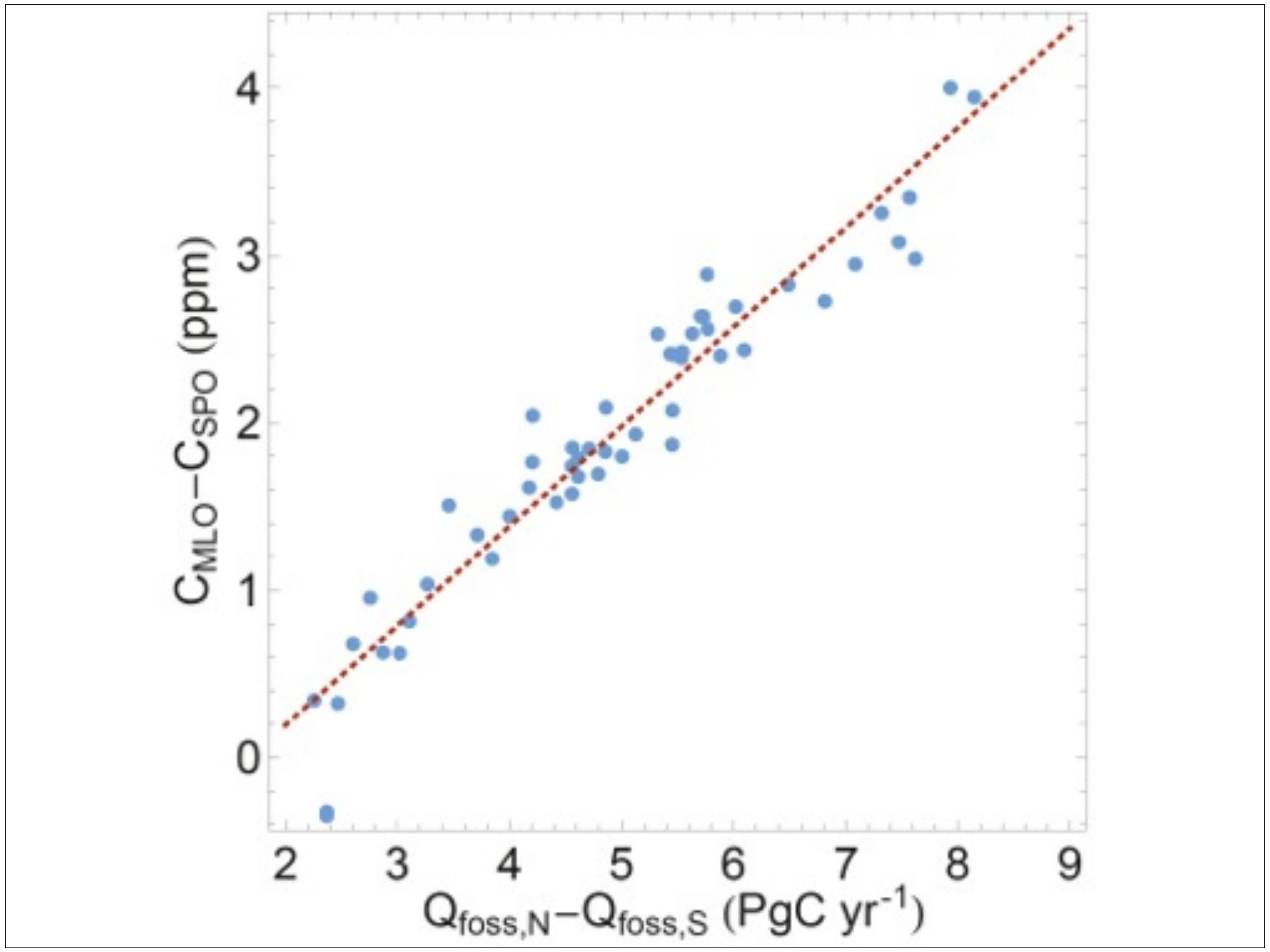


Methane growth rates. They are declining. ENSO spike. Natural sources are the main driver, in response to climate, with high confidence. 9.1±0.9 year lifetime. Reaction with OH consumes 90% of surface emissions, 9% of total burden. Other sinks are three orders of magnitude smaller. Little change in OH concentrations over time 1-3% inter annual variation.

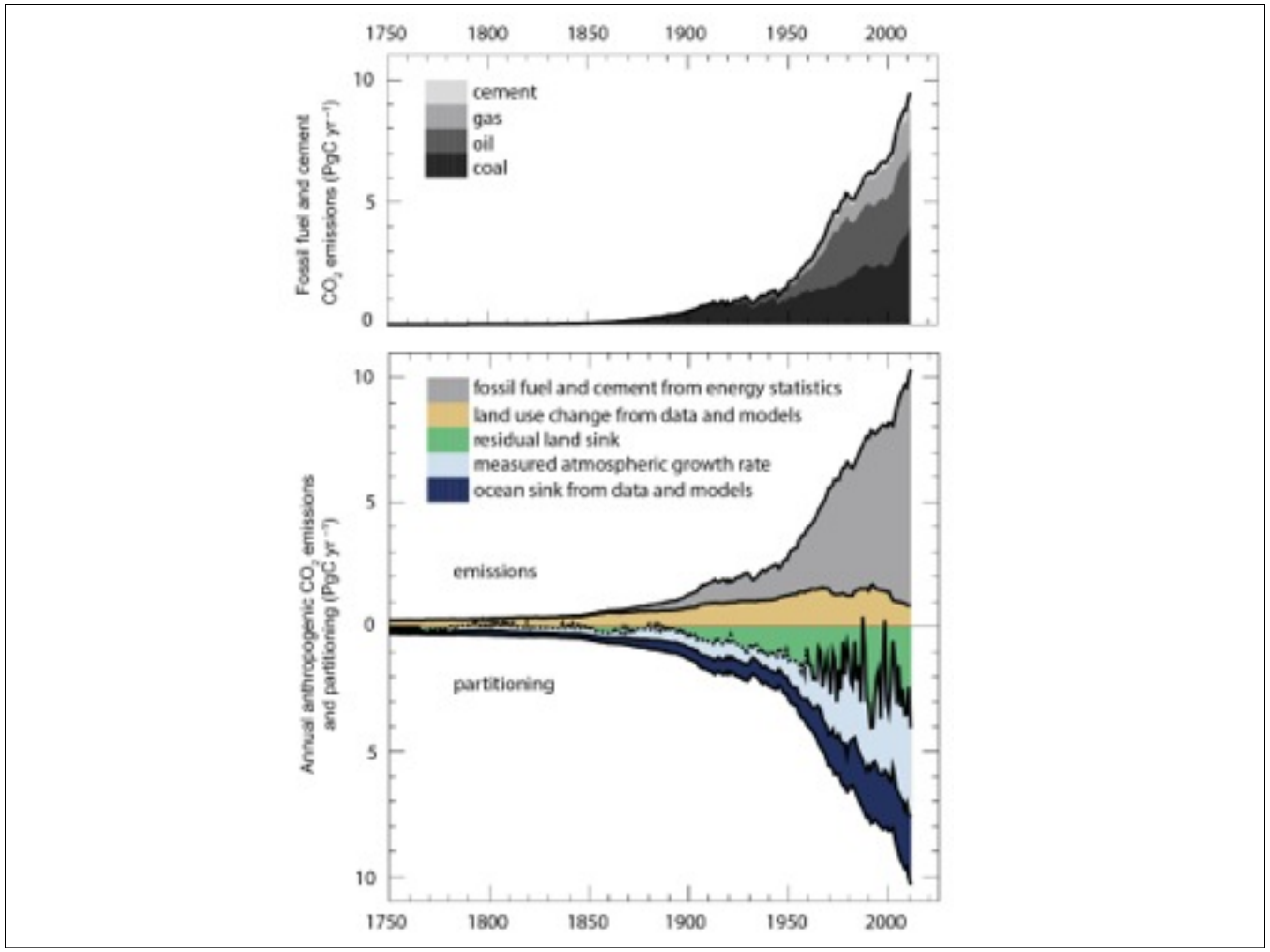


Growth rate of CO2. Globally, always positive. Local decreases seen sometimes.

Rate of CO2 emissions from fossil fuel burning and land use change was almost exponential, and the rate of CO2 increase in the atmosphere was also almost exponential and about half that of the emissions.



Variations in the inter-hemispheric gradient are linearly related to the difference in fossil fuel combustion between the hemispheres.



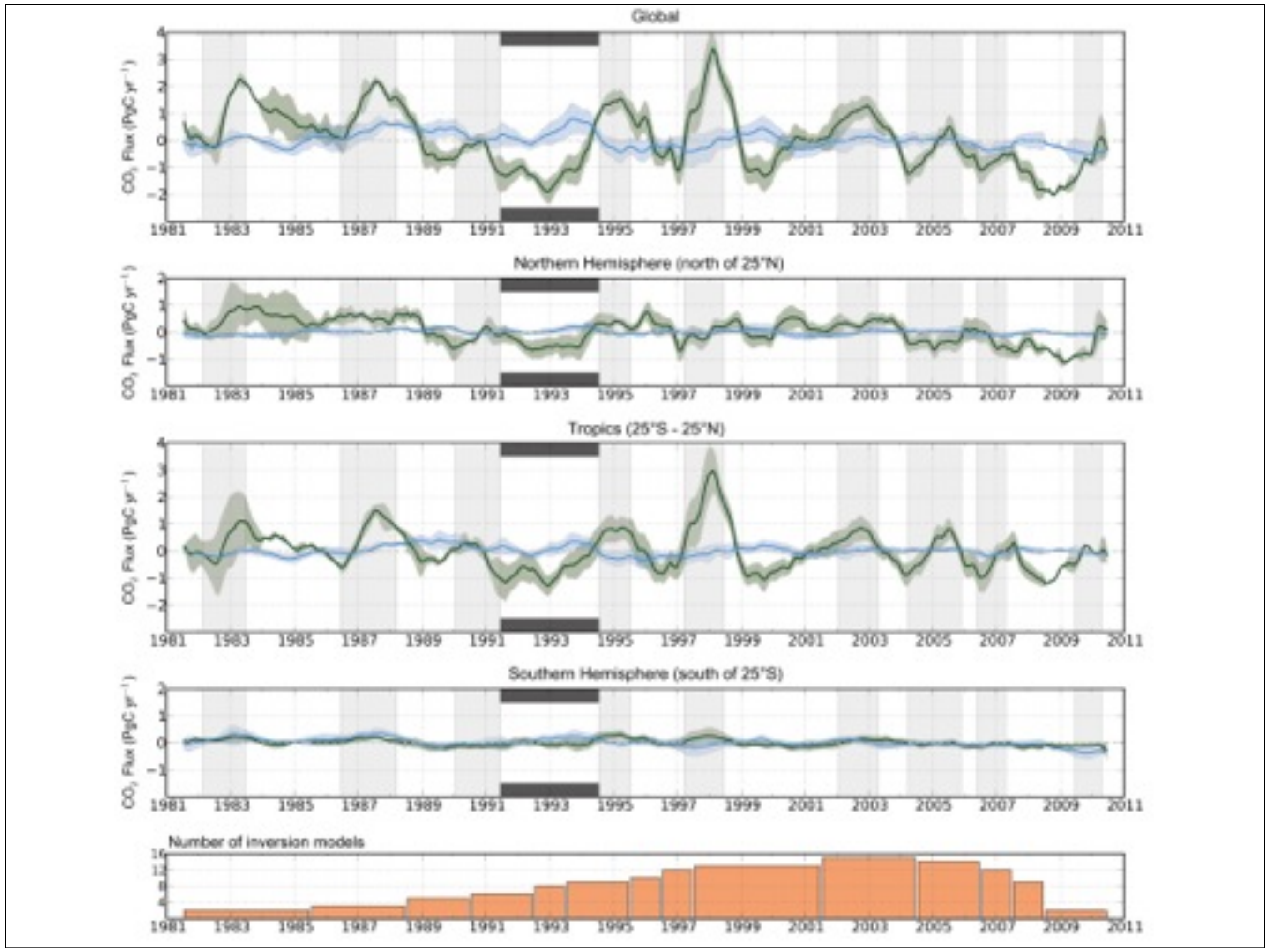
Very high confidence that the increase in CO2 emissions from fossil fuel burning and those arising from land use change are the dominant cause of the observed increase in atmospheric CO2 concentration.

Not all of the emissions can be found in the air and oceans. Of the 55±85 PgC emitted, the ocean has stored 155±30 PgC; meaning 160±90 PgC has accumulated in the biosphere. Nearly compensating for carbon emitted from land use change, estimated as 180±80 PgC.

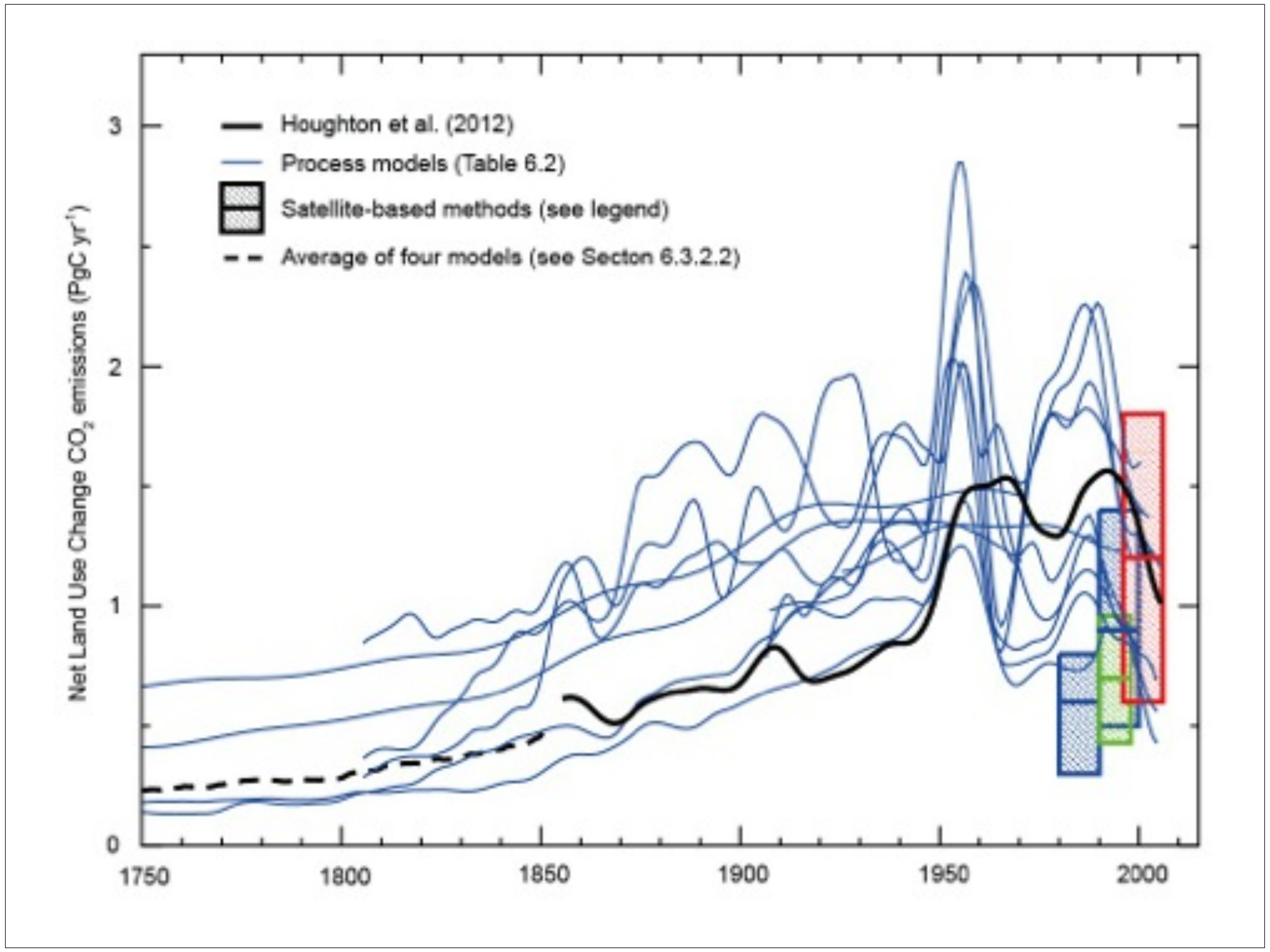
Quite a bit of variability in the land-sink, sign changes sometimes.

CO2 fertilization, nitrogen deposition and favorable climate change. (Likely, [which?]) Forest regrowth, and increased biomass density as well.

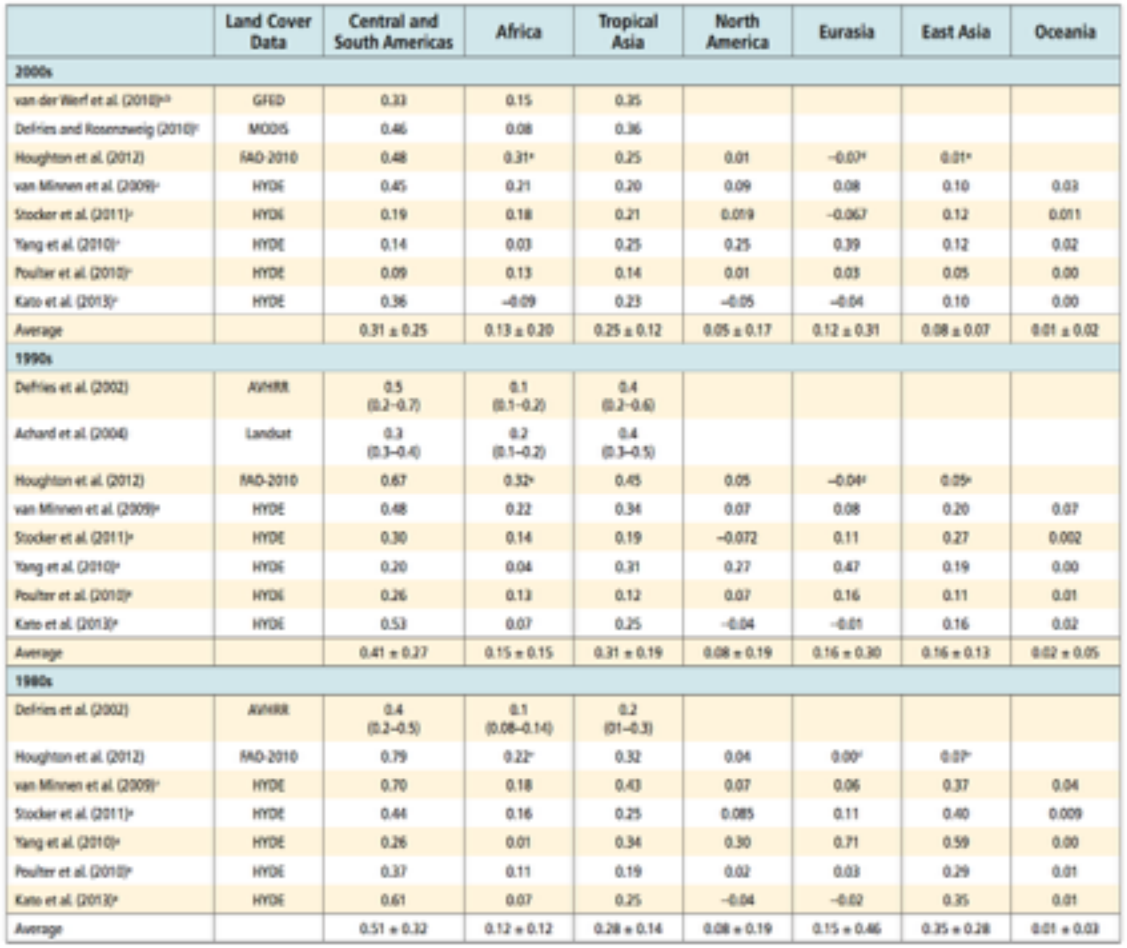
Fossil emissions have an estimated uncertainty of ±8%, and is increasing as more emissions occur in developing economies.



TRANSCOM. Orange, number of models. Blue, oceans; green, land exchange. 1-sigma spread. ENSO shaded, bar for Pinatubo. Eruption increases uptake! Medium to high confidence that the sink is primarily in the terrestrial tropics.

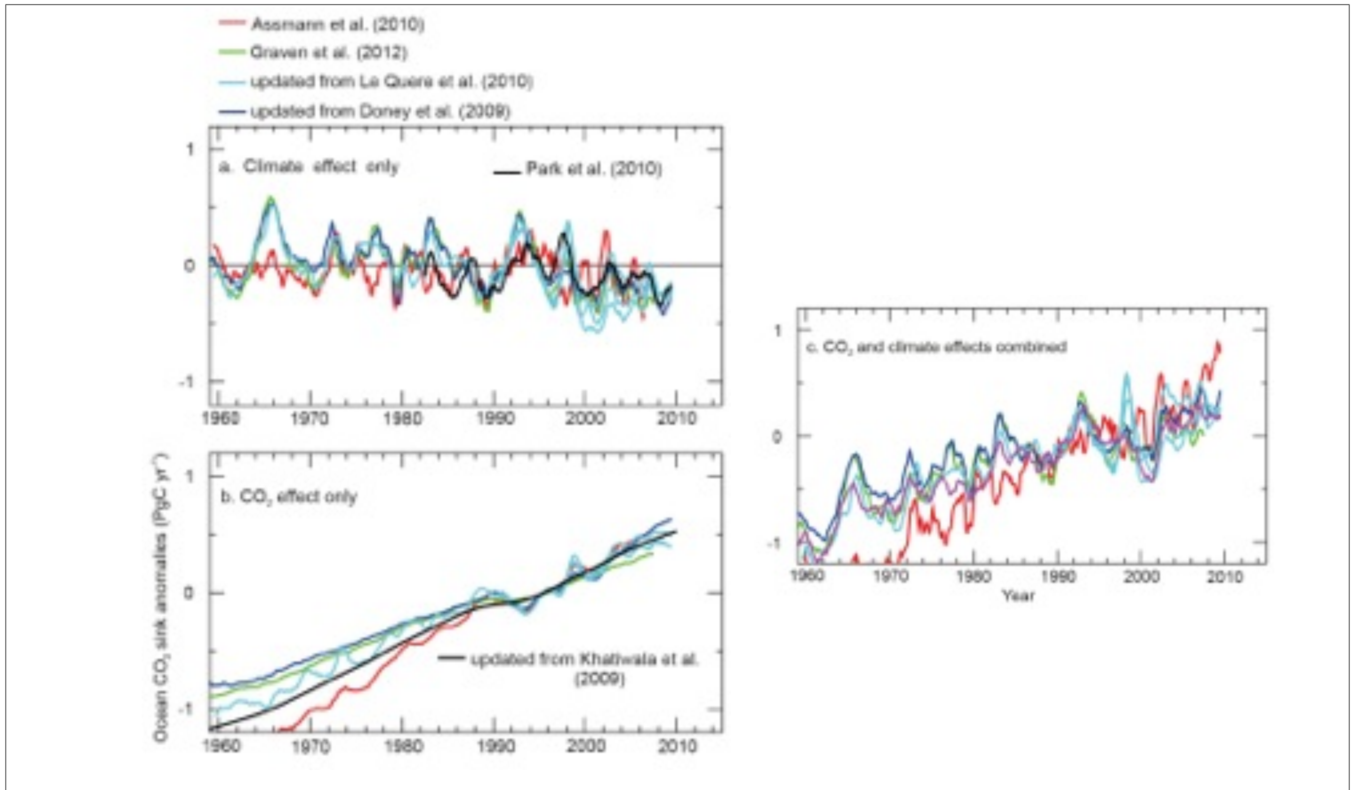


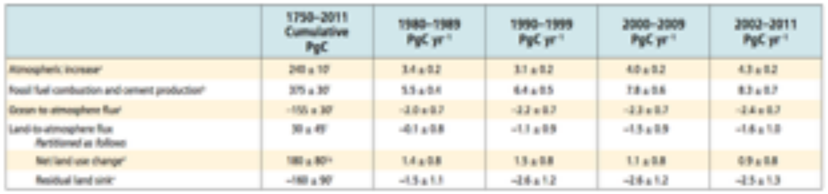
CO2 emissions from land use change are estimated at 1.5 declining to 1.1±0.8 PgC/yr. This is smaller than in the previous report.



	Land Cover Data	Central and South Americas	Africa	Tropical Asia	North America	Eurasia	East Asia	Oceania
2000s								
van der Werf et al. (2010)[a,b]	GFED	0.33	0.15	0.35				
DeFries and Rosenzweig (2010)[c]	MODIS	0.46	0.08	0.36				
Houghton et al. (2012)	FAO-2010	0.48	0.31[e]	0.25	0.01	−0.07[d]	0.01[e]	
van Minnen et al. (2009)[c]	HYDE	0.45	0.21	0.20	0.09	0.08	0.10	0.03
Stocker et al. (2011)[c]	HYDE	0.19	0.18	0.21	0.019	−0.067	0.12	0.011
Yang et al. (2010)[c]	HYDE	0.14	0.03	0.25	0.25	0.39	0.12	0.02
Poulter et al. (2010)[c]	HYDE	0.09	0.13	0.14	0.01	0.03	0.05	0.00
Kato et al. (2013)[c]	HYDE	0.36	−0.09	0.23	−0.05	−0.04	0.10	0.00
Average		0.31 ± 0.25	0.13 ± 0.20	0.25 ± 0.12	0.05 ± 0.17	0.12 ± 0.31	0.08 ± 0.07	0.01 ± 0.02
1990s								
DeFries et al. (2002)	AVHRR	0.5 (0.2–0.7)	0.1 (0.1–0.2)	0.4 (0.2–0.6)				
Achard et al. (2004)	Landsat	0.3 (0.3–0.4)	0.2 (0.1–0.2)	0.4 (0.3–0.5)				
Houghton et al. (2012)	FAO-2010	0.67	0.32[e]	0.45	0.05	−0.04[d]	0.05[e]	
van Minnen et al. (2009)[c]	HYDE	0.48	0.22	0.34	0.07	0.08	0.20	0.07
Stocker et al. (2011)[c]	HYDE	0.30	0.14	0.19	−0.072	0.11	0.27	0.002
Yang et al. (2010)[c]	HYDE	0.20	0.04	0.31	0.27	0.47	0.19	0.00
Poulter et al. (2010)[c]	HYDE	0.26	0.13	0.12	0.07	0.16	0.11	0.01
Kato et al. (2013)[c]	HYDE	0.53	0.07	0.25	−0.04	−0.01	0.16	0.02
Average		0.41 ± 0.27	0.15 ± 0.15	0.31 ± 0.19	0.08 ± 0.19	0.16 ± 0.30	0.16 ± 0.13	0.02 ± 0.05
1980s								
DeFries et al. (2002)	AVHRR	0.4 (0.2–0.5)	0.1 (0.08–0.14)	0.2 (01–0.3)				
Houghton et al. (2012)	FAO-2010	0.79	0.22[e]	0.32	0.04	0.00[d]	0.07[e]	
van Minnen et al. (2009)[c]	HYDE	0.70	0.18	0.43	0.07	0.06	0.37	0.04
Stocker et al. (2011)[c]	HYDE	0.44	0.16	0.25	0.085	0.11	0.40	0.009
Yang et al. (2010)[c]	HYDE	0.26	0.01	0.34	0.30	0.71	0.59	0.00
Poulter et al. (2010)[c]	HYDE	0.37	0.11	0.19	0.02	0.03	0.29	0.01
Kato et al. (2013)[c]	HYDE	0.61	0.07	0.25	−0.04	−0.02	0.35	0.01
Average		0.51 ± 0.32	0.12 ± 0.12	0.28 ± 0.14	0.08 ± 0.19	0.15 ± 0.46	0.35 ± 0.28	0.01 ± 0.03

Deforestation has been declining, and is mostly in Central and South America.





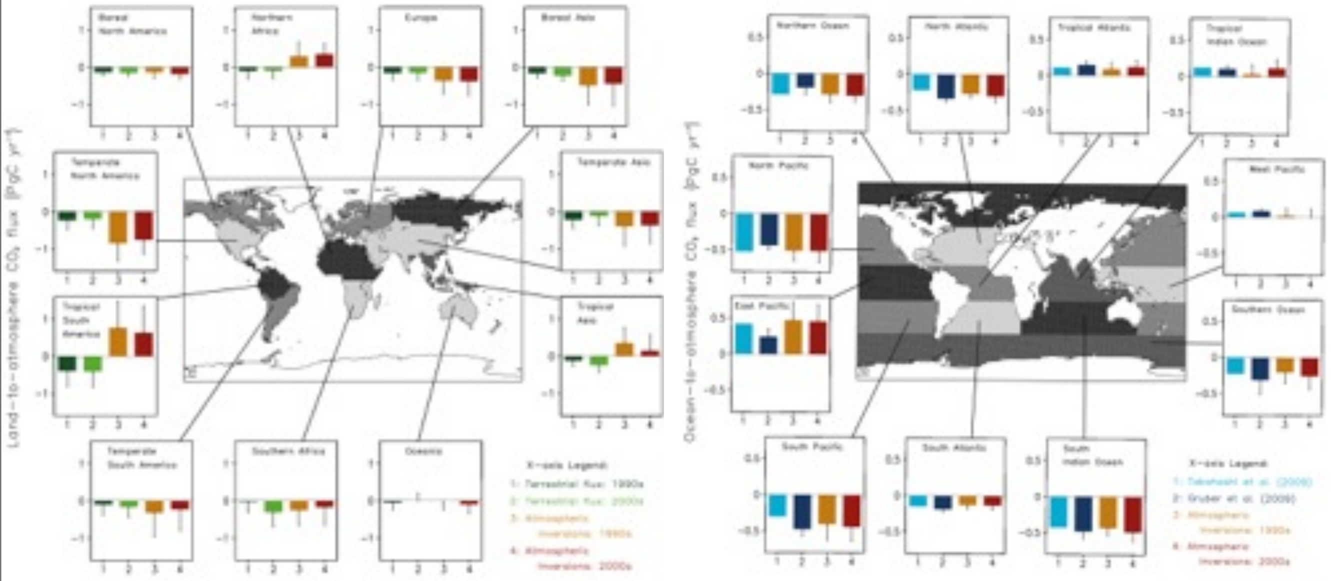
	1750–2011 Cumulative PgC	1980–1989 PgC yr⁻¹	1990–1999 PgC yr⁻¹	2000–2009 PgC yr⁻¹	2002–2011 PgC yr⁻¹
Atmospheric increase	240 ± 10	3.4 ± 0.2	3.1 ± 0.2	4.0 ± 0.2	4.3 ± 0.2
Fossil fuel combustion and cement production	375 ± 30	5.5 ± 0.4	6.4 ± 0.5	7.8 ± 0.6	8.3 ± 0.7
Ocean-to-atmosphere flux	−155 ± 30	−2.0 ± 0.7	−2.2 ± 0.7	−2.3 ± 0.7	−2.4 ± 0.7
Land-to-atmosphere flux *Partitioned as follows*	30 ± 45	−0.1 ± 0.8	−1.1 ± 0.9	−1.5 ± 0.9	−1.6 ± 1.0
Net land use change	180 ± 80	1.4 ± 0.8	1.5 ± 0.8	1.1 ± 0.8	0.9 ± 0.8
Residual land sink	−160 ± 90	−1.5 ± 1.1	−2.6 ± 1.2	−2.6 ± 1.2	−2.5 ± 1.3

Again, 155±30 PgC has been added to the ocean. Positive anomalies are increases in ocean-uptake. Variations are small.

Uptake decreases with temp. by 4.23% per degree.

Fertilization from runoff, between 0.1-0.4 PgC/yr.

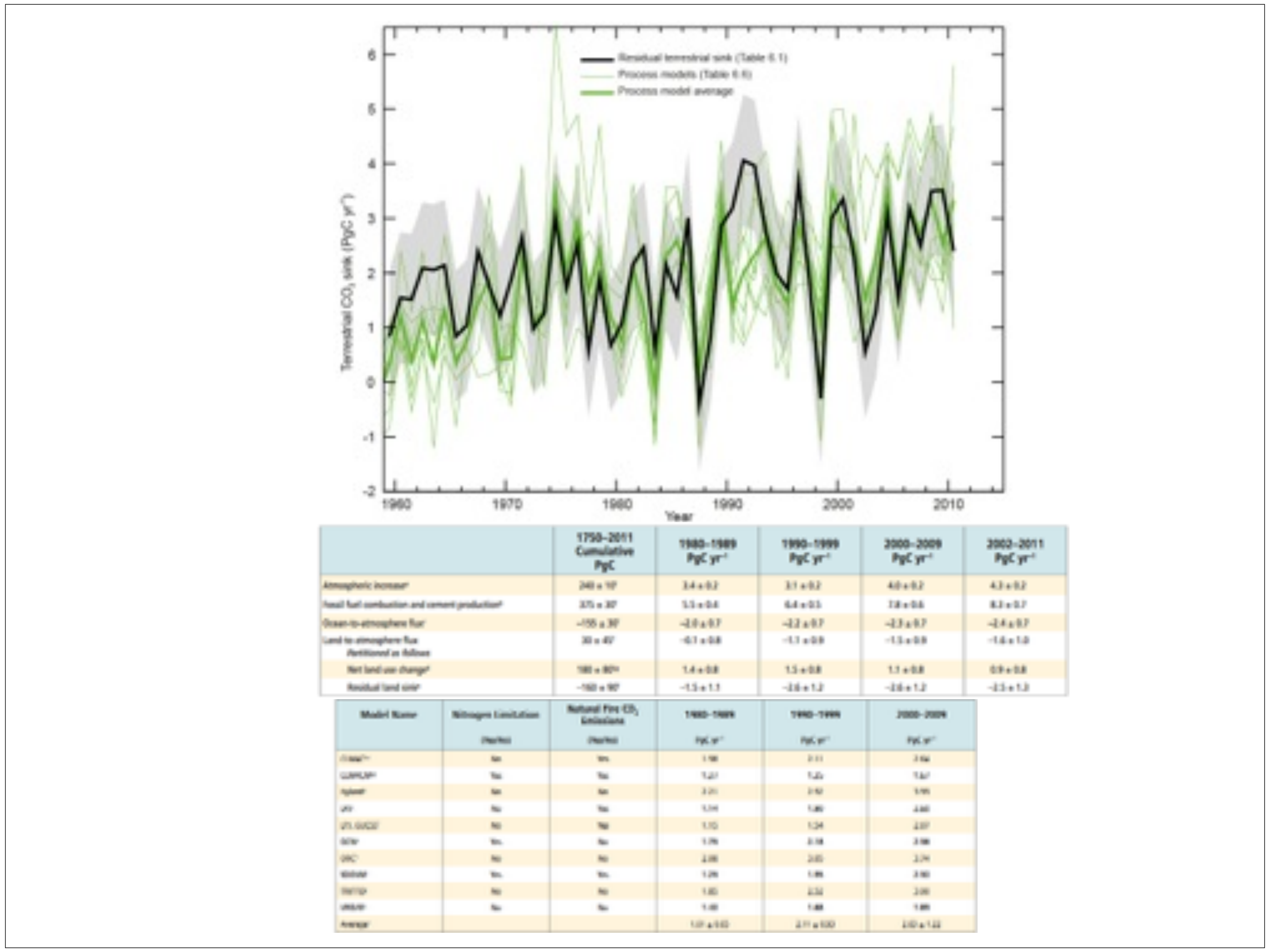
Worry about parameterizations of eddies and brine and of biological models, which only simulate lower trophic levels.



Warming (and possibly the CO2 fertilization effect) has also been cor- related with global trends in satellite greenness observations, which resulted in an estimated 6% increase of global NPP, or the accumulation of 3.4 PgC on land over the period 1982–1999.

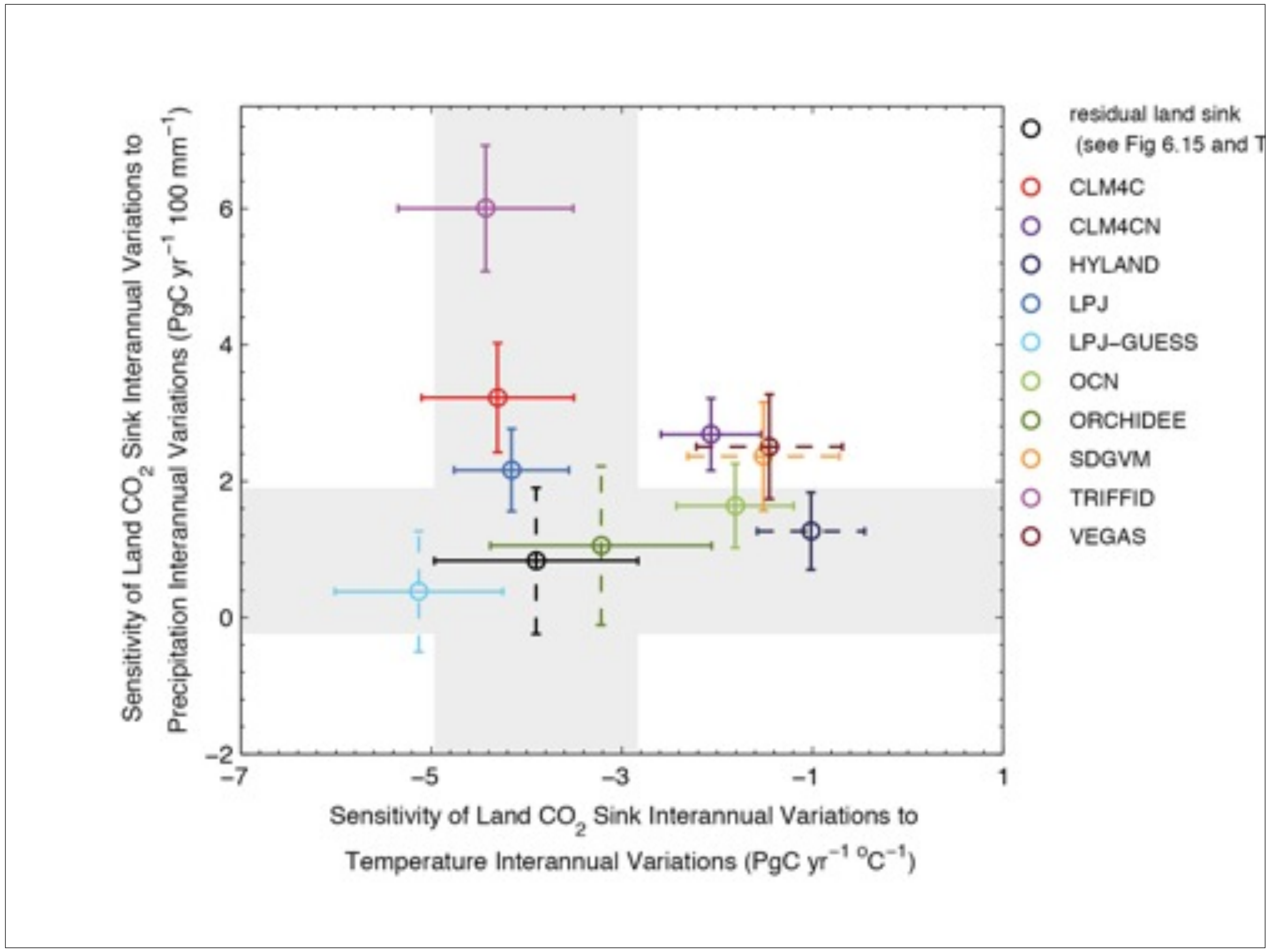
Changes in the physical climate from increasing GHGs as well as in the diffuse fraction of sunlight are likely to be causing significant changes in the carbon cycle.

DGVMs underestimate land sink compared to inversions.

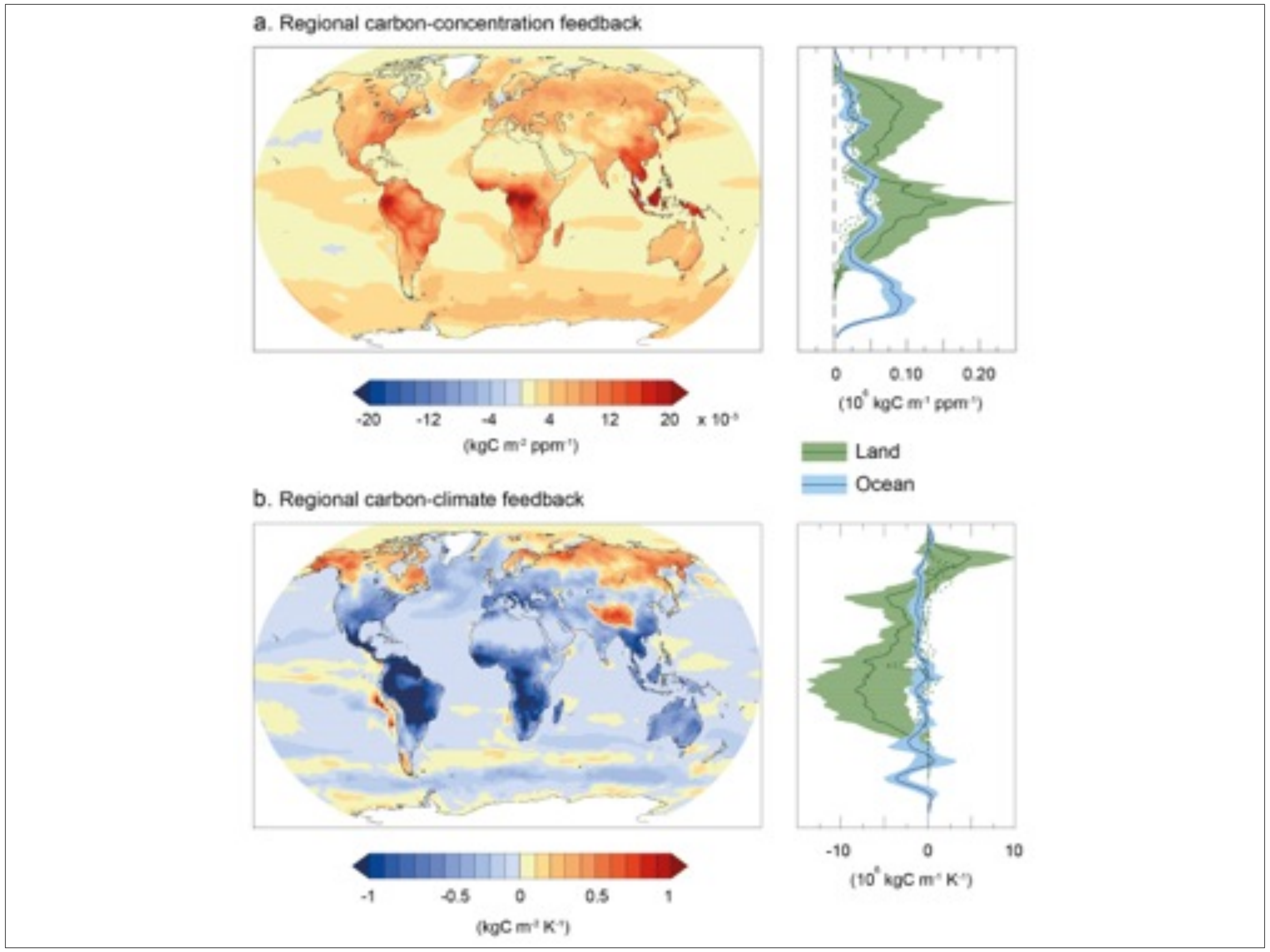


An inter-comparison of 10 process-based models showed increased NPP by 3% to 10% over the last three decades, during which CO2 increased by ~50 ppm.

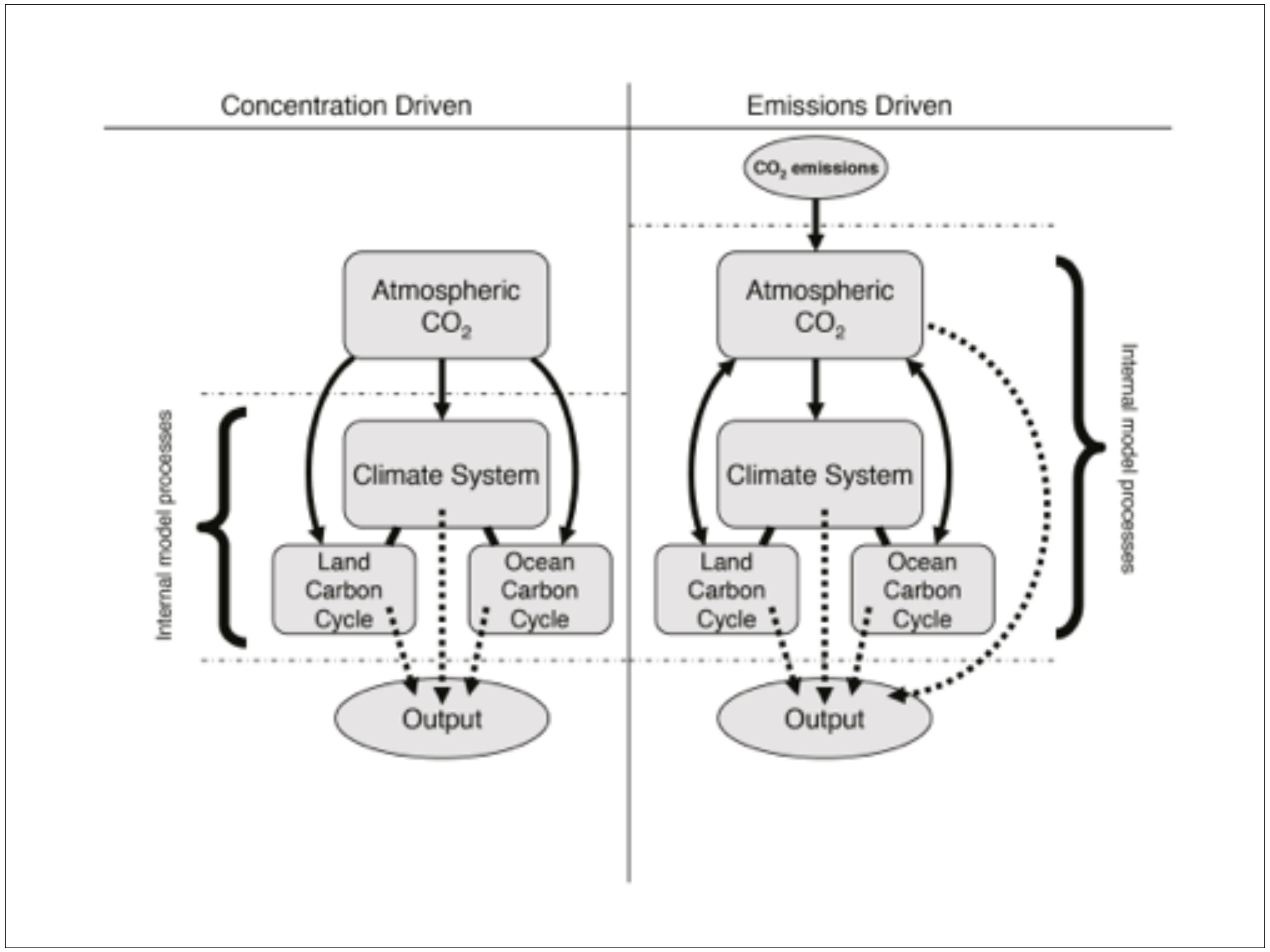
These results are consistent within the broad range of responses from experimental studies (see Box 6.3). However, Hickler et al. (2008) suggested that currently available FACE results (largely from temperate regions) are not applicable to vegetation globally because there may be large spatial heterogeneity in vegetation responses to CO2 fertilization.



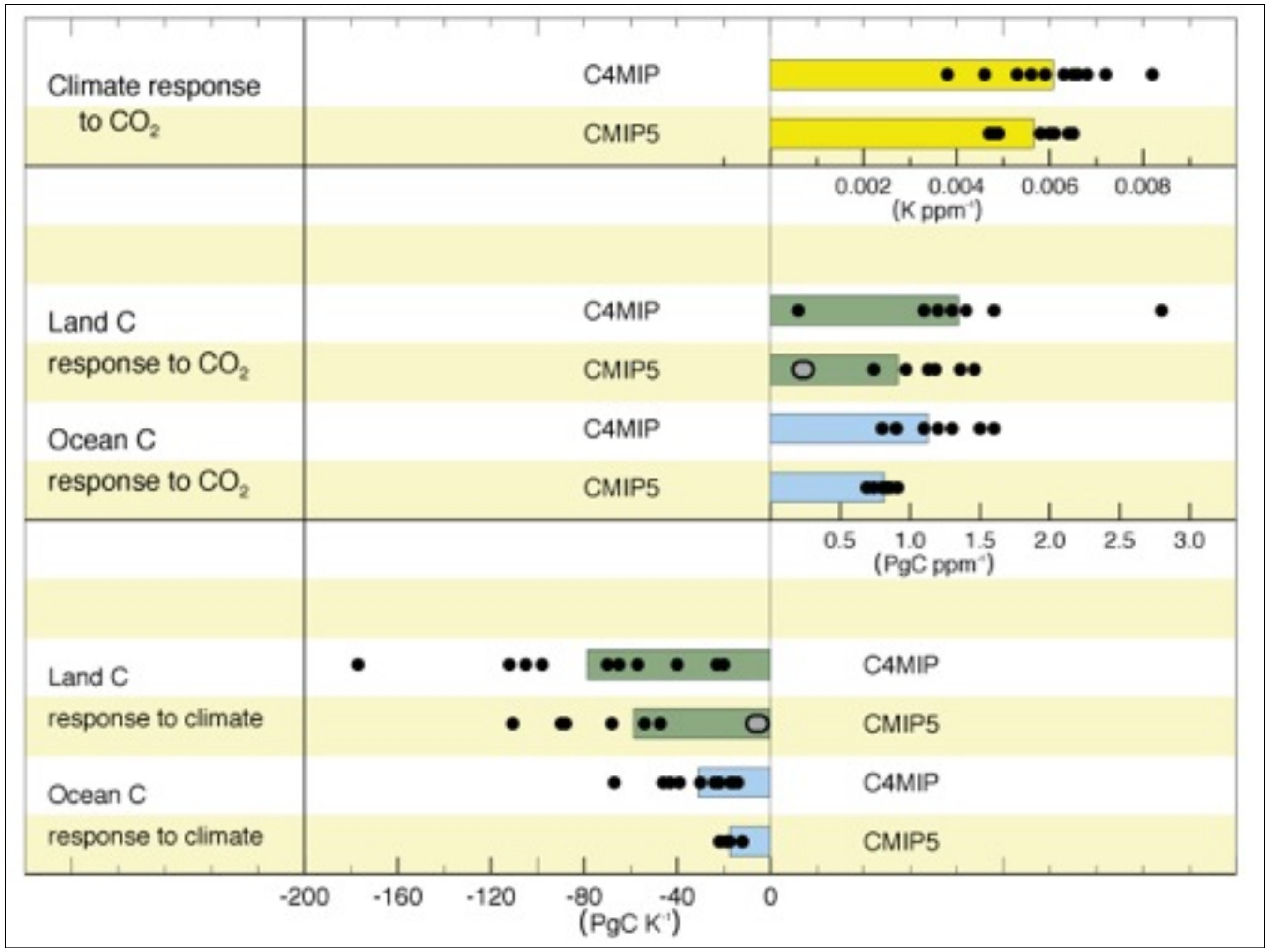
From estimates of inter-annual variations in the residual land sink, 1°C of positive global temperature anomaly leads to a decrease of 4 PgC yr–1 of the global land CO2 sink.



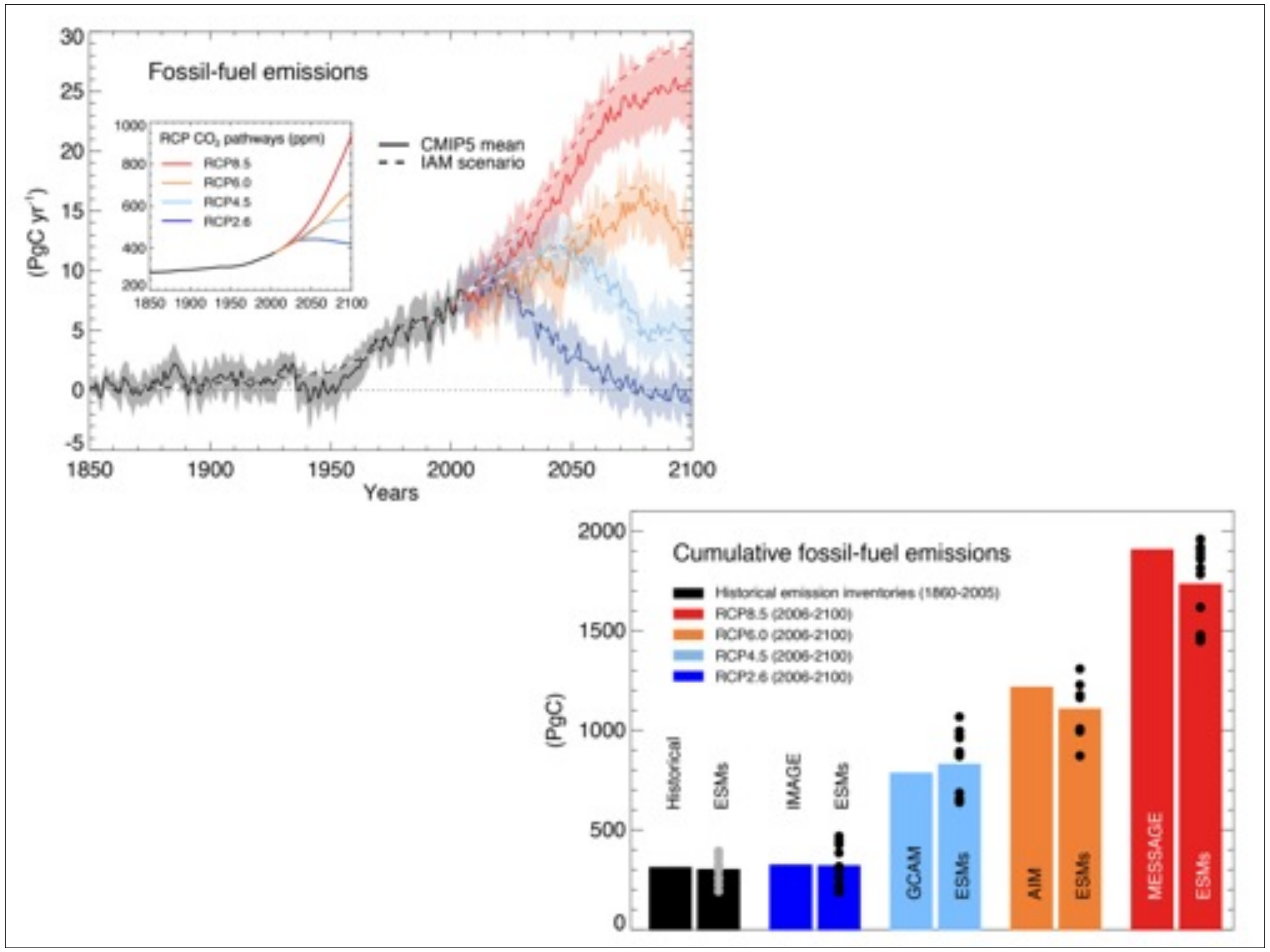
The two basic effects of increased CO2 on the biosphere. Carbon fertilization, and warming. In the CMIP5.



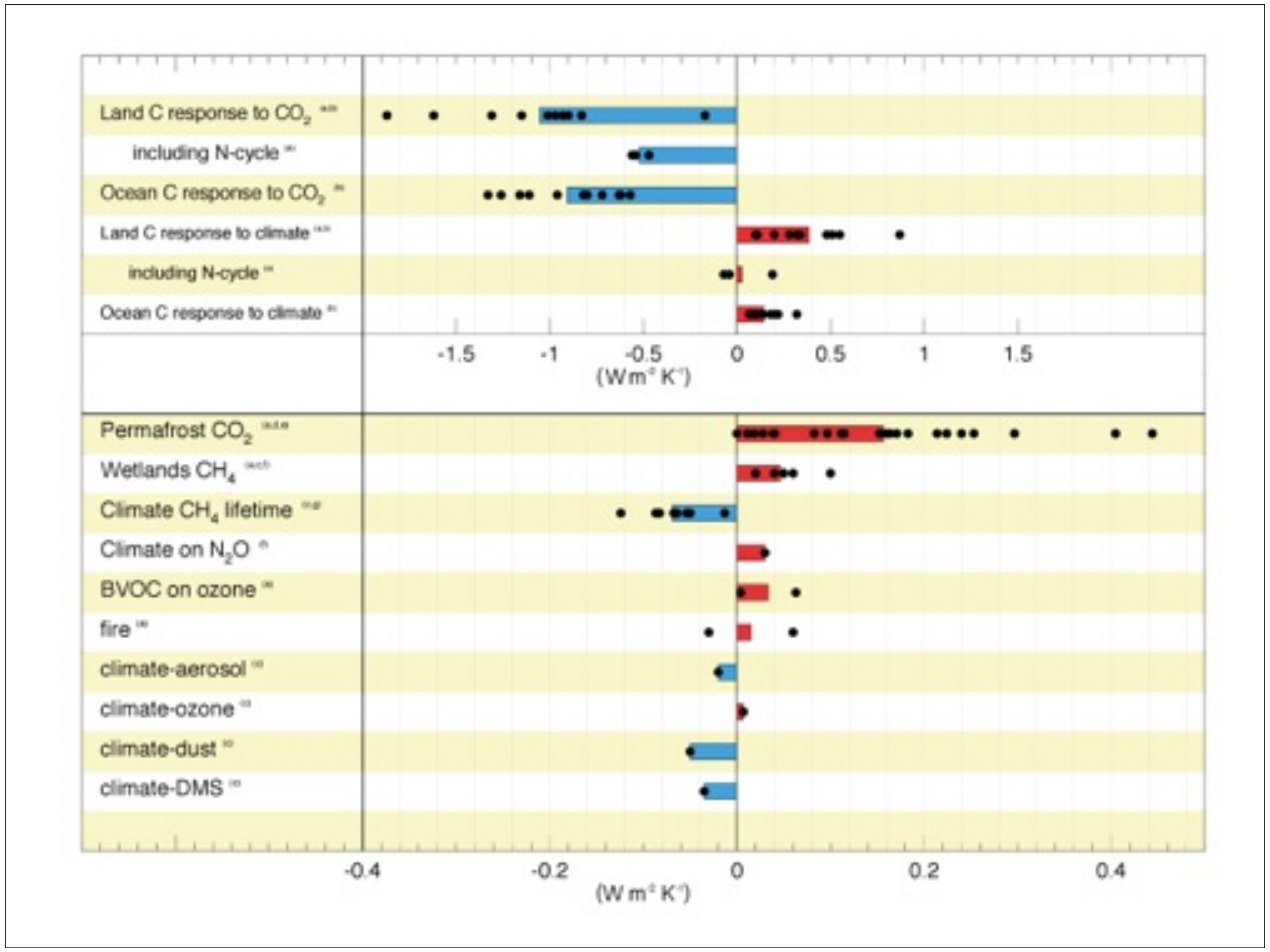
CMIP5 is concentration driven, C4MIP is emissions driven.



Sensitivities in the CMIP5 and C4MIP in the 1% CO2 increase scenario. C4MIP puts more CO2 into the atmosphere than CMIP5 due to warming, this compensates for a greater fertilization effect; leading to a greater climate response to CO2

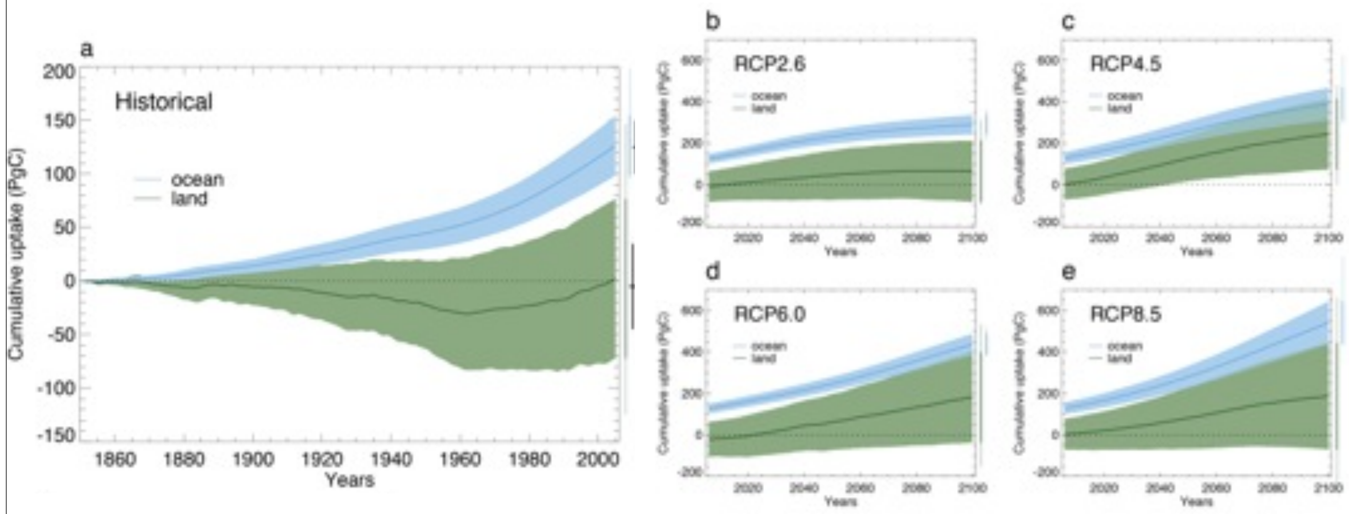


Fossil-fuel emissions can be diagnosed in the CMIP5 models. These are compared with the emissions from the economic models used to create the concentration scenarios. (I think.)

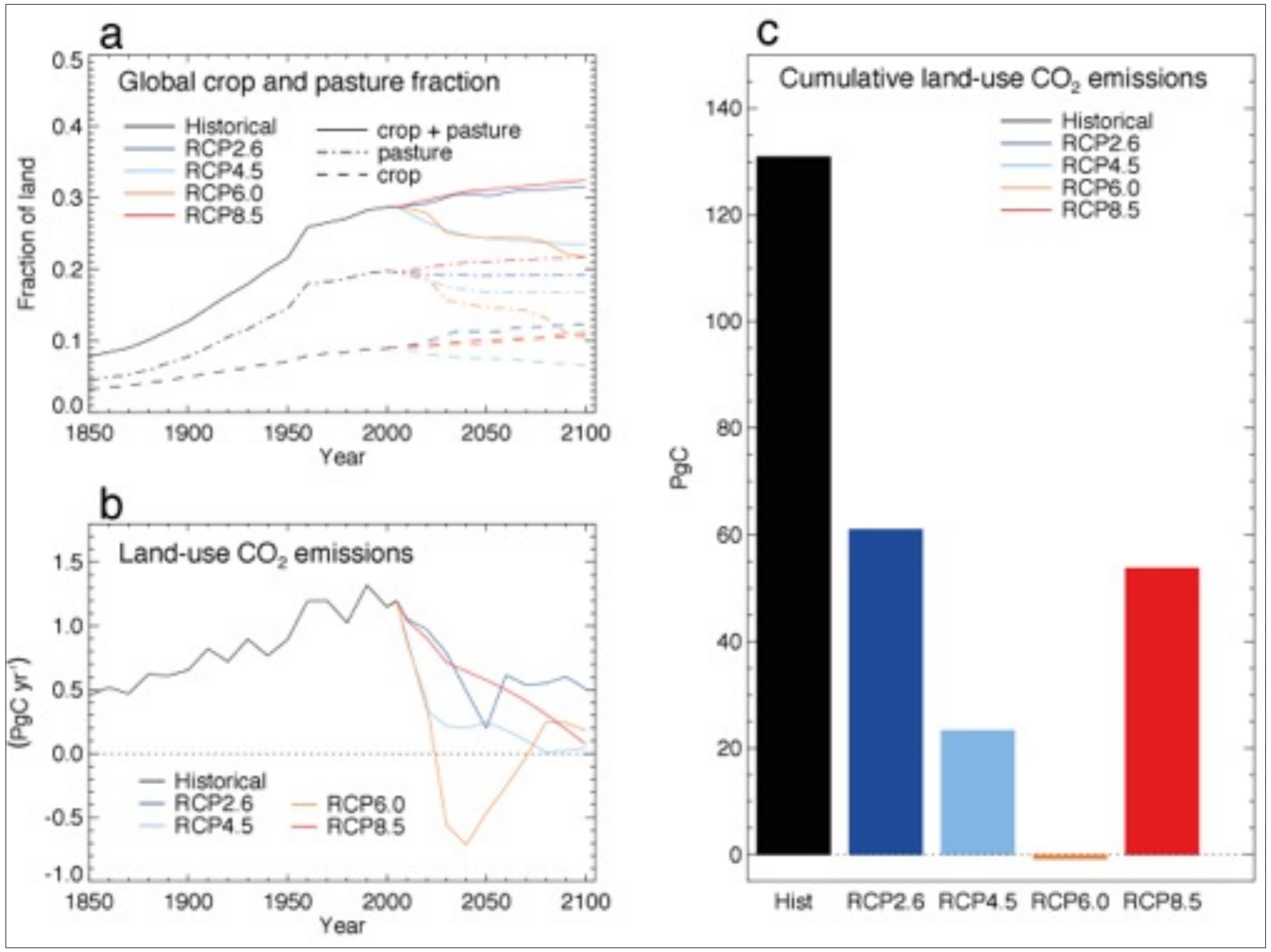


Compiled results from coupled climate carbon models, including the C4MIP. Individual models are dots. Bars are the mean responses.

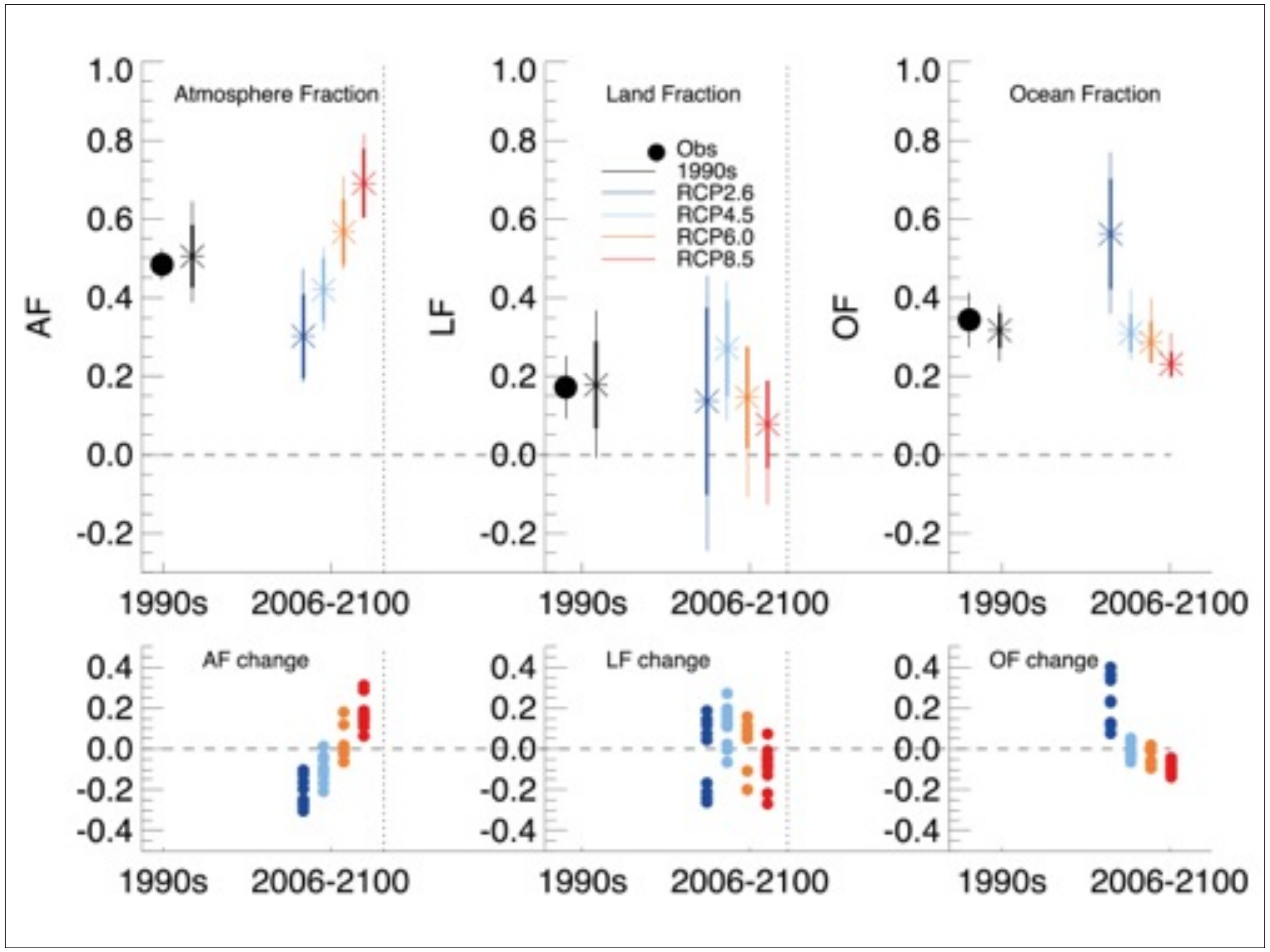
Nitrogen limits land response.



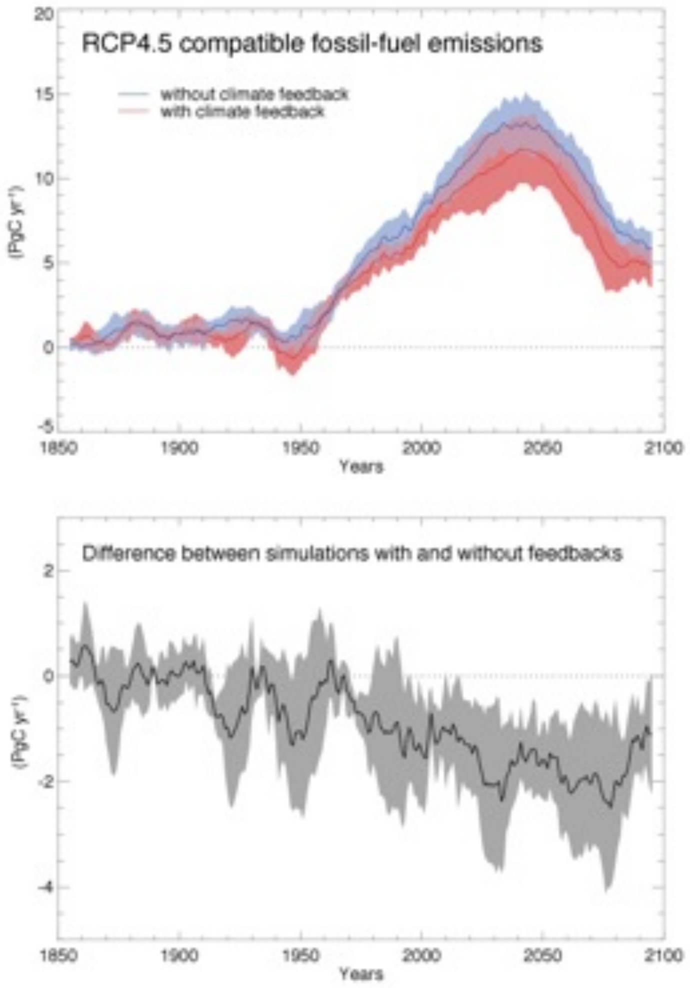
With very high confidence, for all four RCP scenarios, all models project continued ocean uptake throughout the 21st century, with higher uptake corresponding to higher concentration pathways. For RCP4.5, all the models also project an increase in land carbon uptake, but for RCP2.6, RCP6.0 and RCP8.5 a minority of models (4 out of 11 for RCP2.6, 1 out of 8 for RCP6.0 and 4 out of 15 for RCP8.5; Jones et al., 2013) project a decrease in land carbon storage at 2100 relative to 2005.



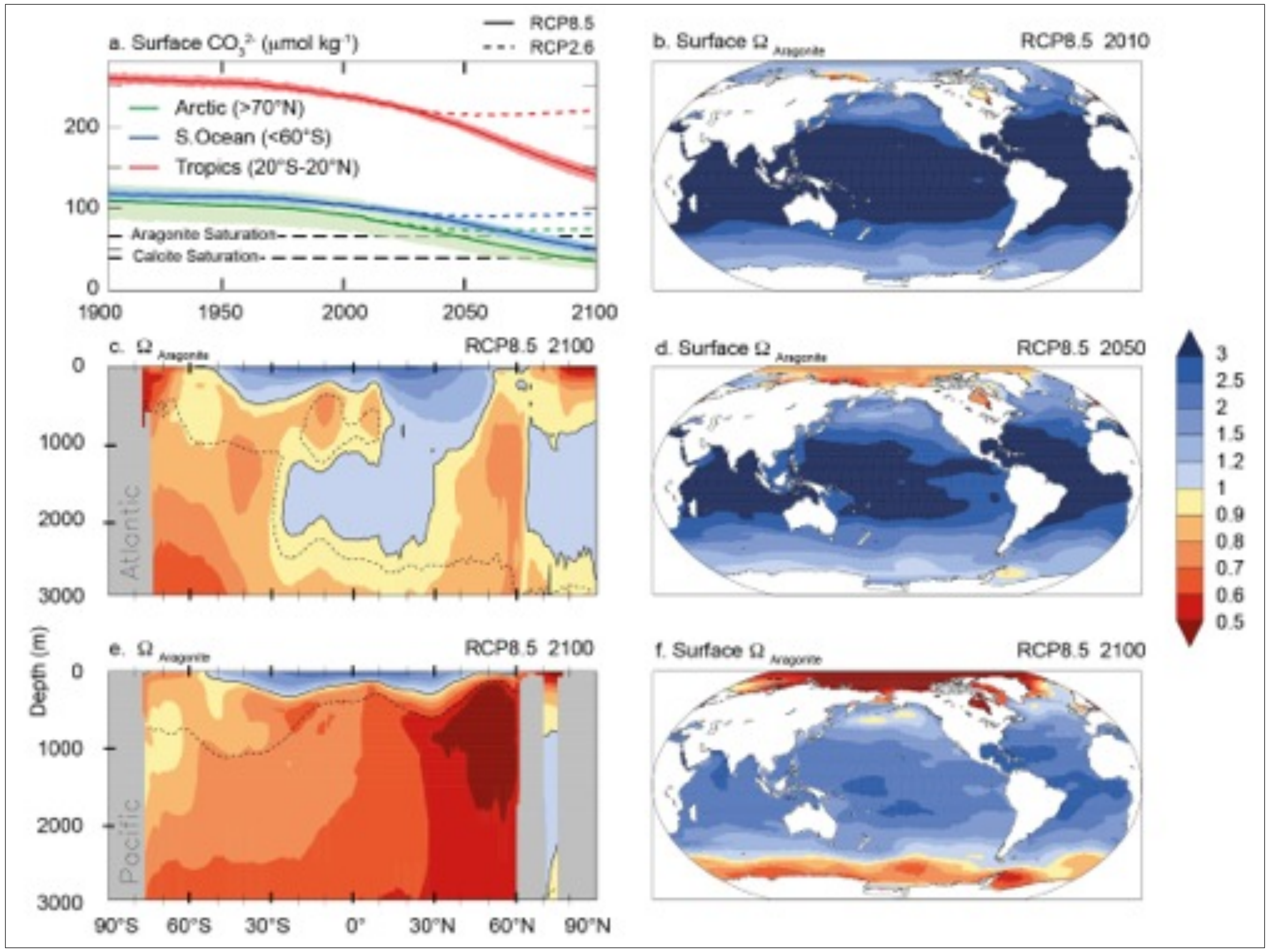
The RCP2.6 scenario achieves this negative emission rate through use of large-scale bio-energy with carbon-capture and storage (BECCS). It is as likely as not that sustained globally negative emissions will be required to achieve the reductions in atmospheric CO2 in the RCP2.6 scenario.



The dominant cause of future changes in the airborne fraction of fossil fuel emissions (see Section 6.3.2.4) is the emissions scenario and not carbon cycle feedbacks.

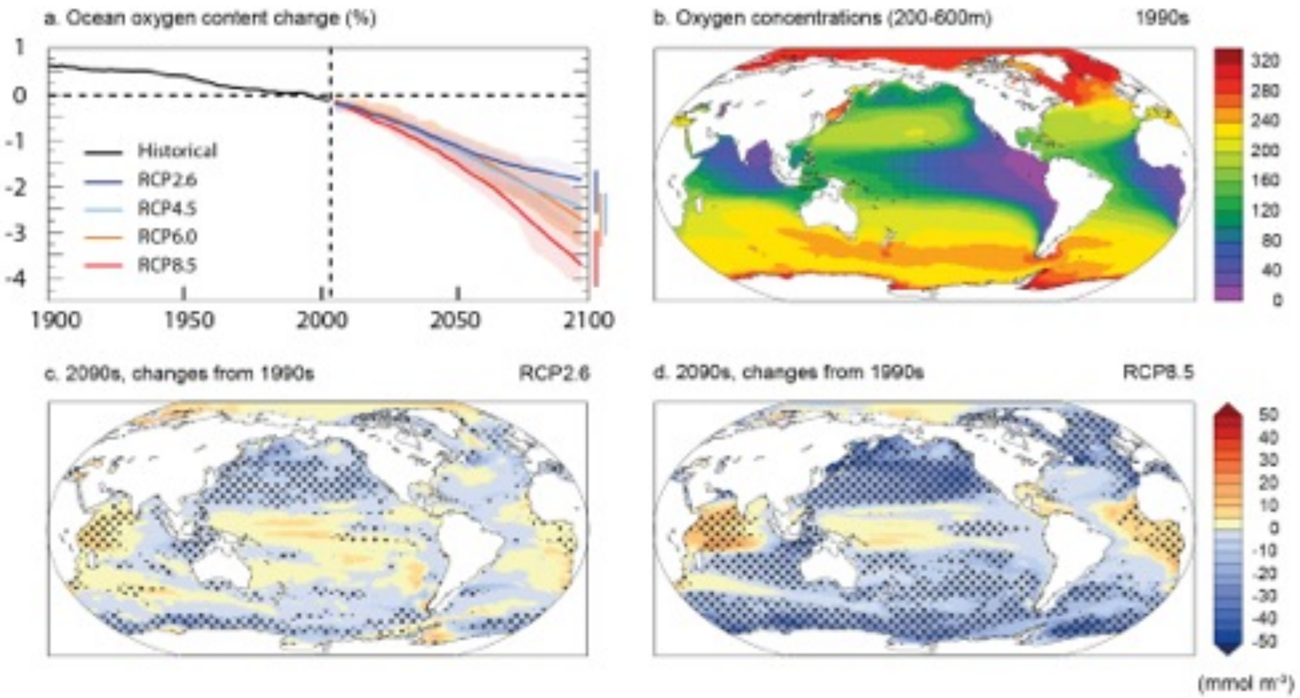


Fossil fuel emissions for the RCP4.5 scenario (top) in the presence (red) and absence (blue) of the climate feedback on the carbon cycle, and the difference between them (bottom). Multi-model mean, 10-year smoothed values are shown, with 1 standard deviation shaded. This shows the impact of climate change on the compatible fossil fuel CO2 emissions to achieve the RCP4.5 CO2 concentration pathway.



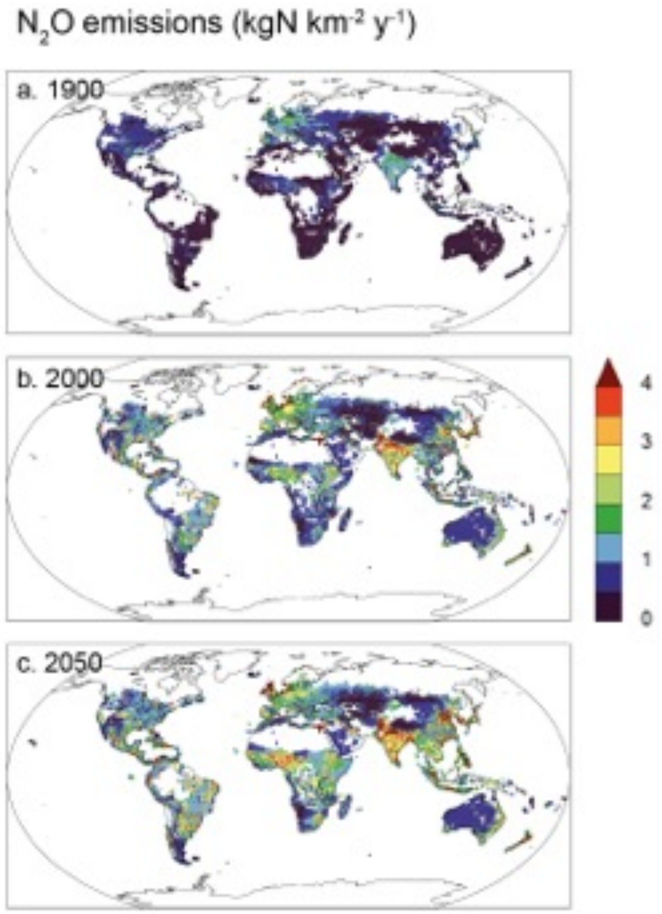
ΩA = [Ca+2][CO32–]/Ksp, where Ksp is the solubility product for the metastable form of CaCO3 known as aragonite; a value of ΩA <1 thus indicates aragonite undersaturation). This aragonite undersaturation in surface waters is reached before the end of the 21st century in the Southern Ocean as highlighted in AR4, but occurs sooner and is more intense in the Arctic (Steinacher et al., 2009). Ten percent of Arctic surface waters are projected to become undersaturated when atmo- spheric CO2 reaches 428 ppm (by 2025 under all IPCC SRES scenarios). That proportion increases to 50% when atmospheric CO2 reaches 534 ppm.

Undersaturated conditions will be reached first in winter.



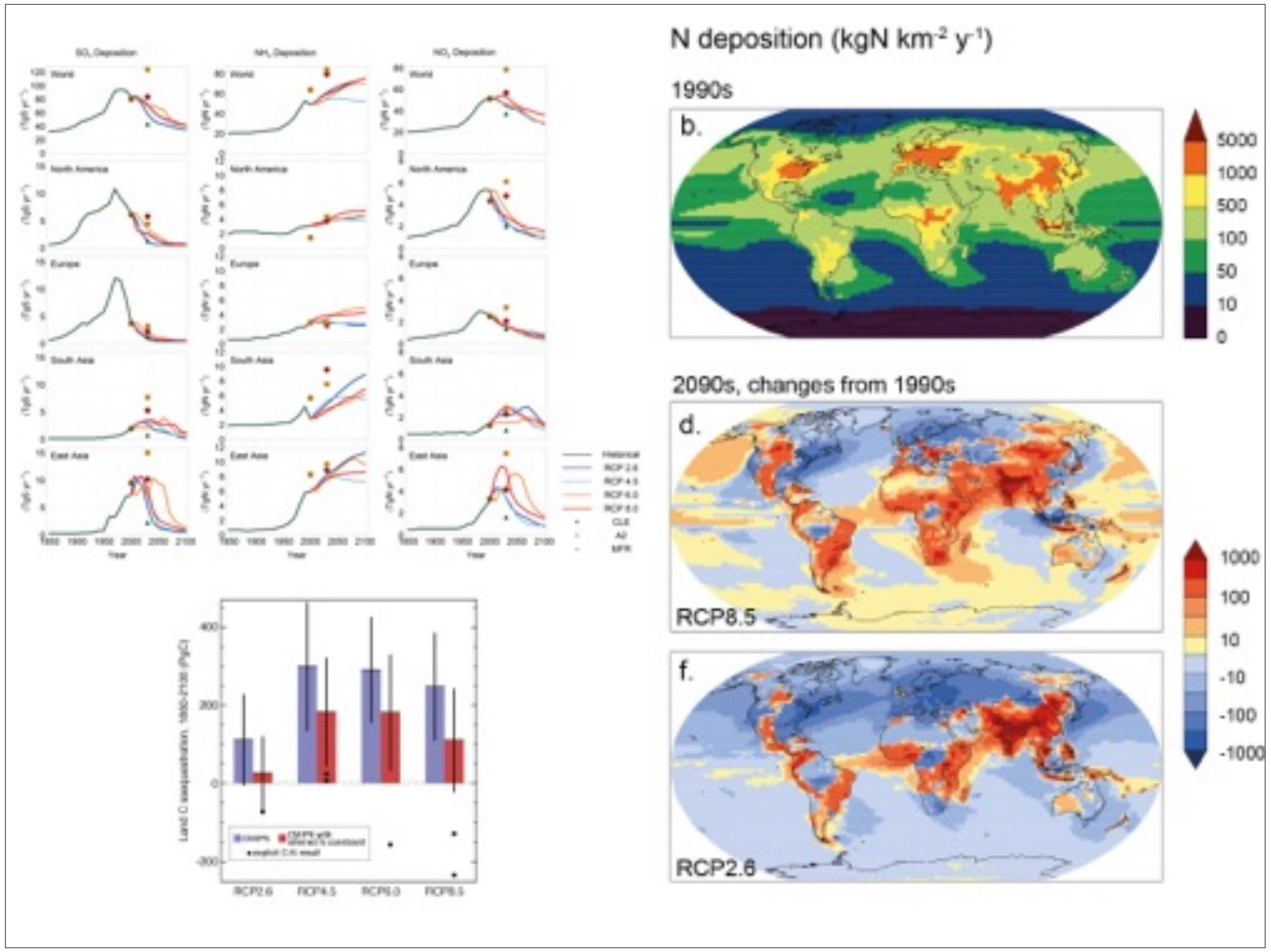
It is very likely that global warming will lead to declines in dissolved O2 in the ocean interior through warming-induced reduction in O2 solubility and increased ocean stratification.

A potential expansion of hypoxic or suboxic water over large parts of the ocean is likely to impact the marine cycling of important nutrients, particularly nitrogen. The intensification of low oxygen waters has been suggested to lead to increases in water column denitrification and N2O emissions.



Regional to global scale model simulations suggest a strong effect of climate variability on inter-annual variability of land N2O emissions (Tian et al., 2010; Zaehle et al., 2011; Xu-Ri et al., 2012). Kesik et al. (2006) found for European forests that higher temperatures and lower soil moisture will decrease future N2O emissions under scenarios of climate change, despite local increases of emission rates by up to 20%.

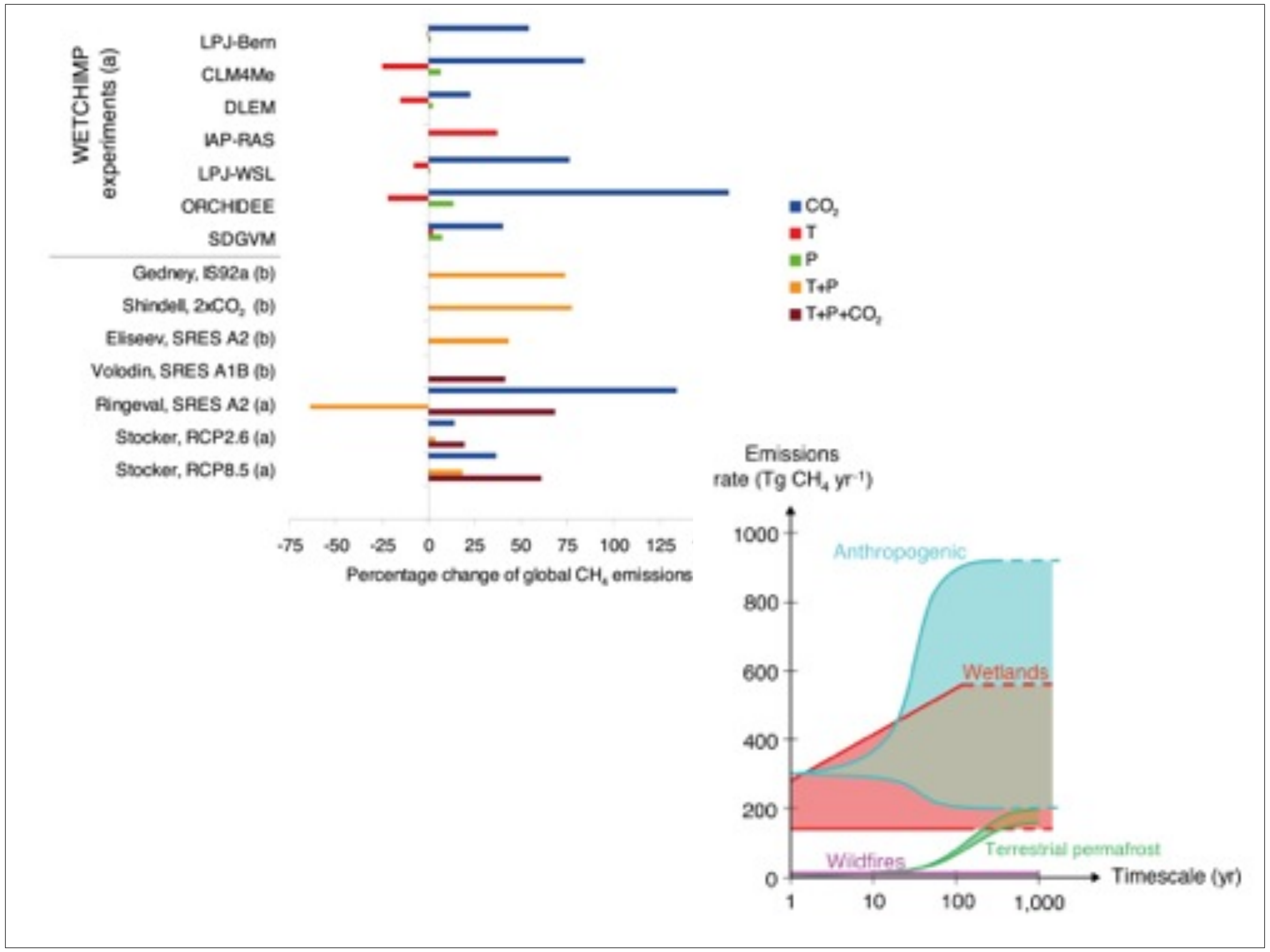
Modelling results (Stocker et al., 2013) suggest that the climate and CO2-related amplification of terrestrial N2O emissions imply a larger feedback of 0.03 to 0.05 W m–2 °C–1 by 2100.



There is low confidence in the projection of future Nr deposition fluxes, particularly in regions remote from anthropogenic emissions.

For the ensemble of CMIP5 projections under the RCP 8.5 scenario, this implies a lack of available nitrogen of 1.3 to 13.1 PgN which would reduce terrestrial C sequestration by an average of 137 PgC over the period 1860–2100, with a range of 41 to 273 PgC among models. This represents an ensemble mean reduction in land carbon sequestration of 55%.

None of the CMIP5 models include phosphorus as a limiting nutrient.

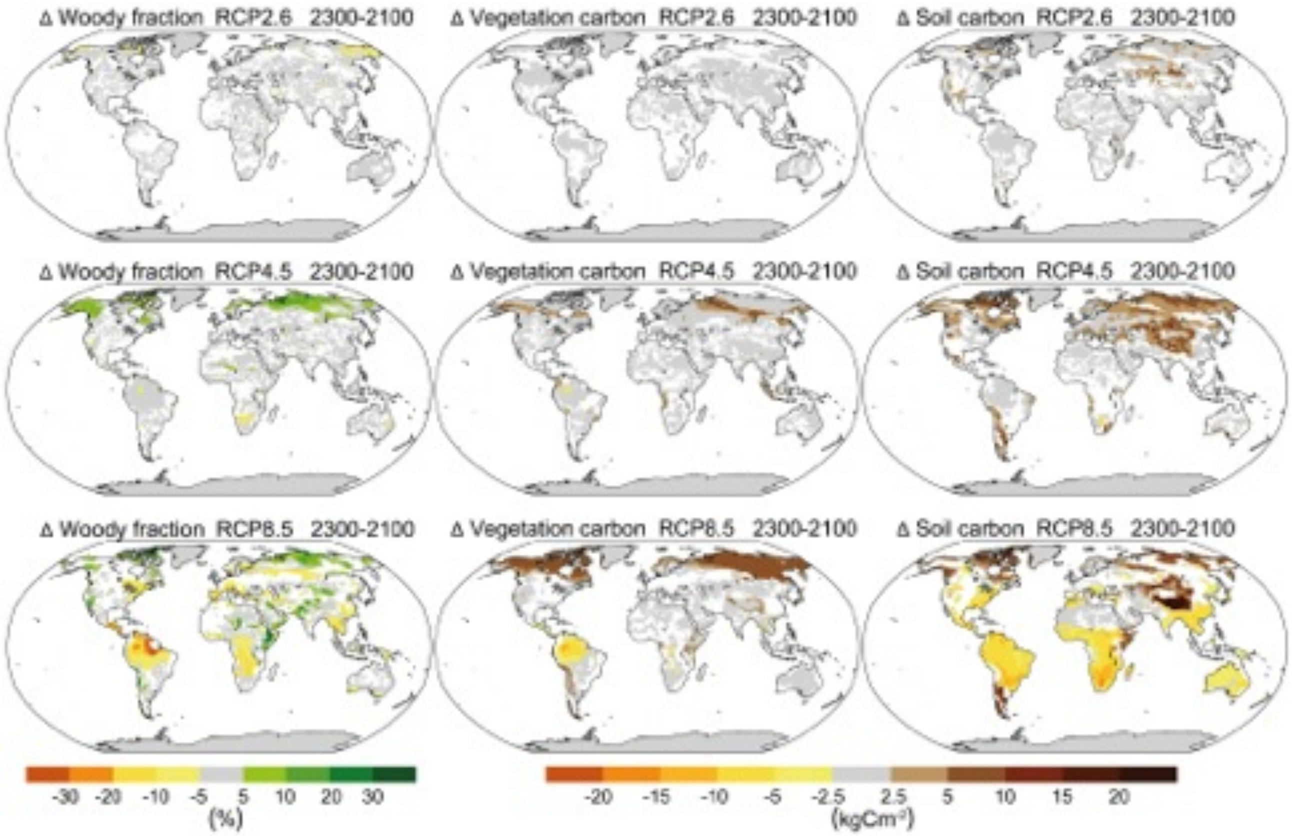


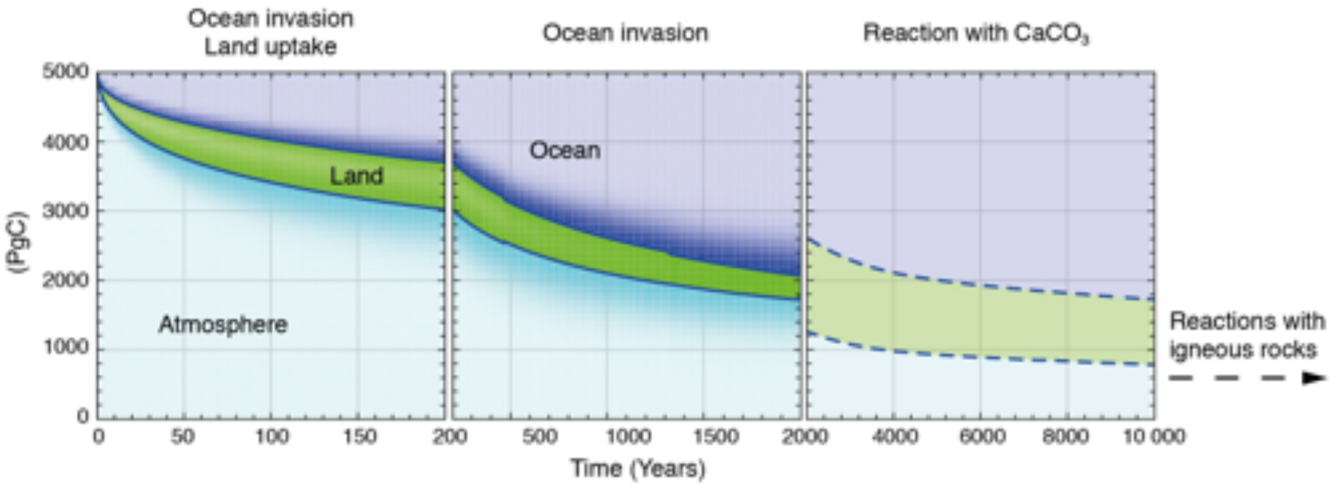
Overall, there is medium confidence that emissions of CH4 from wetlands are likely to increase in the future under elevated CO2 and warmer climate. But there is low confidence in quantitative projections of future wetland CH4 emissions.

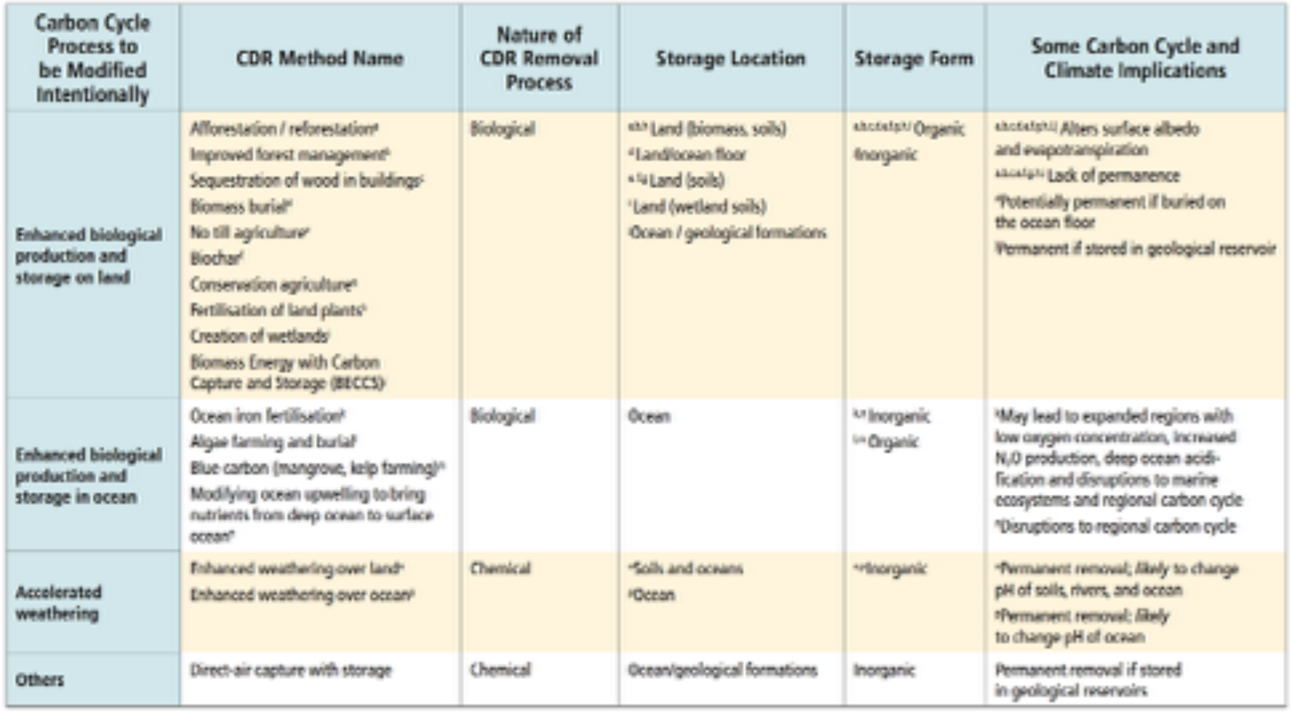
Methane models are of differing complexity. WETCHIMP, assesses their sensitivity. Bars represent CH4 emission changes associated with temperature-only changes (T), precipitation only (P), CO2 only (CO2) or combinations of multiple factors.

There is high agreement between land surface models that permafrost extent is expected to reduce during the 21st century, accompanying particularly rapid warming at high latitudes (Chapter 12). However, estimates vary widely as to the pace of degradation (Lawrence and Slater, 2005; Burn and Nelson, 2006; Lawrence et al., 2008). The LPJ- WHyMe model projected permafrost area loss of 30% (SRES B1) and 47% (SRES A2) by 2100 (Wania, 2007). Marchenko et al. (2008) calcu- late that by 2100, 57% of Alaska will lose permafrost within the top 2 m. For the RCP scenarios, the CMIP5 multi-model ensemble shows a wide range of projections for permafrost loss: 15 to 87% under RCP4.5 and 30 to 99% under RCP8.5 (Koven et al., 2013).

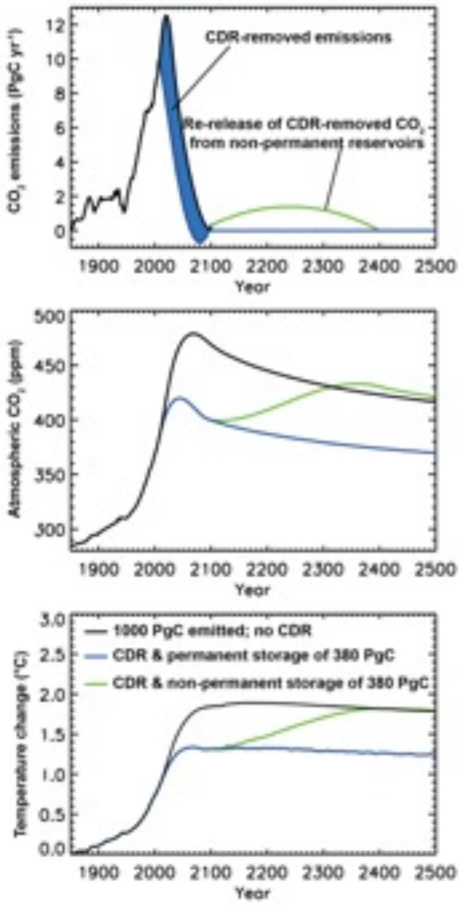
There is low confidence in modelling abilities to simulate transient changes in hydrate inventories, but large CH4 release to the atmo- sphere during this century is unlikely.

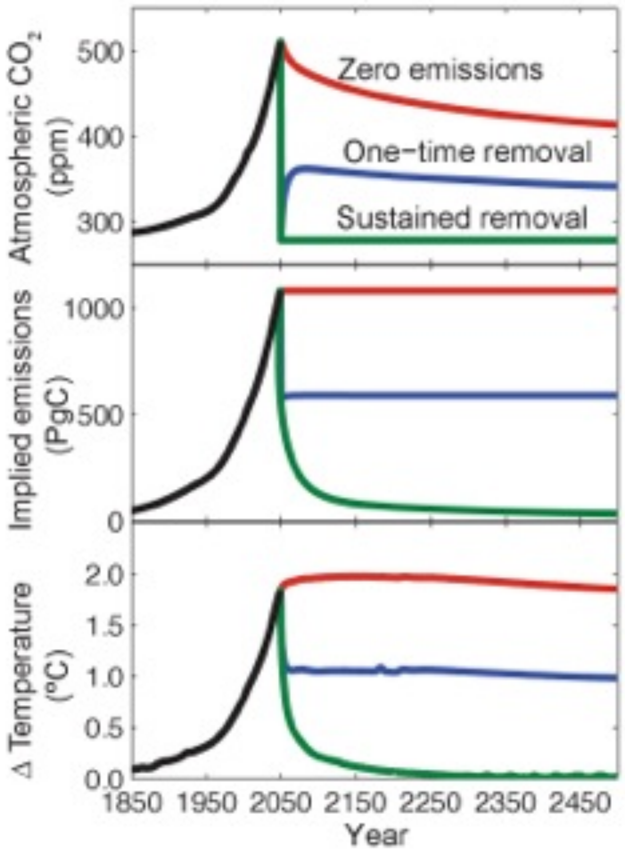

Δ Woody fraction RCP2.6 2300-2100
Δ Vegetation carbon RCP2.6 2300-2100
Δ Soil carbon RCP2.6 2300-2100
Δ Woody fraction RCP4.5 2300-2100
Δ Vegetation carbon RCP4.5 2300-2100
Δ Soil carbon RCP4.5 2300-2100
Δ Woody fraction RCP8.5 2300-2100
Δ Vegetation carbon RCP8.5 2300-2100
Δ Soil carbon RCP8.5 2300-2100
-30 -20 -10 -5 5 10 20 30
(%)
-20 -15 -10 -5 -2.5 2.5 5 10 15 20
(kgCm⁻²)


Ocean invasion
Land uptake
Ocean invasion
Reaction with $CaCO_3$
5000
4000
3000
2000
1000
0
(PgC)
Ocean
Land
Atmosphere
Reactions with
igneous rocks
0
50
100
150
200
500
1000
1500
2000
4000
6000
8000
10 000
Time (Years)



Carbon Cycle Process to be Modified Intentionally	CDR Method Name	Nature of CDR Removal Process	Storage Location	Storage Form	Some Carbon Cycle and Climate Implications
Enhanced biological production and storage on land	Afforestation / reforestation[a] Improved forest management[b] Sequestration of wood in buildings[c] Biomass burial[d] No till agriculture[e] Biochar[f] Conservation agriculture[g] Fertilisation of land plants[h] Creation of wetlands[i] Biomass Energy with Carbon Capture and Storage (BECCS)[j]	Biological	[a,b,h] Land (biomass, soils) [d] Land/ocean floor [e,f,g] Land (soils) [i] Land (wetland soils) [j] Ocean / geological formations	[a,b,c,d,e,f,g,h,i] Organic [j] Inorganic	[a,b,c,d,e,f,g,h,i,j] Alters surface albedo and evapotranspiration [a,b,c,e,f,g,h,i] Lack of permanence [d] Potentially permanent if buried on the ocean floor [j] Permanent if stored in geological reservoir
Enhanced biological production and storage in ocean	Ocean iron fertilisation[k] Algae farming and burial[l] Blue carbon (mangrove, kelp farming)[m] Modifying ocean upwelling to bring nutrients from deep ocean to surface ocean[n]	Biological	Ocean	[k,n] Inorganic [l,m] Organic	[k] May lead to expanded regions with low oxygen concentration, increased N_2O production, deep ocean acidification and disruptions to marine ecosystems and regional carbon cycle [n] Disruptions to regional carbon cycle
Accelerated weathering	Enhanced weathering over land[o] Enhanced weathering over ocean[p]	Chemical	[o] Soils and oceans [p] Ocean	[o,p] Inorganic	[o] Permanent removal; *likely* to change pH of soils, rivers, and ocean [p] Permanent removal; *likely* to change pH of ocean
Others	Direct-air capture with storage	Chemical	Ocean/geological formations	Inorganic	Permanent removal if stored in geological reservoirs


CDR-removed emissions
Re-release of CDR-removed CO₂ from non-permanent reservoirs
CO₂ emissions (PgC yr⁻¹)
12
10
8
6
4
2
0
1900
2000
2100
2200
2300
2400
2500
Year
Atmospheric CO₂ (ppm)
500
450
400
350
300
1900
2000
2100
2200
2300
2400
2500
Year
1000 PgC emitted; no CDR
CDR & permanent storage of 380 PgC
CDR & non-permanent storage of 380 PgC
Temperature change (°C)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1900
2000
2100
2200
2300
2400
2500
Year


Atmospheric CO₂ (ppm)
500
400
300
Zero emissions
One−time removal
Sustained removal
Implied emissions (PgC)
1000
500
0
Δ Temperature (°C)
2.0
1.5
1.0
0.5
0.0
1850
1950
2050
2150
2250
2350
2450
Year