

Alex Dranovsky and E. David Leonardo are in the Department of Psychiatry, Division of Integrative Neuroscience, Columbia University, New York, New York 10032, USA, and at the New York State Psychiatric Institute. e-mails: ad722@cumc.columbia.edu;

el367@cumc.columbia.edu

1. Ramirez, S. *et al.* *Nature* **522**, 335–339 (2015).
2. Squire, L. R. *Neurobiol. Learn. Mem.* **82**, 171–177 (2004).
3. Ramirez, S., Tonegawa, S. & Liu, X. *Front. Behav. Neurosci.* **7**, 226 (2014).

4. Liu, X. *et al.* *Nature* **484**, 381–385 (2012).
5. Blackwell, S. E. *et al.* *Clin. Psychol. Sci.* **3**, 91–111 (2015).
6. Cheung, W.-Y. *et al.* *Pers. Soc. Psychol. Bull.* **39**, 1484–1496 (2013).
7. Harding, E. J., Paul, E. S. & Mendl, M. *Nature* **427**, 312 (2004).
8. Joorman, J., Siemer, M. & Gotlib, I. H. *J. Abnorm. Psychol.* **116**, 484–490 (2007).

GLOBAL WARMING

Growing feedback from ocean carbon to climate

The finding that feedbacks between the ocean's carbon cycle and climate may become larger than terrestrial carbon–climate feedbacks has implications for the socio-economic effects of today's fossil-fuel emissions.

FORTUNAT JOOS

Global warming reduces the uptake of carbon dioxide by the ocean and the land biosphere. This allows more human-caused CO₂ to remain in the atmosphere, where it causes more global warming — an amplifying climate–carbon feedback. The amplifying feedbacks associated with carbon in vegetation and soils are conventionally thought to be several times larger than those associated with carbon in the ocean. Writing in *Global Biogeochemical Cycles*, Randerson *et al.*¹ report that this idea needs to be revisited and refined: in the long term, the ocean will have a larger role than land in climate–carbon coupling.

The authors combined results from long-term simulations using an Earth-system model — specifically the Community Earth System Model (CESM)² — with an established analysis³ of feedbacks in the carbon–climate system. They ran the model up to the year 2300 using contrasting set-ups in which the greenhouse-gas forcing of CO₂ was turned on or off. They report that the ocean carbon–climate feedback (measured as the difference in the amount of carbon cumulatively taken up by the ocean for the set-up that accounts for forcing from all the main anthropogenic emissions, including CO₂, and for the set-up that omits such forcing) is 3% for 1999 and increases to a staggering 23% by 2300. Surprisingly, the ocean–climate feedback becomes larger than the land–climate feedback beyond 2100 (Fig. 1).

This apparent conflict with the conventional view of a smaller ocean than land feedback⁴ results from differences in timescales. Most carbon cycles through plants and soils within decades, whereas it takes centuries to transport

carbon from the sea surface to the deep ocean. Land carbon–climate feedbacks are therefore larger in the near term than marine ones, but this situation will reverse in the long run.

Ocean carbon uptake is primarily a physico-chemical process in which the rate-limiting step is the transport of water from the surface to the deep, and in which the reaction of CO₂ with water releases hydrogen ions, causing ocean acidification⁵. Randerson and co-workers report that warming decreases the solubility of CO₂ in water, reduces the density of surface waters and slows the overturning circulation (the movement of surface water from high latitudes to the deep ocean, compensated for by rising waters from other latitudes). These effects reduce the overall uptake capacity of the ocean for, and the

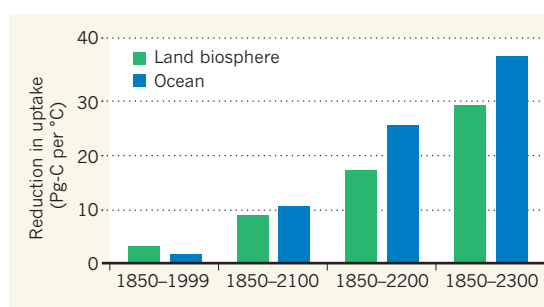


Figure 1 | Feedback between climate and the carbon cycle. Randerson *et al.*¹ have used a computational model to show that the ocean's contribution to feedback between climate and the carbon cycle increases considerably over time, and exceeds contributions from land by the year 2100. The bar chart shows, for different periods, the reduction in the uptake of anthropogenic carbon (measured in petagrams of carbon; 1 petagram is 10¹⁵ grams) by the ocean and the land biosphere that is attributable to climate change, per increase in global mean surface air temperature of 1 °C. The authors computed these sensitivities from differences in cumulative carbon flux and global mean surface air temperature between a simulation in which CO₂ influences climate and another in which the direct influence of CO₂ on global warming is suppressed.

surface-to-deep transport of, anthropogenic carbon. The magnitude of the ocean–climate feedback reported by the researchers, and the main proposed feedback mechanisms — including a near-collapse of the Atlantic overturning circulation and a small role for marine biological processes — are consistent with the findings of earlier studies (see ref. 6, for example) that used models with simpler ocean dynamics than those in the CESM.

On land, the authors find that a loss of carbon results from increased rates of soil-carbon decomposition due to warming. This dominates the stimulation of plant productivity caused by increased moisture and growing-season length at high latitudes. In addition, human land use reduces the amount of carbon in vegetation in their scenario, further limiting the potential amplifying feedback between land carbon and climate.

The representation of biogeochemical processes in the CESM is advanced, but many feedbacks to those processes are uncertain or not represented. These include⁷ the impacts of ocean acidification, warming, increased levels of dissolved CO₂ and a potential increase in the volume of low-oxygen zones on marine ecosystems, biological productivity, the production of the greenhouse gas nitrous oxide, the export of biogenic particles from the surface to the deep ocean, and their sinking velocity and decomposition rate. On land, thawing of permafrost carbon may lead to the release of CO₂ (ref. 8) and methane⁴, processes not accounted for in the version of the CESM used by the authors. More work is needed to address changes in the extent of wetlands and peatlands in model projections, and to better quantify emissions of methane, nitrous oxide and organic compounds from the land biosphere, because these changes and emissions all contribute to climate forcing⁹.

Data for past variations in CO₂ levels and climate can help us to avoid relying exclusively on models to project future trends. Although palaeoclimatic information cannot be directly used to assess how climate change affects the flow of anthropogenic carbon, it does reveal how the natural carbon cycle alters. Palaeoclimatic data document that the ratio of the change in atmospheric CO₂ concentration to the change in global mean surface air temperature is increasing with the timescale of climatic variations, and that the increase of CO₂ on decade-to-century timescales

is probably less than 20 parts per million for each degree of warming¹⁰.

Further constraints on carbon–climate interactions arise from isotope data that allow terrestrial and oceanic greenhouse-gas sources to be disentangled. Carbon isotope data show that decadal CO₂ variations during the past millennium were predominantly driven by land-carbon variations¹¹, consistent with Randerson and colleagues' finding of a small near-term marine feedback. But isotope data for nitrous oxide question the assumption made in the CESM that nitrogen availability strongly limits plant growth. These data show that the land source of nitrous oxide increased during the last deglaciation, which implies that nitrogen flow through the land biosphere increased and that nitrogen limitation was small¹². A long-standing research challenge is to develop Earth system models that perform seamless simulations from the past to the future, consistently integrating palaeoclimatic and modern instrumental information in projections.

Randerson and colleagues' work highlights another research front. The marine carbon–climate feedback increases in proportion to ocean-heat content in their model. Researchers would benefit from observational and modelling studies in which spatial and temporal variations of physical and biogeochemical parameters, such as temperature, carbon and nutrients, are analysed jointly to draw a more complete and self-consistent picture of the changing ocean. Biogeochemical variables are particularly sensitive indicators of change, but ocean physics governs both carbon and heat uptake — and therefore sea-level rise, climate change and their impacts.

The current study acts as a timely reminder of several policy-relevant findings, ahead of the conference to be held by the United Nations Framework Convention on Climate Change in Paris this December. First, the larger the amplifying carbon–climate feedback is, the more stringent will emission reductions have to be to stabilize climate at any given level. Second, shifting the peak in carbon emissions to after 2100 imposes on future generations not only the burden of implementing a carbon-free economy, but also global warming of about 10 °C above preindustrial temperatures¹.

Third, carbon emitted today will change our environment irreversibly for many generations to come, and these changes increase hand in hand with cumulative carbon emissions¹³. Sea level and the ocean's acidity and carbon and heat content — and the associated adverse effects — will continue to increase long after atmospheric CO₂ levels have stabilized, underscoring the need for near-term emission reduction. Finally, carbon-emission reductions are urgently needed if we are to limit global warming and ocean acidification to moderate levels. Any delay will narrow and eventually

close the currently available window to meet stringent climate targets¹⁴. ■

Fortunat Joos is in the Division of Climate and Environmental Physics, Physics Institute and the Oeschger Centre for Climate Change Research, University of Bern, Bern CH-3012, Switzerland.

e-mail: joos@climate.unibe.ch

1. Randerson, J. T. *et al.* *Glob. Biogeochem. Cycles* <http://dx.doi.org/10.1002/2014gb005079> (2015).
2. Hurrell, J. W. *et al.* *Bull. Am. Meteorol. Soc.* **94**, 1339–1360 (2013).
3. Friedlingstein, P. *et al.* *J. Clim.* **19**, 3337–3353 (2006).
4. Ciais, P. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the*

Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Stocker, T. F. *et al.*) 465–570 (Cambridge Univ. Press, 2013).

5. Orr, J. C. *et al.* *Nature* **437**, 681–686 (2005).
6. Joos, F., Plattner, G. K., Stocker, T. F., Marchal, O. & Schmittner, A. *Science* **284**, 464–467 (1999).
7. Heinze, C. *et al.* *Earth Syst. Dyn.* **6**, 327–358 (2015).
8. Koven, C. D., Lawrence, D. M. & Riley, W. J. *Proc. Natl Acad. Sci. USA* **112**, 3752–3757 (2015).
9. Stocker, B. D. *et al.* *Nature Clim. Change* **3**, 666–672 (2013).
10. Heimann, M. *Nova Acta Leopoldina* **NF 121**, 97–99 (2015).
11. Bauska, T. K. *et al.* *Nature Geosci.* **8**, 383–387 (2015).
12. Schilt, A. *et al.* *Nature* **516**, 234–237 (2014).
13. Steinacher, M., Joos, F. & Stocker, T. F. *Nature* **499**, 197–201 (2013).
14. Stocker, T. F. *Science* **339**, 280–282 (2013).

NEURODEGENERATION

Aggregates feel the strain

Aggregates of α -synuclein protein can form in various cell types and cause different neurodegenerative disorders. The existence of strains with distinct structural conformations might explain this variability. SEE LETTER P.340

SEUNG-JAE LEE & ELIEZER MASLIAH

Parkinson's disease, dementia with Lewy bodies and multiple system atrophy are devastating, progressive, age-related neurodegenerative disorders that are characterized by the accumulation of clumps of α -synuclein protein in brain cells¹. These diseases, dubbed synucleinopathies, can be differentiated from one another by the distinct anatomical patterns and cell types in which α -synuclein is deposited². On page 340 of this issue, Peelaerts *et al.*³ propose that different 'strains' of α -synuclein, which adopt different structural conformations, might explain this variability.

According to current models, deposits of α -synuclein are first laid down in the synaptic connections between neurons during the early stages of synucleinopathy⁴. Deposition later spreads to other sites: to neuronal cell bodies, where they form aggregates called Lewy bodies; to neuronal projections called axons and dendrites, forming aggregates called Lewy neurites; and to cells known as oligodendrocytes that support and insulate axons, forming aggregates called glial cytoplasmic inclusions (GCIs)⁵.

These GCIs are the predominant deposits in people with multiple system atrophy². Lewy bodies and Lewy neurites are characteristic of both Parkinson's disease and dementia with Lewy bodies — although the patterns in which the proteins spread vary between these two diseases. Furthermore, patterns of α -synuclein deposition, and consequently clinical

symptoms, can vary between individual cases of the same disease⁵. But the reasons underlying this variability have remained unclear.

Synucleinopathies have several features in common with prion diseases, which are neurodegenerative diseases caused by the accumulation of misfolded prion protein in the brain. For example, the symptoms, biological abnormalities and incubation times of both types of disease are variable. In prion diseases, variability between individuals depends on the conformation adopted by aggregates of prion protein. Aggregates of a specific conformation are thought to propagate throughout the brain by inducing normal prion proteins to clump together into misfolded aggregates of the same conformation — a concept known as 'seeded aggregation'. Evidence suggests⁶ that aggregates of α -synuclein and other neurodegeneration-associated proteins spread through brain cells in a similar way, which might explain the varied patterns in which deposition spreads.

In support of this hypothesis, two distinct aggregates of α -synuclein, fibrils and ribbons, have been characterized⁷. These aggregates faithfully propagate their structural features through seeding, and induce different abnormalities in cultured cells. Following up on these findings, Peelaerts *et al.* investigated whether ribbons and fibrils are genuine protein strains by testing whether they cause different symptoms and biological changes in animals. The authors injected rat brains with four different types of α -synuclein: ribbons; fibrils; homogenized brain samples from mice