operates on both the hot and cold gas in galaxies. Because of this and the fact that radio jets are a common and recurrent phenomenon in galaxies, radio mode feedback could be a key process that governs the growth of elliptical galaxies and the supermassive black holes lurking at their centers.

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10.1126/science.1243114

ATMOSPHERIC SCIENCE

A Hyperventilating Biosphere

Seasonal carbon dioxide uptake and release patterns are changing as a result of global warming.

Inez Fung

In the Northern Hemisphere, CO_2 concentrations in the atmosphere oscillate regularly over the course of each year (see the figure). This "breathing" occurs because CO_2 declines in the atmosphere during the growing season, when CO_2 uptake via photosynthesis exceeds the release from microbial respiration, and increases during the rest of the year, when release exceeds uptake. On page 1085 of this issue, Graven *et al.* (*1*) present evidence that the breathing rate has accelerated greatly over the past 50 years.

The depth of the breathing is captured by the net ecosystem production (NEP), the integrated net uptake over the months when CO_2 uptake exceeds release (see the figure, panel A). NEP would equal the net release integrated over the rest of the year if the biosphere were at equilibrium, with growth balancing mortality and decay. NEP is greatest at high latitudes, where the growing season is short, and smallest in the tropics, where the monthly fluxes into and out of the atmosphere nearly cancel throughout the year.

Long-term increases in the amplitude of the annual CO_2 cycles were first noted by Pearman and Hyson in 1981 (*2*) and have since been established with increasing confidence. They have been attributed to increasing photosynthetic uptake, an earlier growing season, and increasing decomposition in response to changes in climate and atmospheric composition. Even so, the CO_2 monitoring stations are sparse and are located in remote marine locations, and it is not clear how widespread the biosphere response has been.

Graven *et al.*, in a masterful stroke, have stitched together separate pieces of aircraft CO_2 records over the North Pacific (see the figure, panels B to D) to estimate the CO_2 amplitude trends in the middle troposphere, about 3 to 6 km above Earth's surface. They find that the 50-year amplitude trends in the mid-troposphere resemble those at the few monitoring sites at the surface. The trends are huge: ~10% per decade at high latitudes and ~5% per decade over the mid-latitudes. Winds mix CO_2 throughout the atmosphere, albeit incompletely. The mid-tropospheric amplitude trends therefore signify an increasing NEP over a wide swath of the biosphere, with the increase fastest at high latitudes.

The question arises, what is causing the Northern Hemisphere land biosphere, especially at high latitudes, to go into hyperdrive? Surely, the biosphere must be enjoying the warming. Satellite observations show that from 1982 to 2011, the photosynthetic season has been lengthening over the past three decades: On average, the onset of greening of northern ecosystems (>45 N) has advanced by 1 day per decade in the spring, and the seasonally integrated photosynthesis has increased, consistent with the warming and thawing (*3*). However, enhanced photosynthesis alone is not enough to explain the large increase in CO_2 amplitude seen by Graven *et al.* The authors hypothesize that observed changes in the structure of the biosphere—for example, northward migration of the tree line, increased shrub cover in the Arctic, and reestablishment of forests after fires—have enhanced carbon uptake to the extent necessary to explain the amplitude trend.

The satellite data show that the photosynthetic season of northern ecosystems does

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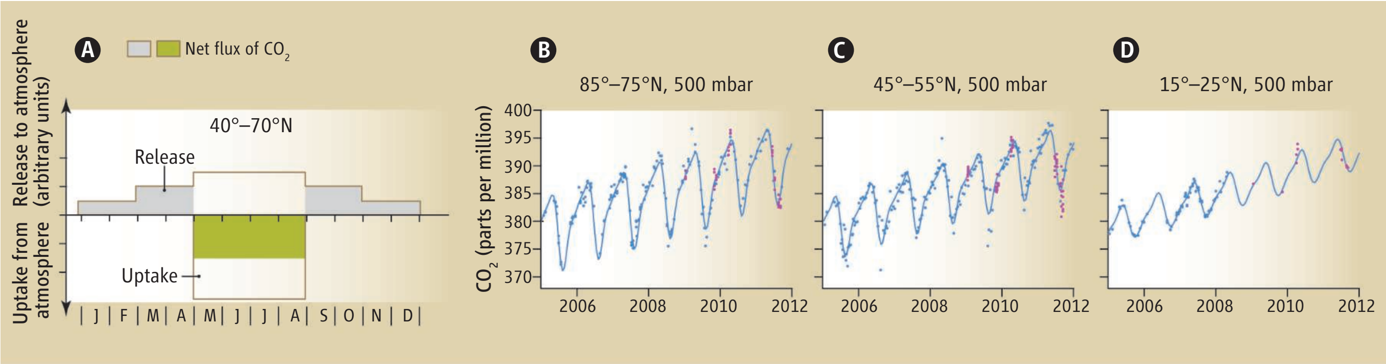

Deeper breathing. The net ecosystem productivity (green) captures the seasonal uptake of carbon dioxide by the biosphere (**A**). Graven *et al.* have used aircraft data to determine how carbon dioxide concentrations have oscillated in the troposphere over recent decades. The seasonal oscillations are largest at high latitudes (**B**) than at mid- (**C**) and low-latitudes (**D**). The amplitude of this "breathing" is increasing, especially at high latitudes. [Panels B to D adapted from fig. S4 in (*1*)]

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not extend as far into autumn as the warming and thawing seasons and ends earlier, by ~0.9 days per decade (*3*).

The longer decomposition season, coupled with greater amounts of detritus from enhanced photosynthesis and faster decomposition rates, would contribute to a higher atmospheric CO_2 buildup and hence a larger CO_2 amplitude (*4*). Microbes, the agents of decomposition, are having a feast not only in the melting permafrost, but in the entire Northern Hemisphere (*5*–*7*). The microbial feast would in turn supply nutrients to enhance photosynthetic uptake and support the poleward march of ecosystems.

Graven *et al*. show that the CO_2 amplitude trend is not well simulated by the current generation of global Earth system models. These models include the life cycles of ecosystems, with photosynthetic uptake sensitive to atmospheric CO_2 and ambient climate; and litter decomposition (and concomitant microbial respiration) varying with temperature and soil moisture. In some models, vegetation structure changes with fires and changing climate. So what is missing?

Permafrost carbon dynamics is just beginning to be incorporated into the next-generation models (*8*). Still, understanding of the transient carbon dynamics of a thawing Arctic is rudimentary. The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), a NASA mission, has observed episodic bursts of high CO_2 and CH_4 throughout the thaw season (*9*), not the slow, steady release predicted by the models. The U.S. Department of Energy's Next Generation Ecosystem Experiments in the Arctic (NGEE-Arctic) (*10*), NASA's Arctic-Boreal Vulnerability Experiment (ABoVE) (*11*), and the European Union's PAGE21 project (*12*) all promise to deliver new insights that will advance the modeling.

The biosphere is changing, and changing rapidly. Currently it is a sink for a quarter of the anthropogenic CO_2 emissions. Will it continue to act as a sink for fossil fuel–derived CO_2? Current results, including those reported by Graven *et al*., suggest that it will do so until microbial respiration overtakes photosynthetic uptake. The race is on.

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10.1126/science.1242004

CHEMISTRY

Uncloaking the Quantum Nature of Inelastic Molecular Collisions

Experiment and theory combine to reveal quantum resonances when hydrogen molecules hit and excite oxygen molecules.

Piergiorgio Casavecchia[1] **and Millard H. Alexander**[2]

Collisions between molecules can be reactive, resulting in a change in their chemical identity, or inelastic, resulting in a change in only their internal energy or orientation. On page 1094 of this issue, Chefdeville *et al*. (*1*) report on the predominant contribution of quantum-mechanical resonances to the inelastic scattering and excitation of molecular oxygen (O_2) by molecular hydrogen (H_2).

A crucial quantity as two partners approach, collide, and then recede is the "orbital" angular momentum l. This quantity is the product of their initial relative velocity, their reduced mass, and the impact parameter b, which is the offset off-axis as the two molecules approach one another (see the figure, panel A; b is zero for a head-on collision). In quantum mechanics, l can take on only integer values, in units of Planck's constant. The overall, or integral, cross section (the effectiveness of reaction or energy transfer) is the weighted sum of the contributions from collisions at separate values of l. To connect these values to chemical kinetics, the thermal rate coefficient is calculated as the average of the integral cross section over a distribution of relative velocities of the colliding molecules. Strictly speaking, the summation is really over all values of the total angular momentum J, which is the vector sum of l, N (the nuclear rotational angular momentum), and S (the total electronic spin angular momentum).

In the experiments of Chefdeville *et al*., the collision energies are low enough, the mass of the H_2 collision partner small enough, and the resolution in collision energy high enough to allow a clean resolution of the contribution of individual partial waves—individual values of J—to the integral inelastic cross section. In scanning the collision energy, they observe sharp peaks in the measured cross sections, which they attribute to resonances associated with low values of J. [A resonance is a metastable, short-lived state that is accessed and then decays during the course of a collision (*2*).]

In O_2, the spins of the two outermost electrons are not paired up, so that $S = 1$. The O_2 molecule has a permanent magnetic moment that lies in the same direction as S, even in the absence of an external magnetic field. Symmetry considerations restrict N to only odd integer values. In the lowest rotational state of O_2, N and S are antiparallel so that the total molecular angular momentum j is zero.

In the sophisticated experiment of Chefdeville *et al*., a collimated, energy-resolved beam of O_2 formed predominantly in its ground state ($N = 1, j = 0$) collided with a beam of H_2 in its singlet ground state ($S = 0$). The H_2 beam was cooled into its lowest possible rotational state ($N = 0$), which corresponds to the *para* nuclear spin modification and is nearly spherical.

In their experiments, O_2 was scattered inelastically into a higher ($N = 1, j = 1$) spin-rotation level, where S and N are perpendicular. The ($N = 1, j = 1$) state lies ~4 cm^{-1} (0.5 meV) higher in energy than the ground state (*3*), a consequence of the weak interaction between the spin magnetic moment and the "end-over-end" rotation of the O_2. As the collision energy increased from 4 to 20 cm^{-1}, the probability of excitation to the $N = 1, j = 1$ level showed three well-resolved peaks.

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