tive forcing of given concentrations of the six greenhouse gases at a given point in time. And one can calculate the amount of CO_2 in the atmosphere that, taken alone, would result in the same radiative forcing. This would then be the 'CO_2 equivalent' concentration. But it is not obvious how to define CO_2-equivalent emissions of different greenhouse gases: such emissions affect gas concentrations in the future, as well as today, because each of them has a different lifetime in the atmosphere.

The GWP of a gas is a measure of such an equivalence. The starting point is a baseline trajectory of radiative forcing over time. If, at some moment, an extra unit (say a tonne) of a gas is injected into the atmosphere, the trajectory is perturbed from that moment on. One measure of the resulting warming effect from that moment to some specified time horizon is simply the integral of that perturbation in radiative forcing. The GWP of a gas is the ratio of that integral to the same measure (out to the same horizon) associated with injection of a unit of CO_2.

In general, natural scientists have been attracted to the GWP concept because of its purely physical quality. Although economists have argued that the tradeoffs cannot be inferred from physical properties alone, but have an inherent economic and policy dimension in terms of targets set[4–7], the message has been slow to be accepted in the scientific community[8,9].

Using a computer model that has been used for various purposes for several years, Manne and Richels[3] show both that the economic perspective matters and that it is possible to implement it. They emphasize that there remains much uncertainty about the parameters of their model, and policy objectives. The important point about their results is less the specific tradeoffs that they derive than the cost-effectiveness logic they apply.

From a technical point of view, climate change is simpler than many environmental challenges: here we are dealing with a set of well-mixed pollutants, each of which has the same effect. The policy interest in the emissions of these gases results from their effects on climate change, but this depends on one thing: the trajectory of radiative forcing. That is, we can completely characterize the consequence of an incremental tonne emitted of a greenhouse gas, holding constant all other emission flows through time, by the perturbation in the trajectory of radiative forcing that it induces. The perturbation that results from an incremental tonne varies a lot from gas to gas (and with the ambient atmospheric conditions, although this effect is generally ignored in these exercises).

To say that emission of an incremental tonne of one gas has the same implications for policy as emission of *x* tonnes of another gas means that we have to assign a value to the change in radiative forcing at different times in the future. There is no way to avoid this step. Using the physical GWP involves an implicit evaluation: a bit of extra radiative forcing at any time up to the chosen horizon has the same (negative) value as the same bit at any other time within that span; an extra bit beyond the horizon has zero value. This is clearly wrong.

The grand aim of optimizing policy on climate change involves placing a value on the costs or benefits of such change — say of a 2 °C rise in temperature. That is a highly controversial step. But suppose we had somehow solved that grand problem. The solution would involve a particular path of radiative forcing. Presumably, if we have really solved the grand problem, the emissions of the various greenhouse gases minimize the cost of attaining that path. Manne and Richels have recognized that we do not know the overall costs and benefits of climate change: instead of solving the grand problem they have solved a cost-effectiveness subproblem.

They take as given a desired limit on global average temperature, and use their model to solve the cost-minimizing way to achieve the specified target by controlling emissions of the various greenhouse gases. (This involves determining a path of radiative forcing, as well as the cost-minimizing paths of greenhouse-gas emissions.) Associated with a solution to this problem will be 'shadow prices' which answer the question of how much the cost of meeting the desired policy objective would be reduced if we were allowed to emit one extra tonne of gas *g* at time *t*. The ratio of that quantity for gas *g* to that quantity for CO_2 is the tradeoff we are after, and which Manne and Richels calculate.

The significance of Manne and Richels' analysis is twofold. First, they have brought a powerful quantitative model to bear on the problem of aggregating greenhouse gases in the implementation of climate policy. Second, the general point that they emphasize is still far from generally understood. I often encounter the view that, arbitrary as they may be, GWPs constitute a reasonable shot at the set of tradeoffs that are appropriate for Kyoto-style regulation. But this is nonsense without a concept of what 'appropriate' means, which in turn forces us to confront the specifics of getting the tradeoffs right. ■

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Daedalus

Warping space

Some while ago, Daedalus devised a method of warping space itself. He used a big capacitor, across which an a.c. electric field maintained an a.c. displacement current. All dielectrics maintain such a current, as their electrons are shifted by the electric field; a magnetic field imposed on the dielectric therefore exerts a force upon it. Sadly, a resonant system with the magnetic field created by the same coils that generate the electric one fails to work (the resonance comes out wrong), so the magnetic field has to be specially generated.

The original idea was to use the device as an aero engine, propelling air as the dielectric. But Daedalus soon realized that the system has a remarkable property. Suppose the dielectric is a pure vacuum. This sustains a displacement current with the best of them. Yet the magnetic field, which imposes its force on any current-carrying conductor, is now exerting that force on space itself.

Thus Daedalus's gadget is an ideal way of studying the 'flexibility' of pure space. Cosmology currently holds that the entire Universe is expanding, like a balloon with markings on it being inflated — the markings in this case being galaxies, which all seem to be receding from one another. This expansion may be an energetic relic of the Big Bang, or it may be maintained by some unrecognized force. Daedalus now plans to measure that force.

His scheme is to set up a line of his electromagnetic thrusters, all pushing on space in the same direction, and to shine a laser beam across it. When the thrusters are turned on, the beam (travelling in the space above them) will be deflected. Interferometric measurements on the beam will thus calibrate the thrusters against the resulting beam deflection.

From the results, Daedalus hopes to measure the force sustaining the observed expansion of the Universe, and to relate it to that exerted by the Big Bang. Of course, space-warp technology has already been developed so enthusiastically by science-fiction writers that Daedalus sees no point in entering the business himself. Instead, he hopes that the measurements show extreme sensitivity in the beam. This would imply that the galaxies are expanding purely ballistically, as suggested by the Big Bang theory. But a small force, either positive or negative, may be needed to square an exactly closed Universe with the Big Bang theory as currently understood. Such fundamental measurements are always worth making.

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