a number of insights, three of which are sketched below (details are in the Supplementary Information).

The first insight concerns experts' overconfidence. Lin and Bier[20] found pervasive overconfidence among experts, measured as the percentage of true values falling outside experts' 90% confidence intervals. However, the differences in expert performance are not random; most expert panels contain statistically accurate experts whose 90% confidence bands tend to contain 90% of the true values. Their results support the case for differential weighting of experts.

Statistical accuracy is only half the story. We want 90% confidence bands that are not only statistically accurate but also informative. The second insight concerns the role of domain expertise and experience in achieving statistical accuracy and informativeness. Using data from the Montserrat Volcano Observatory, Wadge and Aspinall[21] tracked the scores of eighteen specialist volcanologists, and of seven other Earth scientists who act as probabilistic risk assessors. The risk assessors were statistically accurate, but less informative than the most experienced volcanologists. However, some very experienced volcanologists exhibit strong over-confidence.

The third insight concerns performance prediction. Does performance on calibration variables predict performance on the (typically unobservable) variables of interest? When direct observation of the variables of interest is not possible, we rely on expert judgement and need to cross-validate their performance. 'Cross validation' gauges how well performance on a subset of calibration variables (the training set) predicts performance on the complementary subset (the test set). An exhaustive study[22] compares performance-based weighting of experts with equal weighting, for each of 62 studies. Performance weight (PW) combinations of experts based on a training set are applied to a test set and compared with equal weight (EW) combinations. The PW/EW performance ratios for test sets are aggregated over all possible training/test splits for each study. These ratios, shown in Fig. 1, amply attest to the value of performance-based weighting.

The problem of communicating uncertainty cannot be adequately tackled if the communicators don't understand uncertainty. Sprinkling a narrative with uncertainty qualifiers, even if these are given a quantitative interpretation, is not sufficient. Science-based uncertainty quantification is possible, and has been going on for some time in other fields. Much has been learned and climate scientists cannot afford themselves the luxury of repeating the mistakes of the past. ❐

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## Additional information

Supplementary information is available in the online version of this paper.

COMMENTARY:

# A balanced-efforts approach for climate cooperation

Robert C. Schmidt

**Focusing on policies and effort costs rather than emissions may facilitate climate negotiations and improve the chances of reaching a successful agreement. The effort costs of a country comprise investments in low-carbon technologies, in addition to direct mitigation costs.**

In the past, climate negotiations have focused primarily on emissions targets. Stiglitz, however, argues that it would be easier to negotiate about taxes[1]. In his view, the advantage of a common tax over the Kyoto approach would be that most of the distributional debate is sidestepped. In particular, under the Kyoto approach, obtaining the right to pollute is like receiving a gift. Hence, countries may struggle for the best 'deal', which can make an agreement difficult to achieve. In an earlier contribution, Schelling[2] suggests that countries choose their own policy instruments when contributing to climate stability. He argues that a proposal should specify policies, such as taxes, regulations, or research and development subsidies, accompanied by (uncertain) estimates of their probable effects on emissions. I re-evaluate Schelling's proposal in the light of the developments over the past two decades and recent economic research, and develop it further. I argue that this strategy may not only be instrumental in reaching a global climate agreement, but such a flexible approach towards cooperation may also lead to a more efficient outcome than negotiating about emissions.

Schelling suggests a model for climate cooperation similar to the negotiations of Western European countries for distributing Marshall Plan (the European Recovery Plan) dollars after the Second World War, and the negotiations on burden sharing in NATO. He argues that although there was no explicit criterion (such as equal living standards), the submission of data and the open argument that took place led to a reasonable appreciation of the needs of the different countries (for example, investment needs). Schelling goes on to state that in the context of climate negotiations, this model suggests that the main participating countries would "submit for each other's scrutiny and cross-examination plans for reducing carbon emissions". These plans would be accompanied by estimates of emissions (or abatement of emissions). However, any commitment of a country would be to its policies, and not to its emissions.

Let us develop this idea further. If countries do as Schelling suggests, then the efforts that countries undertake can be compared by estimating the costs that the individual mixture of policies will imply for a given country. A natural starting point for negotiations may then be a regime in which countries seek to balance their efforts in terms of percentage costs of gross domestic product (GDP) implied by their climate policies. By contrast, a uniform reduction target for emissions of, say, 20% below the emissions in a base year or below some projected baseline level might impose larger costs (as a percentage of GDP) for one country than for another. An agreement that harmonizes countries' efforts may be easier to agree on than many other suggestions that have been put forward (for example, formula approaches[3]). It implies that richer countries will contribute more in absolute terms to climate stability than poorer countries. Furthermore, when countries negotiate exclusively about emissions, they are essentially restricting themselves to the policy instrument of cap-and-trade. But given the various uncertainties surrounding the problem, the actual welfare cost for a country of implementing a given emissions target may be highly uncertain. Committing themselves to policies (such as an emissions price, or subsidies for low-carbon technologies), may be much easier than adopting commitments about emissions. Given their characteristics, countries can then decide individually which policies are likely to have the largest environmental benefits, while minimizing the risks for their economies.

## Two public goods

Such a flexible approach towards climate cooperation may actually lead to a more efficient outcome. Research conducted during the past several years has highlighted the presence of multiple market failures related to the climate change problem[4]. Namely, in a world with various kinds of technology spillovers, it is not enough to cooperate only in reducing emissions. To reduce emissions globally at the lowest costs, there must also be policies that foster the development and deployment of low-carbon technologies[5]. Otherwise, firms will underinvest, and any emissions targets will be reached at inefficiently high costs. Climate stabilization should, thus, be thought of as a double public goods problem. On the one hand, countries must contribute to the reduction of greenhouse-gas emissions, which would decrease the damages from climate change. On the other hand, countries should contribute to the 'global pool of knowledge' in the area of low-carbon technologies.

Negotiating about policies and effort costs rather than about emissions does not mean that the damages of climate change are taken less seriously.

From a theoretical point of view, it is difficult to pin down the optimal contributions to these public goods. For example, if knowledge accumulates mostly via learning-by-doing rather than research and development, then the impact of induced technological change on the optimal time path of abatement is ambiguous[6]. But apart from the other uncertainties regarding the development and the costs of new technologies, it is not even clear how much of the technological change can be attributed to research and development or to learning-by-doing. Hence, the optimal time path of investments into abatement and knowledge is unknown, and there is no reason to believe that a 'global planner' who fixes contributions to these public goods for different countries would do any better than countries choosing their individual contributions.

Schelling estimates that the world should sacrifice about 2% of its GDP in perpetuity to adequately address the problem of climate change[2]. Given this estimate (which I believe is still reasonable today), I envision a '2% target' for the total contribution to climate stability per country per year. This comprises both direct costs of emissions control (for example, those induced by a carbon price) as well as investment costs in the development of low-carbon technologies. Of course, this 2% could be replaced by a smaller or larger number to raise the chances of reaching a global agreement, or to lower the risks of catastrophic climate change[7].

Negotiating about policies and effort costs rather than about emissions does not mean that the damages of climate change are taken less seriously. It means that the difficulties some countries have in committing themselves to specific emissions targets, as well as the double public goods nature of the climate change problem, are taken more seriously. Ultimately, the goal is climate stabilization. But I believe that in the nearer term, such a flexible approach[8] towards cooperation will prove more effective than other strategies that focus primarily on emissions[9].

## Total effort costs

Interestingly, the pledge-and-review approach that has recently been adopted in climate negotiations resembles the method that is proposed here[10]. Adopting a 2% target, however, would give more structure to the negotiations. It provides us with a simple and transparent criterion to evaluate and compare the pledges of different countries. In particular, the balanced-efforts approach is the first that values direct investments in climate stability and investments in low-carbon technologies equally, and lumps them into a single number that measures the total contribution of each country to both public goods (emissions reductions and knowledge accumulation).

As a starting point, it may be necessary to agree on a set of 'accounting rules' for expenses related to climate change mitigation. For instance, if a country is offering to commit to a carbon tax of, say, US\$20 per ton of $CO_2$, then estimated marginal abatement cost curves can be used to evaluate the probable effects on emissions and the induced total abatement costs. The estimation of costs may be complicated by general equilibrium and trade effects, as well as by co-benefits of induced technological change. I believe, however, that the accounting rules should be simple, and only take into consideration the most immediate of the possible effects. In the presence of significant co-benefits of the policies for the respective country, this may lead to an overestimation of the total costs, but eliminating such effects may render the estimates potentially very complicated and intransparent.

Estimates of abatement costs are already available for many countries. They are often based on specific abatement targets. For example, a recent study evaluates proposals from China and India for their 2020 emissions targets[11]. The results of this study indicate that implementing China's target of reducing the emissions intensity of the economy by 40–45% may require a comparable effort to that implied by the targets announced by the EU and the US. However, to evaluate countries' overall efforts in the area of climate protection, estimates of their total costs that explicitly take into account also their investments into low-carbon technologies will be needed, in addition to their direct mitigation costs.

Let me finally point out that the balanced-efforts approach is also compatible with the adoption of a global carbon tax, which many economists view as the most efficient policy instrument for climate stabilization[1]. While a uniform carbon price can help to implement emissions reductions efficiently, the resulting costs (as percentage of GDP) of such a uniform tax could vary drastically across countries. This could make it hard to reach an international agreement that establishes a uniform carbon tax. To neutralize these cost disparities, a global transfer scheme could be implemented, but this would probably be even harder to agree upon than a global carbon tax, considering the unprecedented amounts of monetary transfers between countries that would be needed. Under a balanced-efforts scheme, such cost disparities can be offset more easily. Countries that suffer less under a uniform carbon tax would simply be asked to contribute more to the other global public good: knowledge in the area of low-carbon technologies. ❐

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COMMENTARY:

# Lessons learned from ocean acidification research

Ulf Riebesell and Jean-Pierre Gattuso

**Reflection on the rapidly growing field of ocean acidification research highlights priorities for future research on the changing ocean.**

Research on ocean acidification has gone through a remarkable surge over the past decade. Known to only a small number of researchers ten years ago, the issue of ocean acidification has developed into one of the fastest growing fields of research in marine sciences, and is among the top three global ocean research priorities[1]. Notably, 50% of the papers have been published in the last three and half years, two-thirds of which deal with biological responses (Fig. 1). The development of this field has greatly benefitted from close collaboration, both within and between national and international projects, from an early community-driven agreement on best practices in ocean acidification research and data reporting[2], from concerted communication spear-headed by a Reference User Group (http://go.nature.com/guz4EE), and from international coordination (www.iaea.org/ocean-acidification). A large number of high-profile reports, targeting the science community and the general public as well as stakeholders and decision makers, have summarized the state of knowledge in this field as concisely and accurately as possible[3,4]. Ocean acidification and its consequences have received growing recognition at intergovernmental levels[5], and more recently also at the governmental level, as reflected by the US State Department's *Our Ocean Conference*, where ocean acidification was one of three topics addressed. In view of its fast and striking development, it is timely to reflect on the successes and deficiencies of ocean acidification research and take