COMMENT

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Pipes transport oil from rigs on Endicott Island in Alaska.

Vast costs of Arctic change

Methane released by melting permafrost will have global impacts that must be better modelled, say **Gail Whiteman**, **Chris Hope** and **Peter Wadhams**.

Unlike the loss of sea ice, the vulnerability of polar bears and the rising human population, the economic impacts of a warming Arctic are being ignored.

Most economic discussion so far assumes that opening up the region will be beneficial. The Arctic is thought to be home to 30% of the world's undiscovered gas and 13% of its undiscovered oil, and new polar shipping routes would increase regional trade[1,2]. The insurance market Lloyd's of London estimates that investment in the Arctic could reach US$100 billion within ten years[3].

The costliness of environmental damage from development is recognized by some, such as Lloyd's[3] and the French oil giant Total, and the dangers of Arctic oil spills are the subject of a current panel investigation by the US National Research Council. What is missing from the equation is a worldwide perspective on Arctic change. Economic modelling of the resulting impacts on the world's climate, in particular, has been scant.

We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher.

Much of the cost will be borne by developing countries, which will face extreme weather, poorer health and lower ▶

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Bubbles of methane emerge from sediments below a frozen Alaskan lake.

agricultural production as Arctic warming affects climate. All nations will be affected, not just those in the far north, and all should be concerned about changes occurring in this region. More modelling is needed to understand which regions and parts of the world economy will be most vulnerable.

ECONOMIC TIME BOMB

As the amount of Arctic sea ice declines at an unprecedented rate[4,5], the thawing of offshore permafrost releases methane. A 50-gigatonne (Gt) reservoir of methane, stored in the form of hydrates, exists on the East Siberian Arctic Shelf. It is likely to be emitted as the seabed warms, either steadily over 50 years or suddenly[6]. Higher methane concentrations in the atmosphere will accelerate global warming and hasten local changes in the Arctic, speeding up sea-ice retreat, reducing the reflection of solar energy and accelerating the melting of the Greenland ice sheet. The ramifications will be felt far from the poles.

To quantify the effects of Arctic methane release on the global economy, we used PAGE09. This integrated assessment model calculates the impacts of climate change and the costs of mitigation and adaptation measures. An earlier version of the PAGE model was used in the UK government's 2006 Stern Review on the Economics of Climate Change to evaluate the effect of extra greenhouse-gas emissions on sea level, temperature, flood risks, health and extreme weather while taking account of uncertainty[7]. The model assesses how the net present value of climate effects varies with each tonne of carbon dioxide emitted or saved.

We ran the PAGE09 model 10,000 times to calculate confidence intervals and to assess the range of risks arising from climate change until the year 2200, taking into account sea-level changes, economic and non-economic sectors and discontinuities such as the melting of the Greenland and West Antarctic ice sheets (see Supplementary Information; go.nature.com/rueid5). We superposed a decade-long pulse of 50 Gt of methane, released into the atmosphere between 2015 and 2025, on two standard emissions scenarios. First was 'business as usual': increasing emissions of CO_2 and other greenhouse gases with no mitigation action (the scenario used by the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios A1B). Second was a 'low-emissions' case, in which there is a 50% chance of keeping the rise in global mean temperatures below 2°C (the 2016r5low scenario from the UK Met Office). We also explored the impacts of later, longer-lasting or smaller pulses of methane.

"There is a steep global price tag attached to physical changes in the Arctic."

In all of these cases there is a steep global price tag attached to physical changes in the Arctic, notwithstanding the short-term economic gains for Arctic nations and some industries.

The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see 'Arctic methane'). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added (see Supplementary Information). These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse.

The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. The extra methane magnifies flooding of low-lying areas, extreme heat stress, droughts and storms.

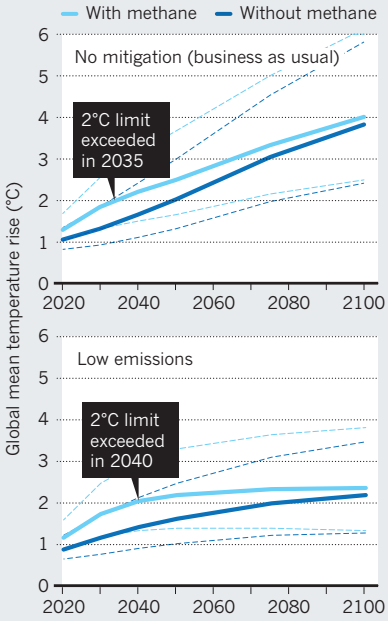
GLOBAL PROBLEM

The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone.

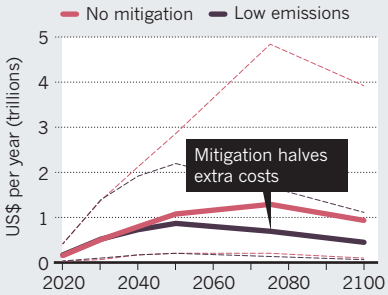
To find out the actual cost, better models are needed to incorporate feedbacks that

ARCTIC METHANE

Global mean temperatures will rise more quickly if 50 gigatonnes of methane is released from permafrost beneath the East Siberian Sea.



The economic impacts of the methane pulse will be felt worldwide.



Solid lines indicate mean results from the PAGE09 model; dashed lines indicate confidence intervals, 5% (lower) and 95% (upper).

are not included in PAGE09, such as linking the extent of Arctic ice to increases in Arctic mean temperature, global sea-level rise and ocean acidification, as well as including estimates of the economic costs and benefits of shipping. Oil-and-gas development in the Arctic should also, for example, take into account the impacts of black carbon, which absorbs solar radiation and speeds up ice melt, from shipping and gas flaring.

Splitting global economic impact figures into countries and industry sectors would raise awareness of specific risks, including the flooding of small-island states or coastal cities such as New York by rising seas. Mid-latitude economies such as those in Europe and the United States could be threatened, for example, by a suggested link between sea-ice retreat and the strength and position of the jet stream[8], bringing extreme winter and spring weather. Unusual positioning of the jet stream over the Atlantic is thought to have caused this year's protracted cold spell in Europe.

Such integrated analyses of Arctic change must enter global economic discussions. But neither the World Economic Forum (WEF) in its *Global Risk Report* nor the International Monetary Fund in its *World Economic Outlook*[9] recognizes the potential economic threat from changes in the Arctic.

In 2012, noting that the far north is increasing in strategic importance and citing the need for informal dialogue among world leaders, the WEF launched its Global Agenda Council on the Arctic. This is welcome but more action is needed. The WEF should kick-start investment in rigorous economic modelling. It must ask world leaders to consider the economic time bomb beyond short-term gains from shipping and extraction.

The WEF should also encourage innovative adaptation and mitigation plans. It will be difficult — perhaps impossible — to avoid large methane releases in the East Siberian Sea without major reductions in global emissions of CO_2. Given that the methane originates in local seabed warming, then reducing black carbon deposits on snow and ice might buy some precious time[10]. But unknown factors could also mean that our impact estimates are conservative. Methane emerging in a sudden burst could linger for longer in the atmosphere, and trigger more rapid temperature changes than if the gas were released gradually.

Arctic science is a strategic asset for human economies, because the region drives critical effects in our biophysical, political and economic systems. Without this recognition, world leaders and economists will miss the big picture. ■

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