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Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route

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Abstract The extensive melting of Arctic sea ice driven by climate change provides opportunities for commercial shipping due to shorter travel distances of up to 40% between Asia and Europe. It has been estimated that around 5% of the world's trade could be shipped through the Northern Sea Route (NSR) in the Arctic alone under year-round and unhampered navigability, generating additional income for many European and East Asian countries. Our analysis shows that for Arctic sea ice conditions under the RCP8.5 emissions scenario and business restrictions facing shipping companies, NSR traffic will increase steadily from the mid-2030s onwards, although it will take over a century to reach the full capacity expected for ice-free conditions. However, in order to achieve a balanced view of Arctic shipping, it is important to include its detrimental environmental impacts, most notably emissions of short-lived pollutants such as black carbon, as well as CO_2 and non-CO_2 emissions associated with the additional economic growth enabled by NSR. The total climate feedback of NSR could contribute 0.05% (0.04%) to global mean temperature rise by 2100 under RCP8.5 (RCP4.5), adding $2.15 trillion ($0.44 trillion) to the NPV of total impacts of climate change over the period until 2200 for the SSP2 socio-economic scenario. The climatic losses offset 33% (24.7%) of the total economic gains from NSR under RCP8.5 (RCP4.5), with the biggest losses set to occur in Africa and India. These findings call for policy instruments aimed at reducing emissions from Arctic shipping and providing compensation to the affected regions.

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1 Introduction

Climate change has contributed to a rapid retreat of Arctic sea ice in recent years, and the trend is likely to continue over the coming decades even under the most ambitious mitigation pledges (Hezel et al. 2014). The Arctic sea ice retreat is opening up both the Northwest Passage (across Canadian Arctic waters) and the Northeast Passage (also known as the Northern Sea Route, NSR, passing along the Siberian north coast), during parts of the year. Both routes have potentially significant effects on global trade; NSR, for example, provides a distance reduction of up to 40% compared to the current Suez Canal route (referred to as the Southern Sear Route, SSR) for trade between Northern Europe and Eastern Asia (UCAM 2013; Bekkers et al. 2016).

Several recent studies have looked at the possible economic and environmental impacts of Arctic shipping routes (Verny and Grigentin 2009; UCAM 2013; Lasserre 2014; ESRI 2014; AMAP 2015; Bekkers et al. 2016; Bensassi et al. 2016). Bekkers et al. (2016) used specialised computable general equilibrium (CGE) and gravity trade models with multiple interlinked industry sectors in 100 countries. They estimate that 4.7% of the world's future trade (equivalent to around two thirds of the expected traffic otherwise going through the Suez Canal) could be re-routed through NSR in 2030 under the "middle of the road" SSP2 socio-economic scenario (Riahi et al. 2017; O'Neill et al. 2017), provided the route is navigable all year round. We refer to this as the full navigability assumption. The re-routing leads to a 6% increase in the trade value between Northwest Europe and East Asia, generating marginal GDP increases in the EU, China, Japan and South Korea of the order of 0.1%. Bensassi et al. (2016), who used a much simpler trade model without sector-level details and macroeconomic feedbacks, predicted a 7% increase in exports between EU and Asia based on CMIP5 climate models' predictions for sea ice under which NSR will be navigable for 6 months per year on average by the end of the twenty-first century under the RCP8.5 climate change scenario.[1]

In recent years, the NSR navigability window has been limited to approximately 50 days per year around the September sea ice minimum (Khon et al. 2010; Eguiluz et al. 2016), and the route has had highly varying sea ice conditions, rendering any large-scale commercial operations impossible. On average, roughly one NSR transit per navigable day has been made in recent years, with considerable year-on-year variations driven largely by global economic and political factors.[2] Building on the earlier work by Verny and Grigentin (2009), Lasserre (2014) and others, Hansen et al. (2016) quantitatively assess the ship owner's business case of investing in ice resilience to seasonally re-route to the NSR. They estimate that under the current sea ice conditions and realistic near-term climate projections, shipping firms will not be able to profit from investments in ice-strengthened container ships capable of operating along NSR at least until 2030s, taking into account the limited navigability windows, lower average utilisation of capacity, waiting times to form an icebreaker convoy, icebreaker fees, insurance costs and other economic factors associated with Arctic operations. Medium-size container ships face additional operational restrictions and therefore may not be able to re-route until the 2050s.

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[1] Melia et al. (2016) extended the navigability analysis based on CMIP5 sea ice projections to other Arctic routes, including the shortest route passing through the North Pole, but these routes are yet to be analysed from the economic point of view.
[2] http://www.highnorthnews.com/frozen-waters-northern-sea-route-traffic-boosted-by-internal-traffic-while-transits-fall-sharply/

The business restrictions facing shipping operators are missing both in the studies such as Smith and Stepherson (2013), Aksenov et al. (2016) and Melia et al. (2016) which more narrowly focus on technical marine accessibility in the Arctic under model sea ice projections,[3] as well as in the studies by Bensassi et al. (2016) and Bekkers et al. (2016) which model possible implications of NSR for global trade and economies in Europe and Asia. Our paper superimposes the business restrictions summarised by Hansen et al. (2016) on the navigability projections and on the results from trade models and macroeconomic models to obtain new downscaled projections for the possible build-up of the traffic on NSR over the next two centuries.

The shipping industry has traditionally relied upon heavy fuel oils (HFOs) that belong to some of the most polluting fossil fuels and generate a broad spectrum of emissions, including CO_2 and short-lived climate forcers (SLCFs) such as sulphate aerosols and black carbon (BC) (Eyring et al. 2010). Although the total emissions from Arctic shipping with a fully operational NSR may be relatively small on a global scale, the impact of these emissions in a climate-sensitive area like the Arctic could be profound. Fuglestvedt et al. (2014) used the atmospheric chemistry model OsloCTM2 to investigate the net climatic effect of re-routing of transit shipping via NSR, based on Arctic shipping inventories for 2030 and 2050 from Peters et al. (2011), and found that the net radiative forcing (RF) effect of NSR is dominated by the following drivers: less cooling from sulphates and indirect aerosols, more warming from black carbon and less warming from CO_2.

Reducing the route length and with it fuel consumption and emissions is the major factor behind these changes, but many SLCFs also experience RF changes due to the unique climatic conditions in the Arctic. This is particularly relevant for BC, which reduces the surface albedo effect when it is deposited on white ice sheets and snow. In addition, the stable atmosphere in the Arctic increases the lifetime of the BC, extending the period over which it causes the additional warming (AMAP 2015). Browse et al. (2013) applied Arctic shipping inventories for 2030 and 2050 from Corbett et al. (2010a, b) to model BC deposition using the atmospheric chemistry model GLOMAP and found that BC emitted by Arctic shipping by 2050 under the default growth scenario is projected to constitute only 1% of the total BC deposited in the Arctic, with the biggest share coming from non-shipping sources at lower latitudes. However, they did not calculate the resulting RF increase and temperature response. Sand et al. (2015), who used CMIP5 earth system models to analyse present-day impact of SLCF emissions from several world regions both on the Arctic temperature as well as the global temperature, found that a unit of BC emitted by Nordic countries currently produces equivalent global RF around four times higher than the unit emitted in East and South Asia.

In addition to the complex effect of emissions directly from the shipping re-routing through NSR, the marginal economic growth in multiple countries enabled by NSR is set to increase their CO_2 and non-CO_2 emissions. Bekkers et al. (2016) were the first to demonstrate that the indirect growth in emissions from European and East Asian economies can potentially offset the reduction in CO_2 associated with the shorter route. They did not consider non-CO_2 components, however.

The key issue addressed in this paper is that although emissions of SLCFs and CO_2 from multiple economic sectors globally are already included in the main IPCC scenarios of climate change (RCPs), the geographic redistribution of emissions due to climate-induced economic opportunities such as Arctic shipping is not. The main purpose of this study is therefore to

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[3] Bensassi et al. (2016) also perform a similar analysis as part of their study.

quantitatively assess the climatic and economic feedback effects of NSR, which requires the integration of a variety of modelling approaches spanning across multiple disciplines.

First, we generate predictions for Arctic sea ice conditions to determine navigability along the NSR under two contrasting climate change scenarios: RCP8.5 (high emissions) and RCP4.5 (medium mitigation levels, Moss et al. 2010). Second, we feed the navigability results into a business model developed by Hansen et al. (2016) to determine when shipping along the NSR becomes profitable. Third, we generate predictions for the amount of trade between the countries using the NSR based on the "middle of the road" SSP2 projections for GDP growth (Riahi et al. 2017). SSP2 largely follows persistent historical trends in social, economic and technological development (Dellink et al. 2017; O'Neill et al. 2017) and provides a reasonable first estimate for the possible state of the future economy. Fourth, we downscale the predictions for the amount of trade along the NSR in Bekkers et al. (2016) based on the NSR profitability from step 2 and the trade growth projections from step 3. Fifth, we use the long-term projections for NSR traffic and the expected increase in fuel efficiency to calculate the geographic redistribution of fuel consumption to the Arctic, and translate it into net additional global equivalent RF gain associated with SLCF emissions from shipping according to the atmospheric chemistry estimates by Fuglestvedt et al. (2014). Sixth, we use the estimates for the reduced global ton-kilometre as a result of NSR from Bekkers et al. and for the reduced fuel use due to slow steaming on Arctic routes from Hansen et al. to calculate the direct decrease in CO_2 emissions. Seventh, we adjust the estimate for the additional indirect CO_2 emissions from NSR-driven marginal economic growth in Europe and Asia from Bekkers et al. using SSP2 GDP projections and extrapolate it to non-CO_2 emissions from these regions under a given RCP scenario. Eighth, the RF and emissions as a result of NSR from steps 5, 6 and 7 are translated into additional climate-related economic losses in different regions using PAGE-ICE integrated assessment model. In the ninth and final step, these losses are compared with the projected economic gains from NSR based on the estimates from Bekkers et al.

The paper is structured as follows. Section 2 describes optimal trade shift towards NSR based on sea ice conditions, business restrictions facing shipping firms and economic opportunities arising from shorter distances and reduced shipping times. In Section 3, the resulting total net emissions due to NSR are converted into the additional climatic and economic impacts globally, which are then compared with the estimated economic gains from NSR. Section 4 concludes and discusses policy implications.

2 Optimal trade shift towards the NSR

We determine the optimal trade shift towards NSR by downscaling the results from Bekkers et al. (2016) which only apply to the case of full navigability (ESM-4). Multiple authors point to barriers for and model feasibility of Arctic shipping. Lasserre (2014) provides a comprehensive review of 26 models and presents a new modelling approach. Hansen et al. (2016) update the previous estimates with the new pricing scheme for transit fees and make additional refinements in their assessment of the business case of investing in ice resilience, which is based on comparing year-round operations using ordinary vessels on SSR with ice-strengthened vessels operating on NSR whenever possible and on SSR otherwise (where the ice-strengthened vessels sail at a disadvantage). Following this literature, we aim to account for the multiple barriers to Arctic shipping, including the following:

- Limited duration of the navigable season on NSR compared with SSR
- Considerable year-on-year variations in the length of the navigable season
- Volatility of the navigability within a season due to unpredictable weather and ice patterns, threatening the reliability of timely delivery
- Ice reinforcements in different ship classes (ICE 1 to 3, Arc 4 to 9 and Icebreaker 7 to 9) leading to higher investments into new fleet and increased fuel consumption on SSR
- Cost increases for insurance and crew
- The need for icebreakers in the outer window navigation regime, leading to waiting time for a convoy to form and payment of fees for icebreakers[4]
- Lower navigation speeds in the presence of sea ice and in nearly ice-free Arctic waters in general, which decreases time savings but also reduces fuel consumption
- Limitations for economies of scale because of shallow straits and the maximum width of the then available icebreaker fleet
- Lower number of ports and markets on NSR compared with SSR (which negatively affects the average utilisation of capacity).[5]

None of these restrictions are considered in the estimates by Bekkers et al. (2016), indicating that the latter represent the likely upper bound. Only one factor acts to further increase the Bekkers' estimates: waiting time at the Suez Canal.

Following Hansen et al. (2016), we consider three consecutive phases within each navigation season: the first and the last few weeks of the season when sea ice concentrations are significant and icebreakers are required to escort the ships, which we refer to as *outer navigability window*, and the height of the season when sea ice concentrations are residual and only limited assistance is required, which we refer to as *inner navigability window*. The section of NSR with significant sea ice concentrations during the outer window regime is called *ice water distance* (around 1200 nm at present); it shortens as the sea ice retreats and then becomes longer again when the ice grows back within each season. We assume further that no icebreakers are required in the inner window, with limited ice strengthening being sufficient for navigating through the nearly ice-free waters with a reduced speed imposed for safety reasons.

At present, most of the navigable days for NSR occur around the September ice minimum and belong to the outer navigability window regime. As the climate warms and sea ice retreats, the inner window opens in the month of September, while the outer window regime moves to August and October, and so on. To describe the likely evolution of the two navigability windows as well as the ice water distance, we developed our own semi-empirical deterministic model for the total area of Arctic sea ice in response to changes in global mean temperature, based on the analysis of the sea ice futures in CMIP5 models (Stroeve et al. 2012a; Hezel et al. 2014). A detailed description of the model is provided in ESM-2, along with an overview of the literature on sea ice modelling for Arctic shipping routes (Smith and Stepherson 2013; Aksenov et al. 2016; Bensassi et al. 2016). The model generates a deterministic proxy for the total area (million km^2) of Arctic sea ice on any day of the year under a given future global mean temperature rise T above the CMIP5 base period (1986–2005), denoted as $A(day, T)$,

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[4] Waiting time and payment of fees also apply at the Suez Canal, suggesting that duopolistic competition between ice-breaker assistance and the Suez Canal may develop. This effect is not included in our estimates.
[5] With higher average utilisation rates for the traffic from Asia to Europe than from Europe to Asia, ice-strengthened vessels could take the SSR on the latter trip to optimise profits. This effect is not included in our estimates.

which is assumed to be correlated with sea ice conditions on NSR (Figs. 2.5 and 2.6 in ESM-2). The temperature could be translated into future years if a global emissions scenario is specified. The sea ice proxy does not account for stochastic effects associated with natural variability and, therefore, should be treated as a *representative trend* only.

We impose additional restrictions on the fleet capable of passing through the Sannikov and Dmitry Laptev straits (Buixadé Farré et al. 2014) and group all the ships into four main categories according to the cargo and size accordingly: <2500 and >2500 TEU *container ships* and <50,000 and >50,000 DWT *non-container ships* (mostly tankers and bulkers).[6] To accommodate the larger ships, a *second route* located to the north of the islands along the Arctic part of NSR is introduced, which is assumed to have no bathymetry restrictions on the size of the ships but has less favourable sea ice conditions compared with the first route (ESM-2).

The downscaling method applied in this study is described in detail in ESM-5, and the resulting maximum traffic through NSR (both routes) as determined by the sea ice conditions is plotted in Fig. 1 (dashed lines) as a function of time under RCP8.5 and RCP4.5 for each of the four ship categories, scaled relative to Bekkers' full navigability conditions. The maximum traffic follows a characteristic nonlinear pattern, with faster initial growth in navigability during the next two decades determined by the underlying seasonal behaviour of the declining sea ice.

Despite the seemingly favourable near-term navigability trend dictated by sea ice retreat from NSR around the month of September in the coming two decades, the shipping companies are not going to invest into large-scale operations along NSR until profitability conditions are met, which we define as a *trigger point*. The business model by Hansen et al. (2016), which has been made available publically,[7] calculates the timing of this trigger point for container ships under three contrasting fuel price scenarios. We adapted this model to include our own estimates for the navigability windows, ice water distances, uptake-dependent trends in icebreaker waiting times and differentiation between ship types, keeping all other parameters unchanged. The differentiation between container and non-container shipping was made by assuming that (i) container ships only take NSR during the *inner navigability window* regime due to their higher reliability requirements and (ii) non-container ships are not affected by the lower average capacity utilisation on NSR because commodity shipments tend to be contracted well in advance.

For the first route that passes through the straits (and therefore limited to ships under 50,000 DWT/2500 TEU), operations are expected to become profitable around year 2035 (2038) for non-container ships and 2051 (2118) for container ships under RCP8.5 (RCP4.5). At these trigger points, investments in ice-resilient vessels are expected to take off.[8] We assume that only newly introduced vessels as well as the existing vessels which require replacement are ice-strengthened in the years after the trigger point. It thus takes up to three decades for the full amount of ice-resilient fleet to be introduced. As a result, the traffic along the first route reaches its maximum possible value as determined by sea ice conditions around 2070 (2140) under RCP8.5 (RCP4.5). The second route, which bypasses the straits and

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[6] The abbreviations TEU and DWT stand for "twenty-foot equivalent unit" and "deadweight tonnage".

[7] http://www.cbs.dk/viden-samfundet/business-in-society/cbs-maritime/downloads

[8] Our approach is more conservative than that of Hansen et al. (2016), who consider feasibility based on a net present value calculation over the whole lifetime of a ship. This implies that shipping operators would also invest in ice resilience if this means operating at a disadvantage for several years in order to be able to obtain the advantages for the remaining lifetime of the ship, while we assume that the operators will only invest when re-routing is profitable in the first year of operations.
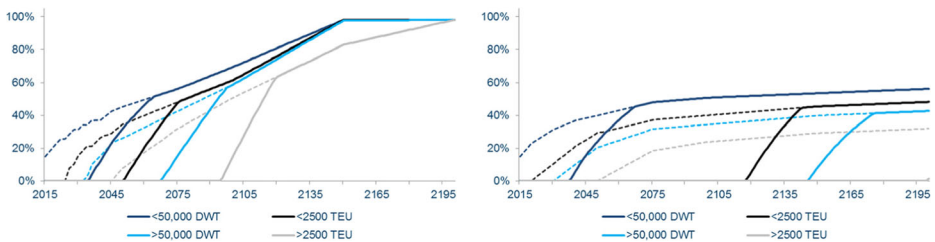
Fig. 1 NSR re-routing of four ship categories under RCP8.5 (*left plot*) and RCP4.5 (*right plot*), expressed as a percentage of the actual number of ships that re-route in each future year relative to the case of full navigability. The actual utilisation is determined by the sea ice conditions (*dashed lines*), trigger points (the *intersections of the continuous line with the X*-axis) and ship renewal rates (the *steep parts of the continuous lines*). The abbreviations for ship sizes are explained in the text (Section 2)

therefore has no tonnage restrictions, becomes profitable around year 2068 (2146) for non-container and 2095 (N.A.) for container ships under RCP8.5 (RCP4.5) (Fig. 1). The aggregate traffic (tons) from all four ship categories is plotted in Fig. 5.6 (ESM-5) for RCP8.5 and RCP4.5 relative to Bekkers' full navigability. The trigger points for each ship class under each RCP represent averages between the three contrasting fuel price scenarios in the otherwise deterministic model by Hansen et al. (2016).

In addition to the navigability and business restrictions described above, the trade shift towards NSR in future years until 2200 is scaled according to the expected long-term growth in global trade under the default SSP2 scenario for global GDP growth (ESM-3). We also account for the predicted decrease in the relative contributions of East Asia and EU to the future global GDP under SSP2, which is going to reduce trade volumes both through NSR and the Suez Canal route (ESM-3). The multiple downscaling steps produce a new and more realistic estimate of the optimal NSR traffic in terms of the actual number of ships for every year until 2200, which then allows us to work out the resulting emissions as well as the economic gains from NSR.

3 Economic impact of the climate feedback due to emissions from NSR shipping

First, we translate the projected re-routing of traffic from SSR to NSR into changes in fuel consumption patterns based on the latest fuel use estimates from Hansen et al. (2016) and IMO (2014) (ESM-7). This allows us to apply recent atmospheric chemistry results from Fuglestvedt et al. (2014) to convert the growing fuel consumption on NSR into net global equivalent RF from SLCFs such as sulphate aerosols and black carbon emitted by the ships (ESM-8). The reduction in the global shipping emissions due to the geographic redistribution of traffic from SSR to NSR is going to have a mixed effect on the net global RF from SLCFs, dominated by the following drivers: less cooling from sulphates and indirect aerosols and more warming from black carbon. As a result, SLCFs are expected to lead to the overall warming globally following the growth in Arctic shipping. We apply additional corrections to account for the effect of reduced ton-kilometre (Bekkers et al. 2016) and slow steaming on the Arctic part of NSR (Hansen et al. 2016) on the RF from SLCFs.

We then estimate the decrease in CO_2 emissions due to less ton-kilometre and slow steaming on NSR, as well as the additional indirect CO_2 and non-CO_2 emissions from the NSR-driven economic growth in Europe and East Asia (Bekkers et al. 2016) (ESM-9). All

these effects contribute to the total climatic feedback of NSR, which is analysed using the latest version of the PAGE IAM called PAGE-ICE.

The PAGE model splits the world into eight large geopolitical regions: EU, US, other OECD countries (OT), former Soviet Union (EE), China+ (CA), India+ (IA), Africa and Middle East (AF) and Latin America (LA). It estimates climate-driven impacts in each region across four broad categories: sea level rise (coastal flood damage, relocation), economic (both direct and indirect damages to the aggregate economy), non-economic (ecosystems services, public health) and discontinuity (large-scale damages associated with a number of possible tipping points in the climate and economy). Anthropogenic GHG emissions are split into six main classes: CO_2, CH_4, N_2O, linear gases, sulphates and the rest of GHGs combined (including BC), and follow IPCC scenarios (SRES or RCPs) extended until year 2200. A simple aggregate climate model is used to link the emissions with global temperature rise, which is then scaled for each of the eight regions and is also used to drive sea level rise as well as the discontinuity impacts.

The rise in regional temperatures serves as a basis for evaluating economic and non-economic impacts, which are calculated as percentage loss/gain of the relevant regional/global GDP in a given future year, and are subtracted from consumption only; endogenous effects on economic growth are not considered in the default model setting. Future GDP and population projections in the eight world regions follow exogenous scenarios from IPCC (SRES or SSPs). The impacts depend on the increases in the regional temperatures and sea level relative to the corresponding tolerable levels determined by the choice of adaptation spending in each of the eight regions. The regional impacts are equity-weighted depending on the relative wealth and are discounted to the base year (2013 in the default setting). The multiple uncertainties in the global climate and economy are accounted for by performing Monte Carlo simulations, with over 100 uncertain inputs such as climate sensitivity to CO_2, discount rates and convexity of the damage functions calibrated using expert climate and economic models. Due to the limitations of the data, especially when it comes to estimating the impacts of climate change on the economy, most of the input probability distributions are subjective. All the outputs are also in the form of probability distributions. A detailed technical description of the PAGE model is provided in Hope (2006, 2013).

PAGE-ICE is based on the PAGE09 model. It includes a number of updates both in natural science and economics based on IPCC AR5 (2014): RCP8.5 and 4.5 scenarios for the emissions, SSP2 scenario for the GDP and population growth, regional temperature amplification factors based on CMIP5 climate models, fat-tailed risk in the sea level rise (corresponding to rapid collapse of the ice sheets), adjusted discontinuity impacts and nonlinearities in Arctic sea ice decline (Yumashev et al. 2016).

In this study, we use PAGE-ICE to conduct the sensitivity analysis of the global climate and economy to the additional warming caused by direct and indirect emissions due to NSR shipping. This allows us to estimate the relevant economic losses in the eight regions of the PAGE model as well as globally. To compare these losses with the relevant macroeconomic gains in Asia and Europe due to the enhanced trade (estimated by Bekkers et al. 2016 using a CGE model), we calculate net present values (NPVs) by aggregating the relevant discounted cash flows over the period between 2013 and 2200.

The additional climatic effect of NSR is added on top of the chosen RCP scenario to one of the two broad policy options in PAGE-ICE, either in the form of global equivalent RF (SLCFs from shipping) or as annual emissions (CO_2 from shipping and indirect GHG emissions due to the economic growth), and the resulting difference in the climatic and economic impacts is

calculated in the end of each Monte Carlo run. This net climatic effect, along with the marginal economic growth due to the enhanced trade, is modelled as deterministic time series that is imported into PAGE-ICE. Of course, each step in our calculations, be it the sea ice projections, the trigger points for the re-routing or the macroeconomic response to the new route, is characterised by high levels of uncertainty. Modelling these uncertainties is beyond the scope of the present study, and therefore, we opted to work with deterministic projections for the effects of NSR while keeping the default probabilistic structure of the PAGE model. To acknowledge the partial nature of the uncertainty representation in our work, the results of PAGE-ICE calculations are presented as mean values only.

Running PAGE-ICE with the projections for the emissions and economic gains discussed in the previous sections and described in detail in the Electronic supplementary materials, we find that the total climate feedback of NSR could contribute 0.05% (0.04%) to global mean temperature rise by 2100 under the RCP8.5 (RCP4.5) climate change scenario, adding $2.15 trillion ($0.44 trillion) to the NPV of total impacts of climate change over the period until 2200 for the SSP2 socio-economic scenario. The climatic losses offset 33% (24.7%) of the total economic gains from NSR under RCP8.5 (RCP4.5), with the biggest losses set to occur in Africa and India. This pattern is associated with high present-day levels of poverty, fast economic and population growth projected to persist for several decades and extreme future temperatures due to climate change in these regions (Hope 2013).

The total GDP gains amount to $6.5 trillion ($1.8 trillion). Nearly two thirds of these gains are set to occur in China, while the EU could account for around a quarter, leaving the bulk of the remaining gains to Japan and South Korea. The regional breakdown of the losses and the gains due to NSR is shown in Fig. 2 both for the RCP8.5 and RCP4.5 scenarios. The considerable restrictions on the use of NSR that persist under the medium climate mitigation scenario RCP4.5 mean that the economic gains under this scenario are around 3.5 times less than under RCP8.5. At the same time, the losses are almost 5 times less than for RCP8.5, which is due to the reduced marginal impact of emissions under RCP4.5.

Of the total climatic losses due to NSR, the indirect GDP-driven GHG emissions account for around 4% (1.5%) under RCP8.5 (RCP4.5), while the reductions in CO_2 due to less ton-kilometre and slow steaming cut the losses by 3% (both RCPs). Therefore, SLCFs from
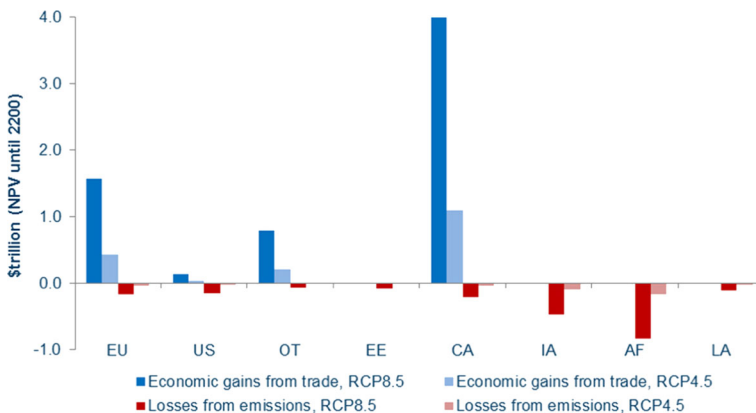
Fig. 2 Economic gains and losses due to NSR (NPV until 2200) in eight world regions under RCP8.5 (*solid fill*) and RCP4.5 (*shaded fill*) climate change scenarios. Emissions: all SLCFs and CO_2 from shipping plus GDP-driven GHGs. Economic scenarios used: SSP2. The regional abbreviations are explained in the text (Section 3)

Table 1 Summary of the results for the climatic losses, gross economic gains and net economic gains from NSR (NPV until 2200) under RCP8.5 and RCP4.5 scenarios for the climate and SSP2 scenario for the economy. The individual contributions to the losses caused by each of the three main sources of emissions are also listed

	Climate losses	Gross gains	Net gains
Total NSR impact, RCP8.5-SSP2	$C = -\$2.15$ trillion	\$6.51 trillion	\$4.36 trillion
SLCF shipping emissions	98.30% of C		
CO_2 shipping emissions	-3.04% of C		
GDP-driven GHG emissions	4.17% of C		
	Climate losses	Gross gains	Net gains
Total NSR impact, RCP4.5-SSP2	$C = -\$0.44$ trillion	\$1.78 trillion	\$1.34 trillion
SLCF shipping emissions	102.36% of C		
CO_2 shipping emissions	-2.97% of C		
GDP-driven GHG emissions	1.43% of C		

shipping account for around 98% (102%) of the total losses under RCP8.5 (RCP4.5),[9] highlighting the importance of moving short-lived pollutants like black carbon and sulphate aerosols into climatically sensitive areas such as the Arctic. The results for the economic losses and gains from NSR are summarised in Table 1.

4 Conclusions and policy implications

A comprehensive assessment of the net economic benefits associated with commercial shipping through the Arctic should include the underlying "hidden" climate costs from the resulting emissions together with an analysis of regional disparities between benefits and costs. In addition to the complex effects of emissions of SLCFs and CO_2 directly from the shipping re-routing through the Northern Sea Route, the marginal economic growth in multiple countries enabled by NSR is set to increase their CO_2 and non-CO_2 emissions.

Using a combination of specialised models, including a business case model for shipping firms by Hansen et al. (2016), we found that according to the latest knowledge on Arctic sea ice futures, as well as on business restrictions facing shipping operators in the region, large-scale commercial shipping through NSR is unlikely going to be possible until mid-2030s for bulk carriers and around 2050 for container ships of small to medium size (<50,000 DWT/<2500 TEU) even under the highest global emissions scenario (RCP8.5). Larger ships have to use alternative routes that bypass the narrow straights, and will therefore take another three to four decades to start re-routing relative to the smaller ships. Under a medium climate mitigation scenario (RCP4.5), small bulk carriers are set to start re-routing in late 2030s, but small container ships may not be able to re-route until the early parts of the twenty-second century, and large bulk carriers may have to wait until mid-twenty-second century. It is unlikely that large container ships may be able to re-route at all under RCP4.5.

Emissions of SLCFs such as sulphate aerosols and black carbon from the re-routing traffic were translated into net RF gains using recent atmospheric chemistry modelling results from Fuglestvedt et al. (2014), while we relied on macroeconomic modelling results from Bekkers et al. (2016) to estimate the effect of NSR on CO_2 emissions from shipping and on GDP-

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[9] Climatic losses are characterised by a nonlinear response to emissions (Stern 2007; Hope 2013). Therefore, the individual impacts from each component of the emissions separately do not add to the total impact from all the components combined.

driven GHG emissions in Europe and East Asia. The total emissions associated with NSR were then translated into marginal increases in global mean temperature, regional temperatures and sea level and subsequently into additional climate-driven losses to the global and regional economies using the PAGE-ICE integrated assessment model. Our results suggest that the climate feedback from NSR can add an extra $2.15 trillion (NPV) to the expected total negative impacts of climate change globally over the period until 2200 under the RCP8.5 and SSP2 scenarios ($1400 trillion, NPV). This is likely going to offset around a third of the expected global gross economic gains associated with NSR over the same period ($6.5 trillion, NPV). The gains will mostly occur in Northern Europe and East Asia, and these regions will likely face relatively small climate losses from the additional emissions. The negative economic impacts of the emissions from NSR shipping, on the other hand, are expected to follow the commonly accepted scenario for climate-induced losses, with poorer regions such as Africa and India set to bear as much as two thirds of the global costs. The most striking picture is for Africa where the losses ($0.84 trillion, NPV) are comparable to the net gains in Japan and South Korea (Fig. 2).

Reducing global emissions by following a moderately ambitions mitigation scenario RCP4.5 will preserve significant amounts of seasonal sea ice, which will limit the long-term NSR use to only around 30% of the use under the full navigability assumption for the entire period under consideration (until 2200). The NPV of the economic gain from NSR under RCP4.5 will be around 3.5 times less compared with RCP8.5, but the climate impact from the emissions will be almost 5 times lower due to the reduced marginal impact of emissions under RCP4.5. Therefore, even though global mitigation efforts will limit the growth in Arctic shipping, they will have a considerably stronger effect on reducing the negative impacts associated with the emissions.

The results presented in this paper are based on a number of simplifying assumptions such as the semi-empirical model for the sea ice decline, the idealised representation of the Arctic shipping routes and the sea ice thresholds required for the navigability, the simplified forecast for future development of global trade and the empirical extrapolation of the existing results for the RF from SLCFs to future climates. Most importantly, our estimates do not account for the multiple layers of uncertainty associated with the future use of NSR and its impact on climate and economy. While these assumptions are justifiable for the purposes of the present study, further methodological advances aimed at making its many components both more realistic and more interlinked are necessary in subsequent research.

The possibility that the losses due to emissions from Arctic shipping could offset a significant part of its economic gains suggests that the economic scope for emission mitigation policies, both technological and regulatory, can be substantial. Due to the regional disparity between economic benefits and costs of increased Arctic shipping, more social science research is required to identify relevant policy options in order to address economic inequities of such effects globally. A number of strategies could be considered, for example regulating emission levels, imposing obligatory slow steaming areas (with co-benefits through increased safety), taxing emissions or incentivising cleaner shipping. Examples of such actions already exist in other parts of the world, such as Emission Control Areas in the Baltic and North Sea, the EEDI and SEEMP agreed at the IMO level and R&D support to promote the development of green shipping technologies within Europe and elsewhere. A (global) tax on CO_2, BC and other pollutants may be an effective market-based mechanism, but as for other global actions, agreements on taxation at a world level are not easy to achieve and would require detailed analysis of the feasibility (e.g. what level of charge would be needed, how to levy it, what to use the revenues for) as well as of the trickle-down economic effects.

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