

# *Sea ice decline and 21st century trans-Arctic shipping routes*

Article

Published Version

Creative Commons: Attribution 4.0 (CC-BY)

Open access

Melia, N., Haines, K. ORCID: <https://orcid.org/0000-0003-2768-2374> and Hawkins, E. ORCID: <https://orcid.org/0000-0001-9477-3677> (2016) Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, 43 (18). pp. 9720-9728. ISSN 1944-8007 doi: <https://doi.org/10.1002/2016GL069315> Available at <https://centaur.reading.ac.uk/66509/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1002/2016GL069315>

Publisher: American Geophysical Union

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

[www.reading.ac.uk/centaur](http://www.reading.ac.uk/centaur)

**CentAUR**

Central Archive at the University of Reading

Reading's research outputs online

## RESEARCH LETTER

10.1002/2016GL069315

## Special Section:

The Arctic: An AGU Joint  
Special Collection

## Key Points:

- Arctic shipping routes to open more frequently and become increasingly faster due to shorter distances and thinner ice
- Considerable interannual variability in sea route accessibility will be present for the whole 21st century
- Arctic sea route projections use calibrated sea ice results with improved spatial sea ice distributions

## Supporting Information:

- Supporting Information S1

## Correspondence to:

N. Melia,  
n.melia@reading.ac.uk

## Citation:

Melia, N., K. Haines, and E. Hawkins (2016), Sea ice decline and 21st century trans-Arctic shipping routes, *Geophys. Res. Lett.*, 43, 9720–9728, doi:10.1002/2016GL069315.

Received 28 APR 2016

Accepted 21 AUG 2016

Accepted article online 23 AUG 2016

Published online 20 SEP 2016

©2016. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

## Sea ice decline and 21st century trans-Arctic shipping routes

N. Melia<sup>1</sup>, K. Haines<sup>2</sup>, and E. Hawkins<sup>3</sup>
<sup>1</sup>Department of Meteorology, University of Reading, Reading, UK, <sup>2</sup>National Centre for Earth Observation, Department of Meteorology, University of Reading, Reading, UK, <sup>3</sup>NCAS-Climate, Department of Meteorology, University of Reading, Reading, UK

**Abstract** The observed decline in Arctic sea ice is projected to continue, opening shorter trade routes across the Arctic Ocean, with potentially global economic implications. Here we quantify, using Coupled Model Intercomparison Project Phase 5 global climate model simulations calibrated to remove spatial biases, how projected sea ice loss might increase opportunities for Arctic transit shipping. By midcentury for standard open water vessels, the frequency of navigable periods doubles, with routes across the central Arctic becoming available. A sea ice-ship speed relationship is used to show that European routes to Asia typically become 10 days faster via the Arctic than alternatives by midcentury, and 13 days faster by late century, while North American routes become 4 days faster. Future greenhouse gas emissions have a larger impact by late century; the shipping season reaching 4–8 months in Representative Concentration Pathway (RCP)8.5 double that of RCP2.6, both with substantial interannual variability. Moderately, ice-strengthened vessels likely enable Arctic transits for 10–12 months by late century.

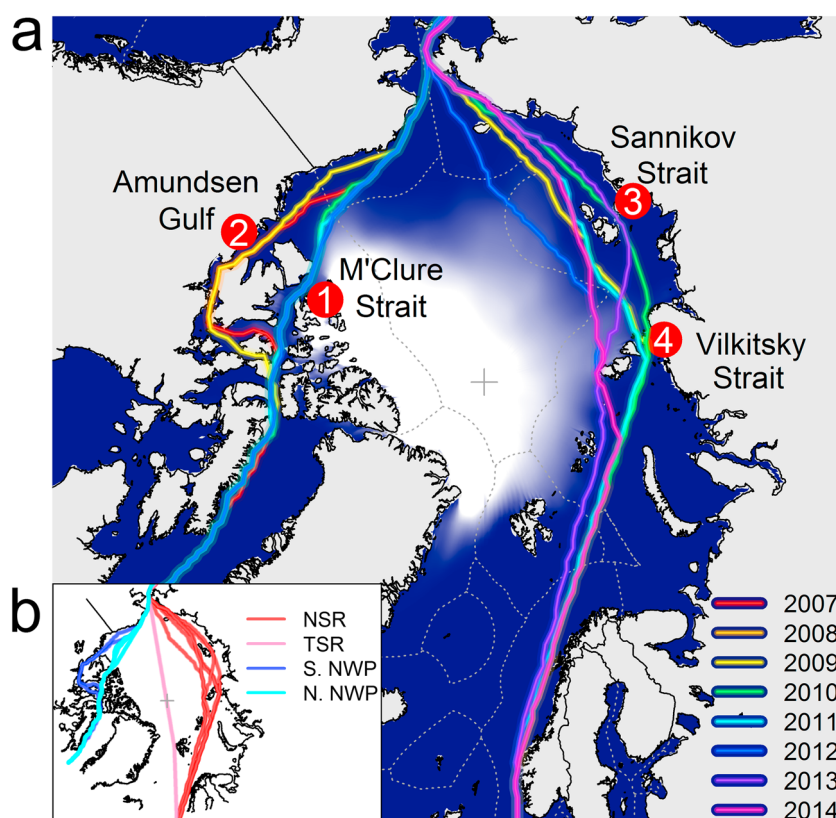
## 1. Introduction

Arctic shipping peaked during the 1980s due to continuous investment in ports and icebreakers by the Soviet Union maintaining the Northern Sea Route (NSR). Activity today is still mostly destination traffic, to and from ports within the Arctic [Eguiluz et al., 2016; Stephenson et al., 2013a]. However, the reduction in summer Arctic sea ice has led to increased interest in the possibility of transit shipping, using the Arctic Ocean as a shortcut between Pacific and Atlantic ports. The substantial reductions in distance compared with Suez and Panama Canal routes could result in large cost savings due to reduced fuel consumption and increased trip frequency [Lasserre, 2014]. This was one reason that major shipping nations such as China, Japan, Singapore, and South Korea sought observer status to the Arctic Council [Bennett, 2014]. Shorter shipping routes also have the potential to reduce global shipping emissions with negligible increase in high-latitude black carbon deposition [Browse et al., 2013].

Currently, the fastest available routes between North Atlantic and Asian Pacific ports for nonspecialized (or open water (OW)) vessels are along the NSR and North West Passage (NWP) (Figure 1a; also see supporting information). Voyage statistics for the NSR and NWP show increasing traffic [Eguiluz et al., 2016] although trans-Arctic voyage numbers are more modest [Moe, 2014] with considerable interannual variability from years when the NWP is open, but not the NSR, and vice versa (Figure 1a). For example, 2007 had the second lowest ice extent on record; however, the NSR was blocked by ice protruding from the main ice pack toward Russia, illustrating that reduced sea ice extent does not necessarily guarantee open routes.

Nonstop sailings from Europe to East Asia currently take 30 days via the Suez Canal; voyages from North America via the Panama Canal take 25 days (see section 2). Here we examine how uninterrupted voyages from Yokohama (representing East Asian ports) to Rotterdam (representing European ports) and New York (representing North American ports) may change over the 21st century through utilizing trans-Arctic routes whenever possible. Many operational factors also affect route choice (e.g., cargo type, intermediate destinations, fuel price, insurance premiums, and draft restrictions); here we focus solely on the sea ice, the biggest physical hazard for Arctic shipping. This study assesses solely the changes to the Arctic sea ice and the consequent increased opportunities for shipping in the region. Other logistic, economic, and geopolitical factors will also influence future trade route choices [Arctic Marine Shipping Assessment, 2009; Hansen et al., 2016].

We utilize simulations from several global climate models (GCMs), each with multiple ensemble members, from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [Taylor et al., 2012]. We note



**Figure 1.** (a) Hypothetical open water vessel routes sailing through the September sea ice thickness field for eight recent years from the Pan-Arctic Ice Ocean Modelling and Assimilation System (PIOMAS) reanalysis [Zhang and Rothrock, 2003]. Routes only plotted when Arctic transits are possible. 1: The M'Clure Strait, the shortest North American route, the northern NWP. 2: Amundsen Gulf, the longer southern NWP. 3: Sannikov Strait. 4: Vilkitsky Strait. (b) Main Arctic transit options.

that simulating robust ice dynamics is challenging at current GCM spatial resolutions, particularly in the Canadian Archipelago; however, each GCM has undergone bias correction to calibrate performance against recent higher-resolution Sea Ice Thickness (SIT) data [Melia *et al.*, 2015]. This calibration is crucial as each GCM contains biases in the spatial distribution and interannual variability of SIT, which strongly influence regional ice patterns along sea routes. Previous Arctic shipping studies have not used such calibration and therefore produce projections that are primarily model dependent [Stephenson and Smith, 2015], masking the roles of interannual variability and future emission scenarios [Melia, 2016]. The calibration approach used here reduces intermodel variations of future sea ice [Melia *et al.*, 2015]. Interannual variability is sampled using multiple ensemble members from each calibrated GCM, allowing uncertainty to be better quantified than only using single simulations, multimodel means, and multiannual means used previously [Khon *et al.*, 2010; Rogers *et al.*, 2013; Stephenson *et al.*, 2011, 2013b]. We also consider the entire seasonal cycle throughout the 21st century, capturing the future lengthening of the shipping season.

Future climate change scenarios are denoted by Representative (greenhouse gas) Concentration Pathways (RCPs) that diverge after 2006 [Van Vuuren *et al.*, 2011]. RCP8.5 is the highest-emission pathway, roughly equivalent to a global mean temperature increase of  $4.3 \pm 0.7^\circ\text{C}$  from preindustrial by 2100; RCP2.6 is the lowest-emission pathway with global mean temperatures stabilizing at  $\sim 1.6 \pm 0.4^\circ\text{C}$  above preindustrial, consistent with the recent United Nations Paris (COP21) targets [Hulme, 2016; Intergovernmental Panel on Climate Change, 2013]. Results from RCP4.5 ( $\sim 2.4 \pm 0.5^\circ\text{C}$ ) are also presented. The prospects for two vessel classes are assessed: OW vessels with no specific ice strengthening and polar class six (PC6) vessels with a 20% capital cost premium [Lasserre, 2014] but capable of operation in medium first-year ice.

**Table 1.** List of GCMs Qualifying for Future Shipping Analysis

Institution	GCM Name: <i>Abbreviation</i> [Literature]
Met Office Hadley Centre	Hadley Centre Global Environment Model version 2-Earth System: <i>HadGEM2-ES</i> [The <i>HadGEM2 Development Team et al.</i> , 2011]
National Center for Atmospheric Research	Community Climate System Model, version 4: <i>CCSM4</i> [Gent et al., 2011; Vavrus et al., 2012]
National Center for Atmospheric Research	Community Earth System Model, Community Atmosphere Model, version 5: <i>CESM1-CAM5</i> [Meehl et al., 2013]
Model for Interdisciplinary Research on Climate (MIROC)	MIROC version 5: <i>MIROC5</i> [Watanabe et al., 2010]
Max Plank Institute for Meteorology (MPI)	MPI Earth System Model, low resolution: <i>MPI-ESM-LR</i> [Jungclaus et al., 2006]
Applied Physics Laboratory (University of Washington)	Pan-Arctic Ice Ocean Modelling and Assimilation System: <i>PIOMAS</i> <sup>a</sup> [Zhang and Rothrock, 2003]

<sup>a</sup>Only used as reanalysis for GCM calibration.

## 2. Calculating Shipping Routes

The European route assumed is Rotterdam to Yokohama (NSR: 6930 nautical miles, ~18 days, Suez: 11,580 nautical miles, ~30 days), and the North American Route is New York to Yokohama (NWP: 7480 nautical miles, ~21 days, Panama: 9720 nautical miles, ~25 days). Sailing times are calculated using 16 knots in open water and slower in sea ice, using vessel speed data as detailed by Tan et al. [2013] (Figure S1). We omit delays and extra time required to navigate the Canals which can be considerable.

The Canadian Coast Guard's Arctic Ice Regime Shipping System [Transport Canada, 1998] defines the capability of vessel classes to enter into ice of a certain thickness and age, generating a SIT threshold of 0.15 m for OW and 1.2 m for PC6 vessels. This system is one of the few outlined in the new International Maritime Organization's Polar Code, designed for safe Arctic navigation to be used by operators to demonstrate that adequate measures have been met to operate in Arctic waters [International Maritime Organization, 2015]. A ship-routing algorithm with the SIT-vessel speed relationship [Tan et al., 2013] is used to find the fastest Arctic route allowing statistics of transit time savings to be presented. The SIT from all ensemble members is converted to an effective ice resistance for the vessels ice class given by the reciprocal of the vessel speed through that grid cell's SIT. A least cost path algorithm [Dijkstra, 1959; Van Etten, 2015] is then implemented to calculate the route between two points that accumulates the lowest total time, which because of the SIT-speed substitution is the fastest route.

## 3. GCM Selection and Calibration

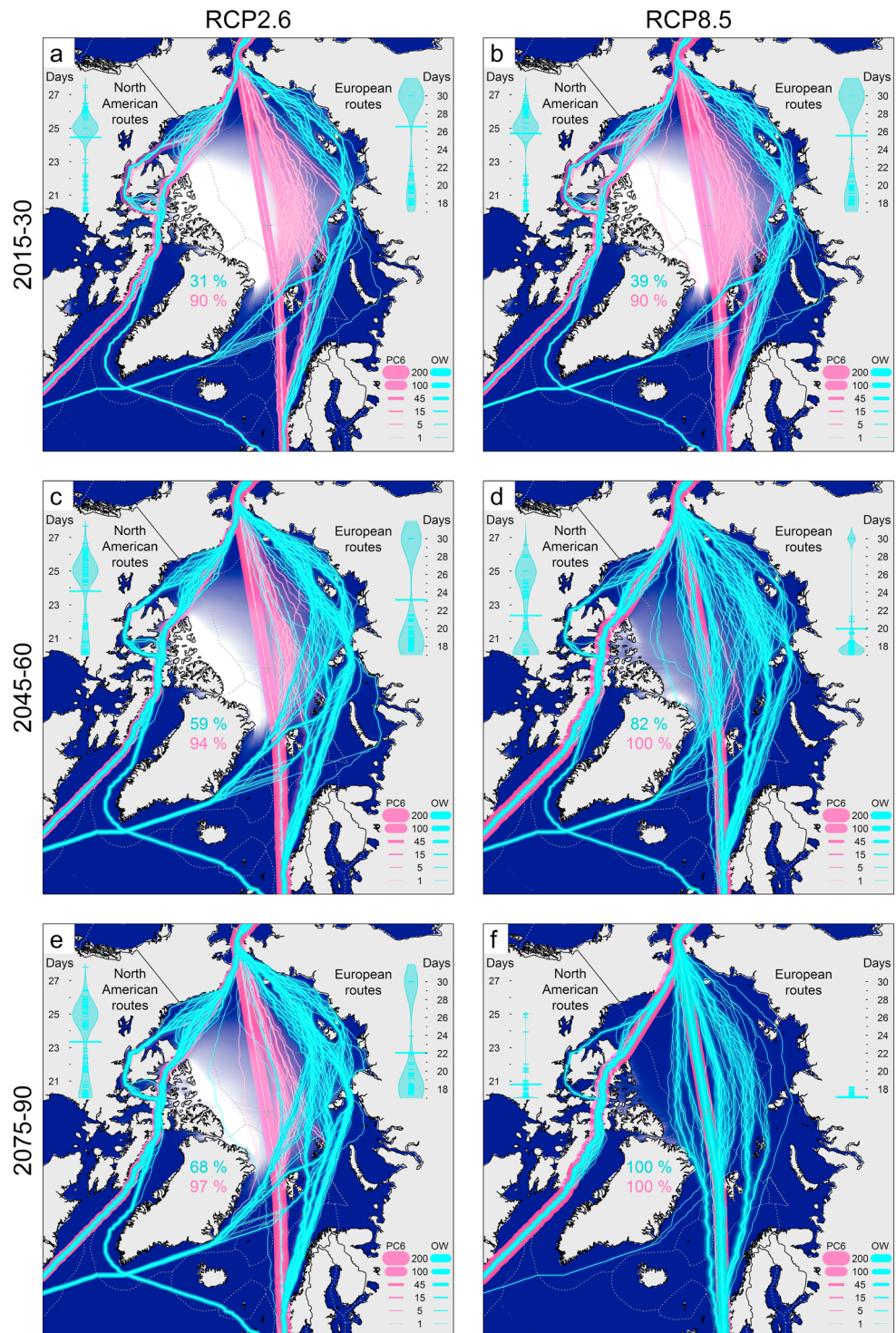
To adequately sample internal variability and scenario uncertainty, we select GCMs with at least three ensemble simulations in the historical period and for each of the RCP2.6, RCP4.5, and RCP8.5 scenarios [Van Vuuren et al., 2011]. In addition, the GCMs must have an adequate spatial resolution to resolve the major islands and straits in the Russian Arctic and Canadian Archipelago for realistic ship routing. The five qualifying GCMs (Table 1) are calibrated to the SIT statistics of the Pan-Arctic Ice Ocean Modelling and Assimilation System (PIOMAS) reanalysis [Zhang and Rothrock, 2003] from the period 1995–2014, utilizing three ensemble members from each model, in accordance with work from Melia et al. [2015]. The method benefits from utilizing ensemble members to calibrate the GCM's mean response rather than each individual member's response, allowing ensemble spread to evolve smoothly to give future uncertainty estimates.

The calibration accounts for the considerable biases in the spatial distribution [Stroeve et al., 2014a] and variability of sea ice that have led to considerable intermodel spread in previous studies of future Arctic marine access, as analyzed in depth by Stephenson and Smith [2015]. The Mean and Variance Correction (MAVRIC) developed in Melia et al. [2015] constrains the spatial SIT distribution and temporal variability in the CMIP5 projections by separating mean and variance calibrations, whereby  $\text{MAVRIC} = \text{mean} \cdot A + \text{anomaly} \cdot B$ . The calibration parameters,  $A$ ,  $B$ , act to reduce the spread in projections of SIT while retaining the climatic fluctuations from individual ensemble members (see Melia et al. [2015] for details).

## 4. Faster 21st Century Trans-Arctic Routes

Early century projections (2015–2029, Figures 2a and 2b) show that Arctic OW vessel transits are possible for at least 30% of Septembers. European routes take a minimum of 18–19 days to East Asia using the NSR, with “switch transits” (i.e., when the NSR is blocked and the NWP is utilized instead), taking 20–22 days. North





**Figure 2.** Fastest available September trans-Arctic routes from multimodel projections. Routes for RCP2.6 (a, c, and e) and RCP8.5 (b, d, and f) split into three periods (rows), each containing 15 consecutive Septembers, from five GCMs each with three ensemble members, equating to 225 simulations per panel. Cyan lines represent open water vessels (OW), and pink lines represent Polar Class 6 vessels (PC6); line weights indicate the number of transits using the same route. Dashed grey lines indicate the Exclusive Economic Zones. The percentages shown over Greenland (colored) represent the trans-Arctic potential for the two vessel classes. Inset “bean” plots show total transit time distributions for North American routes and European routes (New York, Rotterdam, and Yokohama endpoints are used). When Arctic routes are closed, routes through Panama (25 days) and Suez (30 days) Canals, respectively, are assumed (labeled red). Short lines indicate individual voyages, and long lines show the mean transit time for all voyages, with route time distribution indicated by envelope shape.

American voyages utilizing the fastest “northern NWP” route (through the M'Clure Strait; see Figure 1) take a minimum of 21 days, while the longer “southern NWP” (through the Amundsen Gulf) take 22 days, and switch transits via the NSR take 25 days. Early century switch transits comprise ~50% of trans-Arctic routes, illustrating the considerable spatial variability in ice conditions that can exist across the Arctic.

PC6 vessels have an early century transit potential of 90% (Figures 2a and 2b), due to their higher SIT threshold. They can also take advantage of shorter routes impassable to OW vessels, with the majority of simulated European voyages using variations of the Transpolar Sea Route (TSR); the majority of North American voyages use the shorter, northern NWP. In addition to the increased trip frequency, the range in PC6 Arctic voyage times is less than 1 day, compared with a range of 7 days for OW vessels. This consistency is advantageous as ports and shipping companies operate “just-in-time” schedules.

By midcentury (2045–2059, Figures 2c and 2d), irrespective of RCP, the September OW transit potential is projected to double. The TSR is available for the first time [Smith and Stephenson, 2013] and is 1–2 days faster than the NSR. The most common European route is a shorter version of the NSR, omitting the Vilkitsky and Sannikov Straits (see Figure 1a); this is potentially advantageous as the Sannikov Strait contains depth restrictions preventing its use for larger ships. North American routes can prefer the shorter northern NWP over the southern NWP, saving a day. In addition to greater potential utilization, there is also increased diversity in routing choices with large swathes of the Arctic now ice free in September. From midcentury, PC6 vessels may favor the shortest routes along the TSR (European, ~17 days) and the northern NWP (North American, ~20 days), for practically all Septembers.

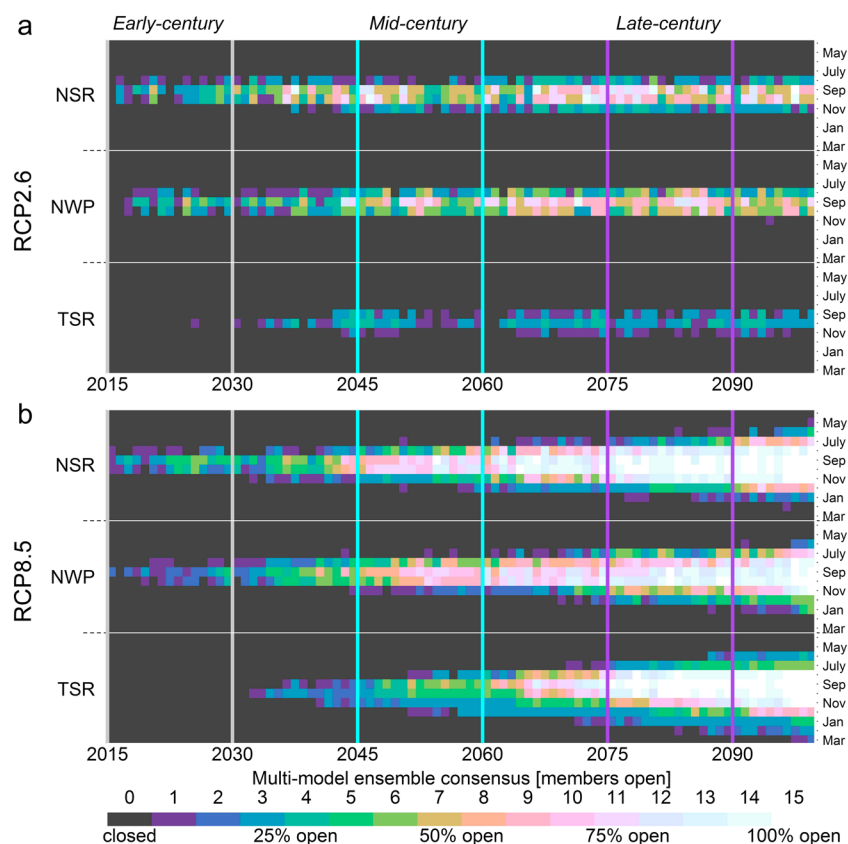
Late century (2075–2089) simulations suggest guaranteed September OW transits across a practically ice-free Arctic for RCP8.5 (Figure 2f). European voyages would favor the TSR taking as little as 17 days; North American voyages favor the northern NWP taking only 20 days. Under RCP2.6 (Figure 2e) European and North American routes are open 68% of the time in September, and take on average 18 and 21 days, respectively, with switch transits and all versions of the NWP and NSR still regularly needed.

By utilizing the Arctic routes shown in Figure 2 when possible, and using traditional European routes via Suez (minimum of 30 days) otherwise, average journey times to East Asia can be dramatically reduced. Savings are achieved as Arctic routes become more available and more direct and ice free through the century. In early century, the average minimum journey time for all European (Arctic + Suez) voyages using open water vessels is 26 days, which becomes 20 days by midcentury and 17 days by late century under RCP8.5. Under RCP2.6 the journey times are 23 days by midcentury and 22 days by late century. Savings are less striking for North America because the route via Panama takes a minimum of only 25 days (Figure 2). Sailing the NWP from North America to East Asia takes 20–22 days depending on channel choice and ice conditions, and when the NWP is impassable, using alternative Arctic routes via the NSR or TSR takes at least 24 days.

## 5. Shipping Season Extension and Variability

Transit conditions always remain optimal around September, but for trans-Arctic shipping to be viable, a longer Arctic shipping season is essential. By the end of the century the majority of the Arctic Ocean is expected to be open water for half the year [Barnhart et al., 2015; Laliberté et al., 2016]; however, GCMs project that the transition to a mostly ice-free Arctic may be nonlinear, with substantial interannual variability [Notz, 2015; Swart et al., 2015]. Figure 3 shows, for all months, the probability of the three trans-Arctic routes being open for OW vessels in RCP2.6 and RCP8.5. In current conditions the NSR is the most open route, followed by the NWP, while the TSR is inaccessible until the 2030s at the earliest. The broadening of the plumes with time illustrates the lengthening of the OW shipping season (PC6 figure in the supporting information). The NSR and NWP are only tentatively open August through October in early century, with the addition of November by midcentury. Under RCP8.5 (Figure 3b) the TSR opens rapidly during midcentury and by late century is open for up to 8 months of the year, consistently so from August through November.

The peak of the shipping season shifts with route choice and later into the century (Figure 4). The peak is mid-September for the NWP, late September for the NSR, and October for the TSR. However, the shipping season curves are skewed with longer tails (later season voyages) toward the end of the century; this is most evident



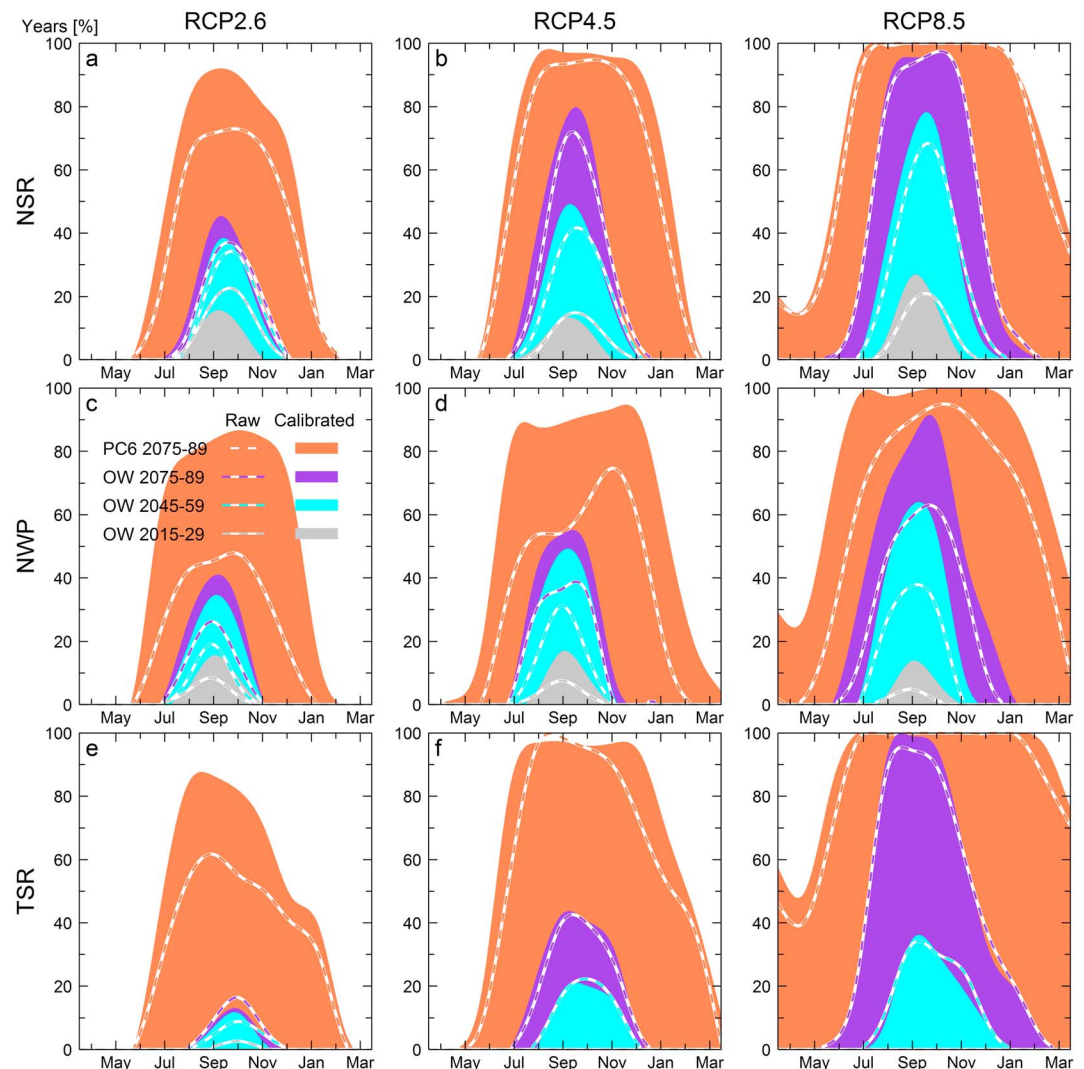
**Figure 3.** Year-round trans-Arctic projections for open water vessels. The different routes are shown in three horizontal bands for (a) RCP2.6 and (b) RCP8.5. Each route further splits into 12 rows representing each month, starting in April at the top, through to the minimum ice months in the middle, to the maximum ice month of March at the bottom. The colors represent the ensemble consensus or simply the number of ensemble members indicating an open route out of the 15 members available each year (three members  $\times$  five models) showing substantial interannual variability.

for the TSR in RCP8.5 (Figure 4f). Early century September conditions are equivalent to late century July/December conditions in RCP8.5 (RCP2.6, August/November). The medium-emissions RCP4.5 shipping season lies between RCP2.6 and RCP8.5. Figure 4 also shows the impact of the sea ice thickness calibration; the “raw” (uncalibrated—dashed lines) GCMs clearly underestimate the number of years open by up to 30%. The calibration also shifts the peak of the shipping season to earlier in the year. Note that Figures 3 and 4 use a set of fixed routes to calculate whether Arctic transits are accessible for computational efficiency (see supporting information).

## 6. Summary and Implications

The Arctic is in transition to a seasonally ice-free state, increasing economic opportunities to a niche commercial shipping market, with the opening of new and faster trans-Arctic routes, and an extended shipping season. By utilizing these Arctic routes when accessible, and using traditional European routes via Suez (minimum of 30 days) otherwise, average journey times to East Asia may be dramatically reduced. Average transit times may decline going through the 21st century to 22 days under the low-emissions RCP2.6 scenario or down to 17 days under high-emissions RCP8.5. Savings are less striking for North American routes because the distance saved via the Arctic relative to Panama is relatively modest. For a high-emissions scenario, by late century trans-Arctic shipping may be potentially commonplace, with a season ranging from 4 to 8 months. For a low-emissions scenario, with global mean temperature stabilization of less than 2°C above preindustrial, the frequency of open water vessel transits still has the potential to double by midcentury with a season ranging from 2 to 4 months.





**Figure 4.** Accessibility through the seasons as simulated by raw (dashed lines) and calibrated (shaded regions) GCMs for RCP2.6, RCP4.5, and RCP8.5 scenarios (columns). Colors represent time periods and vessel class, y axis percentage probability of Arctic transit. The season for the corrected GCMs (shaded regions) has clearly shifted from the raw ensembles. Month tick marks represent the middle of the month. A smoothed fit is applied to the monthly data.

These transit time differences are the potential average savings a shipping company would experience if they were to utilize trans-Arctic routes at every possible opportunity. The results have different implications depending on the destination port; for example, Arctic routes are slightly less advantageous for the more southerly port of Shanghai. For European voyages, trans-Arctic routes are faster when available as even using switch transit routes via the NWP is always considerably faster than traditional routes via Suez. For North American traffic, however, switch transits using the NSR actually take longer than traditional routes via Panama. Assuming efficient passage and short queues through the Canal, North American shipping is likely to stick to the Panama route. To make these decisions, however, requires detailed knowledge of the SIT at least a week in advance. Products like CryoSat-2 near-real-time SIT, typically available 1–3 days after satellite acquisition [Tilling *et al.*, 2016], could help with forecasts at shorter lead times.

The reduced transit times could lead to significant savings from increased voyage turnover and lower costs, in addition to potentially reducing global shipping emissions. As the TSR is the fastest and shortest route, and avoids Russian NSR tariffs, it may become an attractive alternative in the future. Companies wishing to utilize Arctic routes face choices about whether to invest in technologically advanced ice-capable ships enabling a longer and more reliable shipping season (Figure 4). These choices should consider the changing Arctic

environment and the risks and opportunities this will offer. In addition to the dramatic changes to the sea ice pack, climate change is likely to modify other climatic hazards to shipping not assessed here such as ice ridging, fog, waves, and icing as discussed by Aksenov *et al.* [2015]; developing the full potential for trans-Arctic shipping will require knowledge of these along with comprehensive en route infrastructure, providing incentives for substantial investment in Arctic regions. It should be noted that despite these climatic opportunities, economic studies are mixed as to whether trans-Arctic shipping will become a reality due to the vagaries and seasonal nature of Arctic navigation [Bensassi *et al.*, 2016; Lasserre, 2014; Lasserre and Pelletier, 2011]. However, emergent natural resource extraction and an increasingly accessible Arctic Ocean may lead to an increase in destination shipping.

A key innovation is that these results originate from GCMs calibrated with current state-of-the-art SIT data, and so the projections of future transit availability, route choices, and frequency should be more robust. Despite these trends, interannual variability will remain a significant factor in route availability throughout the 21st century, motivating increased efforts in seasonal to interannual forecasting [Eicken, 2013; Guemas *et al.*, 2014; Hawkins *et al.*, 2015; Stroeve *et al.*, 2014b].

# Acknowledgments

We thank the anonymous reviewers and the Editor for their guidance. N. Melia and E. Hawkins are supported by the APPOSITE project (grant NE/I029447/1), funded by the UK Natural Environment Research Council (NERC) as part of the Arctic Research Programme. N. Melia is also supported by the ERGODICS project (grant NE/J005894/1), funded by NERC, as part of the Next Generation Weather and Climate Prediction Programme. E. Hawkins is also funded by NERC Fellowship and the National Centre for Atmospheric Science. K. Haines is partly funded by the National Centre for Earth Observation. The authors declare no competing financial interests. The data used are listed in Table 1 of this paper and techniques developed in Melia *et al.* [2015]. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

# References

- Aksenov, Y., E. E. Popova, A. Yool, A. J. G. Nurser, T. D. Williams, L. Bertino, and J. Bergh (2015), On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice, *Mar. Policy*, doi:10.1016/j.marpol.2015.12.027.
- Arctic Marine Shipping Assessment (2009), *Arctic Marine Shipping Assessment 2009*, Arctic Council Tromsø, Norway.
- Barnhart, K. R., C. R. Miller, I. Overeem, and J. E. Kay (2015), Mapping the future expansion of Arctic open water, *Nat. Clim. Change*, 6, 280–285, doi:10.1038/nclimate2848.
- Bennett, M. M. (2014), North by northeast: Toward an Asian-Arctic region, *Eurasian Geogr. Econ.*, 55(1), 71–93, doi:10.1080/15387216.2014.936480.
- Bensassi, S., J. C. Stroeve, I. Martínez-Zarzoso, and A. P. Barrett (2016), Melting ice, growing trade?, *Elementa: Sci. Anthropolocene*, 4(1), doi:10.12952/journal.elementa.000107.
- Browse, J., K. S. Carslaw, A. Schmidt, and J. J. Corbett (2013), Impact of future Arctic shipping on high-latitude black carbon deposition, *Geophys. Res. Lett.*, 40, 4459–4463, doi:10.1002/grl.50876.
- Dijkstra, E. W. (1959), A note on two problems in connexion with graphs, *Numer. Math.*, 1(1), 269–271, doi:10.1007/bf01386390.
- Eguiluz, V. M., J. Fernández-Gracia, X. Irigoien, and C. M. Duarte (2016), A quantitative assessment of Arctic shipping in 2010–2014, *Sci. Rep.*, 6, 30,682, doi:10.1038/srep30682.
- Eicken, H. (2013), Ocean science: Arctic sea ice needs better forecasts, *Nature*, 497(7450), 431–433, doi:10.1038/497431a.
- Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, and M. Vertenstein (2011), The Community Climate System Model version 4, *J. Clim.*, 24(19), 4973–4991, doi:10.1175/2011JCLI4083.1.
- Guemas, V., *et al.* (2014), A review on Arctic sea-ice predictability and prediction on seasonal to decadal time-scales, *Q. J. R. Meteorol. Soc.*, 142(695), 546–561, doi:10.1002/qj.2401.
- Hansen, C., P. Grønsed, C. Graversen, and C. Hendriksen (2016), *Arctic Shipping Commercial Opportunities and Challenges*, CBS Maritime Copenhagen, Denmark.
- Hawkins, E., S. Tietsche, J. J. Day, N. Melia, K. Haines, and S. Keeley (2015), Aspects of designing and evaluating seasonal-to-interannual Arctic sea-ice prediction systems, *Q. J. R. Meteorol. Soc.*, 142, 672–683, doi:10.1002/qj.2643.
- Hulme, M. (2016), 1.5 °C and climate research after the Paris Agreement, *Nat. Clim. Change*, 6, 222–224, doi:10.1038/nclimate2939.
- International Maritime Organization (2015), International code for ships operating in polar waters (Polar Code). [Available at <http://www.imo.org/en/MediaCentre/HotTopics/polar/>]
- Intergovernmental Panel on Climate Change (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1535, Cambridge Univ. Press, Cambridge, U. K.
- Jungclaus, J., N. Keenlyside, M. Botzet, H. Haak, J.-J. Luo, M. Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner (2006), Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM, *J. Clim.*, 19(16), 3952–3972, doi:10.1175/JCLI3827.1.
- Khon, V. C., I. I. Mokhov, M. Latif, V. A. Semenov, and W. Park (2010), Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century, *Clim. Change*, 100(3–4), 757–768, doi:10.1007/s10584-009-9683-2.
- Laliberté, F., S. E. L. Howell, and P. J. Kushner (2016), Regional variability of a projected sea ice-free Arctic during the summer months, *Geophys. Res. Lett.*, 43, 256–263, doi:10.1002/2015GL066855.
- Lasserre, F. (2014), Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector, *Transp. Res. Part A Policy Pract.*, 66, 144–161, doi:10.1016/j.tra.2014.05.005.
- Lasserre, F., and S. Pelletier (2011), Polar super seaways? Maritime transport in the Arctic: An analysis of shipowners' intentions, *J. Transp. Geogr.*, 19(6), 1465–1473, doi:10.1016/j.jtrangeo.2011.08.006.
- Meehl, G. A., W. M. Washington, J. M. Arblaster, A. Hu, H. Teng, J. E. Kay, A. Gettelman, D. M. Lawrence, B. M. Sanderson, and W. G. Strand (2013), Climate change projections in CESM1 (CAM5) compared to CCSM4, *J. Clim.*, 26(17), 6287–6308, doi:10.1175/JCLI-D-12-00572.1.
- Melia, N. (2016), On predicting the opening of Arctic sea routes, PhD thesis, Univ. of Reading, Reading, Royal Berkshire, U. K. [Available at <http://centaur.reading.ac.uk/66414/>]
- Melia, N., K. Haines, and E. Hawkins (2015), Improved Arctic sea ice thickness projections using bias-corrected CMIP5 simulations, *Cryosphere*, 9(6), 2237–2251, doi:10.5194/tc-9-2237-2015.
- Moe, A. (2014), The Northern Sea Route: Smooth sailing ahead?, *Strategic Anal.*, 38(6), 784–802, doi:10.1080/09700161.2014.952940.
- Notz, D. (2015), How well must climate models agree with observations?, *Philos. Trans. R. Soc. London, Ser. A*, 373(2052), doi:10.1098/rsta.2014.0164.
- Rogers, T., J. Walsh, T. Rupp, L. Brigham, and M. Sfraga (2013), Future Arctic marine access: Analysis and evaluation of observations, models, and projections of sea ice, *Cryosphere*, 7(1), 321–332, doi:10.5194/tc-7-321-2013.

- Smith, L. C., and S. R. Stephenson (2013), New Trans-Arctic shipping routes navigable by midcentury, *Proc. Natl. Acad. Sci. U.S.A.*, *110*(13), E1191–E1195, doi:10.1073/pnas.1214212110.
- Stephenson, S. R., and L. C. Smith (2015), Influence of climate model variability on projected Arctic shipping futures, *Earth's Future*, *3*(11), 331–343, doi:10.1002/2015EF000317.
- Stephenson, S. R., L. C. Smith, and J. A. Agnew (2011), Divergent long-term trajectories of human access to the Arctic, *Nat. Clim. Change*, *1*(3), 156–160, doi:10.1038/nclimate1120.
- Stephenson, S. R., L. W. Brigham, and L. C. Smith (2013a), Marine accessibility along Russia's Northern Sea Route, *Polar Geogr.*, *37*(2), 111–133, doi:10.1080/1088937x.2013.845859.
- Stephenson, S. R., L. C. Smith, L. W. Brigham, and J. A. Agnew (2013b), Projected 21st-century changes to Arctic marine access, *Clim. Change*, *118*(3–4), 885–899, doi:10.1007/s10584-012-0685-0.
- Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger (2014a), Using records from submarine, aircraft and satellite to evaluate climate model simulations of Arctic sea ice thickness, *Cryosphere*, *8*(2), 1839–1845, doi:10.5194/tc-8-1839-2014.
- Stroeve, J., L. C. Hamilton, C. M. Bitz, and E. Blanchard-Wrigglesworth (2014b), Predicting September sea ice: Ensemble skill of the SEARCH Sea Ice Outlook 2008–2013, *Geophys. Res. Lett.*, *41*, 2411–2418, doi:10.1002/2014GL059388.
- Swart, N. C., J. C. Fyfe, E. Hawkins, J. E. Kay, and A. Jahn (2015), Influence of internal variability on Arctic sea-ice trends, *Nat. Clim. Change*, *5*(2), 86–89, doi:10.1038/nclimate2483.
- Tan, X., B. Su, K. Riska, and T. Moan (2013), A six-degrees-of-freedom numerical model for level ice–ship interaction, *Cold Reg. Sci. Technol.*, *92*, 1–16, doi:10.1016/j.coldregions.2013.03.006.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*(4), 485–498, doi:10.1175/Bams-D-11-00094.1.
- The HadGEM2 Development Team, et al. (2011), The HadGEM2 family of Met Office Unified Model climate configurations, *Geosci. Model Dev.*, *4*, 723–757, doi:10.5194/gmd-4-723-2011.
- Tilling, R. L., A. Ridout, and A. Shepherd (2016), Near real time Arctic sea ice thickness and volume from CryoSat-2, *Cryosphere Discuss.*, *2016*, 1–15, doi:10.5194/tc-2016-21.
- Transport Canada (1998), Arctic Ice Regime Shipping System (AIRSS) Standards Transport Publication, 12259 E.
- Van Etten, J. (2015), gdistance: Distances and routes on geographical grids R package.
- Van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, and J.-F. Lamarque (2011), The representative concentration pathways: An overview, *Clim. Change*, *109*, 5–31, doi:10.1007/s10584-011-0148-z.
- Vavrus, S. J., M. M. Holland, A. Jahn, D. A. Bailey, and B. A. Blazey (2012), Twenty-first-century Arctic climate change in CCSM4, *J. Clim.*, *25*(8), 2696–2710, doi:10.1175/jcli-d-11-00220.1.
- Watanabe, M., T. Suzuki, R. Oishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, and M. Sekiguchi (2010), Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity, *J. Clim.*, *23*(23), 6312–6335, doi:10.1175/2010jcli3679.1.
- Zhang, J., and D. Rothrock (2003), Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates, *Mon. Weather Rev.*, *131*(5), 845–861, doi:10.1175/1520-0493(2003)131<0845:MGSIIWA>2.0.CO;2.