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SENSITIVITY OF ARCTIC TRANSIT SHIPPING TO CLIMATE VARIABILITY

Janne Valkonen [1], Lars Ingolf Eide [1]

[1]Det Norske Veritas, Oslo, NORWAY

ABSTRACT

Future emission to air from trans-Arctic shipping can be estimated using projected ice conditions from a climate model and ship performance in ice. An earlier study estimated the transit times, fuel consumptions and emissions from a container vessel during trans-Arctic shipping in 2030 and 2050 using mean ice conditions from a climate model and assuming limitations on ice concentration and ice thickness for the chosen vessel.

This extension investigates the sensitivity of emissions from trans-Arctic shipping in 2030 to internal climate variability by considering ice cover in September from the results of the four individual climate model runs for each of the five years that were the basis of the original mean ice conditions. Thus projected transit times, fuel consumptions and emissions based on ice conditions from 20 individual runs are presented.

It was found that passage in 2030 along the selected Arctic transit route is possible in only 9 out of the 20 ice conditions for the selected limit ice concentration. For these nine ice conditions the annual fuel consumption and the emissions from trans-Arctic container vessels vary from 75% to 110% of the mean value which indicate that the mean seasonal emissions to air in the Arctic give a representative picture but disguise the fact that the transit is possible only less than half of the cases.

The individual climate model runs demonstrate significant impact of internal climate variability on the potential for trans-Arctic shipping until 2040 along the chosen route. After 2040 there is no effect of climate variability on ice conditions in September as the route is virtually ice free and all four runs in each year show ice conditions that allow trans-Arctic shipping on the selected route for the chosen vessel.

INTRODUCTION

Peters et al. (2011) estimated emissions to air from trans-Arctic shipping in 2030 and 2050 by assuming projected ice conditions for the two years. The ice conditions were taken as the running average over five years and four runs of the Community Climate System Model 3 (CCSM3) (Collins et al., 2006), centered on the years 2030 and 2050, for the IPCC emission scenario A2 (IPCC, 2007). They used a route across the Arctic Ocean that would lead vessels outside the Russian domestic waters but east of the North Pole; see Route 3 in the map in Figure 1. They also assumed technology improvements that will give 5% lower fuel consumption in 2030 compared to 2005 and 10% lower in 2050, as well as other technology improvements that reduce emissions of NO_x, SO_x and organic carbon (OC), in line with Marpol Annex VI requirements. The basic scenario was summer traffic across the Arctic Ocean with PC4 ice-class 6500 TEU container vessels with bulbous bow, here called CS6500. The bulbous bow is optimized for open water. Vessel speed dependence on ice thickness was represented by a speed-thickness curve. One conclusion was that trans-Arctic traffic between Asia and Europe will occur only from Tokyo, whereas the distances from other Asian hubs like Hong Kong and Singapore would be too long to be commercially attractive in 2030 and 2050.

The objective of this paper is to demonstrate the uncertainties introduced by internal climate variability. The variability in climate model results is introduced by running a specific global climate model combined with a specific emission scenario several times with slightly varying initial conditions. Each new set of initial conditions is called a run. The assumption is that the mean of all runs, or ensemble mean, yields a robust estimate of the climate change for the given emission scenario. We had four different runs at our disposal extending time frame for years 2001-2100. In this paper the work of Peters et al. (2011) is extended by considering ice conditions from the four individual runs of the GCM CCSM3 and IPCC emission scenario A2 for each of the five years that were basis of the mean ice conditions used by Peters et al. (2011). This gives a set of 20 individual ice conditions based on climate model results. We have used the same vessel specific performance data in terms of vessel speed as a function of ice thickness as in Peters et al. (2011).

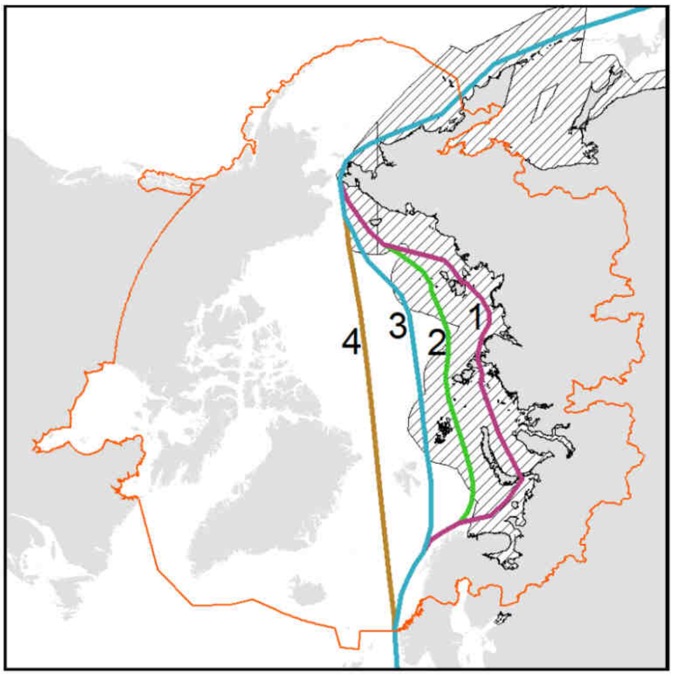

Figure 1. Arctic transit routes as presented by Peters et al. (2011). Route 3 was used in this study.

It is emphasized that this paper only treats the physical impacts of ice conditions on the vessel performance and the implications for transit times and fuel consumption. Other aspects of the commercial attractiveness of using the Arctic have not been included. It is conceivable that traffic from Hong Kong, and even Singapore, may be economically feasible in years with very light ice conditions.

Wang and Overland (2009) showed the sensitivity of the ice conditions to choice of climate models and emission scenario. However, resource restriction limited this study to the use of a single climate model and a single emission scenario.

ANALYSIS

The ship used in the case study is called CS 6500. She is a 84000 DWT container ship with 57 MW power. Its maximum transit speed is 12.3 m/s. Fuel consumption per transit was calculated for the ice conditions in each of the runs during 2028-2032 using the brake specific fuel consumptions of 166 g/kWh.

Ship speed in ice was calculated using the same speed vs. ice thickness curve for CS 6500 as Peters et al. (2011). In each grid cell of ice data, sailing distance across the cell, mean thickness and concentration were found. The distance travelled in ice was assumed equal to the sailing distance across the cell times the ice concentration. The rest of the distance was assumed to take place in open water. The total route length was 12266 km and actual distances in ice varied between 111 km and 1390 km. Total transit time for the route is the sum of the cell transit times. “Getting-stuck” speed limit was set to 1 km/h (0.3 m/s) with the accuracy of one decimal as in Peters et al. (2011). They also assumed that the maximum allowable ice concentration on a transit across the Arctic Ocean is 50%.

Fuel consumption and emissions per transit

The fuel consumption in grams for one transit is given by

$$F_c = PC(\omega_o\, T_{SAo} + \omega_i\, T_{SAi}) \tag{1}$$

where

ω_o	=	Engine load in open water
ω_i	=	Engine load in ice
P	=	Engine power, kW
C	=	Specific fuel consumption for the main engine, g/kWh
T_{SAo}	=	total time per transit spent in open water, hours
T_{SAi}	=	total time per transit spent in ice, hours

As in Peters et al. (2011), we use for the engine load $\omega_o = 0.85$ and $\omega_i = 1.00$.

Number of ships, transits and cargo over the Arctic Ocean

If the sailing season is long and the ice conditions vary during the season, the ship transit time will also vary. Thus the Arctic sailing season should be divided into *n* parts, each with different durations

T_{SAj} $\quad j = 1, n.$

The number ships, N_s, required to transport a total cargo of C_t from Tokyo to Rotterdam in one year is given by

$$N_s = \frac{C_t}{c_w} \cdot \frac{1}{\sum\left(\frac{T_{SAj}}{2(T_{Aj}+2)}\right) + \frac{365-\sum T_{SAj}}{2(T_s+2)}} \tag{2}$$

The addition of 2 to T_{Aj} and T_s is due to an assumed time in harbor of 2 days for each loading and off-loading. The number of transits, N_T, across the Arctic is

$$N_T = N_S \sum\left(\frac{T_{SAj}}{T_{Aj}+2}\right) \tag{3}$$

and the cargo transported westwards, C_{tw}, over the Arctic in one season is, in TEU

$$C_{tw} = \frac{1}{2} \cdot N_T \cdot c_w \tag{4}$$

In Equations (2) – (4) the symbols are;

C_t	=	total cargo to be transported from Tokyo to Rotterdam per year, in TEU
c_w	=	cargo transported westwards on one ship, in TEU per ship and trip
T_{SAj}	=	Duration of part *j* of the Arctic sailing season, in days
T_{Aj}	=	Transit time for part *j* of the season, in days

T_s = transit time for the Suez route between Tokyo and Rotterdam, in days

Length of sailing season

The length of the sailing season has been estimated following the same approach as Peters et al. (2011). As ice data were available for March, June, September and December only the maximum ice concentration for the months June, September and December are plotted and fitted a sine curve to the three points.

A main assumption is that the maximum ice concentration along the route would have to be below 50% for ship owners to risk using the Arctic route. The length of the sailing season was then found as the number of days between the down-crossing and up-crossing of the curve with 50% concentration line. June and December maximum ice concentrations along the route seem fairly stable at 90% and 99% and for simplicity it was assumed that these values did not change, whereas the September number changes dramatically. This is illustrated in Figure 2.

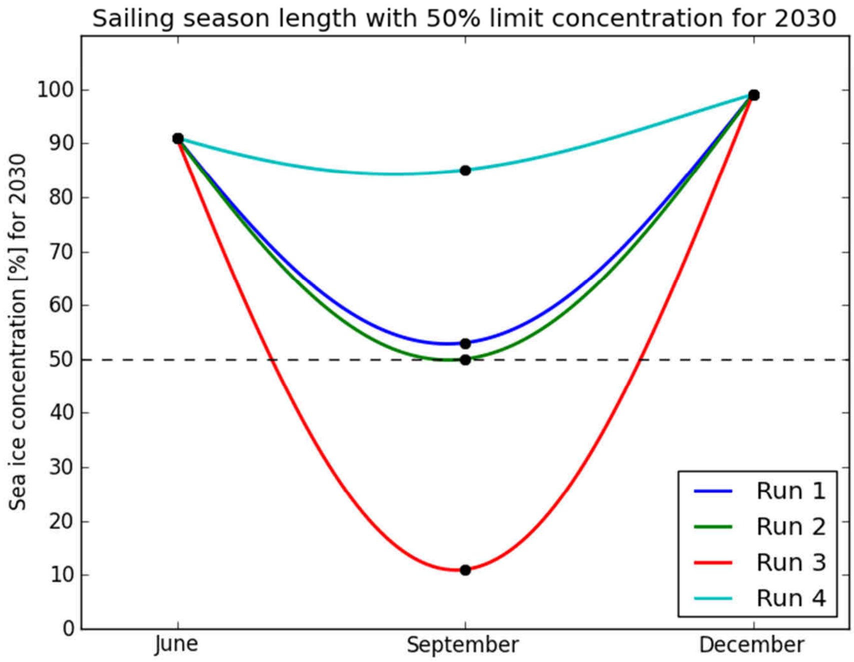

Figure 2. Interpolated sea ice concentration and data points along route 3 for the four runs in 2030, assuming maximum allowable ice concentration of 50%. The number of days between points where the interpolated curves intersect the 50 per cent-line is taken as the length of the season for mean ice conditions.

Table 1 shows the maximum ice concentrations in September and Table 2 the lengths of the sailing season in days for the 20 individual runs for maximum allowable ice concentration 50%. The maximum September ice concentration along route 3 exceeded 50% in eight out of the 20 runs.

Table 1. Maximum ice concentration along the Route 3 in September for the 20 individual runs.

Run	2028 (%)	2029 (%)	2030 (%)	2031 (%)	2032 (%)
1	10	21	53	44	62
2	39	39	50	73	26
3	59	13	11	31	11
4	74	81	85	88	45

Table 2. Length of sailing season in days along the Route 3 per season for the 20 individual runs, assuming a maximum allowable ice concentration of 50%.

Run	2028 (d)	2029 (d)	2030 (d)	2031 (d)	2032 (d)
1	117	106	0	58	0
2	74	74	10	0	100
3	0	115	117	92	117
4	0	0	0	0	53

When a ship encountesr ice thicker than 1.4 m it gets stuck. Figure 3 show the ice thickness and ice concentration in September along route 3 for the run 2 in 2030 as an example.

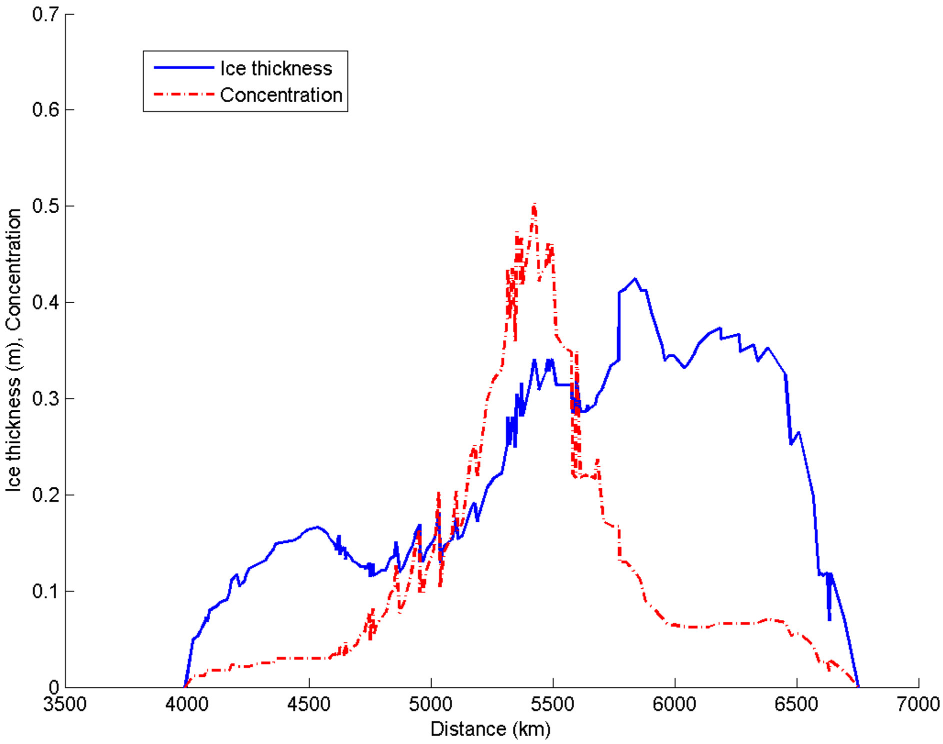

Figure 3. Ice conditions in September for 2030 for run 2.

Emissions for one year

Emissions for a summer season transport through the Arctic was calculated for CS 6500 vessel using the emission factors per unit fuel consumption as in Peters et al. (2011) and the calculated number of transits. The specific fuel consumption and the emission factors are assumed constant and independent on engine load.

RESULTS

Transit times

Transit times for September for all years between 2001-2100 and all runs along route number 3 are presented in Figure 4. The figure shows that the ice conditions for all four runs are sometimes too heavy for transit or the estimated transit time is close to or exceeds that of Suez route between Tokyo and Rotterdam of 20.1 days. We note that transit times vary significantly between the runs up to 2040 and that after 2045-2050 they stabilize at the open water transit time. Thus there will be no variations between the runs for the years 2048 – 2052, which represents the mean for 2050 used in Peters et al. (2011). These years will not be considered further. Calculation of length of the sailing season across the Arctic Ocean, the number of transits and total emissions will only be illustrated for the 20 runs of the years 2028 – 2032. Each black dot in Figure 4 presents the transit time for one of the four runs for each year. Missing values for transit time mean that transit is not possible in September with ships of type CS 6500, either because the ice is too thick or the maximum ice concentration exceeded 50%. Table 3 summarizes transit times for the 20 runs for maximum allowable ice concentrations of 50% and ice thickness of 1.4 m. Transit is possible in only 9 of the 20 runs with the limitations on the vessel that has been imposed.

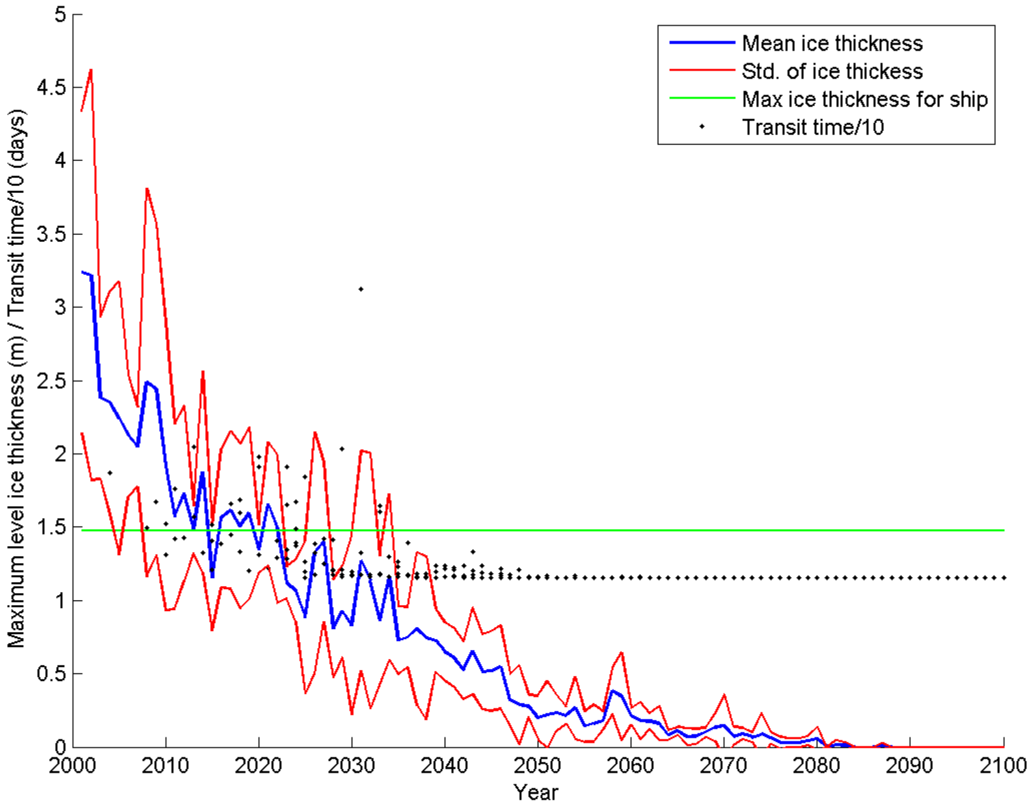

Figure 4 Mean and standard deviation of the maximum ice thickness on the route along with transit times in the summer season (September) 2001-2100. Missing points indicate too heavy ice conditions for transit. The green line presents the maximum ice thickness the ship is capable of advancing.

Table 3. Calculated travel time in days for a vessel for one trip with maximum allowable ice concentration 50% and ice thickness of 1.4m, based on ice conditions in September. Unit: days.

Run	2028 (d)	2029 (d)	2030 (d)	2031 (d)	2032 (d)
1	11.7	11.7	Too high ice concentration	Too thick ice	Too high ice concentration and too thick ice
2	12.1	12.1	Too high ice concentration	Too high ice concentration	11.7
3	Too high ice concentration	11.6	11.6	11.7	11.6
4	Too high ice concentration	Too high ice concentration	Too high ice concentration and too thick ice	Too high ice concentration and too thick ice	Too thick ice

We note from Figure 4 and Table 3 that in 2030 and 2031 only one of the four runs allows trans-Arctic shipping on route 3 in the maximum allowable ice conditions along the route. Note that the mean transit time in Peters et al. (2011), which was 12.74 days, is calculated from the mean ice conditions and is *not* an average of the transit times shown for each run and year in Table 3.

Fuel consumption and emissions per transit

Time spent in open water per transit can be estimated by finding open water distance travelled from Table 1 and setting open water speed to 12.3 m/s. Time spent in ice per transit is then the total transit times from table 2 minus the time spent in open water.

Fuel consumption for one transit for each of the individual runs is presented in Table 4 and the CO_2 emissions are displayed in Figure 5. The calculations have been performed for runs where ice thickness is below 1.4 m. Table 4 shows that there are 9 runs for which these conditions are satisfied. The limiting ice concentration has only impacted the length of sailing season, the number of ships in the fleet and the total number of transit.

The fuel consumption per transit in the average ice conditions used in Peters et al. (2011) is 2459 tons and the corresponding CO_2 emission is 7697 tons. Table 4 shows that the fuel consumption and CO_2 emissions for the 20 runs that went into the mean of Peters et al. (2011) in 2030 vary from 91% to 111% of the mean in 2030.

Table 4. Calculated fuel consumptions in tons for CS6500 for one transit.

Run	2028 (t)	2029 (t)	2030 (t)	2031 (t)	2032 (t)
1	2271	2269	-	-	-
2	2362	2366	-	-	2273
3	-	2244	2245	2270	2245
4	-	-	-	-	-

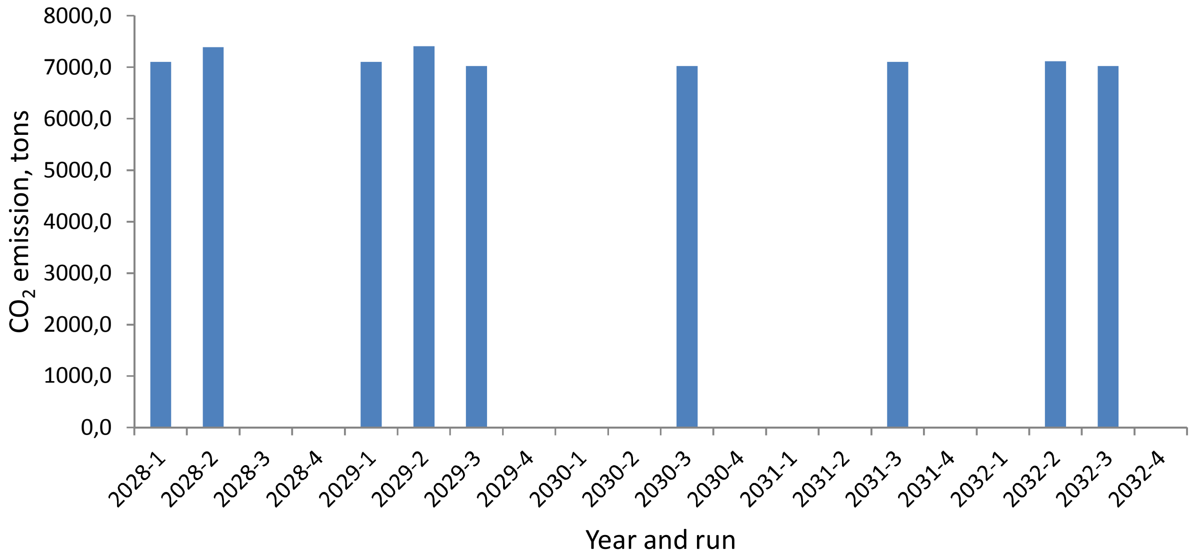

Figure 5. Comparison for CO2 emissions per transit in September for each run long the Arctic route 3, vessel type CS 6500 2028 – 2032.

Number of ships, transits and cargo over the Arctic Ocean

In this study we have estimated the transit time only for ice conditions in September in the case that the maximum allowable ice concentration is 50%. However, we have only the transit times shown in Table 3 available and will thus perform the above calculations without dividing the sailing season into several parts.

Table 5 shows the number of ships required, the number of transits made during one season and the cargo transported westwards in one season for maximum allowable ice concentration 50%. The table is based on Eqs. (2) – (4).

Table 5.

a. Number of ships required along the Route 3 for the 20 individual runs, assuming a maximum allowable ice concentration of 50%.

Run	2028 (# of ships)	2029 (# of ships)	2030 (# of ships)	2031 (# of ships)	2032 (# of ships)
1	67	69	-	-	-
2	72	72	-	-	69
3	-	67	67	70	67
4	-	-	-	-	-

b. Number of transits in one season along the Route 3 for the 20 individual runs, assuming a maximum allowable ice concentration of 50%.

Run	2028 (# of transits)	2029 (# of transits)	2030 (# of transits)	2031 (# of transits)	2032 (# of transits)
1	576	530	-	-	-
2	380	380	-	-	505
3	-	570	579	470	579
4	-	-	-	-	-

c. Amount of cargo transported in million TEUs along the Route 3 in one season for the 20 individual runs, assuming a maximum allowable ice concentration of 50%.

Run	2028 (M TEU)	2029 (M TEU)	2030 (M TEU)	2031 (M TEU)	2032 (M TEU)
1	1.69	1.55	-	-	-
2	1.11	1.11	-	-	1.48
3	-	1.69	1.69	1.37	1.69
4	-	-	-	-	-

For comparison with Table 5, Peters et al. (2011) found that 71 vessels were needed and that they would carry 1.4 million TEU in 482 transits during one season. Thus the variability in cargo transported over the Arctic route is $\pm$ 20% of the mean calculated by Peters et al. (2011).

In the calculations we assumed the same transit time throughout a season even though the transit time is dependent on the ice conditions that vary throughout the season. To get an impression of the uncertainty introduced by using the same transit time for the whole season, the length of the season run 2030-3 for limit concentration on 75 % was calculated and then divided the sailing season into 3 segments with lengths 19, 117 and 19 days, a total of 155 days. The transit times for the segments were 16.1, 11.6 and 16.1 days. This resulted in less than 5% difference in number of transits, westbound cargo and seasonal CO_2-emissions. This implies that using the same transit time for the whole season does not introduce significant error for the calculated number of transits.

Emissions for one year

Emissions for a summer season transport through the Arctic were calculated for CS 6500 vessel using the emission data and the number of transits. The CO_2 emissions are illustrated graphically in Figure 6 for maximum allowable ice concentrations along the route of 50%.

Figure 6 shows that the total seasonal emissions for the years when sailing is possible vary between 75% and 110% of the mean estimate by Peters et al. (2011). The mean seasonal CO_2 emissions along the trans-Arctic route of the nine runs is 3.66 million tons, 0.07 million tons lower than calculated by Peters et al. (2011) for the mean ice condition. The standard deviation is 0.51 million tons or 14% of the mean. The relative variations will be the same for the other emissions as for CO_2.

If the maximum allowable ice concentration along the route is increased from 50% to 75%, transit would be possible in 14 runs. The mean seasonal CO_2 emissions of the 14 runs increases to 4.44 million tons, with a standard deviation of 1.07 million tons or 24% of the mean. The maximum CO_2 emission increases from 4.10 to 5.15 million tons per season.

By increasing the maximum allowable ice concentration from 50% to 75% reduces the required number of ships by less than 10% but leads to 25 – 75% more transits and westbound cargo. This is a direct consequence of the length of the sailing season, as the change in number of vessels is proportional to the inverse of the squared length of the season whereas the change in number of transit is proportional to the change of length of the season (Eqs. (2) and (3)).

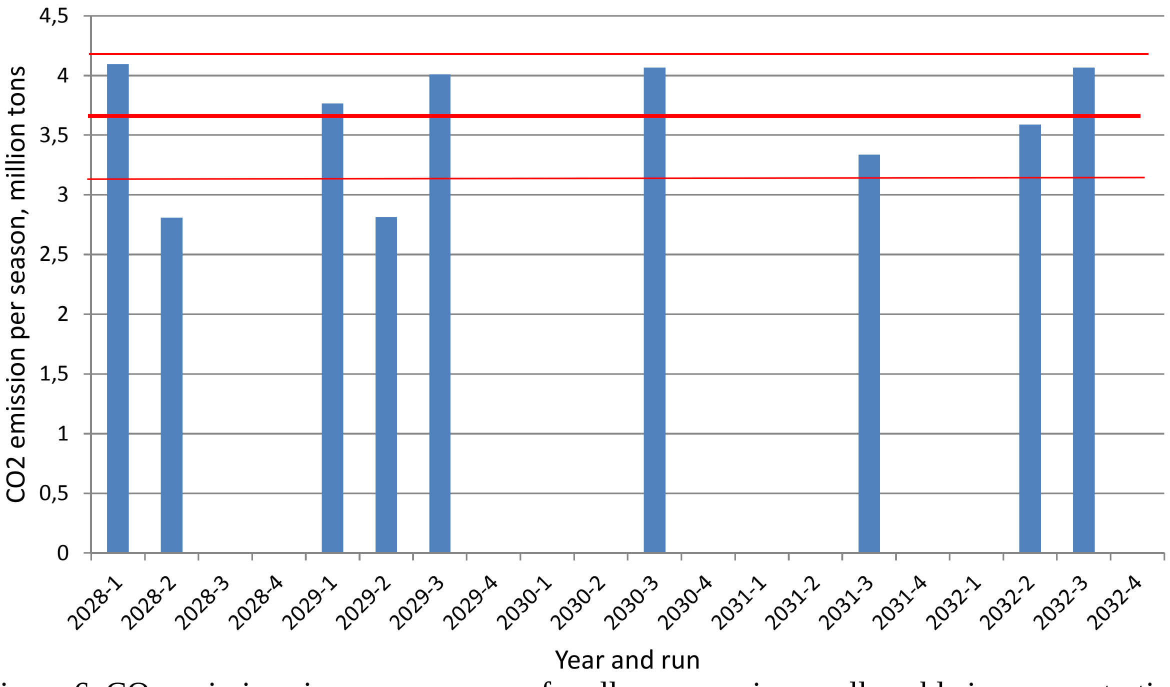

Figure 6. CO_2 emissions in summer season for all runs, maximum allowable ice concentration along the route at 50%. The red horizontal lines are mean (thick) and mean $\pm$ 1 standard deviation (thin).

CONCLUSIONS

For maximum allowable ice thickness of 1.4 m and maximum allowable ice concentration along the Arctic transit route of 50%, passage is possible in only 9 out of 20 runs. For these nine runs the annual fuel consumption and emissions from trans-Arctic container vessels vary from 75% to 110% of the mean value calculated by Peters et al. (2011). This indicates that the results for expected seasonal emissions to air in the Arctic obtained by Peters et al. (2011) give a representative picture.

The mean CO_2 emission per season is 3.66 million tons with a standard deviation of 0.51 million tons or 14% of the mean. The range of seasonal CO_2 emissions is 2.81 - 4.10 million tons.

The individual runs demonstrate significant impact of internal climate variability on the potential for trans-Arctic shipping until 2040 along the chosen route. After 2040 there is no effect of climate variability on ice conditions in September as the route is virtually ice free and all four runs show ice conditions that allow trans-Arctic shipping on this route.

It is only from 2040 that all four runs indicate a transit time that will make the Arctic route commercially competitive with the Suez route in the summer season (exemplified by September). In 2050 there are no variations in annual fuel consumption or emissions, as all 20 runs as well as the mean have the same transit time. If ice conditions are kept constant at the 2001 – 2005 average, passage will not be possible with the considered vessel type.

However, the results rest on several assumptions and simplifications and we have only considered two sources of variability, which are the projections of future ice conditions with one global climate model and one IPCC emission scenario and the limiting ice concentration for sailing across the Arctic.

Furthermore, we point out that this study only treats the physical impacts on the vessel performance of climate variability in ice conditions and the implications for transit times and fuel consumption. The fact that the ice conditions will influence the commercial attractiveness of using the Arctic has not been included. We also emphasize that the results are only indicative of the variations caused by internal climate variability on the emissions from trans-Arctic ship traffic in 2030.

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