Calculations of Financial and Environmental cost of towing icebergs

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1 Introduction

This paper demonstrates the full, detailed calculation of the financial and economic cost of towing icebergs from Antarctica to the equatorial regions to provide fresh water. For simplicity, I used the United Arab Emirates (UAE) as a reference for a country in the equatorial region since the UAE is a country facing water scarcity.[15]

2 Melting of Ice

This section calculates the amount of ice melted during towing from Antarctica to the equatorial regions. In this case, I used the UAE for further calculations.

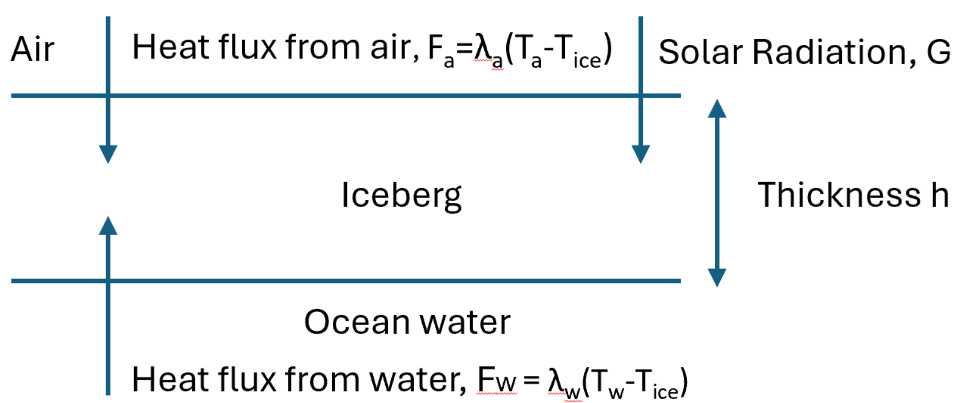

Figure 1: Diagram showing the heat flux within the iceberg

$$\rho L \frac{dh}{dt} = F_a + F_w + G \tag{1}$$

where $F_a = \lambda_a(T_a - T_{ice})$ and $F_w = \lambda_w(T_w - T_{ice})$. F_a, F_w, λ_a, λ_w, G, are the heat flux from air to ice, heat flux from ocean to ice, heat transfer coefficient for air, heat transfer coefficient for water, and solar irradiance on Antarctica respectively.

$$h = -\frac{\lambda_a(T_{air} - T_{ice}) + \lambda_w(T_w - T_{ice}) + G}{\rho L} t + h_o \tag{2}$$

where h and h_o are the final and initial height of ice respectively. This assumes that the dimension of the iceberg is a cube or rectangle.

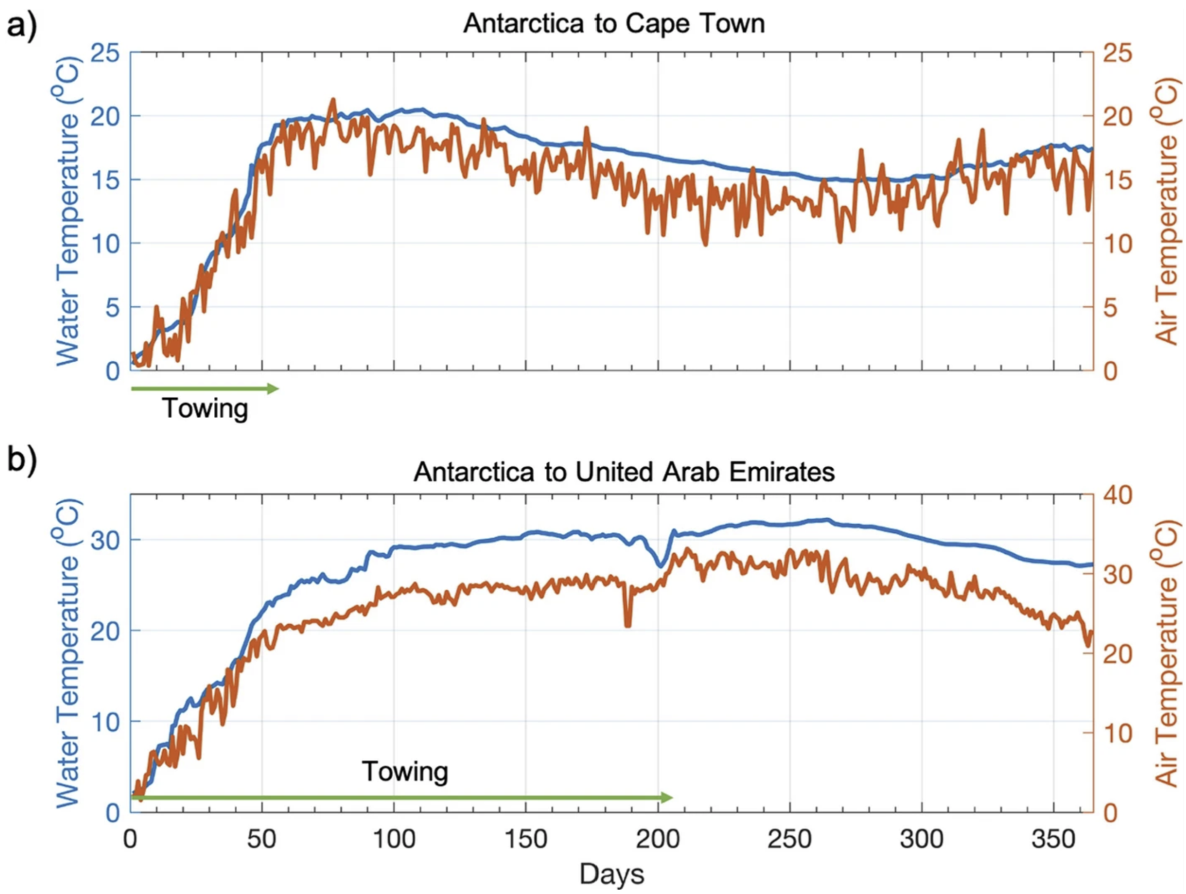

Figure 2: Ocean and atmospheric temperatures experienced by an iceberg towed from Antarctica to (a) Cape Town, South Africa, and (b) the United Arab Emirates. The green arrows represent the period when the iceberg is towed to its destination. At a tow speed of 0.5 m/s, an iceberg will reach Cape Town after 59 days and the United Arab Emirates after 206 days. In this figure, the iceberg tows began on December 1st to correspond with the beginning of the austral summer.[5]

The initial 70 days saw an estimated linear increase in air temperature from 0 to 20°C, and from 0 to 27°C for water temperature. From t=70 days to t=206 days, air and water temperatures remained approximately constant at around 24°C and 29°C respectively. Estimating the average air temperature from t=0 to t=206 days,

$$\frac{70days(0.5)(20°C) + 136days(24°C)}{206days} = 19.243°C \tag{3}$$

Likewise, for average ocean water temperature from t=0 to t=206 days,

$$\frac{70days(0.5)(27°C) + 136days(29°C)}{206days} = 23.733°C \tag{4}$$

Using the values $\lambda_a = 1.1$ W m^{-2} K^{-1}, $\lambda_w = 7.6$ W m^{-2} K^{-1}[8], $\rho_{ice} = 917$kg/m^3, L=334kJ/kg, G = 450 Wm^{-2} [1], t = 206 days into equation 2, I obtain an approximate net decrease in ice height of **37.862 m**. However, the values of λ_a and λ_w are highly variable. λ can exponentially increase with temperature difference from 0.3 W/m^{2}K to 175 W/m^{2}K. [4]. Moreover, the surface area decreases as the ice melts, causing λ to decrease. Additionally, the solar irradiance G on the iceberg will vary greatly. Therefore, it is difficult to determine precisely how much ice has melted, and this is just an estimate.

3 Financial Cost

3.1 Number of Tugboats needed for towing

This subsection will determine the number of tugboats required to tow icebergs from Antarctica. For simplification, we will assume the distance from all icebergs around Antarctica to the UAE to be the same. Considering the massive size of icebergs and the resistance in the water, tugboats of high horsepower(hp) are necessary to ensure sufficient power and maneuverability. For my calculation, I will use diesel-engine tugboats with 27200hp. [11]

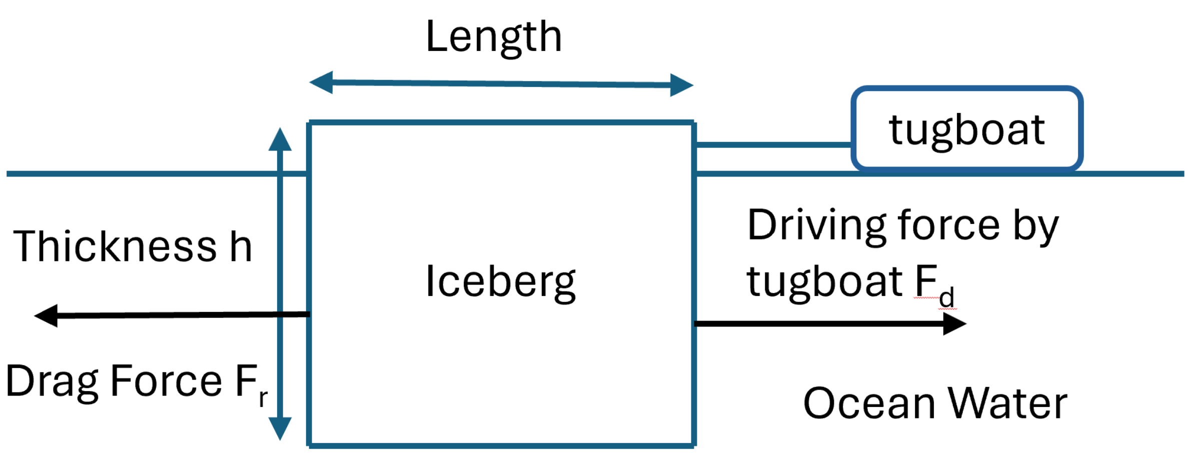

Figure 3: Free body diagram of the forces on a tabular iceberg being towed by a tugboat on water.

By Newton's 2nd Law, assuming constant speed of v = 0.5m/s.[5]

$$F_{net} = ma = F_d - F_r = 0 \tag{5}$$

where F_d and F_r are the driving force by the tugboat, and the frictional force on the iceberg.

$$F_r = 0.5\rho v^2 C_d A \tag{6}$$

where ρ is the density of the fluid, saltwater, v, is the velocity of towing, C_d is the drag coefficient, and A is the reference area.

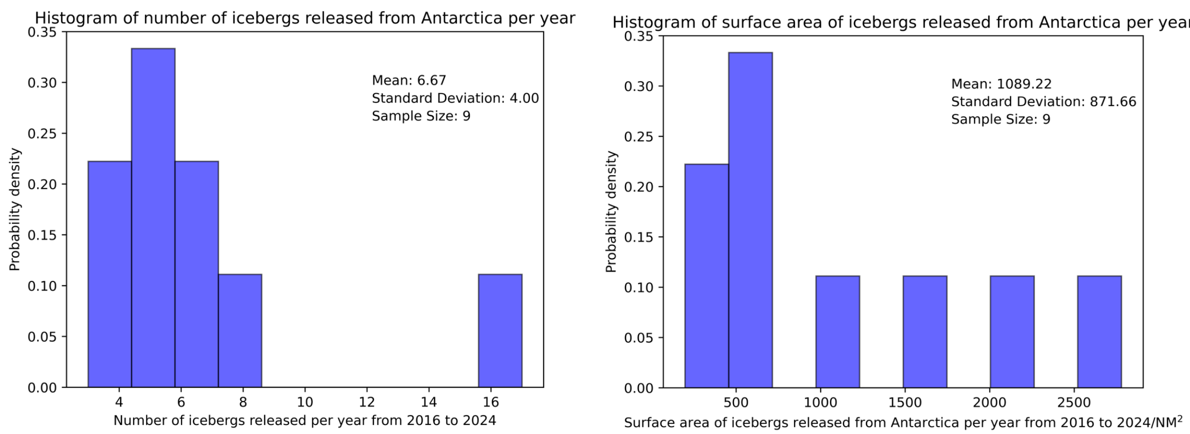

Figure 4: Distribution of the number of new icebergs released each year from Antarctica, and the change in total surface area of all new icebergs released from Antarctica per year between 2016 and 2024. Data were individually complied into 2 histograms to obtain their respective mean and standard deviations.

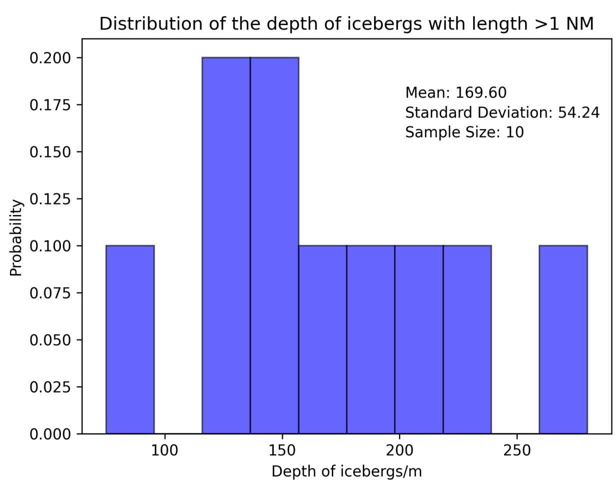

Figure 5: Distribution of the depth of icebergs with length > 1 nautical mile. Data on depth were individually compiled into a histogram to obtain the mean and standard deviation.[6, 12, 16].

I assumed that when towing the iceberg, we tow in a direction where the smallest surface area is facing the direction of travel, i.e. the side view of the iceberg with the least surface area, to reduce the amount of drag on the iceberg. Thus, A = width $\times$ depth. The depth of the iceberg is h = 170 $\pm$ 54.3 m, as shown in Fig.5. The width of an iceberg is taken to be 15740 m $\pm$ 1653 m [2]. As shown in figure 4, the number of icebergs released each year is 6.67 $\pm$ 4.00. Since 89.463% of ice is submerged in water,

$$A = depth(width)(percentage\ underwater)(number\ of\ icebergs\ released\ per\ year) \quad (7)$$

This gives the total surface area of the icebergs towed per year, A = $(\mathbf{1.60}\pm 0.03) \times 10^7$ $\mathbf{m^2}$.

Substituting $\rho_{seawater}$ = 1025 kg/m^3, v = 0.5m/s, and C_d=1.2 [13] into equation 6, F_r = $(\mathbf{2.46}\pm 0.05) \times 10^9$ **N**.

Total power required to be generated by the tugboats:

$$P = Fv \quad (8)$$

Using equation 8, where F = F_{driver} = F_r = 2.455 $\times 10^9$ N(from equation 5), and v = 0.5m/s, I obtain P_{total} = $(\mathbf{1.228}\ \pm 0.025) \times 10^9$ **W**.

$$P_{total} = P_{individual} \times number\ of\ tugboats \quad (9)$$

Taking $P_{individual}$ of each tugboat = 27200 hp = 2.028 $\times 10^7$ W, the number of tugboats required to tow all the icebergs released per year is about **61**$\pm$2.

3.2 Fuel Cost

Since Power = Energy/Time, a 27200 hp tugboat requires **3.610** $\times 10^{14}$ **J** for a 206 days journey.

Assuming 100% efficiency, and given that 1 litre of diesel = 3.8 $\times 10^7$ J [7], the amount of diesel for one tugboat trip from Antarctica to UAE will require **9.596** $\times 10^6$ **L**.

Taking the cost of diesel to be 1.25 USD/litre [9], the total diesel cost of towing icebergs (released yearly) for one trip from Antarctica to the UAE for 61 tugboats is **732 million USD**.

3.3 Tugboat Cost

The cost of a high-end out-in-the-ocean tugboat is up to USD 10 million [14]. The total cost of 61 tugboats will be **610 million USD**.

3.4 Cost of iceberg water per litre per year of towing

Total amount of water obtained per year = Area of iceberg released per year $\times$ average depth of iceberg $\times$ percentage of iceberg left after melting. Taking the area of iceberg released per year (top view) = 1089 $\pm$ 872 NM^2 (as shown in Fig.4), average depth = 170 m $\pm$ 54.3 m, the amount of iceberg left after melting = (170 m-37.9 m)/170 m= 77.71 %, and the density of ice to be 917kg/m^3, the total amount of water obtained per year from Antarctica is $\mathbf{4.525 \times 10^{14}}$ **kg/year**, with an uncertainty of plus or minus 5.068×10^{14} kg/year.

Since 1 litre of water = 1 kg of water, the cost of water per litre per year = (732+610) million / (4.525×10^{14}) L = $\mathbf{2.966 \times 10^{-6}}$ **USD/L**.

Due to the large uncertainty of 112% in the amount of water obtained from Antarctic icebergs, there is a real possibility of obtaining no water at all, resulting in a squandering of both financial resources, and effort.

4 Environmental Cost

Given that 1 litre of diesel emits 2.639 kg of CO_2 [10], the total amount of CO_2 emitted from one tugboat trip from Antarctica to UAE from the tugboats is $\mathbf{2.532 \times 10^{7}}$ **kg**. Therefore, the amount of CO_2 emitted per litre of freshwater obtained from iceberg towing for 61 tugboat trips from Antarctica to UAE per year is $\mathbf{3.413 \times 10^{-6}}$ **kg of CO_2/L**.

5 Conclusion

Towing icebergs from Antarctica for freshwater costs $\mathbf{2.966 \times 10^{-6}}$ **USD/L** and emits $\mathbf{3.413 \times 10^{-6}}$ **kg of CO_2/L** of carbon emissions. This is 875 times cheaper and emits 1000 times less carbon emissions than desalination water. Therefore, it seems viable to tow these icebergs that would otherwise melt in the ocean. Assuming steady state, the number of icebergs released each year is 6.67 $\pm$ 4.00 (Fig. 2), the total amount of water obtained each year from Antarctica is 4.53×10^{14} L, with an uncertainty of plus or minus 5.07×10^{14} L.

Moreover, my results are comparable with this paper. [17]

5.1 Assumptions and Limitations

Firstly, in reality, the icebergs are all around Antarctica and are at different distances from the UAE. However, this model can still be applied if the icebergs around Antarctica are towed to their nearby land masses or equatorial regions. Therefore, each iceberg travels about the same distance to the equatorial regions.

Secondly, in our model, we assumed that the tugboats started their journey from Antarctica to their destination in the UAE. In reality, extra fuel is required for the boat to travel from their origin (near the coast of their respective countries) to Antarctica. Therefore, I am incurring higher financial costs and CO_2 emissions; thus, the financial and environmental costs are underestimated.

Thirdly, we used the UAE, which is 2604.64 km north of the equator. Therefore, I have overestimated the costs as, in reality, if we were to tow to places nearer to Antarctica than the UAE, a low cost would be incurred since a lesser distance is traveled.

Fourthly, there is no water and air current in the ocean when calculating the amount of energy required to tow the iceberg. In reality, there will always be times when the current goes together with or against the iceberg towing direction. Ideally, we hope to take a path that goes net in the direction of the currents.

Fifthly, the datasets in Fig 4 and 5, have a small sample size of 9 - 10. A larger sample size should be obtained to have a better estimate of the total number of icebergs released each year, the total surface area of these icebergs, and the depth of icebergs with lengths >1 NM. However, due to the current limitation of data, estimates were tobtained.

Sixthly, is that G is always varying with time. The highest values, a bit over 450 W/m^2, occur in the weeks around the summer solstice. Daily and hourly variations due to changing cloud cover are apparent. Still, the solar radiation values decrease steadily as the sun lowers in the sky during January, February, and March. The instrument reads values of 1 W/m^2 for about a week after sunset and a week before sunrise; otherwise, the value is zero for the six-month-long polar night. Moreover, G will be different during the towing process since the iceberg is no longer in Antarctica. [1]

Lastly, icebergs were assumed to be cubic/rectangular for ease of calculation. In reality, icebergs come in different shapes. As a result, a more precise model has to be built to calculate an iceberg's surface area and volume.[3]

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