Supplement of

Delaying future sea-level rise by storing water on Antarctica

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Efforts of delaying sea level rise in comparison to local adaptation

Storing ocean water 700km inland on the Antarctic Ice Sheet requires overcoming a height difference of about 4000m. Mitigating a sea-level rise of 3 mm yr$^{-1}$ requires 1275 GW of power to increase the potential energy of the water accordingly. This corresponds to a power of 10 kW that is required to pump 1 m$^3$/s vertically to a height of 1m. The actual energy required for the pumping will be higher due to friction and inefficient pumping. Here we assume a required power of 18 kW to pump 1 m$^3$/s to a height of 1m. This value is based on the project Tagus-Segura Water Transfer$^1$. In its first section (TRAMO I) a power of 135 MW is applied to achieve a throughput of 31.7 m$^3$/s over a height difference of 245 m, which corresponds to 17.3 kW/(m$^3$/s)/m. This would mean that the required power to mitigate a sea-level rise of 3 mm yr$^{-1}$ would reach about 2300 GW. To avoid further greenhouse-gas emissions the power would have to be generated based on local renewable technologies.

That poses a fundamental engineering problem that goes far beyond the scope of existing projects. While wind power plants and pipeline technology readily exist, currently the required technology is not available for the very low temperatures of Antarctica, as far as we know. We cannot provide reliable estimates of the associated costs at this stage.

However, to put the engineering effort into perspective we here compare the technical requirements of the pumping and transporting system to that of the Trans Alaska Pipeline (TAP)$^2$. Thereby we assume that the transport of the water is split up into 90 individual pipelines each ensuring a throughput of 11·10$^9$ m$^3$ yr$^{-1}$ as provided by the largest New Orleans pumping station.
<table>
<thead>
<tr>
<th></th>
<th>Trans Alaska Pipeline</th>
<th>Individual pipeline of the potential Antarctic pumping system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>1287 km</td>
<td>700 km</td>
</tr>
<tr>
<td><strong>Maximum elevation</strong></td>
<td>1444 m</td>
<td>4000 m</td>
</tr>
<tr>
<td><strong>Air temperature along route</strong></td>
<td>-60°C to 35°C</td>
<td>far below 0°C</td>
</tr>
<tr>
<td><strong>Annual throughput</strong></td>
<td>$0.1245 \cdot 10^9 \text{ m}^3$ (assuming a maximum daily throughput as reached in 1988)</td>
<td>$11\cdot10^9 \text{ m}^3$</td>
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The costs of building the TAP amount to a total of 8 billion US$. On the one hand this includes costs not relevant for the Antarctic pipelines and pumps such as:

- costs of the Valdez oil terminal (US$1.4)
- launching/receiving facilities for cleaning pigs that sweep the pipe of built-up wax, water or other solids that precipitate out of the oil stream
- 124,300 heat pipes along the pipeline transferring ground heat into the air during cold periods to lower the ground temperature to ensure that soils remain frozen throughout the summer to steadily support the pipeline (to be replaced by alternatives adequate for Antarctica).

While on the other hand the Antarctic systems will

- have to provide an orders of magnitude higher throughput (assuming 90 individual lines starting at the ocean with an annual throughput of $11\cdot10^9 \text{ m}^3$ as provided by the largest New Orleans pump station would require an upscaling of the maximum annual throughput of the TAP (calculated based on its maximum daily throughput reached in 1988) by a factor of 90 for each individual line).
- have to overcome a larger elevation difference (4000m in comparison to a maximum of 1444 m along the TAP)
- require heating along the pipelines
require a system to distribute the water on the ice sheet

need an adjustments of the pipeline due to moving ice
to provide a simplistic upscaling of the TAP costs excluding the terminal (6.6 US$) to the
required length (L), height (H), and capacity (P) we assume that the overall costs C can be
split up in to components, a first one C₁ that scales with P and H (mainly representing the
costs of the pump stations) and a second one C₂ that scales with L and P (mainly
representing the costs of the pipeline itself). Assume that the two components of the
overall costs of the TAB Cₜₐₜ are given by C₁ₜₐₜ = αCₜₐₜ and accordingly C₂ₜₐₜ = (1-α) Cₜₐₜ
that would mean that

\[ C = C_{1,TAB} \cdot \frac{P}{P_{TAB}} \cdot \frac{H}{H_{TAB}} + C_{2,TAB} \cdot \frac{P}{P_{TAB}} \cdot \frac{L}{L_{TAB}} \]

\[ \approx \alpha \cdot 6.6 \times 10^{12} \text{ US$} \times 8015 \times 3 + (1 - \alpha) \cdot 6.6 \times 10^{12} \text{ US$} \times 8015 \times 50 \]

with C = 158,697 billion US$ for α = 1 and C = 2,644,950 billion US$ for α = 0. Both numbers
do not include the costs of running and maintaining the system. Assuming they are minor
compared to the cost of construction, construction costs could be divided by 100 to
estimate the annual costs over the 21st century. In both cases they are orders of magnitude
higher than the estimated annual investment and maintenance costs of local adaptation by
dikes of US$ 12–71 billion in 2100³ which however only protects regions that are
economically expendient to protect. This might exclude for example the AOSIS small island
states and their culture as well as UNESCO cultural heritage sites⁴.

That means that such a project would only become competitive with major efficiency gains
by technical innovations and learning from the experience of the project itself.
S2 Wind Energy potential in Antarctica

We follow the methodology of ref. 5 to estimate the wind energy that is available in a 200 km wide band along the East Antarctic coast (Fig. S1). We use the yearly mean wind data for 2014 at 10m above the surface from the Era-Interim dataset. Following ref. 5, we use only regions with average wind speed above 6.5 m/s. The power of a single wind turbine can be estimated by (ref. 5, equ. 19):

\[ P = P_{\text{rated}} \times CF = P_{\text{rated}} \times (0.087V - \frac{P_{\text{rated}}}{D^2}) \]

with \( P \) as average power output, \( P_{\text{rated}} \) the rated power of a single wind turbine, \( CF \) the conversion factor, \( V \) the average yearly wind speed and \( D \) the rotor diameter of the wind turbine. Six wind turbines of the 1.5 MW class can be installed per square kilometre.

Integrating over the East Antarctic band area with wind stronger than 6.5 m/s, we estimate a wind power potential of 16.7 TW. Regions difficult to access, such as mountain ranges, and regions of fast flowing ice have not been excluded from the total area. We do not apply a conversion of 10m above-surface winds to such at the height of the rotor (80m in ref. 5).

As winds at 80m are generally higher than at 10m above the surface, the real wind energy potential may be higher.

Wind power utilization in Antarctica will pose a number of major challenges that cannot be addressed here. These include building fundaments on moving and deformable ground, functioning under extremely cold temperatures in Antarctic winters and handling very high wind velocities.
**Fig. S1: Wind energy potential in East Antarctica.** Using ERA-Interim data\(^6\), we use the methodology of ref. 5 to estimate the wind power potential in a 200km-wide strip along the East Antarctic coast. High wind speeds above 6.5 m/s on yearly average in the major part of the strip allow for large-scale wind energy extraction.
**S3 Long term response**

**Fig. S2: Delayed sea-level rise as fraction of the initial reduction.** Colour coding indicates the application band where the ice is added (red: 800 km distance from the coast, violet: 500 km distance from the coast, and blue: 200 km distance from the coast). The colour intensity describes the application rate from 1 mm yr\(^{-1}\) (light), via 3 mm yr\(^{-1}\) (normal) to 10 mm yr\(^{-1}\) (dark). Thin lines show the results of the simulations accounting for latent-heat release while thick lines represent the results without the additional warming. Vertical lines mark the 5\(^{th}\) percentile of the distribution of delay times assuming an ice parcel traveling 800 km (red), 500 km (violet), and 200 km (blue) with a constant surface velocity drawn from the distribution of surface velocities observed within the area of less than 800 km, 500
km and 200 km distance from the coast. Real advection of ice particles to the coast by the surface velocities will even take longer because generally the ice will not be flowing the direct path assumed here.

References


6. ECMWF. ERA-Interim. 2015 at <http://apps.ecmwf.int/datasets/data/interim-full-daily/>