

Supplement of Earth Syst. Dynam. Discuss., 6, 1979–1997, 2015  
<http://www.earth-syst-dynam-discuss.net/6/1979/2015/>  
doi:10.5194/esdd-6-1979-2015-supplement  
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*Supplement of*

## **Delaying future sea-level rise by storing water on Antarctica**

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## 1 **S1 Efforts of delaying sea level rise in comparison to local adaptation**

2 Storing ocean water 700km inland on the Antarctic Ice Sheet requires overcoming a height  
3 difference of about 4000m. Mitigating a sea-level rise of 3 mm yr<sup>-1</sup> requires 1275 GW of  
4 power to increase the potential energy of the water accordingly. This corresponds to a  
5 power of 10 kW that is required to pump 1 m<sup>3</sup>/s vertically to a height of 1m. The actual  
6 energy required for the pumping will be higher due to friction and inefficient pumping. Here  
7 we assume a required power of 18 kW to pump 1 m<sup>3</sup>/s to a height of 1m. This value is  
8 based on the project Tagus-Segura Water Transfer<sup>1</sup>. In its first section (TRAMO I) a power of  
9 135 MW is applied to achieve a through-put of 31.7 m<sup>3</sup>/s over a height difference of 245 m,  
10 which corresponds to 17.3 kW/(m<sup>3</sup>/s)/m. This would mean that the required power to  
11 mitigate a sea-level rise of 3 mm yr<sup>-1</sup> would reach about 2300 GW. To avoid further  
12 greenhouse-gas emissions the power would have to be generated based on local renewable  
13 technologies.

14

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

19

20 However, to put the engineering effort into perspective we here compare the technical  
21 requirements of the pumping and transporting system to that of the Trans Alaska Pipeline  
22 (TAP)<sup>2</sup>. Thereby we assume that the transport of the water is split up into 90 individual  
23 pipelines each ensuring a throughput of  $11 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$  as provided by the largest New  
24 Orleans pumping station.

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	<b>Trans Alaska Pipeline</b>	<b>Individual pipeline of the potential Antarctic pumping system</b>
<b>Length</b>	1287 km	700 km
<b>Maximum elevation</b>	1444 m	4000 m
<b>Air temperature along route</b>	-60°C to 35°C	far below 0°C
<b>Annual throughput</b>	0.1245 · 10 <sup>9</sup> m <sup>3</sup> (assuming a maximum daily throughput as reached in 1988)	11 · 10 <sup>9</sup> m <sup>3</sup>

28

29 The costs of building the TAP amount to a total of 8 billion US\$. On the one hand this  
30 includes costs not relevant for the Antarctic pipelines and pumps such as:

- 31 • costs of the Valdez oil terminal (US\$1.4)
- 32 • launching/receiving facilities for cleaning pigs that sweep the pipe of built-up wax,  
33 water or other solids that precipitate out of the oil stream
- 34 • 124,300 heat pipes along the pipeline transferring ground heat into the air during  
35 cold periods to lower the ground temperature to ensure that soils remain frozen  
36 throughout the summer to steadily support the pipeline (to be replaced by  
37 alternatives adequate for Antarctica).

38

39 While on the other hand the Antarctic systems will

- 40 • have to provide an orders of magnitude higher throughput (assuming 90 individual  
41 lines starting at the ocean with an annual throughput of 11 · 10<sup>9</sup> m<sup>3</sup> as provided by  
42 the largest New Orleans pump station would require an upscaling of the maximum  
43 annual throughput of the TAP (calculated based on its maximum daily throughput  
44 reached in 1988) by a factor of 90 for each individual line).
- 45 • have to overcome a larger elevation difference (4000m in comparison to a maximum  
46 of 1444 m along the TAP)
- 47 • require heating along the pipelines

- 48 • require a system to distribute the water on the ice sheet
- 49 • need an adjustments of the pipeline due to moving ice

50

51 to provide a simplistic upscaling of the TAP costs excluding the terminal (6.6 US\$) to the  
 52 required length (L), height (H), and capacity (P) we assume that the overall costs C can be  
 53 split up in to components, a first one  $C_1$  that scales with P and H (mainly representing the  
 54 costs of the pump stations) and a second one  $C_2$  that scales with L and P (mainly  
 55 representing the costs of the pipeline itself). Assume that the two components of the  
 56 overall costs of the TAB  $C_{TAB}$  are given by  $C_{1,TAP} = \alpha C_{TAP}$  and accordingly  $C_{2,TAP} = (1-\alpha) C_{TAP}$   
 57 that would mean that

58

$$C = C_{1,TAB} * \frac{P}{P_{TAB}} * \frac{H}{H_{TAB}} + C_{2,TAB} * \frac{P}{P_{TAB}} * \frac{L}{L_{TAB}}$$

59

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

60

61 with  $C = 158,697$  billion US\$ for  $\alpha = 1$  and  $C = 2,644,950$  billion US\$ for  $\alpha = 0$ . Both numbers  
 62 do not include the costs of running and maintaining the system. Assuming they are minor  
 63 compared to the cost of construction, construction costs could be divided by 100 to  
 64 estimate the annual costs over the 21<sup>st</sup> century. In both cases they are orders of magnitude  
 65 higher than the estimated annual investment and maintenance costs of local adaptation by  
 66 dikes of US\$ 12–71 billion in 2100<sup>3</sup> which however only protects regions that are  
 67 economically expendent to protect. This might exclude for example the AOSIS small island  
 68 states and their culture as well as UNESCO cultural heritage sites<sup>4</sup>.

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70 That means that such a project would only become competitive with major efficiency gains  
 71 by technical innovations and learning from the experience of the project itself.

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## 75 **S2 Wind Energy potential in Antarctica**

76 We follow the methodology of ref. 5 to estimate the wind energy that is available in a 200  
77 km wide band along the East Antarctic coast (Fig. S1). We use the yearly mean wind data for  
78 2014 at 10m above the surface from the Era-Interim dataset<sup>6</sup>. Following ref. 5, we use only  
79 regions with average wind speed above 6.5 m/s. The power of a single wind turbine can be  
80 estimated by (ref. 5, equ. 19):

81

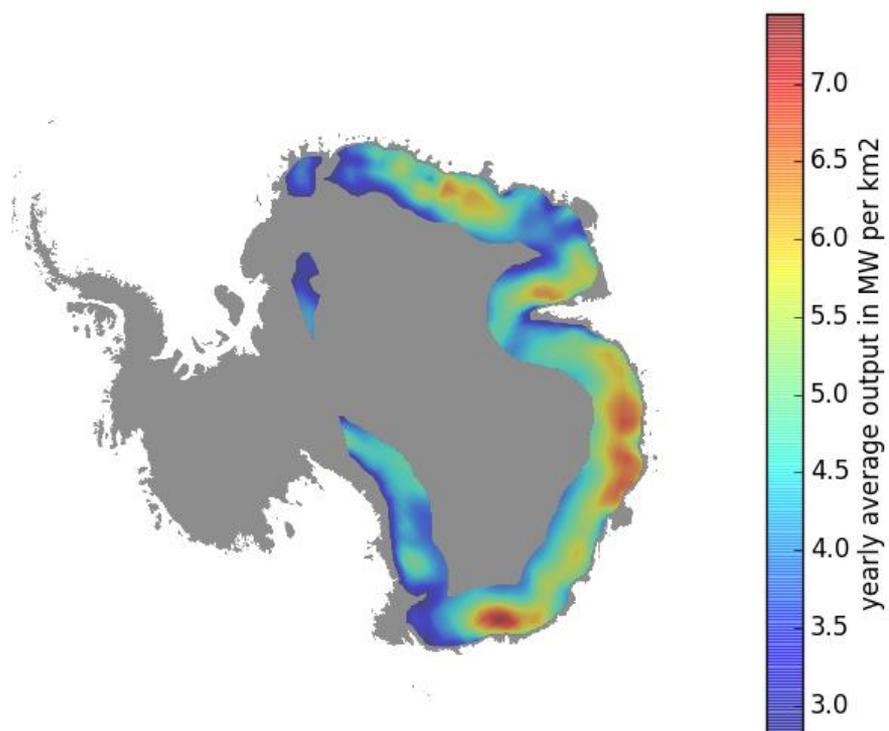
$$P = P_{rated} * CF = P_{rated} * (0.087V - \frac{P_{rated}}{D^2})$$

82

83 with P as average power output,  $P_{rated}$  the rated power of a single wind turbine, CF the  
84 conversion factor, V the average yearly wind speed and D the rotor diameter of the wind  
85 turbine. Six wind turbines of the 1.5 MW class can be installed per square kilometre<sup>5</sup>.  
86 Integrating over the East Antarctic band area with wind stronger than 6.5 m/s, we estimate  
87 a wind power potential of 16.7 TW. Regions difficult to access, such as mountain ranges,  
88 and regions of fast flowing ice have not been excluded from the total area. We do not apply  
89 a conversion of 10m above-surface winds to such at the height of the rotor (80m in ref. 5).  
90 As winds at 80m are generally higher than at 10m above the surface, the real wind energy  
91 potential may be higher.

92 Wind power utilization in Antarctica will pose a number of major challenges that cannot be  
93 addressed here. These include building fundamentals on moving and deformable ground,  
94 functioning under extremely cold temperatures in Antarctic winters and handling very high  
95 wind velocities.

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97

98 **Fig. S1: Wind energy potential in East Antarctica.** Using ERA-Interim data<sup>6</sup>, we use the  
99 methodology of ref. 5 to estimate the wind power potential in a 200km-wide strip along the  
100 East Antarctic coast. High wind speeds above 6.5 m/s on yearly average in the major part of  
101 the strip allow for large-scale wind energy extraction.

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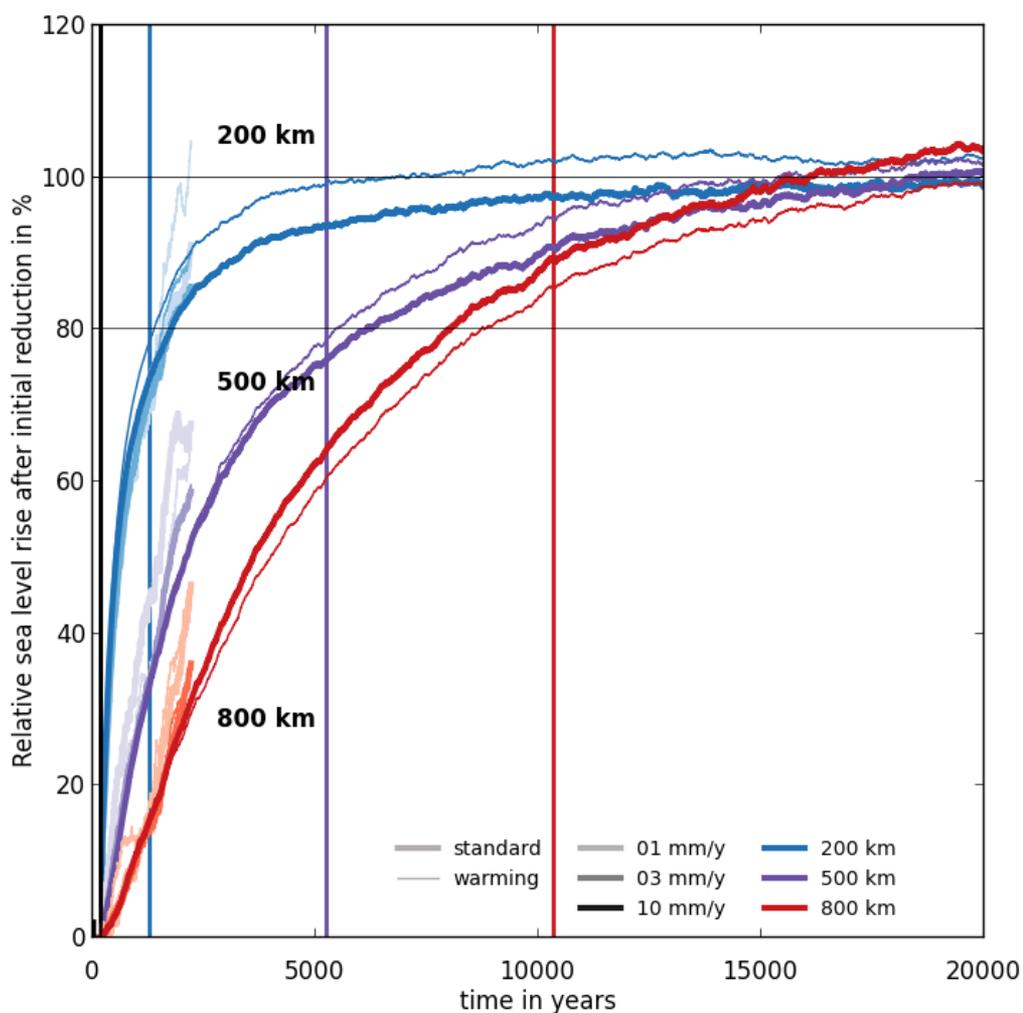
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108 **S3 Long term response**

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110 **Fig. S2: Delayed sea-level rise as fraction of the initial reduction.** Colour coding indicates  
 111 the application band where the ice is added (red: 800 km distance from the coast, violet:  
 112 500 km distance from the coast, and blue: 200 km distance from the coast). The colour  
 113 intensity describes the application rate from  $1\text{ mm yr}^{-1}$  (light), via  $3\text{ mm yr}^{-1}$  (normal) to  $10$   
 114  $\text{mm yr}^{-1}$  (dark). Thin lines show the results of the simulations accounting for latent-heat  
 115 release while thick lines represent the results without the additional warming. Vertical lines  
 116 mark the 5<sup>th</sup> percentile of the distribution of delay times assuming an ice parcel traveling  
 117 800 km (red), 500 km (violet), and 200 km (blue) with a constant surface velocity drawn  
 118 from the distribution of surface velocities observed within the area of less than 800 km, 500

119 km and 200 km distance from the coast. Real advection of ice particles to the coast by the  
120 surface velocities will even take longer because generally the ice will not be flowing the  
121 direct path assumed here.

122

## 123 References

- 124 1. Melgarejo Moreno, Joaquín Sanz Montaña, B. in *Cuad. Interdiscip. Desarro. Sosten.*  
125 174 (2009).
- 126 2. Alyeska Pipeline Service Company. *FACTS, Trans Alaska Pipeline System.* (2013). at  
127 <[www.alyeska-pipe.com](http://www.alyeska-pipe.com)>
- 128 3. Hinkel, J. *et al.* Coastal flood damages and adaptation costs under 21st century sea-  
129 level rise. *PNAS* **111**, 3292–3297 (2014).
- 130 4. Marzeion, B. & Levermann, A. Loss of cultural world heritage and currently inhabited  
131 places to sea-level rise. *Environ. Res. Lett.* **9**, 034001 (2014).
- 132 5. Archer, C. L. Evaluation of global wind power. *J. Geophys. Res.* **110**, 1–20 (2005).
- 133 6. ECMWF. ERA-Interim. 2015 at <[http://apps.ecmwf.int/datasets/data/interim-full-](http://apps.ecmwf.int/datasets/data/interim-full-daily/)  
134 [daily/](http://apps.ecmwf.int/datasets/data/interim-full-daily/)>

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