SEA LEVEL RISE and ICE RECOVERY

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This is a MathCad worksheet which calculates the number of spray vessels needed to reverse the rise in sea levels using John Latham's proposal for marine cloud brightening. I was surprised at the result and would like the arguments and assumptions checked.

Any initial engineering calculation to assess feasibility has to make use of many approximate assumptions with questionable accuracy. These are marked with red text. If there is any chance of a feasible outcome it will be necessary to increase confidence in them. Single lumped numbers should be replaced by multi-decade variables. Blue is plain text. Black is live algebra with automatic unit handling. I can easily adjust the final spray vessel calculation for any other assumptions and would like to know your values.

Key points are that the power to cool ocean water is about 25 times the power needed to save the ice and nearly 600 times the peak electrical generating capacity of the United States in 2018 and just over 35 times total world energy use.

The figure below shows the present design of a spray vessel. If we can index link the 1940 cost of Flower class corvettes, which were built in similar numbers, the mass production cost would be about £3 million.

We have to calculate the energy of melting ice and water warming and then the amount by which the reflection of solar energy from cloud tops has to be increased. Twomey showed that cloud reflectivity depends on the size distribution of drops. Useful equations by Schwartz and Slingo are given at https://pdfs.semanticscholar.org/7e10/1c4bbe3a64dd1f543b5c6b67a958a413f7e1.pdf

COOLING REQUIREMENT

DOI: 10.5194/tc-12-521-2018 gives Antarctic glacier ice melt

$$\text{Mant} := 1929\cdot 10^{9}\cdot\frac{\text{tonne}}{\text{yr}} = 61128\cdot\frac{\text{tonne}}{\text{sec}}$$

A lower figure is reported at https://doi.org/10.1038/s41586-018-0179-y but I will take the higher.

For the Arctic ocean PIOMAS gives Arctic ice loss rate as $\text{Marc} := 25000\cdot\frac{\text{tonne}}{\text{sec}}$

The site https://en.wikipedia.org/wiki/Greenland_ice_sheet gives $\text{Mgrnl} := 6800\cdot\frac{\text{tonne}}{\text{sec}}$

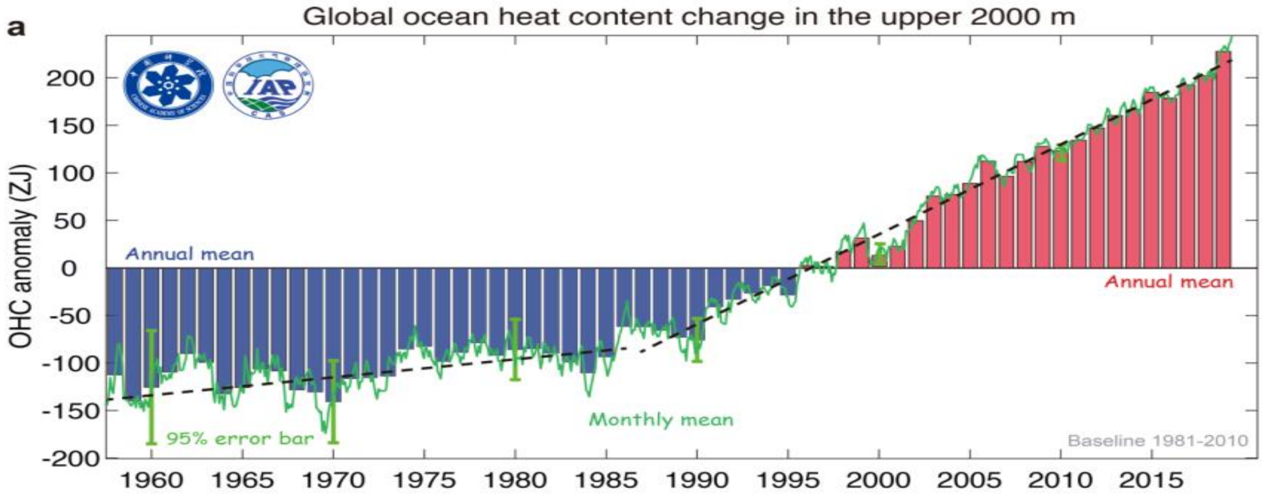
Laghari in doi: 10.1038/502617a gives glacier loss as $\text{Mglac} := \frac{174\cdot 10^{9}}{6\cdot\text{yr}}\cdot\text{tonne} = 918.97\cdot\frac{\text{tonne}}{\text{sec}}$

so total ice mass loss $\text{Mice} := \text{Mant} + \text{Marc} + \text{Mgrnl} + \text{Mglac} = 93847\cdot\frac{\text{tonne}}{\text{sec}}$

Latent heat of fusion of ice $\text{LHT} := 334\cdot\frac{\text{J}}{\text{gm}}$

so ice melt power $\text{PowIce} := \text{Mice}\cdot\text{LHT} = 3.13\times 10^{13}\,\text{W}$

For ocean heat from Cheng et al. https://doi.org/10.1007/s00376-020-9283-7 . Note $\text{ZJ} = 10^{21}\cdot\text{J}$



Assume no change in heat from winds and currents so we should try to remove $\text{EnOc} := 4\cdot 10^{23}\cdot\text{J}$

To remove in $\text{Tcool} := 20\cdot\text{yr}$ the power for historic ocean cooling $\text{PowOc} := \frac{\text{EnOc}}{\text{Tcool}} = 6.34\times 10^{14}\,\text{W}$

To cool the ocean AND save the ice needs power $\text{PowTOT} := \text{PowOc} + \text{PowIce} = 6.65\times 10^{14}\,\text{W}$

Note the ocean water / ice ratio $\frac{\text{PowOc}}{\text{PowIce}} = 20.22$

BP Statistics 2020 gives annual total world human energy use $\text{Ewld} := 556.6\cdot 10^{18}\text{J}$

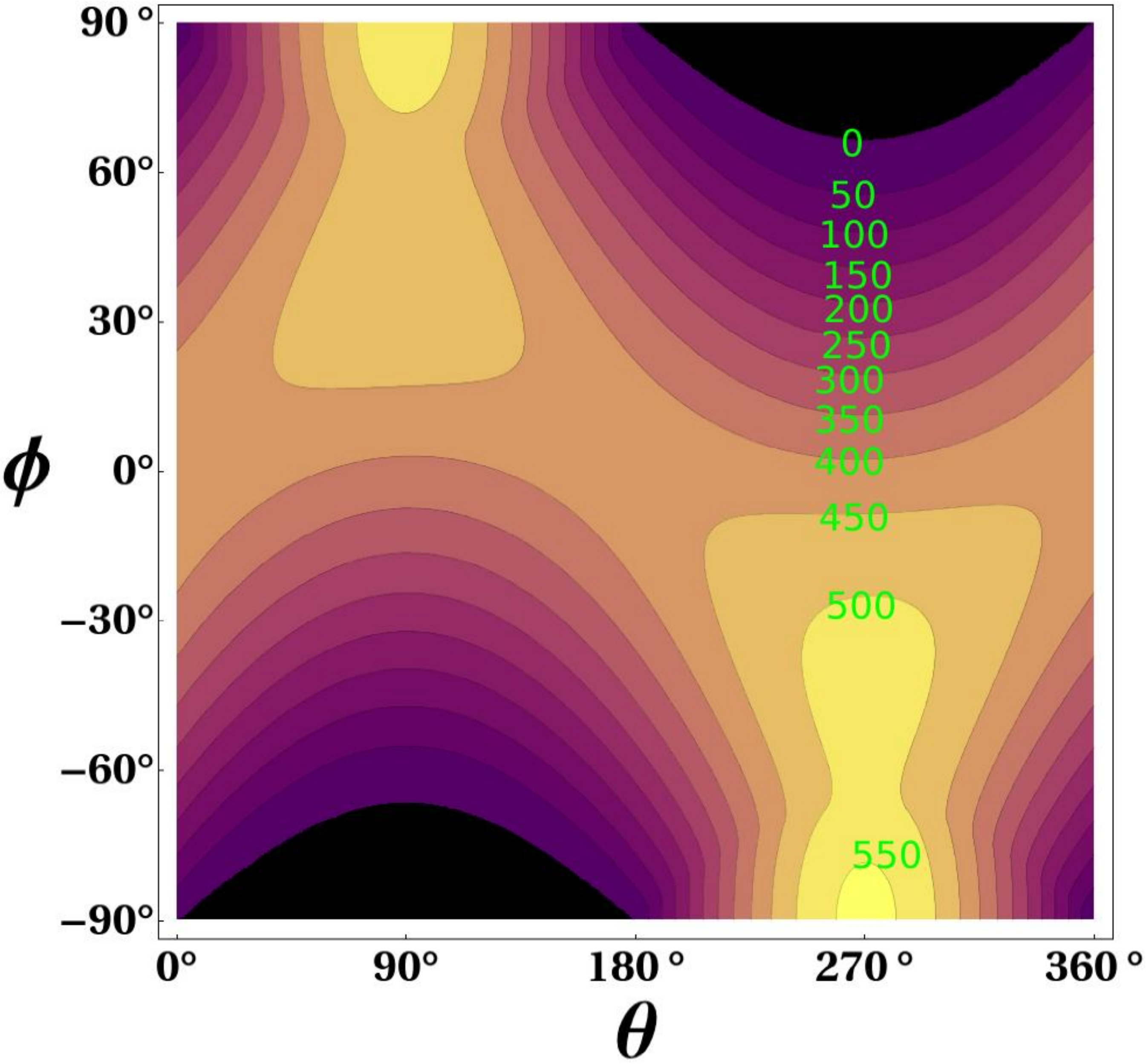
This is power of $\text{Pwld} := \frac{\text{Ewld}}{1\cdot\text{yr}} = 1.76\times 10^{13}\,\text{W}$ Sea cooling to world ratio $\frac{\text{PowTOT}}{\text{Pwld}} = 37.71$

The US electrical generating capacity in 2018 was $\text{PowUS} := 1097\cdot 10^{9}\cdot\text{W}$

so the ratio to ocean cooling is $\frac{\text{PowOc}}{\text{PowUS}} = 577.73$. These ratios are big enough to concentrate the minds of climate engineers.

SOLAR INPUT

Next we must look at the input of solar energy. The input from space is about 1360 W/m2. The site https://en.wikipedia.org/wiki/Solar_irradiance gives a map of 24 hour power per square metre to the top of atmosphere as a function of season and latitude.



If 70% of this reaches cloud top and mobility of spray vessels allows intelligent seasonal migration, especially to polar summer solstices,

solar power density input to cloud top $\text{PowSol} := 400 \cdot 0.7 \cdot \frac{W}{m^2} = 280 \cdot \frac{W}{m^2}$

CLOUD AREA

The area of all the world oceans is $\mathrm{Aoce} := 361.1 \cdot 10^{6} \cdot \mathrm{km}^{2}$
Charlson and Lovelock at doi:10.1038/326655a0 give the low-but-not-high cloud fraction $\mathrm{Kcld} := 0.18$

The mean solar power input to suitable cloud is $\mathrm{POWin} := \mathrm{PowSol} \cdot \mathrm{Aoce} \cdot \mathrm{Kcld} = 1.82 \times 10^{16} \cdot \mathrm{watt}$

We need to increase world-wide cloud reflectivity by $\Delta\mathrm{Ref} := \dfrac{\mathrm{PowTOT}}{\mathrm{POWin}} = 0.0365$

The use of the Twomey effect depends on the initial concentration of cloud condensation nuclei.
At doi 10.1029/2006GB002787. Vallina et al gives seasonal maps of CCN concentration.

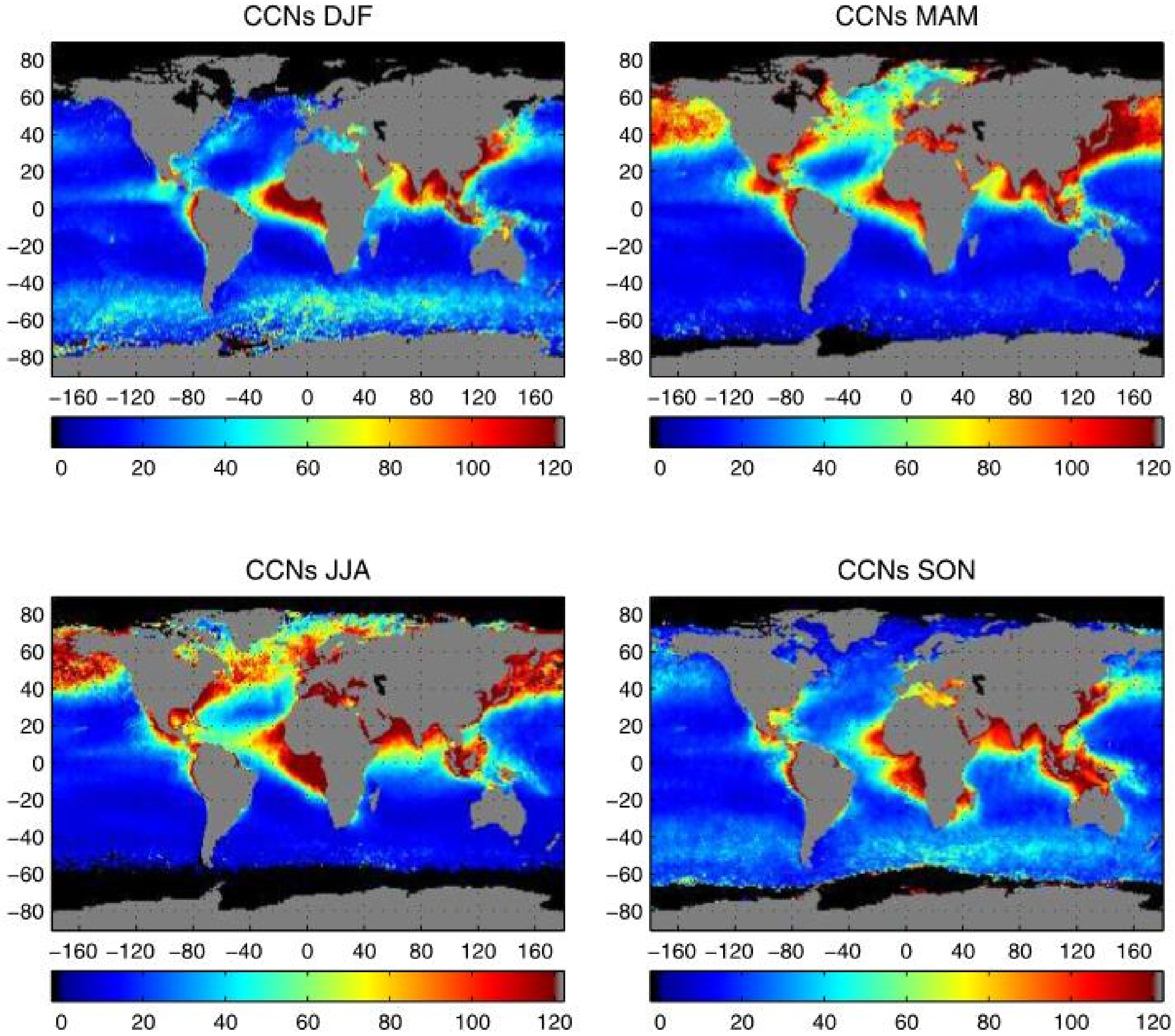


Figure 4. Global maps of monthly climatological (years 2002 to 2004) satellite-derived CCN concentrations (partic cm^{-2}; using the method of Gassó and Hegg [2003]) for the four seasons. DJF, December to February; MAM, March to May; JJA, June to August; SON, September to November.

Note that there is lots of blue outside the cyan region border at 40 /cm3. Until we can run a full global climate model take the initial value for drop concentration as $\mathrm{CCN1} := \dfrac{40}{\mathrm{cm}^{3}}$

Cross check Bennartz. at https://doi.org/10.1029/2006JD007547.

TWOMEY CALCULATION for VESSEL NUMBER

Next we need to have figures for cloud depth $Zc := 300 \cdot m$ and liquid water content $Lw := \frac{0.3 \cdot mL}{m^3}$

From Schwartz and Slingo the present reflectivity $Refl := \frac{0.15 \cdot Zc \cdot Lw^{\frac{2}{3}} \cdot CCN1^{\frac{1}{3}}}{0.15 \cdot Zc \cdot Lw^{\frac{2}{3}} \cdot CCN1^{\frac{1}{3}} + 0.827} = 0.4547$

The reflectivity must increase to $Ref2 := Refl + \Delta Ref = 0.4913$

Nuclei concentration must increase $CCN2 := \left(\frac{Ref2 \cdot 0.827}{0.15 \cdot Zc \cdot Lw^{\frac{2}{3}} - Ref2 \cdot 0.15 \cdot Zc \cdot Lw^{\frac{2}{3}}} \right)^3 = 62.11 \cdot \frac{1}{cm^3}$

If the initial boundary layer depth is $Zbl := 2000 \cdot m$

The initial number of nuclei in the treated region $Nnuc1 := Zbl \cdot Aoce \cdot Kcld \cdot CCN1 = 5.2 \times 10^{24}$

We must increase this to $Nnuc2 := Zbl \cdot Aoce \cdot Kcld \cdot CCN2 = 8.07 \times 10^{24}$

The extra nuclei needed $\Delta Nuc := Nnuc2 - Nnuc1 = 2.87 \times 10^{24}$

If drop diameter $ddrp := 0.8 \cdot micron$ salt mass

$Mslt := \frac{\pi}{6} \cdot ddrp^3 \cdot 1020 \cdot \frac{kg}{m^3} \cdot 0.035 = 9.57 \times 10^{-15} \cdot gm$

good for Kohler nucleation efficiency, The drop volume is $voldrp := \frac{\pi}{6} \cdot ddrp^3 = 2.68 \times 10^{-13} \cdot mL$

If vessel volume rate $Qspr := 0.03 \cdot \frac{m^3}{sec}$ the spray drop number $Nspr := \frac{Qspr}{voldrp} = 1.12 \times 10^{17} \frac{1}{s}$

Reduce coalescence losses by giving drops an electrostatic charge. Three drops initially separated by $Sep := 10 \cdot micron$, charged by $Nelect := 100$ electrons. Offset the central one by $off := 2 \cdot micron$.

Recall the electron charge $qel := 1.602 \cdot 10^{-19} \cdot C$ permeability of free space $\varepsilon 0 := 8.85 \cdot 10^{-12} \cdot \frac{F}{m}$

The restoring force $Fres := \frac{(Nelect \cdot qel)^2}{4 \cdot \pi \cdot \varepsilon 0} \cdot \left[\frac{1}{(Sep - off)^2} - \frac{1}{(Sep + off)^2} \right] = 2 \times 10^{-14} N$

Compare with gravity $Fgrv := \frac{\pi}{6} \cdot ddrp^3 \cdot 1020 \cdot \frac{kg}{m^3} \cdot g = 2.68 \times 10^{-15} N$ The ratio $\frac{Fres}{Fgrv} = 7.47$

The charging current per vessel $Ichrg := Nspr \cdot Nelect \cdot qel = 1.79 A$

If the nucleation efficiency is $Knuc := 0.7$ we need spray increased to

$\Delta Nuc2 := \frac{\Delta Nuc}{Knuc} = 4.11 \times 10^{24}$

If the life of condensation nuclei $Life := 1 \cdot day$ and the spray rate per vessel is $Nspr := \frac{10^{17}}{sec}$

The vessel number for melting ice and for sea level rise $nvess := \frac{\Delta Nuc2}{Life \cdot Nspr} = 475$

But vessels out of action, in wrong place, heavy rain, no wind, pirates, stupid fleet controllers . . .
My guess is we need $Nvess := 700$ .If we can index link from 1940 the £60,000 cost of Flower class corvettes with 1000 tonne displacement and 2 MW power to 90 tonne 300 kW spray vessels the mass production cost would be about $Cost := 4 \cdot 10^6$ \$US.

so the annual cost of owning a fleet to stop sea level rise is $Fleet := Nvess \cdot Cost \cdot 0.1 = 2.8 \times 10^8$

BENEFIT TO COST RATIO

The site https://phys.org/news/2018-07-sea-world-trillion-year.html gives the annual cost of sea level rise as $\mathrm{CostSLR} := 14 \cdot 10^{12}$ \$US but this may be subjective. There is a wide spread of estimates, some higher. If it is correct the annual benefit to cost ratio would be $\mathrm{Bencst} := \frac{\mathrm{CostSLR}}{\mathrm{Fleet}} = 50000$ This is large enough to allow adjustment of the input assumptions. Suggestions for other assumptions would be welcome.

For sea level control we can put vessels anywhere and so can pick either regions with the highest susceptibility for that time of year (Oreopoulos and Platnick doi : 10.1029/2007/JG009655) or where we want to control hurricane breeding, floods and droughts in Africa and Australia due to the Indian Ocean Dipole, save coral reefs or moderate El Nino events. The present hot blob off New Zealand is an obvious place.

For Arctic ice the obvious places are in north-flowing Norwegian and Bering currents. Working at the south end of Greenland would also be useful to halt reductions in AMOC, the Atlantic meridianal over-turning circulation.

It is harder to see how to overcome the salinity barrier at the Antarctic glacier melting area. There is a conflict between the density increase of cooler water and increased salinity. The slope of the temperature density curve levels off near to lower end. However salinity is high because of evaporation somewhere. This must be somewhere along the path of the thermo-haline circulation where there were both high sea-surface temperatures and dry winds. We can back-track along paths from the Antarctic to find where such places are. We will have to wait a while, perhaps quite a long while for cooled water to get from there so the earlier we find out where the right places are the better.

The site dramatically named http://www.killerinourmidst.com/THC.html gives a diagram of the thermo-haline current paths.