
K46 - GeoEngineering:
Global Climate
Modification

No, this is not the "spraying the populace with mind-altering chem-trails" Conspiracy Theory…

- "GeoEngineering" here refers to engineering efforts which would affect global climate. I use the term to mean any engineering effort designed to alter global climate as its prime and perhaps only goal, to distinguish it from other strategies which have other prime benefits (*e.g.* soil rehabilitation).
- The Royal Society (Britain's equivalent of the U.S. National Academy of Science), already concluded as early as 2009 that global climate modification was necessary to halt climate change; that merely lowering emissions and improving energy efficiency was not nearly enough.

It’s highly unfortunate…

- …that too many among the climate activists still believe the notion that it’s either/or...
- …EITHER withdraw from fossil fuels, OR do GeoEngineering
- They hang on to the old thinking that we can halt climate change merely by transitioning to renewable energy and that there’s still time to do it.
- **Because it’s <u>clear</u> that we almost certainly need BOTH immediate and radical transition to zero-carbon fuels AND Geo-Engineering in order to preserve the livable climate animals and human civilization evolved in for the past 10,000 years. Very likely to be impossible.**

GeoEngineering: Efficacy

- **All GeoEngineering ideas must accomplish one or both of the following:**
- **1.** Reduce incoming sunlight. That is the source of our heating
- **2.** Enhance our crippled ability to re-radiate Earth’s heat back out to outer space
- These are well known and well accepted. Nothing new here.

GeoEngineering: Safety

- **<u>I've not seen criteria for safety codified.</u>**
- Perhaps this is because GeoEngineering ideas are largely coming from the entrepreneur / policy people, who are primarily concerned with business success and profitability, and use the emergency aspect to justify low priority to Earth system safety
- As an academic, my concerns instead are for Earth safety - a long term sustainable, natural planet.
- **So - These are the two prime criteria that a bit of logic suggests are critical…**

Safety Criterion #1: Induce No Hysteresis in the Earth System Trajectory

- **This is an important aspect I've not seen discussed at all in terms of safety. In fact, widely ignored by "carbon budget" fans.**
- No hysteresis means; the GeoEngineering strategy backtracks the Earth System back along the ~same climate change trajectory that took us here.
- Strategies which instead make significant changes entirely novel to the Earth system, and over which we have very limited understanding, are the most dangerously unpredictable, to all ecosystems, weather patterns, and civilization

We Know the Prime Changes that are Amplifying Climate Change

- Rising GHG's
- Melting Arctic Ocean ice
- Melting permafrost
- Melting continental ice caps in Greenland, Antarctica
- Slowing ocean thermohaline circulation
- Rising global temperatures, especially in the Arctic
- Drying, eroding, GHG outgasing global soils
- Loss of the boreal and tropical rainforests
- It is along these and other important Earth System variables that we must re-trace, **not send off into new and uncharted directions in search of short-term profits**.

Safety Criterion #2: Leave the SURFACE of the Earth as Pristine as Possible for Current Ecosystems

- The overall goal of halting climate change is to preserve the livability of the planet for all living things. The vast majority live on the Earth’s surface, both on land and the first 100m of the ocean.
- Techno-changes should seek to NOT modify the Earth’s surface except in ways that take it back to their longer-term natural state within which our ecosystems evolved.

“We had to destroy the environment in order to save it” (?)

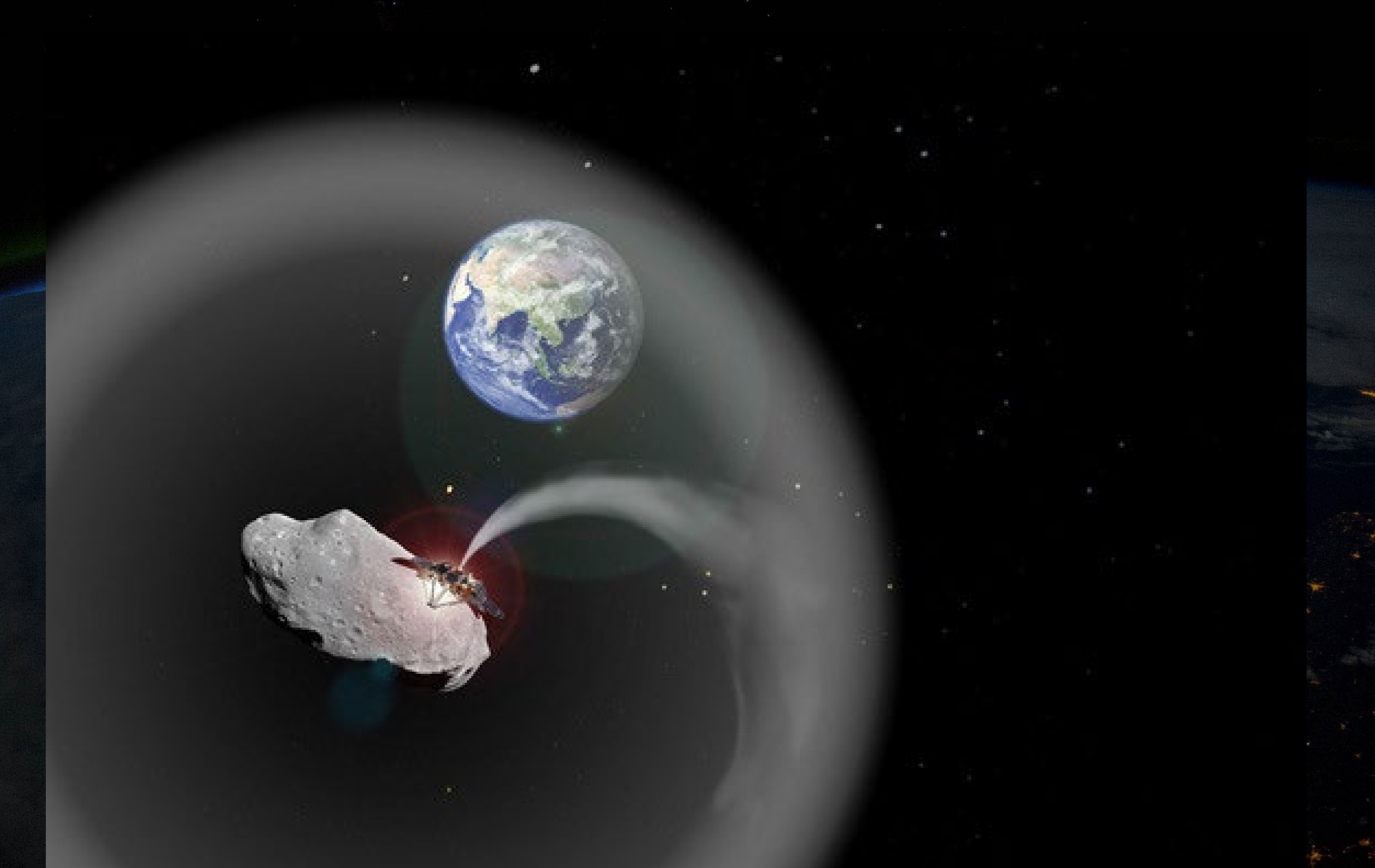
Geo-Engineering should not, like the infamous Vietnam War captain, say to us all **“We had to destroy the Earth in order to save it”**

- In other words, leave the oceans, the forests, and unspoiled Nature as pristine as possible. Make our climate modifications apply only to the atmosphere, perhaps outer space, and/or to the deep underground.
- **<u>Not on the surface</u>** where we and nearly all other species live. Any surface changes should take us BACK towards the environment our ecosystems evolved in.

Solar Radiation Management: SRM

- This category of geo-engineering aims to keep solar incoming heating from reaching the ground, and instead reflecting it back out into space. Satisfies **Criterion #1: Effectiveness.**
- Example: Launch billions of small “butterflies” to the L1 point between Earth and Sun, to block sunlight. Must be actively controlled to keep them there. (Angel *et al.* 2007). Cost beyond calculation because we don’t have the technology. Let’s say, extremely expensive!

Or… Move one or more asteroids to the L1 Lagrangian point between us and Sun, and sputter dust off of it to attenuate sunlight



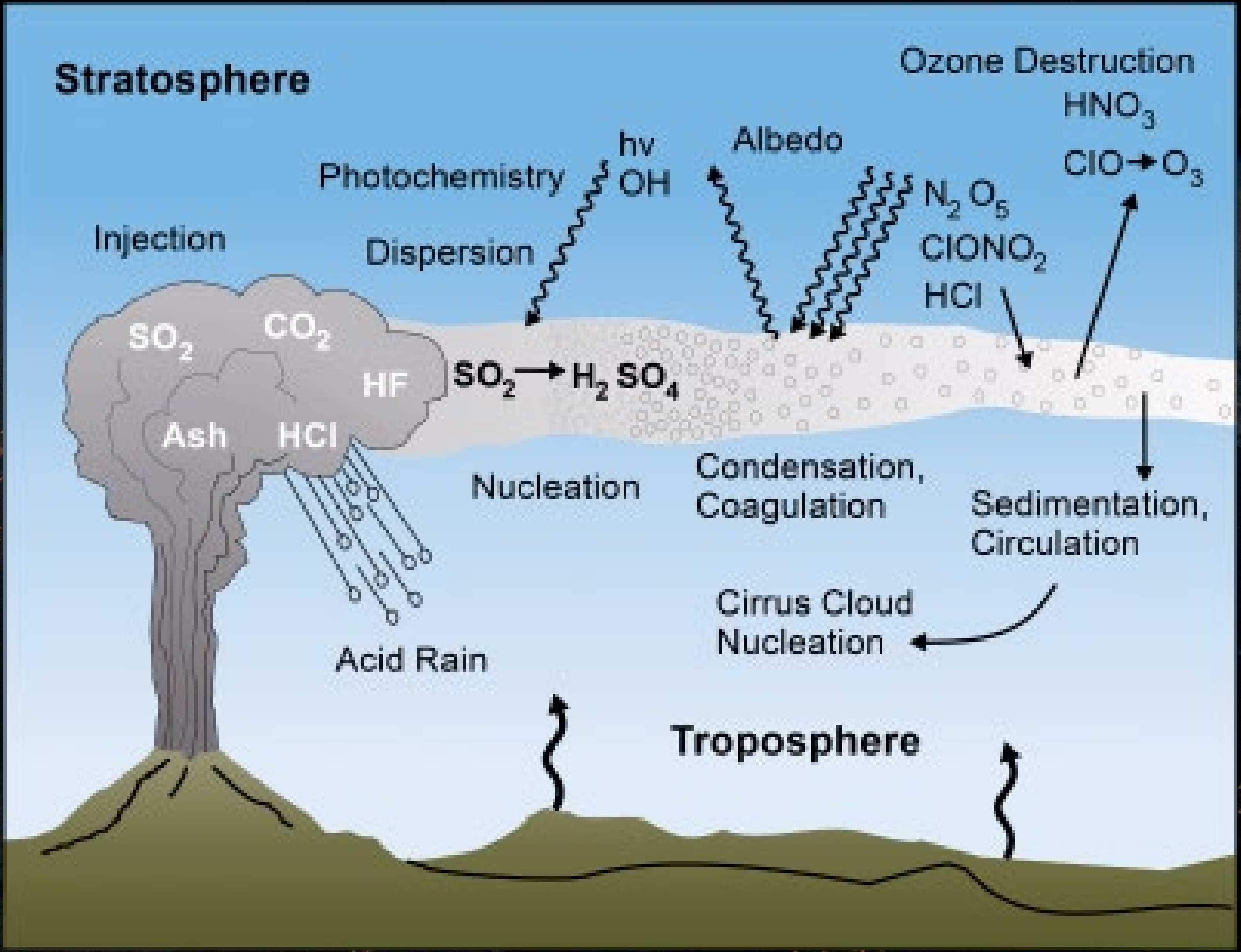
Tug an asteroid to the L1 Lagrangian Point, keep it there and blast off dust to block sunlight from Earth?

- But the L1 point is an unstable gravitational equilibrium point. When you run out of fuel to actively keep it there, the odds are 50/50 it'll head downhill and smash into Earth.
- This would seem quite dangerous to attempt and far too difficult to engineer for now (we need something NOW). Here's the relevant paper (**Bewick *et al.* 2012**), and more thoughts **here**.
- There is precedent, in that there is circumstantial evidence that comet impact(s) / debris associated with the Taurid Meteor Shower may have been the culprit which initiated the Younger-Dryas cooling 12,900 years ago which reversed the exit from the last great Ice Age and cooled the Earth for an additional 1000 years (**Napier 2010 and references therein**), as well as wiping out the great mega-fauna, and Clovis culture of North America.
- Extremely dangerous, and extremely difficult to engineer. A non-starter as a strategy.

Injecting Reflective Aerosols into the Stratosphere

- This would mimic the effect of large volcanic eruptions in their climate effect, and so we are confident they would indeed cool the planet
- The “aerosol direct effect”, reflective sulfate aerosols injected into the lower stratosphere reflecting incoming sunlight, where they would remain for perhaps many months to a year or so because they’d be above the ability of rain clouds to pull them down and rain them out. Gravity, however, would still eventually pull them down.

Definitely cools climate, but danger to Ozone? At Climate Scales, not clear if significant destruction.



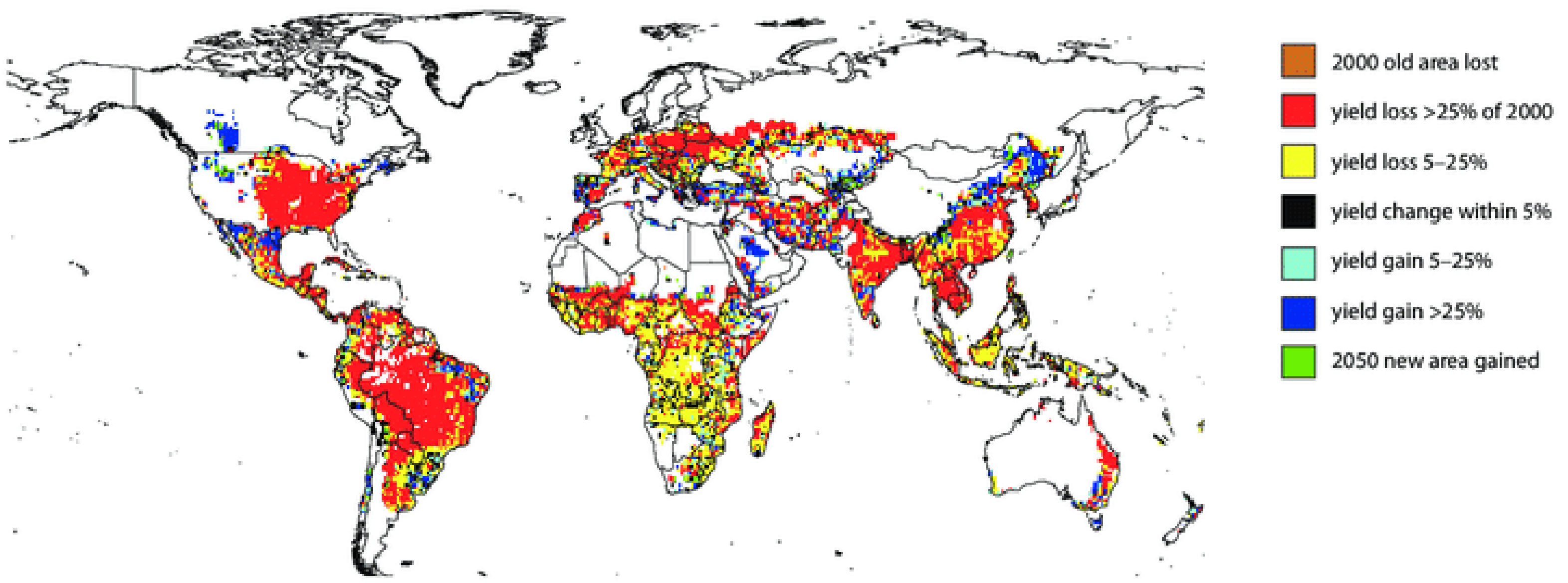
More Climate-warming High Clouds?

- The "aerosol indirect effect" (seeding clouds) would hopefully not apply. In fact, if the aerosols actually caused an excess formation of cirrus clouds at this altitude, this would WARM the Earth, not cool it.
- Currently, this altitude, fortunately, has far fewer cloud nucleation aerosols than does the lower troposphere. But that would appear to change with this strategy.
- However, ice nucleation is less sensitive to CCN's and the guess is that this will not be a serious problem

Sulfate aerosols accelerate loss of stratospheric ozone, further amplified by convective stratospheric water vapor injection

- It would affect not only the poles, but all over the globe.
- A 3:1 observed amplification of ozone loss related to skin cancer incidence. **Every 5% loss of ozone causes a 15% increase in skin cancer.**
- But possibly not fatal, judging from volcanic experience.

Heat damage to staple crops will be significant (Robertson 2015), so cooling will help… but the loss of sunlight will entirely offset this benefit from stratospheric aerosols (Proctor *et al.* 2018)



Source: Robertson (2015).

Note: Decision Support System for Agrotechnology Transfer (DSSAT) crop model results for rainfed maize based on the Hadley Centre Global Environment Model version 2—Earth System (HadGEM2-ES) model and representative concentration pathway (RCP) 8.5 for 2050, before economic adjustments.

Energy, Technology Issues

- Cambridge University Engineering professor Hugh Hunt has looked at this.
- To lower Earth temperatures the required amount would take 1 million tonnes per year, delivered to the stratosphere.
- Current aircraft getting to that altitude can only carry a payload max of 1 tonne (1.1 tons)
- That means **30,000 jet flights PER DAY**, for delivery

30,000 flights per day…

- … delivering not just their aerosol payloads, but also the products of combustion of their jet fuel – into the stratosphere.
- That means water vapor, N_2O, NO_x, other secondary emissions
- Water vapor in the stratosphere catalyzes the destruction of ozone
- And – CO2.
- This would seem a mixed bag of outcomes.

But Perhaps Reduced UV at Surface

- Madronich *et al.* 2018 find that stratospheric SO_2 injection sufficient to keep temperatures at 2020 levels despite “business as usual” emissions, actually reduces ground-level UV in the mid-latitudes by ~20-30%, as the aerosol-induced scattering and reflection more than compensate for ozone destruction.
- However, significantly higher water vapor into the stratosphere than was expected is being measured, especially over the US, from enhanced convection from enhanced surface warming. Water + SO2 = sulfuric acid, dangerous to stratospheric ozone.

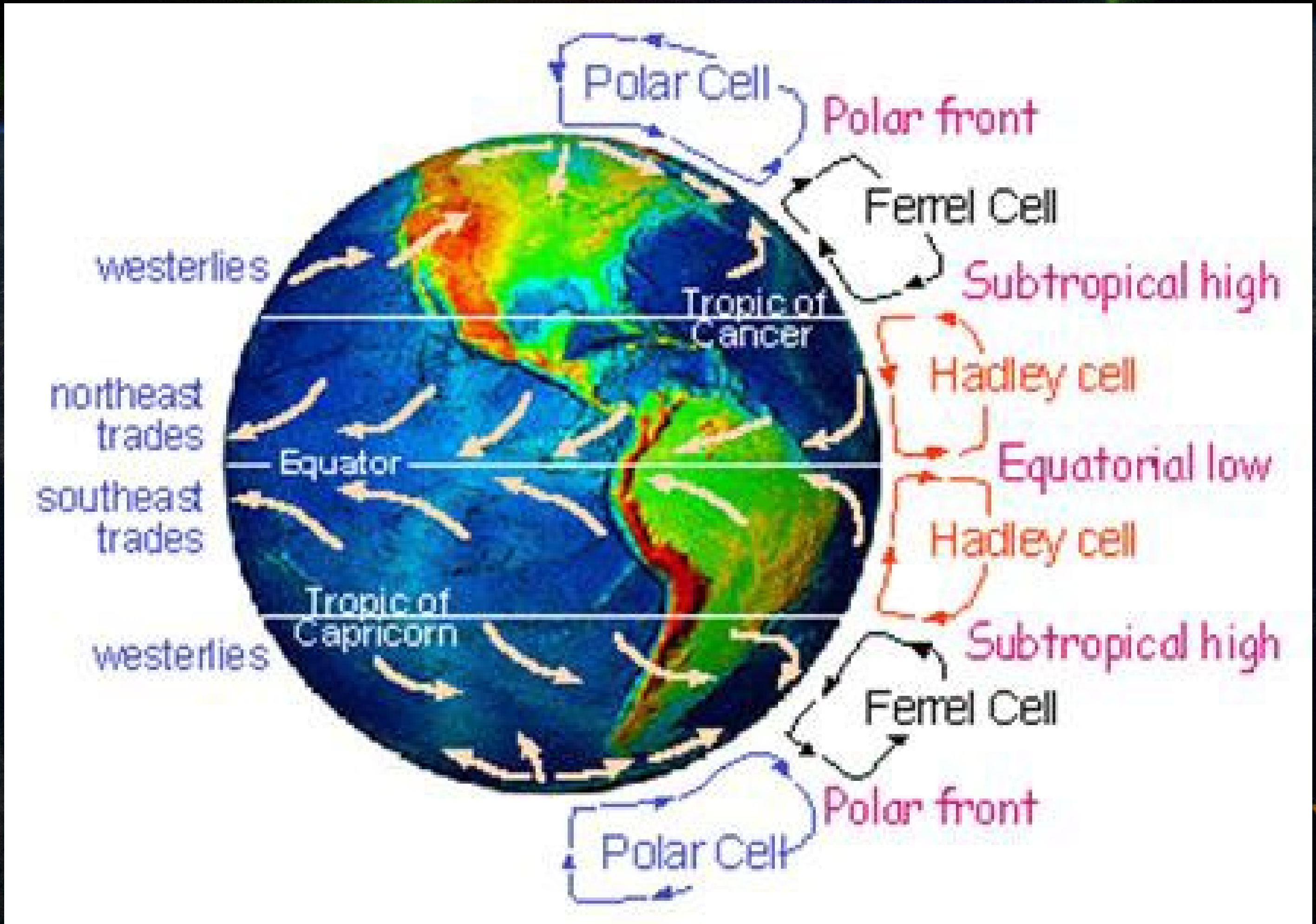
Other Issues with Sulfate Aerosol Injection

- Sulfate aerosols would come down out of the stratosphere on a ~2 years time scale at most.
- Therefore need constant injection, however, the costs look cheap compared to other GeoEngineering ideas. This is why profit-hunters are interested.
- Atmospheric sulfates make sulfuric acid. Continuous acid rain on our surface waters. Acid rain concerns?

Boomerang Trouble with Albedo Feedback from Aerosol Injection?

- These aerosols which, in the stratosphere, act as reflectors of sunlight before it heats the troposphere – it is hoped they would thus let ice remain frozen.
- But if the ice caps are the most important areas to cool, consider that those same aerosols will likely darken the ice onto which it falls.
- I’ve not seen this issue even mentioned, let alone quantified and discussed.

Remember, the ice caps are in the north end of the the Polar Cell, in which tropospheric air descends onto the ice.



More Issues

- Sulfate aerosols partially block Earth's <u>outgoing</u> radiative cooling, but their high reflectivity for <u>incoming</u> sunlight more than make up for this
- Astronomers would not be happy (but, they're not a significant voting block, so who cares?)
- Lowered incoming sunlight would reduce photosynthesis but perhaps aid soil organic carbon capture
- **The moral hazard…. An excuse to foot-drag on actual and long term solutions.**
- **– ALL sun shade strategies at best only cool the planet. By themselves, they do nothing to help the problem of CO2-induced ocean acidification if we continue to burn carbon.**

- *“Different model simulations (e.g. Robock et al. 2008) have shown that injection of 5x10^{12}g) of SO_2 into the tropical lower stratosphere every year (the equivalent of one 1991 Mount Pinatubo eruption every 4 years) could lower global average surface air temperature, but African and Asian summer precipitation would also be reduced, potentially affecting the water and food supplies of more than 2 billion people” (*from Robock *et al.* 2010*)*
- **That’s 5 million tonnes per year, but would only lower temperatures less than 1 C, estimated from Pinatubo’s effect.**

How Much Do We Need?

- Cambridge University's Hugh Hunt points out that to reverse our current warming would require about 1 billion tonnes of sulfates to reverse anthropogenic temperature completely.
- A more modest ambition would be 10 million tonnes of sulfates per year.
- Current aerospace technology can lift only 1 tonne per aircraft flight to the required altitude.
- Which translates to 30,000 flights into the mid stratosphere, far above where current jets fly…. per DAY. (Hunt – "Can we Refreeze the Arctic?" YouTube)
- We do about 100,000 commercial flights globally per day, so this is an additional 1/3 of that number.

Sulfate Aerosols and Corals

- **Kwiatkowski *et al.* 2015** find that higher CO2 emissions but paired with sulfate aerosol shading, does lower sea surface temperatures and therefore helps moderate coral bleaching, *vs.* no aerosol shading and lower CO2 emissions. (but, it hurts aragonite calcification of the corals via acidification, so maybe the algae would be temperature happier, but would they still have a coral host to be symbiotic with??)
- **As a desperation measure to halt temperature rise and therefore ice loss and sea level rise, they should continue to be investigated.**

But ONLY if it somehow proves Safe

- …AND we have the commitment to continue aerosol injection until atmospheric CO2 levels are somehow brought down to ~pre-industrial levels…
- The reason? Stopping aerosols causes abrupt climate change…
- "The Termination Problem"…

“Business as Usual” climate models with, and without, sulfate aerosol injection for 50 years only. At end, aerosols rain out, and high CO2 heat forcing from now too-cool Earth causes rapid catch-up warming (Robock 2014): SRM, once started, MUST be continued until atmospheric CO2 levels are artificially brought back down to levels in equilibrium with SRM-induced temperatures. In other words, the moral hazard cost is very high!

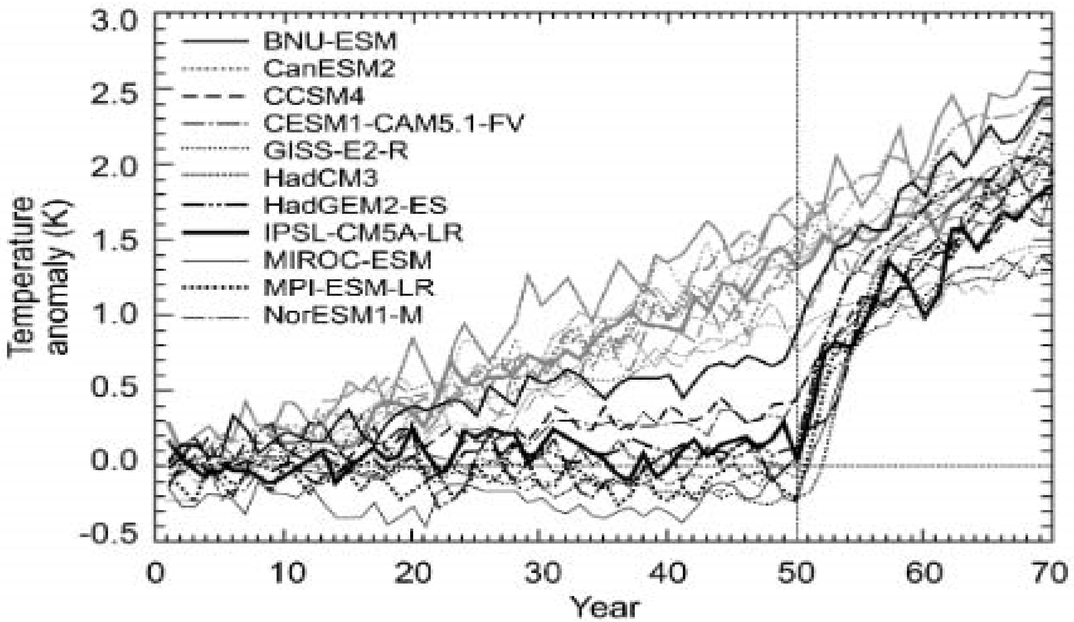


Figure 3 Evolution of annual mean anomaly of global mean near-surface air temperature (K) in the G2 simulations (black lines) with respect to the long-term mean from each model's control simulation. Time series from corresponding 1% CO_2 $year^{-1}$ increase simulations are also shown (gray lines). The termination of geoengineering in the G2 simulations is indicated by the dashed vertical line.
(Figure 1 from ref. 24; see this reference for climate model abbreviations and details).

Ozone Destruction: From an MIT Tech Review Article by Rotman 2013

- *(Harvard's) James Anderson says that adding sulfates to the stratosphere worries him "tremendously" because of the potential impact on ozone. He points to a study his group published last year in the journal* ***Science*** *showing that increasingly intense summer storms over the United States—triggered by climate warming—are injecting more water vapor into the stratosphere. That, he says, could speed the ozone-destroying reactions: "If nature is adding increased water vapor to the stratosphere and we're adding sulfates, it is a very lethal cocktail for ozone loss."*
- Indeed, Mt Pinatubo's 1991 injection of stratospheric sulfate aerosols caused a record loss of stratospheric ozone (Solomon 2009).

Other Stratospheric Aerosols Dangers

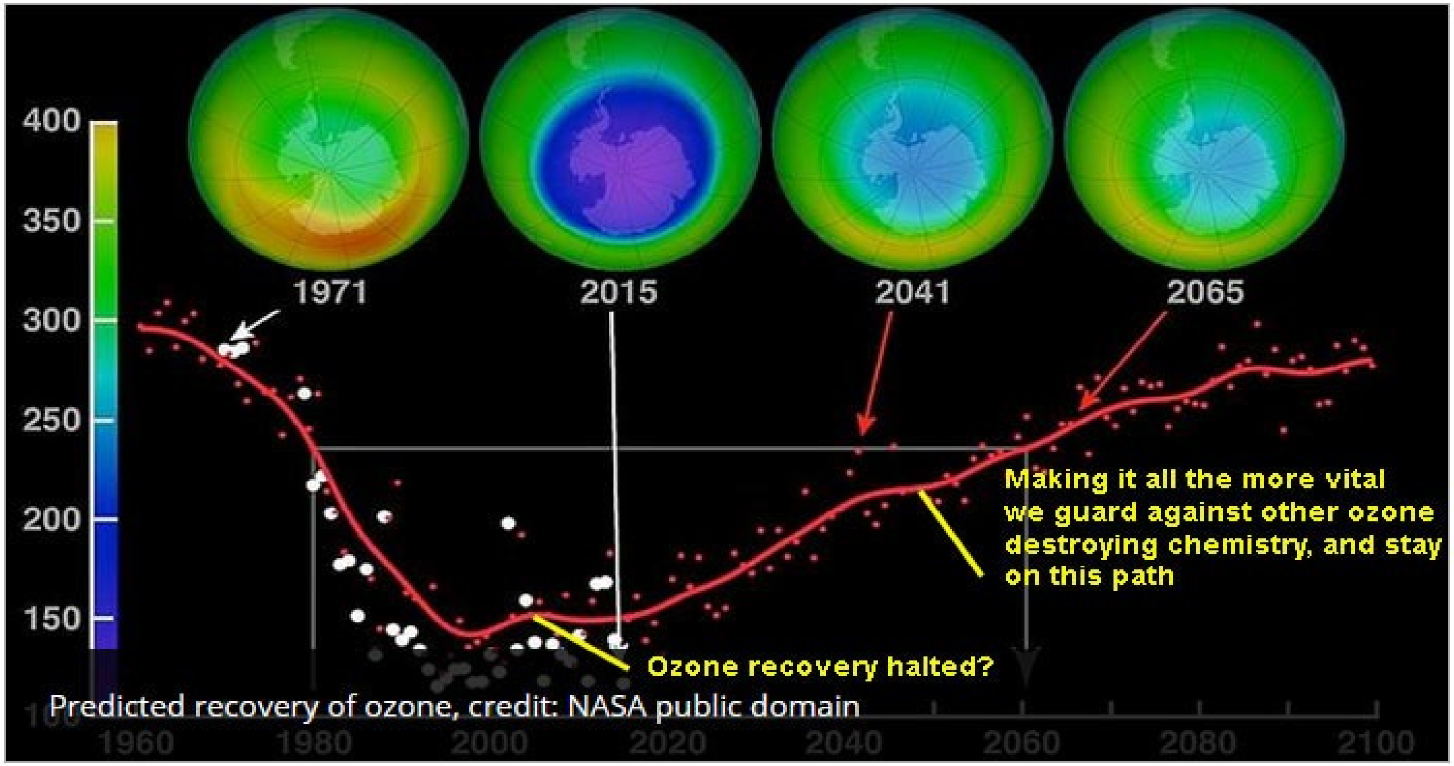
- How would it affect wind and hence weather patterns? A weakening of the Asian monsoon is predicted, other effects poorly known. Mt Pinatubo indeed altered global weather patterns. ANY changes could cause major wars initiated by adversely affected countries (Robock, 2014)
- Would real-world sulfate droplets combine to form larger droplets, as raindrops do? Bad – they would have less surface area/volume, and so reflect sunlight less well, and also fall to ground much faster, therefore causing more acid rain worries per ton injected, and require higher injections rates

Ozone Loss: How Serious?

- Mt Pinatubo's eruption in 1991 caused losses of total column ozone of 6% (Schoeberl *et al.* 1993, Chandra 1993) for ~6 months.
- But we need continuous on-going injections. If these losses turn out not to be additive with the continuous aerosol injections, then ~6% decreases might not be unacceptable, given Robock's study of injections at the rate of ¼ of a Mt. Pinatubo per year.
- But what if they are additive, or worse – self-amplifying, as more chemicals gang-tackle fewer remaining ozone molecules?

Slow ozone recovery from 1992 Montreal Accords banning CFC's has halted, as profit motivates continued illegal CFC's

CFCs and the subsequent healing of the ozone layer. With strict adherence to protocols, the Environmental Protection Agency (EPA) estimated the layer could recover by 2065.

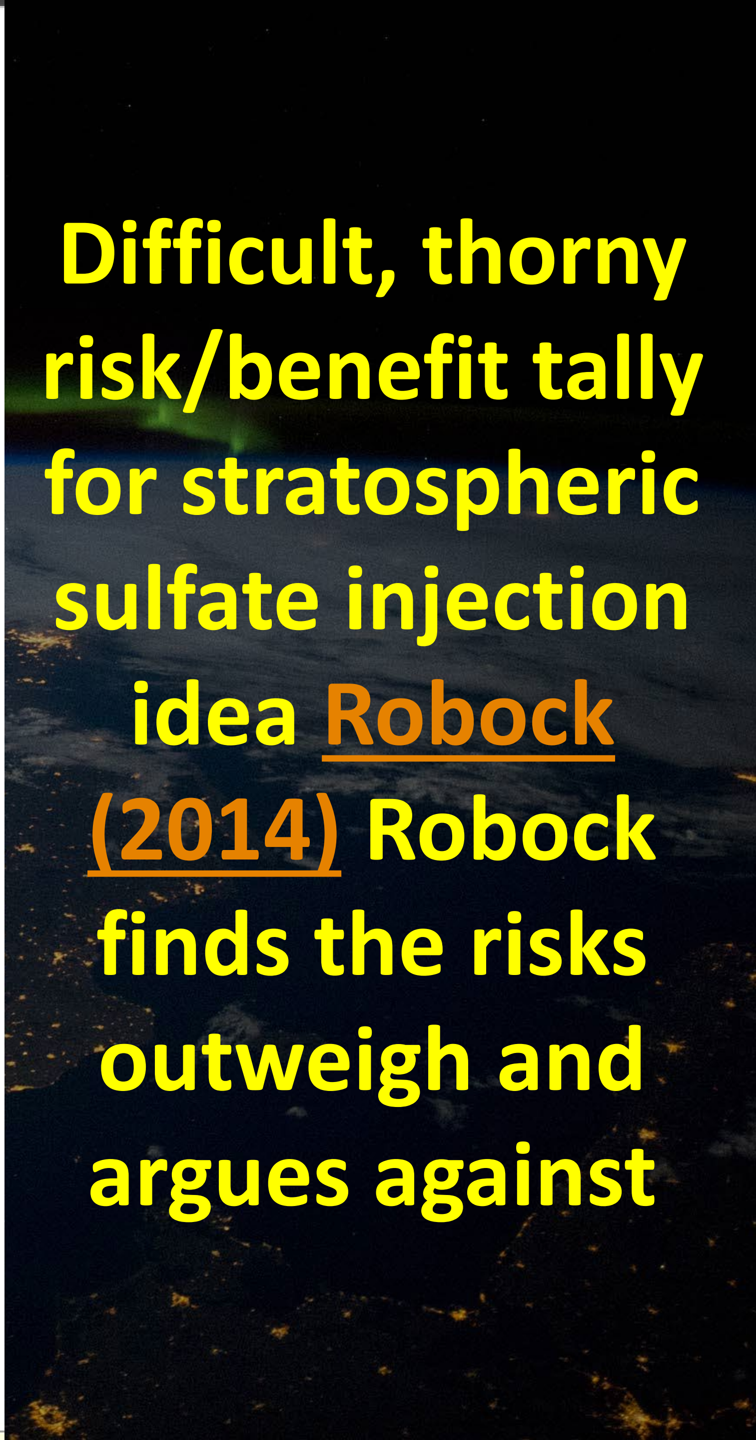


Predicted recovery of ozone, credit: NASA public domain

But a 2018 study reports emissions of the banned ozone-depleting chemical trichlorofluoromethane (CFC-11) are actually increasing and undermining the ozone repair process. While production of this once common insulation foaming agent was supposed to have stopped in 2010, its use continues and is believed to originate in East Asia.

Table 2 Benefits and risks of stratospheric geoengineering. The effects that are observed after volcanic eruptions are indicated by an asterisk (*).[56] (Updated from ref. 57).

Benefits	*Risks*
1. Reduce surface air temperatures*, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting*, land-based ice sheet melting, and sea level rise*	1. Drought in Africa and Asia*
2. Increase plant productivity*	2. Perturb ecology with more diffuse radiation*
3. Increase terrestrial CO_2 sink*	3. Ozone depletion, with more UV at surface*
4. Beautiful red and yellow sunsets*	4. Whiter skies*
5. Unexpected benefits	5. Less solar energy generation*
	6. Degrade passive solar heating
	7. Environmental impact of implementation
	8. Rapid warming if stopped*
	9. Cannot stop effects quickly
	10. Human error
	11. Unexpected consequences
	12. Commercial control
	13. Military use of technology
	14. Conflicts with current treaties
	15. Whose hand on the thermostat?
	16. Degrade terrestrial optical astronomy*
	17. Affect stargazing*
	18. Affect satellite remote sensing*
	19. Societal disruption, conflict between countries
	20. Effects on airplanes flying in stratosphere*
	21. Effects on electrical properties of atmosphere
	22. More sunburn (from diffuse radiation)
	23. Continued ocean acidification
	24. Impacts on tropospheric chemistry
	25. Moral hazard – the prospect of it working would reduce drive for mitigation
	26. Moral authority – do we have the right to do this?



“Barking Mad”?

- Harvard professor James Anderson: we need to do real-world experiments to find out.
- Geophysicist Raymond Pierre-Humbert judges the idea “barking mad”.
- Award winning environmental film maker David Suzuki calls the idea “insane”
- Rutgers Professor Martin Bunzl argues that the worst problem with stratospheric aerosol SRM is that it cannot be tested. It can only be fully implemented and then wait long enough for the signal of its effects to rise above the statistical noise from weather, and find out if it was a good idea. Global weather patterns WILL be affected, in poorly known ways.

A Better Stratospheric Aerosol Idea? CaCO3 (Calcium Carbonate) Aerosols?

- Testing begins soon, Harvard's David Keith and colleagues are now exploring this
- Using CaCO3 aerosol rather than sulfuric acid droplets should negate acid rain, and have less effect on ozone… probably. However, Keith notes…
- *"Stratospheric chemistry is complicated and we don't understand everything about it," Keith said. "There are ways that this approach could increase global ozone but at the same time, because of the climate dynamics in the polar regions, increase the ozone hole."*

Calcium Carbonate Problems

- Unlike sulfates, CaCO3 might require highly energy-intensive pulverizing of massive quantities of limestone, energy which now would have to be fossil-fuel energy.
- Would CaCO3 form droplets at all? It is the liquid droplets of sulfuric acid which are so highly reflective and accomplish the cooling with sulfate aerosol injection
- There are no acidic droplets using CaCO3, but that may also mean there's not as much albedo help. Not clear at present.
- Alteration of global weather patterns still would remain a danger, just as with sulfates

How about Pulverized Salt in the Stratosphere?

- Cheap and plentiful, and doesn't cause acid rain like sulfates. But high energy required to turn salt to the ~0.5 micron size thought optimal (Nelson *et al.* 2018)? Discussed here
- But now we have salty rain instead… ecosystem effects probably not good?
- Would it be as reflective if not in droplet form?
- And salt is made of sodium and chlorine, and it is the chlorine in CFC's which caused the stratospheric ozone destruction prior to the Montreal Accords.
- Cheap raw materials, anyway, if cost/profits is your concern, as it is with the proposers of these schemes.

An SRM Issue I don’t see Discussed:

- The nature of the process means that the major cooling will be where there is the major sunlight – the tropics, daytime side.
- Yet radiative cooling is from all sides of Earth, and that is not changed in this strategy.
- A global shift in the temperature gradients across the Earth will cause large and hard to predict changes in the global atmospheric circulation and ocean currents which re-distribute heat, and also guide the rain-making weather systems.

Aerosol injection could be a strong disruptor of the climate the Earth System has adapted to for 10,000 yrs.

- Global civilization for thousands of years has been built and fine-tuned around precisely the rain patterns that have been stable during the history of civilization.
- Now, there will be rain “winners” and rain “losers” among continents and countries.
- What will the losers do? Shoot down the aerosol-makers’ planes? Start wars? Do their own counter-attacks with even more poorly understood climate weapons?

Serious Political Problems with Climate Intervention Strategies, including Stratospheric Aerosols

- Any scheme could be used as a weapon to *e.g.* increase/decrease rain for one country at the expense of neighbors or political enemies.
- Russia has no evident interest in halting global warming. They benefit from thawing of the Arctic permafrost and easier access to massive underground natural gas reserves there, and in the off-shore Arctic oil reserves, and are definitely a relative winner as global warming harms the rest of the world more.

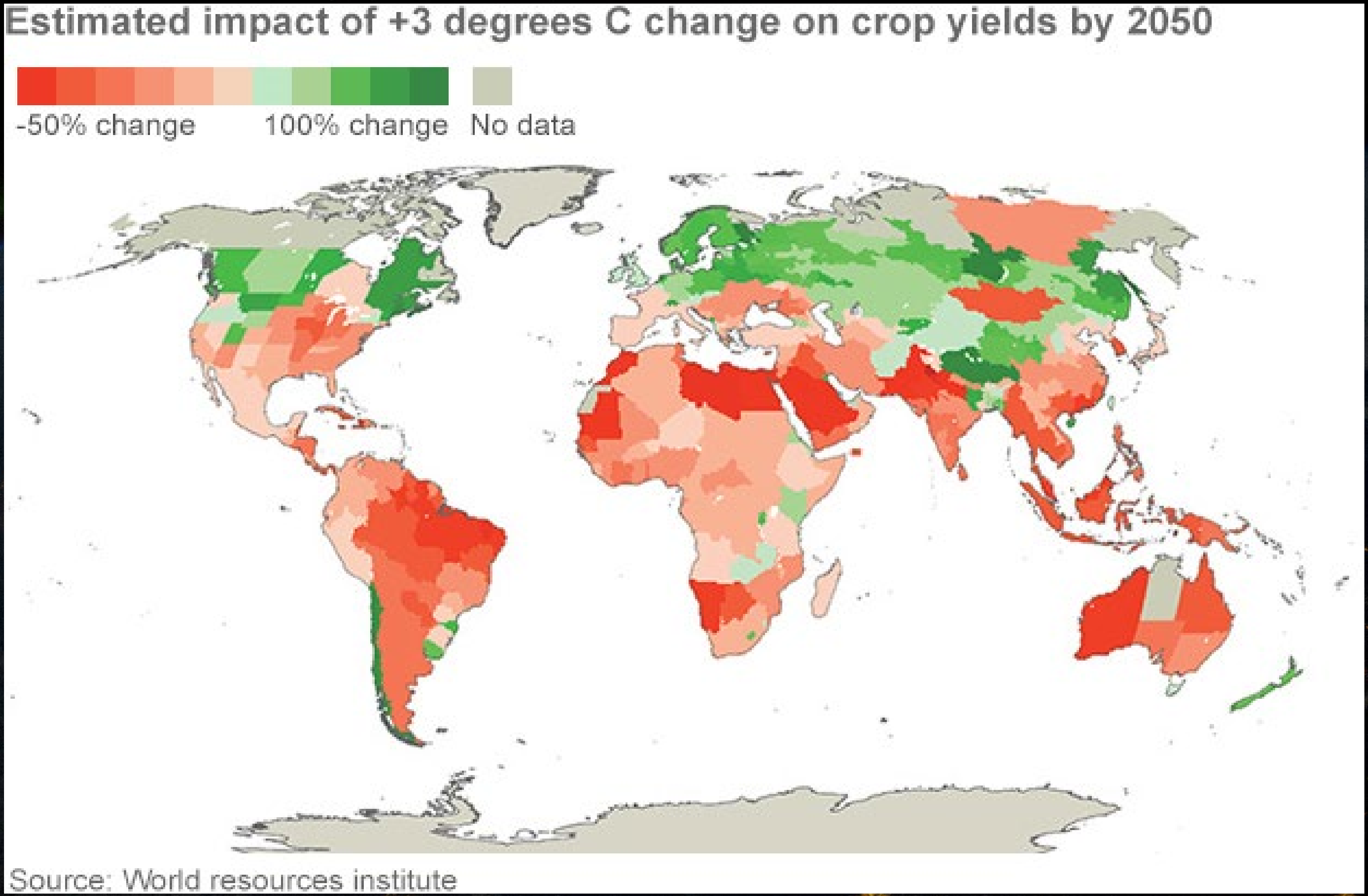
Russian President Putin plans to take advantage of the melting of the Arctic (links here)

Haaretz

Climate change could make Russia great again - Science ...

Any unilateral attempt by the US and/or Europe to begin massive stratospheric aerosol injection may well be regarded as an Act of War.

Russia and Canada are also relative crop yield winners from climate change, and thawing permafrost also helps Russia access frozen oil, gas fields, Siberian Shelf carbon



However, Stratospheric Aerosol Injection is the fastest, cheapest major action we could take, so I think we'll do it anyway

- Proponents claim for about $2.5 billion/year we could inject ~1/4 million tons of sulfates into the stratosphere, less than major volcanic explosions have done this past century
- Yet enough to (perhaps) measurably cool global climate a bit (but makes the rosy assumption that droplets don't merge, which is questionable and cannot be tested adequately without full global implementation)

Desperate People do Desperate Things

- The effects on ozone, increasing cirrus clouds, changing rainfall patterns, and the rest, are not known, even perhaps not knowable with any confidence at all, until deployed.
- Do I think we'll become desperate enough to try it? **Yes. I believe that day will come. In fact, desperate times are already arriving. We'd better study it and thoroughly understand what it will do, NOW...barking mad or not.**

Capturing CO2 by Accelerated Weathering of Limestone

- Greg Rau (UCSC) - the basic idea is to crush limestone, combine it with carbonated water, and capture the CO2 in the form of calcium bicarbonate. The pH of the bicarbonate makes it fairly safe to simply deposit into the ocean

$$CO_{2(g)} + CaCO_{3(s)} + H_2O_{(l)} => Ca^{2+}_{(aq)} + 2HCO_{3}^{-}{}_{(aq)}.$$

- His paper explores the cost of CO2 capture from natural gas fired power plants. Cost estimated at ~$40/ton of **flue gas** CO2 sequestered. (YouTube promo seeking funding). But that's for high-CO2-concentration power plant flue gas, not dilute 400ppm atmospheric concentrations, which would be MUCH costlier.
- http://aftre.nssga.org/Symposium/2004-09.pdf
- I've not found updates to this, but Rau has a newer process which may be better

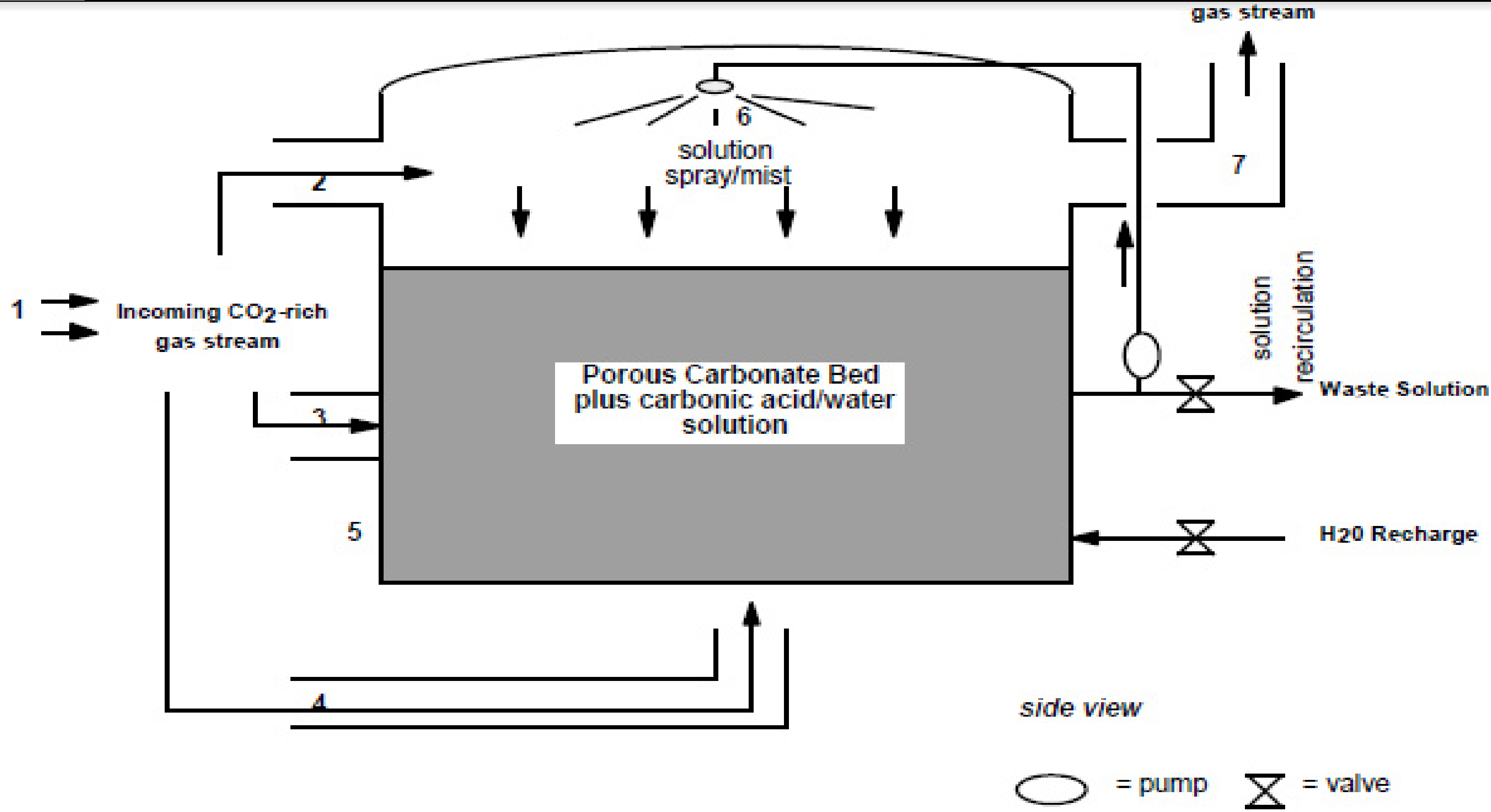


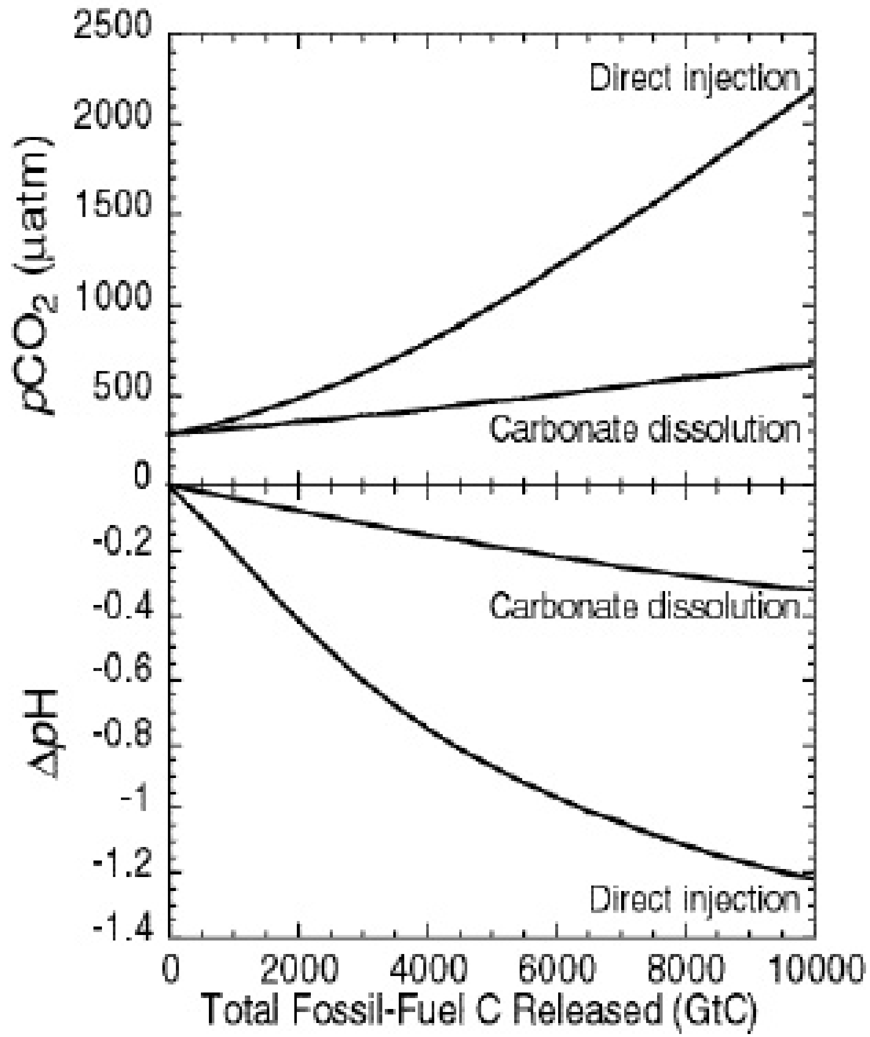
Figure 1. An example of a possible carbonate dissolution reactor design. A CO_2-rich gas stream (1) enters the reactor vessel (5) by one or more entryways (e.g., 2, 3, and/or 4). The gas stream then passes over or through a wetted, porous bed of limestone particles within the reactor. This carbonate mass is sprayed (6) and wetted with and partially submerged in a water/carbonic acid solution which is unsaturated with respect to bicarbonate ion. This arrangement exposes the incoming gas to a large surface area of water/solution in the form of droplets and wetted carbonate particle surfaces in (5), facilitating hydration of the entering CO_2 to form a carbonic acid solution within the reactor. CO_2-depleted gas then exits the reactor (7). The carbonic acid solution formed reacts with the carbonate to form calcium ions and bicarbonate in solution which is either recirculated or bled from the reactor and replaced with unreacted water within the reactor at a rate which maximizes benefit/cost.

In Case the Context isn't Clear

- The dire science is telling us that it's **not - EITHER** we pull CO_2 out of the atmosphere, OR we pull it out of power plant emissions…
- It's BOTH. We need BOTH. I take for granted that power plant CO_2 needs to be captured and sequestered. But it may be cheaper to just scrap the fossil fuel power altogether and substitute renewables, especially modern nuclear.
- I'm taking that for GRANTED (even though it's not being done; foot-dragging fossil fuel companies)

Rau's method w/ outflow to the ocean results in minimal pH and pCO2 effects *vs.* letting atmospheric CO2 directly diffuse into surface waters

Figure 3. Comparison of the effects of direct CO_2 injection and the carbonate dissolution technique, both released into the deep-ocean (mean depth: 1950m), on atmospheric CO_2 content (top panel) and deep-ocean *p*H (bottom panel) 1000 years after injection. If the ocean's anthropogenic carbon capacity were determined by the amount of CO_2 that would shift ocean *p*H by 0.3 units, then the carbonate dissolution technique would increase the ocean's capacity by roughly a factor of six. With the direct-injection method, for large amounts of anthropogenic CO_2 released, over 45 % of the injected CO_2 is in the atmosphere after 1000 yr. With the carbonate dissolution method, less than 15 % of the initially released CO_2 degasses to the atmosphere.



Rau's Silicate or Limestone Processes are among the safer CO2 removal mechanisms I've yet found. However, up-scaling to address climate does not look feasible. A conversation with Rau confirms

- Requires ready source of limestone, so could only be done on large scale from certain coastal locations?
- Results in equilibrium pH change in ocean, after 1000 years, of -0.0014 per 35B tons CO2 processed. (35B tons CO2/yr was about the current rate that we're injecting CO2 into atmosphere), and this is acceptable in terms of its effect on ocean life (compare to our ocean slide show on pH rate of change today)
- More figures and power requirements should be done – it's worth a careful examination

- In 2012 I contacted Greg Rau (he's a professor here at UC Santa Cruz) and suggested he consider ways to apply his chemical process not only to flue gas, but to the atmosphere.
- He has since teamed with Klaus Lackner…
- Rau and Lackner – together! (but behind paywall!)
- Here's a YouTube with Rau

Ocean Chemistry Modifications in General Share a Major Problem…

- **Gradients!** Any strategy to be done at climate-significant scales will be a major change to the existing ocean.
- In contrast, air mixes rapidly, so pulling CO2 out of the air from relatively few massive installations shouldn't cause harmful gradient issues. Not true for the ocean.

The mixing time for the ocean is of order 1,000 – 4,000 years – and getting worse as the thermohaline circulation slows.

- Changing the chemistry of the ocean at only a few cost-favorable locations but yet at climate significant scales meant to help us not in 1,000 years but in the near future, will mean strong gradients in chemistry for as long as they are done.
- In Rau’s case, in bicarbonate and pH. This will have a major effect on ocean ecosystems in these areas, detrimental since change *per se* is bad for adapted climate ecosystems.
- The only solution is to disperse the chemistry from very large number of locations widely spaced.
- I’ve talked with Rau more recently. He agrees this may not be practical. But for localized places where we wish to save *e.g.* shellfish commercial aquaculture, it could be valuable.

The CarbFix Project

- Forces CO_2 dissolved in water into deep underground basalt formations, where in a matter of a few years it turns to carbonate rock. Basically, the silicon is replaced by carbon in silicate-rich basaltic rock
- Pilot project shows some success at very small and slow scales, in thermally favorable locations.
- The idea is: pumping liquid carbonated water underground and letting the porous surface of basaltic rock (if its porous) do the chemistry

Can CarbFix Work on a GeoEngineering Scale?

- On the plus side…
- The required basalt is common worldwide. The Pacific Northwest Columbia River formation might, optimistically, hold 100 Gt of CO_2, or ~3 years of current annual global CO_2 emissions
- Original paper (Matter *et al.* 2009) was a decade ago. The latest update (Matter *et al.* 2016) shows that if the water is pre-alkalized sufficiently (cost??), then mineralization of their small pilot project amounts still took fully 2 years to happen. That's **Slow.**

CarbFix – Minuses…

- Requires 25 tons of water for every 1 ton of CO2
- Pilot project only injected a few hundred tons of CO2. This is microscopic on climate scales. How much CO2 can really be injected at a given site before it plugs up, and yet after all the costly pumping infrastructure has been installed? Hard to know till it suddenly stops taking more injection.
- Once the contact space in the pores is covered, won't further CO2 be isolated from the necessary rock chemistry? Not discussed, but especially worrisome on climate-relevant scales.
- Optimal contact requires powdered basalt, not rocks. Simply looking at tonnage of basalt makes the implicit assumption that all of that basalt is contact-available to the alkalized water. But basalt isn't generally so porous that fossil ~millimeter size bubble pores connect with each other except a small fraction of the time

CarbFix – Minuses Continued…

- Pumping is expensive in energy and dollars, to high pressures necessary to force down ~1/2 km underground – if energy source is fossil fuel combustion, it's a non-starter.
- Toxic metals mobilized in the process, going into our ground water
- Costs are conspicuously absent in update paper of 2016. Other flue gas CCS underground projects are well over $100/ton CO2 as of 2016. Would be much higher if applied to the atmospheric CO2 which is 1000x more dilute
- Still, it is worth more study

Related: Add $CaCO_3$=Calcium Carbonate Powder Directly to the Ocean

- Harvey *et al.* 2012 suggest this, although it would take decades to have an effect on fighting acidification, and it would be a tiny "drop in the bucket".
- Would (marginally) help the ocean absorb CO_2 from the atmosphere, but plenty of limestone is already in contact with the oceans along many shorelines worldwide, so would this be helpful at all?
- ~10% of the Earth's surface is covered by limestone.

Add CaCO3 to upwelling areas…

- …sequesters an additional 0.3 billion tons of CO_2 per year (less than 1% of what we add by fossil fuel burning).
- Would seem to be a pretty minimal effect, and geoEngineering specialist Prof. Ken Caldeira agrees.
- The ocean is home to vital and precious life. Don't these ecosystems deserve stability?
- **<u>Bottom line – doesn't look promising</u>**

Drawing CO_2 out of the atmosphere and using it to make carbonates – limestone rock (Belcher *et al.* 2010)

- … a process which happens naturally by ocean life (but too slowly, and cannot happen at all in a too-acidic ocean such as rapid CO_2 rise is creating).
- Major problems to be overcome; the amount of energy required in the process, scaling up to the levels needed to affect our atmosphere, sourcing calcium, and cost, among others.
- Given that humans have injected an additional 1.2 trillion tons of CO_2 into our atmosphere over the past 250 years, the Belcher *et al.* process would require ~2.4 trillion tons of $CaCO_3$, and at 2.71 g/cc density of calcium carbonate, this means…

Need Mt Everest-sized Block of $CaCO_3$ to Get Back to Pre-Industrial Atmospheric CO_2 Levels

- This would require building 8×10^{17} cc's of rock, or a cube 1 million centimeters on a side, which is a ***<u>Limestone block higher than Mt. Everest (30,500 ft on a side) from sea level.</u>***
- That's also going to require a lot of calcium. Calcium is common, but mostly it is found as - calcium carbonate! Destroying $CaCO_3$ in order to make $CaCO_3$?? is seriously *<u>questionable</u>*.
- Breaking up $CaCO_3$ to get the Ca then leaves you… CO_2, the very thing you're trying to get rid of.
- <u>Bottom Line: **looks like a non-starter.**</u>

Start Smaller?

- To instead immediately drop current CO2 atmospheric levels from 400 ppm to 350 ppm would require a cube of calcium carbonate of only 22,180 ft on a side; still higher than any mountain in the Western Hemisphere.
- At current direct human emission rates of ~40 billion tons of CO2 per year, it requires an additional cube-shaped mountain 8,000 ft on a side every year.
- Is it possible to build "scrubbers" for the atmosphere that could accomplish such a vast task? Where do we put it all - the ocean? We'd better make sure ocean acidification doesn't reach levels (as they will this century, on our current trajectory) that begin to dissolve existing oceanic calcium carbonate.

On the Plus Side: Visualize oil company executives conscripted to toil under the hothouse conditions on 21st Century Earth building the Great Carbonate Pyramids, miles high, sufficient to clean up our atmosphere. At wages comparable to those of the poor souls who built the pyramids of Egypt. Likely we'd find people to donate the necessary land just for the satisfaction of watching them toil.

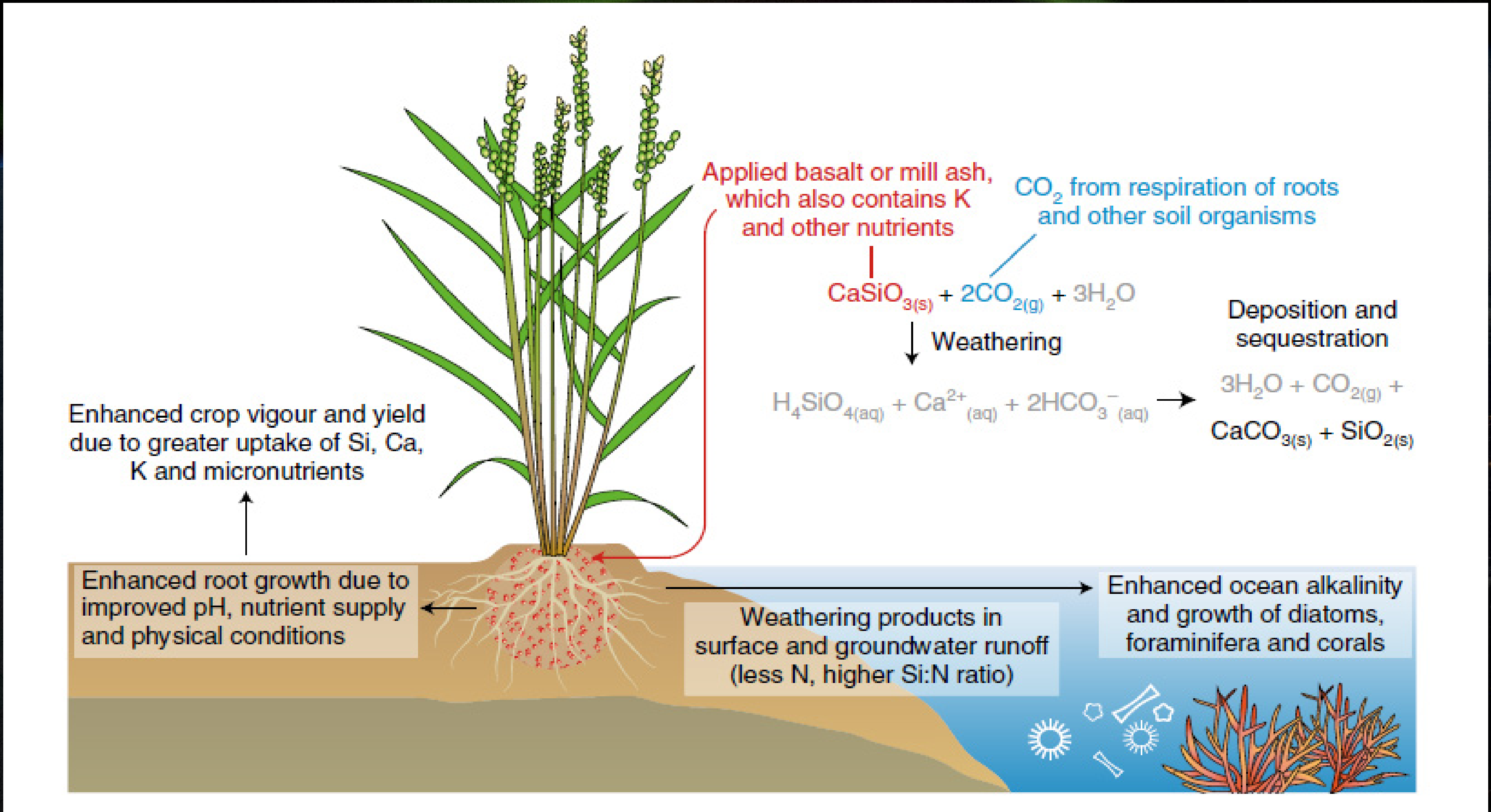
Realize Why So Hard…

- These rock-oriented ideas are all on the "Long Carbon Cycle" scale.
- We saw in **K33: Carbon Cycles**, that the equilibrium of carbon on these million year scales was determined by the primary pre-industrial net source of CO2 into the atmosphere: Volcanos
- But humans today are injecting long sequestered fossil carbon into the atmosphere at rates more than 100 times higher than volcanos.

Silicate Rock Dust Fertilizer

- The idea here is to grind up basalt rock (rich in silicates) and apply to agricultural land
- Water + atmospheric CO2 will chemically weather the silicate, making carbonate which plants can help take up, or remain in soil
- Scale, again, needs to be ~100x Natural, as we just saw, to be climate significant.
- Energy cost of grinding up basalt to proper surface area – to – volume ratio looks very high. That’s fossil fuel energy for the forseeable future

Run-off, deposition can also take the carbonates to the ocean, where organisms can convert to CaCO3 and sequester, slowly (but via rivers – where the altered pH may adversely affect ecosystems?



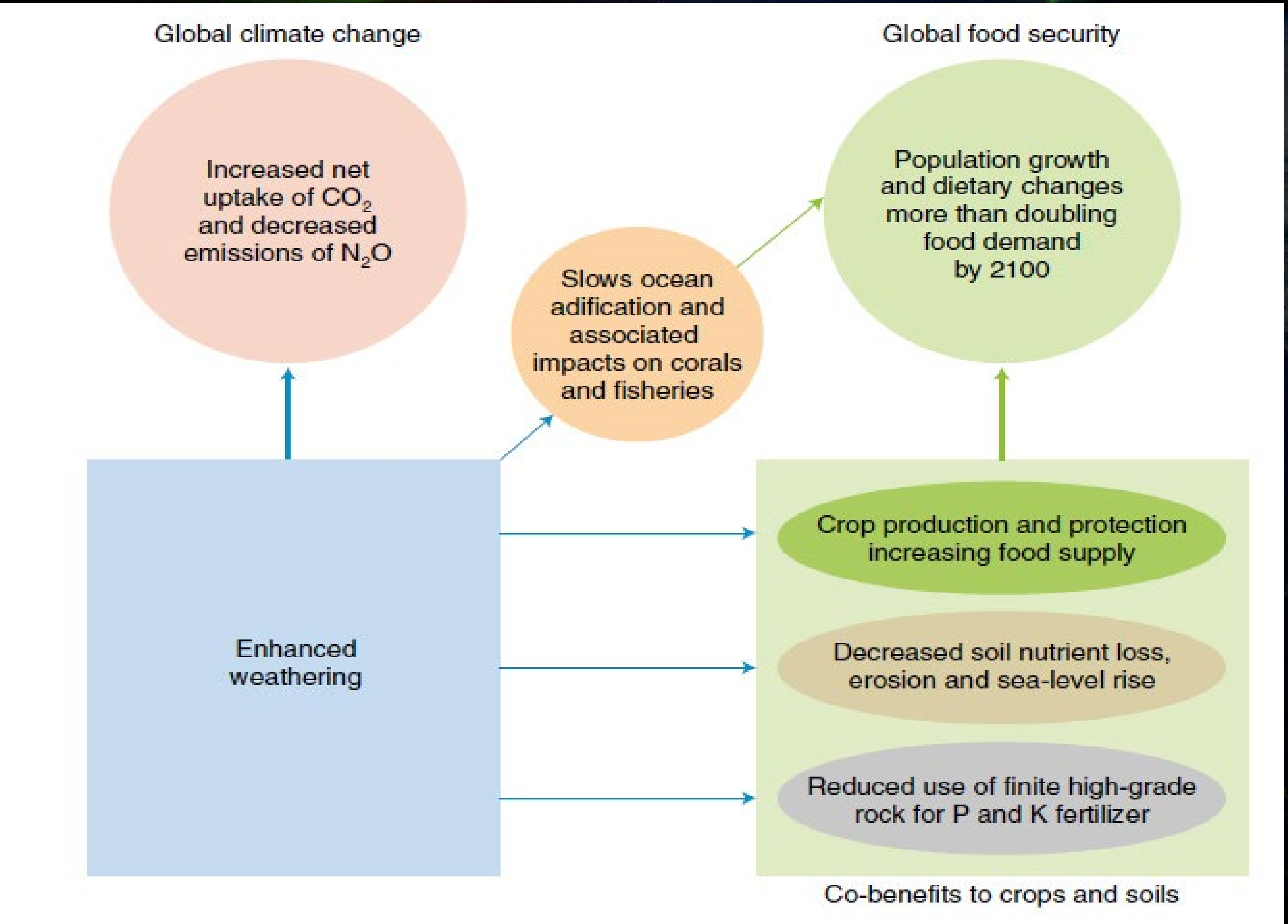
The Future of Agriculture Requires Addressing Critical Erosion

- The rate of erosion of conventional tilled land is 1%/year, and exceeds the production rate of soil, globally by an order of magnitude (10x) or more (Montgomery 2007)
- Adding ground-up common basalt to soil could improve yields and root systems and slow this erosion.
- Costs not addressed

But Can it Be Done? Problems:

- The energy required for grinding is vast
- Climate change is causing soil carbon to be lost, not gained, and expected to worsen (Beerling, *et al.* 2018)
- Care must be used in the rock selected – Olivine-rich rocks release toxic chromium and nickel under the planned chemical weathering.

Costs, environmental negatives are a major concern, but if it can be made feasible, here are the positives. The feasible scale, looks far too small, though (next slide…)



Hartmann and Kempe (2008) : Calculated Costs in Dollars, Energy, and CO2 Creation are Very Discouraging

- *"Applying first estimates of 'normal treatment' amounts from a literature review, we report here a theoretical global* ***maximum potential of 65 million tons sequestered Carbon/year if applied homogenously on all agricultural and forested areas of the world. This is equivalent to 0.9% of anthropogenic CO2 emissions*** *(reference period 2000-2005).*
- *"First, however, the assumed application of (ground silicates) on most of the considered areas is not economically feasible because of logistic issues, and second; the net-CO2 sequestration is expected to amount to only a fraction of consumed CO2 due to the energy demand of the application itself (currently ~11%).*
- *Unless progress in application procedures is provided, the recent realistic maximum net-CO2-consumption potential is expected to be* ***much smaller than 0.1% of anthropogenic emissions****"*

Beerling *et al*. (2018) try to be more hopeful, suggesting refinements, but…

- Some suggestions save money by using industrial wastes and sugar cane ash, but the sheer volumes needed to capture/sequester carbon at climate significant scales, would overwhelm these sources.
- And - more research is needed… *"At present, however, the long-term effects of applying pulverized silicate rocks on the organic carbon content of agricultural soils is not understood and requires further research. Over time, adding crushed rocks to soils will change their porosity, and other factors governing hydrology, with feedbacks on crop performance, trace gas emissions and the diversity and functioning of soil organisms that are still uncertain."*

A.I.M. Arctic Ice Management: Re-Freeze Arctic Ocean with Wind-Powered Pumps?

- Desch *et al.* (2017) calculate we could re-freeze the Arctic Ocean by using 100 million bouy-mounted wind-powered pumps to coat the cold surface of winter ice with sea water, freezing it.
- Their calculations include latent heat, ice conductivity, cloud cover, and past studies' empirical relations to find that pumping 1.3 meters of additional sea water onto the surface of the ice would yield an extra 1m of ice per winter.

How Does A.I.M. Fit Our Safety and Efficacy Criteria?

- **It passes nicely!...**
- **Criterion #3:** Repair modification on crippled Arctic Ocean ice surface only.
- **Criterion #2:** A.I.M. retraces backwards the damage we have done in melting the Arctic Ocean ice cap, without apparent bad side-effects.
- **Criterion #1:** A.I.M. reflects sunlight back out into space in the natural way it did for hundreds of thousands of years prior to the 21st century and human carbon emissions
- The main question is: Can the engineering feasibility be solved?

Need only 10 million pumps if limited to most favorable areas, but ultimate hope to expand to <u>100 million </u>(entire Arctic Ocean) as Arctic re-freezes

- 10 yr implementation of 10 million pumps per year would require 7% of global steel production. That’s do-able.
- Deployment of 10 million pre-built pumps to Arctic in 1 year would require half of global shipping capacity, but 1 million per year spread over 10 years only requires use of less than existing idle shipping capacity. That’s do-able.

Direct Costs?

- High, but not astronomical, and not infeasible. They assume maintenance costs are less than manufacturing costs over life of pump
- $500 billion/yr for 10 yrs covers all Arctic Ocean
- This is only 0.64% of Global GDP, and far less than Big Oil’s existing government subsidies
- It’s about 40% more than the annual revenue of U.S. auto manufacturers
- It’s also about what was spent on the Iraq war (whose main product was suffering).
- To cover 10% of Arctic would be 1/10 of above

A.I.M.: Environmental Costs?

- Manufacture raises global CO2 by only ~0.5%
- This idea fits exactly the kind of strategy we should be pursuing, which is to closely trace backwards those Earth system changes which took us to today. Lost ice is the triggering cause of the **Permafrost Carbon Feedback** and Arctic Amplification aspects of global warming.
- AIM goal is to re-build lost Arctic Ocean ice to a state it was at just a few decades ago. It produces no atmospheric chemicals, no toxic fuels, doesn’t tamper with the global ocean thermocline, doesn’t enlist novel and dangerous changes to global ecosystems, nor tropospheric nor stratospheric chemistry.

Carnegie's Ken Caldiera and Colleagues Studied Whitening the Arctic Ocean

- But in a context after CO2 levels were allowed to keep skyrocketing to levels that would otherwise lead to the almost certain end of civilized society… 4x pre-industrial CO2 = 1138 ppm.
- Not surprising, they found that at such high CO2, the Earth is so hot that permafrost melt is only mildly helped by the far north reflectivity.
- Clearly we'd want to do this long BEFORE such CO2 levels were reached!

But at today's CO2 levels, Arctic Ocean Iced or De-Iced, Makes a Very Large Climate Difference…

- Arctic Ocean ice loss was measured by Pistone *et al.* (2014) to contribute a very large heat input. From their abstract…
- *"We find that the Arctic planetary albedo has decreased from 0.52 to 0.48 between 1979 and 2011, corresponding to an additional 6.4 +/- 0.9 W/m² of solar energy input into the Arctic Ocean region since 1979. Averaged over the globe, this albedo decrease corresponds to a forcing that is 25% as large as that due to the change in CO2 during this period, considerably larger than expectations from models and other less direct recent estimates. Changes in cloudiness appear to play a negligible role in observed Arctic darkening, thus reducing the possibility of Arctic cloud albedo feedbacks mitigating future Arctic warming."*
- **8% Global Albedo loss; Adding fully 25% additional global heating to that already due to our CO2 changes. That's highly climate significant.**

AIM: Could it Really be Made to Work? Questions to be answered…

- Wouldn’t water pumped to the surface just freeze right away and form an “ice mound” instead of a ~uniform sheet over 0.1 km^2 area? How to insure the latter?
- 10-100 million of these, would drift with the currents, perhaps out of the most favorable areas. Cost of towing back to favorable positions? Probably not high. How about throwing down an anchor?
- Effect on Arctic ecology of the effort to service 10-100 million bouyed wind-powered pumps?

Political Non-Starter?

- This all assumes that we WANT to save the ice cap.
- Remember; rational people caring of future generations do not run this planet. Biz people and their neoclassical economists do.
- Fossil fuel companies, tourist cruise companies, shippers of all kinds are eyeing the Northwest Passage free of ice with great anticipation. It means… money! Money **now**!
- Corporations would not favor re-icing the Arctic Ocean, and that may be what kills it.
- Realize this is not THE solution to global warming, it is a safe strategy for neutering an important positive climate feedback while we take CO2 emissions from positive to negative, which ultimately is what must be done.

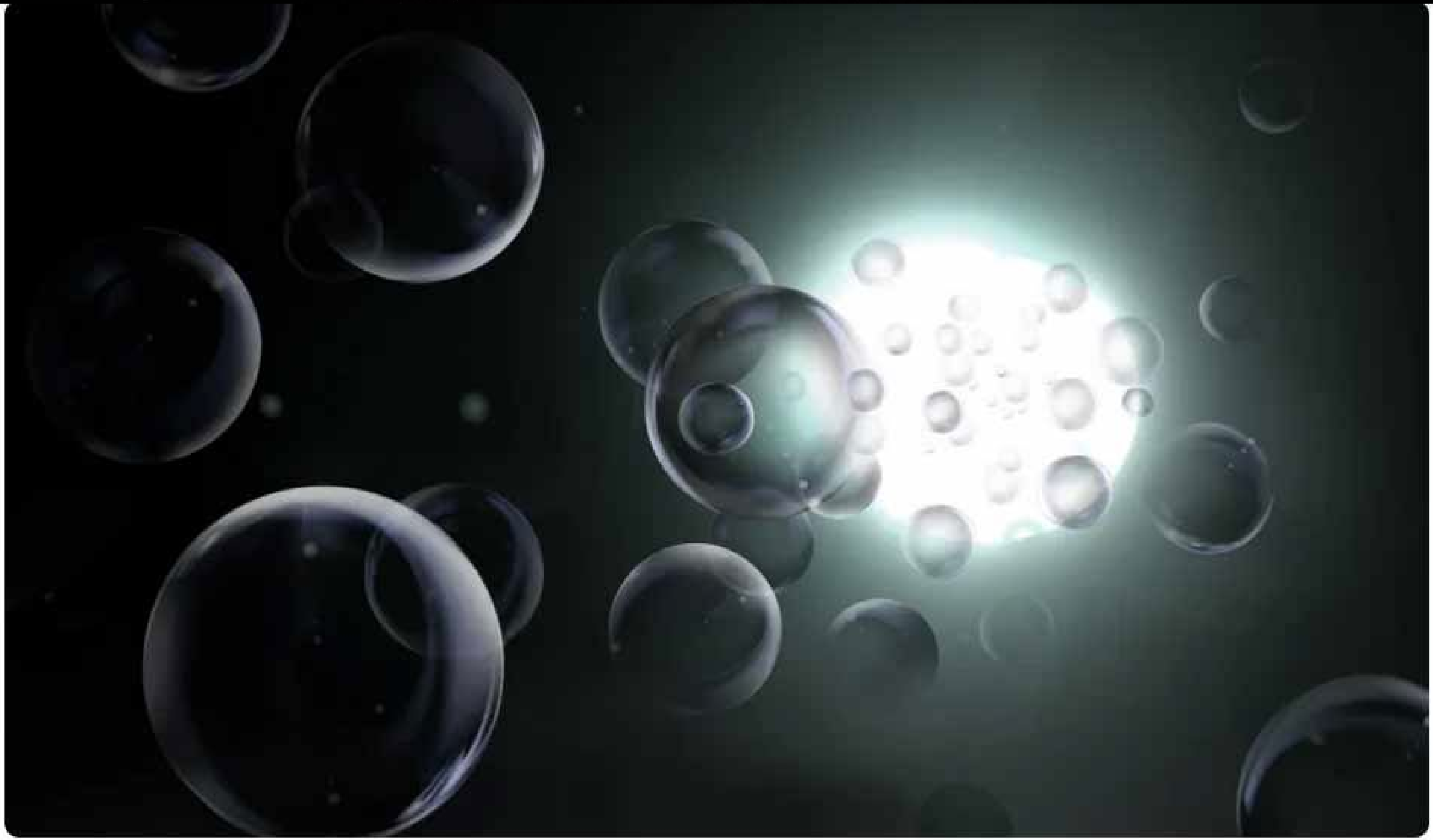
Spreading “Eco-Sand” on the Ice??

- A glossy ad by business interests is promoting spreading their proprietary “eco-sand” on top of Arctic Ocean ice to reduce its melt rate.
- The ad doesn’t answer key concerns:
- 1. The sand will sink when the ice melts
- 2. The sand will only weigh the ice down and yet be covered up by the next bout of snow, and so be ineffective.
- 3. The sand will pile up on the bottom of the ocean, where there are native ecosystems.
- We should be highly skeptical of schemes that are cheap - thus promising high profit margins for the investors - but dangerous and of questionable effectiveness, if not downright catastrophic in the longer term.

Run Ice-Breakers Across the Arctic Ocean in Winter to Let Heat Escape

- Climate Science Veteran Michael McCracken, PhD, explains that in summer, ice is a coolant as it reflects sunlight, but in winter when the sun is absent, ice is instead an insulator preventing warm water beneath from freezing.
- If we run ice breakers through the thinning ice, we let the warm ocean cool to the air and sky, thereby forming more ice than otherwise.
- We need studies to quantify the costs and effectiveness.

Space bubbles at L1 to deflect sunlight?? MIT is floating the idea



space bubbles in front of sun, MIT concept

Albedo Modification of Non-Ice Polar Land: “Pleistocene Park”??

Why? Boreal Forests are dark and absorb solar radiation

- …and actually worsen our heat problem *vs.* the more reflective tundra and grasslands alternative, according to Bala *et al.* 2007 (but controversial, as we saw earlier here)
- This unlikely proposal is to bring back boreal foragers via genetic engineering Woolly Mammoth-like creatures to graze and inhibit tree growth and encourage re-emergence of grassland.
- Off the wall? Probably!! But fun to think about

OIF: Seeding the Ocean with Iron to Stimulate Algae Absorption of CO2

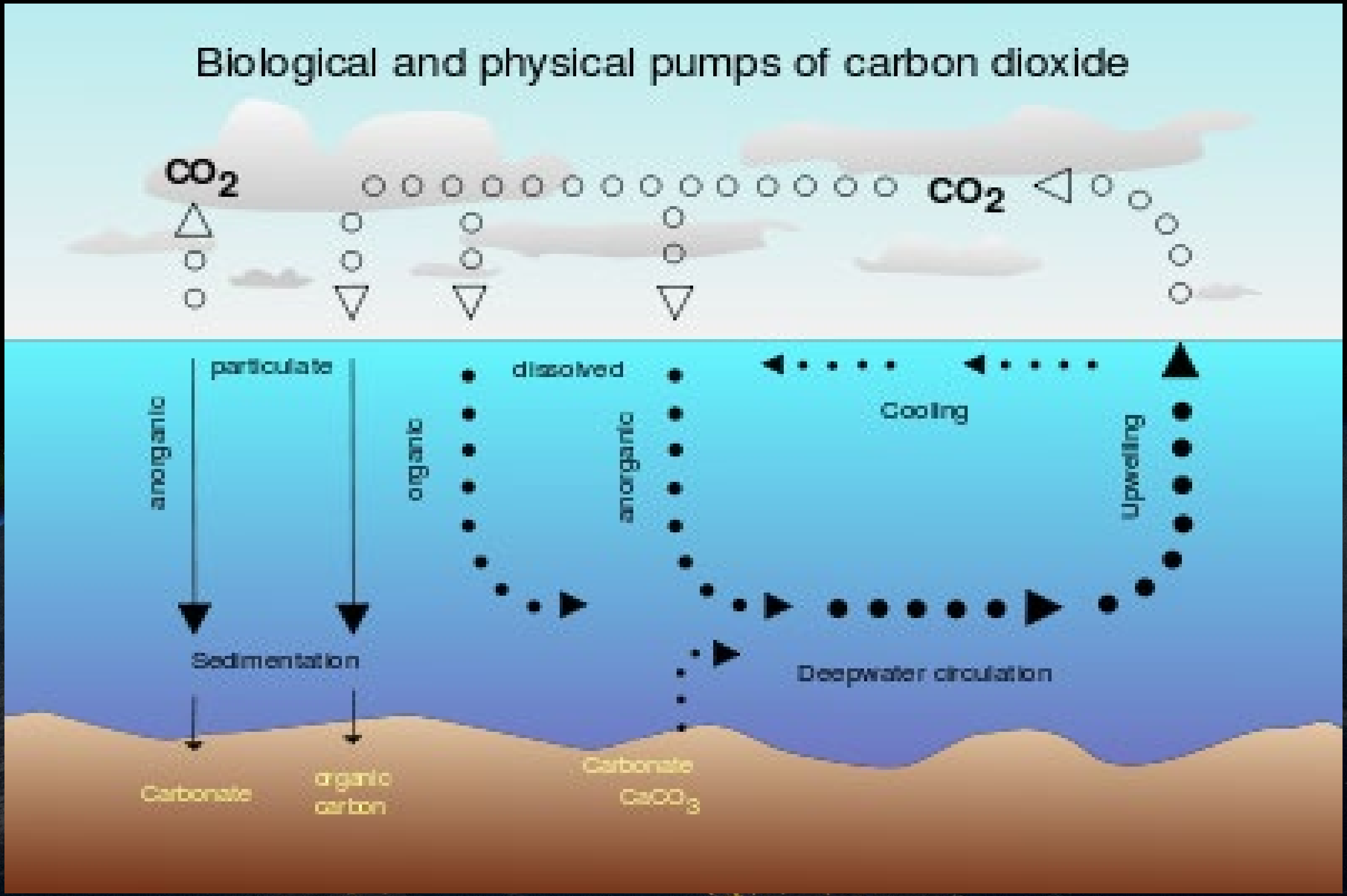
- Originally suggested by John Gribbin in 1988. **O**cean **I**ron **F**ertilization: **OIF**
- Sprinkle iron in iron-poor (but not silica-poor) areas of ocean surface, as iron is critical for photosynthesis, stimulating algae blooms.
- Silica needed for diatoms, foram's and other calcium-carbonate building phytoplankton. Without the silica, iron won't help, studies show.

OIF clearly fails safety criteria #1 and #2 by radically affecting global ecosystems in poorly understood ways

- Mid oceans have NEVER been forced to be iron-rich at the levels proposed
- Our fore-fathers oceans are not going to be the result of OIF.
- Early tests show such iron fertilization does stimulate algae blooms – but is that good?

Algae bloom off Argentina.

So, how does this idea work?



- Iron is (and always has been) critically low in many areas of the open ocean, limiting phytoplankton. Given iron fertilization so they can multiply, certain species make carbonate skeletons, which then sink when they die. Even most of this carbon gets recycled, but some sink deeper where much gets dissolved in colder waters.
- The dissolved CO2 in the deep is sequestered from the surface ocean for decades to centuries (but then resurfaces, releasing to the atmosphere. Not good)
- A much smaller fraction sinks to the sediments and remains; a net sink of carbon, but very slow. Same thing happens naturally on geological time scales.

Iron Fertilization: How Effective? Not Much of a Dent in Our CO2 Emissions

- If the entire Southern Ocean's (the most promising region) nitrate and phosphate were combined with fertilized iron by plankton, it theoretically could absorb only 1.1 Gt of carbon and deposit to 100m depth, per year (Buesseler and Boyd 2003). Realize even that's an impossible theoretical maximum.
- **Even so, this is only about 10% of the rate of what humans emit to the atmosphere**. And doesn't consider the indirect human-caused CO2 from thawing permafrost, nor the other GHG's. Even this may be too optimistic, as we'll see…

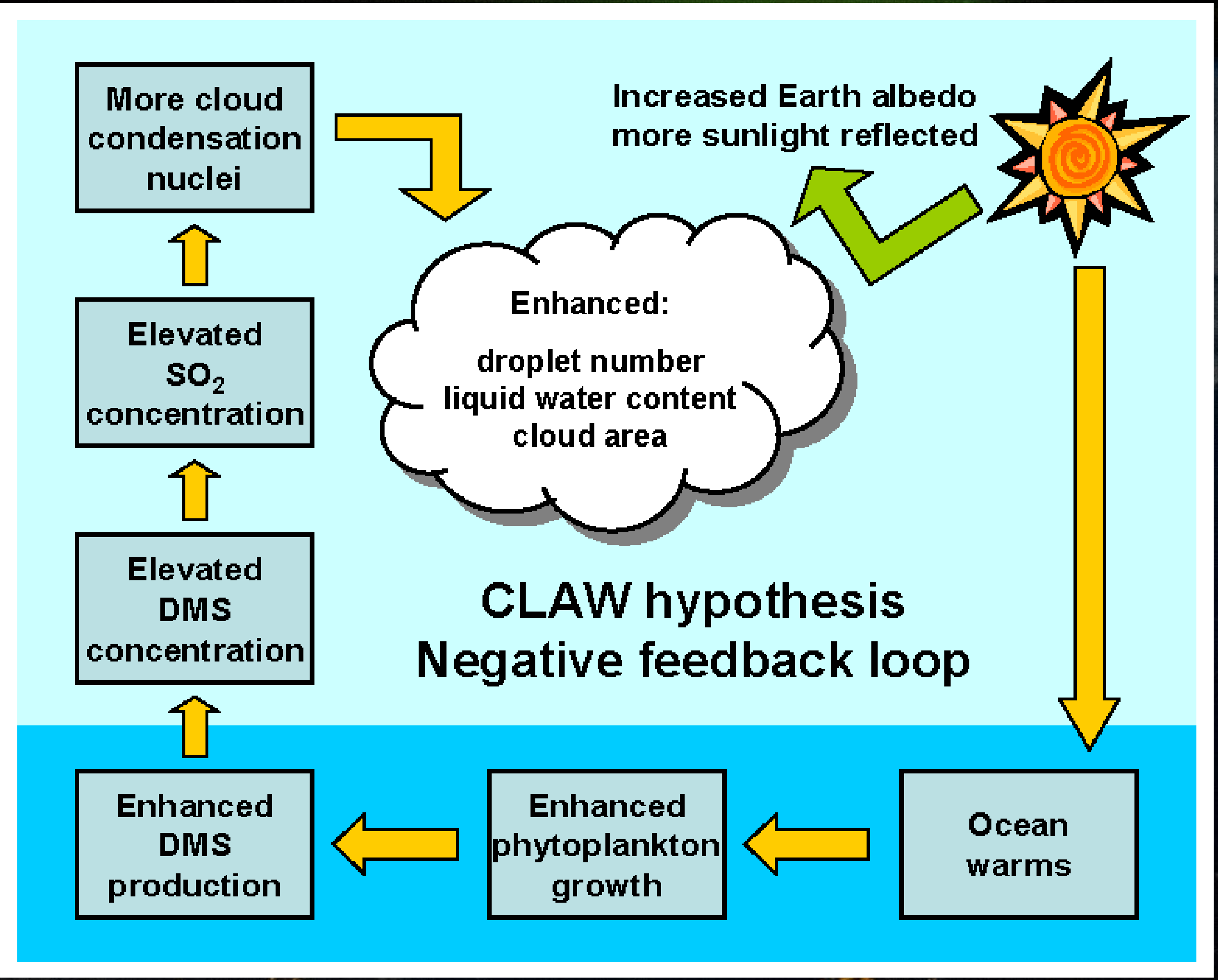
How About Surface Iron Fertilization in the Tropical Ocean?

- Winckler *et al.* 2016 studied the correlation between iron concentrations in the tropical Pacific ocean and productivity over the past 500,000 years with sediment data and finds there is no correlation.
- *"Over the past half-million years, the equatorial Pacific Ocean has seen five spikes in the amount of iron-laden dust blown in from the continents. In theory, those bursts should have turbo-charged the growth of the ocean's carbon-capturing algae – algae need iron to grow – but a new study shows that the excess iron had little to no effect…At some points, as levels of iron-bearing dust increased, productivity actually decreased."* – from discussion at Columbia University
- This confirms an earlier study using paleo data from just the last glacial maximum.

Iron Fertilization: Ineffective in the Tropical Pacific, Despite Favorable Ocean Nutrient Profiles

- *"Neither natural variability of iron sources in the past nor purposeful addition of iron to equatorial Pacific surface water today, proposed as a mechanism for mitigating the anthropogenic increase in atmospheric CO_2 inventory, would have a significant impact,"* the authors concluded.

The CLAW Hypothesis: A negative feedback enhancing climate-cooling low clouds through the aerosol indirect effect



The CLAW Hypothesis – Good or Bad?

- The CLAW Hypothesis originally proposed by Charleson *et al.* in 1987 (Charleson *et al.* 1987).
- But – even if the CLAW Hypothesis turns out correct here, tropospheric aerosols rain out quickly, so only long term continuous large-scale iron seeding would have this additional radiative effect.
- More concerning - putting such artificial clouds into the global climate system in these highly regional ways could well alter circulations and rainfall patterns.

Summary of Review Paper on the 13 OIF Experiments in past 25 years (Yoon *et al.* 2016, p. 15) – Not Good

*"To test the Martin Hypothesis, a total 13 artificial OIF experiments for scientific study were conducted in the HNLC (*high nutrient low chlorophyll*) Regions during the last 25 years The biogeochemical responses to OIF experiments were observed in the increases of primary production as a result of drawdowns of macro nutrients and DIC (*dissolved carbon*) . In most experiments, the dominant phytoplankton group tended to be shifted from small sized groups to large sized groups, resulting in a diatom dominated phytoplankton community .*

*However, the effectiveness in export production enhancing ocean biological pump (*meaning: carbon sequestering to the deeper ocean*) was not clearly confirmed by the OIF experiments except in one, EIFEX.*

Likewise the possible environmental side effects in response to iron addition, such as production of greenhouse gases, development of hypoxia/anoxia in water column, and toxic algal blooms were not fully evaluated due to inconsistent outcomes with large uncertainty depending on OIF experiment conditions and settings"

How Much Iron to Sequester How Much Carbon?

- Lab theory suggested 1 ton of iron would, with ideal chemistry, sequester 106,000 tons of carbon.
- But only one of the 13 OIF experiments found any real-world carbon was dropping even a couple hundred meters (but described falsely as "sequestered to the deep ocean"), with a ratio only 2,600 to 1 (deBaar *et al.* 2008). Assuming that ratio would not drop further even when going to climate-significant scales (a big assumption, considering the other nutrients used up), that would mean 300,000 tons of powdered pure iron to sequester 1 gigaton of carbon, or 10% of human annual CO2 emissions.
- For how long could that go on, using up the other nutrients in the ocean in the process? Not clear.

Here is the IPCC (2013) AR5's Summary Table on Iron Fertilization as a Strategy

- **Iron Fertilization - <u>More dangers than promise</u>…**
- The OIF experiments done so far have not studied these issues, or done so inadequately. The recent experiments we looked at here show that adding iron in one area removes more nutrients which are then unavailable elsewhere as the ocean currents move.
- Large enhanced carbon in deep ocean will consume oxygen, expanded "dead zones", acidifying it as well.

Enhanced biological production and storage in ocean	Ocean iron fertilisation[k] Algae farming and burial[l] Blue carbon (mangrove, kelp farming)[m] Modifying ocean upwelling to bring nutrients from deep ocean to surface ocean[n]	Biological	Ocean	[k,n] Inorganic [l,m] Organic	[k]May lead to expanded regions with low oxygen concentration, increased N_2O production, deep ocean acidification and disruptions to marine ecosystems and regional carbon cycle [n]Disruptions to regional carbon cycle

Safety? At climate-significant levels, OIF is a massive change to the existing ecosystem, which does not have algae blooms in the open ocean. Fails our Safety Criteria.

- A 2010 study (Trick *et al.* 2010) of iron fertilization in an oceanic high-nitrate, low-chlorophyll environment (exactly the environment that is necessary for this strategy) found that fertilized *Pseudo-nitzschia* diatoms, which are generally nontoxic in the open ocean, began producing toxic levels of domoic acid.
- Even short-lived blooms containing such toxins could have *"detrimental effects"* (their delicate words) on marine food webs.
- Finally, **Sigman and Hain (2012)** in **Nature: Education (p. 12)** point out some fatal flaws in the entire OIF paradigm

Sigman and Hain (2012) explain why Iron fertilization is ineffective as a GeoEngineering strategy

- *"First, even if iron fertilization were to lead to complete consumption of nutrients, it takes too long for the deep waters to cycle through the polar ocean surface to substantially alter the currently rapid rise in atmospheric CO2 (Peng & Broecker 1991). Second, humans appear incapable of intentionally fertilizing a significant fraction of the Southern Ocean on a continuous basis; with only sporadic fertilization, a substantial portion of the additional CO2 sequestered in the deep ocean would upwell back to the surface to be released. Third, any modest increase in carbon storage that such fertilization does cause will come at the expense of lower oxygen concentrations in the ocean interior, one climate consequence of which may be enhanced release of the greenhouse gas nitrous oxide to the atmosphere (Jin & Gruber 2003)."*

The Jin and Gruber (2003) Paper is Quite Sobering on the Prospects of the Powerful GHG N_2O being Produced by Iron Fertilization

- It's well worth reading…
- In the tropical oceans *"by assessing the CO_2 and N_2O only over the areas fertilized, one will overestimate the climate radiative benefit by 500%. Therefore, verifications of the benefits of ocean fertilization require essentially global-scale assessments, which are very difficult to obtain given the small signals and the presence of natural variability"*
- Such facts won't stop the promoters though…

OIF: Conflict of Interests. Biases of $Promoters - Politics and Economics

- The existing laws involving carbon credits make OIF tempting for polluters. They can pollute the atmosphere with CO2 and then offset by buying cheap credits which result in OIF (Fuentes-George 2017), which may very well then severely damage the ocean ecosystems evolved in the pre-Industrial / pre-OIF epoch.
- **Two for the Money: A double damage to the Earth System**

BEWARE the PROMOTIONALS!

- You'll certainly be told about increased fish yields in the one "successful" OIF experiment in the Pacific Northwest. And the money to be made there because of it (paid by the native cultures whose fisheries were destroyed by us already).
- You'll certainly catch the flavor that this is the miracle we've been hoping for, and the dangers unmentioned.
- One thing you won't hear, is that the salmon and other fish eagerly taken out of the sea will be eaten and so all that fish carbon from the phytoplankton doesn't get sequestered, instead entering the "fast carbon cycle" and re-entering the atmosphere.

Ecosystem safety has always taken a back seat to profits when there's money to be made. OIF looks no different.

- "Rogue GeoEngineer" / entrepreneur Russ George, looking for "lucrative carbon credits", violated ethics and international moratoria on OIF by convincing a local Native American tribe in the Pacific Northwest to chip in $1 million of tribal money so he could dump 10 million tons of iron sulfate in their waters, saying he was "restoring the salmon fishery" (Guardian 2012).
- This is exactly the same kind of "restoring" that Modern Agriculture has done to our soils, "juicing" them with artificial nitrates to force out more food per acre, exhausting and impoverishing the soil in the process.
- These are people who think of oceans and ecosystems as merely raw commodities to be manipulated for profit. And they show no evident concern for the wider and long term consequences of their actions.

At Best, Carbon Sequestration is only a Small Fraction of the Algae Carbon Take-up. Beware the Wording of the Claims!

- Much of the carbon take up is only temporary. Even in the best cases, only a minor and uncertain fraction (~10%) truly sinks to the abyssal plains permanently.
- The rest is re-cycled to the atmosphere. But the claimed amounts, for carbon offset pricing are, alas, subject to “economics” - with predictable results… (next slide)

Cold water beneath the thermocline will dissolve carbonate skeletons

- Cold water has higher CO2 soluability capacity, so it'll resurface later, into warmer surface waters, and outgas to the atmosphere since warmer water can hold less CO2.
- Long term re-outgasing will happen <u>after the profits are already pocketed.</u>
- <u>**This is because the carbon offset laws were written deliberately with very short-term time horizons for what constitutes "sequestered". If carbon's held underwater for decades, that's long enough to consider it "sequestered", eligible for $$. Future generations? As always, they'll be the ones to suffer most.**</u>

The Fatal Flaw in these Cheap Carbon Schemes…

- Earth has 2 carbon cycles: The "Fast Carbon Cycle" churns carbon rapidly through biology and atmosphere, ocean, soil systems. The "slow cycle involves the conversion of deep fossil carbon and carbonate rock.
- Industrial civilization is rapidly turning 40 billion tons/yr of truly deep "slow cycle" petro-carbon into the atmosphere, becoming part of the "fast carbon cycle".
- Growing trees, OIF, dumping olivine on our beaches… these do not truly sequester carbon. It remains in the "Fast Carbon Cycle".
- We need to instead send that carbon back. "From Hell it Came" and back to Hell it needs to go. Otherwise, we're sweeping it under a temporary rug, for the future to deal with.

And Now for a Third Geo-Engineering Category: The "Loan Shark" Strategies

This is the name I'll give to any strategies which neither enhance Earth re-radiation, nor reflect sunlight, but merely sweep heat temporarily under the rug.

I will examine in detail the worst of these, because it is still promoted by profit-seekers.

Enhance carbon capture by ocean phytoplankton by enhanced upwelling through pumps/pipes

- Lovelock and Rapley (2007) and discussed here
- And in this promotional video by Atmocean Inc. here
- Early evaluation: Too slow to matter (see next page), and quite dangerous to ocean ecosystems, about which we have only sketchy knowledge and will almost certainly remain sketchy, given the millions of marine species and unknown interactions.
- Also, the upwelling merely recycles carbon nutrients which had been drifting down to the ocean bottom for permanent sequestration, so does the accounting really pencil out?
- Worse - deep ocean pipes (OTEC: "Ocean Thermal Energy Conversion") have been found to be thermally very dangerous to future climate…

OTEC Pipes to Cool Ocean Surface And Earth?

- **O**cean **T**hermal **E**nergy **C**onversion (OTEC) is an idea that has been around for a hundred years, and even put into practice in a few places for limited time, producing limited power.
- The idea is to tap the temperature difference between deep ocean (~40F) and tropical surface (~77F) to drive a heat engine to generate power
- Considered too costly for a widespread power source
- But what about OTEC as a way to power cold water upwelling to the surface, where it will absorb heat and thereby cool the atmosphere?

…Elephants deal with heat by sending warm blood to those big heat exchangers – ears! Surface heat is able to radiate away easily. CORE heat is buried and unable to leave. Yes, in all ways, a great strategy! <u>Keep this in mind in what follows…</u>

Capping the surface of the ocean with cold water will indeed cool climate – initially

- But you are now TRAPPING the absorbed heat by burying it under that cap. (sounds a bit like atmospheric GHG's, no?)
- Recall another basic fact, that it is the thermal inertia of the oceans (~700x that of the atmosphere) which prevents temperatures from dropping even if we halt all GHG emissions. <u>The ocean is the Elephant</u>, and the sea <u>surface and atmosphere are the Ears.</u>
- **<u>Clearly - we need to HELP the oceans get rid of their excess heat, not make it harder</u>**

So it should not be surprising that the long term effects of OTEC are very negative.

- **Kwiatkowski, Ricke and Caldiera 2015 in Envir. Res. Lett. (hereafter KRC15) studied the effects on climate of blanketing the oceans with OTEC pipes** (summaries are **here** and **here**)

KRC15's Methods:

- A high resolution fully-coupled climate model integrating ocean, land, air, cryosphere (land and sea ice), with cloud cover and bio/geo chemistry, and time-stepped 1200 years after thermocline altered as it would be by widespread use of OTEC pipes to 1 km depth, and left pumping throughout.
- Their standard case ran OTEC pipes at sufficient strength to reduce ocean surface temperatures by 7C. They also ran smaller vertical mixing strengths of 10% and 1% of standard. The 10% run reduced ocean surface temperatures by 3C which is closest to what was initially proposed by Alan Miller and his "Cool-it Earth" initiative for climate cooling.
- Each case assumed "business as usual" IPCC RCP8.5 human carbon emissions continuing (solid curves) and also a zero emissions control case in which "pre-industrial" atmospheric CO2 was left alone (dotted curves in graphs that follow)

- KRC15 note that any real implementation of OTEC pipes would be on a smaller scale than their full-strength case, **but the pattern and physics would be in the same direction as they find.**
- **They justified that claim by their drastically scaled-back 10% and 1% cases which indeed qualitatively show the same trends.**
- **Note they did not “disrupt” the thermocline. The initial conditions still have a thermocline, reduced in slope by the widespread OTEC pipes; Rather, it was an “Altered” thermocline, in KRC15’s notation**

KRC15 Standard Case: The initial effect is to cool the surface, as warm surface water is displaced deeper by upwelling pipes (left). But ~50 years later (right), the re-emerging buried heat raises the temperature of the entire 1km depth of the pipes, raising sea surface temperatures even higher than if OTEC pipes were never installed. True whether with continuing human CO2 emissions (solid), or without (dashed)

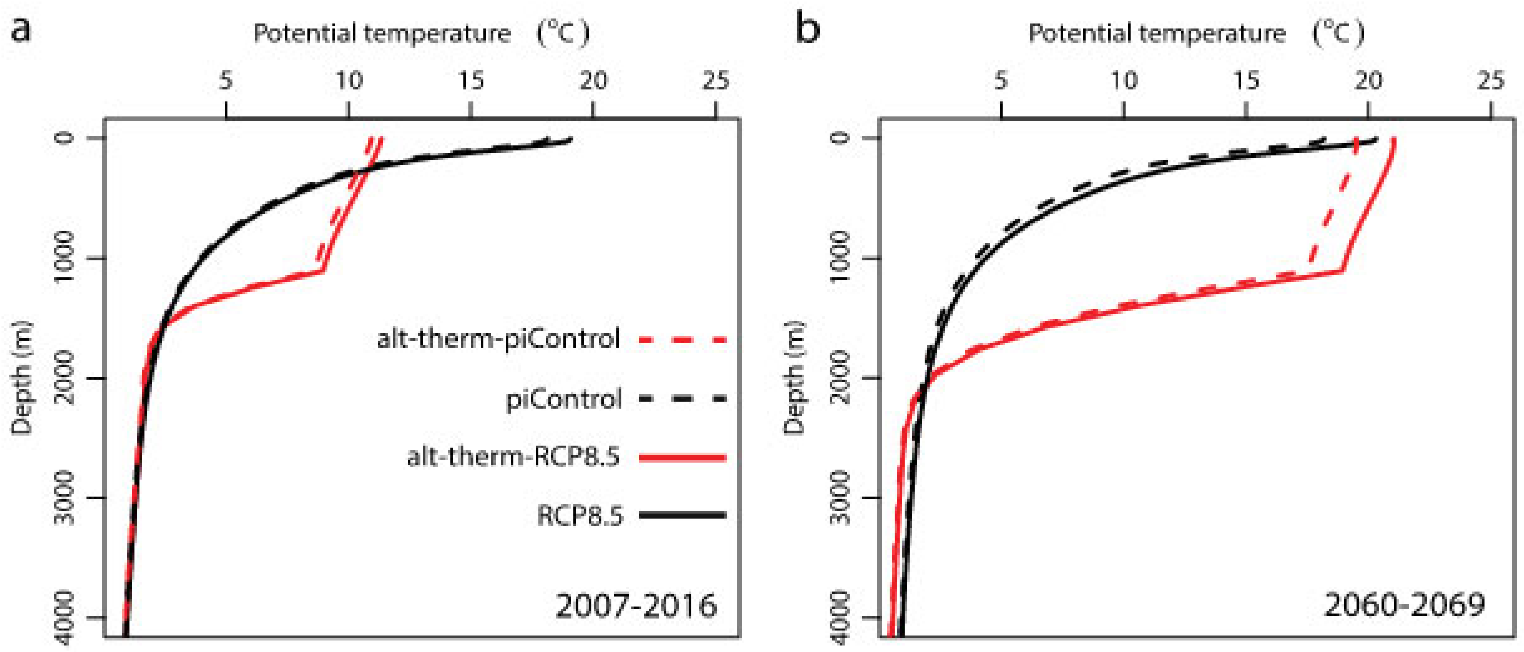


Figure 1. Thermocline impact. Mean (a) 2007–2016 and (b) 2060–2069 global potential temperature across the upper 4000 m of the water column.

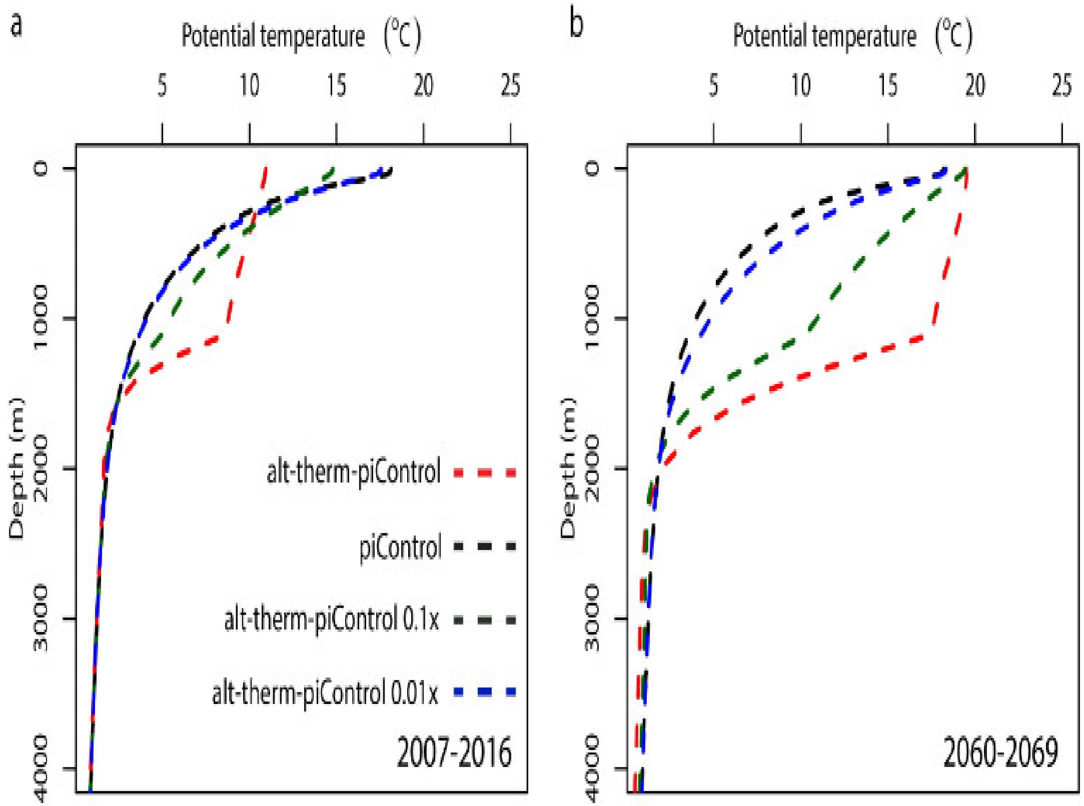


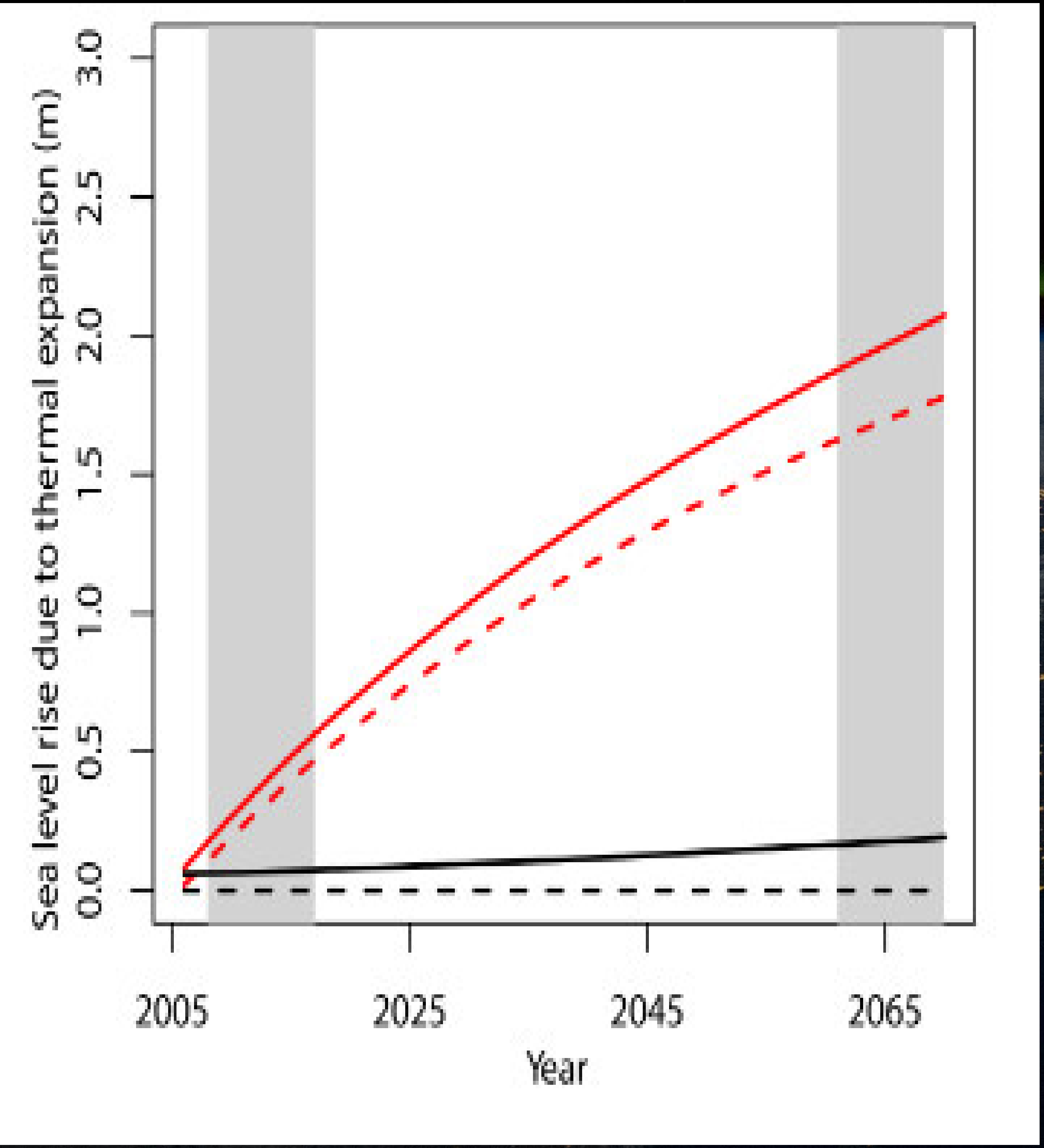
Figure S18. Thermocline sensitivity analysis. Mean a, 2007-2016 and b, 2060-2069 global potential temperature across the upper 4000m of the water column. The *piControl* simulation is shown in black and the standard thermocline disruption simulation in red. Enhanced vertical mixing simulations of 10% ($6cm^2s^{-1}$) and 1% ($0.6cm^2s^{-1}$) of the *alt-therm-piControl* simulation are shown in green and blue respectively.

This is true even in the much milder 10% (green) and 1% (blue) cases. All runs - 100%, 10% and 1% thermal mixing - show rising ocean temperatures right to the surface, as time goes on

And again, all curves on this page assume NO HUMAN CO2 Emissions. Yet future temperatures STILL rise.

More bad effects: Reduction in climate-cooling low clouds…

- You're differentially cooling the ocean more than the continents, leading to massive change in air pressure-driven weather patterns.
- For one, the cooling ocean leads to descending denser air over it (since the continents are not directly cooled and so are relatively warmer), reducing convection and marine cloud cover, so incoming sunlight sees dark absorptive ocean (albedo 4%) instead of reflective cloud tops (albedo ~83%) – raising Earth's absorption of solar heat, <u>worsening</u> our problems.
-
- And additional crippling effects…



KRC15 Standard case: The trapped heat causes thermal expansion in the deeper ocean waters, raising sea levels. Solid red curve: RCP8.5 human emissions continue. Dashed red curve: CO_2 at "pre-industrial" and no emissions. Sea level rise here is clearly due almost entirely to trapped existing heat, very little due to new heating from continuing human CO_2 emissions

Yet More Trouble: For the large majority of the Ocean - The more OTEC is deployed, the more atmospheric CO_2 is Boosted

- Pumping deep cold water to the surface also brings with it the buried CO_2 within that water.
- As that water continues to warm near the sunlit surface, it can hold less CO_2 and so will de-gas that CO_2 back into the atmosphere.
- The oceans become a CO_2 source, rather than the sink that it is now. This is NOT GOOD.

Ancient CO2 Re-animated?

- This outgased CO2 is from the deep ocean; it's CO2 that had long ago been sequestered, not the recent CO2 of what had been the undisturbed surface layers.
- So we may be taking CO2 that had not been an immediate danger of outgasing, and driving it into the atmosphere. That net adds CO2 to the atmosphere. However, there is some take-up of CO2 by land soils (Oschlies *et al*. 2010) from reduced respiration during initial cooling… but only until global temperatures go back up.

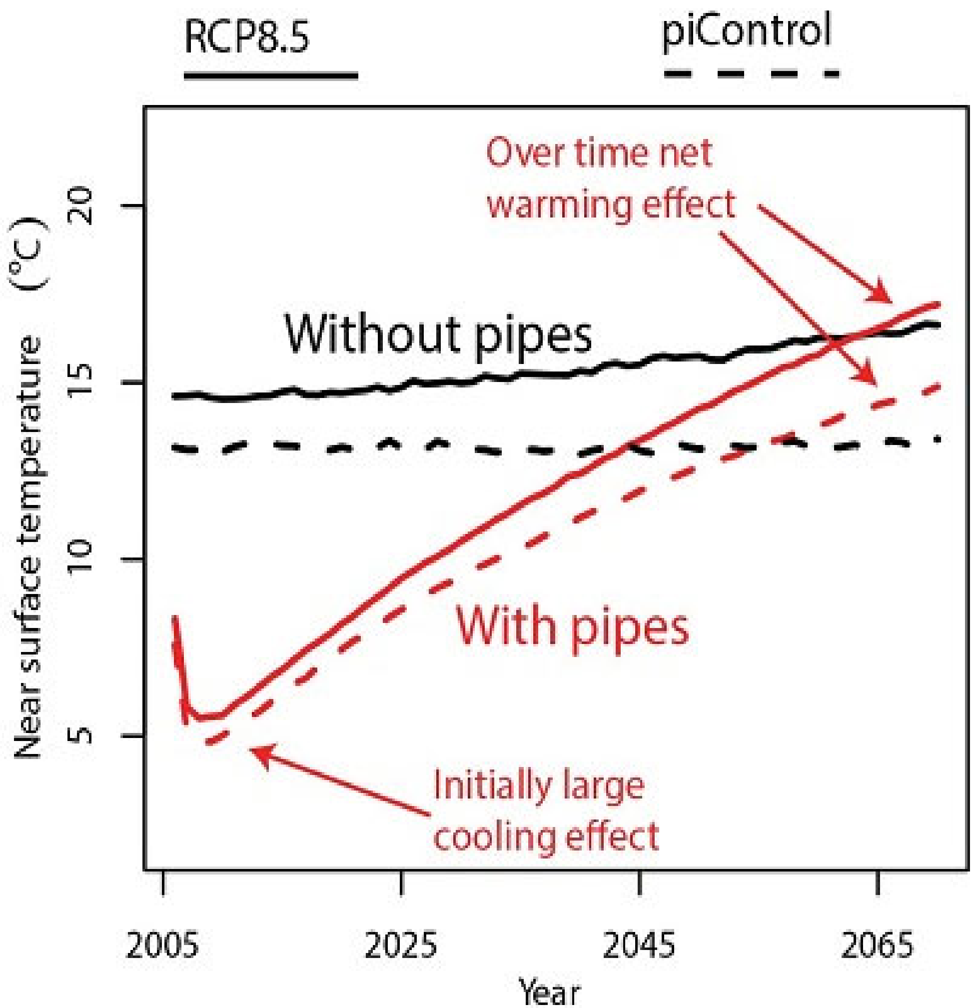
OTEC and Altered Phytoplankton Ecology

- These temperature changes would also significantly affect the phytoplankton ecology currently existing in these warmer mid-ocean surface waters in poorly known ways, as the ecological web is large and complex and with only bits and pieces so far studied. Initial claims that mid-ocean upwelling via pipes would capture CO2 via photosynthesis and then sequester it when it drops are guesses (or worse - see next slide).
- Would it merely get re-circulated? Pipe currents are very different than coastal upwelling. Upwelled nutrients, after all, are just the bodies of carbon-rich sea life that were already heading downward towards sequestration.
- ~1/2 of Earth's oxygen is generated by ocean phytoplankton.

The promoters' claim that enhanced upwelling will stimulate phytoplankton to sequester more atmospheric carbon, is not supported

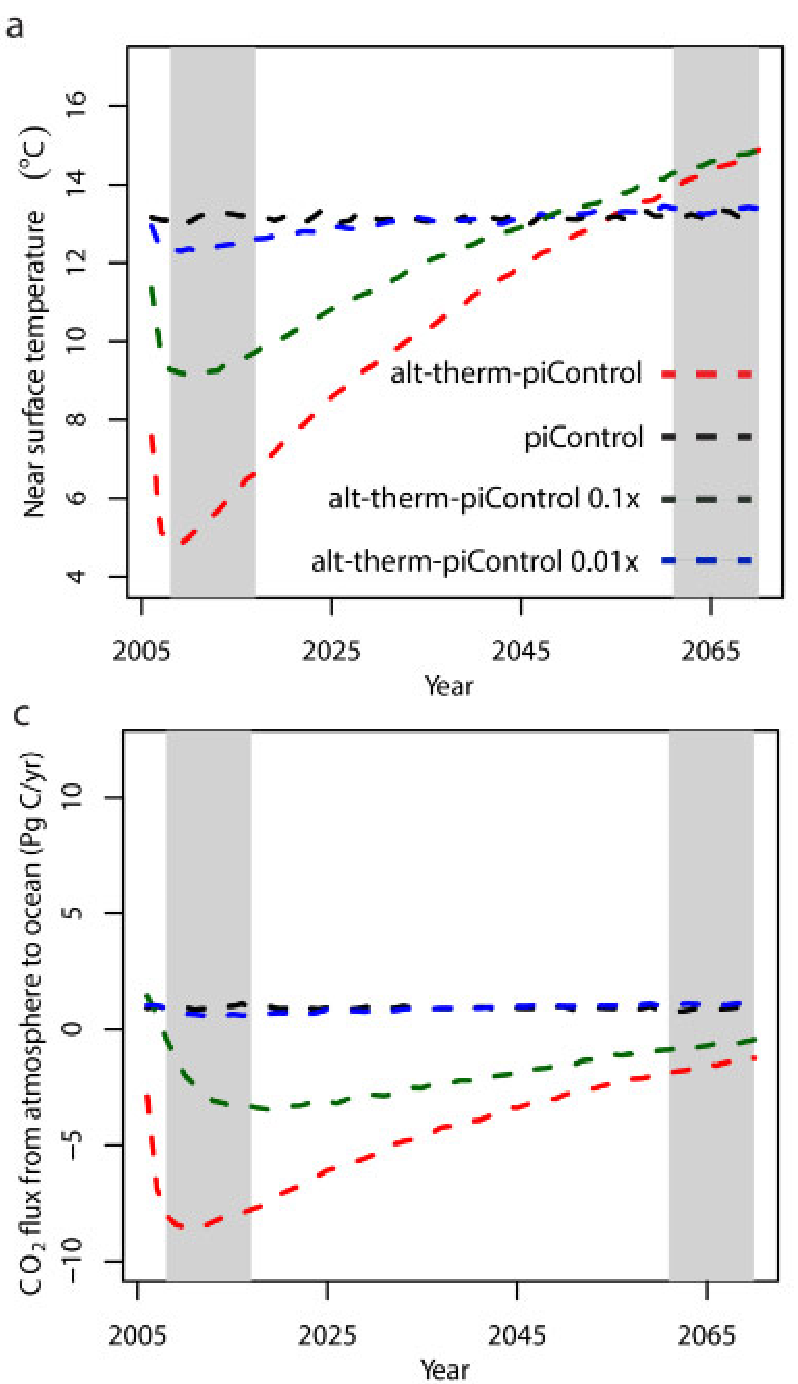
- From Sigman and Hain (2012) in **Nature: Education (p. 12)**…
- *"To address a common misconception, the capacity of ocean productivity to lower atmospheric CO2 is not typically made stronger by simply increasing ocean upwelling rates. Increased upwelling increases the nutrient supply for productivity, but also exposes to the atmosphere the CO2 previously sequestered by the soft tissue pump. **In the low latitude ocean, these effects roughly offset one another**. Productivity is highest in the polar regions (Figure 4), and yet the incompleteness of nutrient consumption in these regions causes them to release biologically sequestered CO2 back to the atmosphere (Figure 6). For a given concentration of the ocean's major nutrients, it is the completeness of nutrient consumption rather than the rate of organic matter export that matters for CO2 sequestration. This is true up to the time scale of 100 thousand years or more" .*
- **I'll add – and doing OTEC at high latitudes won't work since the ocean temperature gradient is too low. So - no power, and no added cooling either.**

<u>KRC15 Standard Case</u>; Re-emerging buried heat added from below to current arriving insolation heat from above leads to global surface <u>temperatures HIGHER than if OTEC was never installed</u>. Note in particular that most of the temperature rise is NOT due to continuing RCP8.5 emissions (solid) but rises even with NO CO2 emissions (dotted). Artificially buried heat is arriving back to the surface by bouyancy: Warm water rises! No surprise.



Caption: This figure shows the change in near surface temperatures over time with ocean pipes and without pipes. It is provided courtesy of Lester Kwiatkowski, Ken Caldeira, and Katharine Ricke.

(Top image credit: NOAA Climate Program Office, NABOS 2006 Expedition. Photographer: Mike Dunn, NC State Museum of Natural Sciences.)



Top: Even the much milder KRC15 10% and 1% OTEC cases, with no human CO2 emissions, show OTEC pipes' buried heat re-emerges (with a vengeance for 10% case) by mid-century, rising past the "no OTEC" temperatures.

Bottom: Indeed, except for the 1% case (blue), deep ocean CO2 outgases back into the atmosphere when OTEC pipes are turned on.

Piping cold water from beneath the thermocline to the surface on a climate-significant scale, looks to be a disaster for future climate

- OTEC Pipes-for-Climate fails all of our essential climate solution criteria: When cloud changes are included, it neither raises Earth albedo, nor aids Earth in radiating, and at climate-relevant scales, it makes profound changes to ocean thermal and convective normality, with large and damaging effects on not only climate, but ocean ecology, currents, atmospheric winds, rainfall patterns, ice melt at the poles… and likely more not yet realized.
- Yet Alan Miller, retired engineer from Lockheed-Martin, is seeking venture capital to advance this as a climate solution . A pipe already patented by him, searching for a purpose?

The Claims…

- As of mid 2016, the promo says half the world's power needs would be solved, by using OTEC power generation to make huge amounts of ammonia on **~70,000 floating factories hooked to OTEC pipes**, to be visited by tankers to carry the ammonia to land where it could be burned as fuel to power the world. An ammonia-powered world economy?
- The title of the promo is *"We CAN hold Temperature to +2C, even +1.5C!"*, a claim which is not at all supported by the evidence shown here.

Ammonia as Our New Energy Source?

- The combustion of ammonia to nitrogen and water is exothermic:
- $4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O\ (g)$ ($\Delta H°_r$ = −1267.20 kJ/mol) The standard enthalpy change of combustion, $\Delta H°_c$, expressed per mole of ammonia and with condensation of the water formed, is −382.81 kJ/mol. Dinitrogen is the thermodynamic product of combustion: all nitrogen oxides are unstable with respect to N_2 and O_2, which is the principle behind the catalytic converter. Nitrogen oxides can be formed as kinetic products in the presence of appropriate catalysts, a reaction of great industrial importance in the production of nitric acid:
- $4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O$, which in the presence of oxygen, such as would happen in air, leads to NO_2 by the reaction
- $2\ NO + O_2 \rightarrow 2\ NO_2$ (a powerful greenhouse gas)
- ***Also, the combustion of ammonia in air is very difficult in the absence of a catalyst (such as platinum gauze or warm chromium(III) oxide),*** because the temperature of the flame is usually lower than the ignition temperature of the ammonia–air mixture. The flammable range of ammonia in air is 16–25%.[22]

- So this would not appear to be an energetically or cost-favorable fuel (platinum catalysts, dangerous chromium?), although the greenhouse warming power of the combustion products would be less than from carbon-based fuels.
- Miller highly optimistically assumes that the cost curve for the pipes will follow the same as did solar PV panels. But tiny PV chips were vastly more favorable for dramatic technological advance and cost cuts.
- His 10 meter diameter OTEC pipes are lower-tech and more of the cost is in materials, labor, and structure, and not in technology. Such costs typically rise, not fall, with inflation).
- He estimates (mid '16) they'd cost $1.2B apiece
- **That's $84 trillion for 70,000, which works out to $12,000 for every man, woman, and child on Earth.**

- Consider the dangers of these floating factories…

Toxicity of Ammonia

- It is not particularly dangerous to humans and other mammals, which have a biological mechanism – the urea mechanism - for removing ammonia from their systems.
- It IS dangerous, however for fish, amphibians, and other aquatic species…
- *"Ammonia even at dilute concentrations is <u>highly toxic to aquatic animals</u>, and for this reason it is <u>classified</u> as dangerous for the environment." (<u>wikipedia</u>)*

Miller's numbers: 70,000 free-floating ammonia factories on the far open ocean, beyond the continental shelf so they have access to ~1 km deep cold water. Is this a good idea, <u>in the coming era of Super Storms (Hansen *et al.* 2016)</u>?

Oschlies *et al.* 2010 also studied artificial upwelling's effect on climate

- They use a very different climate model and assumptions.
- They employ pipes only where the ocean vertical profile suggests surface CO2 would not increase when OTEC is turned on. However, where these rare places are, are very different depending on data and model choice (their Fig 1)
- *Their UVic climate model includes **no cloud modelling**, and so the strong negative effects of a cooling ocean on low cloud formation found by the Stanford team are missed.*
- *Yet, the cooling-induced decrease in marine clouds was a major contributor to the later rising temperatures in the KRC15 models. If this physics is missing in the Oschlies studies, it calls their climate results into serious question.*

Even Very Limited OTEC Deployment Still Ultimately Causes Rising Ocean, Air Temps

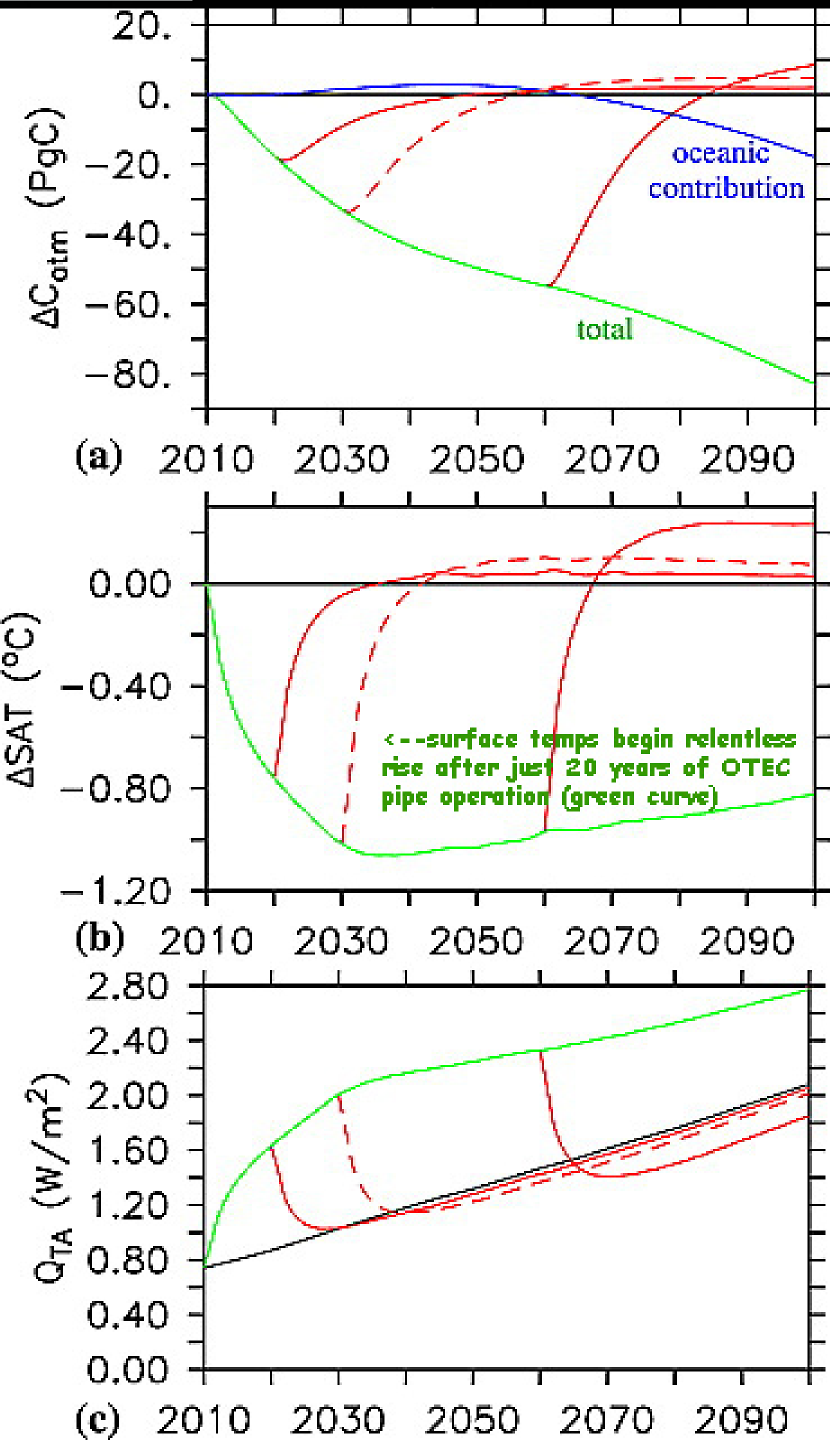
- Even the much smaller and more optimized OTEC deployment studied by (Oschlies *et al.* 2010) found that when the pipes are shut off, Earth warms to HIGHER than it would have been if no pipes had ever been deployed.
- The quick and glib rebuttal from Miller (WiSE talk in Santa Cruz, Fall 2016) was – *"why ever turn them off"?*
- There could be many reasons - like unforeseen tragedy to eco-systems, to weather patterns, failure of the ammonia economy to take hold globally, or better, cheaper, less dangerous technology arriving, for powering civilization. Like solar and wind generating direct electricity and removing the inefficiencies of combustion altogether.

Worse – even if the pipes are NEVER shut off…

- …the surface ocean begins consistent warming only ~20 years after deployment (next slide).
- Miller responded (private comm.) that this was because human CO2 emissions continue (in the Oschlies *et al.* 2010 study). **No.** The evidence says otherwise… note that in the KRC15 studies – in which there is NO human CO2 emissions – that even in the mildest 1% case and when there is NO ocean-vented CO2 release (in fact, oceans continue to absorb atmospheric CO2, as shown), **still surface temperatures rise after a brief initial drop.**

The reason is basic thermodynamics – Conservation of Energy.

- **Buried heat does not simply vanish from existence. Heat in fluids ultimately must rise, by buoyancy, causing worsened radiative imbalance:** Again note in the KRC15 studies that human CO2 emissions do not dominate the rising OTEC temperatures, as we highlighted.
- Oschlies *et al. 2010* did not run a control case with zero human CO2 emissions - a fatal flaw in Miller's claims - which would have made the cause of their own rising temperatures clearer.



From Oschlies *et al.* 2010

(a) Simulated sequestration of atmospheric CO_2 relative to the standard run without pipes. (b) Simulated surface air temperature difference of ocean pipe simulation relative to the standard run without pipes. (c) Simulated radiation balance at the top of the atmosphere. Green lines refer to the standard pipe experiment with pipes deployed wherever a reduction in surface pCO_2 can be expected, and with a maximum vertical pipe extension of 1000 m. Red lines show results from simulations with artificial upwelling stopped after 10, 20, and 50 years, respectively. The blue line in Figure 2a denotes carbon sequestration due to oceanic uptake, the black line in Figure 2b refers to the control experiment without pipes. All simulations assume A2 emissions continue. No control case of no-emissions was run.

(b) (RN: NOTE THAT GLOBAL TEMPERATURES (MIDDLE GRAPH IN GREEN CURVE) REVERSE AND BEGIN RISING AFTER ONLY 20 YEARS, AS TRAPPED HEAT BEGINS TO RE-EMERGE , AND THE LONGER THE PIPES ARE ON, THE GREATER THE OVERSHOOT IN EVENTUAL TEMPERATURES. THE TREND AND ENERGY CONSERVATION SAYS THAT EVEN WITH NO PIPE SHUTOFF, TEMPERATURES WILL EVENTUALLY GO HIGHER THAN IF NO PIPES HAD EVER HAPPENED, JUST AS KRC15 FOUND. For Oschlies et al, some of this is due to human emissions, but according to KRC15, most is trapped heat)

OTEC pipes continually displace warm surface water from where it CAN radiate to space, down to depths where it CANNOT

- Simple freshman physics (Conservation of Energy) says that heat WILL build up, and the longer you engage these pipes, the bigger the thermal disaster when that heat becomes too large to hold down any longer by pipe action, regardless whether pipes are ultimately shut off.
- Remember, incoming heat from the sun is very constant, Think of this as ongoing worsening **"heat constipation"**
- This is just not arguable; it's the "loan shark" (buried heat) coming for his payment, payment which balloons with interest and *"past due"* with each passing year.

A Key Question Remains Unanswered by Alan Miller - Promoter of this Idea

- Why seek venture capital money to launch such an ambitious expensive venture when the science is so clearly negative? Venture capital expects a **return on investment**, *i.e.* expects the wisdom of deployment is already settled in the affirmative.
- This should raise skepticism and “red flag alerts” to anyone.
- Why not instead seek grant money for climate research to clarify the effects? Was any application made for NSF money for such studies?
- Or alternatively, was any attempt made to form a non-profit for donations for supporting your small group for further studies?

- Yet another questionable claim: OTEC-induced cooling would increase polar ice, setting off an albedo feedback that would continue to keep the Earth cool.
- But the KRC15 studies show otherwise. They find that despite the initial rise caused by cooling in the early years of OTEC deployment, sea ice steadily declines as the surface ocean then reverses and warms as buried heat re-emerges (next slide).
- Unlike the Ice Ages, which were initiated by astronomically induced lowered summer Arctic sunlight, OTEC will BURY existing heat. This <u>must</u> be very temporary, by conservation of energy. Missing cloud modelling contributes trouble here as well, as previously quoted research showed.

KRC15: Even for the strongest OTEC cooling case (100% of standard case, no human CO2 emissions), much stronger than Miller's proposal… the initial jump in sea ice (red dotted, left graph) begins decaying back down, and is even smaller than initial by year 2070

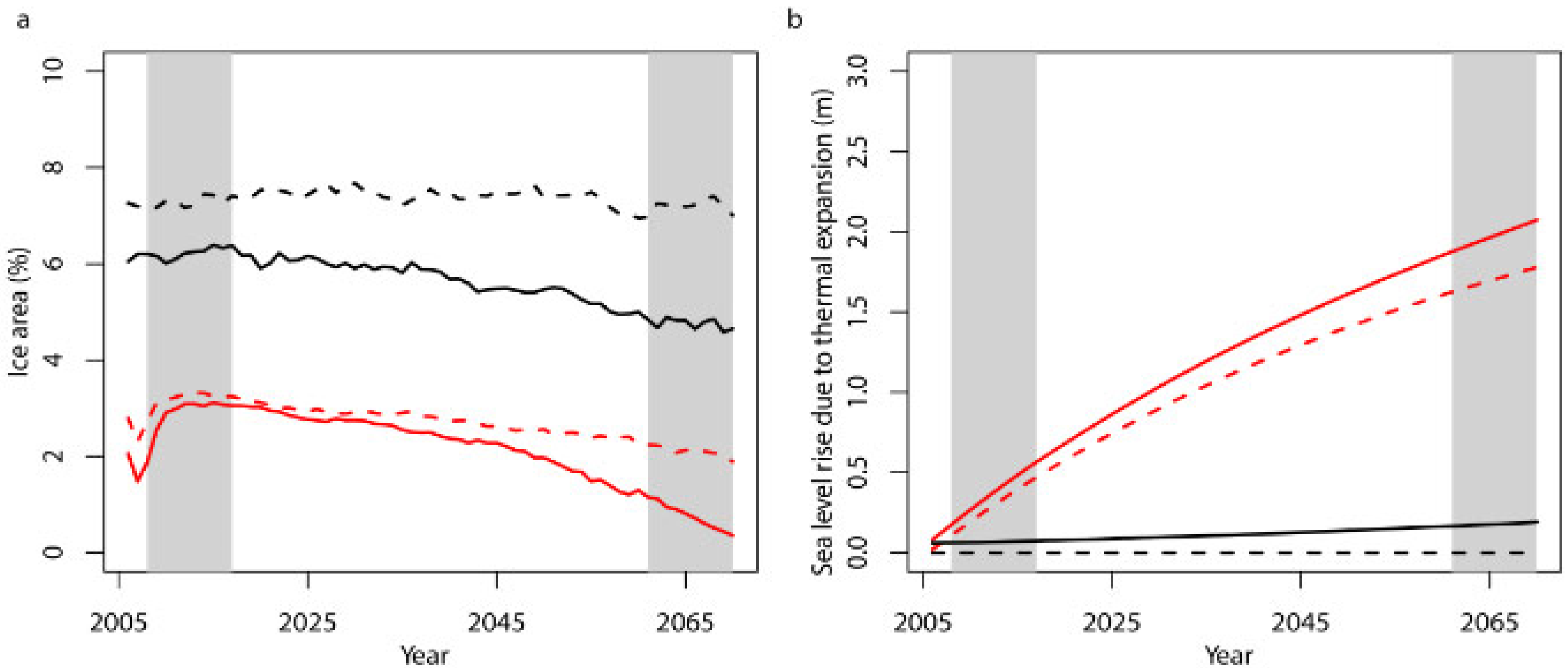
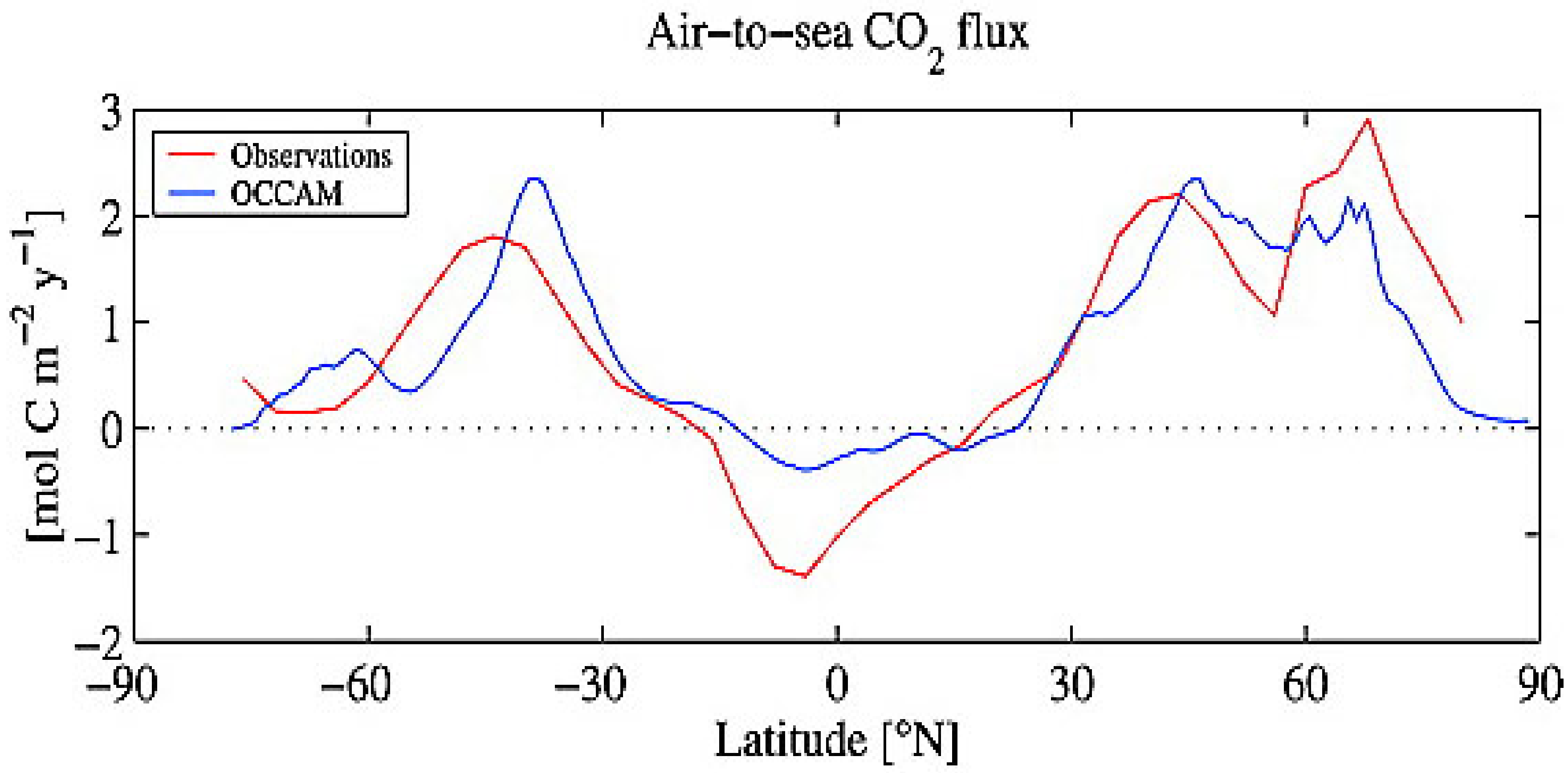


Figure S3. Mean global sea ice area (%) (a), and sea level rise (m) due to thermal expansion (b), for RCP8.5 (bold lines) and pre-industrial control (dashed lines) scenarios. *RCP8.5* and *piControl* simulations are shown in black and thermocline disruption simulations in red. Sea level rise due to thermal expansion is calculated based on (Kuhlbrodt and Gregory, 2012).

While the KRC15 Study May Not Fully Accurately Capture Polar Ice Behavior in a Realistic OTEC Scenario…

- … since their climate model did not include horizontal ocean transport around the pipes, it's also true that only in the tropics can OTEC have warm surface water and acceptable vertical temperature gradients, and horizontal transport of heat would then leave the high latitude oceans WARMER – highly antagonistic to the formation of surface ice to help albedo, as one study showed.
- It seems pretty difficult to contend that OTEC at climate–significant scales, would increase polar ice and improve albedo, when energy balance shows that either the buried heat would emerge at the poles, and/or it would emerge later in other places as well, and cause much worse heating in the longer term.

Observations and Theory (red, blue curves) both show that in the tropics, which is where OTEC pipes must be in order to temporarily cool the air and also to tap thermal gradients strong enough to power the pumps, are precisely where the rising colder water would outgas previously sequestered CO2, and thereby worsen our atmospheric CO2 problem. Below, Fig. 1 from Yool *et al.* 2009



- ***"I cannot envisage any scenario in which a large scale global implementation of ocean pipes would be advisable,"*** ***lead author Kwiatkowski (of KRC15) said.*** ***"In fact, our study shows it could exacerbate long-term warming and is therefore highly inadvisable at global scales."***
- (Kwiatkowski video summary)

Summarizing Geo-Engineering Strategies Studies

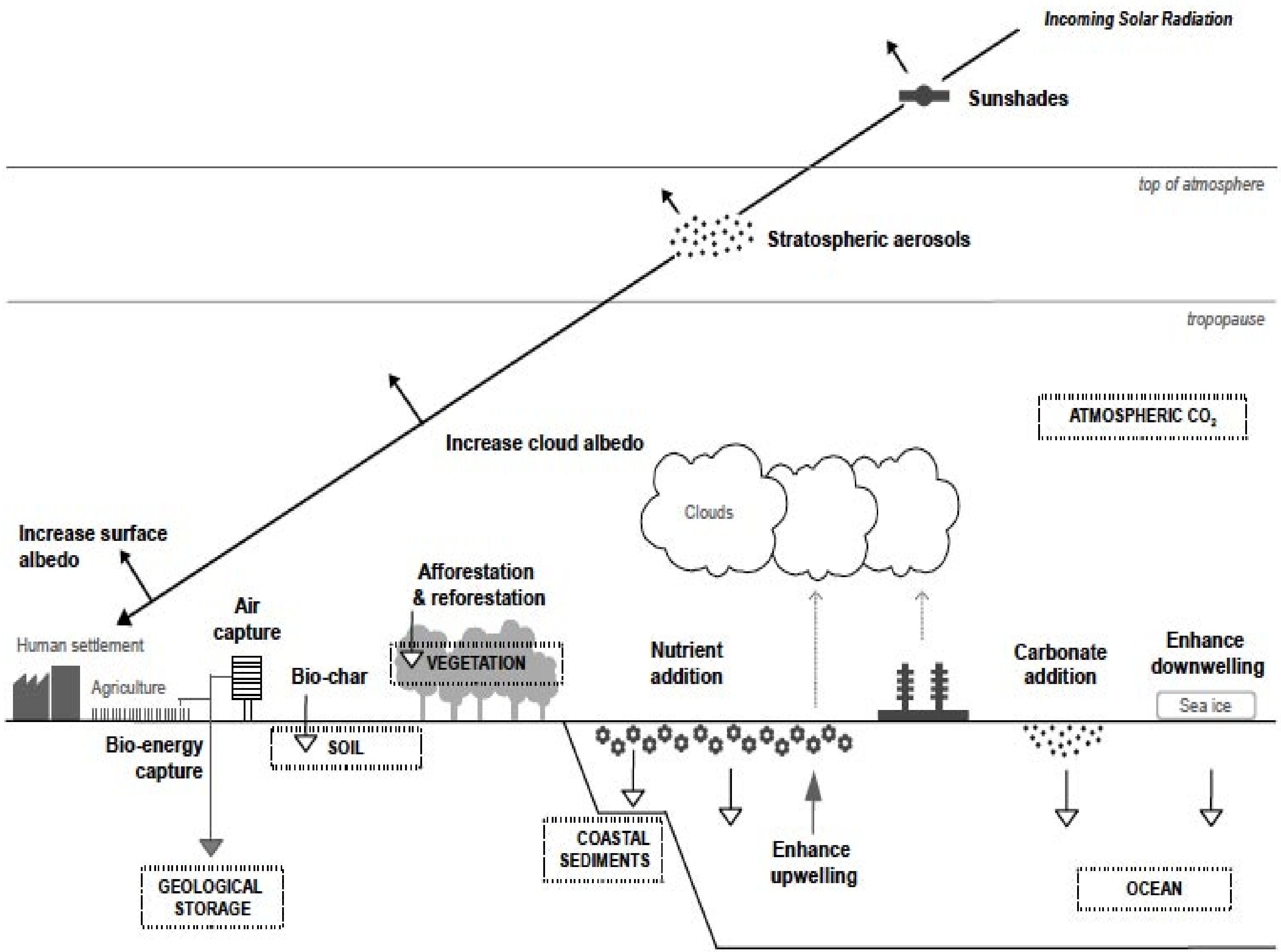


Fig. 1. Schematic overview of the climate geoengineering proposals considered. Black arrowheads indicate shortwave radiation, white arrowheads indicate enhancement of natural flows of carbon, grey downward arrow indicates engineered flow of carbon, grey upward arrow indicates engineered flow of water, dotted vertical arrows illustrate sources of cloud condensation nuclei, and dashed boxes indicate carbon stores. From Vaughan and Lenton (2009), not to scale.

CO2 drop from GeoEngineering Strategies (Lenton & Vaughn 2009). All are tiny compared to what's necessary

Table 2. Estimated radiative forcing potential of carbon cycle geoengineering options. Effects are calculated relative to a strong mitigation scenario in which a total of 1000 PgC are emitted and atmospheric CO_2 (and corresponding radiative forcing) reaches 450 ppm (2.58 $W m^{-2}$) in 2050, stabilises at 500 ppm (3.14 $W m^{-2}$) in 2100 and then declines to 363 ppm (1.43 $W m^{-2}$) on a millennial timescale.

Geoengineering Option	2050		2100			3000	
	ΔCO_2 (ppm)	RF ($W m^{-2}$)	ΔCO_2 (ppm)	RF ($W m^{-2}$)	ΣC_{seq} (PgC)	ΔCO_2 (ppm)	RF_{final} ($W m^{-2}$)
Enhance land carbon sink							
Afforestation	−41	−0.49	−34	−0.37	183	−16	−0.27
Bio-char production	−10	−0.12	−37	−0.40	399	−34	−0.52
Air capture and storage	−58	−0.74	−186	−2.5	>1000	>|−85|	>|−1.43|
Enhance ocean carbon sink							
Phosphorus addition	−5.9	−0.070	−12	−0.13	574	−52	−0.83
Nitrogen fertilisation	−4.5	−0.054	−9.3	−0.10	299	−25	−0.38
Iron fertilisation	−9.0	−0.11	−19	−0.20	227	−19	−0.29
Enhance upwelling	−0.1	−0.0017	−0.3	−0.0032	16*	−1.9	−0.028
Enhance downwelling	−0.08	−0.00095	−0.18	−0.0019	9*	−1.1	−0.016
Carbonate addition	−0.4	−0.0048	−2.3	−0.025	251*	−30	−0.46

* Activities assumed to continue to year 3000 hence larger airborne fraction than for other ocean options.

<u>Keller *et al.* 2014</u> studied a wide range of Geo-Engineering strategies and they too find…

- *"…that even when applied continuously and at scales as large as currently deemed possible, all methods are, individually, either relatively ineffective with limited (<8%) warming reductions, or they have potentially severe side effects and cannot be stopped without causing rapid climate change. Our simulations suggest that the potential for these types of climate engineering to make up for failed mitigation may be very limited."*

Nothing Perfect, a Mixed Bag here

- Massive DAC Direct Air Capture CO2 removal from the atmosphere is safest, and geologist judge it can be safely sequestered, with care, but requires high expense to happen. We're not yet willing to pay up.
- Aerosol injection to the stratosphere is only a quick Band-Aid to temperatures. Safety is in severe question. But it's likely cheap, and low-tech. Might be catastrophic, but might not.
- **Wind-powered pumps to refreeze the Arctic Ocean meets our critical requirements of safety and efficacy, but needs to prove the technology can work, and only addresses one, but very big, feedback in climate change. It's my favorite strategy!**
- Elsewhere….The costs looks far beyond sticker-shock, or are highly dangerous and/or ineffective.
- When the planet is dying, at some point we may finally confront Kurt Vonnegut's Stanford commencement summary…
- ***"We could have saved the Earth, but we were just too damn cheap"***

Finally, To Emphasize a Moral Criterion Not Yet Noted…

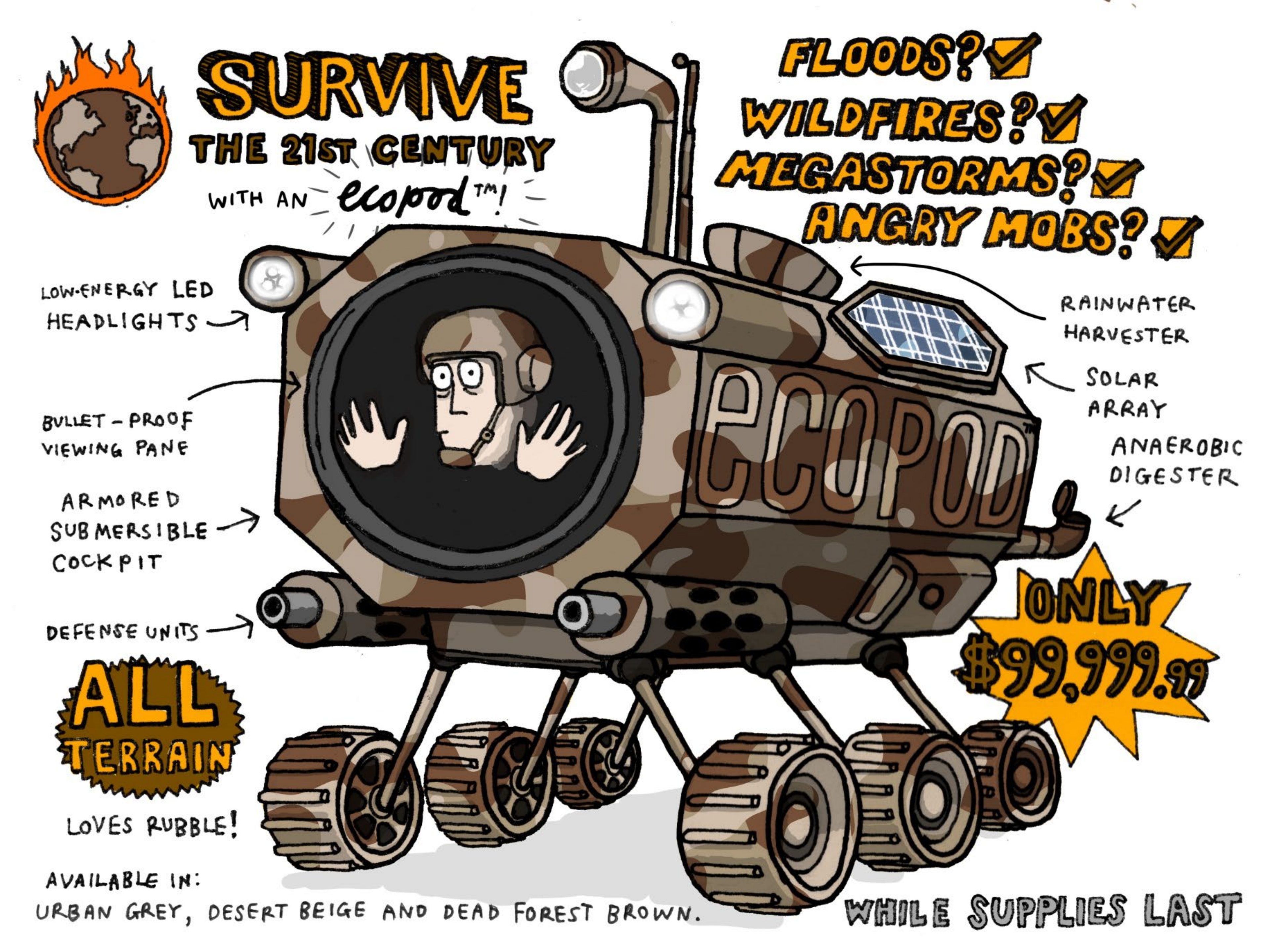
- Life exists in a thin layer at or very close to the surface of the Earth.
- We share that thin sheet with millions of other species symbiotically, and with (we hope) compassion.
- Any GeoEngineering Strategy should respect the surface of the Earth’s habitat for us and our fellow species.
- **Don’t let carbon-offset schemes optimized for short-term profit within poorly drafted laws seduce you!**

On This Criterion…

- Most strategies fail – they make massive changes to Earth's surface and its life. Whether continent-sized tree farm/and/burn, open ocean iron fertilizers, OTEC pipes, dumping carbonates into the ocean, etc.
- **The Key Strategy which most respects Life on Earth's Surface, is DAC: Direct Air Capture and pumping underground into deep sequestration sites, back from where it came.**
- It is also expensive, but if our civilization were ever fully educated on what we face, as a few, including myself, are trying hard to do, then we may motivate the grass roots commitment to stop complaining about the ~5% of global GDP needed for that effort.
- There is only ONE PLANET for US; indeed only ONE PLANET in the Universe known to be home to any life at all.
- **What's it worth to you and your children?**

Will our Insatiable Desire for Growth Continue to Overpower our Need to Restrain Ourselves?

If so, our technology solutions may instead be compelled in different directions…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K46: Key Points – Strategies: Geo-Engineering

- **EFFECTIVE Geo-Engineering strategies either must raise albedo of Earth, or raise ability of Earth to re-radiate its heat.**
- **SAFE GeoEngineering strategies should trace the Earth System backwards along the ~same trajectory that took us to where we are today. It should NOT alter the Earth system in entirely novel ways about which we have little understanding, high risk of disastrous consequences as we learn the hard way.**
- **SAFE strategies leave the Earth surface in as pristine a place as possible. Modifications should be made NOT on surface, but above or especially below ground.**
- **Reducing atmosphere CO2 from 400 ppm to 280 ppm by making calcium carbonate would require a Mt. Everest sized cube**
- **Cost of even the best atmospheric CO2 removal ideas appears to be $10,000+ per person, for entire global population**
- **"Loan shark" GeoEng strategies which merely bury heat cause long-term greater harm when that heat must re-emerge: OTEC Pipes are extremely dangerous.**
- **Beware carbon-offset profit-motivated cheap but dangerous strategies!**
- **Safest and most compassionate to life on Earth, is Direct Air Capture of CO2 (DAC) and sequestration deep underground.**