**CAVEAT: This is a hypothetical proposal that might be plausible in a few years after analysis of observations, modeling, and limited field research has been carried out—results are speculative.**

March 10, 2015

The Honorable John Holdren
Director, Office of Science and Technology Policy
Executive Office of the President
Washington, DC

Dear Dr Holdren:

In support of the International Restoration of the Arctic Initiative (IRAI) that was called for at the ministers meeting last spring in order to deal with the recent acceleration of climate change in the Arctic, and pursuant to your instructions on the matter, the National Climate Intervention Research Program Advisory Committee offers the following recommendations for US contributions to and participation in the Arctic Council's 2015 field test program (Arctic2015).

As you are aware, the international Scientific Steering Committee for IRAI will be meeting in mid-April in Reykjavik to finalize international coordination of activities for Arctic2015. This meeting will precede the meeting of the ministers of the Arctic Council in mid May, the goal of which will be to review and confirm the goals, approaches, and performance metrics of the various component of Arctic2015, to receive input from the international community of nations on problems to be watching for, and to agree on thresholds for terminating each of the proposed field effort in case unplanned outcomes exceed specified limits that would initiate consideration of liability for damages exceeding those that might be expected from a colder than average, but not inordinately extreme, seasonal climate pattern.

The timetable for this summer's activities is extremely tight, and, indeed, the initial stages of several of the proposed field activities must begin within a few weeks in order to begin to evaluate their potential performance as the Sun rises in high latitudes. In that the field program is made up of coordinated multi-national efforts, each nation is responsible for ensuring that its proposed contribution has been adequately peer reviewed by experts (a responsibility our advisory committee has undertaken) and that appropriate governmental approval has taken place (a responsibility of your office, working with DOS and PCAST that we will be pleased to assist with). Working cooperatively with the US national scientific steering committee, we have attempted to structure the planned program in ways that will allow the scientific objectives to be achieved while recognizing the tight timetable and the particular responsibilities of each participating group.

Completion of the planned experiments and field program, together with initial analyses that are expected to be finished by the end of 2015, are expected to provide just enough time for the Arctic Council to make a decision about initiating the implementation phase of IRAI as early as the spring-summer period of 2016, when Arctic ministers are proposing to move forward with initial implementation of the Restore the Arctic Initiative, seeking to return sea ice extent and thickness to late 1990 levels over the ensuing three years (the proposal they are expected to be taking to the United Nations for consideration this fall. If, indeed,implementation can begin under this schedule, the interventions should begin helping to alleviate the impacts of the very unusual weather being caused by the reduced extent and thickness of sea ice of the recent pass and projected for the next 5 years and beyond.

On the larger perspective, these efforts are responsive to the ‘Right to be Cold’ pleading before the World Court of the six Indigenous People’s Councils of the Arctic that explain how global warming and loss of sea ice are quickly threatening their very cultures and the ‘Right to be Dry’ pleading before the World Court of the island and low-lying developing nations that are very concerned about the increasing rate of sea level rise.

The prompt consideration of the Executive Office is essential to moving forward with the research effort and of the Congress and Executive for the planned implementation effort. We would be pleased to assist in your review, presentation to Congress, and public outreach efforts over the coming weeks and months, and to work with you and the State Department in the review of planned contributions of other countries to Arctic 2015 in order to prepare guidance for USG participation in the upcoming meetings of the international scientific steering committee and then later of the Arctic ministers.

Respectfully yours,

Chair, National Climate Intervention Research Program Advisory Committee

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# Restoring Arctic Climate: An Initial Full-Arctic Field Test

Proposed U. S. Contribution to the
2015 Field Test Program of the
Arctic Council's International Restoration of the Arctic Initiative

March 2015

**Context:** Over the past five years, the minimum summertime extent of Arctic sea ice has continued to drop, until in 2014 there was no sea ice over most of the Arctic Ocean from mid-August until early October. The very thin ice through the fall allowed strong heat flux to the atmosphere, significantly affecting mid-latitude weather as reduced generation of very cold air in the Arctic allowed moist tropical air to penetrate and persist in the northern Great Plains until early winter. When cold air did push out of the Arctic, its interaction with the very moist air led to record snowfall depths across southern Canada and the northern Great Plains, setting the stage for exceptional floods this spring over very large areas. Calls for action about the effects that the warm Arctic is having on weather over central and eastern North America (as well as in Scandinavia and across Russia) are intensifying, while the scientific community is expressing growing concern about the accelerating thawing of permafrost and the consequent increases in release of methane and carbon dioxide, both of which will be amplifying and extending future warming. At the same time, the longer Arctic warm season has led to more extensive surface melting over Greenland, acceleration of the Jakobshaven ice stream that could potentially drain the central lobes of the Greenland Ice Sheet, and an accelerated rate of loss of high latitude mountain glaciers, which together are projected to cause a sea level rise of approaching 1.5 meters during the 21$^{st}$ century alone. New model results suggest that there is a significant risk that, once started, this rate of ice loss from the Greenland Ice Sheet would be expected to continue even if carbon dioxide emissions are cut to near zero by 2050, with the sea level rise expected to start to destabilize several ice shelves in Antarctic that are holding back ice streams that could amplify and sustain the increased rate of sea level rise indefinitely into the future.

With the Arctic warming more rapidly than had been projected in IPCC's Fourth Assessment Report, and the newly available government review version of IPCC's Fifth Assessment Report projecting that the rate of warming is very likely to accelerate, Congressional hearings during the fall of 2014 were filled with calls for accelerating the potential implementation effort by relying more heavily on the early results from modeling studies and very limited field testing over the past two years of the four proposed approaches for climate intervention that have been the basis of the since the US Climate Intervention Research Program began in FY-2012.

Concern about Arctic warming in northern Europe is equally high, with permafrost thawing causing increasing disruption. Parliaments in the region recently called for those leading the European research effort that began in 2010 to take action. In response, the Arctic Council has called for extensive field-testing in 2015, aiming to move toward implementation in 2016. Representatives of national scientific teams will be meeting in mid-April in Reykjavik, Iceland, prior to the annual ministers' meeting in mid May that will make the final decisions on moving forward and criteria for stopping the experimental program if unexpected changes arise.

The four components described briefly below represent the proposed US contribution to Arctic 2015 as the Arctic Council coordinates the urgent international effort to restore the Arctic.

**1. Springtime Whole Arctic Solar Radiation Reduction**

Coming out of winter, the near full sea ice coverage over the Arctic Ocean limits atmospheric water vapor and, therefore, cloud cover. The thinning of the sea ice over recent decades has made the cover more vulnerable to early season solar radiation, especially as cleaning up of Arctic haze has made the troposphere more transparent. Modeling studies indicate that sustaining Arctic Ocean sea ice cover and enhancing the regional cooling effect provided by the high albedo of the sea ice and snow on surrounding land areas can most effectively be achieved by increasing the sulfate aerosol loading of the lower stratosphere in high latitudes. Because the increased aerosol loading has only a very small (and perhaps even a negative) effect at very low sun angles, the optimal approach is to initiate stratospheric $SO_2$ injection in the 50-60ºN latitude band in early April and then expand the injection band northward by about 10º every two weeks, continuing injection until the surface melts and extensive cloud cover occurs.

Field tests of lower-stratosphere injection techniques last summer indicated that injection of $SO_2$ through hoses held aloft by balloons above elevated locations in high latitudes provided an efficient approach over land areas. The US and Canada have identified four locations in the mountains of western Canada and Alaska that are readily accessible by roads and than can be easily supplied by sulfur scrubbed from the tar sands refineries of Alberta. Emissions from the four identified sites are planned to begin in early April to early May (so after the time when ozone depletion might be stimulated) and continue through June when the extensive cloud cover reduces the effectiveness of stratospheric aerosol intervention. Over the Arctic Ocean, $SO_2$ injection will be done by USAF tanker aircraft that have been specially equipped for this mission, which would extend from mid-May through June.

Baseline observations will be made by an array of surface observation stations spread across northern North America that will continuously monitor stratospheric opacity and surface solar radiation (direct and diffuse) over the course of the 2-3 month experiment. Additional observations sites across northern Europe and Asia are also expected to be provided by nations in those regions. In addition to the surface-based observations, an extensive in situ aircraft sampling program and near-real time analysis of satellite observations will provide the ability to test and validate model simulations that will be done concurrently, thus ensuring that the experiment is within the agreed upon safety bounds (which were established by considering the observed climatic response to high-latitude volcanic eruptions over the past 50 years).

The objective of this major field test is to achieve a statistically significant 5% reduction in the direct solar beam, which, because of the significant forward scattering by sulfate aerosols, would amount to about a 0.5% reduction in total solar radiation reaching the troposphere. Final calculations are underway to estimate the needed injection amount, but the total is expected to be a few tenths of a TgS, well within the injection capacities of the planned hose and aircraft systems. The aerosols are expected to be carried out of the stratosphere within about two months, and then within a week or so to be removed from the troposphere by convective precipitation systems. The overall sulfur amount being less than1% of Northern Hemisphere emission levels, no noticeable increase in deposition is expected.

While the induced change in downward solar radiation would not be expected to lead to a statistically significant change in regional surface temperature or to cause a statistically significant change in the thinning or onset of surface melting of the sea ice (for the change to be statistically significant it would need to exceed 6 days), this component of the field program would provide vital information about the rate of formation of sulfate, the effectiveness of the resulting size distribution of sulfate aerosols to alter energy fluxes, and the lifetime of the aerosols so that the injections needed for actual implementation could be derived. As an additional analysis capability, NOAA's National Weather Service and other weather services around the world will be running dual sets of weather simulations during the experimental period, with the intent of determining the character and location of significant changes in weather patterns, especially of storm tracks and monsoon extent, both within the region and around the world.

With the US and Canada assuming responsibility for the injection component of the field program, extensive international cooperation in the observation and analysis program is expected. An international scientific safety committee is being established, drawn from the full and associate members of the Arctic Council. In that the impact is expected to be below that of a small high-latitude volcanic eruption and far less than current anthropogenic emissions, it is not anticipated that there should be a reason to end the experiment early. However, should unanticipated consequences arise (e.g., a significant Northern Hemisphere volcanic eruption), the injections could be quickly stopped and, in that model studies indicate that the sulfate aerosol lifetime in the lower stratosphere is roughly two months, a reasonably quick recovery of the system would be expected. Note, however, that while little effect on the large scale hemispheric circulation is expected during the Northern Hemisphere warm season when there is relatively low meridional energy transport, restoring the colder conditions of the Arctic would be expected to increase heat transport during the winter and thus to force the Inter-tropical Convergence Zone slightly southward during that season, thus drawing forth more energy and leaving less energy to provide warmth to the Southern Hemisphere during the next austral winter. While the size of this effect as a result of the field program are projected to not be statistically significant, this effect be monitored, and need to be considered if any of the first three components of this Arctic2015 approach move to the implementation phase.[1]

## 2. Summertime Enhancement of Arctic Cloud Brightness

Once the sea ice surface melts and sea ice cover starts to decline, atmospheric humidity rises and the stable temperature profile leads to extensive coverage of low-level clouds in the Arctic region. Whether incoming solar energy is absorbed at the surface or absorbed in the clouds and radiated to the surface as infrared radiation, it is the Sun's energy that leads to the melting of the sea ice and storing of energy in upper ocean waters. This energy has been responsible for the significant loss in extent and thickness of Arctic sea ice, delaying reformation of sea ice and providing a source of energy to the atmosphere that affects weather patterns and storm tracks well into midlatitudes, especially in the autumn, but with effects extending throughout the year.

Studies indicate that the most effective approach for limiting uptake of solar energy during this period is intervening to brighten Arctic cloud cover. The most effective approach to

[1] Initial model studies indicate that such a shift in the ITCZ, and thus in some low latitude precipitation belts, could be offset by injecting $SO_2$ into the lower stratosphere over the Southern Ocean during austral summer, and that their combined effect would actually help to moderate the global increase in surface temperatures.

doing this is increasing the number of cloud condensation nuclei (CCN)—indeed, reconstruction of energy fluxes and ice conditions over the period 1990-2010 indicate that it was the reduction in CCN resulting from the reduction in $SO_2$ emissions in Europe (due to desulfurization to minimize acid precipitation) and the nations of the former Soviet Union (due to their economic restructuring) that led to the significant reduction in Arctic haze and that inadvertently contributed to a reduction in cloud albedo and accelerated melting of the Arctic sea ice cover.

The proposed 2015 field experiment is aimed at quantifying this relationship by raising summertime CCN loading back to the levels that prevailed in the late 1980s before significant reductions in $SO_2$ emissions began in Europe and Asia. While there would likely be slightly less environmental damage if this could be done by spraying sea salt aerosols into the atmosphere, the logistics of doing this over the Arctic while sea ice is present, even though breaking up, would be extremely difficult.

For the 2015 field program, injecting $SO_2$ into the lower troposphere from a number of mid-altitude, high-latitude land locations has been chosen as the optimal approach (see field test component 3 for a test of the sea salt injection approach to cooling the Arctic). The US will be responsible for the emissions injection site in Alaska (which will near to the site selected for stratospheric injection in component 1 above, so there will need to be only one site for $SO_2$ delivery and storage), while Canada, Norway, Russia, and Greenland (Denmark) are also expected to support mid-altitude injection sites. At each location, the material will be injected into altitudes up to 4 km, but only on days when the wind trajectory is into the Arctic and precipitation is not predicted over the ensuing four days, thus lengthening the average aerosol lifetime and reducing the amount of material that will need to be injected.

Injections would begin in late June to early July, once surface melting of Arctic sea ice begins (i.e., when the surface albedo drops and low-level clouds become extensive due to increased evaporation), and continue until early September when the sun angle is too low for the increase in cloud albedo to have significant effect. The objective would be to increase region-average albedo by about 5% (so from roughly 50 to 55%), which would require increasing cloud albedo in the region by about 8% (the presence of the sulfate aerosol will slightly raise clear air opacity, but the net effect is likely to be small as this will exert a cooling influence only over open water, due to its low albedo, while perhaps exerting a slight warming influence when over higher albedo surfaces).

The goal will be to, on average, reduce uptake of solar radiation by the ocean-sea ice system by about 10%, which model projections indicate would lead to about 5-day earlier reformation of sea ice and providing the opportunity for earlier thickening of the sea ice and so earlier generation of the very cold air masses that can occur, because of the greater insulating effect, once ice thickness exceeds about 1 meter. In that global warming has led to the reformation of significant sea ice cover has been delayed by about a month over the last several decades and that the variation in the date of reformation is about a week, the experimental objective is well-within conditions experienced over the past three decades and so is expected to be well within the adaptive capacity of the peoples, fauna, and flora of the region and high-latitude land areas, especially if warning is provided to those entities (e.g., ocean shipping companies; oil platform suppliers) that have been taking advantage of the longer season of open waters.

With $SO_2$ emissions during this period being only about 5% of emissions two decades ago, no noticeable environmental or societal impacts are expected from deposition during the summer period in surrounding nations, especially because it was sulfate deposition on snow through the winter and then being released in rapid spring thaws that was the primary damage mode from high-latitude sulfur deposition. As an additional back-up, the Arctic Council is expected to approve a special board to monitor this component of the field experiment and modification of the emission pattern or schedule or even termination of the effort could be rapidly accomplished.

### 3. Reducing North Atlantic Warming of the Arctic

Although the increased absorption of solar radiation in the Arctic due to the reduced summertime albedo and absence of sea ice is the major source of energy for altering autumn and winter weather patterns and intensity, the year-long transport of heat into the Arctic by ocean currents in the North Atlantic plays a very important role in determining the resulting ice thickness. For this reason, an additional approach to limiting the thinning of Arctic sea ice is to cool these waters. The UK and Scandinavian nations are leading the proposed activities on this component of the 2015 field program, with the US providing major assistance.

Because the waters that must be cooled are upwind of northern Europe, the mountains of which are very sensitive to acid deposition, because of the complexities of the weather, and because of the particular locations of the areas to be cooled, modeling and analytic studies of the optimal approach for reducing the transport of energy into the Arctic indicate that cloud brightening using sea salt CCN is the optimal approach (an additional complementary approach that may be useful in the future is surface whitening by bubble injection, as will be tested in the fourth component of the 2015 field program—see below). The northward moving waters carrying heat to the Arctic are naturally cooled during the winter and early spring when sea surface temperatures are above the temperature of the overlying air—during this time, cloud brightening would also not have any useful effect because the solar zenith angle is low (whether wintertime cloud clearing might be a useful additional process is being evaluated but will not be tested during the 2015 summer campaign).

The proposed cloud-brightening program is planned to run May through September in the North Atlantic, with roughly a dozen ships carrying the special salt-water spraying equipment. Three of the UK supplied ships will be wind-powered Flettner rotor ships, being prototypes of the type of remotely-controlled vessels that are envisioned for use over the longer term to limit global average temperature, if that becomes necessary. To avoid confounding cloud-brightening effects from the diesel exhausts of conventionally powered ships, the rest of the vessels will be nuclear-powered, drawn from the fleets of naval vessels of the US, Russia, and other nations. Under present plans, both the US and Russia will mount the CCN-generating equipment on nuclear-powered submarines that will be run at the surface during peak periods of the field test program. While the Navy has agreed to participate in this way provided national security concerns are not identified, final approval of this contribution to the international effort is needed by the NSC and the President.

The experimental plan envisions running a series of specific sub-experiments that explore different patterns for injecting the CCN, with different spacings, injection rates, and alignments with the wind to determine the average CCN lifetime, range of influence, zenith angle dependence of albedo effect, effects on different types of clouds and weather conditions, relative influence as the concentration is built up, and more. In addition to our naval participation in providing emissions, the Navy and NOAA will also provide observation support for changes in the ocean, including in temperature (by direct observation and acoustic techniques) and light levels. NOAA will also be providing real-time weather forecasts and running dual forecasts with and without cloud-brightening intervention (forecasts done in addition to the stratospheric and tropospheric aerosol support calculations supporting the first and second components of the field program).

Because any significant impacts of the field program would most immediately affect Europe, the EU is establishing the safety evaluation panel for this experiment, and will be assuming all responsibilities relating to adverse consequences. If additional sea salt sprayers can be constructed by the end of June, however, a US scientific team is hoping to be able to initiate a similar field test program in the Bering Sea to determine the potential for increasing cloud albedo in this region and, if implemented on a continuing basis in the future, cooling the ocean and increasing the likelihood of sea ice. For this program to move forward, a regionally based safety review team will need to be appointed, and contingency planning for such a step is underway.

**4. Slowing the Retreat of the Jakobshaven Glacial Stream**

While cooling the Arctic as a whole is likely to reduce the rate of loss of ice from the Greenland Ice Sheet, the primary cause of ice mass has become loss through ice streams rather than melting exceeding accumulation on the surface of the ice sheet. For Greenland, the most significant loss is occurring as a result of the greatly accelerated calving from the Jakobshaven glacial stream, which is now flowing at record levels and could accelerate further in that the underlying fjord reaches into the interior of the Greenland Ice Sheet. Intensive studies over the past few years have made clear that the primary reason for the accelerating loss is the transport of energy to the ice front by subsurface currents—basically, relatively warm (i.e. about 2ºC) deep water is flowing in the fjord while relatively freshwater from the glacial front is flowing out on the surface. The sources of the incoming salt water are Baffin Bay and the Labrador Sea. With the warming of the Arctic region, sea ice retreat is occurring much earlier in the year and these water bodies are absorbing much greater amounts of solar radiation than in the late 20$^{th}$ century, and this energy is contributing to warming of the ice sheet.

The goal of this component of the field program is to reduce the amount of solar energy being absorbed in Baffin Bay and the northern Labrador Sea. Denmark, Canada, and the US have planned a coordinated program to slow the transport of heat to the face of the ice sheet. The higher winds in this region of the Arctic tend to keep the air clearer than in other regions, such that interventions aiming to increase cloud albedo or to enhance atmospheric opacity would not work well. For this region, the proposed approach to reducing uptake of solar radiation is to increase the surface albedo of the ocean by injection of nanobubbles. An additional effort will be made to slow the rate of waterflow into and out of the fjord such that less heat is transported to the face of the glacier.

For the ocean brightening part of the program, Canadian icebreakers equipped with the bubble generating equipment will begin operations in April in the Labrador Sea and then move into Baffin Bay as the sea ice front retreats. Canadian submarines will also conduct scientific cruises below and near the ice front, providing observations that are expected to be helpful in the detection-attribution studies that are planned. Lacking sufficient icebreakers, the US Navy is equipping three heavy weather ships with bubble-generating equipment and they will be deployed on a bubble-generating mission beginning in May in the Labrador Sea, once the region is free of sea ice. Together with Canada, the US will also be monitoring the outflow current from the Labrador Sea to the Atlantic Ocean. All of the surface ships are diesel powered, and so their exhausts will loft CCN that will have the potential to brighten the clouds that are present. Both the US and Canada will also deploy aircraft to measure the changes in surface albedo (baseline information having been taken in the summer of 2014). Satellite observations will also be jointly analyzed.

The effort to reduce the rate of transport of ocean waters into the fjord will be primarily an effort led by Denmark, but with assistance from the US. In that the fjord is deep and it would be difficult to directly influence the deepwater inflow, the approach to be investigated will be to slow the outflow of the freshwater near the surface. This will be attempted by slowing the movement out of the fjord of ice that has been calved from the ice front, seeking ultimately to create an ice dam that, based on the density difference of fresh and salt water, is projected to build up a back pressure to slow the incoming deep water. The accumulation of ice should also brighten the surface and reduce uptake of solar radiation during the summer, and then during the autumn accelerate the formation of sea ice, releasing cold brine that is expected to also help displace (or at least cool) the incoming water from the Labrador Sea. Stopping ice outflow will be attempted by creating a series of three ice dams using strong, cross-fjord chains (of the size normally used for ship anchors). The chains will be held near the surface using Kevlar inflation bags. Denmark is taking responsibility for the two planned ice dams in the fjord itself while the US Coast Guard will take responsibility for the effort to create the ice dam at the mouth of the fjord. Denmark, in cooperation with other nations, will also monitor the speed of the ice stream seeking to determine if any slowing of the flow is induced.

To oversee the scientific aspects of the field program and the supporting analysis and observation efforts, the three nations have formed a joint scientific committee. The three nations and members of the region's Indigenous Peoples have also formed a safety committee to evaluate the importance and determine the response to unintended consequences. This committee will be chaired by Denmark, not only because of their responsibility for Greenland, but because virtually all of the potential unintended consequences would be likely to affect those living in Greenland. Special observations will be made of fishery catches as fish have proven to be reliable and very sensitive indicators of changes in ocean temperature.