

Summary of Meeting with U.S. DOE to Discuss Geoengineering Options to Prevent Abrupt and Long-Term Climate Change

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Introduction

A meeting was held at the U.S. Department of Energy Headquarters in Washington, D.C. on June 16, 2004 to discuss several geoengineering options to prevent abrupt and long-term climate change and to request funding for climate modeling research in some of these areas. The meeting between Environmental Reference Materials, Inc. of Research Triangle Park, N.C. and the U.S. Climate Change Technology Program was arranged through the offices of Sen. Elizabeth Dole, N.C. and Representative Richard Burr, N.C.

This report summarizes the discussions held at that meeting and subsequent comments submitted by the attendees and others.

In attendance were the Director of the U.S. Climate Change Technology Program, Mr. David Conover, Mr. Alvia Gaskill from Environmental Reference Materials, Inc., Dr. Ken Caldeira from Lawrence Livermore National Laboratory's (LLNL) Climate and Carbon Cycle Modeling Group and Dr. Michael MacCracken, the former Director of the Office of the U.S. Global Change Research Program and now a participating guest scientist at LLNL.

MacCracken noted that he and Dr. Caldeira's participation in the meeting should not be taken as an indication of support of the various geoengineering options presented. Rather, they were there to listen and question and possibly provide an objective analysis of these options should they go beyond the concept stage.

Caldeira said that he also does not support any specific scheme, but does support investigation, evaluation and attempts to improve technologies and approaches that have a prima facie chance of competing in some future marketplace and regulatory environment.

The meeting began at 9:30 a.m. Caldeira and MacCracken discussed with Conover some of the background for thinking about geoengineering as an approach as they waited for Gaskill to complete his research on how long it takes to get to DOE HQ on the Metro Blue Line from Springfield where he had parked his car. It turns out it takes a very long time. It was mentioned that a Dr. Khan from DOE was preparing a report on geoengineering options. He is welcome to reference our work.

Gaskill then arrived and presented a PowerPoint slide show on the topic of Practical Geoengineering Options to Prevent Abrupt and Long-Term Climate Change. A CD version of the slides covering long-term climate change was provided along with an emailed version. An emailed version only was provided of the discussion of abrupt climate change.

Long-Term Climate Change Mitigation

Gaskill reviewed the physics behind the long-term climate change problem. [An error in slide 5 giving the solar radiation wavelength range has been corrected. The correct range is 0.3 to 2.5 micrometers]. Shortwave solar radiation is absorbed by the Earth (atmosphere, surface) and the Earth in turn re-emits this radiation as longwave infrared radiation (IR) that is absorbed by trace gases in the atmosphere, e.g. water vapor and carbon dioxide known as greenhouse gases (GHGs) that in turn re-emit IR back to the surface where it is absorbed and re-emitted again.

The addition of man-made GHGs to the atmosphere from fossil fuel use and food production is increasing the amount of infrared radiation in the atmosphere, enhancing the natural greenhouse effect, causing a global warming and leading to significant global climate change. The Intergovernmental Panel on Climate Change believes that unless GHG levels in the atmosphere can be stabilized by 2050, there will be irreversible climate change with droughts, floods, famines, deadly heat waves, loss of millions of species, significant sea level rise and other consequences.

For this reason, governments have decided to reduce GHG emissions through treaties and legislation and by supporting technological innovation. Gaskill said his group had concluded that neither approach was going to be successful in stabilizing GHG levels by 2050. He cited the failure of the Kyoto Protocol to go into effect and the lack of progress by European Union (EU) nations and Japan in meeting their assigned targets. He said most view

the U.S. Clear Skies program as a business as usual (BAU) hybrid, with most of the projected emissions reduction heavily back-loaded. He also said pending legislation in the U.S. Congress, although well intentioned, is years away from enactment and that the U.S. would eventually rejoin the international treaty process.

He gave three reasons why technology changes would not occur in time to solve the long-term global climate change problem. The first was that emissions are spread across too many sources (transportation, power generation, heating, food production, landfills, pipeline leaks, deforestation, non-transportation halocarbons) to expect changes to be made easily and rapidly. [An error in slide 17 showing the apportionment of GHG emissions contribution to global warming by sector has also been corrected. Food production, landfills and pipeline leaks contribution is 25%, not 20%. The percentages refer to the radiative forcing caused by the emissions, not the raw emissions in GtC].

The second reason is that replacement technologies are either immature or non-existent. Gaskill cited the 2004 National Academy of Engineering report that said hydrogen/fuel cell use would not be significant before 2030. In general, Gaskill said that replacement technologies are 20-40 years away from the beginnings of widespread use. He also cited the long capital lifetimes of vehicles, power stations and heating systems as contributing to the lag time in deployment of replacement technologies until well past 2050.

Gaskill concluded that for all of these reasons, GHG emissions couldn't be reduced in time to prevent a global climate catastrophe. He said that what was needed was more time, a way to delay the anticipated warming as long as possible. He proposed geoengineering or deliberate modification of the Earth's climate as a delaying tactic. He described various geoengineering schemes that have been proposed, noting most of them are presented as alternatives to reducing emissions, not as delaying tactics.

He said most of these cannot be made practical by 2050 or do not work at all. He noted the proposal to add iron to iron-deficient areas of the oceans to stimulate phytoplankton growth and remove carbon dioxide from the air. He said the latest research had determined that silicate was also a limiting nutrient and that the quantities required for human intervention could not be produced. Significant transport of dead phytoplankton biomass to the ocean

bottom will also take hundreds of years, ruling out the use of this strategy in meeting the 2050 target date, irrespective of which nutrient is limiting.

Gaskill then described some of the options that involve reducing solar radiation, the energy source that powers the greenhouse effect. Proposals have been made to reflect sunlight from outside the atmosphere with thousands of square miles of mirrors or just inside the atmosphere with balloons, sulfate aerosols or aluminum oxide particles. If enough sunlight were reflected back into space, the heating from GHG emissions would be offset. The mirror strategy is not feasible and there are concerns the balloons won't stay aloft long enough or stay spread out. Particle injection with sulfate aerosols may damage the ozone layer, while the residence time of aluminum oxide may not be long enough.

Gaskill said this leaves increasing the reflectivity or albedo of the surface of the Earth as the only practical alternative, even though only half the solar radiation that arrives at the top of the atmosphere reaches the surface. Both the downwelling solar and upwelling infrared radiation is measured in watts/meter², a measure of the amount of energy impacting a surface area per unit time or flux. He showed some recent data from a NOAA surface radiation-monitoring site in NV to demonstrate the variation in these fluxes throughout the day. He said GHG emissions since 1700 have added about 2 watts/m² to the IR flux in the atmosphere, about a 1% increase in total radiative forcing and that another 3-5 may be added in the 21st century.

He described several small-scale attempts to lower air temperatures by increasing surface reflectivity related to agriculture and the urban heat island effect. White and aluminized plastic mulches have been used to lower air and soil temperatures around vegetable plants and orchard trees by reflecting sunlight, allowing for better growth during hot weather and increasing the amount and uniformity of sunlight received by the plants. The use in orchards is said to provide for more uniform coloration of fruit. Whitening of shingles and pavements to reduce IR levels in urban areas has also been used.

Gaskill described several proposals to manipulate the global climate by increasing the surface reflectivity of the oceans with white floating plastic islands, white spheres or white foam and of land plants by spray coating them white. These were judged infeasible and/or too expensive.

He said the ideal candidates for surface albedo enhancement are the world's deserts, citing their advantages of being largely uninhabited, sparsely vegetated, flat and stable with a high solar flux and low humidity (meaning less absorption of solar and IR by water vapor) and generally useless and noting their primary disadvantage of having the highest reflectivity of all surface areas except the ice caps.

He said that of the 7.5 million square miles of deserts, 75% are gravel plains, dry lakebeds and mountains with the Sahara, Arabian, Australian and Gobi accounting for 75% of all desert land. He showed examples of some of the flat, featureless terrain of the Sahara from Morocco to Egypt.

He said that as much as 4.5 million square miles of desert may be suitable for covering with a reflective surface for the purpose of offsetting global warming. On the scale required to do so, this would be a Global Albedo Enhancement Project (GAEP). Gaskill listed the assumptions on which the feasibility of this was based. The additional radiative forcing he projects from 2010-2070 of 2.75 watts/m² would be the primary target for reduction. This level is reasonable based on emissions forecasts. By 2070, GHG emissions BEGIN to be controlled globally. All additional radiation reflected at the surface is returned to space.

A calculation was presented of net reflected solar radiation from a typical desert vs. one covered with a reflective material. Increasing the surface reflectivity or albedo from 36% to 80% resulted in an additional 136 watts/m² reflected. This reflected flux was used to calculate the land area coverage required to offset the radiative forcing from various scenarios. All forcing from 1750-2070 would require 7.9 million square miles, more than all available desert land; the forcing from 1750-2000, 3.6 million; the U.S. Kyoto target for 2012 290,000; all U.S. electric power generation from 1750-2070 390,000 and all U.S. forcing from 1750-2000, 2 million.

Of greatest relevance was that 4 million square miles would be required to offset all of the forcing from 2010-2070, almost all of the desert land likely suitable. These numbers point out that the GAEP is not an alternative to emissions reduction, but a delaying tactic until the emissions can be brought under control.

Gaskill noted that averaged over 60 years, the annual coverage would be around 67,000 square miles or about the size of Missouri. However, the

coverage in earlier years could be much less since the GHG emissions are expected to increase non-linearly over time. He also noted that 80,000 square miles is planted in wheat annually in the U.S. Thus, the scale of this project is comparable to what is practiced today in modern agriculture.

Gaskill then discussed how the GAEP might be implemented. He said that both global and regional (mesoscale) climate modeling should be done first to detect possible impacts such as changes in temperature, wind flow patterns, precipitation and hydrology. The models could be designed to avoid distortions likely from natural variability. One of these would be that from changing the conditions incrementally as would be the case with the reflective cover. Instead, an instantaneous application of say 60 years of coverage allowed to reach equilibrium, would help define the conditions of importance in applying the cover incrementally. Both Drs. MacCracken and Caldeira helped explain this.

Examples of global climate modeling performed by LLNL were reviewed in which the radiative forcing resulting from a doubling of atmospheric CO₂ (280 to 560 ppm or 355 to 710 ppm) levels was completely offset by reducing incoming solar radiation by 1.7% from outside the atmosphere. In these models, there were no temperature increases or decreases observed in the troposphere either globally, regionally, or seasonally, indicating the reduction of solar luminosity compensated for the effects of increased CO₂. Gaskill said modeling like this should be done to predict the impact of the GAEP since an uneven reduction in solar radiation absorbed at the surface, like that expected from the GAEP, would be expected to produce uneven heating globally, regionally and seasonally.

Examples of regional modeling performed by Dr. Haider Taha of Altostatus, Inc. were also presented in which impacts of surface albedo enhancement on regional meteorology and tropospheric ozone were studied. The resolution of the regional modeling was 4 km², while that for the global modeling was around 40,000 square miles, illustrating the need for the mesoscale modeling in predicting impacts over smaller areas.

Gaskill described the characteristics of an ideal surface cover: inexpensive to produce, install, maintain; highly reflective, reflecting >80% of incident sunlight; puncture and tear resistant; stable for years in a field environment; recyclable as cover material and available today or within 5 years. Based on these criteria, he said white polyethylene film is the best choice. The

whiteness is due to titanium dioxide pigment. Plastic film used in the field contains additives such as antioxidants, thermal stabilizers and UV inhibitors designed to prolong its life. Such films are often embossed to resist wind fatigue and cracking. However, they are not completely opaque at typical thicknesses (1-6 mil) and may only reflect 60% of sunlight.

For the GAEP cover, he said a composite film consisting of white plastic on the top and aluminized plastic on the bottom may be most effective in reflecting sunlight. The aluminized plastic can reflect as much as 90% of incident sunlight, but only emits 25% of the IR it absorbs, while the white plastic reflects 60% of the sunlight and emits 90% of the IR it absorbs. Combined, they could yield an overall reflectivity of sunlight of 80% and an emissivity of IR of 90%, the best of both worlds.

He showed an example of the use of aluminized surface cover in orchards (slide 96), noting there is still much to be learned about the ideal plastic film for this application.

He said installation would require removal of material that could puncture the plastic and might require grading of the surface. Installation equipment could be patterned after the large installers used for geomembranes. The cover could be kept in place with commercially available mechanical anchors that resemble giant thumbtacks as indicated in slides 98 and 99.

Accurate monitoring of surface albedo would be required for input data for models, to calculate “thermal credits” for emissions trading or in meeting emission reduction targets and to ensure albedo is above its target value. Other radiometric and meteorological parameters would also be determined. Monitoring would be accomplished through a combination of ground stations, unmanned aerial vehicles and satellites.

The cover would be replaced every 3 years and cleaned as necessary using robotic vacuum cleaners to remove dust that would darken the surface. Gaskill said their research found that conventional robotic vacuum cleaners spread fine particles of soil over the surface that could not be removed by vacuuming. Developing vacuum systems that can limit particle adherence to the surface by electrostatic or other means or covering land from which the dust originates are both topics that should be pursued.

Gaskill presented an estimate of the cost of the GAEP, based on the maximum possible coverage of 4 million square miles done equally over 60 years. The following assumptions were made. The plastic is a 3-layer 4-mil polyethylene film costing 1.7-cents/square foot (SF), which can be recycled 3 times at 50% the cost of the original. If aluminized composites are used, they will be more difficult to recycle and may cost more. The cost of installation was 12% the cost of the plastic and the combined cost of monitoring and maintenance were 14%. Maintenance costs were based on 24/7 vacuum operations. [Cost assumptions slide 105 revised to reflect these changes].

The land to be used was provided free in return for jobs and debt forgiveness where applicable. No allowance was made for inflation or increase in resin prices due to crude oil price rises. The cover was installed over a 60-year period and kept in place 150 years.

These assumptions resulted in a cost at the end of 150 years of \$75 trillion or \$500 billion/year or \$19 million/square mile. If the cover project is concluded before the 150-year period, but after 60 years, the costs will be progressively lower the sooner it ends.

Noteworthy is the fact that the cost of the plastic film is almost 80% of the total cost of the project and bringing it down an important step. This must be weighed against the performance that is also of paramount importance.

Gaskill said the project could be paid for by the purchase of thermal credits relatable to GHG emissions under a successor treaty to Kyoto. The cost per tonne (metric ton) of carbon emissions equivalent whose radiative forcing is offset by the cover is based on a future scenario in which an average of 19.5 GtC/year are emitted from 2010-2070 or 1170 GtC. This results in an average cost per tonne of \$64. Looking at this from the perspective of some future exchange traded commodity, the GAEP offsets approximately 300,000 tonnes of carbon per square mile or around 0.01 tonnes (24 lbs)/SF. Thus, a SF of coverage should trade for around \$0.69. Valued equally over the 60 year period, then, each year that square foot is worth \$0.01.

Gaskill presented a pro forma schedule in which the modeling is completed by the end of 2004 and cover development and increasingly larger field trials occur from 2005-2012, culminating in full-scale implementation starting around 2012. Caldeira said that the global modeling could be completed in

one month, but analyses of the data might take an additional 4 months, so at least the global modeling could fit this schedule. Dr. Taha from Altostratus, Inc. says that the mesoscale modeling will take much longer to complete, around one year per region chosen due to the time needed for the computers to produce results.

Gaskill addressed several other issues. He said that GHG emissions from the production, transportation, installation and recycling of the plastic film would result in emissions of 1.8% of total present day GHG emissions, dropping proportionally as global emissions rise. Thus, although these emissions are not insignificant, the cover would offset around 100X the emissions its production and deployment would produce. Capture and sequestration of the GAEP emissions would reduce this even further.

Alteration of desert dust storms might affect the Amazon and N. Atlantic, which depend on Saharan dust transported by upper level winds across the Atlantic for iron in both the Amazon and N. Atlantic and for phosphorous in the Amazon. Nearly 50% of the iron needed by phytoplankton in the N. Atlantic is supplied by Saharan dust, while almost all the phosphorous needed to support the bromeliad ecology of the Amazon comes from this source. The potential impact of altering these nutrient flows must be studied by climate modeling.

The geopolitical consequences of a GAEP must be considered as the land involved includes politically unstable and volatile nations, oil producing nations and large emitters like China. There is also a 1977 UN treaty prohibiting hostile use of weather/climate modification.

Gaskill recommended an international treaty indemnifying all involved with the project from lawsuits resulting from alleged or actual damage to the climate or economy of a country or region due to the GAEP.

Urban Heat Island Mitigation

Gaskill also addressed the potential application of large-scale surface albedo enhancement to the urban heat island problem. This is caused by the absorption and re-emission of solar radiation by the low reflectivity surfaces of building roofs and pavement in urban areas. The low reflectivity plus the lack of trees to carry off heat as transpired water results in higher daytime

and nighttime temperatures, higher air conditioning costs and greater tropospheric ozone formation.

Gaskill reviewed some of the work conducted by Lawrence Berkeley National Laboratory (LBNL) and the California Energy Commission (CEC) that have been studying ways to reduce the urban heat island effect for more than 20 years. Their proposals have included whitening of roofs and pavements and the planting of trees. The “whitening” includes the total solar spectrum so some “dark” surfaces can be made “whiter” relative to the total solar spectrum.

LBNL estimates that raising the albedo of the greater Los Angeles area by 7.5% (approximately 4000 square miles) by whitening 1000 square miles of roofs and pavement and planting 11 million trees will reduce the air temperature by 5°F. They estimate this would save almost \$500 million annually in electricity and smog costs. Applied nationally to urban areas, nearly \$5 billion could be saved.

The CEC takes this a step further and says that raising the albedo of the 100 largest cities on Earth could offset GHG emissions by 2.5% as well as save money from the other benefits noted in the Los Angeles example. This would also serve to lessen the impact of future global warming driven heat waves. It should be noted that although the 100 largest cities include many candidates that might fit a Los Angeles model with lots of paved surfaces and dark rooftops, this list also includes many third world cities like Lagos, Nigeria (7), Karachi, Pakistan (13), Dhaka, Bangladesh (15) and Jakarta, Indonesia (21) that have populations of around 10 million, but probably little in the way of paved streets and roofs amenable to whitening.

Gaskill suggested that the GAEP might be applied to the urban heat island problem by albedo enhancement of areas outside some of these cities by covering land with white plastic. The cooler air produced by this would mix with the hotter air from the city, cooling it. He gave examples of Las Vegas, NV and Phoenix, AZ. The areas mentioned in slide 145 of 5-20 square miles may be too low to be effective.

A more realistic estimate is calculated as follows. Start with the goal of raising the albedo of one fourth the urban area as in the Los Angeles case. Applied to Phoenix, which has an area of around 700 square miles, the land to have its albedo raised by 7.5% would be 175 square miles. However, the

albedo in this case is raised by 60% (from 20% to 80%) not 7.5% and no trees are planted, since the albedo increase is outside the city and would not help as much. This would increase the albedo by nearly 4 times and should reduce the land area required to around 45 square miles. At around \$500,000/square mile, averaged over 3 years, the plastic cover costs around \$8 million per year and should provide savings comparable to roof and pavement whitening. This can also be done much sooner than the whitening of urban surfaces and large scale tree planting, which may take decades to complete. Covering a 45 square mile area around Phoenix could probably be completed in one year.

Proposed Research on Long-Term Climate Change and Urban Heat Island Mitigation

Gaskill recommended that global and mesoscale (regional) modeling of the impact of the GAEP be performed by LLNL and Altostratus, Inc. possibly using conditions in previous LLNL published studies for comparison. The impact of incremental vs. instantaneous coverage would be studied. Similarly, global and mesoscale modeling by LBNL and Altostratus of the application of the GAEP to land surrounding urban heat islands could be studied for the 100 largest cities and for selected urban areas in the U.S. for which the GAEP may be applicable, comparing this with the albedo enhancement of pavement and roof tops.

At this point, Mr. Conover had to leave to attend another meeting, indicating he would email the presentations to others in DOE. Gaskill, MacCracken and Caldeira remained and discussed issues related to hurricane mitigation and abrupt climate change.

In written comments submitted later, Drs. MacCracken and Caldeira recommended that an evaluation be conducted of various engineering approaches to solving the problem of global climate change including the GAEP and such no regrets alternatives as massive introduction of photovoltaic (PV) arrays. Gaskill estimates that replacement of all 21st century electricity, transportation and heating needs with energy from PV arrays would require coverage of around 200,000 square miles, about 5% of the area of the maximum GAEP coverage.

Caldeira said that a lot of careful analysis should be done before we embark on any course that could significantly alter climate on a large scale. The

main question he had about the GAEP was one of scale, noting that a square meter can be sheeted over with plastic with little harm; a square kilometer, perhaps; hundreds of thousands of square kilometers and there is some concern about impacts and feasibility.

Gaskill noted that massive heat island mitigation as proposed by LBNL and the CEC would involve altering the surface reflectivity of around 100,000 square miles, also a very large area, albeit spread out across the globe. The GAEP could also cover a large area spread out across the globe. Although most of the attention of this plan has focused on the Sahara, there are other deserts and the modeling may show that we can get away with covering a great deal of surface area by proper spacing of the coverage before any regional climate impacts are felt.

Caldeira said that we need to take albedo changes into consideration in thinking about human impacts on climate. “This is perhaps most clear in the attempts to ameliorate urban heat islands. From a research point of view, the question of how surface changes in one area might affect climate in a distant area is interesting. How would increasing reflectivity in the Sahara affect climate in New York or Mumbai (Bombay)? Would they see a cooling? Would they see changes in the hydrological cycle or winds? What are the distal consequences of tropical deforestation?”

Caldeira then noted, “It is becoming clearer that, because of albedo effects, it would not make sense to (deliberately) expand boreal forests to increase carbon storage. If albedo would need to be taken into account for crediting carbon storage in forests, this has the potential to complicate proposed carbon trading schemes and could possibly lead to economic value for albedo changes.”

Gaskill noted that this could also lead to economic costs for planting trees! Countries would be penalized for having too much forestland vs. a baseline. Irrespective of any tree planting schemes, it is likely that the boreal forest will expand into the tundra anyway as the Arctic warms in this century.

Caldeira said that since albedo changes can be measured from space, they would be easy to quantify and verify. He suggested that in the future, people might pay an albedo tax if they install a black asphalt driveway and get credit for installing a reflective one. This isn't the case now, but recent

California building regulations do give credits to pay for white roofs and require new ones to be highly reflective.

Dr. Akbari from LBNL submitted written comments on proposed Urban Heat Island Mitigation research. He provided further details of how the increases in surface albedo for the Los Angeles basin were calculated. They estimated that if the albedo of roofs were increased by 30% and pavements by 15%, then the albedo for all such surfaces in the Los Angeles basin (totaling 1000 square miles) would be increased by 22.5% and the albedo of the entire basin (4000 square miles) by 5.6%, not 7.5% as indicated in the text of this report.

Applying such a strategy aggressively, by changing the albedo of roofs by 60% (applying white roofs and keeping them clean) and pavements by 25%, then the average albedo of these surfaces is increased by 42.5% and that of the entire basin by 10.6%.

For Phoenix, he estimates that half of the surface areas are amenable to having their albedo increased or around 350 square miles. Using the first Los Angeles example, the albedo of 350 square miles could be increased by 22.5%. It's not clear if the massive tree planting included in the assumptions for Los Angeles would apply to Phoenix or could be applied, given the scarcity of water. It is also unclear what the effect on air temperatures a 22.5% whitening of 350 square miles of urban Phoenix would have vs. that of a 60% whitening of a 45 square mile area just outside Phoenix. Clearly, these are calculations that require a detailed analysis.

Akbari says that increasing the albedo inside the city should be the first priority, since it saves energy, reduces GHG emissions and improves air quality. After taking care of the largest 100 heat islands around the globe (assumed to be 100 largest cities by population), if we were going to increase the albedo of the desert adjacent to Phoenix (as an experiment to see how it could be done for the Sahara), we should also design its implementation such that it would reduce the ambient air temperature in Phoenix.

Dr. Taha from Altostratus noted that each city has be considered separately, pointing out that although Los Angeles and Houston are about the same size geographically, only 5 million trees would be required to achieve the same degree of cooling there as 11 million in Los Angeles.

Cape Verde Hurricane Mitigation by Surface Albedo Enhancement

Gaskill gave a brief presentation of how the number of Cape Verde hurricanes could be reduced by applying the GAEP to selected areas of the Sahara desert.

He said that although tropical storms and hurricanes can form in a variety of ways, tropical waves are the most common. They begin as disturbed areas of wind flow or cloud clusters. One area from which such disturbed air masses originate is the southwestern Sahara desert. When these disturbed air masses enter the Atlantic Ocean, they can progress to form tropical waves, tropical depressions, tropical storms and then hurricanes. These storms are then sometimes referred to as Cape Verde hurricanes, since they pass near the Cape Verde Islands.

Because tropical waves that form Cape Verde hurricanes may have several weeks to develop as they cross the Atlantic, they have the greatest potential to grow into Category 5 storms, the most dangerous and destructive. The Cape Verde storms are nearly 85% of the most intense Atlantic hurricanes. A relevant example is Hurricane Andrew in 1992.

Gaskill said there is limited evidence that future warming in this region of the Sahara will lead to increased water vapor levels and more tropical waves. By raising the albedo of the southwestern Sahara, the evaporation rate for precipitation in this region may be decreased, lowering the water vapor level in the atmosphere and decreasing or at least not increasing the number of tropical waves produced. The surface coverage may also change the direction of wind flow in the area and prevent the formation of tropical waves altogether, removing an annual threat to the Caribbean and mainland U.S.

For these reasons, Gaskill said climate modeling of this specific application of the GAEP should be performed.

Catastrophic Methane Hydrate Release Mitigation

This topic falls under the category of abrupt climate change as will be clear shortly. Methane hydrates or clathrates are combinations of water and methane in the form of an ice-like matrix. The methane is the result of the action of methanogenic bacteria on sediment over thousands of years. The

methane is kept in an ice form where appropriate combinations of temperature and pressure exist.

Methane hydrates are widespread in sea sediments hundreds of meters below the sea floor along the outer continental margins and are also found in Arctic permafrost. Some deposits are close to the ocean floor and at water depths as shallow as 150 m, although at low latitudes they are generally only found below 500 m. The deposits can be 300-600 m thick and cover large horizontal areas. A nearby deposit nearly 500 km in length is found along the Blake Ridge off the coast of N.C. at depths of 2000-4000 m.

The total quantity of methane hydrates in the ocean sediment is estimated to be around 10,000 GtC. The methane hydrates in sediment considered part of U.S. territory alone could supply U.S. natural gas needs for 1000 years. Because of this enormous quantity, methane hydrates are being investigated as an energy source to replace petroleum and conventional sources of natural gas, although an extraction technology for ocean sediments does not presently exist.

There is some evidence that massive releases of methane from ocean sediment hydrate deposits may have been indirectly responsible for ending some of the ice ages. Were such releases to occur today because of warming of the oceans or as a result of seismic events, the result could be a sudden rise in atmospheric temperature, triggering feedback mechanisms that might lead to rapid melting of polar ice.

In the slides, the example of a 1 GtC release was used. That represents 0.01% of the total methane hydrates in the ocean. The quantity degassed to the atmosphere 15,000 years ago, at the end of the last ice age is now believed to be around 4 GtC as methane or 0.04%. The average temperature of the Earth increased from 30°F to 60°F within a few decades. The radiative forcing from the methane alone would have been insufficient to cause more than a 3°F increase. It is thought that feedback effects from additional methane released from melting permafrost, carbon dioxide and water vapor contributed to the rest of the warming. But the initial methane hydrate release from the ocean may have been the catalyst.

All of the conditions that may have led to the methane hydrate release 15,000 years ago do not exist today. Sea levels were much lower and thus, the pressure on the sediments was less. However, there is some evidence

that ocean currents that impinge on ocean sediments are getting warmer, especially in the Arctic. Global warming is thus a possible triggering mechanism for massive methane hydrate release in today's climate.

What causes release of methane hydrates is still poorly understood. Warm waters may destabilize the hydrate zone. Hydrates on the surface of the ocean floor on a ridge may then degass. The sediment may then become unstable and slide down the ridge, exposing other layers of methane hydrate, accelerating the release. As an example, the Storegga slump off the coast of Norway 8000 years ago could have released between 1 and 4 GtC as methane.

Alternatively, an undersea earthquake today, say off the Blake Ridge or the coast of Japan or California might loosen and cause some of the sediment to slide down the ridge or slump, exposing the hydrate layer to the warmer water. That in turn could cause a chain reaction of events, leading to the release of massive quantities of methane.

Another possibility is drilling and other activities related to exploration and recovery of methane hydrates as an energy resource. The hydrates tend to occur in the pores of sediment and help to bind it together. Attempting to remove the hydrates may cause the sediment to collapse and release the hydrates. So, it may not take thousands of years to warm the ocean and the sediments enough to cause massive releases, only lots of drilling rigs.

Returning to the 4 GtC release scenario, assume such a release occurs over a one-year period sometime in the next 50 years as result of slope failure. According to the Report of the Methane Hydrate Advisory Committee, "Catastrophic slope failure appears to be necessary to release a sufficiently large quantity of methane rapidly enough to be transported to the atmosphere without significant oxidation or dissolution."

In this event, methane will enter the atmosphere as methane gas. It will have a residence time of several decades and a global warming potential of 62 times that of carbon dioxide over a 20-year period.

This would be the equivalent of 248 GtC as carbon dioxide or 31 times the annual man-made GHG emissions of today. Put another way, this would have the impact of nearly 30 years worth of GHG warming all at once. The result would almost certainly be a rapid rise in the average air temperature,

perhaps as much as 3°F immediately. This might be tolerable if that's as far as things go. But, just like 15,000 years ago, if the feedback mechanisms kick in, we can expect rapid melting of Greenland and Antarctic ice and an overall temperature increase of 30°F.

For point of reference, the average temperature of the Earth (atmosphere, land and top layer of the ocean) in 2004 is around 60°F. The methane hydrate release projected here would raise the temperature to around 90°F or more. Such high temperatures would undoubtedly destabilize all of the other methane hydrates in the ocean and arctic permafrost, some 10,000 GtC or 620,000 GtC equivalent as carbon dioxide. This would have the impact of 78,000 years worth of GHG warming over a few decades. The temperatures reached and sustained would most likely cause a rapid die off in ocean phytoplankton and other sea life as well as most land plants and animals, including humans. The result would be a mass extinction and mark a major transition point in the Earth's geological history.

Although a 1000 or 10,000 GtC methane release in one year or over several decades is very unlikely, a 4 GtC release is entirely plausible. Even if the feedback mechanisms that were operative 15,000 years ago became partly active, the outcome could be just as disastrous as the scenario outlined above.

Gaskill said that if any massive releases of methane from methane hydrates were to occur, attempts should be made to ignite and burn the methane gas at the ocean's surface. By converting the methane to carbon dioxide, the threat of abrupt climate change is reduced by a factor of 62, to less than one-year's worth of GHG emissions. Even if the mitigation effort is only partly successful, say 75% is converted to carbon dioxide, the remaining methane, equivalent to an 8-year pulse of all present day GHG emissions in a single year might still spell trouble, but it would be far preferable to the nightmare scenarios outlined above.

Combustion could be accomplished by aerial release and ignition of distillate fuel over the area where the methane is entering the atmosphere. There are several potential problems with this approach. The area to be covered may be too large to effectively treat in this way. Advection may also make continuous burning difficult. Dr. MacCracken pointed out that the methane level in the air at the surface might be too low to ignite. This would, of course depend on how fast the gas is being released.

Regardless, the potential for massive methane release from sediments represents such a significant threat that emergency mitigation plans like the one suggested here need to be prepared. The Methane Hydrate Research and Development Act of 2000, Public Law 106-193 does not address such catastrophic scenarios and we are unaware of anyone working on such plans.

Thermohaline Circulation Collapse Mitigation

This is the subject of the movie now in theatres, “The Day After Tomorrow,” and a recent Pentagon commissioned study, that explored the ramifications of this from a geopolitical and economic perspective. We decided to include this topic after reading this report and seeing its proposed mitigation strategy.

The basis for the concern is the oceanic thermohaline circulation (THC) system that brings warm salty water northward from the equator to the Arctic, where its heat is released in the form of moist air. This air moderates the climate of Europe and Eastern North America, making them warmer and wetter than would otherwise be the case.

The North Atlantic portion of this system ceased functioning for 100-1000 years twice in the last 15,000 years, apparently due to an influx of fresh water from melting glaciers and/or increased rainfall and discharge of river water. The result was much colder and in some cases, drier weather for N. America and Europe, bringing a return of the ice sheets southward. Icebergs were found as far south as Portugal.

A similar shutdown could occur in this century if enough melt water and rainwater enters the N. Atlantic. There is some evidence of a drop in the salinity of the N. Atlantic near the upper end of the THC occurring since the 1940's. The results of such a shutdown in this century, which might occur over a 10-100 year period (and not over a couple of days as portrayed in the movie) would, according to the Pentagon study, cause economic hardship and political instability as resources such as water and food are constrained by unfavorable climatic conditions.

The authors suggested injection of hydrofluorocarbons (HFCs) into the air to counteract the cooling of the Atlantic basin. Gaskill said HFC injection would not necessarily restore the salinity of the N. Atlantic to restart the THC and might instead, prolong the event by increasing melting of Antarctic

ice, since the Southern Hemisphere would be expected to get much warmer in this scenario. He said a better approach would involve forcing the event to a more rapid conclusion by initiating a more rapid cooling of the areas contributing the fresh water.

This would be accomplished by injection of aluminum oxide particles into the troposphere or stratosphere over Greenland, the Eastern Arctic Sea and related areas that are the source of the fresh water flowing into the N. Atlantic. By doing so, the air temperatures in this region will be lowered enough due to reflection of sunlight to refreeze the freshwater sources flowing into the N. Atlantic and speed the recovery of the THC.

MacCracken said that tropospheric injection would be ineffective due to short residence times. Gaskill said that the presence of a persistent stagnant air mass over the region would help in maintaining the particle cover. He said other materials such as sulfate aerosol or soil could also be used. He said the delivery system could involve aircraft, but a more efficient method would use naval rocket shells (5-inch) fired from destroyers.

As unlikely as this scenario is, in spite of the movie and the Pentagon study, the potential for it to happen in this century cannot be fully discounted and thus, possible mitigation strategies should be investigated.

Alteration of Hurricane Steering Currents

The final topic discussed did not involve either the GAEP or abrupt climate change, but alteration of the path of hurricanes. This would involve a spin off of some of the technology developed to mitigate THC shutdown.

Gaskill said that past efforts to control or destroy hurricanes have failed due to the complexity and size of these storms. Project Storm Fury, which ran from the 60's through the mid 80's tried to cause the eye wall to rain itself out by cloud seeding. Positive results seen then are now believed to have been simply the natural variability in eyes that come and go during a storm's lifetime, which is measured from a few days to a few weeks.

Other proposals made, but never acted on, have included modifying sea-level temperature with chemical films and altering steering currents to change a hurricane's course and cause it to miss landfall. Steering currents

are the upper and mid level winds caused by other weather systems such as high-pressure and low-pressure areas that the hurricane passes by.

One researcher has proposed injecting soot into the air over an area of 600 x 60 miles in the path of a hurricane. This black cloud would absorb and reflect sunlight, cooling the air beneath it and possibly drying it out. When the hurricane passes through this dry air, it may lose some strength as a result of the dry air or change its course.

Gaskill proposed exploring a similar strategy, by creating a man-made low-pressure area to the north or south of the storm center by injection of particulate matter in the atmosphere. The particulate matter would reflect sunlight, cooling the air, causing it to sink and creating a dry trough. The storm would then tend to move towards the trough and away from land.

Similarly, if the wind can be made to blow in opposite directions at different levels of the atmosphere by particulate injection, wind shear may be created that would tear the storm apart.

Although these ideas are highly speculative, Gaskill said they are worth investigating since we are now in a cycle of increased hurricane activity in the Atlantic basin.

With that, the meeting ended at 12:30 pm.

Summary of Research Areas That Should be Funded

1. Global and mesoscale (regional) modeling of the impact of the GAEP by LLNL and Altostratus, Inc., possibly using conditions in previous LLNL published studies for comparison. The impact of incremental vs. instantaneous coverage would be studied. Similarly, global and mesoscale modeling by LBNL and Altostratus of the application of the GAEP to land surrounding urban heat islands for the 100 largest cities and for selected urban areas in the U.S. for which the GAEP may be applicable, comparing this with the albedo enhancement of pavement and roof tops.
2. Modeling of the effect of changing the albedo of the southwestern Sahara on the formation of Cape Verde hurricanes.

3. Development and evaluations of emergency mitigation plans to address massive methane release from sediments.
4. Development and evaluations of mitigation plans in event of partial or complete shutdown of North Atlantic arm of the oceanic thermohaline circulation system with emphasis on examination of atmospheric particulate injection to speed its recovery.
5. Investigation of plans to alter hurricane steering currents and create wind shear to destroy hurricanes using atmospheric particulate injection.

For Further Reading on the Topics Discussed at This Meeting

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