HURRICANE MODIFICATION WORKSHOP REPORT
February 6 – 7, 2008
David Skaggs Research Center
Boulder, Colorado

The Department of Homeland Security
Science and Technology Directorate

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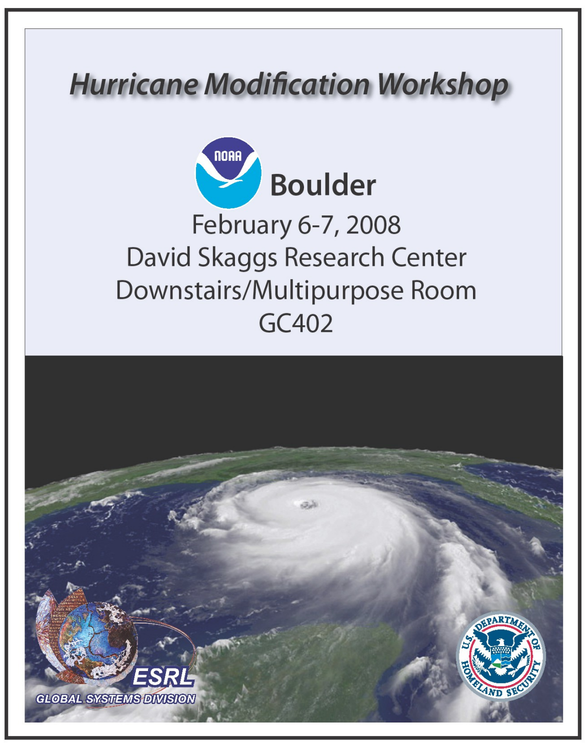

HURRICANE MODIFICAITON WORKSHOP

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I. EXECUTIVE SUMMARY

The potential loss of life, physical devastation, economic impact and loss of public confidence posed by a major hurricane could be as detrimental to the United States as any terrorist attack. These threats are significant and the magnitude of the impacts are increasing as a result of continued population shifts to coastal areas and potentially from the resultant changes to the environment. This trend is evidenced by the destruction of Hurricanes Katrina and Rita in 2005 and Andrew and Iniki at the end of the Twentieth Century. Can we cause change to these horrific events that would reduce their destructive forces? This workshop was the first step in answering that question.

In view of these realities, the Department of Homeland Security (DHS) with the organizational assistance of the National Oceanic and Atmospheric Administration (NOAA)/Global Systems Division of the Earth Systems Research Laboratory sponsored a workshop on hurricane modification at the David Skaggs Research Center in Boulder, Colorado February 6-7, 2008. This action is consistent with the Homeland Security Act of 2002, the Department of Homeland Security (DHS) mission to respond to threats and hazards to the nation and the Science and Technology Directorate (S&T) goal to accelerate delivery of enhanced technological capabilities to meet requirements and fill capability gaps to support DHS agencies in accomplishing their mission. The focus of the workshop was to:

- Identify viable hurricane modification hypothesis that warrant further study
- Understand hurricane physical processes including their initial development, mechanics, life cycle, instabilities and responses to outside dynamics and forces
- Understand DHS specific concerns regarding hurricane threats to life and property caused by wind, rain and storm surge
- Define potential DHS-specific hurricane modification factors, requirements and risks (i.e. pre-development modification, track changes, intensity change)
- Address projected effort/cost/viability/time-lines for hurricane modification implementation
- Recommend a path forward

An international group of recognized experts in the disciplines related to hurricane formation, dynamics and modification gathered to present, discuss and assess hypotheses that might have potential applicability to DHS's mission to protect the nation from natural disasters caused by Hurricanes. Discussions were focused on how best to modify hurricanes in such a way to minimize its destructive forces. Two potential areas of interest were: 1) Changing a hurricane's course and 2) Reducing the destructive forces by either reducing the winds or rains that accompany a hurricane. Great strides have been made in the ability to predict which way hurricanes will move across the oceans, however, limited skills exist for predicting Hurricane intensities in advance, as much is still unknown about how these massive storm systems work. The following areas were suggested for further investigation:

- Basic Research into all stages of a Hurricanes' Lifecycle

- Detailed Numerical Modeling to Include:
  - Hierarchy of models. Requiring access to a super computer system to do the simulations.
  - Global modeling studies to estimate large scale impact of cloud and/or Sea Surface Temperature (SST) cooling methods
    - Atmospheric General Circulation Models (GCMs)
    - Coupled ocean-atmosphere models

  - Cloud-scale modeling to better understand impact of seeding on clouds – (1) fully-fledged hurricanes: (2) clouds which might develop into hurricanes: (3) clouds which could be seeded to increase their reflectivity and therefore cool ocean surface waters.
  - Plume model, large eddy simulation of wave-powered down-pump and up-pump impact on ocean mixed layer homogenization
  - High-resolution coupled Hurricane-wave-ocean modeling tests with input into a storm surge model (or three-way interaction)
  - Basic research on modeling physics packages, coupling capabilities, and resolution issues.
  - The Modeling Program should have an observational component to measure: (1) the aerosols within the storm (e.g., the aerosol that feeds the storm); (2) measurements of the aerosols along the inflow trajectories to the point where the sea spray dominates; (3) Cloud Condensation Nuclei (CCN) activation spectra and total aerosol counts; (4) size spectra of the cloud and hydrometeor size distributions in clouds outside the hurricane, in clouds around the hurricane periphery, in clouds up to the point where sea spray dominates and clouds within the region of strong sea spray.
  - 4-Dimensional Variation Analysis
  - Atmospheric Perturbations
  - Statistical Analysis

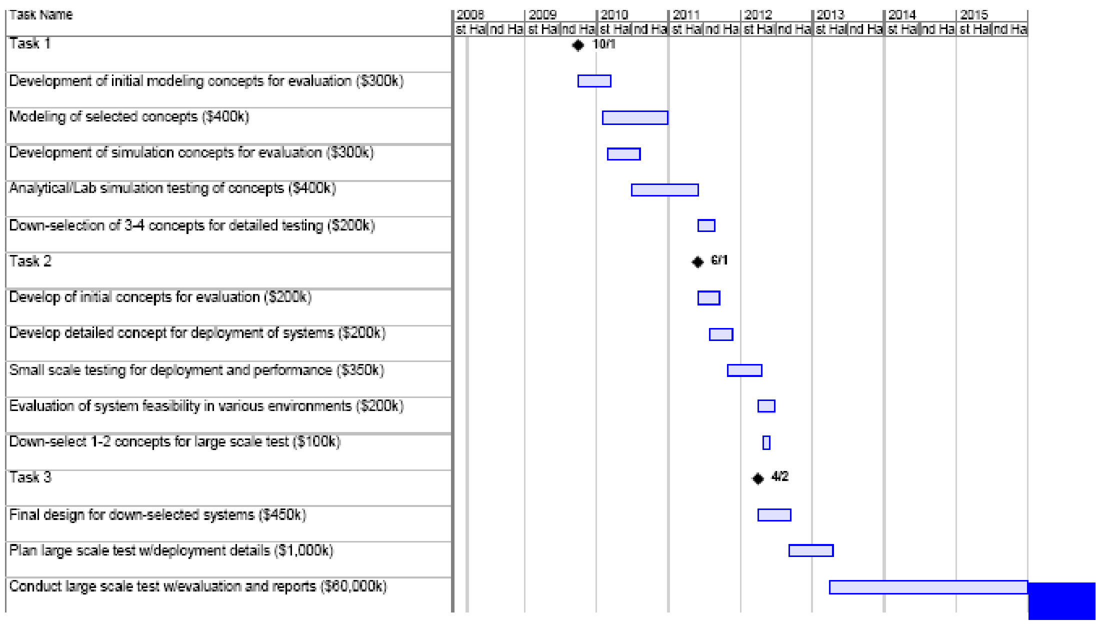
- Test physical means of modifying a Hurricane
  - Lab tests in a tank to examine prototypes, and field tests with existing technologies.
  - Cloud seeding with sea-salt aerosol to enhance cloud albedo and longevity, thus producing ocean surface-water cooling. Some laboratory work would also be required.
  - Limited scale field tests:
    - Salt Seeding Tests
    - Carbon Black Aerosol (CBA)
    - Upper Ocean Cooling
    - Ion Generators
    - Seeding
    - Monolayer Films

- Proposed Program Plan

From the efforts of all workshop participants the following program plan was developed. More detail would be required before funds could be expended, but the path being recommended is solid and feasible.

Work Element	**Est. Cost**	**Est. Time**
Task I		
Development of initial modeling concepts for evaluation	$300K	6 Months
Modeling of selected concepts	$400K	18 Months
Development of simulation concepts for evaluation	$300K	6 Months
Analytical/Lab simulation testing of concepts	$400K	18 Months
Down-selection of 3-4 concepts for detailed testing	$200K	3 Months
TOTAL TASK I COST	$1,600K	

<u>Task II</u>		
Development of initial concepts for evaluation	$200K	4 Months
Develop detailed concept for deployment of systems	$200K	4 Months
Small scale testing for deployment and performance	$350K	6 Months
Evaluation of system feasibility in various environments	$200K	3 Months
Down-select 1-2 concepts for large scale test	$100K	1 Month
TOTAL TASK II COST	$1,050K	
<u>Task III</u>		
Final design for down-selected systems	$450K	6 Months
Plan large scale test w/deployment details	$1,000K	8 Months
Conduct large scale test w/evaluation and reports	$60,000K	36 Months
TOTAL TASK III COST	$61,450K	
TOTAL COST OF PROJECT	$64,100K	



[redacted]

Tropical cyclones (typhoons and hurricanes) are the most violent large-scale storms on earth, sometimes taking the lives of thousands of people and causing billons of dollars in damage. The effects of hurricane Katrina on the United States are well documented. Even though, in making policies and taking any action we must be mindful that tropical cyclones such as hurricanes serve a useful purpose in the earth's energy budget and in providing rainfall to areas in which rainfall from tropical cyclones is a vital component of the regional water supply. Therefore, any policies adopted and its subsequent actions must not eliminate all tropical cyclones, but reduce their devastation. If we have any chance of reducing the tremendous destructive power of these massive storms we need a better understanding on how they form, develop, change intensities, change track, and then dissipate. With the above approach and today's technologies this just may be possible.

INTRODUCTION

The potential loss of life, physical devastation, economic impact and loss of public confidence posed by a major hurricane could be as detrimental to the United States as any terrorist attack. These threats are significant and appear to be increasing as a result of continued population shifts to coastal areas and potentially from the resultant changes to the environment. This trend is evidenced by the destruction caused by Hurricanes Katrina and Rita in 2005 and Andrew and Iniki at the end of the Twentieth Century.

Recognition of this complex problem is evidenced in both enacted and proposed treaties and legislation designed to address both the lack of understanding as well as the acknowledgement that attempts to alter or interfere with the natural formation and or effects of a hurricane could have or be intentionally used to cause collateral effects. Of particular note are:

- U.N. Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques, October 5, 1978

- 109th Congress 1st Session: S-517 *Weather Modification Research and Development Policy Authorization Act of 2005* to develop and implement a comprehensive and coordinated national weather modification research policy and a national cooperative Federal and State program of weather modification research development. *Specifically, the Office of Science and Technology Policy (OSTP) shall:*
    - *Establish a Weather Modification Subcommittee…..*
    - *Establish a national research program…..*
    - *Establish a Weather Modification Research Advisory Board…..*

- 110th Congress 1st Session: H.R. 3445 and S 1807 *Weather Mitigation Research and Technology Transfer Authorization Act of 2007* to develop and implement a comprehensive and coordinated national weather mitigation policy and a national cooperative Federal and State program of weather mitigation research and development.

There have been three previous attempts at the federal level to modify hurricanes, the last one ended in 1983. The results from each were disappointing and only caused further push-back on continued research.

- Project Cirrus: The first Hurricane modification effort, used dry ice to seed Hurricane Beulah off the coast of Jacksonville, Florida. The hurricane did change course after the seeding and made landfall in Georgia and South Carolina; no causal relationship could be determined.

- Project Scud: Carried out by New York University with funding from the Office of Naval Research. Focus was on determining the effects of artificial nucleation on cyclogenesis in the Atlantic Ocean off the east coast of the US. Used dry ice dispensed from an aircraft at 150 pounds/s for 12 hours. Results couldn’t differentiate from normal fluctuations in weather patterns.

- Project Stormfury: Collaborative project between the Department of Commerce and the US Navy lasting from 1962 to 1983. Seeded four different hurricanes with silver iodide, results were ambiguous.

The National Research council of the National Academies published a report in 2003, *Critical Issues in Weather Modification Research*[1], which basically recommends a renewed commitment to advancing the understanding of fundamental atmospheric processes that are central to the issues of intentional and inadvertent weather modification; call for a coordinated national program to conduct sustained research in cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding and a focus on fundamental research questions rather than on near-term applications of weather modification.

The key element of the National Academies Report is its emphasis on basic research to better understand hurricane processes (e.g., initiation, intensification, life cycle including eye replacement cycles, movement, aerosol and air-sea interactions, effects of wind shear, dissipation) before the application of modification procedures. By calling for a coordinated national research program the National Academies demonstrated that it understands the difficulty and complexity of the hurricane modification problem and recognized that it will take the expertise of a number of groups and individuals to address the problem adequately.

The next section of this report discusses the purpose of the workshop followed by a description and abstracts of all the presentations given. The following sections contain a list of recommendations as derived from the workshop and a conclusion of the report followed by a suggested program plan.

[1] NRC (National Research Council) of the National Academy of Sciences, 2003: *Critical Issues in Weather Modification Research*, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, The National Academy Press.

III. PURPOSE OF WORKSHOP

The Hurricane Modification Workshop was initiated by Under Secretary Jay Cohen, DHS S&T, to investigate the possibility of minimizing the tremendous loss of life, property, and economic stability by reducing the destructive forces of a hurricane. This may be accomplished by modifying its track, speed, winds, and rain.

The DHS with the organizational assistance of the National Oceanic and Atmospheric Administration (NOAA)/Global Systems Division of the Earth Systems Research Laboratory sponsored a workshop on hurricane modification at the David Skaggs Research Center in Boulder, Colorado February 6-7, 2008. This action is consistent with the Homeland Security Act of 2002, the Department of Homeland Security (DHS) mission to respond to threats and hazards to the nation and the Science and Technology Directorate (S&T) goal to accelerate delivery of enhanced technological capabilities to meet requirements and fill capability gaps to support DHS agencies in accomplishing their mission. The focus of the workshop was to:

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An international group of recognized experts in the disciplines related to hurricane formation, dynamics and modification gathered to present, discuss and assess hypotheses that might have potential applicability to DHS's mission to protect the nation from natural disasters. Topics of discussion were:

- Characteristics of Category 5 Hurricanes
- Collaborative Research on Hurricane Modification by Carbon Black Dispersion: Methods, Risk Mitigation and Risk Communication
- Hurricane Modification by Seeding Clouds with CCN for Suppressing Warm Rain
- Hurricane Emasculation via Ocean Surface Cooling
- Hurricane Intensity Reduction Effort via Sea Surface Cooling
- Methodology for Reducing Hurricane Intensity Using Arrays of Wave-Driven Upwelling Pumps
- Wave Energy, Fish Feeding and Hurricane Suppression
- Review of Two Hurricane Modification Schemes
- On Hydroscopic Seeding of Hurricanes
- Gulf Coast Partnership for the Promotion of GEMS: Gulf Eddy Monitoring System An Acoustic Tomographic Solution

The next section describes each presentation given during the workshop by stating the focus and presenting abstracts on each.

IV. OVERAL THEMES OF THE PRESENTATIONS

There were ten (10) presentations given during this workshop covering topics from Category 5 Hurricanes to Hurricane Emasculation. What follows is information on each presentation to include a brief focus and abstract on each.

Guidelines for the presentations included:

- What is the origin of the hypothesis? Who has been involved in its promotion?
- Does your modification hypothesis focus primarily on storm intensity (i.e., minimum sea-level pressure and winds) or on changes in storm track?
- What is your step-by-step conceptual model for the hurricane modification?
- Has this modification scenario been addressed by numerical modeling?
- Is there concrete evidence that the specified intervention (e.g., cooling of the sea surface, inhibition of evaporation from the sea surface, the ejection of aerosols into the hurricane circulation) will work as intended and that it will have the desired effect on the hurricane?
- Has the modification hypothesis been presented to the scientific community either through refereed scientific publications or at scientific meetings? If so, the provision of reprints of the most relevant paper to the meeting attendees would be helpful.
- Is it possible that your proposed hurricane modification will have undesirable secondary effects such as the suppression of the pre-storm and post-storm rainfall in the area of modification?
- Will the proposed modification require actions prior to the existence of the storm in a set location or will it be possible to go to an existing storm to carry out the modification activity? If the former, what criteria will be used to specify the protected area? What happens if the hurricane does not materialize?
- What level of effort will be required to carry out the modifications? Are the hypothesized changes realistic in view of the scale and intensity of the hurricane?
- Will the modification activity be carried out from ships on the sea surface in advance of the storm or from the air from which modification agents might be dispersed at desired locations in and around the storm? If the former, must the sea-based activity be carried out at the core of the storm? Is this a realistic requirement?
- What are the logistic requirements for conduct of the seeding activity? Realistically, can this be done? At what cost?
- What are your key recommendations for initial testing of your hurricane modification hypothesis? Would it be based on model simulations and/or on limited atmospheric testing? What would be the time frame of such studies? How much would they cost?
- Does your modification scenario allow for collaboration with colleagues who are promoting their own modification hypotheses? If so, how might this be done?

1. Characteristics of Category 5 Hurricanes – Dr. Jay Hobgood

Focus: This presentation examined the characteristics common to Category 5 hurricanes over the Atlantic basin. Warm Sea Surface Temperatures and little vertical wind shear are necessary to allow these hurricanes to approach the theoretical upper limits of their intensity. Most Category 5 hurricanes undergo a period of rapid intensification, which makes forecasting their ultimate intensity even more challenging. The potential for rapid intensification, combined with uncertainties in the forecasts of track and intensity complicates potential mitigation strategies.

Abstract: Hurricanes Dean and Felix made landfall in the northwest Caribbean Sea as Category 5 hurricanes within two weeks of each other in 2007. This marks the first time that two Category 5 hurricanes made landfall during the same hurricane season. It also represented only the fourth year when multiple Category 5 hurricanes have been observed over the Atlantic basin. The other three years with multiple Category 5s were 1960, 1961 and 2005. This research examines the characteristics common to Category 5 hurricanes over the Atlantic basin. There have been 31 Category 5 hurricanes over the Atlantic since 1900. Fourteen of those hurricanes reached Category 5 status over the Caribbean Sea, while seven did so over the western Atlantic, seven over the Gulf of Mexico and only three over the tropical Atlantic. No Category 5 hurricane has been observed over the Atlantic basin north of 31 degrees of latitude. The environmental factors common to these Category 5 hurricanes are also examined. Warm Sea Surface Temperatures and little vertical wind shear are necessary to allow these hurricanes to approach the theoretical upper limits of their intensity. Only three hurricanes, the “Unnamed Labor Day Hurricane of 1935”, Camille (1969) and Andrew (1992) made landfall in the U.S. However, other hurricanes such as Katrina and Rita in 2005 reached Category 5 intensity in the Gulf of Mexico. Their large size and intensity contributed to the magnitude of the storm surge they produced, even though they weakened before making landfall in the U.S. Most Category 5 hurricanes undergo a period of rapid intensification, which makes forecasting their ultimate intensity even more challenging. The potential for rapid intensification, combined with uncertainties in the forecasts of track and intensity complicates potential mitigation strategies.

2. Collaborative Research: On Hurricane Modification by Carbon Black Dispersion: Methods, Risk Mitigation, and Risk Communication – Dr. Moshe Alamaro

Focus: This presentation focused on the use of carbon black aerosol (CBA) to selectively heat parts of the atmosphere by dispersion of CBA above a hurricane. This scenario is motivated by the fact that the energy cycle of a hurricane may be represented as a Carnot heat engine, and reducing the contrast between “hot and cold reservoirs” should reduce the power of a hurricane and the CBA will absorb incident solar radiation to warm the “cold reservoir.” Objectives of this study are to demonstrate direct control of the intensity or track of simulated hurricanes; to quantify amounts of CBA needed; to enhance understanding of the web of physical processes that power hurricanes in relation to the overall thermodynamics of hurricanes; to determine optimal dispersion scenarios; to enhance understanding of the radiative and flow properties of CBA; to establish causes, effects, and outcomes of CBA dispersion; and to develop methods to communicate risk to the public of large-scale weather modification efforts. To accomplish all this we will employ a diverse set of tools and methods, including a high-resolution mesoscale numerical weather prediction model to simulate hurricanes and the effect of adding CBA; engineering tools to develop manufacturing, transport, and dispersion strategies; and both semi-structured interviews and structured surveys to capture expert information and lay public perceptions.

Abstract: Can the damage caused by hurricanes be reduced by large-scale weather control? Significant changes to the atmosphere are now caused by inadvertent anthropogenic additions of materials that either capture or release large amounts of energy already present–cloud condensation nuclei release latent heat of water vapor and optically active aerosol particles absorb or reflect solar radiation.

This proposal focuses on the use of carbon black aerosol (CBA) to selectively heat parts of the atmosphere. One specific example that will be investigated is dispersion of CBA above a hurricane.

This scenario is motivated by the fact that the energy cycle of a hurricane may be represented as a Carnot heat engine, and reducing the contrast between "hot and cold reservoirs" should reduce the power of a hurricane and the CBA will absorb incident solar radiation to warm the "cold reservoir."

CBA is routinely manufactured in large quantities in low-density fractal form, and has optical properties that starkly contrast with the highly reflective clouds found for example in the divergent flow at the top of a hurricane. The proposed work includes (i) numerical simulation experiments to unravel the complexity of the atmospheric response to adding CBA to alter the environment of a hurricane; (ii) laboratory and engineering studies to optimize CBA in terms of both efficiency for absorbing sunlight *and* flow characteristics for different delivery methods; and (iii) detailed examinations of potential societal responses to actual and/or perceived health, safety, and environmental costs and benefits, and examination within this framework of best practices to inform and prepare the public and emergency responders for intentional CBA dispersion for large-scale weather modification.

Objectives of this study are to demonstrate direct control of the intensity or track of simulated hurricanes; to quantify amounts of CBA needed; to enhance understanding of the web of physical processes that power hurricanes in relation to the overall thermodynamics of hurricanes; to determine optimal dispersion scenarios; to enhance understanding of the radiative and flow properties of CBA; to establish causes, effects, and outcomes of CBA dispersion; and to develop methods to communicate risk to the public of large-scale weather modification efforts. To accomplish all this we will employ a diverse set of tools and methods, including a high-resolution mesoscale numerical weather prediction model to simulate hurricanes and the effect of adding CBA; engineering tools to develop manufacturing, transport, and dispersion strategies; and both semi-structured interviews and structured surveys to capture expert information and lay public perceptions.

The intellectual merits of the proposed work include advancing knowledge of hurricane dynamics and potential hurricane modification; development and testing of a novel approach to optimize impacts of weather modification actions that should also reduce the uncertainty of attribution of cause and effect relative to natural weather variability; application of this to the CBA dispersion problem for hurricanes; development of a new field research tool for experimental meteorology; development of real-time remote sensing of CBA to support the adaptive dispersion of CBA in the hurricane environment; development of a quantitative predictive capability of CBA properties in terms of process parameters; and a refined framework for communicating warning and potential impacts of large-scale weather modification to a threatened population. The proposed team is highly experienced and qualified and many of the tools that will be refitted for this work are at a high technical readiness level.

This project clearly has very significant potential for societal benefits in terms of hurricane forecasting, modification, and warning. Furthermore, this project is expected to enhance the scientific and technological infrastructure for weather modification activities.

3. Hurricane Modification by Seeding Clouds with CCN for Suppressing Warm Rain – Dr. Daniel Rosenfeld

Focus: This presentation discussed the feasibility of modifying an individual storm event (hurricane Katrina) by cloud seeding using the Weather Research and Forecasting Model (WRF). The seeding is practical by dispersing at the marine boundary layer around the hurricane cloud condensation nuclei (CCN) in concentrations exceeding 2000 cm^{-3}. This can be done by flying or ship cruising more than 100 km outside the outer spiral bands of the storm, in the cloud free air that converges to the storm at the low levels.

Abstract: The feasibility of modifying an individual storm event (hurricane Katrina) by cloud seeding was investigated using the Weather Research and Forecasting Model (WRF). The seeding is practical by dispersing at the marine boundary layer around the hurricane cloud condensation nuclei (CCN) in concentrations exceeding 2000 cm^{-3}. This can be done by flying or ship cruising more than 100 km outside the outer spiral bands of the storm, in the cloud free air that converges to the storm at the low levels.

This was simulated for Katrina. The clouds on the storm's periphery, where the wind speeds were less than 22 ms^{-1} and the effects of sea spray were minimal, were seeded with submicron CCN, resulting in the "turning-off" of warm rain formation in the clouds there. This simplification of the simulation of aerosol effects is aimed at evaluating the largest possible response to the seeding intervention. This resulted in nearly halving of the area covered by hurricane force winds. It produced a weakening of the hurricane surface winds compared to the "non-seeded" simulated storm during the first 24 h within the entire tropical cyclone (TC) area compared to a control simulation without warm rain suppression. Later, the seeding-induced evaporative cooling at the TC periphery led to a shrinking of the eye and hence to some increase in the wind within the small central area of the TC. Yet, the overall strength of the hurricane, as defined by the area covered by hurricane force winds, decreased in response to the suppressed warm rain at the periphery, as measured by a 25% reduction in the radius of hurricane force winds. In a simulation with warm rain suppression throughout the hurricane, an unreasonable expectation due to the offsetting effects of sea spray, the radius of the hurricane force winds was reduced by more than 42%, and, although the diameter of the eye shrunk even further, the maximum winds weakened. This shows that the main mechanism by which suppressing warm rain weakens the TC is the low level evaporative cooling of the un-precipitated cloud drops, the added load of the cloud water, and the added cooling due to melting of precipitation that falls from above.
The lack of realism of the simulated cloud processes allowed simulating the effects qualitatively, thereby showing that the physical mechanism is robust for all of our numerical experiments. However, explicit microphysics (bin resolving) simulations are required for simulating quantitatively the potential effects with any degree of confidence. Although this will require greater computer resources than are currently available to us, such resources are used regularly for more detailed climate simulations.

4. Hurricane Emasculation via Ocean Surface Cooling – Dr. John Latham

Focus: This presentation discussed cooling ocean surface waters in the regions in which the genesis of hurricanes occurs by seeding low-level maritime stratocumulus clouds covering these regions – or ones from which ocean currents flow into these regions – in order to increase their reflectivity for incoming sunlight: thus producing a cooling.

Abstract: The basic idea under examination is to cool ocean surface waters in the regions in which the genesis of hurricanes occurs. This would be achieved by seeding low-level maritime stratocumulus clouds covering these regions – or ones from which ocean currents flow into these regions – in order to increase their reflectivity for incoming sunlight: thus producing a cooling.

Marine stratocumulus clouds cover about one-third of the ocean surface. They are characteristically a few hundred metres deep, with bases a few hundred metres above the ocean surface, and have albedos within the range 0.3 to 0.7. Our idea – based on a scheme proposed and developed by Latham (1990, 2002) and Bower et al. (2006) in connection with global warming mitigation – is to disseminate sprays of monodisperse seawater droplets (of size about 1μm) in large quantities from disseminators mounted on a fleet of wind-powered, satellite-controlled, unmanned Flettner rotor vessels sailing in optimally

located regions. A significant fraction of these aerosol particles will rise into the clouds, be nucleated as cloud condensation nuclei (CCN) to form additional droplets, elevating the cloud droplet number concentrations to significantly higher values, thus increasing the albedo and possibly the lifetimes of the clouds. The amount of cooling can be controlled, and GCM computations indicate that it would not be infeasible to produce local negative forcings of up to at least -60 W/m^2.

Plans are well advanced for dealing with the crucial engineering problems of the production and dissemination of these seawater droplets at the rates and on the geographical scales required. This proposed technique has the advantage that the only raw materials required are wind and seawater.

5. Hurricane Intensity Reduction Effort via Sea Surface Cooling – Dr. Alan F. Blumberg

Focus: This presentation explored the possibility of reducing the force of hurricanes (and consequent damage potential) by lowering the temperature of the sea surface in the storms' paths. The proposition is to induce cold, deep water upwelling through wave action. While the genesis of this idea originated nearly 40 years ago, it is only now that we have the tools and technology to assess the feasibly of an undertaking.

Abstract: A collaboration among Princeton University, Massachusetts Institute of Technology and Stevens Institute of Technology has been exploring the possibility of reducing the force of hurricanes (and consequent damage potential) by lowering the temperature of the sea surface in the storms' paths. The proposition is to induce cold, deep water upwelling through wave action. While the genesis of this idea originated nearly 40 years ago, it is only now that we have the tools and technology to assess the feasibly of an undertaking.

Clusters of tubes – wave pumps - will be buoyed at one end to float vertically, and restrained from bobbing by a tethered damping disk. Oncoming wave crests will cause ascension of water in the tube. Trough-induced descent will be prevented by a butterfly valve in the tube. Thus, each succeeding wave will impel the water upwards until it flows over the top onto the surface of the ocean. A tube extending several hundreds of meters will bring up water that is at least 15C colder than the surface temperature. A sufficient amount of water thus introduced to the surface in a hurricane's path can, we believe, reduce the temperature of that surface a few degrees, which will be adequate to lower the intensity of a hurricane one level to two levels in the Saffir-Simpson scale.

Physically consistent hydrostatic and non-hydrostatic models based on the Princeton Ocean Model (POM [Blumberg and Mellor, 1987]) of both the near field and far field environment will be implemented to describe the response of the ocean to the introduction of cold water at the surface. For the near field wherein the fluid dynamics around a single tube is to be researched, a non-hydrostatic POM model will be used to assess if the cold water, when pumped to the surface, will simply advect down the sides of the tube to the level from which it originated. That model will also be used to study a likely induced cyclonic circulation around the pump which will may trap the denser water around the pump and prevent mixing with the surrounding ocean. The basic POM hydrostatic model will be used to examine the effects on the circulation of the Gulf of Mexico after the deployment of many thousands of pumps.

The research also involves an estimation of the optimal diameter of the tube and the optimal number of tubes or clusters of tubes necessary to convey the needed amount of water to the surface and an exploration of comparative efficiencies of various possible tube delivery systems. Utilization of the above mentioned modeling analysis will enable derivation of optimals. This refers to such variables as individual tube diameter, optimal number of tubes in a cluster, and optimal number of clusters necessary to successfully confront a hurricane of a given frontal area. In like manner, the proposal addresses the problem of optimizing the temperature-related trade-offs, such as depth of the tube vs. rate of flow vs. sea surface temperature reduction vs. diminution of hurricane force. Physical evaluation will take advantage of the laboratory testing wave tank facilities at Stevens Institute of Technology.

6. Methodology for Reducing Hurricane Intensity Using Arrays of Wave-Driven Upwelling Pumps – Dr. Isaac Ginis

Focus: This presentation discussed a methodology, predicated on the well established correlation between hurricane intensity and the upper ocean heat content (OHC), to significantly reduce hurricane intensity via ocean cooling under the hurricane core using wave-driven upwelling pumps that are capable to bring cold water from the deep ocean to reduce the OHC.

Abstract: The proposed methodology is predicated on the well established correlation between hurricane intensity and the upper ocean heat content (OHC). Observational and numerical studies show that hurricane intensity may be significantly reduced due to the ocean cooling under the hurricane core. Atmocean, Inc. has developed wave-driven upwelling pumps that are capable to bring cold water from the deep ocean to reduce the OHC. We suggest that an array of wave-driven pumps deployed in advance of a moving hurricane can reduce the OHC on a sufficiently large area and consequently mitigate hurricane intensity. We will present 1) the results of experimental data and theoretical estimates showing the efficiency of the wave-driven pumps; 2) the results of idealized and real-case numerical simulations using a coupled hurricane-ocean model that provide preliminary estimates of the horizontal scales and magnitudes of the OHC reduction needed to mitigate hurricane intensity by 10-20%; 3) a proposal for pump deployment and recovery strategy; 4) a program of experimental and theoretical research to study further the feasibility of the proposed methodology and its costs.

7. Wave Energy, Fish Feeding and Hurricane Suppression – Dr. Stephen Salter

Focus: This presentation examined the concept that, since hurricanes grow in sea areas where surface temperatures exceed 26.5 Celsius, perhaps their frequency and severity can be reduced by reducing water temperatures to below the critical value. Doing this directly over large areas of ocean would need a prodigious amount of energy but it may be possible to provide it in a low grade form that is already available in sufficient quantity in the form of ocean waves.

Abstract: If it is the case that hurricanes grow in sea areas where surface temperatures exceed 26.5 Celsius, perhaps we can reduce their frequency and severity by reducing water temperatures to below the critical value. Doing this directly over large areas of ocean would need a prodigious amount of energy but it may be possible to provide it in a low grade form that is already available in sufficient quantity in the form of ocean waves.

A wave power device should present the waves with the right force for each amplitude and period so that both large and small waves can do their fair share without the small ones being locked out and the big ones taking things too easy. One perfect interface for all amplitudes and periods is the next bit of ocean and the transmission from one wave to the next is extremely efficient. We therefore want, as far as possible, to let each particle of water move as would have done in the absence of our equipment.

The proposed design consists of a hollow cylindrical floating enclosure say 90 metres in diameter and 20 metres deep. Buoyancy is provided by an inflated ring with a low freeboard. The cylindrical surface is a

continuous wall of non-return valves. Below this is a tube made of a plastic with slightly negative buoyancy long enough to reach down to the thermocline. Water can flow into the cylinder with very little resistance but cannot flow back through the valve wall. This will initially raise a head inside the cylinder which would be similar in magnitude to the amplitude of each incoming wave. But as soon as the head exceeds that needed to overcome the difference in density between the warm surface and the cold water below the thermocline, water will start to flow downwards. The head needed for a surface temperature of 25 C, constant down to a depth of 200 metres followed by a drop to 10 C at the thermocline is only 0.14 metres. The inertia of the water column inside the down-tube is so large that the velocity will be almost steady and water will be sucked into the cylinder during any lull of the incoming waves.

If we look at the decaying orbital motions of waves as a function of depth and wavelength, we see that the horizontal displacements of long period waves go deeper than short ones but that short ones do their displacing more often. The transfer rates for all periods between 6 and 10 second are nearly the same for valve wall depths of 15 to 20 metres. For a 20 metre wall depth the flow volume would be about 2.8 cubic metres per second for each metre width of installation and each metre amplitude of the incoming wave. In a one-metre amplitude regular wave this would be about 250 m3/second for a 90 metre diameter unit. The thermal energy transfer would be this flow rate times the specific heat of water (4.28 MJ per m3 Kelvin) times the temperature difference of 15 C. This comes out to 16 GW.

Real waves are not regular and oceanographers describe the wave climate of a site using scatter diagram which gives the annual probability of any combination of height and period. If we take the rather gentle climate of the Canaries, reduce wave amplitudes by the size of the thermal head and the pressure drop of a practical valve, we still get a mean thermal transfer of about 10GW per unit.

Longuet-Higgens and Stewart have shown that in addition to the drag from any currents there is also a large force due to the momentum of waves which depends on the square of incident plus reflected minus transmitted amplitudes. The proposed structures will have no firm attachment points for a mooring. As nearly all ocean systems consist of gyres it may be possible to let the units drift freely but to release the water in a direction to produce a controlled amount of thrust towards the centre of the local gyre.

A side-effect will be an increased flow of nutrients to the sunlit surface which will have beneficial effects on phytoplankton which are the start of the marine food chain.

8. Review of Two Hurricane Modification Schemes – Dr. Moshe Alamaro

Focus: This presentation examined two preliminary experimental and theoretical studies on hurricane modification schemes. The first was the use of monolayer films to retard evaporation and the second was the use of jet engines to form upward vertical jet to induce atmospheric perturbations. The hypothesis of the first study was that spreading monolayer films in front of the hurricane track might reduce evaporation and latent heat transfer into the storm, reducing its intensity. The second study conceptually studied the potential for mitigation of natural hurricanes by inducing anthropogenic perturbations prior to or in front of an advancing hurricane.

Abstract: Two preliminary experimental and theoretical studies on hurricane modification schemes will be briefly reviewed. The first is the use of monolayer films to retard evaporation and the second is the use of jet engines to form upward vertical jet to induce atmospheric perturbations.

Early work on the relationship between monolayers and hurricanes evaluated the ability of monolayers to retard evaporation as a possible technique for hurricane mitigation. Experiments on this topic took place separately in the 1980s in Russia and 1999-2002 at the Air Sea Interaction Lab at the Massachusetts Institute of Technology (MIT). The Russian experiments were done in the Black Sea using a 30-meter diameter circular wind wave tank and used a mixture of fatty alcohols. The MIT experiments used a 0.99-meter diameter circular annular tank containing fresh water with and without monolayer films of hexadecanol $C_{16}H_{34}O$. Extensive laboratory and field experiments in the 1950s and 1960s, mainly in the US and Australia, established hexadecanol as one of the best monolayer materials for retarding evaporation from water reservoirs.

The hypothesis for both of these research programs was that spreading monolayer films in front of the hurricane track might reduce evaporation and latent heat transfer into the storm, reducing its intensity. These experiments revealed, however, that monolayer films would not be effective for evaporation retardation during the brief duration of the storm because they are disrupted by high winds. Ironically, monolayer films due to crude oil seepage in the Gulf of Mexico may cause long-term evaporation retardation that may lead to increased heat stored in the ocean. That stored heat could be then released into the storm when the monolayer is broken down by wind and wave action, contributing to hurricane intensification.

In the second scheme we have conceptually studied the potential for mitigation of natural hurricanes by inducing anthropogenic perturbations prior to or in front of an advancing hurricane. The actual hardware for the task consists of multiple jet engines mounted on barges or ships. The engines will direct compressible high momentum, high-speed free jets skyward causing entrainment of even larger amounts of additional air to form plumes and updrafts. The unstable humid updraft will itself produce conditions for additional entrainment. If properly designed these perturbations may create or remove atmospheric ridges and troughs leading to hurricane modification.

9. On Hygroscopic Seeding of Hurricanes – Dr. William R. Cotton

Focus: This presentation proposed that seeding hurricanes with small hygroscopic particles, as opposed to conventional giant hygroscopic particle seeding, could lead to the reduction in their intensity. This hypothesis was based preliminary on results of simulations of the impact of African dust on hurricane intensity which showed that dust acting as CCN influenced the storm development by inducing changes in the hydrometeor properties, modifying the storm diabatic heating distribution and thermodynamic structure, and ultimately influencing the storm intensity through complex dynamical responses. Some simulated storm intensities showed a monotonic decrease in storm intensity with increasing concentrations of CCN under certain configurations of the model but this trend was easily modified just by introducing slight variations in the GCCN profile. Thus, Zhang et al. (2007) concluded that the physical processes responsible for the impact of dust as nucleating aerosols on hurricane development need to be examined in the future under a wide range of environmental conditions.

Abstract: In the last year there have been two papers that have proposed that seeding hurricanes with small hygroscopic particles, as opposed to conventional giant hygroscopic particle seeding, could lead to the reduction in their intensity (Cotton et al., 2007; Rosenfeld et al., 2007). The Cotton et al. (2007) paper was based preliminary results of simulations of the impact of African dust on hurricane intensity (Zhang et al., 2007), which showed that dust acting as CCN influenced the storm development by inducing changes in the hydrometeor properties, modifying the storm diabatic heating distribution and thermodynamic structure, and ultimately influencing the storm intensity through complex dynamical responses. Some simulated storm intensities showed a monotonic decrease in storm intensity with

increasing concentrations of CCN under certain configurations of the model but this trend was easily modified just by introducing slight variations in the GCCN profile. Thus, Zhang et al. (2007) concluded that the physical processes responsible for the impact of dust as nucleating aerosols on hurricane development need to be examined in the future under a wide range of environmental conditions.

Since then Henian Zhang has carried out more simulations that illustrate that the response is by no means simple. In some cases increasing CCN leads to a strengthening of hurricane intensity. Moreover, the results of introducing dust acting at CCN further in the lifecycle of the storm reveals that the response to CCN varies greatly depending on the stage of introduction of the aerosol. Thus this work illustrates that even using simple, rather idealized simulations the response of a hurricane to aerosol can be quite nonlinear. This makes the potential modification of hurricanes to small-particle hygroscopic seeding even more challenging than envisioned by Cotton et al. (2007) and Rosenfeld et al. (2007). Nonetheless we urge that this topic should be investigated much more extensively and in further detail.

10. Gulf Coast Partnership for the Promotion of GEMS: Gulf Eddy Monitoring System An Acoustic Tomographic Solution – Dr. Jerald Caruthers

Focus: None Given

Abstract: Hurricanes Katrina and Rita both intensified while transiting the Gulf of Mexico in part due to the presence of warm-core eddies in the Gulf of Mexico. For decades, Gulf eddies have been monitored from satellite, NOAA buoys, and occasional ship surveys. A satellite senses only surface effects with either IR or radar and integrated water-column effects with altimetry sensors. NOAA buoy data are valuable for depth information, but are sparse. And ship surveys are both sparse and sporadic. Deep expendable sensors for conductivity and temperature deployed by aircraft can provide timely data, but only acoustic tomography is a proven technology available for continuous sensing of deep parameters needed for describing these eddies. Such data, when fed into ocean dynamic models, allow for improved predicting the character and movement of the eddies.

At the Royal Society in London, Walter Munk and Carl Wunsch offered a paper entitled "Observing the ocean in the 1990s." That was twenty-four years ago (1982). However, they seem to have been a bit overly optimistic. The Ocean Acoustics Program of the Office of Naval Research believes that Ocean Acoustic Tomography (OAT) is sufficiently mature that further research investment is not warranted. More recently, Munk and others offered an update (2005) on the state of OAT technology answering their question, "Where do we stand in the application of acoustic remote sensing methods to observing the ocean on basin scales?" and, specifically, they were addressing the question to "acoustic remote sensing of ocean gyres." Their final answer to their question is "It is *inconceivable* [our italics] to us that oceanographers ... should not take advantage of the fact that the ocean is transparent to sound." Our question is "Why?"

Although OAT is a proven technology, it has not yet become a member of the national backbone for ocean monitoring or dynamic modeling. OAT is "big" science, initially expensive, and it does require a national effort to achieve fruitful results, just as does satellite sensing. However, despite initial investment costs, Pacific experiences suggest that long-term operational cost could be very reasonable. We are at a cross-roads; today's emphasis on integrated and sustained ocean observations is missing a major enabling technology.

These recent hurricanes attest to the need for better prediction that we expect acoustic tomography can offer. But it is not just for hurricanes that OAT in the Gulf offers information for scientists and practitioners alike. Weather prediction in general, especially winter storms in the entire eastern US, support for national fisheries and the offshore oil and shipping industries would all benefit from the data that OAT can offer. The Gulf of Mexico is an important oceanic basin requiring an

integrated and sustained observation system. The basin's unique geography, currents, eddies and especially the thermal structure argue strongly for the application of OAT to this region.

V. RECOMMENDATIONS

Once all the presentations were given the workshop was divided into three groups to go over the material discussed and develop a proposed road ahead. Each group had its own theme as follows: Group 1) Large Time and Spatial Scale Hurricane Modification Methods, Group 2) Diminishing hurricane intensity by reducing upper-ocean heat content, and Group 3) The modification of hurricane structure and intensity through aerosols. The output from each is stated below and used for developing our proposed road ahead.

A. Large Time and Spatial Scale Hurricane Modification Methods

- Two methods considered to have potential on a physical basis
  - Cooling by increased cloud reflectivity
  - Salt spray seeding over large regions
      - Global cooling, including TC genesis regions
    - Similar to global warming mitigation
    - Possible global circulation impacts
  - Cooling of SST by increased ocean mixing
    - Modification of genesis frequency
    - Possible global circulation impacts
  - Energy of jet engines many orders of magnitude too small
  - Predictability problems

Recommendations

- Modification of global tropical climate may have serious side effects
  - None of the proposed large-scale methods are ready for field tests
  - Global and regional modeling studies listed below should be pursued to better understand total impact of modification
- Global modeling studies to estimate large scale impact of cloud and/or SST cooling methods
  - Atmospheric GCMs
  - Coupled ocean-atmosphere models
- Downscale modeling to estimate impact on hurricane climate
  - e.g., Knutson et al (2007), *Bulletin of the American Meteorological Society*, **88(10)**, 1549-1566.
- Cloud-scale modeling to better understand impact of seeding on clouds
- Plume models, large eddy simulation of wave-powered down pump impact on ocean mixed layer homogenization
- Feasibility Studies
- Limited scale field salt seeding tests
- Effectiveness of cloud seeding with sea-salt on cloud albedo and cloud longevity
- Tests of prototype of ocean filters
- Continued vessel design study

B. Diminishing hurricane intensity by reducing upper-ocean heat content

1) Technology capability: can we reduce the heat content of the upper mixed layer of the ocean ahead of a hurricane?
    a. An array of wave-driven pumps is a possibility. There are two types: upwelling pumps and downwelling pumps. Testing is required. The timescale of the downwelling pumps is not known, but may be too slow for a pending landfall hurricane, and probably is more useful for regional climate change influence. Therefore, the upwelling pumps apparently are the best choice. Issues to examine:
        i. Proximity of pumps
        ii. Depth of tubes
        iii. Ocean advection issues - plume dynamics
        iv. Cooling time
        v. Upwelling effectiveness and "warming" recovery time
        vi. The efficiency of upwelling pumps based on wave heights and periods.
        vii. Upwelling pumps may require 15,000-40,000 devices (for forward right eyewall quadrant), to 100,000-200,000 for whole eyewall region. A deployment plan should be developed.
        viii. Economic tradeoff analysis – depth of tubes vs. DT (temperature anomaly at the surface), number of tubes, etc
    b. Other possibilities: liquefied natural gas technology; mixing by generating turbulence at bottom of mixed layer (using submarines).
    c. Combination of these methods to cool mixed layer may be needed.
    d. It should be noted that downwelling pumps would require only a few hundred devices, but again this is for regional climate modification over a large region. However, downwelling pumps also have potential and require investigation.
    e. Carbon black or film layers probably will not work in strong wind and large wave conditions.
    f. We recommend lab tests in a tank to examine prototypes, and field tests with existing technologies. The Gulf of Mexico is the first choice, with the East Coast as a backup (because the Gulf Stream causes analysis problems of this technology). We recommend a two-year effort.
    g. This approach is possibly the least likely to affect track. It impacts the inner core, while the storm is generally affected by large-scale wind patterns.
2) If it can be achieved, how much will it affect the hurricane?
    a. Requires high-resolution coupled ocean-wave-atmosphere modeling tests.
    b. Input into a storm surge model also needed
    c. Basic research on modeling physics packages, coupling capabilities, resolution issues are highly encouraged. A better observation network is required as well for the ocean and atmosphere.
    d. We recommend a two-year effort of initial feasibility study.
    e. Off-shore oil rigs are a potential deployment platform

C. The Modification of Hurricane Structure and Intensity through Aerosols

1. What We Know

- Aerosols are Important to Hurricane Structure and Intensity
- This is known qualitatively, but it is important to document this quantitatively through modeling efforts and through a systematic program of observations in the hurricane.

- The addition of sub-micron aerosols can invigorate the clouds especially on the periphery of the storm and the aerosols can increase the cooling at the low levels in the hurricane due to drop evaporation and melting of ice crystals
- The change of the overall heating profile leads to changes in storm intensity and the physical processes in the eye wall region including eye wall replacement

2. Key Questions and Uncertainties

- Do aerosols play a role in eye wall replacement? At what stage is a hurricane most susceptible to the manipulation of the aerosols? Is the storm size important? What is the response of the hurricane to the distribution of carbon black aerosols in the hurricane circulation (e.g., just above the outflow cirrus from the storm center or at low levels on the periphery of the storm)?

3. Interactive Modeling and Measurement Program

- A measurement and modeling program are essential to investigation of the modification hypotheses. Envisioned as a collaboration of modeling groups having the needed interest and expertise and their interaction with scientists making observations of relevance to the hurricane simulations.
- The modeling effort should document the differences between bulk and detailed explicit microphysics. Use a hierarchy of models. Access a super computer system to do the simulations. Use a coupled oceanic/atmospheric model
- The Modeling Program should have an observational component to measure the aerosols within the storm (e.g., the aerosol that feeds the storm), measurements of the aerosols along the inflow trajectories to the point where the sea spray dominates, need CCN activation spectra and total aerosol counts, measure size spectra of the cloud and hydrometeor size distributions in clouds outside the hurricane, in clouds on the hurricane periphery, in clouds up to the point where sea spray dominates and clouds within the region of strong sea spray. It is important to document the thermodynamic environment, including any cool pools that may exist within the storm as a function of the aerosol concentrations. Need to specify the supercooled liquid water within the storm. Do the above for a variety of storms for unseeded storms initial and later under seeded conditions. HRD of NOAA is already conducting a measurement program in hurricanes. This should be expanded and focused.

4. Seeding Considerations

- Distribute the CCN aerosols on the periphery of the hurricane using aircraft and ships. When distributing carbon black, release it above the core of the hurricane. Accomplishing the seeding will take further study.

VI. CONCLUSION

The United States (US) faces continuing threats to its national security. These threats come from human activities within and outside the US intended to disrupt its way of life by causing loss of life, destroying property, and disrupting our economic stability. These threats are being confronted on a continuing basis by a number of groups and agencies within the United States especially the Department of Homeland Security.

The second level of threats to homeland security are natural disasters such as earthquakes, floods, fires and severe storms, including destructive straight-line winds, tornadoes and hurricanes. In most cases all that can be done is to develop a means to cope with such disasters after they occur. In rare cases it may be possible to mitigate the destructive effects of some natural phenomena by intervening prior to and during the destructive event. This may be possible with hurricanes. Proposals for hurricane modification have been on the table for many years, but have not been successful. Since at least the middle of the 20th Century serious thought and planning have been given to the development and testing of methods intended to weaken hurricanes or change their paths. If such a tested proven technology had been available prior to the landfall of Katrina, it might have been used to weaken the storm and/or turn it aside. Intense hurricanes are not stable phenomena and are given to rapid intensity fluctuations due to the influence of eye-wall reorganization, increased wind shear, changes in the underlying sea surface temperature and perhaps eventually due to human-induced perturbations.

After the devastation of the U.S. East Coast by hurricanes in the 1950's, a program to decrease hurricane winds, named Project Stormfury, was designed and implemented. Project Stormfury, which was a cooperative effort of the U.S. Department of Commerce and the U.S. Navy, was designed to introduce instabilities in the inner core of the hurricane circulation by judicious seeding with a glaciogenic seeding agent (silver iodide) of vigorous hurricane convective clouds just exterior to the eyewall. The Stormfury conceptual model of the process indicated that the seeding would freeze the supercooled water that was presumed to exist within the seeded clouds, which would release heat that would produce a pressure perturbation, resulting in an instability that would force the hurricane to reorganize at a larger radius, thereby effectively lowering the overall wind speed.

Although the Stormfury conceptual model or hypothesis was viewed as plausible, there were no model simulations to verify its plausibility. Further, there were no measurements to verify the existence of the needed supercooled water. The Stormfury seeding was relatively easy to implement because the required seeding could be accomplished virtually anywhere by bringing the seeding and monitoring aircraft to the storm. Although three hurricane seedings were conducted and some rises in minimum sea-level pressure observed, these changes could not be ascribed unambiguously to the seeding. Further, when later developments in technology permitted the measurement of supercooled liquid water in the hurricane environment, very little supercooled liquid water could be found in the vigorous convective clouds near the eyewall.

The time is right now for revisiting the possibility of hurricane modification with new approaches. Certainly the motivation is there after the devastation of the 2005 season. Major improvement in measurement technology now permits the documentation of the properties of the clouds and underlying sea surface within the hurricane. Had these tools been available prior to the inception of Project Stormfury, it is questionable whether this project would have been launched based on the requirement for supercooled liquid water. Even more important has been the tremendous improvement in numerical models that make it possible to simulate cloud and environmental processes within the hurricane. Thus, the conjunctive use of the new measurement and simulation tools greatly facilitate the development and testing of hurricane modification hypotheses. These developments obviously have raised the bar on proposals for the hurricane modification. If such proposals do not measure up favorably relative to observations and the results of numerical simulations, they should be reconsidered or discarded. Even when they compare favorably, there is still the pivotal question whether there is a realistic probability that the proposed modifications can be accomplished after factoring in logistic, budgetary and political constraints.

The Department of Homeland Security (DHS) exists to address imminent threats to life and property in the United States such as the intense land-falling storms that devastated the country in 2005. If a tested methodology to modify such storms existed, there would be few objections to its use to weaken or turn them aside before striking the United States. This would not be the case, however, if a hurricane modification methodology involved large scale and long term modifications prior to the existence of a specific hurricane threat such as the cooling of vast expanses of the tropical oceans or the wide distribution of aerosols to change cloud structure and reflectivity. Such schemes would be incredibly expensive and not logically the purview of the DHS unless it is to be tasked with addressing global warming. They would also possibly have unanticipated and unintended effects, such as altering a country's rainfall, that would certainly require international treaties with the countries potentially affected. As the history of Project Stormfury has shown, obtaining such treaties is virtually impossible. Countries may not object to a country taking unilateral action to protect itself from a specific threat. They will not, however, tolerate massive large-scale actions with potentially unknown consequences for them so that the country taking the action might address a threat that has not yet materialized. Thus, the first guideline for a viable hurricane mitigation strategy is that it must address immediate threats to lives and property in the United States.

The second guideline involves the scientific plausibility of the proposed modification concept. Virtually any knowledgeable tropical meteorologist could propose a favorite hurricane modification hypothesis. If it is to garner the attention of the DHS, however, its scientific plausibility must be demonstrated, preferably by numerical simulation using tested realistic numerical models of atmospheric processes, especially those attendant to hurricanes. In a few cases, this scientific plausibility might be demonstrated with the support of the DHS. In most cases it should be demonstrated by the parties proposing the modification hypothesis to the DHS since there are literally dozens of hypotheses that might be tested. Logically, there must be some "weeding-out" process before a specific hypothesis and attendant conceptual model is brought to the attention of the DHS.

When it finally comes to that, the following questions should be addressed in the presentation of the hurricane modification hypothesis to the DHS:

- What is the origin of the hypothesis? Who has been involved in its promotion?
- Does your modification hypothesis focus primarily on storm intensity (i.e., minimum sea-level pressure and winds) or on changes in storm track?
- What is your step-by-step conceptual model for the hurricane modification?
- Has this modification scenario been addressed by numerical modeling?
- Is there concrete evidence that the specified intervention (e.g., cooling of the sea surface, inhibition of evaporation from the sea surface, the ejection of aerosols into the hurricane circulation) will work as intended and that it will have the desired effect on the hurricane?

- Has the modification hypothesis been presented to the scientific community either through refereed scientific publications or at scientific meetings? If so, the provision of reprints of the most relevant paper to the meeting attendees would be helpful.
- Is it possible that your proposed hurricane modification will have undesirable secondary effects such as the suppression of the pre-storm and post-storm rainfall in the area of modification?
- Will the proposed modification require actions prior to the existence of the storm in a fixed predetermined location or will it be possible to go to an existing storm to carry out the modification activity? If the former, what criteria will be used to specify the protected area? What happens if the hurricane does not materialize?
- What level of effort will be required to carry out the modifications? Are the hypothesized changes realistic in view of the scale and intensity of the hurricane?
- Will the modification activity be carried out from ships on the sea surface in advance of the storm or from the air from which modification agents might be dispersed at desired locations in and around the storm? If the former, must the sea-based activity be carried out at the core of the storm? Is this a realistic requirement?
- What are the logistic requirements for conduct of the modification activity? Realistically, can this be done? At what cost?
- What are your key recommendations for initial testing of your hurricane modification hypothesis? Would it be based on model simulations and/or on limited atmospheric testing? What would be the time frame of such studies? How much would they cost?
- Does your modification scenario allow for collaboration with colleagues who are promoting their own modification hypotheses? If so, how might this be done?

The National Research council of the National Academies published a report in 2003, *Critical Issues in Weather Modification Research*[2], which basically recommends a renewed commitment to advancing the understanding of fundamental atmospheric processes that are central to the issues of intentional and inadvertent weather modification; call for a coordinated national program to conduct sustained research in cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding and a focus on fundamental research questions rather than on near-term applications of weather modification.

The consensus from this workshop closely follows the recommendations from the NRC report. Before attempting to modify a hurricane we need a better understanding on how they initially form, the physics behind development, direction, speed, wind forces, and rain. It has been 25 years since the last coordinated effort to modify hurricanes has occurred. Since than our knowledge and technology has improved dramatically and we are in a better position to approach this problem. It is the recommendation from the Hurricane Modification Workshop participants that we go forward by doing additional research into most of the areas already discussed while attempting actual demonstrations if results justify the expense.

[2] Ibid

VII. Road Ahead

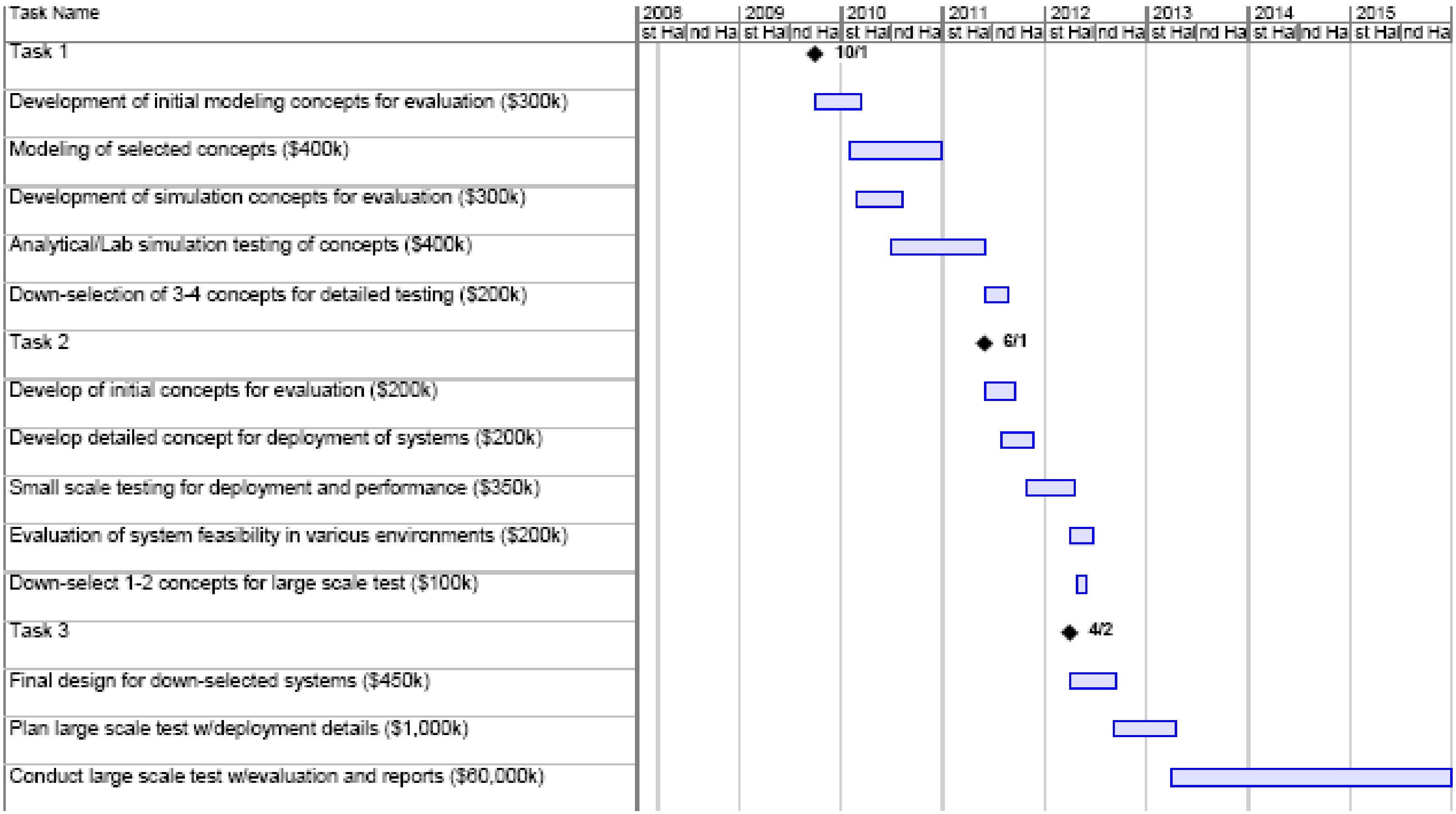
If we have any chance of reducing the tremendous destructive forces of Hurricanes we need to better understand how they form, develop, change intensities, change track, and then dissipate. With the knowledge gained and advances in technologies over the past 25 years we have a better understanding of Hurricanes and in a much better position to continue the research that was stopped many years ago.

Input from workshop participants and coordination with other sources led to the below suggested "Road Ahead". The plan has three tasks beginning in 1 Qtr FY11 and ending 2 Qtr FY16. The basic areas of research are: development of an initial model/simulation concept for evaluation; development of concepts for possible deployment; and finally testing one or two concepts at full scale. Changes in the overall plan are anticipated especially as more data/information is collected. If given the approval to proceed with any of the tasks listed, to get the best input industry or academia has to offer it is suggested first going out with a RFI to see where the current level of technology stands and then go out with a RFP.

Estimated cost by Work Item

Work Element	Est. Cost	Est. Time
Task I Est. Start: 1 QTR FY10[3] Est. End: 3 Qtr FY11		
Development of initial modeling concepts for evaluation	$300K	6 Months
Modeling of selected concepts	$400K	18 Months
Development of simulation concepts for evaluation	$300K	6 Months
Analytical/Lab simulation testing of concepts	$400K	18 Months
Down-selection of 3-4 concepts for detailed testing	$200K	3 Months
TOTAL TASK I	$1,600K	
Task II Est. Start: 4 Qtr FY11 Est. End: 3 Qtr FY12		
Develop of initial testing concepts for evaluation	$200K	4 Months
Develop detailed concept for deployment of systems	$200K	4 Months
Small scale testing for deployment and performance	$350K	6 Months
Evaluation of system feasibility in various environments	$200K	3 Months
Down-selection of 1-2 concepts for large scale test	$100K	1 Month
TOTAL TASK II	$1,050K	
Task III Est. Start: 2 Qtr FY12 Est. End: 2 Qtr FY16		
Final design for down-selected systems	$450K	6 Months
Plan large scale test w/deployment details	$1,000K	8 Months
Conduct large scale test w/evaluation and reports	$60,000K	36 Months
TOTAL TASK III	$61,450K	
TOTAL COST OF PROJECT	$64,100K	

[3] Assuming program starts FY10


Task Name
2008
2009
2010
2011
2012
2013
2014
2015
Task 1
10/1
Development of initial modeling concepts for evaluation ($300k)
Modeling of selected concepts ($400k)
Development of simulation concepts for evaluation ($300k)
Analytical/Lab simulation testing of concepts ($400k)
Down-selection of 3-4 concepts for detailed testing ($200k)
Task 2
6/1
Develop of initial concepts for evaluation ($200k)
Develop detailed concept for deployment of systems ($200k)
Small scale testing for deployment and performance ($350k)
Evaluation of system feasibility in various environments ($200k)
Down-select 1-2 concepts for large scale test ($100k)
Task 3
4/2
Final design for down-selected systems ($450k)
Plan large scale test w/deployment details ($1,000k)
Conduct large scale test w/evaluation and reports ($60,000k)

APPENDIX A – HURRICANE MODIFICATION WORKSHOP PARTICIPANTS

1. Mr. William Laska – Department of Homeland Security
2. Dr. Edward Hume - Johns Hopkins University Applied Physics Laboratory
3. Dr. Joe Golden - National Oceanic and Atmospheric Administration
4. Dr. William Cotton - Colorado State University
5. Dr. Bob Kurzeja - Savannah River National Laboratory
6. Dr. Alan Blumberg - Stevens Institute of Technology
7. Dr. Jerald Carithers - University of Southern Mississippi
8. Dr. William Woodley – Woodley Weather Consultants
9. Dr. Jay Hobgood - Ohio State University
10. Dr. Moshe Alamaro - Massachusetts Institute of Technology
11. Dr. Stephen Salter University of Edinburgh
12. Dr. Daniel Rosenfeld - Hebrew University
13. Dr. Mark DeMaria - National Oceanic and Atmospheric Administration
14. Dr. Edward Walsh - National Oceanic and Atmospheric Administration
15. Dr. Isaac Ginis - University of Rhode Island
16. Dr. John Latham – University Corporation for Atmospheric Research
17. Dr. Patrick Fitzpatrick - Mississippi State University
18. Dr. Sundararaman Gopalakrishnan - National Oceanic and Atmospheric Administration
19. Ms. Paula Lantzer – Department of Homeland Security

Not Pictured: Dr. Roelof Bruintjes - National Center for Atmospheric Research

APPENDIX B – AGENDA

AGENDA
HURRICANE MODIFICATION WORKSHOP
February 6 - 7, 2008
David Skaggs Research Center
Boulder, Colorado

February 6, 2008

8:30 - 9:00	Check In	
9:00 - 9:10	Welcome/Administrative Comments/Agenda	Joe Golden
9:10 - 9:30	Workshop Objectives	Wil Laska
9:30 - 9:45	History	William Woodley
9:45 - 10:15	Current Research	Wil Laska
10:15 - 10:30	Break	
10:30 - 11:05	Characteristics of Category 5 Hurricanes	Jay Hobgood
11:05 - 11:40	Collaborative Research On Hurricane Modification by Carbon Black Dispersion: Methods, Risk Mitigation and Risk Communication	Moshe Alamaro
11:40 - 12:15	Hurricane Modification by Seeding Clouds with CCN for Suppressing Warm Rain	Danny Rosenfeld
12:15 - 12:50	Hurricane Emasculation via Ocean Surface Cooling	John Latham
12:50 - 1:50	Lunch	
1:50 - 2:25	Hurricane Intensity Reduction Effort via Sea Surface Cooling	Alan Blumberg
2:25 - 3:00	Methodology for Reducing Hurricane Intensity Using Arrays of Wave-Driven Upwelling Pumps	Isaac Ginis
3:00 - 3:35	Wave Energy, Fish Feeding and Hurricane Suppression	Stephen Salter
3:35 - 3:50	Break	
3:50 - 4:25	Review of Two Hurricane Modification Schemes	Moshe Alamaro
4:25 - 5:00	On Hygroscopic Seeding of Tropical Cyclones	William Cotton
5:00 - 5:30	Gulf Coast Partnership for the Promotion of GEMS: Gulf Eddy Monitoring System An Acoustic Tomographic Solution	Jerald Caruthers
5:30 - 6:00	Next Day Plan	Wil Laska

February 7, 2008

9:00 - 10:00	Recap Previous Day/Discuss Research Gaps	Wil Laska
10:00 - 11:15	Discoveries/Needs/Concerns/Concurrences	Wil Laska
11:15 - 11:30	Break-Out Sessions	Wil Laska
11:30 - 12:30	Road Ahead	Wil Laska
12:30	Adjourn	