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**THE SKIES WILL BE FALLING: FUTURE TECHNOLOGIES AND  
TECHNIQUES FOR THE DISRUPTION AND DIMINISHMENT OF  
SELF-SUSTAINMENT CYCLES IN TROPICAL CYCLONIC  
SYSTEMS**

by

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In Partial Fulfillment of the Graduation Requirements

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**Tropical cyclones, or hurricanes, are massive chaotic systems that have threatened coastal populations for millennia. The destructive power of these systems kills thousands every year and causes billions of dollars of damage. Hurricane Katrina alone claimed more than 1,800 lives and caused over \$125 billion in damage. With an increasing percentage of the worlds population living near coastlines, tropical cyclones present an ever-greater threat to life and property. In addition, nearly half of all U.S. military bases are within sixty miles of a coastline directly threatened by tropical cyclones. What can be done to mitigate this threat? This paper will examine three possible weather modification technologies and techniques to disrupt and diminish the destructive power of tropical cyclones in the 2030 timeframe: specifically tuned microwaves from space-based solar power stations, biodegradable monomolecular surface materials (monolayers), and moisture-absorbing materials. Various scenarios along with analysis of several experiments and simulations will reveal that the basic technology exists today for hurricane modification within in the next thirty years. This paper will also discuss enabling technologies such as improved computer modeling, better forecasting, and more precise data collection. Finally, substantial issues regarding liability, international treaties, and domestic politics must be addressed in order for this possible future to become a reality. Yet, more than anything, the most essential requirement for future success is a recommitment to research and experimentation that has all but been abandoned over the last forty years. Put simply, we have to be willing to try. Future generations may not forgive us if we dont.**

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## *Preface*

The original inspiration for this research came from the Q&A period following a briefing delivered by a visiting general officer in the first few weeks of Air Command and Staff College. Still searching for a research topic, I brazenly asked the general which technologies, in their infant stage today, he believed would be at the level of the Internet, stealth, and UAVs in the next twenty years. He laughed saying that if he knew that he'd get out of the Air Force and get into the stock market. After the laughter dissipated, he stated that weather was still one of the greatest obstacles to employing air power. He said that obtaining "weather superiority," providing good or bad weather at a time and place of our choosing, would change everything. Within the next few weeks a series of tropical storms and hurricanes made landfall in the U.S. In fact, as Hurricane Ike made its way up through the central United States it caused severe wind damage and power outages in Dayton, Ohio...and the plane carrying all of the Blue Horizons students made an adrenaline-filled, white-knuckled landing at the Dayton airport. The idea of creating and controlling the weather was gone and diminishing hurricanes took center stage.

As someone who decided to research meteorology and so many concepts "outside my lane," I have several experts and mentors to thank. This paper was made possible by the generous contributions of Dr. Kerry Emanuel and Moshe Alamaro (MIT), Joe Ingarra (GelTech), and Ross Hoffman (AER). I am grateful to my advisor, Lt Col Angela Stout, who provided the guidance necessary to complete this research. Finally, I would like to thank my wife, Dawn, and daughter, Rory, for their many sacrifices and struggles as we spent this year apart. Daddy's coming home.

## *Abstract*

Tropical cyclones, or hurricanes, are massive chaotic systems that have threatened coastal populations for millennia. The destructive power of these systems kills thousands every year and causes billions of dollars of damage. Hurricane Katrina alone claimed more than 1,800 lives and caused over \$125 billion in damage. With an increasing percentage of the world's population living near coastlines, tropical cyclones present an ever-greater threat to life and property. In addition, nearly half of all U.S. military bases are within sixty miles of a coastline directly threatened by tropical cyclones. What can be done to mitigate this threat?

This paper will examine three possible weather modification technologies and techniques to disrupt and diminish the destructive power of tropical cyclones in the 2030 timeframe: specifically tuned microwaves from space-based solar power stations, biodegradable monomolecular surface materials ("monolayers"), and moisture-absorbing materials. Various scenarios along with analysis of several experiments and simulations will reveal that the basic technology exists today for hurricane modification within in the next thirty years. This paper will also discuss enabling technologies such as improved computer modeling, better forecasting, and more precise data collection. Finally, substantial issues regarding liability, international treaties, and domestic politics must be addressed in order for this possible future to become a reality. Yet, more than anything, the most essential requirement for future success is a recommitment to research and experimentation that has all but been abandoned over the last forty years. Put simply, we have to be willing to try. Future generations may not forgive us if we don't.

## **PART 1: INTRODUCTION**

### **Scenario 1: “Terror in Miami”**

The evacuation of Miami progresses slowly over several days as forecasters warn of a Category-3 hurricane headed towards southern Florida. Thousands of vehicles clog highways heading north as frightened and despairing citizens make the all-to-familiar trek to escape yet another hurricane. Meanwhile, Air Force personnel at four Florida AF bases furiously scramble to get every aircraft possible into the air and safely away from the impending storm. Some still question where to send the aircraft as the hurricane’s post-landfall path remains uncertain just hours before hitting Florida. Meteorologists give no guarantees and Air Force leaders don’t know if the bases in North and South Carolina will be spared from Hurricane Lisa’s wrath.

Just hours before the making landfall, the Category-3 storm encounters warmer than normal waters heated by weeks of persistent sunshine. An already dire situation elevates to sheer devastation as 175 mph sustained winds, blinding rain, and a terrifying 25-foot storm surge slams into the heart of Miami. Key Biscayne, Fisher Island, and twenty other small islands, along with the entire town of Miami Beach simply disappear. Hundreds of citizens, who stubbornly decided to stay and try to ride out the storm, watch in horror as the waves continue to grow into a three-story storm surge that destroys everything in its path and causes flooding as far as 10 miles inland. Hurricane Lisa’s path of devastation heads Northwest across Florida, up through Tampa, and towards Pensacola. When the storm finally moves on to flood large portions of Georgia and Alabama, the devastation in Florida can only be described as apocalyptic. Thousands are dead, millions are homeless, and the largest natural disaster since Hurricane Katrina leaves billions, if

not trillions, of dollars of damage in its wake. To make matters worse, Fort Meyers, NAS Key West, MacDill AFB, Tyndall AFB, Eglin AFB, and Pensacola NAS lay in ruins. It will be months, if not years, before normal operations resume.

### **Thesis Statement**

The question is not if this horrifying scenario will happen, but *when* it will happen. It has happened before and it will happen again. On August 29, 2005, Hurricane Katrina slammed into the gulf coast region of the U.S. The largest natural disaster in U.S. history, Katrina flooded 80% of New Orleans, destroyed or severely damaged nearly 200,000 homes, displaced over 1 million people, and killed more than 1,800.<sup>1</sup> In economic terms, Katrina caused over \$150 billion in personal property and economic damage and cost the U.S. government over \$100 billion in relief dollars and reconstruction.<sup>2</sup> Even the slightest diminishment of a hurricane's power could make a tremendous difference in terms of avoiding damage to critical infrastructure and preventing loss of life.

Millions of Americans live in states regularly threatened by tropical cyclones. Worldwide, the U.S. military currently maintains over 80 major installations (including at least 20 Air Force bases) and dozens of minor installations within 60 miles of a coastline threatened by hurricanes. This means that nearly fifty percent of U.S. combat power is susceptible to destruction not from our enemies, but from Mother Nature. In addition to the threat to civilian populations and infrastructure, our national security is at risk.

Advancements in directed energy and material science over the next few decades may give mankind the ability to make a measurable difference in combating hurricanes. Tropical cyclones are massive systems with unimaginable amounts of energy, but small alterations to these highly complex systems may have significant effects. It is analogous to grains of sand being introduced

into a large engine. By 2030, the future of space-based directed energy and material science will make it possible for the USAF to disrupt and diminish the strength of tropical cyclones. Three technologies in particular might be highly effective in this effort: space-based directed energy, biodegradable surface materials, and moisture-absorbing materials. These technologies, used singularly or in concert, will preserve critical military assets, national infrastructure, and save lives.

### **Profile of a Tropical Cyclone**

Tropical cyclones, also known as hurricanes, typhoons, or cyclones depending on which region they occur, are intense storm systems that form in the tropical belt (23.5° north and south of the equator) and draw their strength from the warm waters of the northern Atlantic and eastern North Pacific oceans. Meteorologists categorize storms based on their strength and wind speed. They start as a tropical disturbance; a thunderstorm with minor wind circulation. It becomes a tropical depression when the winds reach 20 knots and a tropical storm at 35 knots. Once its winds exceed 64 knots (74 mph) the tropical storm is categorized as a hurricane. By definition, Category 5 storms have winds in excess of 156 miles per hour. The strength of cyclonic systems unpredictably fluctuates as the system moves across the ocean. Hence, a Category 2 system in open waters can pick up energy and rapidly grow into a much more devastating Category 4 storm in a matter of hours.

The eye of the hurricane, with its calm winds and absence of rainfall, is the most recognizable physical feature of the tropical cyclone. The eye is surrounded by a ring of intense thunderstorms that extend upwards to nearly 15 kilometers (50,000 feet) above sea level known as the eyewall.<sup>3</sup> The average size of the eyewall is typically between 20 to 50 kilometers (12 to 30 miles) across and encapsulates the lowest pressure in the storm. If one could look at a cross

section of a hurricane, they would see that a hurricane is a series of concentric rings of thunderstorms. At the ocean's surface, the low pressure at the center draws moist tropical air towards the eye. This air rises and condenses forming the violent thunderstorms at the eyewall due to the release of massive amounts of latent heat from the condensation process.<sup>4</sup> The release of latent heat causes the upper part of the eye to become warmer creating an area of high pressure at the top of the eye. This causes the now-dry air to flow out the top of the hurricane and away from the center. The concentric rings of thunderstorms, driven by this positive feedback loop, constitute the self-sustainment cycle (also known as the eyewall replacement cycle) that must be disrupted in order to affect the devastating power of tropical cyclones.

| <i>Stage</i>                   | <i>Description</i>   |
|--------------------------------|--|
| Tropical wave                  | A trough of low pressure in the trade-wind easterlies  |
| Tropical disturbance           | A moving area of thunderstorms in the tropics that maintains its identity for 24 hours or more   |
| Tropical depression            | A tropical cyclone in which the maximum sustained surface wind is $\leq 38$ miles/hour ( $\leq 61$ km/hour; $\leq 33$ knots <sup>†</sup> )                     |
| Tropical storm                 | A tropical cyclone in which the maximum sustained surface wind ranges from 39 miles/hour (62 km/hour; $>33$ knots) to 73 miles/hour (117 km/hour; $<64$ knots) |
| Hurricane/<br>typhoon/ cyclone | A tropical cyclone in which maximum sustained surface wind is $\geq 74$ miles/hour ( $\geq 118$ km/hour; $\geq 64$ knots). This is a Category-1 storm.         |
| Category-2                     | Sustained surface winds $\geq 96$ mph ( $\geq 154$ km/hr; $\geq 83$ knots).  |
| Category-3                     | Sustained surface winds $\geq 111$ mph ( $\geq 178$ km/hr; $\geq 96$ knots).   |
| Category-4                     | Sustained surface winds $\geq 131$ mph ( $\geq 210$ km/hr; $\geq 114$ knots).  |
| Category-5                     | Sustained surface winds $\geq 155$ mph ( $\geq 249$ km/hr; $\geq 135$ knots).  |

Table 1: Stages of Development of a Tropical Cyclone and the Saffir-Simpson Hurricane Scale<sup>5</sup>

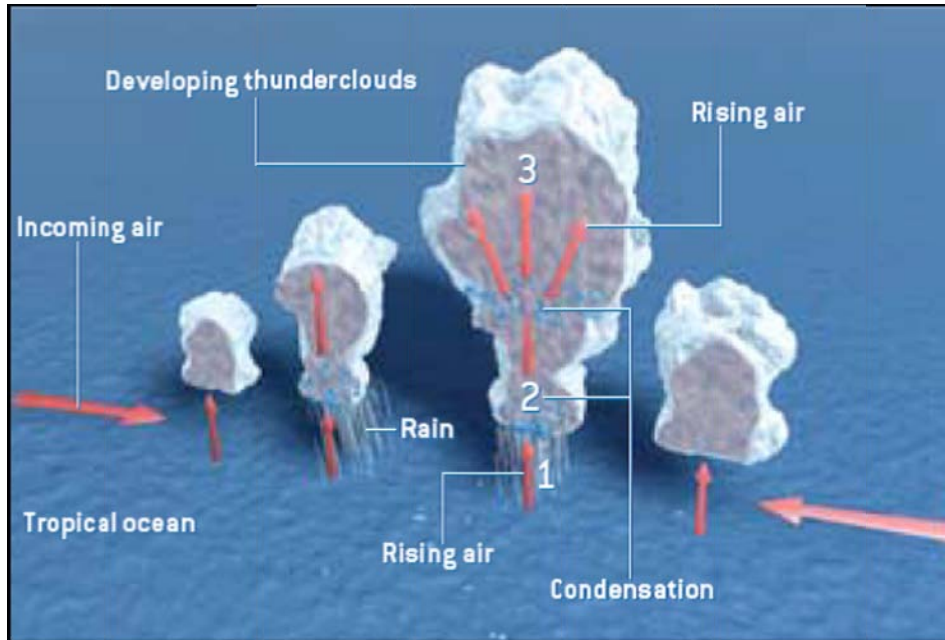


Figure 1: Initial Development of a Hurricane

A hurricane begins as humid air rises from the ocean's surface [1], and the water vapor in the moist air condenses to form rain clouds [2]. This condensation releases latent heat causing air to rise into even greater clouds.<sup>6</sup>

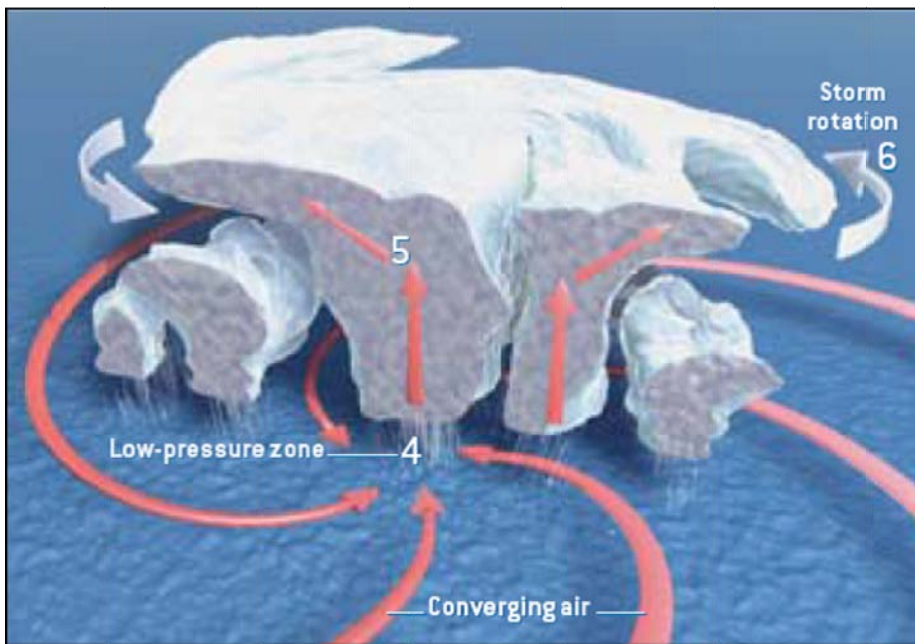


Figure 2: Intermediate Development of a Hurricane

As the low-pressure at the surface increases, more warm air is drawn towards the center [4] and pushes the thunderclouds higher and higher [5]. The rotation of the earth causes a Coriolis Effect which causes the storm to circulate [6] as it continues to grow.<sup>7</sup>

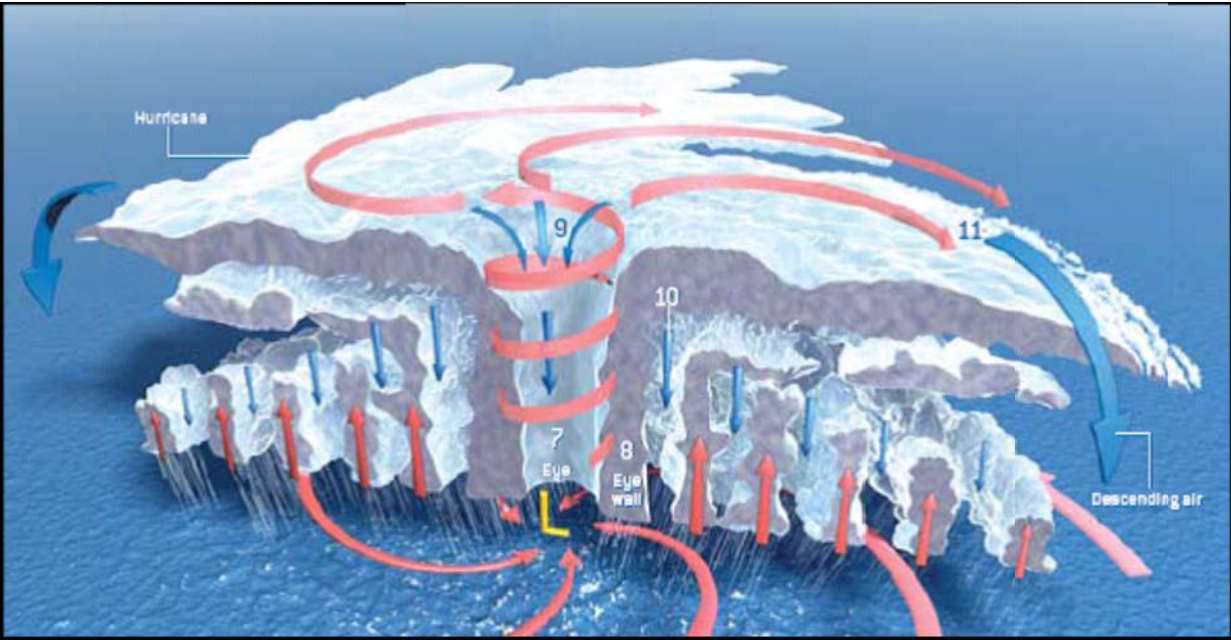


Figure 3: Fully Developed Hurricane

The eye [7] is a calm hub of low pressure surrounded by the high winds of the eyewall [8]. The previously rising air has now lost most of its moisture and descends into the eye [9], in between the bands of clouds [10], or out from the storms center [11] where it descends and rejoins the warm moist air moving in towards the center.<sup>8</sup>

In order for a tropical cyclone to form and sustain itself (known as cyclogenesis), several basic conditions must be present. First is a warm ocean between 78° F to 81°F at the ocean's surface (the top 50 meters). The potential energy in the evaporation of this warm water is the primary source of fuel for the system as the rising air condenses rapidly; transforming latent heat into thunderstorms. This translates into a relative humidity approaching 100% and a low pressure of around 965 millibars (mb) to offer the optimal conditions for formation. As the system develops, layers of moist air in the mid-troposphere must be present to support and reinforce increasing thunderstorm activity. Finally, the system requires the *absence* of vertical wind shear as crosswinds can tear the system apart. There are several other secondary factors to the formation of a hurricane, but if you can alter any or all of the basic requirements using various technologies, you may affect the life and course of the hurricane.



## Previous Mitigation Efforts

Given the loss of 1.9 million lives over the last two centuries, it is no surprise that governments have made attempts over the years to modify the weather using various technologies and techniques.<sup>9</sup> What is surprising is the lack of advances and attempts in the last few decades. Most have resigned themselves to simply improving forecasting and disaster relief believing that to be the most prudent course of action. The Air Force 2025 study on weather modification refused to discuss large-scale climate modification or the control of severe storms because the authors believed that “the technical obstacles preventing their application appear insurmountable within 30 years.”<sup>10</sup> Yet, the aftermath of Hurricane Katrina in 2005 and the increase in the number of hurricanes over the last decade caused some scientists and government officials to investigate new possibilities and review previous attempts.

The first and only serious attempt by the United States government to alter hurricanes, known as Project STORMFURY, began in 1962 and ended, unsuccessfully, in 1983. The concept centered on artificially stimulating convection in the area just outside of the eyewall by seeding the clouds with silver iodide. The government hoped the modified clouds would compete with and replace the original eyewall with a larger, artificially influenced eyewall with a lower wind speed and less destructive power.

In 1961, the working hypothesis was that the area around the eyewall of a hurricane was either inertially unstable or nearly so and that the clouds there contained abundant supercooled water. Seeding near the eye was intended to perturb the surface pressure through additional latent heat release. The perturbation would then trigger the inertial instability and cause outward migration of the eyewall, leading to reduction of the maximum wind through conservation of angular momentum.<sup>11</sup>

Scientists attempted to modify four hurricanes from 1961 to 1971 and reported roughly a 10-30% decrease in wind speed each time they made an attempt.<sup>12</sup> Despite early perceived

successes, the advances in techniques and tools for observing and measuring hurricanes that came out of the project started exposing cracks in the project's hypothesis. Observations of hurricanes between 1977 and 1981 revealed new insights in cloud physics and vortex dynamics that "substantiated doubts about the physical basis of the STORMFURY hypothesis and the interpretation of past experimental results."<sup>13</sup> The observations proved the initial hypothesis incorrect and showed that hurricanes possessed insufficient amounts of supercooled water. When the government officially shut down the project in 1983, "none of the five conditions (or perhaps only one: dynamic feasibility) for development of an operational hurricane amelioration strategy could be met."<sup>14</sup> Additionally, the project was labeled a failure because researchers could not distinguish between their results and naturally occurring phenomena. However, the advances in forecasting and the basic understanding of hurricane formation and structure serve as a positive legacy for the project.

### Notes

<sup>1</sup> GAO, *Hurricane Katrina: Continuing Debris Removal and Disposal Issues*, 1. and DHS, *Current Housing Unit Damage Estimates*, 8.

<sup>2</sup> St. Onge, "Ex-Chief Says FEMA Readiness Even Worse," *Boston.com*, 1 April 2006. See also the Marshall University report, *Hurricane Katrina: Preliminary Estimate of Commercial and Public Sector Damages*, by Dr. Mark Burton and Dr. Michael Hicks.

<sup>3</sup> Aherns, *Meteorology Today*, 431.

<sup>4</sup> The estimates on "massive amounts of energy" vary from one source to another, but the reality does not. According to Donald Ahrens, the energy released by a mature hurricane is the equivalent to 400 twenty-megaton hydrogen bombs in a single day or the energy consumption of the United States for six months. The US National Center for Atmospheric Research and the University Corporation for Atmospheric Research estimate that tropical cyclones release anywhere between 50 and 200 exajoules (10<sup>18</sup> J) per day – equivalent to exploding a ten-megaton nuclear bomb every 20 minutes. More information can be found at <http://www.ucar.edu/news/backgrounders/hurricanes.jsp>. While estimates may vary by an order of magnitude, either 720 megatons or 8000 megatons of energy are "massive" by any definition.

<sup>5</sup> Aherns, *Meteorology Today*, 429.

<sup>6</sup> Hoffman, "Controlling Hurricanes," *Scientific American*, 72.

<sup>7</sup> *Ibid.*

<sup>8</sup> Hoffman, "Controlling Hurricanes," *Scientific American*, 73.

<sup>9</sup> Nicholls et al., "Climate Change in South and South-East Asia," 137.

## Notes

<sup>10</sup> House et al, “Weather as a Force Multiplier: Owning the Weather in 2025,” 6.

<sup>11</sup> Willoughby, “Project STORMFURY: A Scientific Chronicle, 1962-1983”, 505.

<sup>12</sup> *Ibid*, 507. Very few hurricanes met the criteria for experimentation during the 1960’s and 1970’s. The first attempt on Hurricane Esther in September 1961 led to the formal establishment of Project STORMFURY. Other attempts to modify took place on Hurricane Beulah in August 1963, Hurricane Debbie in August 1969, and Hurricane Ginger in late 1971.

<sup>13</sup> *Ibid*, 508.

<sup>14</sup> *Ibid*, 513.

## **PART 2: FUTURE TECHNOLOGIES AND TECHNIQUES**

### **Space-Based Directed Energy**

#### **Scenario 2: “The China Gambit”**

The year is 2029. The earth has once again become a bi-polar world dominated by two superpowers: the United States and China. The Chinese have steadily and purposely developed their military capabilities in an effort to thwart the long-held advantages of the United States. Yet, despite their development into a global hegemon, the most painful thorn in their side remains less than 90 miles off their coast: Taiwan. The United States continues to uphold its commitment to aid Taiwan in the event of a Chinese invasion and the United States Navy continually conducts fleet exercises in the Taiwan Strait and East China Sea. For several years, China appeared to be developing into a more liberal and open nation, but a regime change in 2018 ushered in a new group of hard-line communist leaders dedicated to enforcing the “One China” policy...by force if necessary. The last several years have seen an increase in Chinese military forces in the Fujian province directly across the Taiwan Strait and a build-up of mobility aircraft and amphibious landing craft necessary for an invasion. While concerned about the current posture of the People’s Republic of China (PRC) military and the rhetoric coming out of Beijing, the United States is confident in the ability of the U.S. military, especially the Navy, to halt any invasion attempt.

In Beijing, the planners for the invasion of Formosa hope to secure Taipei in time to celebrate the PRC’s 80<sup>th</sup> anniversary on October 1<sup>st</sup>. They are confident that once their ground

forces are in control, the United States will not risk all-out war to liberate the island. Therefore, the plan hinges on the ability of PRC forces to successfully invade Formosa and secure the island without interference from the U.S. Navy. In order for this to happen the planners are counting on the weather. Advancements made possible by more than 70 years of weather modification experiments and the efforts of the Weather Modification Department of the Chinese Academy of Meteorological Sciences have progressed far beyond the simple cloud seeding used to ensure cloud-free days during the 2008 Olympic Games.<sup>1</sup> Now they have the ability to *create and control* weather.

PRC military leaders were extremely satisfied with the successful field test of their weather generation system two months earlier that created an average-sized tropical cyclone in the Indian Ocean. Less than 30 hours after its formation, technicians successfully steered the cyclone into the Arabian Sea where it made landfall within 10 kilometers of their intended target of Mumbai, India. The cyclone's 18-foot storm surge moved up the mouth of the Ulhas River resulting in massive flooding and destruction. The devastation of India's largest city has resulted in a successful global distraction and humanitarian relief effort that has diverted a significant number of U.S. Navy vessels to the western coast of India. The PRC will direct their next artificial typhoon towards Taiwan to force the U.S. Navy to abandon the Taiwan Strait and then steer the typhoon north towards Japan to keep U.S. forces at bay while PRC air and naval forces complete the invasion.

Meteorologists and intelligence analysts at United States Pacific Command (USPACOM) Headquarters in Hawaii brief CDRUSPACOM on both the unusual level of chatter intercepted from military units in Fujian and the mysterious typhoon that has suddenly developed west of the Marshall Islands. After CDRUSPACOM briefs the National Command Authority, the President

authorizes the employment of the Space Based Solar Power for Weather Modification (SBSP-WM) System. The SBSP system is regularly used to convert intense solar energy into microwaves and send them to ground collection stations in wavelengths that pass through the atmosphere without heating it and wasting precious energy. The ground stations then turn the microwaves into bountiful, clean energy. Today, however, this source of power will be used to modify the weather.

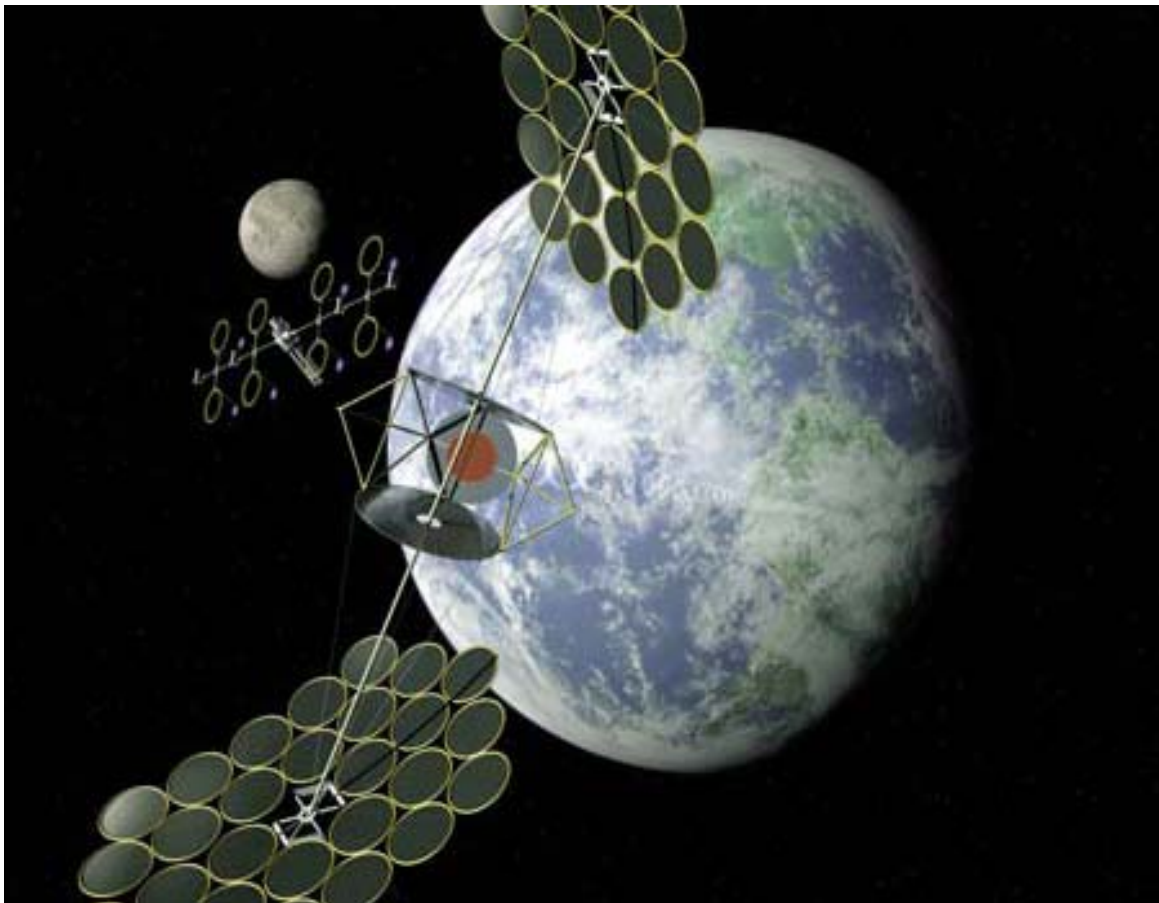


Figure 4: Concept Drawing of SBSP satellite<sup>2</sup>

A SBSP-WM satellite, designed with adjustable targeting and tunable frequencies, begins sending microwaves (now tuned to be absorbed by water molecules rather than avoid them) towards the northern-most point of the eyewall. Meteorologists monitor the storm as the instability in the eyewall disrupts the positive feedback system and causes the hurricane to shift

track. As required, the SBSP-WM system continues to heat parts of the eyewall until the instabilities send the hurricane harmlessly into the open, colder waters of the northern Pacific. The following week at the PRC's 80<sup>th</sup> anniversary celebration in Beijing, the U.S. ambassador to China makes a point to seek out the head of the Chinese Academy of Meteorological Sciences. Shaking the director's hand, he delivers the President's cryptic message: "Nice try."

### **Space-Based Directed Energy: A Dual-Use Technology**

This potential vision of future benefits from the possibilities of a future dual-use technology. According to a National Security Space Office (NSSO) study, "the magnitude of the looming energy and environmental problems is significant to warrant consideration of all options, to include revisiting a concept called Space Based Solar Power (SBSP)."<sup>3</sup> The idea is fairly simple (while the execution is obviously not): place large solar arrays in orbit to collect huge amounts of sunlight (at 1366 watts per minute), convert it to microwaves, and then beam the energy down to ground stations for distribution. This is not a small amount of energy as a "single kilometer-wide band of geo-synchronous orbit experiences enough solar flux in one year to nearly equal the amount of energy contained within all known recoverable conventional oil reserves on Earth."<sup>4</sup> This bountiful source of energy may possess a significant secondary benefit: disrupting tropical cyclones.

### **Requirements and Specifications: Five Criteria for Use**

In order for a Space Based Solar Power Weather Modification (SBSP-WM) system to be considered a viable technology for disrupting tropical cyclones it must meet at least five basic criteria: (1) provide a persistent source of microwaves converted from solar energy, (2) tunable to specific frequencies of microwaves that effect water vapor (183 to 190 GHz) at various

altitudes, (3) possess the targeting ability to direct energy towards a specific location over a large area of the ocean, (4) generate on the order of six gigawatts (GW) of power of a 4 km<sup>2</sup> area to provide 1500 watts per square meter, (5) include a suite of sensors and computing power capable of accurately measuring minute changes in the storm, analyzing the collected data, and projecting the storm's response to perturbations. The figure below presents one possible system in which large panels of photovoltaic cells collect solar energy with 35-50% efficiency. The energy is then transferred to a phased array that converts the energy to microwaves for wireless transmission to Earth with efficiency around 90%.

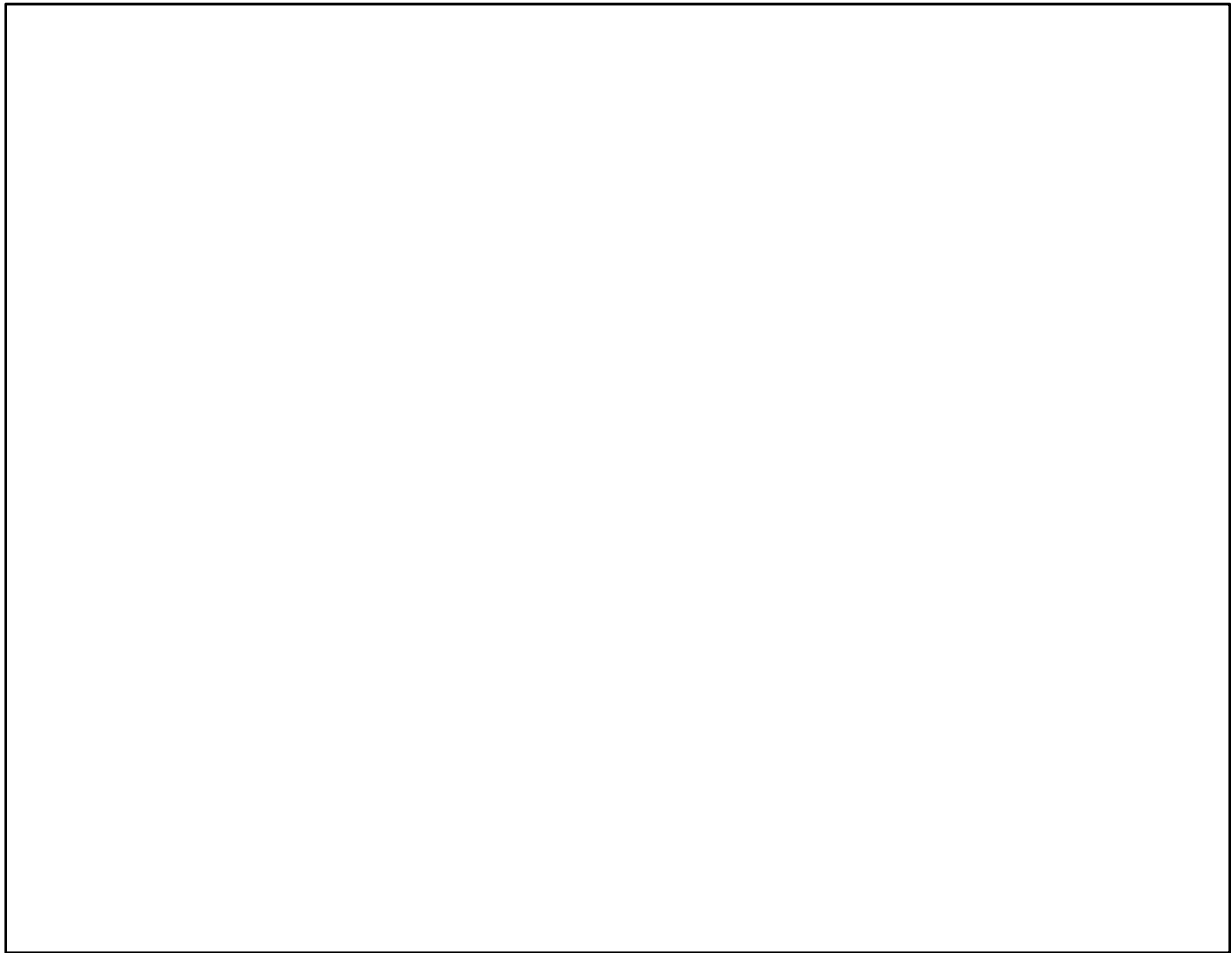


Figure 5: Integrated Symmetrical Concentrator Concept<sup>5</sup>



Obviously, there is no current system capable of meeting any of the above criteria, but the potential is significant as the basic technologies for several of the criteria currently exist. The process for converting solar energy to microwaves has been known for decades and, by definition, a satellite in geo-synchronous orbit is persistent over a specific point over the Earth's surface. Frequency modulation, area coverage, and targeting would be functions of the aperture of the microwave transmitter. While the engineering necessary to create a system capable of targeting a large area of the ocean and providing a wide enough beam would be daunting, they are not outside the realm of what is currently possible. Finally, a data assimilation program capable of measuring the effects of perturbations, known as Four-Dimensional Variational Analysis (4D-VAR), is currently used by the European Centre for Medium-range Weather Forecasts (ECMWF) but currently lacks the resolution to adequately track small fluctuations in cyclonic systems.

### **Results of 4D-VAR Experiments on Simulated Hurricanes**

Experiments conducted by Atmospheric and Environmental Research, Inc. in Lexington, Massachusetts used the 4D-VAR system to forecast the optimal perturbations necessary to effect the course and strength of simulated tropical cyclones. The overarching goal of this effort was minimize or find the optimal number of perturbations necessary to impact what the researchers called the "damage cost function" which is a calculation of projected damage related to wind speed. Given that hurricanes are intrinsically chaotic systems, these simulations are built on the principle that minor changes to a chaotic system can propagate into larger, dramatic effects. The 4D-VAR system uses an incredibly complex numerical weather prediction (NWP) model that accounts for the estimated mass, energy, momentum and moisture of a hurricane. The model also takes into account numerous variables such as pressure, temperature, relative humidity,

wind speed, and wind direction. The NWP is a “snapshot” of all of the qualities within a three dimensional model of a hurricane at a given moment. The 4D-VAR system then advances the NWP through the fourth dimension of time. Hence, the process is analogous to flipping the pages of book of drawings to create a moving cartoon as the system time steps (a few seconds or a few minutes for each step) through several hurricane model “snapshots” to give a forecast of how the storm might behave. Unfortunately, the models can never be completely accurate. The system has a lower limit on its resolution, so changes which are smaller than the resolution cannot be represented. Also, our knowledge and observations of hurricanes are not 100% comprehensive, so it must be understood that there might be variables that exist in real hurricanes that are not included in the simulated calculations.

With that understanding, the results of the experiments show definite promise. All of the simulations used a model of Hurricane Iniki that struck the Hawaiian island of Kauai in September 1992 killing six and causing \$1.8 billion in damage. The researchers conducted numerous experiments in which wind speeds were measured at ten different “layers” or altitudes. These slices can be combined to provide the entire three-dimensional picture, but the layer of greatest interest is the lowest layer which represents the surface wind speed. Figure 3 below shows the graphical results of two of the experiments. The three images on the left show the hurricane surface winds at 4 hours, 6 hours, and 8 hours in a simulation that is unchanged (the control). The three images in the right column show the surface winds speeds at the same time intervals and the exact same conditions except that a temperature perturbation was introduced at hour zero.

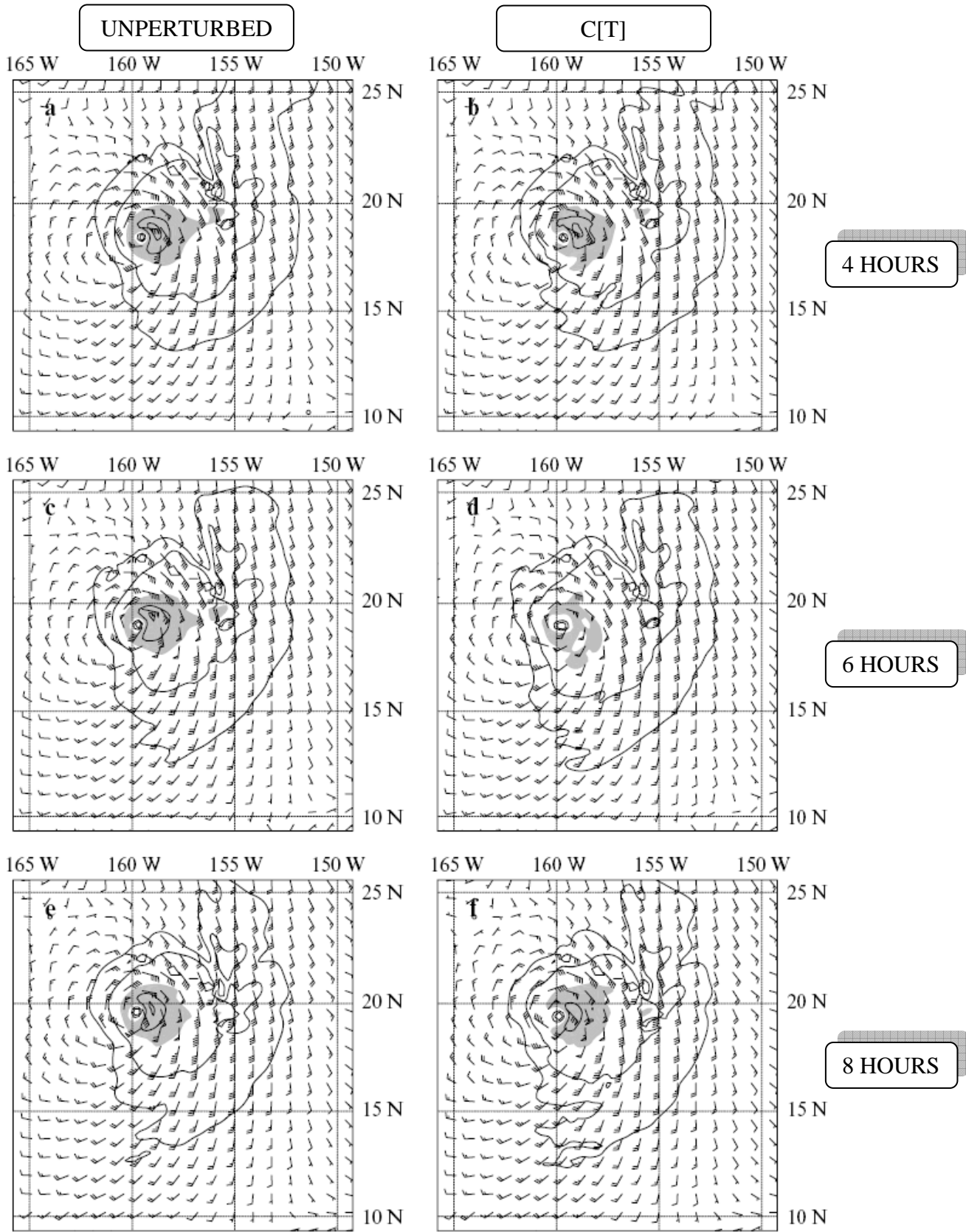


Figure 6: Evolution of surface wind speeds for unpertured (left) and C[T] (right) at 4, 6, and 8 hours<sup>6</sup>

These results are from one of the various iterations, but “in all cases, the extent and intensity of damaging winds (winds >25 m/s [or 55.9 mph]) were drastically reduced.”<sup>7</sup> While the winds did increase significantly after the time period of the experiments, the majority of damage is done as the hurricane makes landfall, so an increase in wind speed after landfall is irrelevant. These simulations demonstrate the possibility that “precisely prescribed heating might serve to control hurricanes and other weather phenomena in the future.”<sup>8</sup> In future experiments, the researchers intend to determine the exact timing, duration, pattern, and strength required to modify a hurricane. However, it is clear that more precise models and increased computing power to collect and analyze climate data is necessary before any SBSP-WM system could be successfully employed.

### **Way Ahead: 2030 Operational Employment**

The NSSO and other advocates of SBSP have urged the Obama Administration to pursue SBSP as an inexhaustible and environmentally-friendly energy alternative for terrestrial power needs.<sup>9</sup> The federal government has invested more than \$21 billion over the last 50 years and the Department of Energy currently spends approximately \$300 million per year on fusion energy research.<sup>10</sup> Advocates hope that a similar effort will be put forth for space based solar power. If the basic technology is already going to be in orbit, it is not a dramatic leap to foresee the possibility of satellites dedicated to SBSP-WM systems in geo-synchronous orbit over the three tropical cyclone “nurseries.”<sup>11</sup> Once in place, these systems will apply significant energy to precise locations and can do so for as long as necessary. Experiments on simulated hurricanes demonstrate that small perturbations, caused by changes in temperature, can alter their destructive potential.

## **Biodegradable Surface Materials**

### **Scenario 3: “Entering the ‘Kill Zone’”**

It’s August 2027 and it is a deceptively beautiful summer day in Puerto Rico as the first of four Puerto Rico Air National Guard (PRANG) aircraft take off from Muñiz Air National Guard Base. A Category-2 hurricane is about to enter the southern Atlantic “kill zone” – a 7,000 mi<sup>2</sup> area approximately 750 miles southeast of Puerto Rico. Advances in forecasting models and simulations have shown that storms passing through this area have a greater than 90% possibility of striking the various islands of the Lesser Antilles. A coalition unit consisting of representatives from six Caribbean nations and the United States monitors hurricanes in this area and directs hurricane mitigation missions. Meanwhile, PRANG maintains and operates a fleet of eight C-17 aircraft specifically modified to execute these weather modification missions.

As the aircraft reaches a point 150 miles inside the western edge of the “kill zone” (approximately 250 miles from the leading edge of the hurricane), the crew begins to release their cargo: 50,000 pounds of advanced evaporation inhibitor (AEI) over the open ocean. The AEI is carried in ten 5,000-pound pill-shaped pods. These pods, dropped in a specific pattern, release the AEI underwater and then dissolve harmlessly. The AEI material is similar to cetyl alcohol and is composed of saturate paraffinic chains of carbon, oxygen and hydrogen atoms.<sup>12</sup> Once released from its dispersal pod, the AEI does not mix with the water, but behaves like oil. It comes to the surface and begins to spread out eventually covering nearly 1000 square miles in a molecule-thick monolayer that suppresses surface evaporation. In total, the ten pods provide the initial coverage of over 7,000 square miles in front of the hurricane’s path. Additional sorties drop more pods over the next few hours to reinforce and adjust the monolayer as necessary as the hurricane shifts track. When the hurricane reaches the monolayer, the churning ocean

disintegrates the monolayer which dissolves into the ocean harmlessly. However, the monolayer has performed perfectly. Surface evaporation and humidity, now reduced by nearly 50 percent, successfully deprives the storm of its much needed source of energy. When it makes landfall a few hours later over the small islands of St. Kitts and Nevis, the Category-2 hurricane is now only a tropical storm.

### **Biodegradable Surface Materials: Exploring the Monolayer**

One promising future technology for mitigating hurricanes hinges on reducing the amount of surface evaporation from the ocean's surface using biodegradable oils or other materials. Like placing a cover over a pot of boiling water, the surface material restricts the release of evaporation and the potential energy (in the form of latent heat) from fueling a hurricane. The idea of using oils or other type of biodegradable material to inhibit evaporation is not new. In 1765, Benjamin Franklin discovered that certain types of oil spread out over the surface of a body of water resulting in a very thin layer of oil only a few molecules thick. In one experiment, Franklin observed that a single teaspoon of olive oil spread out to a thickness of just 25 Angstroms (one ten-millionth of an inch) over the surface of a small pond.<sup>13</sup> In 1917, the efforts of scientists resulted in the discovery of several materials that expand until their thickness is only one molecule thick with the chains packed tightly together in a single layer. This pattern is known as a monomolecular film and the materials are referred to simply as monolayers. In 1962, scientists Victor LaMer and Geoff Barnes conducted several field tests that proved that various "fatty alcohol" monolayers effectively suppressed surface evaporation.<sup>14</sup>

## **Requirements and Specifications: Five Criteria for Use**

In order to be considered as a potential technology for combating hurricanes, such a surface material would have to possess five critical attributes: (1) be easily deployable and spread rapidly, (2) provide sufficient evaporation resistance, (3) maintain structural integrity once subjected to surface winds and wave action on the open ocean, (4) have zero ecological impact on marine life, and (5) degrade naturally after a few hours or days.

Monolayers such as hexadecanol (cetyl alcohol –  $C_{16}OH$ ) or octadecanol ( $C_{18}OH$ ) meet several of the five criteria listed above. Experiments conducted by La Mer and Barnes in the 1960's revealed that while a monolayer's resistance to evaporation increased exponentially with increased number of carbon atoms in the chain, the longer chains had an exponentially slower spreading rate (see Figure 4). Hexadecanol and octadecanol possess a decent trade-off between spreading rates and resistance to evaporation. Finally, experiments conducted at the Massachusetts Institute of Technology (MIT) Air-Sea Interaction Lab demonstrated that hexadecanol degrades in 30 to 60 hours.<sup>15</sup> Four of the five criteria required for use in reducing evaporation and diminishing hurricanes can be met by monolayers.

## **Results of Hexadecanol and Octadecanol Experiments**

The major drawback of monolayers is that they tend to drift once subjected to wind and are susceptible to collapse when subjected to waves. Yu-Lin Lawrence Hsin, a student at MIT, conducted a series of experiments that demonstrated the inability of a hexadecanol film to repair itself once disrupted. This is attributed to the use of n-hexane as a solvent for hexadecanol (which is a solid at room temperature) and that the churning of the surface causes the hexadecanol to lose its solvent and make it unable to return to the surface.<sup>16</sup> Other experiments

involving monolayers and wind interaction show that these alcohol monolayers can avoid collapse and adequately suppress evaporation in surface winds up to 8 meters per second (m/s) or approximately 18 miles per hour.<sup>17</sup> Obviously, these wind speeds are far too low to survive the wind speeds experienced as a hurricane approaches, but it provides a basis for future experimentation.



Figure 7: Monolayer Performance While Subject to Surface Winds

Additionally, Hsin's use of n-hexane as a solvent for the hexadecanol presents an additional problem: ecological impact. These fatty alcohols are a waxy solid at room temperature and must be dissolved in some type of solvent in order to form the oil-like film necessary to retard surface evaporation. While n-hexane easily evaporates and is "rapidly transported to the atmosphere without major damage to biota," it contributes to "the formation of photochemical smog."<sup>18</sup> Hazardous side effects quickly negate any potential benefits hurricane mitigation technologies may provide so different spreading solvents will have to be found. However, monolayer materials such as hexadecanol and octadecanol are by themselves non-toxic molecules of carbon, oxygen, and hydrogen that are derived from naturally occurring oils found in plants and animals. Monolayers also have the benefit of being only one-molecule thick which would make the monolayer completely invisible to marine animals, allow sunlight to penetrate the ocean surface



to reach aquatic plant life, and have very little, if any, ecological impact. Yet, until new spreading solvents can be found, monolayers currently fail this critical requirement.

### **Way Ahead: 2030 New Monolayer Cocktails**

Further experimentation on monolayers is required, but the basic principles are sound. The vast majority of research involving monolayers over large bodies of water took place in the 1950s and 1960s. With the exception of a handful of scientists, modern-day research into monolayers over bodies of water is almost nonexistent. This technology is being thoroughly tested and tried to provide invisible coatings to metallic surfaces in industrial applications, but study of its application for evaporation retardation and weather modification is severely lacking. Research is desperately needed to investigate and test other types of hydrophobic materials and monolayers. In a 2000 study, Dr. Geoff Barnes from the University of Queensland, Australia, postulated that long-chain alcohols could be mixed with several different polymers that would still maintain the same level of evaporation resistance, but be much stronger than current monolayers.<sup>19</sup> Chemistry has come a long way in the last four decades and in the next two decades it should be possible to find an optimal material for suppressing evaporation and diminishing the strength of hurricanes.

## Moisture Absorbing Materials

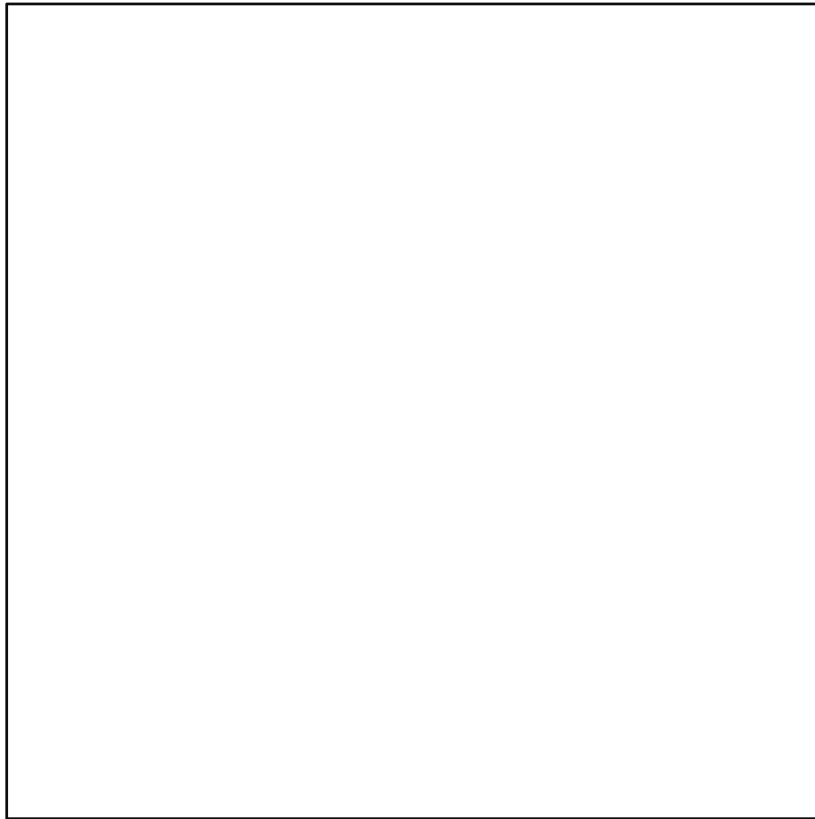


Figure 8: Artist Concept Drawing of Deployment of Moisture-Absorbing Material<sup>20</sup>

### **Scenario 4: “Weather Combat in the D.C. AOR”**

Following another hot summer, residents of Washington D.C. are looking forward to the cooler fall months of 2031. The Labor Day weekend brings thousands of additional tourists to the nation’s capital clogging already congested streets and highways. Northeast of the Leeward Islands a tropical storm is detected and during the week appears to be heading towards South Carolina and Georgia. Yet, late Friday night the storm veers unexpectedly northwest towards Virginia, Delaware, and Eastern Maryland. It now appears that the hurricane will briefly make landfall on Sunday night roughly 30 miles north of Virginia Beach crossing the Delmarva

Peninsula and entering Chesapeake Bay. The expected storm surge in D.C. alone is expected to be greater than 15 feet.

Despite the mayor's declaration of a state of emergency for the district, the evacuation of Washington on Saturday is not going as smoothly as planned. The additional tourists in town for the holiday weekend make a difficult situation even worse. Given the dire situation, the President authorizes National Oceanic and Atmospheric Administration (NOAA) and the Department of Defence (DoD) to launch two converted Boeing 787 cargo aircraft carrying thousands of pounds of moisture-absorbing material towards the incoming storm. The two aircraft launch out of Andrews Air Force Base and fly two hundred miles south to intercept the target at 50,000 feet and drop their payload. Splitting up and moving out from the center of the eye, the two aircraft disperse the moisture-absorbing powder in a roughly wedge-shaped pattern.

As the material descends, meteorologists on board and back on land observe with great interest as the material appears to almost magically cut away a large section of clouds from the eyewall to the outer cloud banks. As the moisture in the concentric thunderstorms is absorbed into the material, the circular motion of the hurricane as well as the self-sustainment loop is interrupted. The storm does manage to reform just before making landfall, but its course has been shifted several miles north and its strength has diminished by over fifty percent. When it does make landfall near Ocean City, Maryland, the winds gust up to a manageable 45 miles per hour and the storm surge never poses a serious threat. In D.C., tourists complete their Labor Day vacations touring monuments in raincoats rather than evacuating or seeking refuge in shelters.

### **Moisture-Absorbing Material: Bringing the Rain**

The final technology that demonstrates significant potential for mitigating tropical cyclones is moisture-absorbing materials. Similar in many respects to the surface material described

above, the underlying principle is to deny a hurricane of its fuel; namely moist air that rises, condenses, and releases latent heat. The primary difference between this technology and surface materials is that this technology exists today. According to GelTech Solution's "Hurricane Suppression Project," the project seeks to increase friction and remove heat from the hurricane by "taking a 'wedge' out of its spiraling winds and thereby reducing its intensity."<sup>21</sup> This would be done by dispersing several tons of a fine, white powder (similar in look and feel as baby powder) they call "SK-1000" (SK stands for "Storm Killer") into a hurricane. SK-1000 is a "hygroscopic" inorganic polymer that "absorbs water into its three-dimensional network."<sup>22</sup> The basic theory is that the powder will absorb cold water out of the atmosphere and take it to the ocean's surface thereby reducing the overall surface temperature. Additionally, the material would absorb some of the condensing moisture in the storm itself and prevent some of the latent heat release which fuels the storm.

### **Requirements and Specifications: Five Criteria for Use**

The requirements for moisture-absorbing material (MAM) are very similar to those for biodegradable oils with a few differences. In order to be considered as a potential technology for combating hurricanes, such a moisture-absorbing material would have to possess five critical attributes: (1) be released and dispersed easily, (2) be easily deployable with a minimum number of assets, (3) provide sufficient moisture absorption, (4) have zero ecological impact on marine life or life on shore, and (5) degrade naturally after a few hours or days.

The SK-1000 MAM tentatively meets four of the five of the above criteria. Hygroscopic materials, such as sugar, iodine, and many different salts, readily absorb and retain moisture to varying degrees. SK-1000 changes from a powder into a gel as it absorbs water; even moisture from the surrounding air. The material's high degree of hygroscopy will require special handling

to avoid early absorption (i.e. be encased in air-tight containers until release) but will otherwise be easy to deploy and should provide sufficient moisture absorption. Similar in technique to aerial firefighting, the powder could be easily released from numerous aircraft in the U.S. inventory. The number of aircraft required to deliver sufficient material is the primary unknown. Until more extensive tests can be conducted, the amount of material required (and the number of sorties required) to significantly modify a hurricane will remain unknown. The last two requirements regarding ecological impact and degradability are areas that will require additional study. GelTech Solutions asserts that SK-1000 is non-toxic and would be harmless to marine life or animals on shore should any of the material be blown back onto land. Once the material reaches the ocean's surface it will sink to the bottom and completely degrade in three to five days. These estimates have not been fully tested, but initial observations put SK-1000 on par with the degrading rate of hexadecanol.

### **Results of Moisture Absorption Field Tests**

In July 2001, at the suggestion of the director of NOAA, a team from GelTech Solutions conducted field tests on a thunderstorm off the coast of Jupiter, Florida. During the "Jupiter Tests," the GelTech team dispensed approximately 1000 pounds of SK-1000 in less than five minutes from the bomb bay of a Mk-20 Canberra aircraft over the thunderstorm. The thunderstorm "was cut in half almost immediately" according to GelTech CEO, Joe Ingarra. In addition to visual accounts, the Palm Beach Airport control tower monitored the storm using their radar system. The tower supervisor later told the Associated Press that "the people in the tower visually confirmed that there was a tall buildup and the next moment it was gone."<sup>23</sup> Given the proprietary nature of the material and the nature of the experiment, no hard data on moisture absorption rates, wind speed, temperature, or pressure is available.

## Way Ahead: 2030 Operational Use

The initial field tests, while promising, were conducted by a private company and not independent scientists. This is not to say that there is anything wrong with the technology, but quite to the contrary. Innovation and motivation from the private sector will be essential if any of the technologies described in this paper are going to be fielded by 2030. Concern for the plight of people threatened by tropical cyclones combined with a modest profit margin may very well produce an environment with less bureaucracy capable of moving at a faster pace.

According to CEO of GelTech Solutions, Joe Ingarra:

We know the documented amount of money and effort that went into 'Storm Fury'. The technology they had at that time was nowhere near what we have today. A person would think that at least giving it a shot would make some sense. We're not talking billions of dollars to put some simple tests into place. I feel that we could run parallel tests to see if it would make sense. Plane tests, environmental impact studies and deployment strategies would probably be under the \$10M range to get started. If there is no real traction going forward at least it was given a 'real' shot.<sup>24</sup>

Additional laboratory experimentation and field tests conducted by independent researchers will have to be performed, but the potential for successful hurricane mitigation exists and perhaps this technology will one day get "a 'real' shot."

## Notes

<sup>1</sup> This part is not fantasy. The Weather Modification Department of the Chinese Academy of Meteorological Sciences actually exists. Weather modification has been a program in China since 1958. For the opening ceremonies of the Olympics, the Chinese government launched over 1,000 rockets to initiate rainfall outside of Beijing. (See "Can China Control the Weather?" by Jacob Silverman and Robert Lamb at <http://science.howstuffworks.com/cloud-seeding1.htm>) According to Wang Guanghe, the director of the Weather Modification Department, "ours is the largest artificial weather program in the world in terms of equipment, size and budget." Their annual weather modification budget is between \$60 and \$90 million. For more information: Asia Times article at <http://www.atimes.com/atimes/China/IG13Ad01.html>

<sup>2</sup> NSSO, "Space-Based Solar Power: An Opportunity for Strategic Study," 10 October 2007, <http://www.acq.osd.mil/nssso/solar/solar.htm>, 7.

<sup>3</sup> *Ibid*, 1.

<sup>4</sup> *Ibid*.

<sup>5</sup> *Ibid*, 7.

## Notes

<sup>6</sup> Hoffman et al, “A Dual Use for Solar Power,” 107.

<sup>7</sup> *Ibid.*

<sup>8</sup> *Ibid.*, 87.

<sup>9</sup> Obama-Biden Transition Team, “Space Solar Power (SSP) — A Solution for Energy Independence & Climate Change,” 1.

<sup>10</sup> *Ibid.*

<sup>11</sup> See image in Appendix A. There are three tropical cyclone “nurseries” or areas where the vast majority of northern-hemisphere tropical storms get their start. The vast majority of the hurricanes in the Atlantic originate in the same general location south of Cape Verde off the western coast of Africa. Most Eastern Pacific hurricanes that threaten the western U.S. originate off the western coast of Nicaragua. Finally, the area around the Marshall Islands serves as the birthplace of most Northwest Pacific typhoons. Southern-hemisphere typhoons and cyclones originate throughout a wide band stretching from Madagascar to French Polynesia in the South Pacific. The term “nurseries” is common vernacular and is not taken from any specific source.

<sup>12</sup> Hsin, “Feasibility Experiments,” 5.

<sup>13</sup> Chandler, “Eyes On the Stormy Season,” C1.

<sup>14</sup> Barnes and LaMer, *Retardation of Evaporation by Monolayer: Transport Process*, 9-33. Fatty alcohols are not alcohols as we typically think of them. Fatty alcohols are derived from natural fats and oils and cetyl alcohol at room temperature is a solid, waxy substance. It is commonly used in shampoos, skin creams, and lotions.

<sup>15</sup> Hsin, “Feasibility Experiments,” 12.

<sup>16</sup> Hsin, “Feasibility Experiments,” 15.

<sup>17</sup> Alamaro, “Evaporation Retardation from Water Reservoirs Using Monolayers,” <http://alamaro.home.comcast.net/~alamaro/Evaporationretardation.htm> (accessed on 23 January 2009).

<sup>18</sup> Government of Australia Department of the Environment, Water, Heritage, and the Arts, “n-Hexane Substance Fact Sheet,” <http://www.npi.gov.au/database/substance-info/profiles/47.html> (accessed on 6 February 2009).

<sup>19</sup> Dr. G.T. Barnes is one of the few scientists continuing to conduct research on evaporation resistance over the last four decades. He was the co-author of *Retardation of evaporation by monolayers: Transport Processes* with Victor La Mer in 1962 and has published several scholarly articles which can be found in the bibliography.

<sup>20</sup> Ingarra, GelTech Solutions, E-mail, 24 March 2009.

<sup>21</sup> Strenta, “Research Projects: WeatherTech Innovations.” [www.geltechsolutions.com](http://www.geltechsolutions.com) (accessed on 7 January 2009).

<sup>22</sup> Ingarra, GelTech Solutions, E-mail, 24 March 2009.

<sup>23</sup> *Ibid.*

<sup>24</sup> *Ibid.*

## **PART 3: OPTIONS, OBSTACLES, AND CONCERNS**

### **Other Ideas for Mitigation**

In addition to the three main technologies already discussed, there are several other concepts and alternatives that should be briefly mentioned to provide a full view of the mitigation landscape. Hurricane mitigation expert, Moshe Alamaro, from MIT advocates several additional techniques. First is a plan to “paint” the top of the hurricane. The idea calls for using soot, coal dust, or black material left over from the manufacturing of tires to absorb solar energy (like tarring a roof) and has been around for several decades.<sup>1</sup> The idea is sound as changing the temperature differences between the surface and the top of the system would alter the structure of the storm. However, the ecological impact and public distain at the idea of dropping coal into the ocean will probably keep this idea *on* the drawing board.

Another idea involves a twist on the Project STORMFURY idea of using cloud seeding to cause an increase rain so the hurricane exhausts its supply of energy. Typically, silver iodide is used to seed clouds because its crystalline structure is very similar to ice particles and it serves as a good agent for nucleation. Mr. Alamaro recommends replacing the silver iodide with a different material: ice. In an interview with Mr. Alamaro he stated that if silver iodide is used because it is so similar to ice, “why not just use ice?”<sup>2</sup> The genius of the idea is in its simplicity. From an ecological standpoint, there is absolutely nothing more environmentally friendly and the science is pretty solid. There are several questions that still need to be answered such as how to overcome the problems encountered during Project STORMFURY, how to optimize and



maintain the crystal size, and finding optimal distribution patterns. This is a very new idea and hopefully future studies will provide answers to these pending questions.

The third idea from Mr. Alamaro involves using decommissioned jet engines from Boeing 707s and B-52s to create artificial tornados, or “anthropogenic perturbations” that will “extract enthalpy from the ocean” successfully “cooling the ocean’s surface, and depriving the advancing hurricane of its needed thermal energy.”<sup>3</sup> He suggests mounting jet engines on barges (see figure below) strategically placed throughout the Atlantic to create several small cyclones thereby reducing the overall surface temperature. The plan is analogous to the way firefighters use small fires to clear brush and deny fuel to a larger fire. The primary concern from this technique is that you would actually be creating new, albeit smaller, tropical cyclones that may grow into larger storms and threaten populated areas. Additionally, the amount of jet fuel required to run the engines and the diesel required to continuously patrol the ocean creating these perturbations would result in a substantial carbon footprint. Like using n-hexane for monolayers, it does little good to diminish a hurricane if it means harming the atmosphere in the process. While these ideas may not be as promising as others, the underlying scientific principles for all three ideas are sound. Creative ideas like these may very well serve as the nuclei for future technologies or lead to successful mitigation techniques.



Figure 9: Concept Drawing of a Jet-Engine Barge Patrolling the Atlantic.<sup>4</sup>

## **Enabling Technologies: Forecasting, Simulations, and Modeling**

All of the various scenarios provided in this paper demonstrate that while the basic foundational technologies for mitigating hurricanes currently exist, several enabling technologies must be developed in order for them to be successfully implemented. First and foremost, our ability to forecast the weather must continue to improve. A century ago, meteorologists had virtually no knowledge on the formation or behavior of tropical cyclones and forecasting, for the most part, did not exist. During Project STORMFURY, our knowledge grew tremendously and during the 1970s crude (by today's standard) forecasting models were developed and improved. At that time, the National Weather Service and NOAA produced forecasts with average track errors on the order of 250 miles just 48 hours before landfall (see Figure 10 below). At 24 hours prior to land fall, the average error was still plus or minus 100 miles. Today, we have models that allow us to look out five days before landfall and predict its path with almost as much accuracy as the 48-hour predictions during the 1970s. Unfortunately, our forecasting and modeling capability still has significant errors just 12 and 24 hours out. Meteorologist can only provide a corridor of probability that is 60 to 100 miles wide. Similarly, our ability to forecast the intensity of an approaching storm just 24 hours prior to landfall is plus or minus ten knots and almost plus or minus 20 knots at 48 hours. That margin of error is enough to deny us the ability to accurately predict what the strength of the storm will be (see Table 1) when it makes landfall.

Errors are inherent in chaotic systems where thousands of variables can influence the overall behavior of the system. Our forecasting models and computer simulations do not have the resolution or the computer processing power to take all of these variables into account. In February 2009, the President's Stimulus Bill included a provision for \$170 million dollars

“directed to specifically support supercomputer activities, especially as they relate to climate research” which would go to NOAA’s National Center for Environmental Prediction in Maryland.<sup>5</sup> The following week, negotiations between Republicans and Democrats resulted in the elimination of this provision in the Senate’s version of the bill.



Figure 10: Average Track Errors for Atlantic Storms by Decade<sup>6</sup>

The August 1996 study “Weather as a Force Multiplier: Owning the Weather in 2025” identified five areas for technological advancement including “advanced nonlinear modeling techniques, computational capability, information gathering and transmission, a global sensor array, and weather intervention techniques.”<sup>7</sup> This paper has demonstrated the possibility of the

fifth area of weather intervention techniques for mitigation of tropical cyclones, but has also demonstrated that the evaluation in the decade-old study of our technological capability in regards to weather is still viable. Systems like 4D-VAR may provide the necessary nonlinear modeling, but we must improve our ability to gather data and the computational capability to rapidly analyze that information.

### **Lawsuits and International Treaties**

While the technological challenges required for modifying hurricanes in 2030 will be daunting, the greatest obstacle to future experiments and missions to stop hurricanes is “not the science...it’s the lawyers.”<sup>8</sup> Any modification of a tropical system will inevitably shift its track to some degree and if it makes landfall it will strike a different location and cause damage that otherwise would not have happened. Even though the strength might be significantly reduced or the hurricane might be diverted away from a large population center, weather modifiers and the government will be accused of “playing God” and blamed for damage caused by the weaker hurricane. Given our litigious society, several researchers including Mr. Alamaro believe that the aftermath of a modified storm will be a storm of lawsuits and have advocated legal protection for hurricane modifiers.<sup>9</sup>

Despite the fears of researchers, some of the legal protections for the government and hurricane modifiers might already exist. It is possible that weather modification, conducted under the oversight of the federal government, could fall under the legal precedents of eminent domain and sovereign immunity. The Taking Clause of the Fifth Amendment states that “private property shall not be taken for public use without just compensation.”<sup>10</sup> This means that the government can deprive a citizen of personal property if it is in the public interest and provides just compensation. However, the taking of property must be an intentional action by the

government and “accidental” taking would have to be proven via “inverse condemnation” which is extremely difficult to prove.<sup>11</sup> More likely, however, modifiers working for the federal government would be protected by the doctrine of sovereign immunity which “precludes the institution of a suit against the sovereign [government] without its consent.”<sup>12</sup> In simpler terms, you cannot sue the federal government or any individual employees (including contractors) who act in good faith. The Tucker Act of 1887 waives some of the federal government’s sovereign immunity specifically allowing citizens to bring a suit against federal agencies, but again, not against individual employees unless they intentionally do something harmful or act negligently.<sup>13</sup> Additionally, the Tucker Act allows Congress to arbitrarily decide which agencies are and are not protected by sovereign immunity.

The bottom line is that if the government created an agency for hurricane modifiers and regulated their actions, sovereign immunity could apply and the modifiers could conduct their experiments with little fear of legal action. More importantly, however, the government would have to put laws in place to ensure that insurance companies could not use a loophole to deny insurance claims on the basis that the modified hurricane was no longer an “act of God” but an “act of man.”<sup>14</sup> Whether the government would be willing to take these steps to protect hurricane modifiers and homeowners is uncertain, but public outcry might press the issue should hurricanes on the scale of Katrina and Ike continue to strike densely populated areas. In the opinion of one weather researcher, “when people get themselves pounded into oblivion, they start talking to their representatives.”<sup>15</sup> Hopefully, it will not take another disaster for changes to take place.

In addition to domestic lawsuits, international politics will have to be addressed in order for weather modification experiments to go forward. The United States became a member of the

arms control treaty known as the *Convention on the Prohibition of Military or other Hostile Use of Environmental Modification Techniques* (ENMOD) in 1980. The treaty prohibits “military or any other hostile use of environmental modification techniques having widespread, long lasting, or severe effects as the means of destruction, damage, or injury to any other State Party.”<sup>16</sup> Any hurricane modification would have to be conducted openly and transparently; most likely in cooperation with other nations threatened by severe storms. A coalition of nations from South America, Central America, and the Caribbean would spread out risks, costs, and manpower while providing potential launching points for weather mitigation missions.

Similar organizations already exist. Sixteen Caribbean nations founded the Caribbean Disaster Emergency Response Agency (CDERA) in September 1991 to “make an immediate and coordinated response to any disastrous event affecting and Participating State, once the state requests such assistance.”<sup>17</sup> Meanwhile, United States Southern Command (USSOUTHCOM) works with eleven Central American and Caribbean nations for its Humanitarian Assistance and Disaster Preparedness Program (HAP) and includes sixteen disaster relief warehouses and pre-positioned supplies that can be used in response to a disaster. USSOUTHCOM’s disaster relief capability also includes Joint Task Force-Bravo (JTF-B) stationed at Soto Cano Air Base in Honduras. These organizations and relationships may provide the foundation and framework for a future weather modification effort comprised of several partner nations that respond proactively to mitigate hurricanes that threaten participating nations.

### **Arguments Against Hurricane Modification**

While this paper focuses on mitigating tropical cyclones, it is important to acknowledge and address the various arguments against modification. Who will provide proper oversight of weather (or hurricane) modification? Will the costs be too immense and outweigh the benefits of

modifying a hurricane? These are valid questions that will have to be addressed before any weather modification program is put in place. Yet, these arguments are rather minor compared to the large number of concerns regarding the environmental impact of messing with Mother Nature. To be completely clear, any technology that harms the environment in order to mitigate storms should not be considered a valid technology. Environmental impact studies will have to be conducted on any material to be placed on the ocean's surface or dispersed into the clouds. More than this, researchers will have to consider the second and third-order effects of modifying hurricanes.

Hurricanes perform several positive environmental actions and affecting the storms may adversely affect the environment. It is estimated that perhaps as much as 25% of rainfall in the southeastern U.S. comes from tropical storms and if that precipitation were cut off, "the results might be ruinous for farmers, industry, and drinking-water supplies."<sup>18</sup> Hurricanes also transfer heat from the tropics to colder latitudes and more evenly distribute heat over more of the earth's surface. If this heat were not transported, a massive build up of energy at the tropics could result in super hurricanes that would dwarf a Category-5. Finally, hurricanes churn and mix the ocean's waters and provide a physical mechanism that improves the environment. Researchers at Duke University have found that hurricanes are a key mechanism in rebuilding and replenishing beaches and the small barrier islands off the Atlantic coast. Sediment from the ocean floor is moved along by the churning waves and storm surge and deposited on shore. According to Professor Orrin H. Pilkey, "Barrier islands need hurricanes for their survival, especially at times of rising sea levels such as now. It's during hurricanes that islands get higher and wider."<sup>19</sup> Despite their destructive power, hurricanes are a critical part of our planet's atmospheric and environmental mechanics.

This is why this paper does not call for the *elimination* of hurricanes. While we should investigate the possibility of disrupting hurricanes and diminishing their destructive power, completely defeating hurricanes would almost certainly have far more disastrous results. Hurricanes are necessary. They improve the health of coral reefs, recycle our beaches, spread warmth across our planet, and provide much needed rain to our fields. However, a Category-1 storm can probably perform these functions as well as a Category-5 storm. Is it possible that we can continue to reap the benefits of hurricanes while limiting their destructive power? This will have to be one of the paramount questions, if not *the* most important question, for any future mitigation effort.



## CONCLUSIONS AND RECOMMENDATIONS

By 2030, the future of space-based directed energy and material science will make it possible for the USAF to diminish the strength of tropical cyclones. The three technologies discussed in this paper meet many of the criteria for employment and all have the potential to achieve the desired results. Space-Based Solar Power probably has the greatest likelihood of success, but it will be extremely costly and its employment is several decades away. The basic foundational technology exists today and with the rapidly increasing capability of computers and sensor equipment, this system could reach maturity by 2030 if the effort begins soon. Monolayers have significant drawbacks in terms of survivability, but the substantially lower cost and ease of deployment make evaporation suppression an extremely viable mitigation strategy. If the alcohol chains are combined with a different solvent that doesn't harm the environment and increases the self-repair capability of the monolayer, monolayer technology could reach maturity and be deployed at least a decade before SBSP. Finally, moisture absorbing materials are comparatively inexpensive and are available today. All that is required now is to take the next step in its development and begin independent laboratory and field testing. The degree and likelihood of success may not be as great as SBSP or monolayers, but the minimal development timeframe and proven deployment techniques place this technology at the front of the line for hurricane modification.

If these technologies are not successful, it is clear that there are a myriad of other avenues to pursue for hurricane mitigation. Reflective particles, ice crystals, or barges with jet engines may not be the answer, but they may lead us to the right answer. We will never know unless we

improve our forecasting, simulation, and modeling technology and establish the legal protections necessary to facilitate meaningful research.

After nearly 40 years since the last experiment on a hurricane, the government must consider both the advantages and disadvantages of hurricane mitigation. We must reevaluate our strategy of “run and hide” and take the opportunity to look for a proactive solution. The government should invest in advanced weather research and provide resources for the oversight and coordination of weather modification and mitigation. Finally, this is an area where the Air Force could provide significant advocacy and simultaneously develop a new mission area that combines various aspects of air, space, and cyberspace. By 2030, Air Force satellites and sensors in space could relay information about a tropical cyclone to computer networks which analyze the data and provide real-time, detailed mitigation instructions to pilots flying into the eye of the storm.

### **Scenario 5: “Going Back to Miami”**

The year is 2030. The evacuation of Miami progresses smoothly as motorists move their way northward to get out of the way of Hurricane Lisa. There is no panic and no despair. Parents comment to their children that “it wasn’t like this when *I* was your age.” At the various AF bases in Florida, pilots fly their planes confidently to pre-determined evacuation bases in North and South Carolina. The storm is sixteen hours out and, while the evacuees do move with urgency, there’s no frantic rush. This is because they have faith.

After failed attempts in 2005 and 2007, the United States Congress finally passed the Weather Mitigation Research Act in 2010.<sup>20</sup> In addition to apportioning a sufficient budget to conduct research and providing legal protection for weather modifiers, the act established a new agency under NOAA called the Weather Mitigation Research Agency (WMRA). Since 2010,

the mission of the WMRA has been to conduct advanced weather mitigation research and provide civilian oversight in the areas of cloud-seeding, hail suppression and mitigation of tornados, thunderstorms, and hurricanes. The WMRA works hand-in-hand with the Department of Defense and the Air Force who operate the majority of the various air, space, and cyberspace assets used in the weather mitigation missions. Additionally, the WMRA works very closely with United Nations Weather Relief Organization (UNWRO). UNWRO, formed in 2012, seeks to mitigate dangerous storms for coastal nations and use cloud-seeding to bring rain to the drought-stricken regions of the world. Finally, the WMRA is part of America's contribution to the North Atlantic Coalition (NAC) which consists of 19 member nations from throughout the Caribbean and Central America. Nearly all of WMRA's missions in the Atlantic are conducted as coalition missions with NAC member nations. When a hurricane is detected in the Atlantic it is tracked and monitored to see if it will become a viable threat. If a hurricane is deemed a viable threat, the nation where the hurricane will first make landfall is given the option for mitigation. In this case, the Bahamas will be hit approximately 4 hours before the United States, so the "go/no-go" decision on the mitigation mission is their call.

The first flight of aircraft from Muñiz Air National Guard Base in Puerto Rico arrive over the "kill zone" 300 miles to the east of the Bahamas approximately 12 hours before scheduled landfall and drop their containers of monolayer material. Simultaneously, microwaves from the SBSP-WM satellite in geo-synchronous orbit over the Atlantic ensure that the hurricane stays on track for the time being and passes through the desired "kill zone." If needed, the microwaves can alter the hurricane's track away from the Bahamas if the deployment of the monolayer is unsuccessful for some reason or the hurricane regains sufficient energy after passing through the "kill zone." Finally, should the now tropical storm regain its hurricane-level strength in the

warm waters between the Bahamas and Miami, a second flight of aircraft stand ready to dispense “SK-3000” over the storm and slow the surface wind speed.

The evacuees watch the news from their hotels in northern Florida and southern Georgia as Tropical Storm Lisa makes landfall twenty miles north of downtown Miami. The storm is still violent with torrential rains and powerful winds, but the storm surge reaches only nine feet. Key Biscayne, Fisher Island, and the twenty other small islands just off the coast suffer some moderate damage, but officials estimate repairs in southern Florida to take less than a month. The storm crosses over Florida just as forecasters said it would and continues across the Gulf of Mexico where it is monitored and mitigated again if necessary. Those who evacuated knew the storm would still be bad despite mitigation efforts and are glad they heeded the call to evacuate. That night they sleep peacefully confident that their houses are still standing and tomorrow they get to go home. This is one of many possible futures. Which shall we choose?

### Notes

<sup>1</sup> For more information on the original concept for using carbon dust, see Gray, William M. et al, "Weather Modification by Carbon Dust Absorption of Solar Energy." *Journal of Applied Meteorology* 15, (Jan 1976) [355-386]. For current new articles see “Boston-Area Scientists Study Controlling Hurricanes with Soot” at [www.ITWire.com](http://www.ITWire.com) and “Scientists a Step Closer to Steering Hurricanes” in *The Sunday Telegraph*, 21 October 2007.

<sup>2</sup> Telephone interview with Moshe Alamaro, 3 February 2009.

<sup>3</sup> Alamaro et al, “A Preliminary Assessment of Inducing Anthropogenic Tropical Cyclones Using Compressible Free Jets and the Potential for Hurricane Mitigation,” 82.

<sup>4</sup> *Ibid.*

<sup>5</sup> “Supercomputing in the US Senate Stimulus Bill” <http://insidehpc.com/2009/02/02/supercomputing-in-the-us-senate-stimulus-bill/> (accessed on 6 February 2009) For additional information, see the 4 March 2009 article, “NOAA Maps Stimulus Projects,” by Becky Evans at <http://www.southcoasttoday.com/apps/pbcs.dll/article?AID=2009903040327>.

<sup>6</sup> National Hurricane Center, “National Hurricane Center Forecast Verification” <http://www.nhc.noaa.gov/verification> (accessed on 20 March 2009)

<sup>7</sup> House et al, “Weather as a Force Multiplier: Owning the Weather in 2025,” vi.

<sup>8</sup> Wood, “Riders On the Storm,” 1.

<sup>9</sup> *Ibid.*, 2.

## Notes

<sup>10</sup> U.S. Const. amend. V, cl. 4.

<sup>11</sup> Telephone interview with Virginia L. Brady, Attorney, Property Law Firm, LLC, Overland Park, KS, 24 March 2009.

<sup>12</sup> Lectric Law, "Sovereign Immunity," *www.lectlaw.com* (accessed on 11 March 2009).

<sup>13</sup> Lectric Law, "Tucker Act," *www.lectlaw.com* (accessed on 11 March 2009).

<sup>14</sup> Interview with Virginia Brady, 24 March 2009. This is a particularly important point. After Hurricane Katrina, several insurance companies agreed to pay claims for roofs blown off by the storm, but did not consider the flooding from the broken levees as an "act of God" but as an "act of man" and refused to pay the claims. This resulted in many homeowners receiving only a fraction of the value of their destroyed homes. For more information on the flood of lawsuits against the insurance companies that followed, see "Insurance Woes for Katrina Homeowners", 20 Feb 2007, at *ABC News*, <http://abcnews.go.com/GMA/story?id=2888654> and "Court Vacates Part of Katrina Insurance Case Award", 12 March 2009, *Yahoo! News*, [http://news.yahoo.com/s/ap/20090312/ap\\_on\\_bi\\_ge/katrina\\_state\\_farm\\_1](http://news.yahoo.com/s/ap/20090312/ap_on_bi_ge/katrina_state_farm_1)

<sup>15</sup> *Ibid*, 2.

<sup>16</sup> CJCSI 3801.01, *Meteorological and Oceanographic Operations*, C-1.

<sup>17</sup> CDERA, "About Us," *www.cdera.org* (accessed on 2 March 2009).

<sup>18</sup> Time, "The Benefits of Hurricanes," 24 September 1973.

<sup>19</sup> Duke University, "Hurricanes Bring Benefits to Barrier Islands and Beaches," 13 September 2004.

<sup>20</sup> DiLorenzo, "Weather Modification Law and Technology in the United States," *University of Pittsburgh Journal of Technology Law and Policy*, 15 January 2008 [http://tlp.law.pitt.edu/SP\\_DiLorenzo\\_Weather%20Modification.htm](http://tlp.law.pitt.edu/SP_DiLorenzo_Weather%20Modification.htm) (accessed on 22 March 2009). U.S. Senate Bill 517 and U.S. House Bill 2995 were two laws proposed in 2005. Both sought to support weather modification and establish a Weather Modification Operations and Research Board. U.S. Senate Bill 1807 and U.S. House Bill 3445 were identical bills introduced on July 17, 2007. They proposed to establish a Weather Mitigation Advisory and Research Board to federally fund weather modification research with an annual budget of \$10 million. All four bills failed to become law. At the time of publication in April 2009, a bill to establish a Weather Mitigation Research Office had been introduced to the Commerce Committee of the United States Senate.

## APPENDIX A

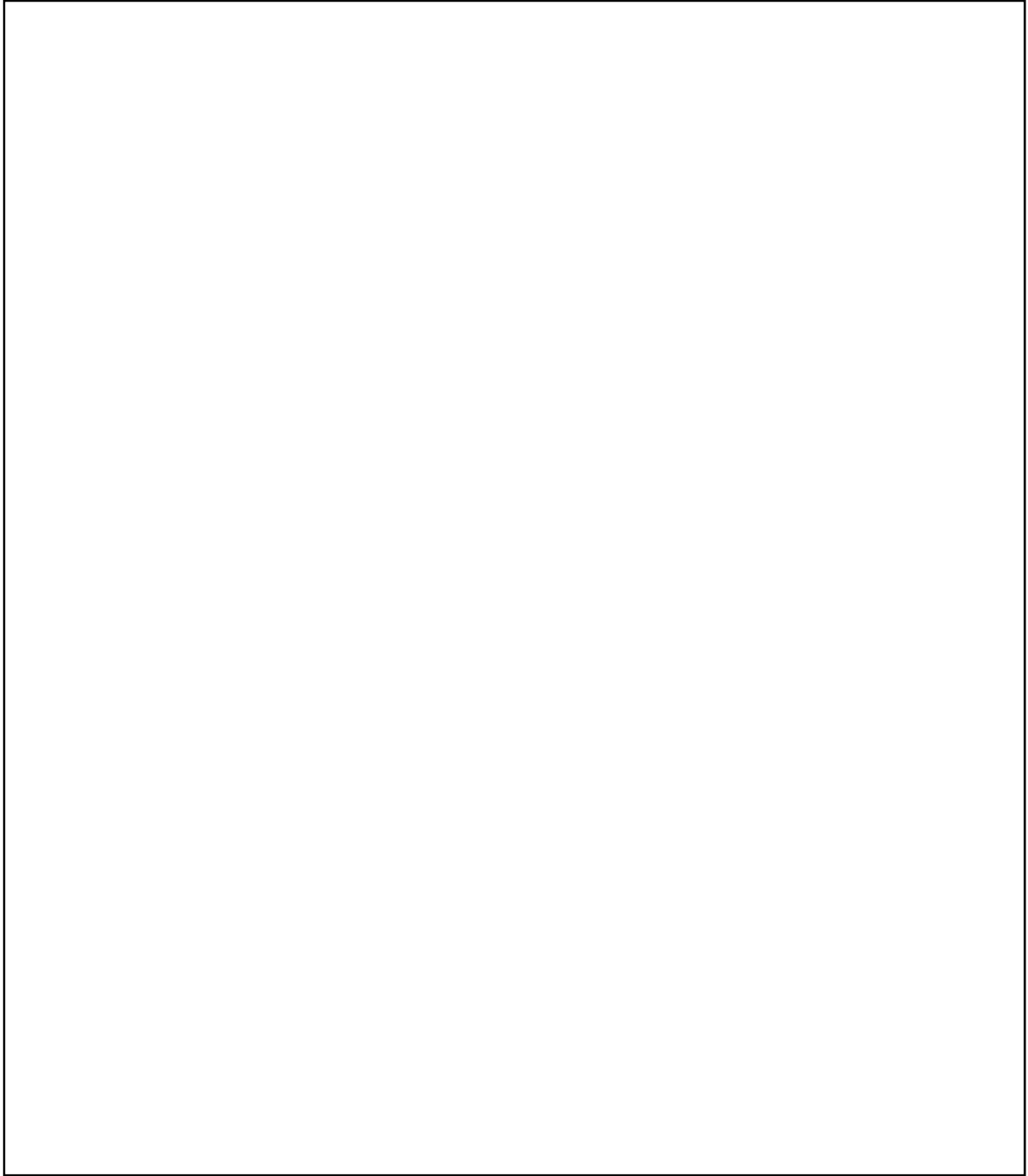


Figure 11: Tropical Cyclones, 1945-2006

The photo above, used with permission from Citynoise, displays all of the tracks and intensities for all of the tropical storms and tropical cyclones from 1945 to 2006. It is a compilation of data from the Joint Typhoon Warning Center and the U.S. National Oceanographic and Atmospheric Administration. It clearly shows the three hurricane “nurseries” and the band in the southern hemisphere where the majority of tropical cyclones begin. The map also reveals the amount of coastline worldwide threatened by tropical cyclones. This is a global threat.

## APPENDIX B

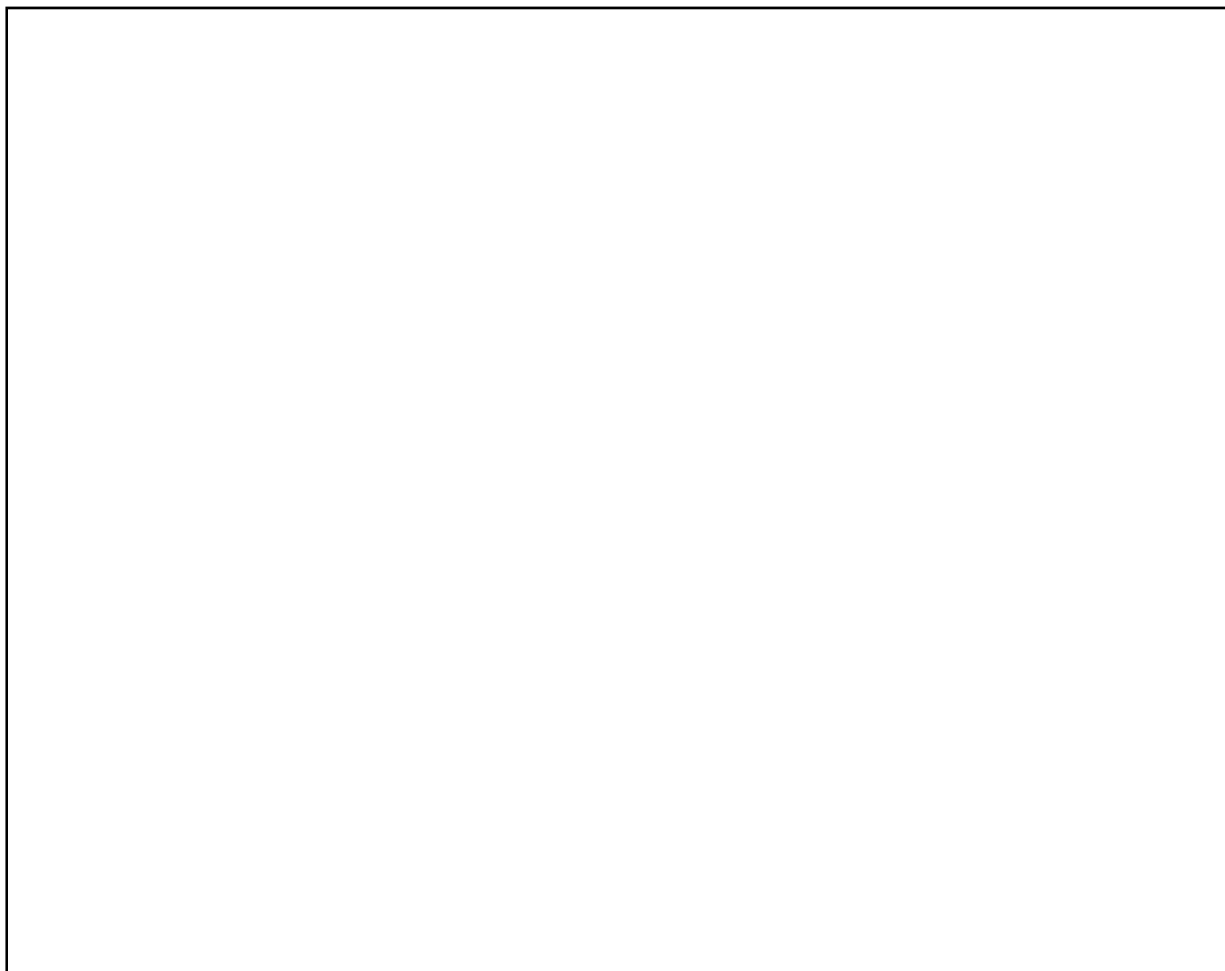


Figure 12: Annual Average Track Errors for Atlantic Storms

These graphs are the cumulative error data from NOAA's National Hurricane Center. More can be found at <http://www.nhc.noaa.gov/verification>.

From the NHC Website:

For all operationally-designated tropical cyclones in the Atlantic and eastern North Pacific basins, the NHC issues "official" forecasts of the cyclone's center position and maximum 1-min surface wind speed. These forecasts are issued every 6 hours (at 0300, 0900, 1500, and 2100 UTC), and each contains projections valid 12, 24, 36, 48, 72, 96, and 120 h after the forecast's nominal initial time (0000, 0600, 1200, and 1800 UTC, respectively). These forecasts can be found in two of NHC's public products, the Tropical Cyclone Forecast/Advisory and the Tropical Cyclone Discussion.





Figure 13: Average Intensity (Wind Speed) Errors for Atlantic Hurricanes

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