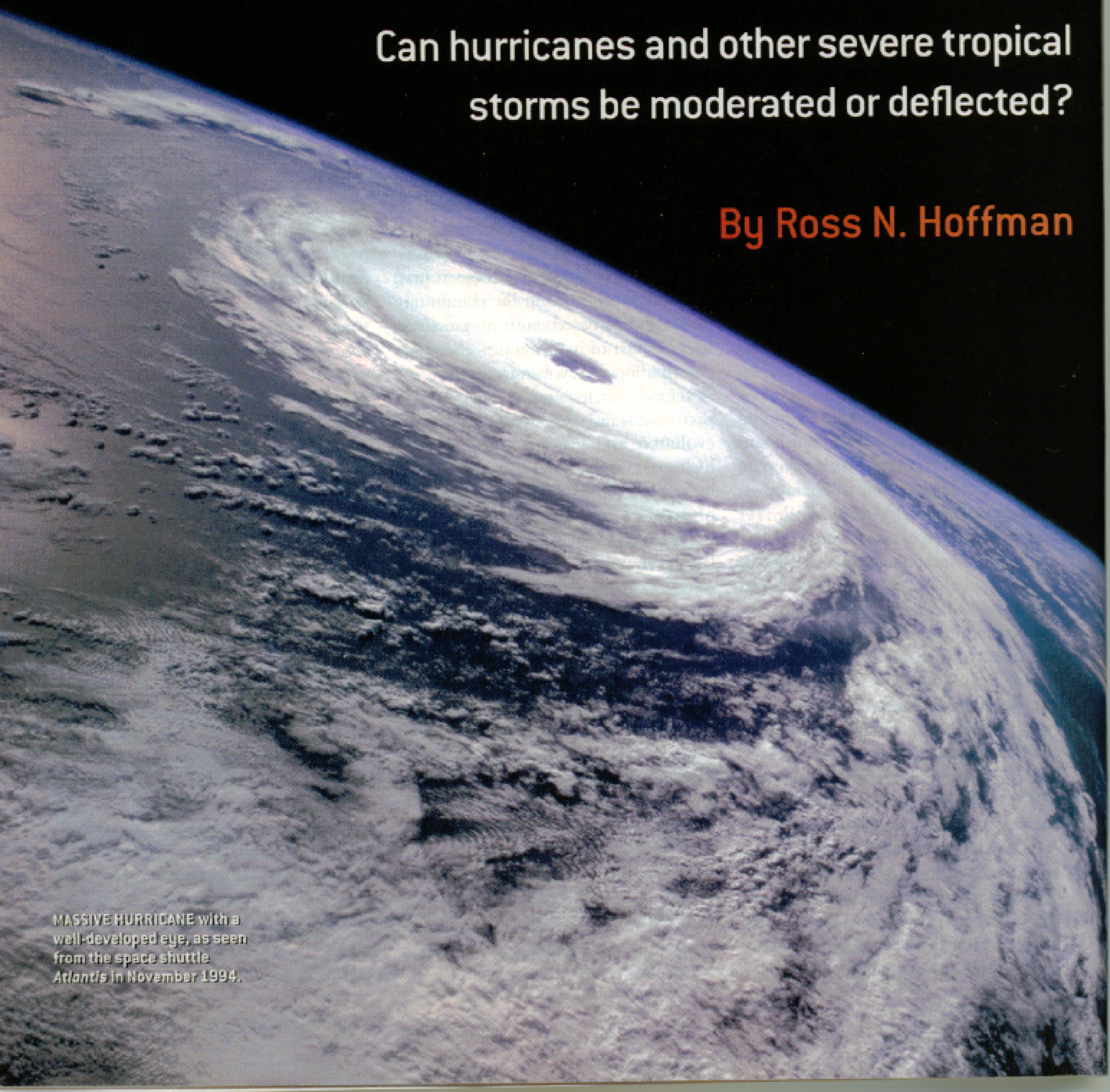
Controlling Hurricanes

Can hurricanes and other severe tropical storms be moderated or deflected?

By Ross N. Hoffman



MASSIVE HURRICANE with a well-developed eye, as seen from the space shuttle *Atlantis* in November 1994.

Every year huge rotating storms packing winds greater than 74 miles per hour sweep across tropical seas

and onto shorelines—often devastating large swaths of territory. When these roiling tempests—called hurricanes in the Atlantic and the eastern Pacific oceans, typhoons in the western Pacific and cyclones in the Indian Ocean—strike heavily populated areas, they can kill thousands and cause billions of dollars of property damage. And nothing, absolutely nothing, stands in their way.

But must these fearful forces of nature be forever beyond our control? My research colleagues and I think not. Our team is investigating how we might learn to nudge hurricanes onto more benign paths or otherwise defuse them. Although this bold goal probably lies decades in the future, we think our results show that it is not too early to study the possibilities.

To even consider controlling hurricanes, researchers will need to be able to predict a storm's course extremely accurately, to identify the physical changes (such as alterations in air temperature) that would influence its behavior, and to find ways to effect those changes. This work is in its infancy, but successful computer simulations of hurricanes carried out during the past few years suggest that modification could one day be feasible. What is more, it turns out the very thing that makes forecasting any weather difficult—the atmosphere's extreme sensitivity to small stimuli—may well be the key to achieving the control we seek. Our first attempt at influencing the course of a simulated hurricane by making minor changes to the storm's initial state, for example, proved remarkably successful, and the subsequent results have continued to look favorable, too.

To see why hurricanes and other severe tropical storms may be susceptible to human intervention, one must understand their nature and origins [*see box on next two pages*]. Hurricanes grow as clusters of thunderstorms over the tropical oceans. Low-latitude seas continuously provide heat and moisture to the atmosphere, producing warm, humid air above the sea surface. When this air rises, the water vapor in it condenses to form clouds and precipitation. Condensation releases heat—the solar heat it took to evaporate the water at the ocean surface. This so-called latent heat of condensation makes the air more buoy-

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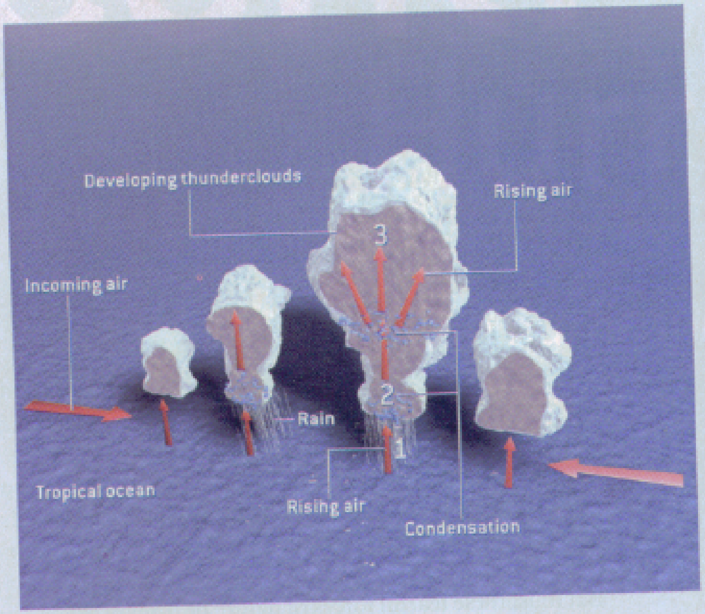
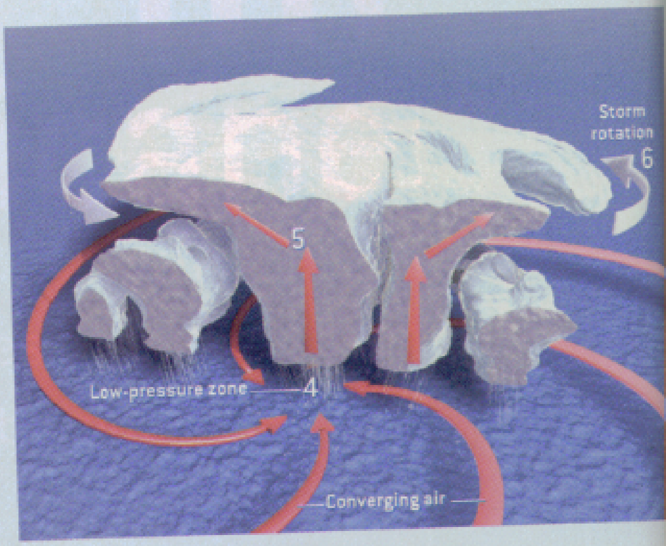
ANATOMY OF A HURRICANE

Some scientists believe that they may be able to weaken or move hurricanes onto less dangerous tracks by altering the initial physical conditions [the air temperature or humidity, for example] in the center of the storm or even in the surrounding areas. To succeed, they need to make accurate and detailed forecasts of hurricanes. Here are the outlines of how these powerful storms arise.



Hurricanes start to form when tropical oceans release heat and water into the atmosphere, producing large amounts of warm, humid air above the surface [1]. Warm air rises, and as it does so, the water vapor in it condenses to form clouds and rain [2]. This condensation produces heat, causing air in the developing thunderclouds to climb still farther [3].



The release of heat above the tropical seas creates a surface low-pressure zone, where additional warm, moist air from the outer perimeter converges [4]. This continuous movement into the burgeoning thunderstorm shifts hu amounts of heat, air and water skyward [5]. This upward transfer and relea of heat further enhance the convergence of surrounding air toward the growing storm center, which starts to circulate under the influence of the earth's rotation [6]. The process continues apace, strengthening and organizing the storm.

ant, causing it to ascend still higher in a self-reinforcing feedback process. Eventually, the tropical depression begins to organize and strengthen, forming the familiar eye—the calm central hub around which a hurricane spins. On reaching land, the hurricane's sustaining source of warm water is cut off, which leads to the storm's rapid weakening.

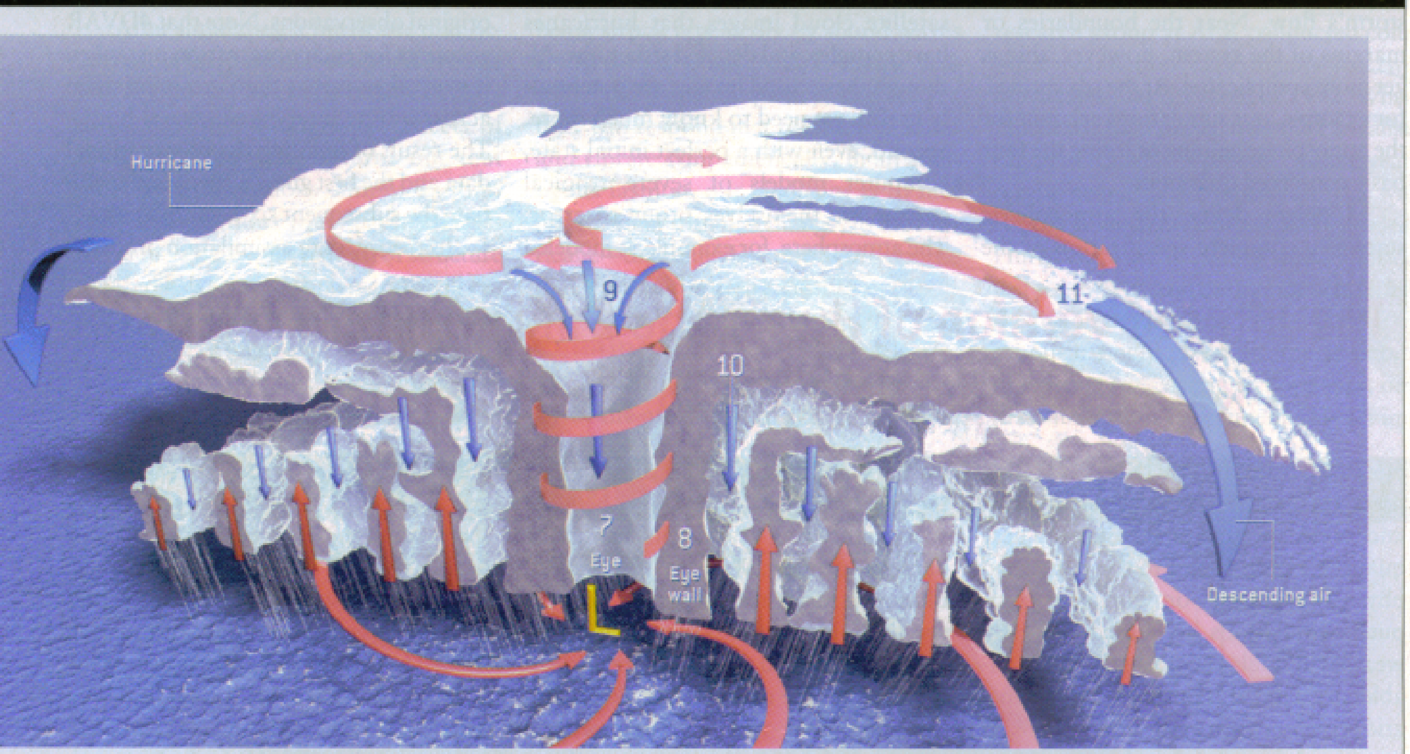
Dreams of Control

BECAUSE A HURRICANE draws much of its energy from heat released when water vapor over the ocean condenses into clouds and rain, the first researchers to dream of taming these unruly giants focused on trying to alter the condensation process using cloud-seeding techniques—then the only practical way to try to affect weather. In the early 1960s a U.S. government-appointed scientific advisory panel named Project Stormfury performed a series of courageous (or perhaps foolhardy) experiments to determine whether that approach might work.

Project Stormfury aimed to slow the development of a hurricane by augmenting precipitation in the first rain band outside the eye wall—the ring of clouds and high winds that encircle the eye [see "Experiments in Hurricane Modification," by R. H. Simpson and Joanne S. Malkus; SCIENTIFIC AMERICAN, December 1964]. They attempted to accomplish this goal by seeding the clouds there with silver iodide particles dispersed by aircraft, which would serve as nuclei for the formation of ice from water vapor that had been supercooled after rising to the highest, coldest reaches of the storm. If all went as envisioned, the clouds would grow more quickly, consuming the supplies of warm, moist air near the ocean surface, thus replacing the old eye wall. This process

Overview/*Taming Hurricanes*

- Meteorological researchers are simulating past hurricanes using sophisticated weather-forecasting models that closely reproduce the complex internal processes crucial to the development and evolution of severe tropical storms.
- The work confirms that these massive, chaotic systems are susceptible to minor changes in their initial conditions—for instance, the air temperature and humidity near the center of the storm and in the surrounding regions.
- Using complex mathematical optimization techniques, the researchers are learning what modifications to a hurricane could weaken its winds or divert it from populated areas.
- If these theoretical studies are ultimately successful, they should point the way toward practical methods for intervening in the life cycle of hurricanes to protect life and property.



s the storm intensifies, an eye—a calm, low-pressure hub—typically forms
7]. The eye is encircled by a ring of clouds and high winds called the eye wall
8]. The storm has become a hurricane. At the same time, the rising air, now
eated and having lost much of its moisture, can rise no further, because the stratosphere acts like a lid above the hurricane. Some of this dry air falls into the eye (9) and between the cloud bands (10), while the remainder spirals away from the storm center and descends (11). Meanwhile large-scale air currents nearby steer the hurricane along its path.

would then expand the radius of the eye, lessening the hurricane's intensity in a manner akin to a spinning skater who extends her arms to slow down.

The Stormfury results were ambiguous at best. Meteorologists today do not expect this particular application of cloud seeding to be effective in hurricanes because, contrary to the early beliefs, the storms contain little supercooled water vapor.

Chaotic Weather

OUR CURRENT STUDIES grew out of an intuition I had 30 years ago when I was a graduate student learning about chaos theory. A chaotic system is one that appears to behave randomly but is, in fact, governed by rules. It is also highly sensitive to initial conditions, so that seemingly insignificant, arbitrary inputs can have profound effects that lead quickly to unpredictable consequences. In the case of hurricanes, small changes in such features as the ocean's temperature, the location of the large-scale wind currents (which drive the storms' movements), or even the shape of the rain clouds spinning around the eye can strongly influence a hurricane's potential path and power.

The atmosphere's great sensitivity to tiny influences—and the rapid compounding of small errors in weather-forecasting models—is what makes long-range forecasting (more than five days in advance) so difficult. But this sensitivity also made me wonder whether slight, purposely applied inputs to a hurricane might generate powerful effects that could influence the storms, whether by steering them away from population centers or by reducing their wind speeds.

I was not able to pursue those ideas back then, but in the past decade computer simulation and remote-sensing technologies have advanced enough to renew my interest in large-scale weather control. With funding support from the NASA Institute for Advanced Concepts, my co-workers and I at Atmospheric and Environmental Research (AER), an R&D consulting firm, are employing detailed computer models of hurricanes to try to identify the kinds of actions that might eventually be attempted in the real world. In particular, we use weather-forecasting technology to simulate the behavior of past hurricanes and then test the effects of various interventions by observing changes in the modeled storms.

Modeling Chaos

EVEN TODAY'S BEST weather prediction computer models leave much to be desired when it comes to forecasting, but with effort they can be useful for modeling these storms. The models depend on numerical methods that simulate a storm's complex development process by computing the estimated atmospheric conditions in brief, successive time steps. Numerical weather prediction calculations are based on the assumption that within the atmosphere there can be no creation or destruction of mass, energy, momentum and moisture. In a fluid system like a hurricane, these conserved quantities are carried along with the storm's flow. Near the boundaries or margins of the system, however, things get more complicated. At the sea surface, for example, our simulations account for the atmosphere gaining or losing the four basic conserved quantities.

Modelers define the atmospheric state as a complete specification of the measurable physical variables, including pressure, temperature, relative humidity, and wind speed and direction. These quantities correspond to the conserved physical properties on which the computer simulations are based. In most weather models these observable variables are defined on a three-dimensional grid representation of the atmosphere, so one can plot a map of each property for each elevation. Modelers call the collection of values of all the variables at all the grid points the model state.

To generate a forecast, a numerical weather prediction model repeatedly advances the model state from one instant through a small time step (a few seconds to a few minutes depending on the scales of motion resolved by the model). It calculates the effects during each time step of winds carrying along the various atmospheric properties and of the processes of evaporation, rainfall, surface friction, infrared cooling and solar heating that occur in the area of interest.

Unfortunately, meteorological forecasts are imperfect. In the first place, the beginning model state is always incomplete and inexact. Initial states for hurricanes are particularly difficult to define because direct observations are few and difficult to make. Yet we do know from satellite cloud images that hurricanes have complex and detailed structures. Although these cloud images are potentially useful, we need to know much more. Second, even with a perfect initial state, computer models of severe tropical storms are themselves prone to error. The atmosphere, for example, is modeled only at a grid of points. Features smaller than the grid length, the distance between two neighboring grid points, cannot be handled correctly. Without very high resolution, a hurricane's structure near the eye wall—its most important feature—is smoothed out and the details are unclear. In addition, the models, just like the atmosphere they simulate, behave in a chaotic fashion, and inaccuracies from both these error sources grow rapidly as the forecast computations proceed.

Despite its limitations, this technology is still valuable for our purposes. We have modified for our experiments a highly effective forecast initialization system called four-dimensional variational data assimilation (4DVAR). The fourth dimension to which the name refers is time. Researchers at the European Center for Medium-Range Weather Forecasts, one of the world's premier meteorological centers, use this sophisticated technique to predict the weather every day. To make best use of all the observations collected by satellites, ships, buoys and airborne sensors before the forecast begins, 4DVAR combines these measurements with an educated first guess of the initial atmospheric state—a process called data assimilation. This first guess is usually a six-hour forecast valid at the time of the original observations. Note that 4DVAR accounts for each observation just when it was taken rather than grouping them across a time interval of several hours. The result of merging the observational data and the first guess is then used to initiate the subsequent six-hour forecast.

The altered version of Hurricane Iniki veered off, so that Kauai escaped the storm's most damaging winds.

In theory, data assimilation produces an optimal approximation of the weather in which the fit of the model's representation to the observations is balanced against its fit to the first guess. Although the statistical theory for this problem is clear, the assumptions and information needed for its proper application are only approximate. As a result, practical data assimilation is part art and part science.

Specifically, 4DVAR finds the atmospheric state that satisfies the model equations and that is also close to both the first guess and the real-world observations. It accomplishes this difficult task by back-adjusting the original model state at the start of the six-hour interval according to the difference between observations and model simulation made during that period. In particular, 4DVAR employs these differences to calculate the model's sensitivity—how small changes in each of the parameters would affect the degree to which the simulation fit the observations. This computation, using the so-called adjoint model, runs backward in time over the six-hour interval. An optimization program then chooses the best adjustments to make to the original model state to achieve a simulation that most closely matches the progress of the actual hurricane during the six-hour period.

Because this adjustment is made using an approximation of the model equations, the entire process—the simulation, the comparisons, the adjoint model and the optimization—must be repeated again and again to fine-tune the results. When the process is complete, the conditions of the simulation at the end of the

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six-hour period then supplies the first guess for the next six-hour interval.

After simulating a hurricane that occurred in the past, we can then change one or more of its characteristics at any given time and examine the effects of these perturbations. It turns out that most such alterations simply die out. Only interventions with special characteristics—a particular pattern or structure that induces self-reinforcement—will develop sufficiently to have a major effect on a storm. To get an idea of what this means, think of a pair of tuning forks, one vibrating, the other stationary. If the forks are tuned to different frequencies, the second fork does not move, despite being struck repeatedly by sound waves emitted by the first. But if the devices share the same frequency, the second fork will respond in a resonant manner and vibrate sympathetically. In an analogous fashion, our challenge is to find just the right stimuli—changes to the hurricane—that will yield a robust response that leads to the desired results.

Calming the Tempest

TO EXPLORE WHETHER the sensitivity of the atmospheric system could be exploited to modify atmospheric phenomena as powerful as hurricanes, our research group at AER conducted computer simulation experiments for two hurricanes that occurred in 1992. When Hurricane Iniki passed over the Hawaiian island of Kauai in September of that year, several people died, property damage was enormous and entire forests were leveled. Hurricane Andrew, which struck Florida just south of Miami the month before, left the region devastated.

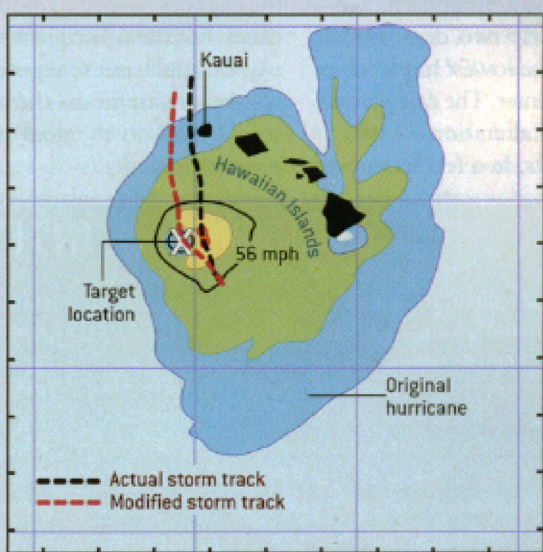
Surprisingly, given the imperfections of existing forecasting technologies, our first simulation experiment was an im-

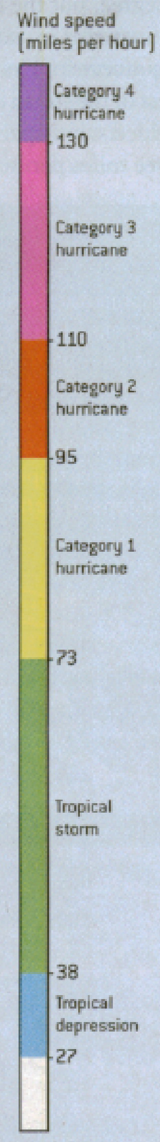
CONTROL OF SIMULATED HURRICANES

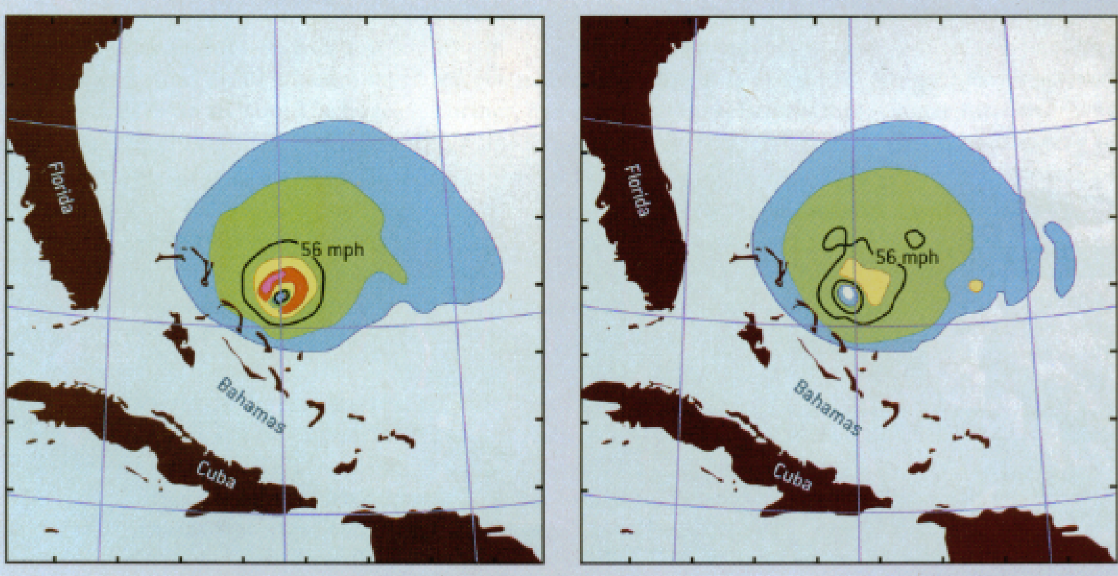
Researchers are using computer models to simulate two destructive 1992 hurricanes, Iniki and Andrew. The colors represent wind-velocity categories, whereas black contour lines indicate gales of 56 miles per hour, generally the lowest wind speed that produces damage.

In the simulations of Iniki (*right*), the original track of the eye (*black dotted line*) takes the storm's high winds onto the Hawaiian island of Kauai. But when several of the model's initial conditions, including its temperature and humidity at various points, were altered slightly, the simulated storm track (*red dotted line*) veered to the west of Kauai, passing over a target location some 60 miles away. It then continued northward, moving farther west of the island.

The maps of the seas off Florida and the Bahamas below depict simulations of Andrew in its unaltered state (*left*) and in an artificially perturbed (*right*) form. Although damaging winds remain in the controlled case, maximum velocities have been reduced significantly, thus calming a Category 3 hurricane to a much milder Category 1 state.







mediate success. To alter the path of Iniki, we first chose where we wanted the storm to end up after six hours—about 60 miles west of the expected track. Then we used this target to create artificial observations and fed these into 4DVAR. We set the computer to calculate the smallest change to the initial set of the hurricane's key defining properties that would yield a track leading to the target location. In this early experiment we permitted any kind of possible artificial alteration to the storm system to take place.

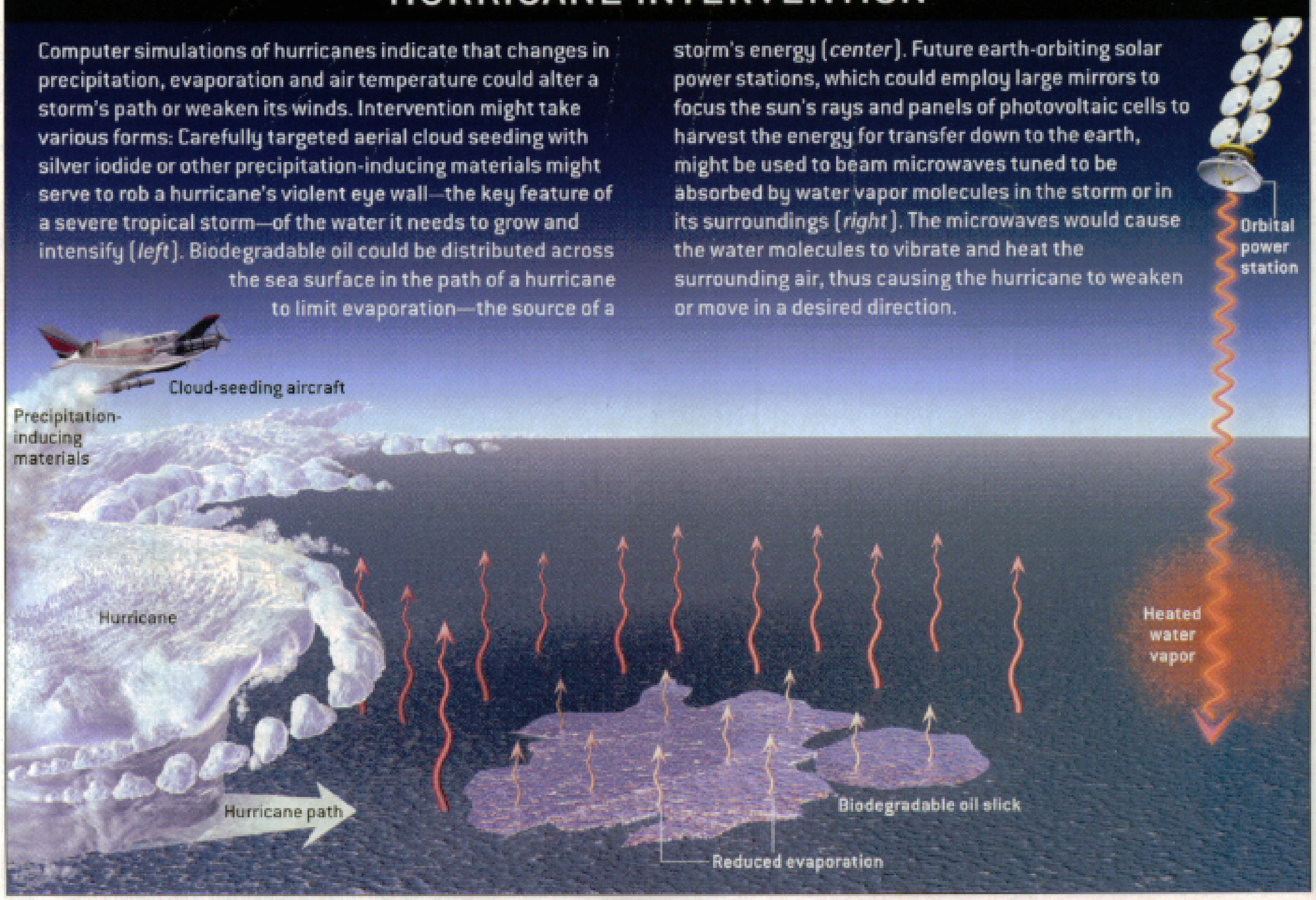
The most significant modifications proved to be in the starting temperatures and winds. Typical temperature adjustments across the grid were mere tenths of a degree, but the most notable change—an increase of nearly two degrees Celsius—occurred in the lowest model layer west of the storm center. The calculations yielded wind-speed alterations of two or three miles per hour. In a few locations, though, the velocities changed by as much as 20 mph because of minor redirections of the winds near the storm's center.

Although the original and altered versions of Hurricane Iniki looked nearly identical in structure, the changes in the key variables were large enough that the latter veered off to the west for the first six hours of the simulation and then traveled due north, so that Kauai escaped the storm's most damaging winds. The relatively small, artificial alterations to the storm's initial conditions had propagated through the complex set of nonlinear equations that simulated the storm to result in the desired relocation after six hours. This run gave us confidence that we were on the right path to determining the changes needed to modify real hurricanes. For the subsequent hurricane simulation trials, our team used higher grid resolutions to model the hurricane and set 4DVAR to the goal of minimizing property damage.

In one experiment using the modified code, we calculated the temperature increments needed to limit the surface wind damage caused by Hurricane Andrew as it hit the Florida coast. Our goal was to keep the initial temperature perturbation to a minimum (to make it as easy to accomplish as possible in real life) and to curtail the most destructive winds over the last two hours of the first six-hour interval. In this trial, 4DVAR determined that the best way to limit wind damage would be to make the greatest modifications to the beginning temperature near the storm's eye. Here the simulation produced changes as large as two or three degrees C at a few locations. Smaller temperature alterations (less than 0.5 degree C) extended out 500 to 600 miles from the eye. These perturbations feature a wavelike pattern of alternating rings of heating and cooling centered on the hurricane. Although only temperature had been changed at the start, all key variables were

HURRICANE INTERVENTION

Computer simulations of hurricanes indicate that changes in precipitation, evaporation and air temperature could alter a storm's path or weaken its winds. Intervention might take various forms: Carefully targeted aerial cloud seeding with silver iodide or other precipitation-inducing materials might serve to rob a hurricane's violent eye wall—the key feature of a severe tropical storm—of the water it needs to grow and intensify (*left*). Biodegradable oil could be distributed across the sea surface in the path of a hurricane to limit evaporation—the source of a storm's energy (*center*). Future earth-orbiting solar power stations, which could employ large mirrors to focus the sun's rays and panels of photovoltaic cells to harvest the energy for transfer down to the earth, might be used to beam microwaves tuned to be absorbed by water vapor molecules in the storm or in its surroundings (*right*). The microwaves would cause the water molecules to vibrate and heat the surrounding air, thus causing the hurricane to weaken or move in a desired direction.



soon affected. In the case of the original simulated hurricane, damaging winds (greater than about 56 mph) covered populated areas in South Florida by the end of six hours, but in the altered model run, they did not do so.

As a test of the robustness of these results, we applied the same perturbation to a more sophisticated, higher-resolution version of the model. We obtained very similar results, which show that our experiments are reasonably insensitive to our particular choice of model configuration. After six hours, however, damaging winds reappeared in the altered simulation, so additional interventions would have been required to keep South Florida safe. Indeed, it looks as if a series of planned disturbances would be required to control a hurricane for any length of time.

Who Can Stop the Rain?

IF IT IS TRUE, as our results suggest, that small changes in the temperature in and around a hurricane can shift its path in a predictable direction or slow its winds, the question becomes, How can such perturbations be achieved? No one, of course, can alter the temperature throughout something as large as a hurricane instantaneously. It might be possible, however, to heat the air around a hurricane and thus adjust the temperature over time.

Our team plans to conduct experiments in which we will calculate the precise pattern and strength of atmospheric heating needed to moderate hurricane intensity or alter its track. Undoubtedly, the energy required to do so would be huge, but an array of earth-orbiting solar power stations could eventually be used to supply sufficient energy. These power-generating satellites might use giant mirrors to focus sunlight on solar cells and then beam the collected energy down to microwave receivers on the ground. Current designs for space solar power stations would radiate microwaves at frequencies that pass through the atmosphere without heating it, so as to not waste energy. For weather control, however, tuning the microwave downlink to frequencies better absorbed by water vapor could heat different levels in the atmosphere as desired. Because raindrops strongly absorb microwaves, parts of the hurricane inside and beneath rain clouds would be shielded and so could not be heated in this way.

In our previous experiments, 4DVAR determined large temperature changes just where microwave heating could not work, so we ran an experiment in which we forced the temperature in the center of the hurricane to remain constant during our calculation of the optimal perturbations. The final results resembled those of the original, but to compensate for making no initial temperature changes in the storm center the remaining temperature changes had to be larger. Notably, temperature changes developed rapidly near the storm center during the simulation.

Another potential method to modify severe tropical storms would be to directly limit the availability of energy by coating the ocean surface with a thin film of a biodegradable oil that slows evaporation. Hurricanes might also be influenced by introducing gradual modifications days in advance of their approach and thousands of miles away from their eventual targets. By altering air pressure, these efforts might stimulate changes in the large-scale wind patterns at the jet-stream level, which can have major effects on a hurricane's intensity and track. Further, it is possible that relatively minor alterations to our normal activities—such as directing aircraft flight plans to precisely position contrails and thus increase cloud cover or varying crop irrigation practices to enhance or decrease evaporation—might generate the appropriate starting alterations.

Small changes can strongly influence a hurricane's potential path and power.

What if Control Works?

IF METEOROLOGICAL control does turn out to work at some point in the future, it would raise serious political problems. What if intervention causes a hurricane to damage another country's territory? And, although the use of weather modification as a weapon was banned by a United Nations Convention in the late 1970s, some countries might be tempted.

Before those kinds of concerns arise, however, our methods would need to be proved on atmospheric phenomena other than hurricanes. In fact, we believe our techniques should first be tried out in an effort to enhance rainfall. This approach could then serve as a test bed for our concepts in a relatively small region that could be instrumented densely with sensors. For such reduced size scales, perturbations could be introduced from aircraft or from the ground. If our understanding of cloud physics, computer simulation of clouds and data assimilation techniques advance as quickly as we hope, these modest trials could be instituted in perhaps 10 to 20 years. With success there, larger-scale weather control using space-based heating may become a reasonable goal that nations around the globe could agree to pursue. ■

MORE TO EXPLORE

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NOAA's Hurricane Research Division: **www.aoml.noaa.gov/hrd/tcfaq**

Ross N. Hoffman's technical presentations on weather modification can be found at **www.niac.usra.edu/studies/**