Stalking the Weather Bombs

Last winter, scientists enlisted an extensive array of instruments to hunt and record the atmospheric patterns that, with little warning, explode into paralyzing storms along the East Coast

By STEFI WEISBURD

It started out as a relatively innocuous storm system off the Carolina coast on the morning of Feb. 18, 1979. By late that evening, it had mushroomed into what some meteorologists call a bomb — a cyclonic fury, hundreds of kilometers wide, that develops in less than a day.

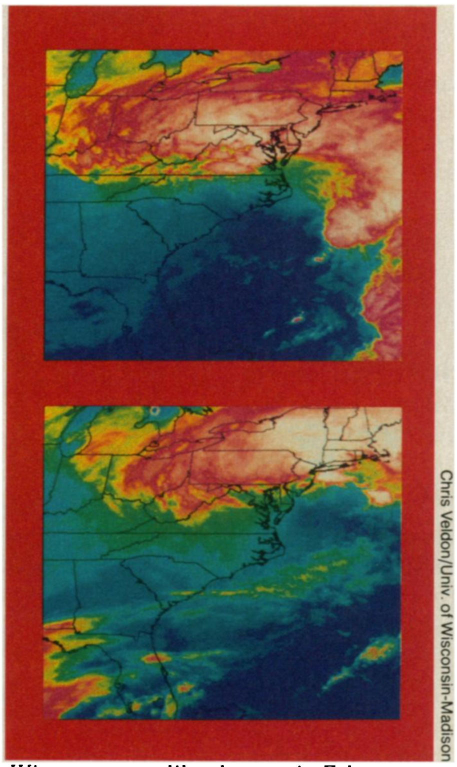
By the end of the next day, the storm had immobilized mid-Atlantic cities with up to 20 inches of snow. It was the largest storm to strike Washington, D.C., since 1922, and because it fell on President's Day weekend, it spelled economic disaster for merchants who had been expecting a shopping surge during the federal holiday. In Baltimore the storm made national headlines when the police were unable to prevent looting because the snow, falling at up to 4 inches per hour, had completely buried their cars.

Not one forecasting model had predicted the severity of the President's Day storm. Meteorologists had thought the weak system would simply move out over the ocean, dumping at most several inches of snow on the Washington-Baltimore region.

The President's Day storm is only one of many East Coast winter storms for which forecasting has been cloudy. These storms, swirling around regions of low atmospheric pressure, can affect more than 30 million people and are responsible for $1 billion in property damage each year, according to the National Center for Atmospheric Research in Boulder, Colo.

"It's become fairly obvious that the numerical models used to forecast these events have major deficiencies," says meteorologist Louis Uccellini at NASA Goddard Space Flight Center in Greenbelt, Md. "We need a better understanding of what's going on in order to improve our ability to forecast these storms."

With that aim in mind, Uccellini and 200 other scientists, engineers and technicians gathered from January to March at the Raleigh-Durham (N.C.) airport for the Genesis of Atlantic Lows Experiment (GALE). In terms of numbers of scientists, radar instruments and aircraft, GALE was the largest field experiment on winter storms ever conducted in the United States. The primary purpose of the $10 million program was to record and dissect the symphony of atmospheric and oceanic motions that come together in cyclogenesis — the making of a storm — along the Carolina coast, paying special attention to how small storms become major ones.



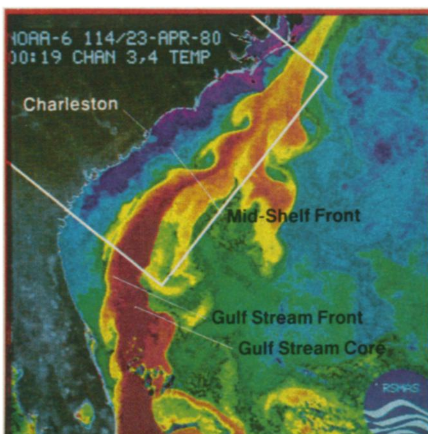
Winter storms, like the one in February 1983 shown here, have been particularly difficult to forecast, partly because they develop so rapidly. These two satellite images show the last 24 hours of the sequence begun on the cover.

Chris Veldon/Univ. of Wisconsin-Madison

Their instruments included 50 portable ground stations, radar and lightning networks, and weather balloons launched every three hours — four times more frequently than the National Weather Service's normal schedule. With this extensive array, the GALE researchers hoped to cast a finer-than-usual observational net to catch the relatively small, "mesoscale" weather features that occur on scales of about 200 to 2,000 kilometers and develop over a period of about 1 to 24 hours.

Unlike the "synoptic-scale" weather features, which span 5,000 km and operate on time scales of a couple of days, mesoscale processes have been poorly understood and poorly modeled, although numerical models have hinted at their existence and importance. This is largely because measurements by the normal weather-observation network are taken much too infrequently and from sites too far apart to detect mesoscale changes. But these processes may be very powerful forces in weather development, especially in places like the Carolina coast.

"What's happening now in meteorology," says Robert Grossman, an atmospheric scientist at the University of Colorado at Boulder, "is that small entities that cover large areas may have a bigger influence than a lot of the larger systems, like hurricanes, that have been well studied."

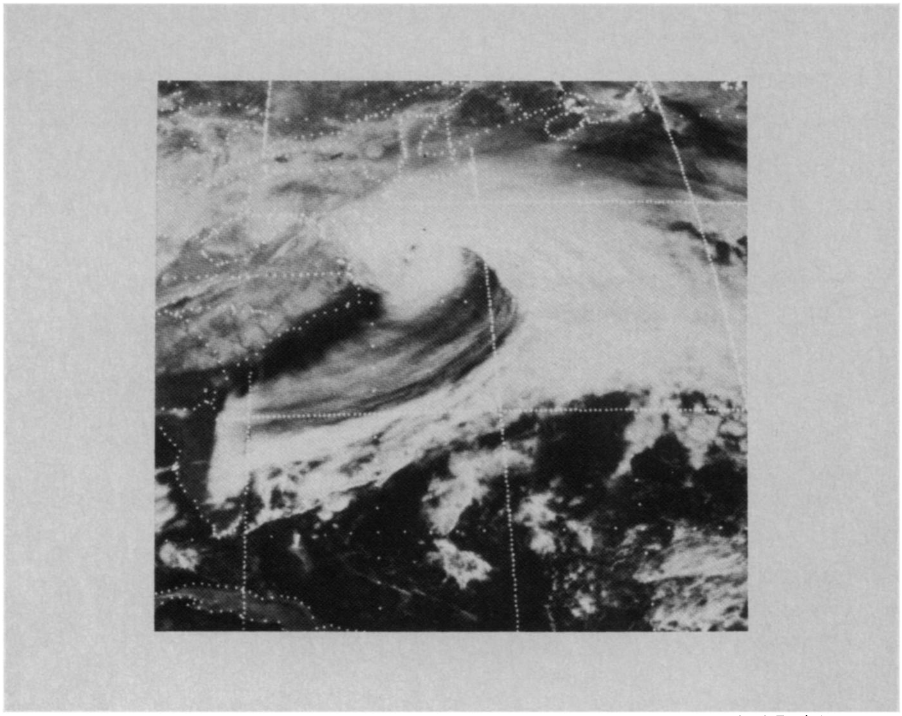


The warm Gulf Stream is key to the formation of East Coast storms because it releases much energy and moisture to the overlying colder atmosphere; the heat flux from the Gulf Stream measures up to 25 times the global average from the ocean. And because the surface temperatures change abruptly over relatively short distances, the Gulf Stream influences the atmospheric patterns on very small scales. This satellite image of the sea-surface temperature off the southeastern United States shows the meanders, eddies and other Gulf Stream structures that shape wind fields and rain bands. The core of the gulf stream (dark red) is about 26° C, the midshelf region (yellow, green, blue) ranges from 22° C to about 20° C and the surrounding waters (dark purple) are about 14° C in winter. The box is the GALE study region.

Brown and Evans/Univ. of Miami

Another focus of GALE was to collect sorely lacking data over the ocean. "We probably know less about what goes on over the ocean from day to day now than we did 30 years ago, because 30 years ago we had weather ships, and weather reports from other ships were more numerous," says Kerry A. Emanuel, a meteorologist at Massachusetts Institute of Technology. "And satellites give only crude estimates of temperature and moisture content."

Many GALE researchers say they came into the program with the suspicion that the ocean plays a more important role in cyclogenesis than most models assumed. But during GALE, with the aid of a fleet of research ships and aircraft, weather buoys and measurement balloons, scientists were struck by just how key the ocean *is* in making storms. And both atmospheric and oceanic scientists say they came away with a much-enhanced understanding of the complexity of ocean-atmosphere interactions. "We all have developed an appreciation for how strongly the atmosphere and ocean are coupled," says oceanographer John Bane at the University of North Carolina at Chapel Hill.



National Climatic Data Center

Satellite image of the President's Day storm that buried cars and crippled Baltimore, Washington and other East Coast areas in 1979.

The thrust of much GALE research was to record the atmospheric conditions that must exist before a storm can form and rapidly grow. Previous studies had indicated that a number of factors make the Carolina coast south of Cape Hatteras a brewing ground for storms before they move northward. Some researchers argue, for example, that the Appalachian Mountains, which reach their tallest height in western North Carolina, help to focus cyclogenesis along the coast by redirecting airflow. The mountains also dam up cold air flowing from a pressure high in the Northeast. This ensures that the air in metropolitan areas is cold enough for water to condense or snow to form. Most important, when warm air from the ocean flows over this wedge of cold air, the damming also provides the strong temperature contrasts needed to energize the storm.

The Gulf Stream, an ocean river of warm water flowing along the coast from the south, is another local feature that contributes to the development of a storm. When the sea-surface temperature of the Gulf Stream is much greater than that of the air, moisture and energy escape from the ocean into the lower 2 km or so of the atmosphere, a zone called the boundary layer. Heating from the ocean destabilizes the atmosphere — since warm air rises — making it easier for storm processes to evolve. And this instability is enhanced because the well-defined edges of the Gulf Stream focus the heating in certain regions. "We haven't emphasized the effect of the Gulf Stream on the boundary layer," says Grossman. "It's an obvious thing, but we didn't realize how important it is [until GALE]."

Flowing across the Gulf Stream from the east is a low-level jet of air called the warm conveyor belt, which carries the boundary-layer moisture and energy up over the cold-air dam, where the moisture and energy are released, producing heavy precipitation over the coast. One goal of GALE was to study the conveyor belt and measure the energy and moisture fluxes into the atmosphere. According to Grossman, observations prior to GALE had portrayed the conveyor belt as a broad stream about 200 miles wide. "What we're finding as GALE is directed toward the smaller scale is that this broad stream is in fact made up of fingers or streaks," he says. "So moisture and energy are being sent into the storm in very specific areas."

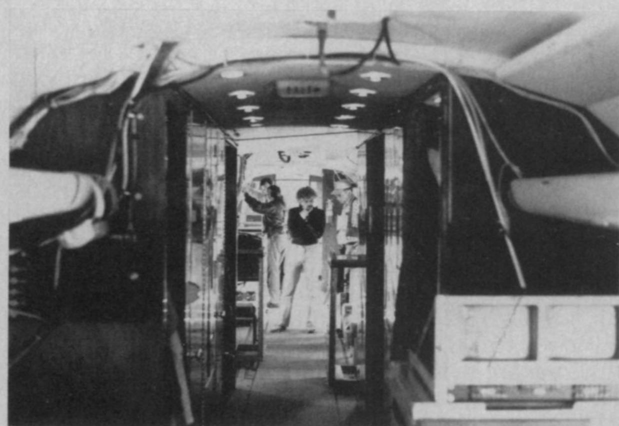
And at even higher altitudes of about 25,000 to 40,000 feet is the jet stream, another element thought to be important in cyclogenesis. The jet stream is a ribbon of high-speed winds that wanders around the globe. Within the jet stream are jet streaks, smaller regions of even greater wind speeds. The differences in wind speeds between sharply defined regions generate vertical motion of air parcels. Upward motion often causes clouds, rain and snow to form.

One consequence of downward motion is a phenomenon called tropopause fold, in which a tongue of dry, ozone-rich air from the stratosphere intrudes into the troposphere below. According to one theory, the tropopause fold spawns the cyclonic rotation of lower-level air necessary for cyclogenesis: When the slowly rotating stratospheric air is stretched into a more narrow tongue, it spins faster, just as ice skaters turn more rapidly when they bring in their arms. During GALE, scientists systematically studied tropopause folds in conjunction with cyclones for the first time.

Meteorologists Ronald B. Smith and Wen-Dar Chen at Yale University in New Haven, Conn., report that they found several clear cases of tropopause folding, some extending more than halfway down the troposphere, and all with very sharply defined boundaries. "As anticipated by some, this tropopause fold seems to be a very common event when cyclogenesis processes are occurring," says Smith. But, caution the researchers, it's still too early in the data analyses to know exactly how such upper-level processes influence, or possibly initiate, lower-level cyclones.

Scientists knew before the GALE program that each of these features — from cold-air damming to the jet stream — and other factors contribute to the formation of storms. "What we've learned [during GALE] is that in order to get a big storm out of a little one, all the component parts have to fall together," says Lance Bosart, an atmospheric scientist at the State University of New York at Albany. "It's like a recipe: If you don't have all the right ingredients, you can't make a good soup."

In the coming months and years, researchers will be studying GALE data to quantify the effects of all these ingredients and to determine when and where they are most important to storm devel-



A GALE scrapbook. Top left: This NCAR Electra was one of several research planes used during GALE. On its nose are instruments that measure wind turbulence, temperature and water vapor. Other instruments include an infrared detector on its belly for measuring sea-surface temperatures, two altimeters, a wind gauge and pressure sensors. Top right: Stickers in the Electra's cabin show that the plane and its pilots are well traveled. Bottom right: A view from inside the plane of atmospheric scientist Robert Grossman and others discussing the flight. Bottom left: On the ground, Lance Bosart studies weather maps in the National Weather Service office before making his forecast for the next day's weather.

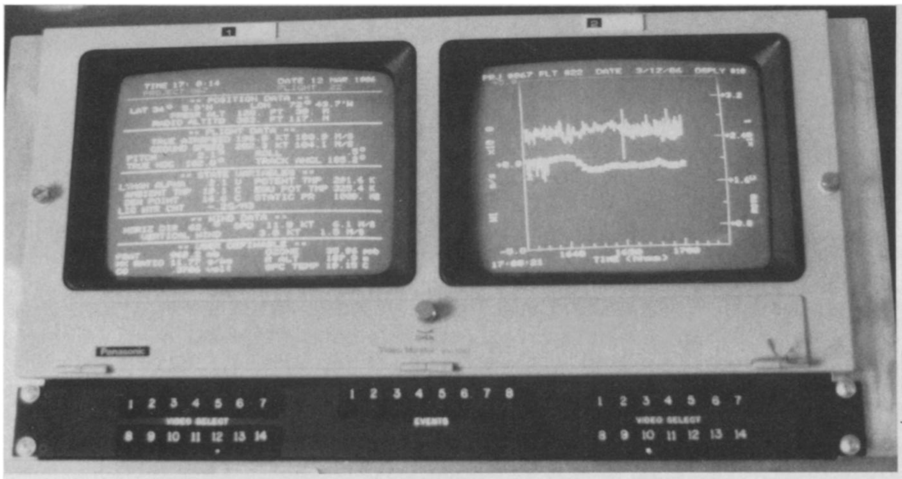
Photos: S. Weisburd

opment. "We think we know what all of the various ingredients are, but we don't know the contribution of each of those ingredients to the ultimate result," adds Bosart.

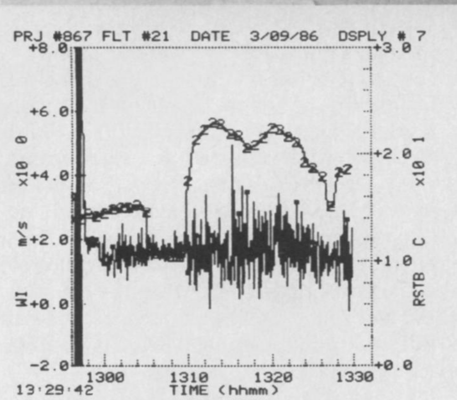
While it's too soon for project scientists to have many definitive results, a number of interesting observations have emerged from GALE. After studying the development of rain bands in West Coast storms, Peter Hobbs, an atmospheric scientist at the University of Washington in Seattle, and his co-workers discovered that strong bands of rain frequently develop off Cape Hatteras over the Gulf Stream. "This came as a complete surprise," says Hobbs. The researchers think the rain bands are fed by the energy and moisture arising from the Gulf Stream and intensify as they move northward along the warm Gulf Stream waters. "We believe that this may be the generating box for a lot of cyclogenesis," says Hobbs. The structure of the rain bands, like other atmospheric features observed during GALE, reflects the intricate eddies and meanders of the Gulf Stream.

On two research flights, MIT's Emanuel and his colleagues also found indications that the cores of storms forming over the ocean were warmer than the surrounding air. If these preliminary indications hold up, they may help explain why winter storms over the ocean tend to be more energetic than their counterparts over land, which typically have cold cores. Emanuel suspects that once an ocean cyclone reaches a particular intensity, it is given an extra energy kick by the same process that drives tropical cyclones such as hurricanes.

The cores of tropical storms, he notes, are heated by the warm water. The rate of heat transfer is proportional to the speed of surface winds, which in turn are driven by temperature contrasts between adjacent air masses and are normally greatest at the center of the storm. As the core of the cyclone is warmed, the temperature contrasts intensify, increasing the wind speed and energy transfer, and so on. In this positive feedback process, the storm rapidly intensifies into a weather bomb. Emanuel adds that the ocean storms may also be energized, especially in the early stages, by the sharp



Grossman/NCAR



During research flights, scientists were able to monitor in real time the complex temperature, pressure, moisture and wind structure of the invisible air (above). The printout at left from an NCAR Electra flying 100 feet above the water shows sea-surface temperatures of the Gulf Stream (top) and the vertical wind turbulence (bottom). This graph illustrates how the flux of energy and moisture from the ocean, which creates turbulence in the air, is heightened when the temperature difference between the ocean surface and the overlying cold air increases.

air-temperature contrasts above the edges of the Gulf Stream, where differences in sea-surface temperatures between the center of the Gulf Stream and the surrounding waters can be as high as 15° C.

GALE also produced some studies on lightning. Recent research over the Atlantic and off the coast of Japan has shown that there is a lot more lightning over the ocean than previously thought and that more often than not the lightning from clouds to the ocean surface is positive. This was unexpected because most lightning over land is negative; clouds have positive charge in their tops, and the negative charge that discharges to the ground comes from the bottom of the clouds.

One theory explaining the difference between ocean and land lightning holds that the polarity of the many clouds over the ocean is inverted, with positive charge on the bottom and negative charge at the top. Another idea is that strong winds above the ocean distort the clouds into an anvil shape, displacing the positively charged tops away from the shielding influence of the negative bottoms. At this point, the results from GALE paint a mixed picture, says Earle Williams, an atmospheric scientist at MIT. According to Williams there is evidence for tilted clouds, but he adds that researchers flying above the clouds also found unmistakable signs of negative tops. "That's a striking result because in two earlier studies investigators had found only positive tops," Williams says.

GALE researchers had expected that the ocean would affect thunderstorm development because the high levels of moisture and energy released by the warm waters feed the processes that create clouds and that separate charges in the clouds before they produce lightning. Hobbs notes that these high ocean fluxes probably enable rain-band thunderstorms to occur in clouds that are much shallower than those over land. But researchers in the experiment were still impressed by the ocean's influence.

"There was a lot more lightning going on out over the Gulf Stream, a lot more of the time than anybody had supposed," says Emanuel. "I noticed too that there was a strong correlation between the amount of lightning and the temperature of the water. It was concentrated over the Gulf Stream to such a detail that we could actually see the outline of meanders in the side of the Gulf Stream in the lightning fields."

One group that clearly benefited from GALE was the National Weather Service, whose forecasters had access to GALE information throughout the project. High-resolution GALE data have "really been a great help," says Mike Sabones of the National Weather Service. "It would be nice to have this all the time. We've gotten spoiled."

In spite of the reams of data collected during GALE, the experiment had its disappointments. Although there were a number of storms, "we didn't really get a bomb," laments Grossman, "just a few grenades." Research was limited also by the need to get air space for research flights on relatively short notice; GALE was given 7th-place priority for flying in an area that is heavily trafficked, especially by military operations.

And scientists trying to forecast the next day's weather – so that they could plan for aircraft flights and other data-taking – were often frustrated by the limits of the forecasting models they were using. "The models predict three different outcomes, and knowing nature, it will pick the fourth," joked Bosart at one weather briefing in the final days of the project. On the overhead projector Bosart was showing a series of maps drawn to capture the essence of the next day's weather. Just then a mass of dark clouds rumbled on the horizon. A burst of wet wind shot into the building, slamming shut windows and doors. There was weather happening out there. The researchers left their models and maps, satellite images and predictions, and were drawn outside to stand in awe of the powerful and majestic dance of the atmosphere. □