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Tempests + *Terrain*

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BY MATT ALDERTON

Beginning of a tornado on a deserted highway in the Oklahoma panhandle.

EVERY MUNDANE CONVERSATION you've ever had has probably included empty banter about the weather. And you're not alone. In 1897, American writer Charles Dudley Warner quipped, "Everybody talks about the weather, but nobody does anything about it."

Talk is the only thing about weather that's small, however. Everything else about it is big, including its effects, which have economic, social, and political implications of growing consequence for individuals, communities, businesses, governments, and militaries. This is particularly true in an era of increasing meteorological tumult, when extreme weather events like Hurricanes Harvey, Irma, and Maria are broadcasting in no uncertain terms, "Severe weather ahead!" As such events become more routine than rare, Warner's jocular observation begs a serious call to action: Instead of talking about the weather, the time has come to better anticipate, harness, and respond to it.

"Hurricanes, cyclones, thunderstorms, and other extreme weather events are becoming more common due to climate change and global warming," said Peter Platzer, CEO of Spire, a cubesat startup with plans to collect and distribute high-frequency weather data to commercial customers. "So the contribution you can make to humanity by improving weather forecasting is really substantial."

Weather has always been important. Not only because of the innumerable crises it has created, but also because of the many opportunities.

"In U.S. history alone, there have been all kinds of events where weather played an important role, going all the way back to George Washington crossing the Delaware to win the Battle of Trenton," said meteorologist Paul Dorian, a senior systems engineer at Vencore, whose weather division provides weather forecasting for government clients like the U.S. Air Force Weather Agency and NASA. "One of the most famous, of course, is D-Day. Weather was >>

critical for the Normandy invasion because Gen. Eisenhower made the decision to invade based on the weather forecast. It turns out we had better forecasters than the Germans did, and that's [a primary reason the] invasion worked out so well for us."

Bad forecasting can be just as impactful as good forecasting.

"In 1980, there was a hostage crisis in Iran and President Carter ordered a rescue mission," Dorian continued. "Helicopters flew into the Iranian desert to try to rescue the hostages, but the winds kicked up and dust was blowing everywhere. It brought down one of the helicopters, which [contributed significantly] to the mission being aborted."

Neither sandstorms nor hurricanes can be prevented. They can, however, be predicted. And if you can predict weather, you can manage it, according to Dr. Peter Neilley, an IBM Distinguished Engineer and director of weather and forecasting technologies for The Weather Company, which was bought by IBM last year and includes The Weather Channel and Weather Underground.

"Weather forecasts aren't perfect, and they never will be. But they have gotten a lot better," Neilley said. "As a result, decisions are being made every day based fundamentally on the weather forecast."

But meteorology alone can't ensure more D-Days and fewer failed missions. Because all weather has a location and all locations have weather, weather forecasting must work in concert with GEOINT, according to Neilley. "Weather is fundamentally a geospatial science," he continued, noting, for instance, the temperature differences between low and high elevations, and between inland and coastal communities. "The terrain can have a significant impact on what the local weather is."

It's not just terrain. Other GEOINT variables such as land type, latitude, water proximity, and even human geography also influence weather.

"GEOINT is the exploitation and analysis of imaging and geospatial information that's describing, assessing, and visually depicting physical features and geo-referenced activities. Weather exploitation is the same thing; it's exploiting and analyzing images and atmospheric information to describe, assess, and visually depict physical features that are geo-referenced," explained Eric Webster, vice president and general manager of environmental solutions at Harris Corp.

Understanding and exploiting these parallels could help humankind recast weather as an opportunity instead of a threat.

WHY WEATHER MATTERS

Few people understand the significance of weather better than Rep. Jim Bridenstine (R-Okla.), who serves on the U.S. House of Representatives' Armed Services and Science, Space, and Technology committees, and at press time was nominated by President Trump to be the new NASA administrator. "As a member of Congress from … Oklahoma, until this year I have had constituents die every year in tornadoes," said Bridenstine, a Navy combat veteran. "I will also tell you as a naval aviator—and now as a pilot in the Air National Guard—that I have been very affected by weather many times in my military career, from the ability to do strikes on a target to the ability to land on an aircraft carrier in high seas. So it's very important to me and very important for our country to make sure we're doing everything we can to get the right [weather] intelligence to the right people at the right time."

Weather forecasts are equally consequential for civilians and warfighters. For the former, it boils down to lives and livelihoods.

"The physical and economic losses the world suffers because of inaccurate weather forecasts are staggering," said Platzer, who added weather impacts a third of the global economy and 100 percent of the global population. "When the weather forecast calls for a blizzard

Airmen from the 3rd Weather Squadron set up a Tactical Meteorological Observing System (TMOS) during Spartan Warrior May 13, 2015, at Avon Park Air Force Range, Fla. TMOS is used in the field to measure wind speeds, cloud levels, and temperature.

PHOTO COURTESY OF U.S. AIR FORCE

in New York, but it actually takes place in Boston, there's loss of life, loss of property, and loss of money."

For the military, what's ultimately lost is the mission.

"Let's say you're going to take out some ISIS guys in Libya, and you're going to fly an airplane across the pond from the United States to do it," said Air Force Director of Weather Ralph Stoffler. "Obviously, you want to know from a weather perspective when is the best time to take off; when is the best time to conduct aerial refueling operations, and where; when is the target going to be clear, and if it's not going to be clear, should you use a different weapon that potentially works better when you can't see the target? Those are all questions that we help answer."

The Army leverages weather forecasting to answer similar questions, according to Bill Spendley Jr., weather team chief in the Army's Office of the Deputy Chief of Staff, G-2. "The Army has six warfighting functions, and every one of those warfighting functions has capabilities therein that are affected by weather," said Spendley, who described weather's effects on brigade combat teams as a "mud-to-sun situation."

In space, for instance, extreme weather can affect satellite communications and GPS signals. In the air, it can hamper the ability to drop weapons or paratroopers. And on the ground it can affect trafficability, interrupting the delivery of fuel, ammunition, supplies, and medical care.

"If weather impedes one warfighting function, that has repercussions for the entire brigade combat team in terms of being able to conduct its mission and defeat the adversary," Spendley said.

Because cloud cover can obstruct images taken by Earth observation satellites, which supply more than 90 percent of data used in weather forecasts, weather likewise is mission-critical for the Intelligence Community (IC), according to Air Force Col. Herb Keyser, a senior meteorology and oceanography (METOC) officer at the National Geospatial-Intelligence Agency (NGA). If you're looking at weather through an ISR lens, he said: "It's all about clouds. Not many people care about cloud forecasting to the extent that we do."

In truth, it's not all about clouds. It's also about context. "NGA is looking at population-forcing functions like potential landslides, vegetation health, and water security," Keyser continued.

Weather's impact on human geography can be simple—people stay home because they don't want to go out in the rain—or complex: Climatological problems catalyze large population shifts.

"Weather influences crops and drought, which influence political instability, which influences refugees," said Patrick Biltgen, director of data analytics for Vencore's intelligence group. "If you're able to forecast changes in weather and climate, you can predict massive geopolitical changes."

TARGETING TERRAIN

Citizens, soldiers, and decision-makers are no longer content with talking about the weather; faced with so many impacts, they're acting on it, too.

GEOINT deserves a lot of the credit, according to Bridenstine. "When you talk about national security, weather, and climate, all of it requires geospatial intelligence," he said, noting that Earth observation satellites launched for GEOINT missions are benefitting weather forecasters every day by collecting data about the atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere—Earth's air, land, water, ice, and organisms, respectively. "[Using satellites], we're now discovering that we can see massive sandstorms in the Sahara Desert that are moving over the Atlantic Ocean, where they absorb large quantities of radiant energy from the sun. That affects the temperature of the ocean and in some cases actually mitigates the hurricane seasons that affect the United States … That's just one example of many where GEOINT has benefited the weather community."

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>
> —BILL SPENDLEY JR., ARMY OFFICE OF THE DEPUTY CHIEF OF STAFF, G-2

GEOINT and weather are especially symbiotic in the military, according to Spendley and Stoffler, who agree that terrain is ground zero for GEOINT-weather synthesis.

"The intersection to a great extent happens at the tactical level," explained Stoffler, who said Army topography teams collaborate with Air Force weather officers to determine trafficability based on terrain and weather inputs.

"An example would be years ago when we deployed to Rwanda. We had to support a 1,000-truck convoy of humanitarian-relief mission sets," Stoffler said. "The Army was very concerned that the roads would wash out because of the monsoons that happen at that time of year, but they couldn't do a proper trafficability forecast because they didn't have the weather information. So we provided that to them and they in return provided things back to us, which allowed us to produce an integrated forecast on when the best time was to move those trucks and the best route to take."

Echoed Spendley, "The intersection of terrain and the atmospheric conditions touching that terrain is obviously critical in terms of being able to conduct operations. METT-TC—mission, enemy, terrain and weather, troops and support available, time available, and civil considerations—is the lens through which the Army plans, conducts, and executes operations. Notice how it's 'terrain and weather.'"

METOC personnel from across the services collaborated this year to author a new edition of Joint Publication 3-59: Meteorological and Oceanographic Operations for the chairman of the Joint Chiefs of Staff.

"The armed forces use joint doctrine as principles of how to fight and win wars," Spendley explained. "This entire joint publication was completely rewritten with a focus on the integration of the most accurate, timely, and relevant weather information into the joint force commanders' decision-making process."

Civil stakeholders also are invested in the terrain-weather nexus. An area of particular interest is flooding. In 2015, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) launched the National Water Center at the University of Alabama in Tuscaloosa. Geospatial scientists and weather forecasters at the 65,000-square-foot facility collaborate to analyze, model, and forecast water conditions—including stream flow, water level, runoff, flood inundation, snowpack, soil moisture, and evapotranspiration—for 2.7 million rivers and streams.

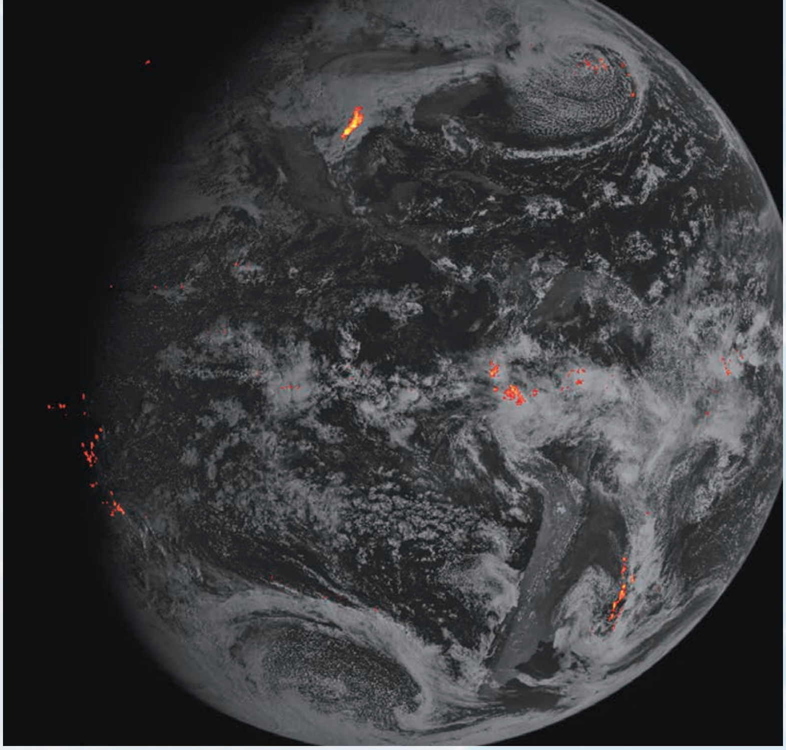

IMAGE COURTESY OF NASA

The Geostationary Lightning Mapper is a single-channel, near-infrared optical transient detector that can detect the momentary changes in an optical scene, indicating the presence of lightning.

"They have implemented a new National Water Model that uses geospatial information like terrain and slope to forecast basins so we know better how water is going to flow through them," explained NWS Observations Portfolio Manager Kevin Schrab.

Forecast models that fuse geospatial and weather information likewise can help mitigate wild fires.

"There are three primary drivers of wild fire behavior. One is terrain, or how the landscape is arranged. The other two are wind and fuels, both of which are dependent on what's going on with the weather," said former California State Fire Marshal Kate Dargan, co-founder and chief strategy officer at Intterra, a software company that provides situational awareness to public safety customers. Dargan is also a member of USGIF's Board of Directors. "So, everything about wildland firefighting and wildfire risk is geospatial and weather-based in nature."

FORTIFYING FORECASTS

The most coveted weather data includes forecasts that are more detailed, accurate, local, and protracted.

Improvements are inevitable yet incremental, according to Neilley, who said weather forecasting accuracy historically has improved at the pace of one day per decade, such that a three-day forecast today is as accurate as a two-day forecast was 10 years ago. "Weather forecasting is an evolutionary science, and there's a perpetual pipeline of things that are coming along and contributing to those evolutions," he explained.

The most significant items in the weather pipeline today are the next generation of weather satellites, which are fundamentally better than their predecessors, according to Neilley. Specifically, NOAA operates two types of satellites: Polar Operational Environmental Satellites (POES), which provide global coverage twice daily, and Geostationary Operational Environmental Satellites (GOES), which have a fixed position from which they provide near-continuous observation of a certain region. NOAA and NASA are collaborating on upgrades to both.

At press time, the next iteration of POES, the Joint Polar Satellite System (JPSS), is scheduled to launch its second of five satellites, JPSS-1/NOAA-20, in November. Carrying a payload of five weather-monitoring instruments, the system will gather global measurements of atmospheric, terrestrial, and oceanic conditions. Its measurements will support accurate seven-day weather forecasts that will help meteorologists predict the intensity and location of severe weather events days before they occur.

The next iteration of GOES, the GOES-R Series, launched its first of four satellites, GOES-R/-16/-East, in November 2016 with a payload of six instruments. The satellite, slated to become operational in November, has already demonstrated a number of new capabilities that promise to improve the detail and accuracy of weather forecasts.

GOES-R satellites feature an advanced baseline imager (ABI) that views Earth across 16 spectral bands. It can scan the entire Western Hemisphere every five minutes or take multiple images concurrently, in which case it's capable of imaging the Western Hemisphere every 15 minutes, the continental U.S. every five minutes, and two specific storms every 60 seconds. The previous generation of GOES features five spectral bands and can image the Western Hemisphere just once every 30 minutes.

"The picture is much clearer; there's three times the spectral bands, which allows you to see variations in temperatures and other things within clouds; and you're able to get information to forecasters much more quickly," said Webster of Harris, which developed the GOES-R ABI for NOAA.

That increased capability will assist not only with forecasting weather on Earth, but also in space.

"Space weather is becoming more important as electronics and satellites become more and more embedded in our society," said Dorian of Vencore, which is working with NOAA on GOES-R in a systems engineering capacity.

Destructive solar storms represent a growing threat to satellite operations and communications.

"GOES-R gives us better capability to monitor solar activity, which is critical to the Intelligence Community because satellites can be impacted as a result of solar wind," Dorian added.

Another notable instrument aboard GOES-R satellites is Lockheed Martin's Geostationary Lightning Mapper (GLM), a sensor that can detect and measure lightning activity continuously.

"This is the very first lighting sensor from space that's in the geostationary orbit," said Dr. Allan Weiner, senior scientist in charge of the GOES-R ground processing system at Harris. "This particular sensor in combination with the ABI is going to be very exciting because we're going to learn all-new information from it."

Historically, meteorologists have forecast storms based on cloud formation and rainfall. Measuring lightning activity alongside those traditional inputs adds another dimension to weather forecasting that will make it easier to identify whether storms are escalating or de-escalating. GLM images the Earth at a rate of 500 frames per second, then performs onboard image processing in the form of automated change detection. The resulting data is especially promising for forecasting tornadoes.

"Right now the accuracy of predicting tornadoes is quite terrible. Even with all the information [meteorologists] have, it's on the order of 60 percent of the time that they're wrong," said Dr. Samantha Edgington, Lockheed Martin's chief GLM scientist.

Weather forecasters typically rely on radar to identify tornadoes—which often leads to missed tornadoes when radar coverage is poor.

"As you can imagine, if you live in a place where there are tornado warnings often, and more than half of the time they're wrong, eventually you stop paying attention to them," Edgington continued. "The goal of lightning data is to not only detect those tornadoes that are missed because of poor radar coverage, but also to make tornado predictions more accurate so that when the National Weather Service says a tornado is coming, people will actually listen and do something about it."

BRIDGING THE WEATHER GAP

Despite the advent of new satellite systems like JPSS and GOES-R, the U.S. Government Accountability Office (GAO) says the country is facing an "imminent satellite data gap."

"Federal agencies are currently planning or executing major satellite acquisition programs to replace existing polar and geostationary satellite systems that are nearing the end of, or are beyond, their expected life spans," the GAO reported to Congress in early 2017. "However, these programs have troubled legacies of cost increases, missed milestones, technical problems, and management challenges that have reduced functionality and delayed launch dates. As a result, the continuity of weather satellite data is at risk."

Of special concern, according to the GAO, are aging polar satellite systems the Department of Defense (DoD) operates. Not only has DoD been slow to plan and launch replacements, it said, but the department has also been plagued with misfortune. For example, its newest weather satellite, Defense Meteorological Satellite Program (DMSP)-19, launched in 2014 but experienced a power failure in 2016 and was subsequently lost.

"There's a gap that's coming," Webster said. "The military has acknowledged that, and now they're trying to figure out how to fill it."

One potential solution represents yet another shared interest between weather and GEOINT: commercial data sources.

"We have made it clear to the commercial world that we are very interested [in commercial weather data]," Stoffler said. "Within DoD, to maintain our own capability that covers the entire globe is a challenge. It costs a lot of money to do that. And frankly, we've been relying a lot upon international players … [that] are now being replaced by Russian and Chinese capabilities that we legally can't use—and wouldn't use even if we could."

Bridenstine is among commercial weather data's biggest advocates. "I've been working on … encouraging the Department of Defense and other government agencies—NOAA, specifically—to purchase commercial space-based weather data," he said. "A lot of commercial entities are launching satellites to furnish this data because private industry has signaled demand for it. Transportation companies, agriculture companies, and insurance companies all are interested in gaining a competitive advantage by being able to better predict the weather. The question is: Will the government purchase the same data to improve our weather prediction capabilities?"

Bridenstine co-sponsored the bipartisan Weather Research and Forecasting Innovation Act of 2017 that President Donald Trump signed in April, giving NOAA permission to explore, test, and purchase commercial weather data.

"NOAA already is conducting a pilot project to test and validate that data," Bridenstine continued. "The next step is to have the Department of Defense do the same thing, and we're going to accomplish that through the National Defense Authorization Act and defense appropriations."

Of greatest interest is commercial GPS radio occultation (GPS-RO) data, which is being furnished by companies like Spire and PlanetiQ. Spire, which was awarded NOAA's first-ever commercial weather contract in September 2016, already has 40 cubesats in orbit, with plans to eventually have more than 100. PlanetiQ plans to have a constellation of 12 to 18 microsatellites in orbit by the end of 2019, the first two of which are expected to launch in summer 2018.

"GPS radio occultation is pure physics," said Chris McCormick, PlanetiQ's chairman, founder, and former CEO. "It's refraction. When you see the sunrise and sunset, the reds, oranges, and yellows are light being refracted, or bent, by the atmosphere … GPS signals also get bent by the atmosphere."

When the atmosphere bends GPS signals, it delays them. Measuring the delay allows scientists to deduce the makeup of the atmosphere, including its temperature, pressure, and—most importantly—moisture.

"The next day's weather, or the next week's weather, is created in the ocean by the sun-ocean interface," McCormick explained. "If you know how much water

Shaina Johl, one of Spire's engineers, inspects an early Lemur-2 satellite model while Joel Spark, co-CTO at Spire, looks on from outside the clean room. Lemur-2 satellites are among the 40 cubesats Spire currently has in orbit. The company was awarded NASA's first commercial weather contract in 2016.

PHOTO COURTESY OF SPIRE

> In a world where extreme weather events are increasingly common, action will be weather forecasting's most important output—not only for citizens in the path of destructive storms, but also for military commanders and intelligence officers seeking strategic advantage over powerful enemies.

PHOTO COURTESY OF SPIRE

vapor is in the atmosphere, and what the variability is of the temperature of that water vapor, it's much easier to predict where clouds will form, when, and for how long."

The more measurements one has, the more accurate the forecast. "It's not the size of the sensor, but the number of sensors, that drives value," Platzer said. "That's why companies like Spire can make a difference."

COMPUTING AND COMMUNICATION

What ultimately will unlock the next generation of weather forecasting are computing and communication, both of which will enable a new order of GEOINT-weather integration.

The observations of next generation weather satellites will be rendered useless without sufficient processing power to interpret them. Quantum computing is one likely solution. Artificial intelligence and machine learning is another.

"DoD, specifically, has been working on service-enabling weather data to be able to get it to organizations like NGA … so [analysts] can search for patterns that they can then extract intelligence from," NGA's Keyser said. "Because we don't have time for somebody to sit and look at a wind gauge, for example, we need to be able to do machine-to-machine processing that frees up the analyst to actually think about problems instead of just looking at them."

Which leads to forecasting's other major opportunity: communication.

"The weather community needs to do a better job of being less esoteric," Platzer said.

Echoed Biltgen, "Generally, people don't really understand the weather. The forecaster comes on TV with a map that has triangles and half-moons and 'high pressure' and 'low pressure,' but all anyone really wants to know is: Do I need a jacket and an umbrella?'"

Neither civilians, warfighters, first responders, nor intelligence analysts care about weather science; all four, however, care about weather impacts, which can be understood and communicated better with the assistance of GEOINT. For example, the National Center for Atmospheric Research is testing technology that marries ground data with atmospheric predictions to give wildland firefighters real-time, location-based insights.

NWS is doing similar research via its Weather Ready Nation (WRN) program, whose charge is exploring new ways to present and disseminate weather information so decision-makers and citizens will take it seriously.

"One of our sterling successes has been a storm-surge inundation map," said WRN spokesperson Douglas Hilderbrand. "A few years ago, the way we quantified and communicated storm surge was very complicated; you had to go to the National Hurricane Center and the National Ocean Service, consult a tide chart, and incorporate on your own wave and elevation information to answer the basic question: Is my house vulnerable to storm surge? Now we have a very intuitive map that incorporates all the storm surge science and allows people to determine their home's risk in a much more visual way … We're trying to make NOAA information more personal and more applicable … because that's when people listen and take action."

And in a world where extreme weather events are increasingly common, action will be weather forecasting's most important output—not only for citizens in the path of destructive storms, but also for military commanders and intelligence officers seeking strategic advantage over powerful enemies.

"If you've got a brigade combat team commander with a rotary wing assault force that needs a 500-foot cloud ceiling and two-mile visibility, they need to know if there's only a 300-foot cloud ceiling and a quarter-mile visibility so they can make decisions in the most informed way possible," Spendley concluded. "They're not interested in knowing that there's a high chance of rain today; they're only interested in what the effects of weather will be on their mission, either where they're operating or where they're projected to operate. That's where the rubber meets the road."