Hurricane Sandy (2012), the TRMM Satellite, and the Physics of the Hot Towers

Alan Stahler of KVMR interviews Owen Kelley of NASA Goddard

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Broadcast on Tuesday, 27 November 2012,
on the 15th Anniversary of the Launch of the TRMM Satellite

Broadcast: 38.5 minutes duration starting at noon PST on KVMR-FM, Nevada City, California
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00:00 The TRMM Instruments

Stahler: Owen, how does TRMM, the Tropical Rainfall Measuring Mission, see rain?

Kelley: It is called the flying rain gauge[1] because it has every instrument ever used from space to measure rain. It has an infrared camera that sees how high and cold the clouds are...

Stahler: You can see those images from GOES. GOES is a geostationary satellite. That means it hovers over the equator and gives us our daily weather picture.

Kelley: Since the 60s, we've had that view from space.[2]

Stahler: Because it's infrared, it is essentially giving you the temperature of the clouds, and the colder the cloud, the higher up it is in the atmosphere. This lets you see how high, how tall the clouds are...

Kelley: And that matters because air doesn't get lifted from the earth's surface to high up unless there is energy being transformed into strong updrafts. So [cloud top temperature] tells you something about the physics that is going on inside the clouds. If you are out on a sunny day and a little puffy cloud comes along, you don't get worried, but if you suddenly see it get dark and a cloud shoots up and starts to cover a lot of territory, then you know it's a big storm cloud and you might not want to set out on a hike.

Stahler: And you can see that from space. The colder the cloud the brighter it is in the image so these bright white clouds, and sometimes they are even colorized red or yellow, those are the really cold, high, powerful clouds.

Kelley: What is nice about the infrared is that it works at night. You don't need sunlight to illuminate the cloud. You can see how warm it is and you know high it is.

Stahler: It is like putting your hands to the stove. You are measuring its warmth, how much heat is coming off

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[1] NASA, 1988; Simpson et al., 1988; NASA, 2000.

[2] Under the direction of the newly formed NASA (Chapman, 1968), the first satellite carrying an infrared instrument was TIROS II launched on 23 November 1960 and operated until the following July. TIROS II included the 11 micrometer frequency used still today (Alison, 1962; Astheimer et al., 1961). On 12 July 1961, TIROS III launched, the first infrared satellite to fly during hurricane season and whose observations were used to direct evacuations prior to Hurricane Carl's landfall (Jakes, 1966, pp. 119–125). TIROS III also saw Hurricane Anna (Bandeen et al., 1963; Fujita and Arnold,1963). Starting in the late 1970s, the United States had geosynchronous satellites providing infrared images at least every 3 hours, while global coverage in the infrared did not occur until the early 1980s (Knaff et al., 2011, Fig. 1).

that cloud, even though it is, like, minus 50 degrees Fahrenheit.

Kelley: It can be even colder than that. Clouds at the top of some of these hot tower storms that we look at are negative 90 degrees Celsius.[3]

Stahler: That is minus 130 Fahrenheit. Those are ice clouds.

Kelley: Yeah, it's a different kind of cold. Even in the middle of the tropical ocean, clouds that get above about three miles high are ice clouds. Because the earth is warmed by the sun, and the atmosphere cools as it gets further away from the earth, the temperature falls off. There is a general circulation of the atmosphere: air in the tropics rises generally, and at high altitude, travels to where we live, and then settles down.

Stahler: As warm air rises it cools down, like when you blow into a freezer, which makes its water vapor condense to form clouds, which make rain. When air rises, it typically dries out.

Kelley: There is a kind of wringer that squeezes out all of the water before the air can come across to us. When you have high pressure systems in the part of the world we live in, that is generally sinking air, and that air is very dry.

Stahler: That's why you get the Chihuahuan Desert, which is mainly in Mexico, but it does stretch up into New Mexico. And that is one dry desert because you have the sinking dry air.

Kelley: In fact, most of the hottest, driest places on the earth are not directly at the Equator, but instead at this dry band where you have sinking dry air.

Stahler: How does TRMM see rain?

Kelley: We've thrown everything we've got at the weather with TRMM. We have an infrared camera, just like GOES, so you can see the cloud tops. We have a passive microwave radiometer,[4] which just means a camera without a flash that observes radiation in the microwave region, the same as your microwave oven uses.[5] The trick is that clouds are sort of semi-transparent in the microwave and so you get a sense of the total radiation coming out throughout the cloud, which gives you a sense of the total amount of water vapor in the cloud. But height matters in the atmosphere. [Height] gives you clues about the energy transformations in the clouds. The passive radiometers are not good enough,[6] so the third and most recent technology is the radar. TRMM is the first satellite to actually have a radar in space, powered with solar panels. It's a camera with a flash. It illuminates the cloud. That energy is absorbed by the raindrops, re-emitted in every direction, and a tiny fraction of that energy comes back to the radar.

Stahler: The radiation is not being directly reflected; it's being absorbed by these cloud droplets or raindrops, and then re-emitted in all directions.

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[3] -90 C temperatures are regularly observed, such as in the outflow of Typhoon Bopha (2012) and even -100 C temperatures are occasionally observed (Ebert, 1992). See the 2 December 2012 TRMM satellite overflight of Typhoon Bopha at http://www.nasa.gov/mission_pages/hurricanes/archives/2012/h2012_Bopha.html .

[4] Global coverage in the infrared began in the early 1980s, while twice-daily observations from operational passive-microwave radiometers began in the early 1990s with the Special Sensor Microwave Imager (SSMI) series of instruments.

[5] While both a microwave oven and the TRMM satellite radar operate within the microwave spectrum, microwave ovens typically operate at 2.5 GHz while the TRMM radar operates at 37.8 GHz.

[6] "The radar [on the TRMM satellite] provides the data needed to help diagnose the vertical distribution of latent heating" (Simpson, 1988, pg. 280). "The rain radar has the potential to overcome disadvantages of the visible and infrared radiometers and microwave radiometers. The rain radar can detect rain directly over both ocean or land..." (Nakamura et al., 1990).

Kelley: That's right. They become little spherical antennas,[7] radiating in every direction. Travelling at the speed of light, it takes about a thousandth of a second for light to travel down a couple hundred [miles] and then travel back to the satellite.[8]

Stahler: But you can measure things so precisely that you can tell if [the return echo] is coming from down deep in the cloud or up near the top of the cloud by the "time of flight."

Kelley: By the amount of time, a fraction more or a fraction less, that tells you where [the raindrop] is and how much [radiation] tells you whether its drizzle or if it is a torrential downpour.

Stahler: How close is this to the weather radar that we see on TV or on our computer screens?

It is kind of a miracle to get this [radar] miniaturized enough to fly on a satellite and run off solar panels. The TRMM satellite's radar uses less power than the microwave oven that you use to heat your lunch.

Kelley: The frequency of radiation is similar but the size and power requirements are totally different.[9] It is kind of a miracle to get this [radar] miniaturized enough to fly on a satellite and run off solar panels. The TRMM satellite's radar uses less power than the microwave oven that you use to heat your lunch,[10] and yet it can sense clouds that are as far away as... here I am in Washington and if I could see to New York City, that's about the distance that the clouds are from the radar. All on a thousand watt charge. The machinery is huge for the ground radars that the National Weather Service uses,[11] whereas the TRMM radar fits in something that is the size of a king-sized bed.

Stahler: When was TRMM launched?

Kelley: It was launched on Thanksgiving Day, 1997.

05:30 Joanne Simpson

Stahler: Everyone aware of hurricanes is aware of the Saffir-Simpson index: category 1, category 2, cat 4, cat 5. Robert Simpson was the husband of Joanne Simpson. What was Joanne Simpson's role in TRMM?

Kelley: It is hard to think of the right adjective to describe Joanne. Joanne was a meticulous scientist, a motivated person who didn't accept obstacles. She basically made sure TRMM happened. She was the head of the science team that proposed TRMM.[12] And she was the head of the science team in the

[7] Small drain drops (1–2 millimeters in diameter) are approximately spherical, but atmospheric drag flattens the bottoms of large raindrops (2–6 millimeter), so they are not spherical (Beard et al., 2010).

[8] The one-way trip down from the TRMM satellite's 402.5 km orbit to precipitation that is 0 to 20 km above the earth's surface takes approximately 1.3 thousandths of a second traveling at the speed of light. The earth's atmosphere is not dense enough to significantly slow light from its speed in a vacuum: 3×10^8 m/s.

[9] The TRMM radar uses on average 250 watts of power or less (NASA, 1996) to generate extremely brief pulses of energy with a 500-watt peak power (Kummerow et al., 1998). In contrast, weather radars on the ground typically have a peak transmit power of about three quarters of a megawatt (NOAA, 2005, Table 2-1). The TRMM radar and ground radars transmit at 13.8 and 2.8 GHz, respectively (Kummerow et al., 1998; Rinehart, 1997).

[10] A typical microwave oven uses approximately 1000 watts and continuously transmits approximately 500 watts. In contrast, the TRMM radar was designed to always use less than 250 watts and transmits only brief pulses that have 500-watt peak power.

[11] The National Weather Service's WSR-88D weather radars have antennas that are 28 feet in diameter (NOAA, 2005, Table 2-1).

[12] John Theon states in Tao and Adler (2003, pg. 178) that Joanne Simpson was the Study Scientist for TRMM in 1986 and she convened a science team and edited their report in 1988 (NASA, 1988). Her career has been described in

years just prior to launch. She was also a mentor to generations of scientists. So Joanne Simpson is a huge figure in the world. Her husband, Robert Simpson, didn't just invent the category 1 through 5 scale. He was also head of the National Hurricane Center for a while.[13] Both he and his wife liked to look at clouds together. They were both fascinated by them.

Stahler: Joanne Simpson, early in her career, was guided into studying clouds because that was something that was "more appropriate for a girl." [14]

Kelley: I hope that the world has changed for the better in some ways because what she faced was rather unkind. She was one of the first women to earn a Ph.D. in Meteorology. After that, she was not allowed to fly on the aircraft collecting data for her experiments. And she faced people who were dismissive of her talents because she was a woman. Some of her early work, where she meticulously analyzed tropical clouds over the Pacific Ocean—satellites didn't see clouds at that point, this was a couple of decades before satellites made that job easy—and she found patterns that led to the "hot tower hypothesis."

Stahler: Which we will get into.

Kelley: She was not allowed to fly on those aircraft and direct where they went. Not only did she find ways to work around that, but she was generous with her time helping young scientists thereafter. So it didn't make her bitter. It made her care more about helping other people.

07:45 The General Circulation of the Atmosphere

Stahler: You were one of those young scientists. You were looking at the data, you saw a pattern. We all know that we have tropical rainforests because it rains a lot in the tropics. You were talking about how there is this flow of warm air rising off the tropics and then settling down over the deserts about 30 degrees north or 30 degrees south. You look at this cartoon in the textbooks and you get this image of the air just gently rising, flowing north or south, and then gently coming down again.

Kelley: Those pictures are about half a century out of date. It's a beautiful image... of air kind of rolling up and away from the Equator and back down.

Stahler: The vast majority of that air is not rising so gently. It's coming up in thunderclouds.

Kelley: That's right.[15] Your and my experience would perhaps lead us to the same conclusion that Joanne Simpson put into scientific equations and scientific arguments. When you see a storm cloud, you don't see all of the air suddenly rise up and then light rain drizzle out. Rain happens really intensely, and then it won't rain for a week. So we all have some sense that the way clouds and storms work is often downpours. Now, I don't want to say that you never get this light drizzle that goes on for a day or two because that can happen. In fact, those are the two modes of rainfall. They're called convective and stratiform. Convective rain is named after the mode of energy transfer that is called convection.

Stahler: That's what you get when you put a pot of water on the stove. You get the heat below. Just like warm air rises, warm water rises, it bubbles up, and then the cold water sinks.

Kelley: And that is the type of cloud that frequently keeps tropical jungles moist. And that Joanne Simpson argued convincingly, and it turned out she was right, that [convective storm cells] are the cause of the

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numerous places including Tao and Adler (2003) and the online biography written by John Weier in 2004 available at http://earthobservatory.nasa.gov/Features/Simpson/simpson.php .

[13] 1968–1974 (Wikipedia, "Robert Simpson")

[14] Joanne Simpson herself recounted this story in Taba (1988, pg. 271).

[15] Joanne Simpson and her Ph.D. advisor proposed that 5,000 hot towers ring the equator and contribute the majority of the upward mass flux that drives the general circulation (Riehl and Malkus, 1958).

general circulation.

Stahler: In other words, it is these huge thunderclouds that are lifting most of the air off the tropics and bringing it north and south.

Kelley: And when you have bubbling motion like that, with rapid upward motion, there is a lid that weather can't punch through. And that is the top of the troposphere. So if you have rising motion, especially if it's very fast, [some of that air] has to settle nearby because air doesn't just disappear. This is one reason why convective storms have a well-defined scale. There is a sudden downpour, and right next to it, it's not raining at all or only lightly because you need room for the downdrafts to space out any convective storms that you have coming across.

Stahler: I'm speaking with Owen Kelley. He is a research scientist at Goddard Space Flight Center. He works with TRMM, the Tropical Rainfall Measuring Mission. You are listening to Soundings. I'm Al Stahler.

11:15 How Storm Cells Work

Stahler: So we have this picture of warm air. Warm air rises, and as it rises, it cools, as when you blow in a freezer, and the water vapor condenses into cloud droplets. We are all familiar with sweating. Sweat evaporates off our skin. It takes energy. It takes heat with it. So it takes heat to evaporate water. When water condenses, say on a glass of ice water on a summer's day—same trick backwards. It gives up energy. Just as it takes an extraordinary amount of energy to evaporate water, to boil water, it gives up that exact same amount of extraordinary energy when it condenses. You have tremendous energy in a thunderstorm.

Kelley: The trick is a thunderstorm by itself probably won't last an hour and it may not be over your head for even that full hour.

Stahler: Which is why vegetation in the desert is so spotty. It will green up in one place one year and not at all in another place because the desert will get a thunderstorm and that will water those plants, but half a mile away, nothing.

Kelley: But the interesting question—and building on Joanne Simpson's work—that is where she was leading us to go... These thunderstorms can either be building blocks for larger systems[16] or they can nudge a bigger system, one way or another, to intensify or to just peter out.

Stahler: "Bigger system"? You are not talking about hurricanes yet are you?

Kelley: It can be hurricanes. Another kind of system is a squall line.

Stahler: Let's do that first.

Kelley: Where I live on the East Coast, there is a pattern of very heavy thunderstorms, sometimes with tornadoes. And they form in the afternoon. A line of storms will form off the Appalachian Mountains and then come eastward toward the coast and hit us before sunset. These are called squall lines. They can produce very intense rain and hail and thunder and occasionally tornadoes. [Squall lines] are a line of hot tower storms, and the downdraft of one connects with and can help form the next one. It is a whole system built up of hot towers.

Stahler: If you hold a beach ball underwater and let go, it will pop up. These hot towers are in an atmosphere that is so unstable, so ready for air to rise, that the air just rises and rises, and pops up higher than even normal thunderstorms, which makes it a "hot tower."

[16] See the discussion of single-cell storms, multi-cell storms, and squall lines in Houze (1993).

Kelley: It is not enough that you have enough fuel just waiting to be released. You also need to have a little bit of wind shear. Because without that, if the wind was just calm, then the updraft would shoot up, the water would condense, form drops, and fall down. That falling water would slow down and drag the updraft, and that would kill off the storm within 15 minutes. To get a really strong thunderstorm, you have to have it tilted a little bit. You have to have wind shear so that the winds high up are pushing in a slightly different direction than the winds below. The storm's top isn't where the storm's bottom is, and the rain falls out not on top of the updraft.

Stahler: We are all familiar with scissors being referred to as shears. That is because they have a shearing motion. You have the two blades of the scissors moving in slightly different directions. If you have two layers of wind moving in slightly different directions or even slightly different speeds in the same direction, you've got shear. That will push the storm over.

Kelley: But too much shear will not just push it over gently, but will rip it apart. There are lots of little things like that. Believe it or not, that simple idea of wind shear is an active area of research. Scientists do not know to what degree shear contributes to hurricanes and to what degree it is detrimental.

Stahler: An El Nino year is often good for hurricanes because the trade winds die down up high and you get less wind shear.

Kelley: You get some [shear], so if wind shear is beneficial, then you have enough [shear] to be beneficial to the hurricane, but the higher wind shears happen less often. Everything in the atmosphere is fluctuations on fluctuations on multiple scales. So if you turn down the static a little bit, then you get less destructive wind shear.

Stahler: I am glad you brought that up because, again, you look at the textbooks and you see these beautiful images, cartoons, of the jet stream moving this way and that. But what we are seeing [in these cartoons] is the average velocity of the wind day after day. It is not blowing constantly 24-7.

15:15 The Question of Hurricane Genesis

Stahler: We've got these thunderstorms developing in the tropics. As you say, they will normally last an hour, a few hours, and die down. They are individual, they don't have much of an effect on each other, although as you say, with the squall line, one as it is dying it will build up the next, kind of like dominoes, but that doesn't last forever either. Sometimes over the Atlantic Ocean, 15 degrees or so north of the Equator, thunderstorms can become organized. How can you organize a bunch of thunderstorms?

Kelley: This is actually something that scientists are still trying to figure out. The basic story for how thunderstorms are organized to form a hurricane frequently can be traced all of the way back to Ethiopia on the eastern side of Africa.[17] Winds moving over the Ethiopian mountains dodge to the north and south to get around the mountains, which sets up a wave. So you have air moving north and south across Africa. As you pointed out, there are tropical jungles there with lots of moisture, and that causes thunderstorms to happen in sync with these waves that come across. It's about once every three or four days one of these waves comes off [Africa] and onto the Atlantic Ocean. Over the Atlantic Ocean, there is much more moisture because it's a body of water, obviously. To get the thunderstorms organized, you need two things: you need fuel for thunderstorms, which is moist air, and you need a wave to serve as a nest. These waves that oscillate north and south also have a little bit of circular motion in them. When winds circulate, it can trap the energy that these thunderstorms are releasing. Another way to think about it is take a cup of coffee and take coffee stirrer and stir it around until it

[17] See the NASA video clip on this subject at http://svs.gsfc.nasa.gov/goto?2987 titled "Hurricane Isabel Genesis" produced by the NASA Goddard Scientific Visualization Studio.

looks like a vortex. If there is a little bubble on the surface of that water, you'll see it just circling around and around wherever it is in that vortex. [The bubble] is not going to travel out to the edge. It is trapped within that swirling fluid.

Stahler: And the fuel you say is the water vapor that will condense. That water vapor condensing gives off tremendous amounts of energy.

Kelley: I agree, although some scientists get huffy if you say that, because ultimately the fuel is sunshine. Sunshine is the heat that drives the weather. That heat gets absorbed by the ocean or by the surface of the land. Water evaporates from the ocean surface or from the soil. And only then is water vapor the fuel. There is a whole chain of causation that can be traced back to the sun. What you said is basically correct.

Stahler: Some people like to point out that half of our iPods, iPads, electric vehicles, and all that are essentially powered by coal because it is coal that is generating the electricity.

Kelley: Sometimes it is useful to take a couple of steps back and look at a familiar thing in an unfamiliar way. I am not saying it is bad for scientists to nitpick about what is cause and effect. That's how you sometimes get your good ideas. I think of the fuel of a hurricane as the water vapor that has evaporated from the ocean surface, and then, what happens next is what is interesting to me.

Stahler: What happens is you get thunderstorms. Thunderstorms get caught up in this nest caused by the circulating air. Then what happens?

Kelley: You keep asking me the tough questions.

Stahler: Hah.

Kelley: That is an area of active research. There are students trying to defend their Ph.D. [dissertations] on this very subject. There are probably different ways that it can happen, but the basic picture is you need to get a group of strong enough thunderstorms, releasing enough energy, close together, that you get a warm pool of air. The winds start circulating preferentially around that and you end up with a warm core hurricane. It is feedback between some energy being released, which encourages winds to circle around a little bit more, which helps trap more energy. Eventually, the feedback loop creates something different than just a bunch of thunderstorms over the ocean. You have an organized hurricane hundreds of miles across.

Stahler: If we accept that the fuel of the hurricane is water vapor, and the ash—just like you take ash out of a wood stove—the ash is the condensed water. Just like you can measure the ash taken out of a wood stove to figure out how much wood had been burned, you can measure the raindrops and cloud droplets and figure out how much water vapor has condensed and therefore how much energy has gone into this storm. That is what you are doing with TRMM.

TRMM cannot see energy. Energy is devilishly hard to see. What TRMM sees is the water that once carried that energy, and gram for gram, the water that condensed is a certain number of Joules of energy that have been released in the atmosphere.

Kelley: That is what TRMM does. TRMM can not see energy. Energy is devilishly hard to see. What TRMM sees is the water that once carried that energy, and gram for gram, the water that condensed is a certain number of Joules of energy that have been released in the atmosphere.[18]

[18] 2,500 Joules of energy are released for each gram of water vapor that condenses, and an extra 330 Joules are released higher up in the cloud if that gram of water freezes. In contrast, if a gram of air cools one degree Celsius at constant

Stahler: It is a tremendous amount of energy.

Kelley: Yes it is. To actually get water to evaporate, you need a huge amount of heat. I study hurricanes. I am interested in weather. I am interested in phenomena that occur on scales of hours or minutes, but to understand climate, you need to understand what water vapor is doing and its transformations from liquid to solid, liquid to vapor, and every permutation of that. It's such a huge amount of energy that I think there is a lot of work that needs to be done with that.[19]

20:35 What the TRMM Radar Reveals about Hurricanes

Stahler: Let's take a quick break here. I am talking with Owen Kelley. He is a research scientist at Goddard Space Flight Center. He works with TRMM, the Tropical Rainfall Measuring Mission. You are listening to Soundings. I am Al Stahler. Owen, you take the data and you program computers to turn it into visual pictures of what is going on inside of a hurricane. They are very three-dimensional pictures, and you can see where the air is rising. You can see where the most energy is being given off. What kind of relationships do you see?

Kelley: In a hurricane, the place to look at first is called the eyewall. It is the ring of strong storm clouds that circles the eye. The energy that sustains a hurricane's low-pressure center is released in that ring of strong storms. [The eyewall] can have all sorts of different shapes. It can look literally like a wedding ring, a circle of strong storms uniform in height all of the way around. Sometimes it looks lopsided. Sometimes there is a complete absence of rain on one side of a hurricane. And this tells you nothing for sure, but it gives you clues about a lot of things.

Stahler: As a hurricane is passing over you, you get the most violence as you pass directly under the eyewall. When the eyewall passes, you are in the eye, and it's not like being in the teeth of the storm. The eye of a hurricane is a very gentle place. The sky clears, the winds even die down, until the other side of the eyewall comes in, and you are in the teeth of the storm again.

Kelley: This is a public service announcement: If you've just been through a hurricane and it suddenly looks sunny and calm and warm, you may not be [finished] with the hurricane, you just may be in the eye. In the days before satellites, people frequently made that mistake and went surfing because there were nice waves and sunny weather, and then the other side of the eyewall hits you, and people perish.

Stahler: You are looking at the eyewall with this data from TRMM, and you are turning it into pictures. What you see is clouds rising up tens of thousands of feet, some of them fifty, sixty thousand feet. That's right up to the stratosphere. Those are hot towers.

Kelley: NASA sends airplanes through hurricanes. We've learned in the past ten years or so that, even though it is impressive for a hot tower to reach sixty thousand feet, if you fly a high-altitude jet above that, there can be severe turbulence, clear-air turbulence. The last bits of ice particles have fallen out but there is so much kinetic energy flowing out of these thunderstorms that high-altitude jets in excess of

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pressure only 1 Joule of energy has radiated away (Wallace and Hobbs, 2006).

[19] Pre-industrial CO_2 at 300 parts per million directly accounts for a radiative flux of approximately 25 watts/m^2 (*Houghton*, 2004, p. 25). If the carbon dioxide concentration were to double from the pre-industrial concentration, only an additional 4 watts/m^2 of forcing would occur because the portion of the radiation spectrum affected by carbon dioxide is already near saturation at the pre-industrial concentration (*Houghton*, 2004, p. 24). In contrast, condensing water vapor warms the atmosphere by adding 80 watts/m^2 of latent heat while clouds cool the Earth by reflecting an approximately equal amount of solar energy (*Thomas and Stamnes*, 1999, p. 439). Water's contribution to the Earth's radiation budget is considerable since 235 watt/m^2 of solar energy are absorbed by the Earth and atmosphere (*Thomas and Stamnes*, 1999, p. 439). In addition, the mid-troposphere's humidity has a large influence on the rate of radiative cooling to space. *Mapes* (2001) states that "water vapor is the dominant radiatively active gas even in dry regions of the atmosphere" (see also *Harries*, 1997).

sixty thousand feet have almost had their wings ripped off, and pilots have refused to continue flying the mission because they fear for their lives.[20] The system is even bigger than what TRMM can show you. We can only show you where there are chunks of ice or raindrops that are big enough to fall out of the atmosphere. Water vapor cannot be seen by our radar. We can only see chunks of ice and raindrops.

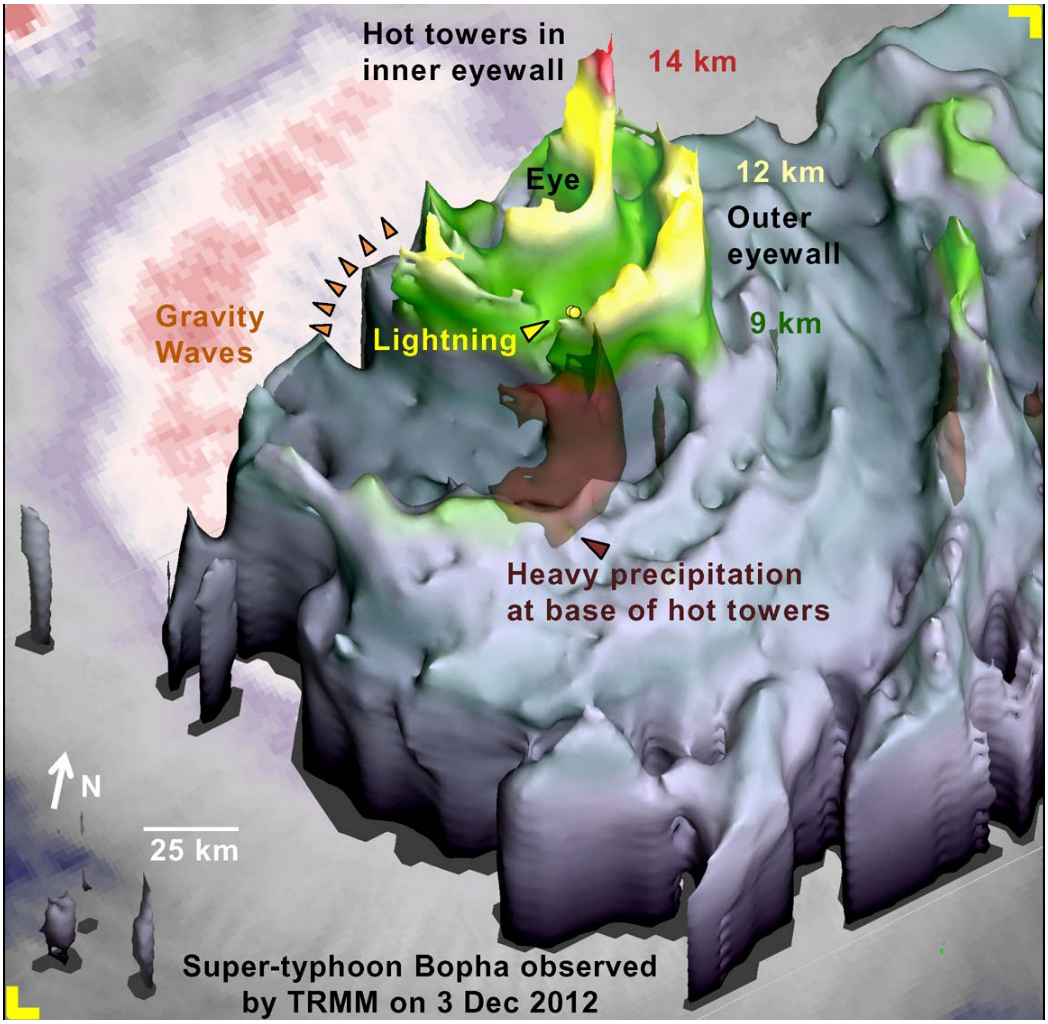
Stahler: When Joanne Simpson began work, half a century ago, she developed this hypothesis of "hot towers," and then with other people she was able to show that these hot towers do in fact exist and they lift tremendous amounts of air and energy off the tropics. But they also seem to have a relationship to the development of the hurricane, and that is work that has kind of petered out over the decades, and then you, in putting together these pictures, spotted some patterns.

I and a number of others have come to think of hot towers as energy pipelines. They are the protected paths by which energy can reach from the ocean into the hurricane. Once there, the hurricane can make use of this energy and convert it into kinetic energy of circling winds that become faster and more destructive.

Kelley: It is not me single-handedly. At least a segment of the research community took a fresh look at Joanne Simpson's fifty-year-old theories when TRMM launched.[21] I and a number of others have come to think of hot towers as energy pipelines. They are the protected paths by which energy can reach from the ocean into the hurricane. Once there, the hurricane can make use of this energy and convert it into kinetic energy of circling winds that become faster and more destructive. There are so many different angles to this. Kerry Emanuel of MIT said that the reason why he cannot stop writing papers about hurricanes is that there are so many subtleties to the problem. It does not ever become boring. And that is certainly true about hot towers.

[20] Halverson et al. (2007, pg. 875)

[21] For Joanne Simpson's application of hot towers to tropical cyclones, see the conclusion section of Malkus (1958). A sample of the related work by others since the 1997 launch of the TRMM satellite: Heymsfield et al., 2001; Kelley et al., 2004; Montgomery et al., 2006; Braun et al., 2006; Hennon, 2006; Heymsfield et al., 2010; Molinari and Vollaro, 2010; Fierro et al., 2011; Guimond et al., 2011.



A tropical cyclone in which the TRMM satellite saw many indicators of eyewall vigor. For a description of this image, visit the NASA Hurricane Resource Page at http://www.nasa.gov/mission_pages/hurricanes/features/BophaFullCatastrophe.html

25:00 Convective Bursts and Hurricane Rapid Intensification

Stahler: You are looking at a hurricane, and there are more or less normal-sized storm cells. Thunderstorms, even though there isn't much thunder over the ocean. These convective storms are circling around the eyewall. And then hot towers appear. What is the significance?

Kelley: Scientists will argue that a hot tower doesn't matter. It's too small. It lasts for an hour or two at best. It's maybe five miles across at best. Okay, it's ten, twelve miles high,[22] that's impressive but so what. There's just not enough energy being released in such a short-lived object to affect the fate of a hurricane. What we really need to be thinking about is something called a "convective burst." A convective burst is a sequence of hot towers that forms on one side of a hurricane's eyewall and that persists for hours, even a full day.

[22] Kelley et al. (2010) provide a TRMM-based census of storm cells over the ocean that lift precipitation-size ice to a 17 to 19.75 km altitude (10.6 to 12.3 miles). Kelley et al. (2004) study storm cells in tropical cyclone eyewall that reach at least 14.5 km high (9.0 miles).

Stahler: This would be like one beach ball popping up out of the water, one after another.

Kelley: Right, sometimes two or three at once. Because a hurricane is a big blender, if you can pump enough energy [into it], it will get mixed up and eventually converted into kinetic energy.

Stahler: Kinetic energy being the energy of motion. In this case, the energy of the wind.

Kelley: Yes, the energy of wind. What the group of researchers that I was part of did was to calculate estimates of how much water was condensing in these hot towers. Based on TRMM observations we can bracket how much water is condensing and multiply by the duration of these convective bursts,[23] which can be nine hours, twelve hours, even twenty-four hours or more. We found that even if you assume that only a small fraction of the energy that is released gets converted into kinetic energy by the machinery of the inner core of a hurricane, there is more than enough energy released by a convective burst, by a sequence of hot towers, [to] intensify the winds. Perhaps, that alone could cause what is called "rapid intensification."

Stahler: Rapid intensification. That is when a category 2 or 3 becomes a cat 4 or cat 5.

Kelley: Right. In a day. A thirty-knot-in-twenty-four-hours wind increase is the rule of thumb.[24]

Stahler: Thirty nautical miles per hour.

Kelley: That may not seem like much to call it rapid, but if you already have something that is traveling at 75 miles per hour, another 30 is enough to make the difference between a scary experience that takes the shingles off your roof and an experience that takes the roof off.[25] Remember, the destructive power of a hurricane goes to some power of the wind speed.[26] There are arguments about that too. Scientists are never satisfied with simple answers.

Stahler: If you double the wind speed, you might double that. So the destructiveness might go up by four times.

The bottom line is that when winds that are already fast increase only a little bit, it can be the difference between a scary-sounding wind and a wind that takes your roof off.

Kelley: By four, or by eight. People have gone around where hurricanes have made direct hits and examined exactly what sort of failures there were and estimated what damage was caused to estimate what is the power relationship between a increase in wind speed and destructive force. There are different rules of thumb. Generally, strong hurricanes are larger, so it is not just that the winds pack more energy when they become a little bit faster but the hurricane also tends to be bigger so a larger area is affected. All these things affect the exact relationship. The bottom line is that when winds that are already fast increase only a little bit, it can be the difference between a scary-sounding wind and a wind that takes your roof off. Rapid intensification is one of the hardest things to forecast. Models do

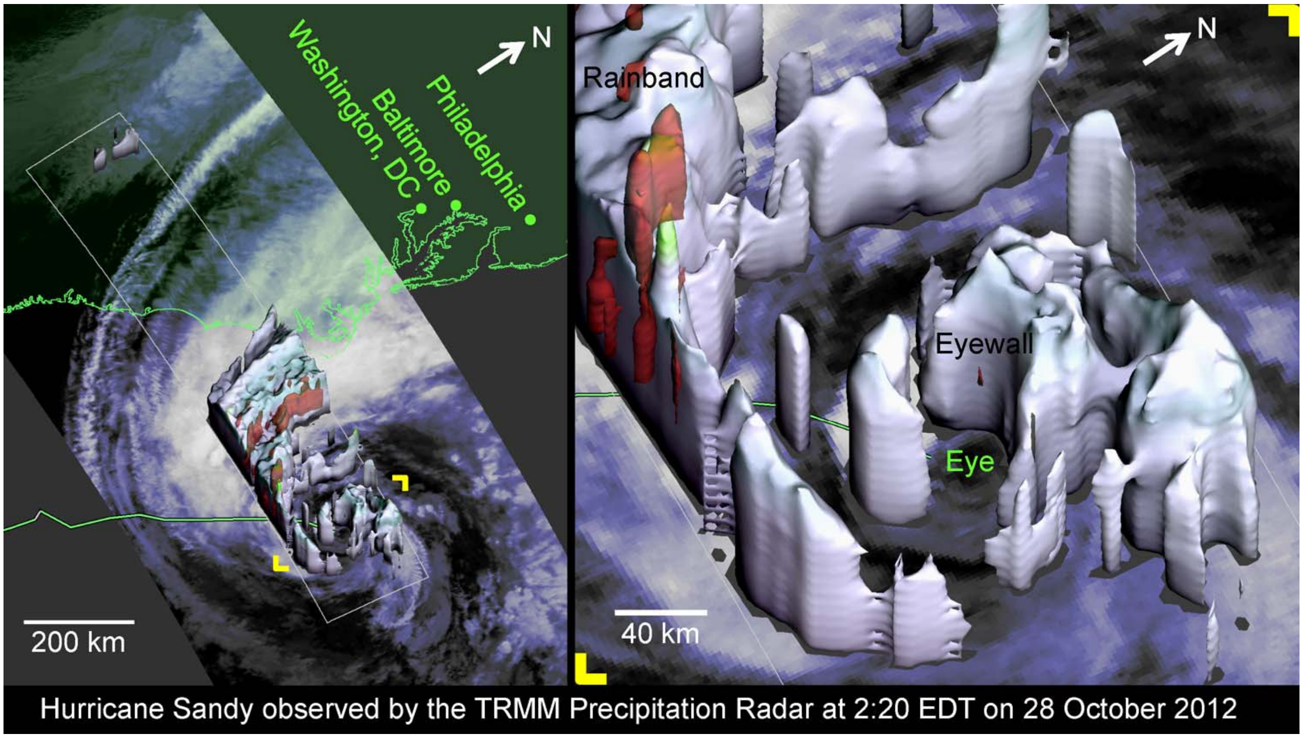
[23] Kelley et al. (2011)

[24] Kaplan et al. (2010, pg. 211).

[25] The National Hurricane Center's website suggests that a category 1 storm (74-95 mph) can remove roof shingles, a category 2 storm (96-110 mph) can remove the plywood sheathing of a roof, and a category 3 storm (111 mph) can demolish a poorly constructed home.

[26] Nordhaus (2006) points out that the ACE index of hurricane destructive potential uses the square of intensity, the PDI index uses the cube of intensity, and Nordhaus' own work suggests as high as the eight power of intensity is proportional to damage. Any such power-law should be seen as a rough approximation, since a category 1 storm, such as Hurricane Sandy (2012) can cause much more damage than other storms with higher intensity in the list of top ten most costly U.S. hurricane landfalls.

not do it very well. The only somewhat successful tool that is in use today operationally to save life and property is a statistical model.[27] Scientists use statistical models when they throw up their hands and say: we don't know the exact physical equations governing this phenomenon. We don't know what is causing hurricanes to rapidly intensify. But we know, by looking in the past, that if the ocean is this certain temperature and the wind shear is this certain amount then there is an increased likelihood of rapid intensification.



For a description of this image, visit the NASA Earth Observatory http://earthobservatory.nasa.gov/blogs/earthmatters/ . Alternatively, view the companion video to the NPR *Science Friday* radio program for 2 November 2012: http://www.sciencefriday.com/video/11/02/2012/sandy-s-ct-scan-and-other-vital-images.html .

29:15 What TRMM Saw in Hurricane Sandy

Stahler: I am talking with Owen Kelley. He is a research scientist at Goddard Space Flight Center. He works with TRMM, the Tropical Rainfall Measuring Mission. You are listening to Soundings. I am Al Stahler. What did Hurricane Sandy look like in TRMM's eyes?

Kelley: I was looking at Hurricane Sandy. It was about a day before it was going to make landfall. They were closing NASA down in Greenbelt, Maryland. In a few hours, they were going to declare Code Red and everyone was going to be ordered off NASA. And we got this amazing overflight that amazingly well captured what was going on in the eyewall.

Stahler: An "overflight" means that the TRMM satellite went right over the hurricane.

Kelley: That's right. The TRMM satellite flew directly over the eye and the eyewall of Hurricane Sandy,

[27] DeMaria (2010)

which is the part of the storm that houses the machinery that transforms warm ocean water into destructive hurricane winds.

Stahler: That machinery is such a tiny bit of the storm itself. If we look at these satellite images, it's this huge storm hundreds of miles across. What is generating that storm is all in a tiny area up in the center.

Kelley: [The eyewall] is about 40 miles in diameter. Different storms are different. They can vary by a factor of three how big they are, but [the eyewall] is still small if you consider that Hurricane Sandy covered basically half the East Coast. Its outer clouds were that big. So yeah, it's a small area, and within that, there are even smaller hot towers that are only five miles across.

Stahler: The machinery of Sandy would be especially interesting because it left the tropics and became an extratropical storm. We have mid-latitude cyclones here all the time. As we record, we are enjoying one here in the foot hills. Those [cyclones] are what bring us our rain in the winter. They are very different from a tropical cyclone, in other words a hurricane. Sandy transitioned.

Kelley: The exact time of transition is subject for debate and will probably take years to figure out. But the idea is that a hurricane's fuel source is warm ocean water that evaporates. The fuel source for the mid-latitude cyclones that travel from California to Washington DC once a week or so... their energy source is driven by weather fronts, temperature differences in large air masses. What happened with Sandy, and where Sandy was relatively well forecast, it could have been worse. What you had was this mid-latitude source of energy colliding with this tropical source of energy, which was the inner machinery of the eyewall of Sandy.

Stahler: That frontal energy was the low-pressure system coming in from the west.

Kelley: Or at least the remnants of it. You could look on the Weather Channel and you would never actually see a circling mid-latitude storm bump into the circling hurricane.

Stahler: With a big "L" in the middle of it.

Kelley: Right. That doesn't happen in nature. It wasn't that obvious. I looked at the cloud loops, and I think I can see some interaction going on, but the trick is, was it significant in allowing energy [to] be converted into energy of wind motion. That you cannot tell just by looking.

Stahler: That is why it is going to take years to figure out just what happened.

What I saw with Hurricane Sandy a day before it made landfall was pretty convincing evidence that the hurricane machinery, the original part of the storm, was functioning. And it was functioning rather well.

Kelley: There is debate already, but partially you have to wait for more data to come in because not all observations are available in realtime. What I saw with Hurricane Sandy a day before it made landfall was pretty convincing evidence that the hurricane machinery, the original part of the storm, was functioning. And it was functioning rather well. There was an intact eyewall. There were no hot towers, which suggests [Sandy] was not intensifying, but then again it was not supposed to be rapidly intensifying. It was on water that was marginally warm enough to sustain a hurricane, it was experiencing strong wind shear, and it ought to be dying out. In fact, it had been limping along as a barely hurricane-category-one-strength storm. The stronger a storm, the better it is as a container of energy, so whatever is released in the eyewall is trapped there. But if you are limping along as a category 1 storm, you are not a very efficient containment vessel. If I had not seen this TRMM overflight, I would have assumed that the storm was donefor and any energy coming in from the mid-latitude system that was merging with it would be too late and the storm would not be too bad. Not that NASA does hurricane forecasts. My opinion did not in any way affect the warnings that the public received, but as a scientist trying to figure out how these storms work, [this TRMM overflight] certainly focused my attention. NASA was about to be closed down, the storm was headed directly toward my parents who live in New Jersey and my brother who lives in New York City, and I wanted to know what the storm was doing. Having a nice 3D shot of the inner workings of what the hurricane was doing was nice.

NASA was about to be closed down, the storm was headed directly toward my parents who live in New Jersey and my brother who lives in New York City, and I wanted to know what the storm was doing.

34:15 The Global Precipitation Measurement Mission

Stahler: You are part of a group at NASA that is developing the next spacecraft to follow on from TRMM. What will it look like?

Kelley: It will look like the big brother of TRMM. The radar on TRMM is the size of a king-size bed. The new satellite, which is supposed to launch in 2014—Global Precipitation Measurement mission—will have two radars. So it will have the king-size bed plus it will have another the size of a crib, which is a different frequency radar. With two frequencies, you can do really interesting things that you cannot do with TRMM. With two frequencies, you can get a sense of whether the chunks of ice high in a storm cloud are large or if there are lots of little chunks. Large chunks of ice reflect a lot of energy. They can fool you into thinking there is a large amount of water that has condensed, when really it's just a few huge chunks. It's called the size distribution. If you know the size distribution, then you get a better handle on the energy transformations. GPM will do that.

Stahler: Different frequencies are affected differently by different-sized chunks of ice. If you only have one frequency then you say: okay, we've got a good echo there and we've got a lot of ice. But if you get a good echo with one frequency and a not-so-good echo with another frequency, you can say: we've got a lot of size and it's all of a certain size.

Kelley: Another advantage is a souped-up version of the passive instrument, the camera without a flash. The GPM passive microwave radiometer will have extra channels, high-frequency channels, that are very sensitive to small ice particles. That is something that is difficult to study any other way. That will help us study [precipitation] far north, and that's a good thing because the reason why there is the "G" in GPM is because it's going global. The TRMM satellite stays in the tropics, whereas GPM goes to the northern regions of Canada, Europe, and Russia. There is going to be a lot of snow we are going to be observing and that will give us a better picture of weather systems, including some very poorly understood systems called "polar lows," which are like miniature, short-lived hurricanes that sometimes form over ice sheets in the arctic and then smash into northern Europe and cause great destruction.

Stahler: One of the mysteries that people have been working on for centuries is how thunderclouds make lightning. And some of the best hypotheses are that ice has something to do with it. Large chunks get broken up into small chunks and they bang into each other. Some of them take the negative charges here and some of them take the positive charges there. By its ability to look at ice clouds, will this next mission give us some clues—I hesitate to say solve the mystery—at least tell us more about how lightning is generated?

Kelley: [GPM] probably will. [Lightning] is not one of the top goals for the mission. Before NASA will fund the creation of a new satellite, there have to be very clearly stated scientific goals. The goals for GPM are things like latent heating, how water vapor releases energy in the atmosphere. Goals of understanding how rainfall gets incorporated into the possibility of floods and landslides and applications like that. Lightning is not the focus of GPM, although there is an interesting development happening at the same time as GPM. There is a world-wide system of lightning detectors on the ground that can detect lightning even that cannot be seen, that's over the horizon. This network is getting better and better. Pretty soon, we'll be able to measure lightning wherever it happens in the world. So having very high-quality rainfall data [from GPM]—which is the other half of lightning because lightning does not form in empty air—will be very useful. Certainly, when you have a lot of lightning in a storm, it tells you that you have some pretty strong updrafts. You look at it more closely.

Stahler: It is always fun talking with you, and this conversation has been delightful. Thank you very much. I look forward to talking with you again.

Kelley: Thank you. I appreciate you taking the time to call us here at NASA.

Stahler: I have been talking with Owen Kelley. He is a research scientist at Goddard Space Flight Center, working with the TRMM spacecraft. For KVMR, I am Al Stahler.

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