RAINDROPS KEEP FALLING ON MY HEAD

BY

KEVIN E TRENBERTH

***Dr Kevin Trenberth** is a climate scientist. He is a Distinguished Scholar at the National Center of Atmospheric Research in Boulder, Colorado, and an Honorary Academic in the Department of Physics at the University of Auckland in New Zealand. From New Zealand he obtained his doctorate from Massachusetts Institute of Technology. He has been prominent in most of the Intergovernmental Panel on Climate Change (IPCC) scientific assessments of climate change and has also extensively served the World Climate Research Programme (WCRP) in numerous ways and many US national committees. He is a fellow of the American Meteorological Society, the American Association for Advancement of Science, the American Geophysical Union and is an honorary fellow of the Royal Society of New Zealand. He has published over 590 articles and books and is one of the most cited scientists in his field. More than anyone else he has promoted how extremes of climate arise from climate change. His most recent book is* The Changing Flow of Energy Through the Climate System, *2022, Cambridge University Press.*

Water, water, everywhere

The rain is pelting down, and visibility is very low even in the middle of the afternoon. Water is all around on the ground and flooding is obviously widespread. At our house, water is flowing into the basement which is flooding. An examination that got me thoroughly drenched reveals a blocked downspout as well as several downspouts emptying their huge deluge from the roof onto the lawn where it is circulated back to a window-well. The latter is one metre deep and full of water; the adjacent window is leaking vigorously into the basement of our house. Climbing a ladder with a broken foot in pouring rain is not recommended but it is what it takes for me to free up the blocked downspout, thereby redistributing the load. Then deployment of some innovative plastic and pipes redirected the downspout flows away from our house (no doubt to the guy next door). But it eased, and even ceased, the flow of water into our basement.

This was the day, Thursday, September 12, 2013, when Boulder, Colorado, smashed all precipitation records with over nine inches of rainfall. It was my fourth time caught up in an extreme weather event—and one I will cover in more detail below.

Climate scientists can tell weather (or not)!

I began my scientific career long ago (1966) in the New Zealand Meteorological Service. For a period, I became a junior weather forecaster, doing shift work. At the same time, I was playing senior level rugby (sometimes against All Blacks, members of the NZ national team). Watching weather go by, I perceived certain weather patterns that affected rugby practice and games. I was fortunate to win a New Zealand Research Fellowship to study for my doctorate at MIT, but on my return to New Zealand, I explored from whence those patterns arose. Analyses of the rather different weather from one year to the next led to discovery of weather regimes: a quasi-biennial oscillation, plus patterns that turned out to be related teleconnections (global-scale wave patterns) associated with the El Niño Southern Oscillation (ENSO).

At that time no-one was working on that topic, but I published a paper in 1976 on my findings that became sort of a classic. I moved with my family from New Zealand to the United States in 1977. Interest in El Niño blossomed soon thereafter, and I was invited to be on a new NOAA committee to explore the topic along with extensive field work (using ships and buoys). In due course, I and others proposed and became involved in the international TOGA (Tropical Oceans Global Atmosphere) Program that was set up in 1985 to explore ENSO as the first project under the new World Climate Research Programme. Climate change was not a public concern at that time, but an ad hoc National Academy of Sciences report chaired by Jule G. Charney was published in 1979 saying it should be. It was not until the 1980s that concern became great enough to establish the Intergovernmental Panel on Climate Change (IPCC) whose first report came out in 1990.

As a junior weather forecaster in New Zealand, I had gained experience in answering queries from the public about all sorts of things related to the weather. It led to my approach in how to explain climate variations. The framing I have always intuitively used is to recognise the huge chaotic variability of weather systems, but also to recognise the maybe small but systematic influences of effects external to the atmosphere, especially the oceans. Fundamentally, if all that is happening is atmospheric variability, then there should be no reason for systematic patterns to occur. Accordingly, when persistent patterns exist, it is a sign of systematic forcing of the atmosphere, the most notable example being El Niño.

Global climate change has only become strongly evident since the late-1970s. As the climate has changed, so too has the environment for all weather systems. Most important are the changes in temperatures in the ocean and atmosphere, and associated changes in water vapour in the atmosphere. The oceans are warmer; accordingly, sea levels are higher and the air over the oceans is warmer. Because the water-holding capacity of the atmosphere depends strongly on temperature—it increases seven percent per degree Celsius—there is also a direct relationship with humidity and there is now more moisture over the oceans by five to 15 percent compared with pre-1970 values. Accordingly, as cyclonic weather systems reach out and bring the low-level moist air into the system, precipitation intensity increases. It rains harder! That in turn releases latent energy into the weather system, potentially making it more intense, bigger and longer lasting.

Of course, none of us experience global climate directly. It is one thing to write about what we think is happening to weather in association with weather regimes, teleconnections and climate change, but it is through each individual event that we experience it.

And, it turns out, I have experienced more than my share of disasters: the *Wahine disaster* in Wellington, New Zealand, 10 April

1968; *Lower Hutt flooding*, New Zealand, 20 December 1976; *Superstorm Sandy*, New York, 29-31 October 2012; and *Record flooding in Boulder*, Colorado, 9-16 September 2013. The first two were before climate change was a factor, but the last two were clearly made worse by climate change.

The *Wahine disaster* was caused by a rapidly developing hybrid storm (ex-hurricane with extratropical influences) with local winds up to 168 mph in Wellington. I was caught out in the storm and my small Austin car had the paint sand-blasted off in places. I reached the Met. Office about 10am just as peak wind gusts of 123 mph were recorded there, and I had tremendous difficulty getting from where my car was parked into the building. Four times I rounded a corner of the building to make a beeline for the main entrance, but I was knocked back.

I was fortunate to be able to observe a lot of subsequent developments from the Met. Office, about 150 metres above the main city, in relative safety. Debris and bits of roofs were flying all over the place. The inter-island ferry, *Wahine* (a roll-on, roll-off ship 150 metres in length) carried many cars and had 610 passengers and 123 crew on board. Fifty-three people lost their lives when the ship foundered on Barrett Reef at the entrance to Wellington Harbour and capsized. The wrecking of the *Wahine* is by far the best-known maritime disaster in New Zealand's history. On the same day, some 98 houses in Wellington lost their roofs. Insurance industry payouts exceeded $200 million (2008 NZD) on 3,657 claims. While climate change was not factor, the hybrid nature of the storm was a preview of *Superstorm Sandy*.

In 1976, my family and I lived in Normandale, a suburb on the western hills overlooking Lower Hutt, New Zealand, about 20 kilometres northeast of Wellington. *The Lower Hutt flooding* on 20 December was a rare rainfall event that dropped 280mm of rain in our neighbourhood. The weather situation produced very high levels of water vapour in the atmosphere, a forerunner to a climate change signal in more recent floods. Many slips pushed houses off foundations, destroyed some houses and cars and caused power failures. Ground slope failure and mud flows were common, and it was estimated that there were some 925 slips in the area. Over 100 families were evacuated.

It took me many hours to get home to my wife and two-year-old daughter that day from the Met. Office, and it was fortunate that there was another indirect route to our house near the crest of the hills. While our house was sound, it was located near the top of a fairly steep hill, and a huge chasm opened up from erosion on the next property to the south. Our house was cut off from Lower Hutt for weeks and damage was severe all around us, right at Christmas time. The cost was estimated as $205.2 million (2009 NZD). As of 1995, it was New Zealand's most expensive flood.

Superstorm Sandy caused tremendous damage when it made landfall on the New Jersey coast and New York area on Tuesday, 30 October 2012. It began as a hurricane but became a huge hybrid storm as it moved erratically north before making landfall. The worst problems on the Jersey Shore were caused by the strong winds and the associated storm surge, leading to extensive flooding. Farther inland, heavy precipitation was also a major problem. Widespread damage from flooding streets, tunnels and subway lines plus cuts of power in and around New York City led to damages exceeding $65 billion (2013 USD) and more than 110 lives were lost in the New York and New Jersey area.

Superstorm Sandy was the first disaster I had a personal connection to where climate change was a factor. Climate change made the storm much more powerful than it otherwise would have been–and made it clear that our warming climate was changing the scale of what humankind can expect from 'natural' disasters.

I was involved in two different ways with *Sandy*, one professional and the other very personal. I was in Boulder at the time. From there I wrote several popular articles that were published in many places, as well as a scientific article on the role of climate change in *Superstorm Sandy*, and I spent several days in dealing with the media, including appearing on NBC Nightly News and local TV. Meanwhile my wife Gail was visiting my daughter and other family in Hoboken, New Jersey: ground zero.

I had alerted them of the prospects for a severe storm a week ahead based on the ECMWF forecast, which was excellent. They prepared well, given they had a garden level apartment with the first floor below the road, but they were evacuated. The area lost power for a week.

Fortunately, their place was okay as sandbags kept the water out. A week later my daughter and family returned home, but Hoboken was still in terrible shape with nothing in stores, some roads closed and no train to New York (through tunnels underneath the Hudson River). Commuting to New York City, where both my daughter and her husband worked, was not possible as the New York financial district not only had no power, their backup was gone, and they also had no heat.

Record flooding in Boulder: 9–16 September 2013

Yet another major flooding disaster—and one also shaped by climate change—was the one my family I experienced in September 2013, at our home in Boulder. Boulder lies about

40 kilometres northwest of Denver at the base of the foothills of the Rockies, at 5,400 feet (1,646 metres) above sea level. Consequently, it can be subjected to upslope rains: the wind direction matters a lot.

In this case, I was on travel in Europe as the storm began and I strived, in the middle of the event, to return home where my wife, Gail, was struggling to deal with some basement flooding in our house. On Thursday September 12, there was over nine inches (23 centimetres) of rainfall in Boulder and the eight-day total was over 17 inches (43 centimetres), both roughly double previous high values.

Starting on September 11, 2013, a slow-moving cold front stalled over Colorado, clashing with warm humid monsoonal air from the south. The situation intensified on September 11 and 12. Boulder County was worst hit, although the whole front range was affected. At least eight deaths were reported and more than 11,000 people were evacuated. Many buildings suffered severe damage and over 19,000 homes were damaged to some extent.

Throughout the storm, it was known that rain was falling, but amounts were grossly underestimated because the radar reflectivity gave wrong answers, owing to the tropical nature of much of the heavy rains. Accordingly, those monitoring the rainfalls greatly underestimated the flood risk. In Denver the three highest atmospheric total column water vapour amounts ever recorded for September (since 1956) occurred on 12–13 September 2013 (as high as 34 millimetres). This may not seem huge, but recall Denver is a mile (more than 1,600 metres) above sea level.

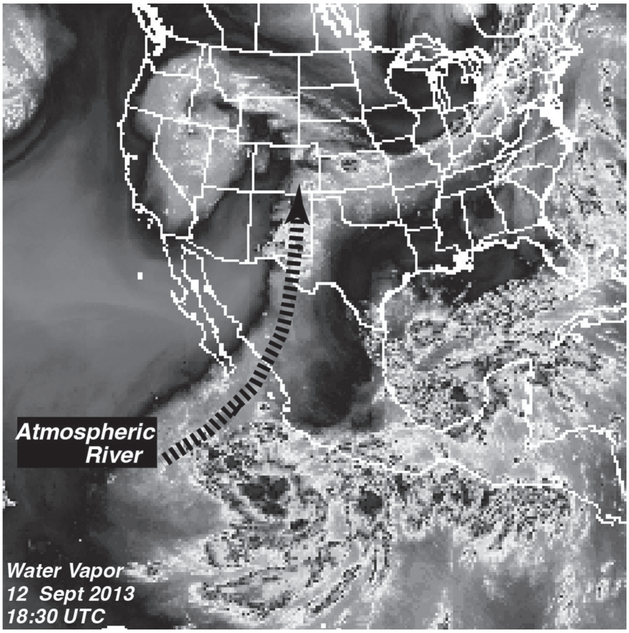

Fig. 1. Water vapour channel imagery for 18:30 GMT on 12 September 2013 showing the extensive water vapour and associated activity both west of Mexico and in the Caribbean Sea and the river of moisture from south of Baja, Mexico to eastern Colorado. Adapted from NOAA.

It so happens that the sea surface temperatures (SSTs) off the West Coast of Mexico, south of Baja, west of Guadalajara, were over 30 degrees Celsius—more than one degree Celsius above normal—in August 2013. This made it the hottest spot in the ocean in the western hemisphere. An incredible 75 millimetres of total column water vapour was recorded in the atmosphere in that region by NASA satellites.

The high SSTs led to the large-scale convergence of moisture flowing that was siphoned north by a very unusual synoptic situation. This led in turn to a river of atmospheric moisture flowing into Colorado. After that atmospheric river shut off, twin tropical storms formed both sides of Mexico: Manuel (to the west) and Ingrid (to the east). This created a double whammy for Mexico, leading to hundreds of deaths, tens of thousands evacuated, tens of thousands of homes damaged and billions of dollars of damage.

SSTs have been as high in the past in this region west of Mexico, but in previous cases they were part of a much larger-scale pattern associated with El Niño events such as in 1997-98, 2004-5, 2009-10. What seemed unique in 2013 was that this was the warmest spot in the Western hemisphere and hence this was the preferred location for low pressure to form and low-level wind convergence, which brought large amounts of moisture into the region. Hence there was clearly an internal variability component to the patterns of SST. At the same time, however, the overall increase of global SST associated with global warming occurring on multi-decadal time scales was also a factor.

Meanwhile, I was at a conference in Graz, Austria, and on the last day (Wednesday) the conference finished a bit early and some of us were taken on a journey to a castle that was somewhat nearby—only 50 kilometres away. We were nearly there and stopped to take pictures of the castle in the distance when I had an accident. I failed to see a curb, fell heavily, and broke a bone in my foot. I did not realise it was broken at the time and so we went to the castle and walked quite a long way (hobbled for me).

I had no time for treatment as I flew back to Denver partly overnight via Frankfurt. A colleague, Bill Kuo, was on the same flight and we arrived back on Thursday in the middle of the major storm during the heaviest rainfalls. We were unable to get a bus to Boulder but shared a cab ($100; double normal costs) and we barely made it into the city before route US36, the main highway between Boulder and Denver, closed. The cabbie was probably stuck in Boulder unless he had the wherewithal to make it out via South Boulder Road. Bill dropped me off and I arrived home to flooding and a deluge.

The back yard was flooded and so was the basement, with about two to three inches (five to seven centimetres) of water, although the sump pump worked. Hence, I had to climb the ladder (all with a broken foot) to clear the downspout (in pouring rain) and reroute and extend the downspouts at ground level to redirect the water from the roof and prevent it from circulating into the window wells. I got soaked, but it worked. Gail and I used a water vac and sucked up the water in the basement to get that under control. The basement was unfinished and so the damage was minimal.

The next day, Friday, the rain eased but devastation was everywhere. Masses of water lay where it shouldn't, many roads were washed out and there was much debris; at least eight deaths were reported and more than 11,000 were evacuated. For some it took years to recover.

There were no Urgent Care facilities open. Boulder Medical Center was entirely closed and Boulder was effectively shut down. I was eventually able to get seen in the emergency ward of the new Boulder Community Hospital at Arapahoe and Foothills although they also had some flooding. They confirmed that the foot was broken and put me in a 'boot'. I was subsequently x-rayed every three weeks and I wore the damn thing for 12 weeks. Then my foot would not work; it was swollen and needed physical therapy. I took trips to London, Beijing, Wichita KS and

New Haven CT (Yale) wearing the boot. My experience finding medical assistance for my broken foot made it starkly clear to me how difficult it could be for other natural disaster survivors to access the treatment they need.

As well as my own published study on this event, there have been several others, with disparate conclusions regarding the role of climate change. Some studies note the unusual weather situation that led to the unprecedented atmospheric river into Boulder and concluded the cause of the event was natural variability. Indeed, the exact setup, no doubt, was dominated by chance. But that statement says nothing about the role of the record high SSTs and the fact that climate change was responsible for at least a significant fraction of that. It is important to ask the right questions. None of the model-based studies were able to replicate the event and part of this is because of inadequate model resolution to be able to represent the structure of the Rockies, in particular.

The most definitive study was not published until 2017. It used an approach that specified the weather pattern and ran a high-resolution model multiple times with and without changes in SSTs from climate change, estimated elsewhere. The result was that anthropogenic drivers increased the magnitude of heavy northeast Colorado rainfall for the wet week in September 2013 by 30 percent. Locally these effects were further amplified on the ground as runoff waters drained into channels and rivers.

Do something!

Disasters of course occur without climate change being a factor, but climate change influences typically make them worse—sometimes much worse. In most respects, my family and I came through the above disasters relatively well compared with many others. For us, it was mostly bad luck: being in the wrong place at the wrong time. But clearly some places are more vulnerable than others, especially as climate change rears its head. In fact, climate change concerns are one reason my family and I now live in New Zealand. It is also prudent to consider the flow of water around and through any place one chooses to live in, as I have done.

It is also important for communities to take measures to build resilience to any possible event. This is often done in wealthy countries, and the available infrastructure can help enormously when a surprise event does take place. But it is not always the case, and I have been surprised at how poor the infrastructure is in many places, largely because of the failure of communities to tax themselves to build adequate drainage systems. This happened in Houston with Hurricane Harvey in 2017 and Florida with Irma (also 2017) and Ian (2022).

The ability to prepare for disaster is also unfortunately much less the case in developing countries. And too many people, often with few other options, are building on flood plains, such as in Pakistan, where they were badly flooded in 2022. Many developing countries and small island states have not contributed much to the problem of climate change but are suffering disproportionately from the consequences.

Given that climate change contributed to the Pakistan disaster by increasing rains by up to 50 percent, and that over 1,600 people died and more than two million homes were destroyed, the question of reparations arises. At COP27 in Egypt in November 2022, 'loss and damage' was one major concern that received overall support, although it is unclear how well it will be funded and how it would work.

Human-induced effects through increases in heat-trapping gases in the atmosphere continue, and warmer oceans and higher sea levels are guaranteed. As we have seen in 2022, whether from drought, heat waves and wildfires, or floods and super storms, there is a cost to not taking action to slow climate change, and we all are experiencing this now.

According to a quote from the late 19th century, often attributed to Mark Twain, 'Everybody talks about the weather, but nobody does anything about it.' Now humans are changing the weather, and still nobody does anything about it!