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Attribution of climate extreme events

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37 **There is a tremendous desire to attribute causes to weather and climate events**
38 **that is often challenging from a physical standpoint. Headlines attributing an**
39 **event solely to either human-induced climate change or natural variability can be**
40 **misleading when both are invariably in play. The conventional attribution**
41 **framework struggles with dynamically-driven extremes because of the small**
42 **signal-to-noise and often uncertain nature of the forced changes. Here, we**
43 **suggest that a different framing is desirable, which asks why such extremes**
44 **unfold the way they do. Specifically, that it is more useful to regard the extreme**
45 **circulation regime or weather event as being largely unaffected by climate**
46 **change, and question whether known changes in the climate system's**
47 **thermodynamic state affected the impact of the particular event. Some examples**
48 **briefly illustrated include “snowmageddon” in February 2010, super storm Sandy**
49 **in October 2012, and super typhoon Haiyan in November 2013 and, in more detail,**
50 **the Boulder floods of September 2013, all of which were influenced by high sea**
51 **surface temperatures that had a discernible human component.**

52
53 Weather and climate extremes happen all of the time, even in an unchanging climate. Yet
54 there is a justifiably strong sense that some of these extremes are changing to be more
55 frequent, and that the main reason is because of human-induced climate change. Indeed,
56 the main way climate change is likely to be manifested on societies around the world is
57 through changes in extremes. As a result, the scientific community faces an increasing
58 demand for regularly updated appraisals of evolving climate conditions and extreme
59 weather. Such information would be immensely beneficial for adaptation planning.

60
61 The large-scale atmospheric circulation determines where it is dry, where it is wet, where
62 it is hot, and so on. A recent example is documented for the Pacific Northwest¹. Yet as
63 discussed below, in contrast to thermodynamic aspects of climate, forced circulation
64 changes in climate models can be very non-robust, and physical understanding of the
65 causes of these changes is generally lacking². Therefore, we suggest that separating out the
66 thermodynamic from dynamic effects may be a very fruitful way forward and result in a
67 different set of questions to be addressed. In turn, these provide a better basis for
68 communication of climate change to the public.

69 70 **Complexities associated with extreme event attribution**

71
72 The climate community has responded to the demand for timely information by attempting
73 to perform attribution of climate extremes, both through the Intergovernmental Panel on
74 Climate Change (IPCC)³ reports but most evident in closer to real time through an annual
75 report, the most recent of which — *“Explaining extreme events of 2013 from a climate*
76 *perspective”* — was published by the American Meteorological Society in September 2014⁴
77 and reported on several events from 2013. The question posed in each case was whether
78 the likelihood or strength of the event was affected by anthropogenic climate change.

79
80 More generally, there are perhaps two main kinds of attribution performed. The first
81 relates the particular extreme event to the associated weather and weather patterns, and
82 this has been a useful and long-standing activity in climate science. We hear statements

83 like “the drought was caused by a blocking anticyclone”; or the “outbreak of tornadoes was
84 caused by a displaced and active storm track and jet stream”; “the flooding was caused by
85 El Niño”, and so on. However, because these studies relate the event and phenomenon to
86 the weather situation or weather pattern, they are really a description of the event, not a
87 cause. As an explanation, the question should be, “why did that weather phenomenon
88 behave the way it did?” In particular, “what influences external to the atmosphere were
89 playing a role and what climate factors were in play?”

90
91 The second kind of attribution relates especially to the objective of assessing the role of
92 human activities, and especially human-induced climate change in the event. Or perhaps
93 this might be generalized to a goal of assessing the role of external influences in the climate
94 system on the event in question. So as well as human influences there may be influences
95 from volcanic eruptions or the sun. However, results depend upon how questions are
96 framed⁵⁻⁷.

97
98 The conventional approach to attribution of climate events is described by Stott et al.⁸.
99 Clearly, it is not possible to attribute a single climate extreme event, which by definition is
100 unique and which has a large element of chance in its occurrence, to a specific cause. Thus,
101 the approach is to characterize the event and ask (i) whether the likelihood or strength of
102 such events has changed in the observational record, and (ii) whether this change is
103 consistent with the anthropogenic influence as found in one or more climate models, and
104 thereby assess the “Fraction of Attributable Risk”. The conventional approach has had
105 considerable success with extremes that are strongly governed by thermodynamic aspects
106 of climate change, especially those related to temperature. Since the attribution is
107 unconditional — the null hypothesis is that there is no effect of climate change — each
108 finding provides another independent line of evidence that anthropogenic climate change
109 is affecting climate extremes.

110
111 However, the conventional approach is severely challenged when it comes to climate
112 extremes that are strongly governed by atmospheric circulation, including local aspects of
113 precipitation. The main reason is because changes in the atmospheric circulation related to
114 climate change are fairly small compared to natural variability, as has been shown
115 especially by several studies at NCAR using “large ensembles”^{9, 10} for 60 years into the
116 future. While large changes in atmospheric circulation can be readily apparent in a single
117 climate model run, they are not robust and change a lot in the next run or model. Indeed
118 what have often been interpreted as differences between models used in IPCC reports may
119 have arisen at least in part from natural variability. Hence forced circulation changes are
120 not well established and it is difficult to detect changes in circulation-related extremes in
121 observations because of small signal-to-noise. Thus, the anomalous weather pattern is
122 *always* the dominant influence for all short-lived events of a week or two, and this is
123 generally true even for years or decades. Accordingly, the conventional approach to
124 extreme event attribution is rather ineffectual in cases that rely on the changed circulation,
125 with generally an inconclusive outcome. Even when a detectable anthropogenic influence is
126 found in a model, the reliability of that finding cannot carry much weight.

127

128 Yet from a risk perspective, it is still important to assess the likely anthropogenic impact on
129 such events. By starting from the null hypothesis of no climate change, the conventional
130 approach to extreme-event attribution has to re-establish an anthropogenic influence for
131 each kind of event *ab initio*, which makes it inherently conservative and prone to “Type II
132 errors” which underestimate the true likelihood of the human influence^{5,6}. Given that we
133 have a large amount of confidence in many aspects of climate change³, it seems rather
134 peculiar to ignore that prior knowledge in our assessment of climate events⁵.

135

136 As noted above the predictability of the dynamics is problematical² and it is mainly through
137 the thermodynamics that reliable statements can be made with confidence about the role
138 of climate change. In other words, changes in temperatures and temperature extremes
139 have a much more robust basis. That carries over to the atmospheric moisture amounts
140 through the Clausius-Clapeyron equation in which the water-holding capacity of the
141 atmosphere goes up exponentially at a rate of about 7% per degree Celsius. Indeed this is
142 what is observed in actual changes in moisture in the atmosphere over the oceans and
143 where surface moisture is not limited. But over land, especially in summer, water
144 availability is also a vital factor¹¹. Because the main rainfall almost always comes from
145 moisture convergence in the atmosphere, increased water vapor in the environment leads
146 to more intense rains and a risk of flooding^{12,13}, even if the total amount does not change
147 much. Moreover, it is in droughts that the extra heat from increased greenhouse gases
148 accumulates whereas more generally the presence of surface moisture adds an evaporative
149 cooling effect.

150

151 **More fruitful scientific questions**

152

153 One can ask questions such as: *What was the role of internal natural variability in setting up*
154 *the pattern?* Studies to explore this question include those documenting the role of
155 anomalous SSTs and especially El Niño-Southern Oscillation (ENSO), the Pacific Decadal
156 Oscillation (PDO)¹⁴, the North Atlantic Oscillation (NAO), and other so-called modes of
157 variability. In general, it may not be possible to say much concrete about regional climate
158 change unless one can understand and predict such modes of variability and their statistics.
159 ENSO may be predictable for up to 18 months or so, some decadal predictability may exist
160 for decadal modes for several years¹⁵, but in general chaotic elements in the weather and
161 climate system preclude longer-term statements because these regional patterns are not
162 externally forced.

163

164 In most of these cases, the result of these studies will be a description of the large-scale
165 patterns, the anomalous SSTs, and the relationships between the atmospheric circulation,
166 storm tracks, blocking, temperatures and precipitation, and perhaps extremes. If
167 considered, this part will undoubtedly conclude that greenhouse gas forcing or aerosols
168 played little or no role in the circulation changes, although sometimes claims otherwise are
169 made.

170

171 Instead, with regard to climate change, the questions to be answered could be:

- 172 • Given the weather pattern, how were the temperatures, precipitation, and
173 associated impacts influenced by climate change?

- 174 • Given a drought, how was the drying (evapotranspiration) enhanced by climate
175 change and how did that influence the moisture deficits and dryness of soils, and
176 wild fire risk? Did it lead to a more intense and perhaps longer lasting drought, as
177 is likely^{16, 17}?
- 178 • Given a flood, where did the moisture come from? Was it enhanced by high ocean
179 temperatures that may have had a climate change component?
- 180 • Given a heat wave, how was that influenced by drought, changes in precipitation
181 (absence of evaporative cooling from dry land), and extra heat from global
182 warming?
- 183 • Given extreme snow, where did the moisture come from? Was it related to higher
184 than normal SSTs off the coast or farther afield?
- 185 • Given an extreme storm, how was it influenced by anomalous SSTs and ocean heat
186 content, anomalous moisture transports into the storm, and associated rainfall and
187 latent heating? Was the storm surge worse because of high sea levels?

188 In other words, given the change in atmospheric circulation that brought about the event,
189 how did climate change alter its impacts?

190

191 To summarize therefore, at least in the present state of knowledge, in our view a more
192 fruitful and robust approach to climate extreme-event attribution is to regard the
193 circulation regime or weather event as a conditional state (whose change in likelihood is
194 not assessed), and ask whether the impact of the particular event was affected by known
195 changes in the climate system's thermodynamic state (e.g., sea level, sea surface
196 temperature, or atmospheric moisture content), concerning which there is a reasonably
197 high level of confidence. Such questions immediately lead to a physically-based approach
198 that is strongly linked to the event in question. Although such questions differ from the
199 conventional "frequentist" approach, they are perfectly reasonable from a Bayesian
200 perspective, which can accommodate questions about single events¹⁸. Because the
201 questions are posed differently, their answers have a different meaning and focus more on
202 impacts. That is still useful information.

203

204 Frequently, the main influences identified external to the atmosphere are the changes in
205 SSTs. Of course the SSTs at any time have a large natural variability component but the
206 values are very often inflated over what they would have been without climate change. The
207 latter accounts for order 0.6°C increase since the 1950s globally³ and because this
208 inherently occurs on multi-decadal timescales with a memory through the ocean heat
209 content, it is always present. Small increases in atmospheric moisture associated with
210 such an increase in SSTs are of order 5% (ref. 19). We also assume that the global sea level
211 rise for the past century of 19 cm (1901-2010)³ reflects the underlying human influence
212 while regional values vary owing to atmospheric circulation variations.

213

214 **Some examples**

215

216 The following examples briefly discuss a few events whose attribution has not been
217 addressed but which received an enormous amount of media attention.

218

219 Consider the widely publicized event called “snowmageddon” in Washington, DC²⁰ in
220 February 5-6, 2010. Key features included (1) it was winter and there was plenty of cold
221 continental air; (2) there was a storm in the right place; and (3) the unusually high SSTs in
222 the tropical Atlantic Ocean (1.5°C above normal) led to an exceptional amount of moisture
223 flowing into the storm, which resulted in very large snow amounts. It is this last part that
224 then relates in part to anomalous external influences on the atmosphere through the effects
225 of climate change on SSTs. So while internal variability is also playing a role, the extremes
226 are magnified by climate change.

227

228 Super-storm Sandy caused tremendous damage when it made landfall on the New Jersey
229 coast and New York area on 30 October 2012. It began as a hurricane, with peak strengths
230 making it a category 3 storm, and it caused substantial impacts in the Caribbean²¹.
231 However, as it moved north it became a hybrid storm before making landfall, which greatly
232 increased its overall size. The worst problems on the Jersey Shore were caused by the
233 strong winds and the associated storm surge, leading to extensive flooding. Farther inland,
234 heavy precipitation was also a major problem. Widespread damage from flooding streets,
235 tunnels and subway lines and cutting power in and around New York City led to damages
236 exceeding \$65 billion (2013 USD)²². Fortunately, the storm was well forecast a week in
237 advance in particular by European Centre for Medium-Range Weather Forecasts (ECMWF),
238 including the very unusual left hook turn in the track toward the coast. ECMWF has
239 performed a number of experiments on the performance and behavior of the storm using
240 an ensemble of forecasts five days in advance of landfall²³. Of note is that they swapped the
241 observed SSTs for climatological values that average 1 to 1.5°C cooler in a broad strip along
242 the coast. Only small changes occurred to the track of the storm but the observed SSTs led
243 to a bigger more intense storm, stronger winds and greater precipitation. The average
244 depth of the storm was increased by 7.6 hPa, the wind speeds were increased by 3.6 m s⁻¹
245 and the precipitation increased by 35%. Moreover the storm was riding on sea levels that
246 were higher by about 19 cm due to global warming. Although perhaps only one-half to
247 one-third of the SST increase can be blamed on global warming from human activities, it is
248 readily apparent that the storm surge and associated damage was considerably influenced
249 by climate change. It is quite possible that the subways and tunnels may not have flooded
250 without the warming-induced increase in sea level and storm intensity and size, putting a
251 potential price tag of human climate change in this storm in the tens of billions of dollars.

252

253 Another example is super typhoon Haiyan²⁴ that devastated the Philippines in early
254 November 2013. It is among the largest and most intense typhoons on record with
255 estimated surface pressure in the eye down to 895 hPa and 1-minute sustained winds of
256 315 km/h (gusts to 378 km/h) on November 7, 2013 which makes it the strongest
257 recorded storm to ever strike land (Fig. 1). It has been called a “category 6” storm²⁵. The
258 ocean heat content (OHC) and sea level in the region had increased a great deal since 1993
259 and especially since 1998 in association with the PDO negative phase^{26, 14} so that since
260 1993 the linear trend in sea level was over 16 mm/yr as compared to the global trend of
261 3.3 mm/yr (Fig. 1; using data from AVISO²⁷). Consequently, as the typhoon approached the
262 Philippines, it was riding on very high SSTs with very deep support through the high OHC,
263 and the strong winds and ocean mixing did not cause as much cooling as would normally
264 be experienced, very likely helping the storm to maintain its tremendous strength²⁵.

265 Moreover, the storm surge was undoubtedly exacerbated considerably by the sea levels
266 that were some 30 cm above 1993 values. Although natural variability through the PDO
267 played a major role, there is also a global component through increased OHC from the
268 Earth's energy imbalance²⁸.

269
270 A conclusion then, is that while climate change is no doubt altering the atmospheric
271 circulation, the change is relatively small and can only be discerned from a very large
272 ensemble of model runs. That sets the change in odds. But for any event, the particular
273 character of that storm or synoptic situation and natural variability rule, while
274 thermodynamic effects increase the impacts.

275 276 **A case in point: the Boulder floods of September 2013**

277
278 One of the recent BAMS studies is of the major floods centered in Boulder in September
279 2013²⁹. The unfortunate headline of the news release which carried over in large letters to
280 the front page of the local newspaper in Boulder (*Daily Camera* 30 Sept 2014)³⁰ was:
281 "*Climate change not to blame for 2013 Colorado floods*". The paper summary was: "The
282 probability for an extreme five-day September rainfall event over northeast Colorado, as
283 was observed in early September 2013, has likely decreased due to climate change."

284
285 As noted above, in any weather event like this, the weather situation is always the main
286 player in the developments but that in and of itself says nothing about the role of climate
287 change. The study did note the importance of having abundant moisture in the region in
288 order to produce high rainfall amounts. But it did not include an assessment as to where
289 the moisture came from. In Denver the three highest total column water vapor amounts
290 ever recorded for September (since 1956) occurred on 12-13 September 2013 (as high as
291 34 mm). [This may not seem huge but recall Denver is a mile (>1600 m) above sea level].

292
293 It so happens that the SSTs off the West Coast of Mexico, south of Baja, west of Guadalajara,
294 were over 30°C and more than 1°C above normal in August 2013 (see Fig. 2), which made it
295 the hottest spot for the ocean in the western hemisphere. An incredible 75 mm of total
296 column water vapor was recorded in the atmosphere in that region by NASA satellites. The
297 high SSTs led to the large-scale convergence of moisture flowing into the region that was
298 siphoned north by a very unusual synoptic situation leading to a river of atmospheric
299 moisture flowing into Colorado (Figs. 3 and 4). The heaviest moisture convergence into
300 eastern Colorado coincided with the times of the plots in Fig. 4, while breaks in the rain
301 occurred in between times in some locations (Fig. 3). After that river shut off, twin tropical
302 storms formed both sides of Mexico: Manuel (to the west)³¹ and Ingrid (to the east)³² (Fig.
303 5) that formed a double whammy for Mexico and led to hundreds of deaths, tens of
304 thousands evacuated, tens of thousands of homes damaged and billions of dollars of
305 damage^{31, 32}.

306
307 Experience with simulations of atmospheric rivers at NCAR has shown that quite high
308 resolution of order one quarter the size of that used by Hoerling et al.²⁹ is required to
309 perform realistic simulations, and coarse resolution can lead to discrepancies in the
310 atmospheric moisture amounts simulated. Hoerling et al.²⁹ is likely correct in concluding

311 that the set up of weather systems was rare, and climate change is not a discernible factor
312 in that respect. However, one cannot realistically do attribution using a model that does
313 not have the requisite spatial resolution to represent the relevant dynamics and is unable
314 to replicate the event in question, and it is desirable to use more than one model. Moreover,
315 the extremely high SSTs and record water vapor amounts that accompanied the event and
316 were instrumental in its evolution likely would not have occurred without climate change.
317 Even a 10% increase in moisture in the atmosphere becomes concentrated when focused
318 by topography, and further amplified when on the ground as water drains into channels
319 and rivers.

320

321 SSTs have been as high in the past in this region west of Mexico (Fig. 2), but in previous
322 cases they were part of a much larger-scale pattern associated with El Niño events such as
323 in 1997-98, 2004-5, 2009-10. What seems to be unique in 2013 is that this was the
324 warmest spot in the western hemisphere and hence this was the preferred location for low
325 pressure to form and low-level wind convergence, which brought large amounts of
326 moisture into the region. Hence there was clearly an internal variability component to the
327 patterns of SST, but at the same time, the overall increase of global SST associated with
328 global warming that occurs on multi-decadal time scales was also a factor. In Fig. 2 this
329 warming is especially evident after 1997 when SSTs average $>0.4^{\circ}\text{C}$ above the mean.

330

331 **Concluding remarks**

332

333 We have suggested four climate events in which anomalously high SSTs played a key role in
334 feeding moisture into storms, helping to intensify the storm and causing heavy rains. Of
335 course the SSTs at any time have a large natural variability component on top of the
336 human-induced warming. Associated increases in atmospheric moisture are of order 5%
337 (ref. 19), which is magnified as moisture converges into a storm, further magnified as the
338 storm intensifies, and concentrated when it runs up against orography, and in streamflows.
339 Hence even though natural variability always dominates in such storms, the research task
340 is to refine the above estimates and properly account for the human component as at least
341 a partial explanation for why extremes are being magnified.

342

343 There are many other possible examples. For instance, conflicting results occurred for the
344 Russian heat wave in 2010^{33, 34} that were to some extent reconciled³⁵ by recognizing that
345 each study was about different aspects. One study³³ focused on dynamical aspects while
346 the other³⁴ was much more about the record high temperatures and thermodynamic
347 aspects. Indeed, the record high SSTs and associated nearby rains in several areas
348 (including the Pakistan floods) were factors external to the atmosphere³⁶ that altered
349 teleconnections into the Russian region.

350

351 Another very recent example is the California drought beginning in 2012. While one
352 study³⁷ found no significant trends in winter precipitation in recent decades, another³⁸
353 pointed out the critical role of the record high annual mean temperatures in combination
354 with record low annual mean precipitation for 2013 which led to increased
355 evapotranspiration and more intense drought that had impacts on water shortages,
356 vegetation and agriculture, and increased wildfire risk. The odds of this combination have

357 increased with human-induced climate change and that anthropogenic warming has
358 increased drought risk³⁹. Again these two studies are consistent with the view that the
359 atmospheric circulation changes are not the dominant factor as far as the climate change
360 aspects are concerned.

361

362 In addition there were 22 articles in the special BAMS issue⁴. Over two-thirds focused on
363 aspects of atmospheric circulation and generally concluded there was little or no influence
364 of anthropogenic climate change. None of the eight studies that dealt with heavy rains or
365 snows performed an analysis of the moisture budget and where the abundant water came
366 from. Of the three studies that analyzed the California drought, none dealt with land
367 surface effects or changes in evapotranspiration associated with climate change. In
368 contrast, for the Australian heat wave, the role of decreased soil moisture and drought
369 were noted for their effects on temperatures. The summary Table focused on columns
370 about anthropogenic influences vs no such influence detected.

371

372 There are many other examples of studies that might ask more targeted questions that
373 better serve societal needs. Reframing the null hypothesis and asking different questions
374 would help advance the understanding. Because global warming is real and present, it is
375 not a question as to whether it is playing a role but what that role is. A Bayesian approach
376 takes these “priors” appropriately into account. We can talk about these effects in terms of
377 changing odds, as many have done. But we can also talk about them in physical terms.

378

379 To implement the approach suggested here, one needs to be able to simulate the event in
380 question (perhaps with short-term forecasts, as in the Sandy example, or with simulations
381 whose circulation is constrained in some manner), and then assess the impact of known
382 anthropogenic changes in the climate system's thermodynamic state, including changed
383 amounts of water vapor. Only in this way can the necessarily conditional nature of the
384 event attribution be implemented. Necessarily this addresses only a subset of the possible
385 influences and conditions. However, with the underlying assumption that the phenomena
386 are largely unchanged, this is perhaps as much as can be expected for event attribution.
387 After all a single extreme event is not a repeatable thing.

388

389 The climate is changing: we have a new normal! The environment in which all weather
390 events occur is different than it used to be. All storms, without exception, are different.
391 Even if most of them look just like the ones we used to have, they are not the same.
392 However, we cannot sort out these questions of degree without a large ensemble of model
393 simulations, particularly for events as rare as the Boulder floods, and the kinds of models
394 that can be run in such a way are often incapable of simulating the event in question and
395 thus lack physical credibility. We argue that under such conditions it is better for event
396 attribution to focus not on the synoptic event, but rather on the influences of the changed
397 large-scale thermodynamic environment on the extremes and temperatures and moisture
398 associated with the event.

399

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488

489 **Author contributions**

490 K.E.T led the writing of the paper and conceived of the paper and figures. J.T.F analyzed some data
491 and contributed to 2 figures. All authors contributed to writing the manuscript.

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493 **Additional information**

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496 **Competing financial interests**

497 The authors declare no competing financial interests

498 Figure captions

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500 Fig. 1. Haiyan and sea level: Linear sea level trends from August 1993 to July 2013 in mm/y,
501 from AVISO. The global mean is 3.3 mm/y and the track of super Typhoon Haiyan from 3-
502 11 November 2013 is shown, with the most intense phase when it was a category 5 storm
503 highlighted.

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505 Fig. 2. August SSTs for 12-20°N 110-100°W, just west of Mexico. The mean value is
506 28.92°C for 1982-1999. The last value is for 2013.

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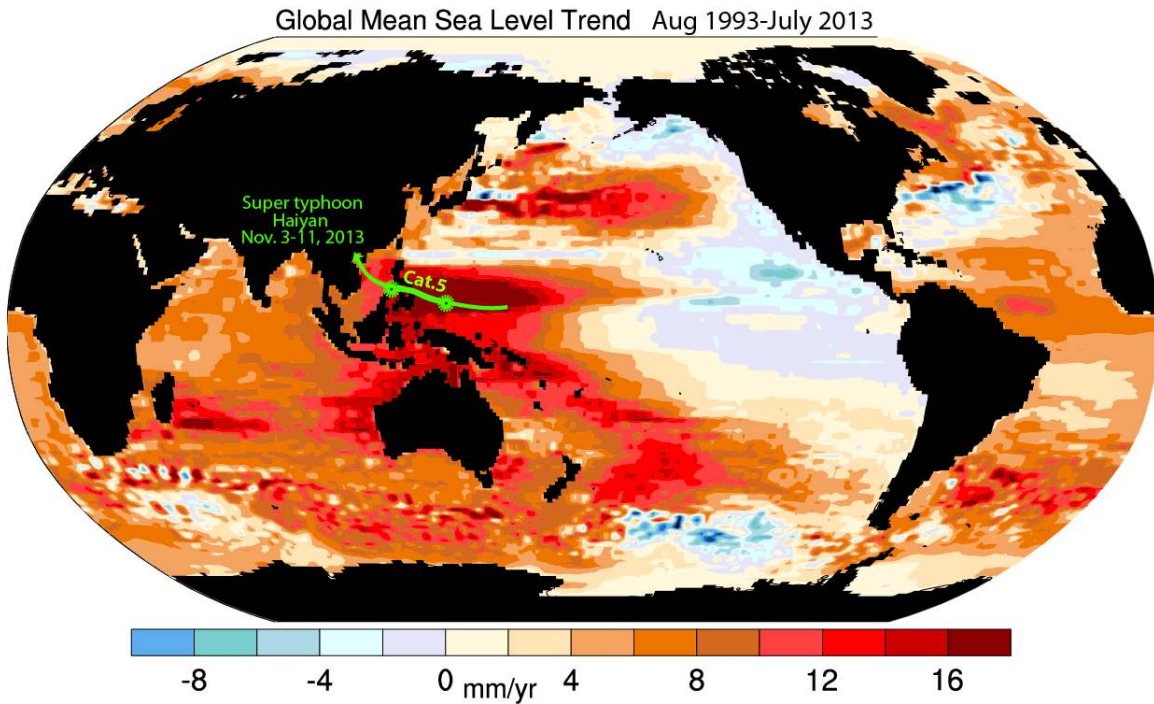
508 Fig. 3. Water vapor channel imagery for 18:45 GMT on 12 September 2013 showing the
509 extensive water vapor and associated activity both west of Mexico and in the Caribbean Sea
510 and the river of moisture from south of Baja, Mexico to eastern Colorado. Courtesy
511 weathertap.com, published with permission.

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513 Fig. 4. GOES 13 imagery from the 6.5 micron water vapor channel at 0545 GMT on 11 (top)
514 and 13 (bottom) of September 2013. The water vapor is in the mid to upper troposphere
515 and the brighter the imagery, the more saturated the air. Courtesy Axel Graumann,
516 NOAA/NESDIS/NCDC.

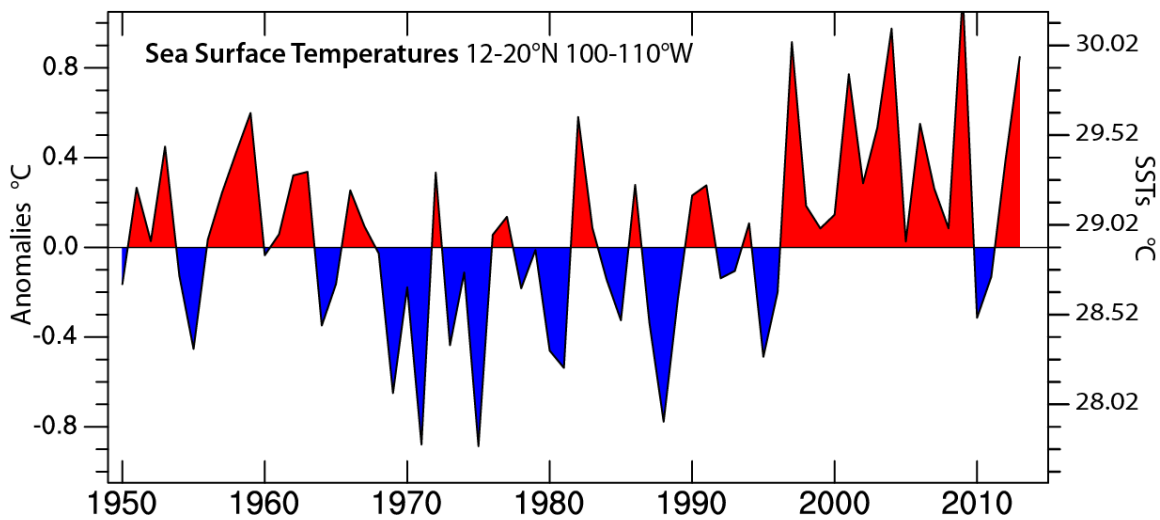
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518 Fig. 5. Imagery on 15 September 2013 showing tropical storms Manuel and Ingrid from
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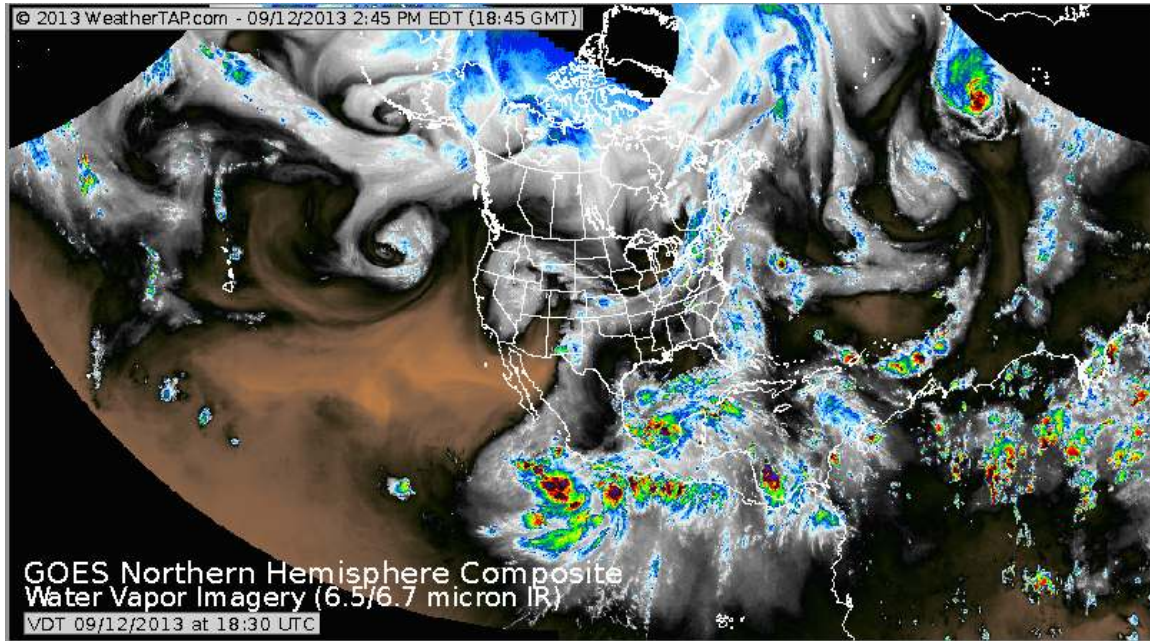
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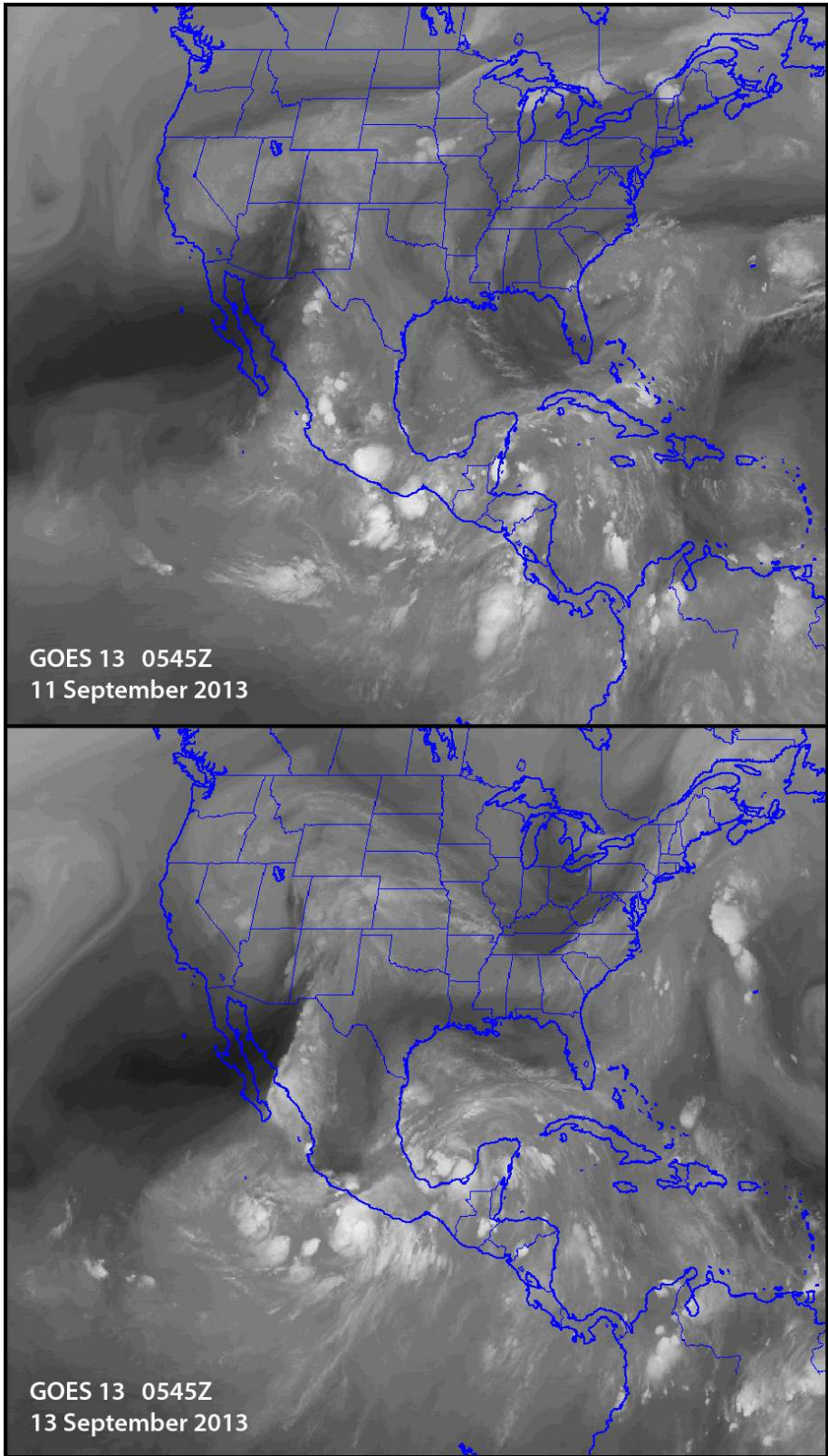
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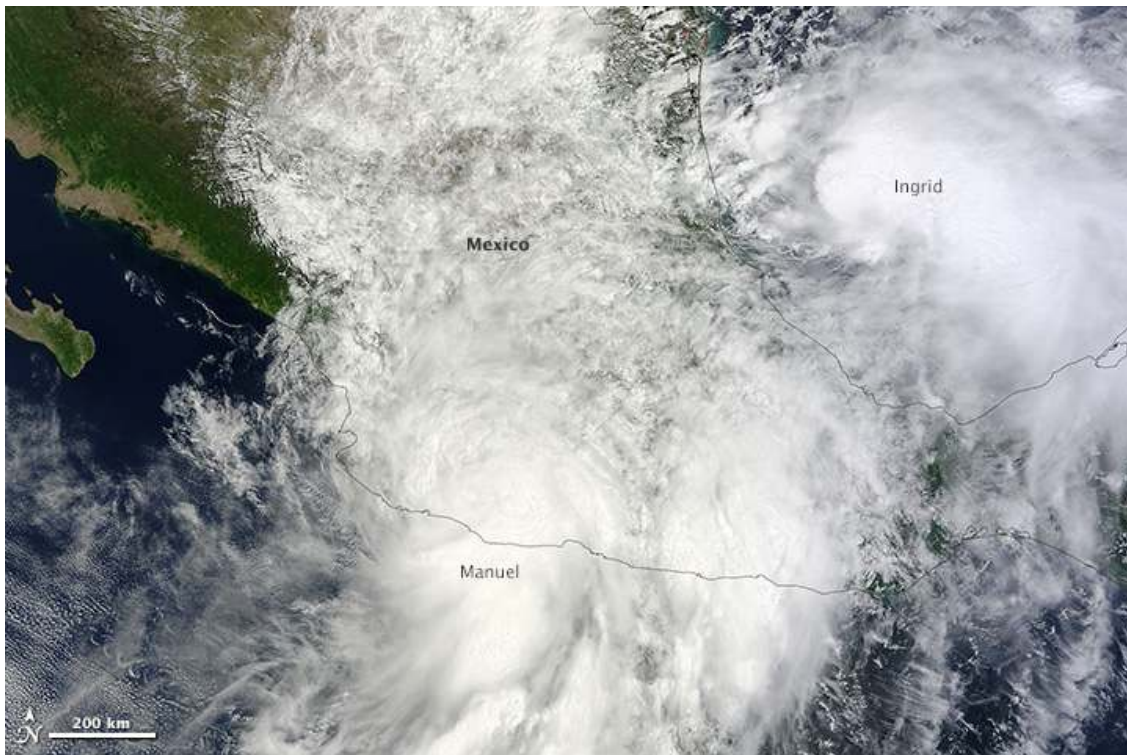


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