EXPLAINING EXTREME EVENTS OF 2015

From A Climate Perspective

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EXPLAINING EXTREME EVENTS OF 2015 FROM A CLIMATE PERSPECTIVE

Editors

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Carl J. Schreck III, and Peter A. Stott

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COVER CREDIT:

©Photo by Joe Raedle/Getty Images—A vehicle drives through flooded streets caused by a combination of the lunar orbit which caused seasonal high tides and what many believe is the rising sea levels due to climate change on September 30, 2015, in Fort Lauderdale, Florida. South Florida is projected to continue to feel the effects of climate change, and many of the cities have begun programs such as installing pumps or building up sea walls to try and combat the rising oceans.

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TABLE OF CONTENTS

Abstract.....	ii
1. Introduction to Explaining Extreme Events of 2015 from a Climate Perspective.....	I
2. Multimodel Assessment of Anthropogenic Influence on Record Global and Regional Warmth During 2015	4
3. What History Tells Us About 2015 U.S. Daily Rainfall Extremes	9
4. An Assessment of the Role of Anthropogenic Climate Change in the Alaska Fire Season of 2015	14
5. The 2014/15 Snowpack Drought in Washington State and its Climate Forcing	19
6. In Tide's Way: Southeast Florida's September 2015 Sunny-day Flood	25
7. Extreme Eastern U.S. Winter of 2015 Not Symptomatic of Climate Change.....	31
8. The Role of Arctic Sea Ice and Sea Surface Temperatures on the Cold 2015 February Over North America.....	36
9. The 2015 Extreme Drought in Western Canada.....	42
10. Human Contribution to the Record Sunshine of Winter 2014/15 in the United Kingdom	47
11. The Role of Anthropogenic Warming in 2015 Central European Heat Waves.....	51
12. The 2015 European Heat Wave.....	57
13. The Late Onset of the 2015 Wet Season in Nigeria.....	63
14. Human Influences on Heat-Related Health Indicators During the 2015 Egyptian Heat Wave.....	70
15. Assessing the Contributions of Local and East Pacific Warming to the 2015 Droughts in Ethiopia and Southern Africa.....	75
16. The Deadly Combination of Heat and Humidity in India and Pakistan in Summer 2015.....	81
17. The Heavy Precipitation Event of December 2015 in Chennai, India.....	87
18. Attribution of Extreme Rainfall in Southeast China During May 2015	92
19. Record-Breaking Heat in Northwest China in July 2015: Analysis of the Severity and Underlying Causes.....	97
20. Human Influence on the 2015 Extreme High Temperature Events in Western China.....	102
21. A Persistent Japanese Heat Wave in Early August 2015: Roles of Natural Variability and Human-Induced Warming	107
22. Climate Change and El Niño Increase Likelihood of Indonesian Heat and Drought.....	113
23. Southern Australia's Warmest October on Record: The Role of ENSO and Climate Change.....	118
24. What Caused the Record-Breaking Heat Across Australia in October 2015?.....	122
25. The Roles of Climate Change and El Niño in the Record Low Rainfall in October 2015 in Tasmania, Australia.....	127
26. Influences of Natural Variability and Anthropogenic Forcing on the Extreme 2015 Accumulated Cyclone Energy in the Western North Pacific	131
27. Record Low Northern Hemisphere Sea Ice Extent in March 2015	136
28. Summary and Broader Context.....	141

This fifth edition of explaining extreme events of the previous year (2015) from a climate perspective continues to provide evidence that climate change is altering some extreme event risk. Without exception, all the heat-related events studied in this year's report were found to have been made more intense or likely due to human-induced climate change, and this was discernible even for those events strongly influenced by the 2015 El Niño. Furthermore, many papers in this year's report demonstrate that attribution science is capable of separating the effects of natural drivers including the strong 2015 El Niño from the influences of long-term human-induced climate change.

Other event types investigated include cold winters, tropical cyclone activity, extreme sunshine in the United Kingdom, tidal flooding, precipitation, drought, reduced snowpack in the U.S. mountain west, arctic sea ice extent, and wildfires in Alaska. Two studies investigated extreme cold waves and monthly-mean cold conditions over eastern North America during 2015, and find these not to have been symptomatic of human-induced climate change. Instead, they find the cold conditions were caused primarily by internally generated natural variability. One of these studies shows winters are becoming warmer, less variable, with no increase in daily temperature extremes over the eastern United States. Tropical cyclone activity was extreme in 2015 in the western North Pacific (WNP) as measured by accumulated cyclone energy (ACE). In this

report, a study finds that human-caused climate change largely increased the odds of this extreme cyclone activity season. The 2015 Alaska fire season burned the second largest number of acres since records began in 1940. Investigators find that human-induced climate change has increased the likelihood of a fire season of this severity.

Confidence in results and ability to quickly do an attribution analysis depend on the “three pillars” of event attribution: the quality of the observational record, the ability of models to simulate the event, and our understanding of the physical processes that drive the event and how they are being impacted by climate change. A result that does not find a role for climate change may be because one or more of these three elements is insufficient to draw a clear conclusion. As these pillars are strengthened for different event types, confidence in the presence and absence of a climate change influence will increase.

This year researchers also link how changes in extreme event risk impact human health and discomfort during heat waves, specifically by looking at the role of climate change on the wet bulb globe temperature during a deadly heat wave in Egypt. This report reflects a growing interest within the attribution community to connect attribution science to societal impacts to inform risk management through “impact attribution.” Many will watch with great interest as this area of research evolves in the coming years.

6. IN TIDE'S WAY: SOUTHEAST FLORIDA'S SEPTEMBER 2015 SUNNY-DAY FLOOD

WILLIAM V. SWEET, MELISA MENENDEZ, AYESHA GENZ, JAYANTHA OBEYSEKERA,
JOSEPH PARK, AND JOHN J. MARRA

The probability of a 0.57-m tidal flood within the Miami region has increased by >500% since 1994 from a 10.9-cm sea level rise (SLR)-related trend in monthly highest tides.

The Flood Event. High tides on 27 September 2015 flooded several Miami-region communities with 0.57 m of ocean water. The flooding was concerning because of the sunny-day conditions and awareness that trends of such events are accelerating within U.S. Atlantic Coast cities from rising seas (Sweet et al. 2014; Ezer and Atkinson 2014; Sweet and Marra 2016). It was the sixth largest flood measured by the National Oceanic and Atmospheric Administration (NOAA) tide gauge in Virginia Key, Florida (Miami region), since its 1994 installation (Fig. 6.1a). The five higher floods were in response to hurricanes.

The flood had substantial astronomical underpinnings (Fig. 6.1b); it occurred during spring tides and near the peak of the seasonal mean sea level (MSL), the lunar 8.8-year perigee, and the 18.6-year nodal cycles. These factors explain the 0.24-m NOAA tide prediction relative to mean higher high water (MHHW) tidal datum that delineates typical tidal inundation (Schureman 2001; Parker 2007). Yet, tide forcing alone was insufficient to produce the observed impacts as minor “nuisance” flooding begins in excess of 0.4 meters in this region (Sweet et al. 2014).

Other dynamics were at play. A nontidal sea level anomaly (Fig. 6.1b, green line), which exceeded 0.15 m for a month starting September 22, reached 0.33 m during the flood and even higher for weeks afterwards. Strong high pressure over Eastern Canada (Fig. 6.1c) with $>15 \text{ m s}^{-1}$ northeasterlies offshore of

the mid-Atlantic Bight (not shown) drove an Ekman-related setup along much of the U.S. East Coast. During the flood, setup was $>20 \text{ cm}$ along the southeast Florida coast as modeled by NOAA's extratropical surge and tide operational forecast system (Funakoshi et al. 2013). Local winds, however, were calm ($<3 \text{ m s}^{-1}$; <http://tidesandcurrents.noaa.gov/met>), inverse barometer effects nonexistent (Fig. 6.1c), and dynamical wave effects minimal as inferred by the $\sim 1 \text{ cm}$ standard deviations during tide measurements (Sweet et al. 2015). Interestingly, Gulf Stream transport measured upstream in the Florida Current (FC) slowed to a monthly minimum of 23.4 Sverdrup (Sv; $1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) on 25 September (Fig. 6.1d), which persisted through the flood. Transport slowdowns raise MSL along the US southeast (Zhao and Johns 2014; Ezer 2016) and Florida coasts (Park and Sweet 2015) from adjustments to meridional Ekman transport (Lee and Williams 1988) and shelf-wave dynamics (Czeschel et al. 2012; Ezer 2016). Previous studies report a 0.5–1.5 cm rise in coastal MSL per 1-Sv decline in Gulf Stream system transport (Ezer et al. 2013; Woodworth et al. 2014; Goddard et al. 2015; Ezer 2016); when it slows, local tidal-flood risks increase (Sweet et al. 2009; Ezer and Atkinson 2014; Wdowinski et al. 2016).

Here, we derive a contemporary return period of the flood using a time-dependent extreme value statistical model. Then, we assess the degree that (i) seasonal variability, (ii) tide cycles, (iii) FC monthly transport minimums, and (iv) a multidecadal trend have independently affected Virginia Key's extreme water level distribution and estimate their attribution during the flood. We conclude by analyzing how the flood's return period changes under future SLR projections for the Miami region forced by three representative concentration pathways (RCP).

Data and Methods. Verified 6-minute and monthly water levels, sampling standard deviations, and tide

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FIG. 6.1. (a) Highest monthly water levels (m) since 1994 at NOAA tide gauge Virginia Key, FL, indicating the local “nuisance” flood level; (b) hourly water levels (m) in Sep and Oct 2015 showing tidal and nontidal anomaly components highlighting the 27 Sep flood; (c) 5-day composite (www.esrl.noaa.gov/psd) of SLP (hPa) anomaly during the flood showing location of the tide gauge and FC measurements; and (d) scatterplot between monthly minimum FC transport (Sv) and monthly maximum water level (WL; m) highlighting Sep–Nov months (yellow) and the Sep 2015 event (red).

predictions are used for NOAA tide gauge Virginia Key (<http://tidesandcurrents.noaa.gov>). Daily FC transport is available from www.aoml.noaa.gov/phod/floridacurrent. We analyze monthly highest water levels using a generalized extreme value (GEV) model to assess flood height probabilities and decompose independent time-dependencies in the model’s location parameter. We follow methods of Menendez and Woodworth (2010) described in the online supplemental information.

Return level interval curves (Coles 2001) are constructed on a monthly and a 2015-annualized (12-month integrated) basis. Monthly return interval curves are vertically shifted by the time-dependent location parameter components (equation 2 in the online supplemental information) to assess climate

variability and trend effects on the flood’s return period. We use the classic (annual scale) curves to compute future projections for annual relevancy purposes. Return periods are approximated as $-1/\ln(F_z)$, where F is the cumulative probability of a flood with height z , instead of the traditional $1/(1-F_z)$ method (Beran and Nozdryn-Plotnicki 1977; Coles 2001) to better estimate shorter return periods (e.g., <1 year).

What role did climatic variability and trends play in the September 2015 flood? Our model estimates that a 0.57-m flood has a 6-year return period (black curve in Fig. 6.2a) during Septembers assuming conditions (e.g., nodal cycle, FC transport) match those during September 2015. The flood has a 3-year return period when considering (integrating across) all months

FIG. 6.2. (a) GEV-estimated return level interval curves from monthly maximum WL (m) at Virginia Key for Sep 2015 (black curve) and annualized for all months in 2015 (red curve) indicating the 27 Sep flood level (dots) and GEV model parameter standard errors. (b) Time-varying location parameter (black line) and its components (plotted to scale but with arbitrary values) with component magnitudes (m) during the 27 Sep flood (circles) and their total ranges in parenthesis. (c) Annual MSL (m) at Virginia Key since 1994 overlaid upon local RCP-based SLR projections of Kopp et al. (2014). (d) Return periods by decade of the Sep 2015 flood height (0.57 m above MHHW) in response to SLR projections.

during 2015 (red curve in Fig. 6.2a), reflecting the peak seasonal location parameter during Octobers (Fig. 6.2b, green line). Highest water levels occur September–November (Fig. 6.1d, yellow dots), typically during Octobers. If a 0.57-m flood occurred in February 2015 when the seasonal location parameter is minimum (21.1 cm lower than in September), a higher (less probable) water level would be required; it would have a >100-year return period. Our estimates (Fig. 6.2a) are based upon a 22-year data record with a sample size 7 times longer than the flood’s annualized return period, which results in low GEV-parameter estimate uncertainties (Fig. 6.2a). We note our return periods agree with those from a 50-year record from the nearby historic Miami NOAA gauge (<http://tidesandcurrents.noaa.gov/est>; Zervas 2013) and our

seasonal location-parameter range of 23.9 cm matches its 23.7-cm MSL cycle (Zervas 2009).

The 18.6-year lunar nodal cycle is estimated as having a 6-cm location-parameter range, which was near-peak during the flood (Fig. 6.2b). If at its minimum (and all other factors the same), the return period of this flood occurring in a September would have been 16.5 years instead of 6 years (>150% probability increase). The periodicity of the lunar perigee, which amplifies the tidal range on a ~4.4-year cycle (Haigh et al. 2011), was included in our model but found to be insignificant. Similarly, had the flood occurred during a September with higher FC transport (e.g., 33.1 Sv in September 1997 and a 9-cm location parameter decrease shown in Fig. 6.2b), the return period would have been 29 years instead

of 6 years (>350% probability increase). Our model estimates a 17-cm total range in location parameter due to co-variability with FC transport minimums, equating to a 0.9 ± 0.2 cm increase for every 1-Sv decline, which agrees with previous estimates. Lastly, our model estimates a long-term trend in the location parameter of 0.5 ± 0.1 cm year⁻¹ (10.9 cm rise since beginning of 1994), which closely matches the trend in MSL (~11 cm in Fig. 6.2c). If the flood had occurred in September 1994, its return period would have been 39 years instead of 6 years (>500% probability increase).

What does the future hold in terms of more September 2015 flooding? The logical question is *how much more frequent will these kinds of floods become in the future?* To answer this question, the September 2015 flood is assessed in terms of its annualized return period (3 years; red curve in Fig. 6.2a), although flood frequencies will likely remain most prevalent during the fall (e.g., Fig. 6.1d). It is assumed that future changes in tidal flooding will occur only in response to local SLR, though variability (shown here) is significant. We use the 50th and 95th% SLR projections for Virginia Key forced by RCPs modeled by Kopp et al. (2014), which correspond to global SLR of 0.5–1.21 m by 2100. An overlay of Virginia Key's annual MSL (Fig. 6.2c) shows a current trajectory between the 50th and 95th% of the RCP 8.5 SLR projections. By 2030, the flood is likely to become a 0.6-year event (~twice a year) under the median RCP 2.6, 4.5, and 8.5 projections (Fig. 6.2d) and a 0.2-year event (≥ 5 times a year) under the 95th% of the RCP 8.5 projection. With 0.2 m more local SLR, which is exceeded under all local SLR projections between 2040–2050, the flood will occur >10 times a year (<0.1 year return period).

Conclusion. Our time-dependent GEV model disentangles and probabilistically decomposes independent contributions from concurrent processes attributing to the Miami-region floods during 27 September 2015. Seasonal and tide cycles are quite predictable, whereas FC transport variability is less so (e.g., DiNezio et al. 2009). In terms of decades-old infrastructure, two major factors were at play: a 9-cm increase from FC variability and a 10.9-cm rise from a climate-related SLR trend since 1994 of which a fraction (~0.05 cm year⁻¹) is downward vertical land motion (Zervas et al. 2013; Kopp et al. 2014) common to south Florida. There is a decreasing trend (significant at the 99% level) in monthly minimum FC transport of 2.3 Sv since 1994, which likely

contributed ~2 cm to the SLR-related trend (Fig. 6.2b, blue line).

A decline in the large-scale Gulf Stream transport, which is expected this century (Yin 2012) to exacerbate flooding along the mid-Atlantic (Hall et al. 2016), is not well resolved for the FC locally within the SLR projections (Kopp et al. 2014). Because of this, and since we use a parametric extreme distribution to quantify the transition to a more recurrent event better estimated empirically (Sweet and Park 2014), our flood-frequency projections should be considered conservative underestimates. In closing, flooding on 27 September inundated 0.57 m of normally dry land (~2 feet; <https://coast.noaa.gov/slr>) and capped a week-long event in which daily high tides exceeded the local nuisance flood threshold (Fig. 6.1b). Tidal floods of this magnitude occur only every few years now but will become commonplace in the coming decades.

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Table 28.1. Summary of Results

ANTHROPOGENIC INFLUENCE ON EVENT			
	INCREASE	DECREASE	NOT FOUND OR UNCERTAIN
Heat	Global Temperature (Ch. 2) South India & Sri Lanka (Ch. 2) Central Europe (Ch. 11) Europe (Ch. 12) Ethiopia and Southern Africa (Ch. 15) N.W. China (Ch. 19) W. China (Ch. 20) Japan (Ch. 21) Indonesia (Ch. 22) S. Australia (Ch. 23) Australia (Ch. 24)		Central Equatorial Pacific (Ch. 2)
Cold		Northeastern U.S. (Ch. 7)	Mid-South Atlantic U.S. (Ch. 7) N. America (Ch. 8)
Heat & Humidity	Egypt (Ch. 14) India & Pakistan (Ch. 16)		
Dryness	Indonesia (Ch. 22) Tasmania (Ch. 25)		
Heavy Precipitation	China (Ch. 18)		Nigeria (Ch. 13) India (Ch. 17)
Sunshine	United Kingdom (Ch. 10)		
Drought	Canada (Ch. 9) Ethiopia and Southern Africa (Ch. 15)		
Tropical Cyclones	Western North Pacific (Ch. 26)		
Wildfires	Alaska (Ch. 4)		
Sea Ice Extent		Arctic (Ch. 27)	
HIGH TIDE FLOODS	SOUTHEASTERN U.S. (Ch. 6)		
SNOWPACK DROUGHT	WASHINGTON U.S. (Ch. 5)		
TOTAL	23	2	5

	METHOD USED	Total Events
Heat	Ch. 2: CMIP5 modeling Ch. 11: Observations; weather@home modeling Ch. 12: HadGEM3-A modeling Ch. 15: CMIP5 modeling Ch. 19: CMIP5 modeling with ROF; FAR Ch. 20: CMIP5 modeling with ROF; FAR Ch. 21: MIROC5-AGCM modeling Ch. 22: Observations; CMIP5 modeling Ch. 23: weather@home modeling; FAR Ch. 24: BoM seasonal forecast attribution system and seasonal forecasts	12
Cold	Ch. 7: Observations; CMIP5 modeling Ch. 8: AMIP (IFS model) modeling	3
Heat & Humidity	Ch. 14: weather@home modeling Ch. 16: Non-stationary EV theory; C20C+ Attribution Subproject	2
Dryness	Ch. 22: Observations; CMIP5 modeling Ch. 25: Observations; Modeling with CMIP5 and weather@home	2
Heavy Precipitation	Ch. 13: Observations; Modeling with CAM5.1 and MIROC5 Ch. 17: Observations; Modeling with weather@home, EC-Earth and CMIP5 Ch. 18: HadGEM3-A-N216 modeling; FAR	3
Sunshine	Ch. 10: Hadley Centre event attribution system built on the high-resolution version of HadGEM3-A	1
Drought	Ch. 9: Observations; CMIP5 modeling; Trend and FAR analyses Ch. 15: CMIP5 modeling, land surface model simulations, and statistical analyses	2
Tropical Cyclones	Ch. 26: GFDL FLOR modeling; FAR	1
Wildfires	Ch. 4: WRF-ARW optimized for Alaska with metric of fire risk (BUI) to calculate FAR	1
Sea Ice Extent	Ch. 27: OGCM modeling	1
HIGH TIDE FLOODS	Ch. 6: TIDE-GAUGE DATA; TIME-DEPENDENT EV STATISTICAL MODEL	1
SNOWPACK DROUGHT	Ch. 5: OBSERVATIONS; CESM1 MODELING	1
		30

ACRONYMS:

AMIP: Atmospheric Model Intercomparison Project

BoM: Bureau of Meteorology, Australia

BUI: Buildup Index

CAM: Community Atmosphere Model, <http://www.cesm.ucar.edu>

CESM: Community Earth System Model

CMIP: Coupled Model Intercomparison Project

FAR: Fraction of Attributable Risk

EC-EARTH: <https://verc.enes.org/>

EV: Extreme Value

GFDL FLOR: Geophysical Fluid Dynamics Laboratory Forecast version Low Ocean Resolution

GHCN: Global Historical Climatology Network

IFS: Integrated Forecast System

MIROC5-AGCM: Model for Interdisciplinary Research on Climate-Atmospheric General Circulation Model

OGCM: Ocean General Circulation Model

ROF: Regularized Optimal Fingerprinting

weather@home: <http://www.climateprediction.net/weatherathome>

WRF-ARW: Advanced Research (ARW) version of the Weather Research and Forecasting (WRF) model