A photograph of a snowy park path, likely in Central Park, New York. The path is covered in a thick layer of snow, with footprints visible. On either side of the path are ornate blue and gold lampposts. In the background, a large brick building is visible. The sky is overcast and it appears to be snowing.

EXPLAINING EXTREME EVENTS OF 2014

From A Climate Perspective

Special Supplement to the
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EXPLAINING EXTREME EVENTS OF 2014 FROM A CLIMATE PERSPECTIVE

Editors

Stephanie C. Herring, Martin P. Hoerling, James P. Kossin, Thomas C. Peterson, and Peter A. Stott

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FRONT: ©iStockphotos.com/coleong—Winter snow, Boston, Massachusetts, United States.

BACK: ©iStockphotos.com/nathanphoto—Legget, California, United States – August 13, 2014: CAL FIRE helicopter surveys a part of the Lodge Fire, Mendocino County.

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TABLE OF CONTENTS

Abstract.....	ii
1. Introduction to Explaining Extreme Events of 2014 from a Climate Perspective	1
2. Extreme Fire Season in California: A Glimpse Into the Future?	5
3. How Unusual was the Cold Winter of 2013/14 in the Upper Midwest?.....	10
4. Was the Cold Eastern Us Winter of 2014 Due to Increased Variability?	15
5. The 2014 Extreme Flood on the Southeastern Canadian Prairies	20
6. Extreme North America Winter Storm Season of 2013/14: Roles of Radiative Forcing and the Global Warming Hiatus.....	25
7. Was the Extreme Storm Season in Winter 2013/14 Over the North Atlantic and the United Kingdom Triggered by Changes in the West Pacific Warm Pool?	29
8. Factors Other Than Climate Change, Main Drivers of 2014/15 Water Shortage in Southeast Brazil.....	35
9. Causal Influence of Anthropogenic Forcings on the Argentinian Heat Wave of December 2013	41
10. Extreme Rainfall in the United Kingdom During Winter 2013/14: The Role of Atmospheric Circulation and Climate Change.....	46
11. Hurricane Gonzalo and its Extratropical Transition to a Strong European Storm.....	51
12. Extreme Fall 2014 Precipitation in the Cévennes Mountains	56
13. Record Annual Mean Warmth Over Europe, the Northeast Pacific, and the Northwest Atlantic During 2014: Assessment of Anthropogenic Influence.....	61
14. The Contribution of Human-Induced Climate Change to the Drought of 2014 in the Southern Levant Region.....	66
15. Drought in the Middle East and Central–Southwest Asia During Winter 2013/14.....	71
16. Assessing the Contributions of East African and West Pacific Warming to the 2014 Boreal Spring East African Drought	77
17. The 2014 Drought in the Horn of Africa: Attribution of Meteorological Drivers.....	83
18. The Deadly Himalayan Snowstorm of October 2014: Synoptic Conditions and Associated Trends	89
19. Anthropogenic Influence on the 2014 Record-Hot Spring in Korea	95
20. Human Contribution to the 2014 Record High Sea Surface Temperatures Over the Western Tropical And Northeast Pacific Ocean	100
21. The 2014 Hot, Dry Summer in Northeast Asia.....	105
22. Role of Anthropogenic Forcing in 2014 Hot Spring in Northern China	111
23. Investigating the Influence of Anthropogenic Forcing and Natural Variability on the 2014 Hawaiian Hurricane Season.	115
24. Anomalous Tropical Cyclone Activity in the Western North Pacific in August 2014	120
25. The 2014 Record Dry Spell at Singapore: An Intertropical Convergence Zone (ITCZ) Drought.....	126
26. Trends in High-Daily Precipitation Events in Jakarta and the Flooding of January 2014	131
27. Extreme Rainfall in Early July 2014 in Northland, New Zealand—Was There an Anthropogenic Influence?	136
28. Increased Likelihood of Brisbane, Australia, G20 Heat Event Due to Anthropogenic Climate Change	141
29. The Contribution of Anthropogenic Forcing to the Adelaide and Melbourne, Australia, Heat Waves of January 2014	145
30. Contributors to the Record High Temperatures Across Australia in Late Spring 2014	149
31. Increased Risk of the 2014 Australian May Heatwave Due to Anthropogenic Activity.....	154
32. Attribution of Exceptional Mean Sea Level Pressure Anomalies South of Australia in August 2014	158
33. The 2014 High Record of Antarctic Sea Ice Extent.....	163
34. Summary and Broader Context.....	168

Understanding how long-term global change affects the intensity and likelihood of extreme weather events is a frontier science challenge. This fourth edition of explaining extreme events of the previous year (2014) from a climate perspective is the most extensive yet with 33 different research groups exploring the causes of 29 different events that occurred in 2014. A number of this year's studies indicate that human-caused climate change greatly increased the likelihood and intensity for extreme heat waves in 2014 over various regions. For other types of extreme events, such as droughts, heavy rains, and winter storms, a climate change influence was found in some instances and not in others. This year's report also included many different types of extreme events. The tropical cyclones that impacted Hawaii were made more likely due to human-caused climate change. Climate change also decreased the Antarctic sea ice extent in 2014 and increased the strength and likelihood of high sea surface temperatures in both the Atlantic and Pacific Oceans. For western U.S. wildfires, no link to the individual events in 2014 could be detected, but the overall probability of western U.S. wildfires has increased due to human impacts on the climate.

Challenges that attribution assessments face include the often limited observational record and inability of models to reproduce some extreme events well. In general, when attribution assessments fail to find anthropogenic signals this alone does not prove anthropogenic climate change did not influence the event. The failure to find a human fingerprint could be due to insufficient data or poor models and not the absence of anthropogenic effects.

This year researchers also considered other human-caused drivers of extreme events beyond the usual radiative drivers. For example, flooding in the Canadian prairies was found to be more likely because of human land-use changes that affect drainage mechanisms. Similarly, the Jakarta floods may have been compounded by land-use change via urban development and associated land subsidence. These types of mechanical factors re-emphasize the various pathways beyond climate change by which human activity can increase regional risk of extreme events.

20. HUMAN CONTRIBUTION TO THE 2014 RECORD HIGH SEA SURFACE TEMPERATURES OVER THE WESTERN TROPICAL AND NORTHEAST PACIFIC OCEAN

EVAN WELLER, SEUNG-KI MIN, DONGHYUN LEE, WENJU CAI, SANG-WOOK YEH, AND JONG-SEONG KUG

CMIP5 models suggest that human influence has increased the probability of regional high SST extremes over the western tropical and northeast Pacific Ocean during the 2014 calendar year and summer.

Introduction. Global mean sea surface temperature (SST) during 2014 was the highest over observational records, with distinct patterns of regional and seasonal extremes (Figs. 20.1a,b). This surpassed the previous record high in 1998, which followed an extreme El Niño event (Cai et al. 2014). However, the 2014 record-breaking SST is of great importance as it occurred without the influence of a strong El Niño event and follows a long-term pause, or hiatus, in global warming since the late 1990s (e.g., Watanabe et al. 2014). Thus, this event provides evidence of long-term warming trends due to anthropogenic forcing and/or possible shifts in multidecadal variability. Maps of 2014 annual and boreal summer (June–August, JJA) SST anomalies (Figs. 20.1a,b) reveal that the unprecedented global warmth was primarily due to anomalously high temperatures in the western tropical Pacific, northeast Pacific, southern Indian, and Atlantic Oceans. Overall, the fraction of global ocean with record positive anomalies in 2014 was less than half of that observed in 1998, but the 2014 warming over these regions was indeed an extreme event (Supplementary Fig. S20.1). The western tropical Pacific was the largest region for record-breaking SSTs (Figs. 20.1a–d), whilst in the northeast Pacific, although less widespread, prominent SST anomalies exceeded the 1971–2000 climatology by up to 1.76°C (Figs. 20.1e,f). Interestingly, both regions exhibited

the highest seasonal mean during JJA (Supplementary Fig. S20.2). Here, we examine the observed 2014 SST extremes in these two key regions in the context of anthropogenic climate change.

Data and Methods. We assess SST changes in the western tropical Pacific (hereinafter WTP) and the northeast Pacific (hereinafter NEP) regions. Observations are monthly SST data from Extended Reconstruction Sea Surface Temperature (ERSST) version 3 (Smith et al. 2008). We use multimodel data available from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012). We consider the “historical” experiment (anthropogenic and natural forcings) from 1953 to 2005, extended to 2014 utilizing the “RCP4.5” (Representative Concentration Pathway 4.5) experiment, resulting in a 62-year-long all-forcing experiment period, referred to as ALL_P1. We also utilize “historicalGHG” (greenhouse gas only forcing, GHG_P1) and “historicalNat” (natural only forcing, NAT_P1) experiments to examine relative contributions by individual forcing factors, and preindustrial control (CTL_P0) experiments to provide a measure and test of the unforced internal climate variability. Anomalies are calculated relative to the 1971–2000 climatology. Refer to the online supplemental material for full details on CMIP5 data processing.

An attribution analysis of the 2014 record-breaking SSTs is carried out by comparing observed trends (calculated using the least squares method) and anomalies with those from the models. We employ the fraction of attributable risk (FAR; Stott et al. 2004) approach in which the probability of extreme events occurring is compared between worlds without and with human influences to quantitatively estimate anthropogenic influence. Here, FAR is calculated as $FAR = 1 - (P_0 / P_1)$, with P_0 being the probability of extremes exceeding the observed strength in CTL_P0,

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FIG. 20.1. (a,b) Observed (a) annual and (b) boreal summer (JJA) SST anomalies ($^{\circ}\text{C}$) during 2014, relative to the 1971–2000 mean. Stippling indicates regions where 2014 was the highest on record since 1900. (c,d) Time series of (c) annual and (d) summer SST anomalies ($^{\circ}\text{C}$), respectively, averaged over the western tropical Pacific Ocean [see dashed box in (a)], relative to the 1971–2000 climatology. (e,f) As in (c,d), but for the northeast Pacific Ocean [see dashed box in (a)]. In (c)–(f), green lines and shading indicate the all-forcing (historical and RCP4.5, ALL_PI) ensemble mean and 10%–90% range across ensemble members, blue indicates the natural-forcing (historicalNat, NAT_PI) ensemble means, and the dashed black indicates the observed SSTs (ERSST v3), with the 2014 record-breaking values represented by black circles. In (c), the observed global mean SST anomaly is also indicated by the brown line, with the record high 2014 and the previous record high 1998 values represented by brown circles. Note that SST anomalies in individual ensemble natural-forcing time series are obtained relative to each 1971–2000 mean of ALL_PI to account for varying climatology responses to different forcing factors.

and P_1 the probability in ALL_PI or GHG_PI. FAR values of 0.5 and 0.67, for example, indicate doubled and tripled risk of extreme events due to human influences, respectively.

Results. The observed annual SST anomalies in the WTP reveal the 2014 record high has occurred in conjunction with long-term warming since the 1950s, at a faster rate than the global mean (Fig. 20.1c). The

ALL_PI ensemble mean and range are consistent with the observed changes with similar trends (Figs. 20.1c and 20.2a). Trends in CTL_P0 and NAT_P1 are centered on zero and weak, whereas GHG_PI has stronger positive trends than the observations (Fig. 20.2a) because it does not include offsetting forcing, such as anthropogenic aerosols. Results for summer trends are similar (Fig. 20.1d and Supplementary Fig. S20.3a). The histograms of modeled trends show none

FIG. 20.2. (a,b) Histogram of the annual SST trends (1953–2014) in the (a) western tropical Pacific Ocean and (b) northeast Pacific Ocean, from preindustrial (CTL_P0, gray), historicalNat only (NAT_P1, blue), all (ALL_P1, green), and greenhouse-gas-only (GHG_P1, red) forcing experiments, compared with the observed trend and its 90% confidence interval (ERSST v3, vertical solid and dashed black lines). (c,d) As in (a,b), but for annual SST anomalies from models and the observed extreme 2014 anomaly. (e,f) As in (c,d), but for boreal summer (JJA) SST anomalies. In all panels, the interquartile range for each distribution is shown where differences between forced experiments (NAT_P1, ALL_P1, and GHG_P1) and unforced experiments (CTL_P0) indicate estimates of the uncertainty due to intermodel spread of climate sensitivity.

of CTL_P0 and NAT_P1 trends exceed the observed trend ($0.62^{\circ}\text{C } 62 \text{ yr}^{-1}$), whereas it is positioned near the center (49.21 percentile) of ALL_P1 and 100% exceeded in GHG_P1. Thus, the modeled fraction of risk of the SST trend in the WTP that is attributable to anthropogenic forcing is 100% (FAR = 1, Table 20.1), with a negligible influence of natural forcing.

In contrast, Figs. 20.1e,f show little to no significant long-term observed trend of SST anomalies in the NEP. Probability of occurrence exceeding the observed annual trend in ALL_P1 is 84.92%, and also increases, compared to the WTP, for CTL_P0 (16.67%) and NAT_P1 (21.95%; Fig. 20.2b). Similar

are compared in Figs. 20.2c and d, together with the observed record 2014 anomaly value for the WTP and NEP, respectively. Similar to SST trend distributions, there is an increase in the probability of extreme annual SST anomalies in the WTP when anthropogenic forcings are included (Fig. 20.2c). SST anomalies exceeding the 2014 anomaly (0.56°C) do not occur in CTL_P0 or NAT_P1. Probability increases to 2.79% (1 in 35 years) and 24.72% (1 in 4 years) in ALL_P1 and GHG_P1, respectively. Thus, the modeled fraction of risk of the extreme 2014 WTP SST anomaly is 100% attributable to anthropogenic forcing (FAR = 1, Table 20.1), which appears to be exacerbated by

results are found for summer (Supplementary Fig. S20.3b). FAR values for NEP SST trends range from 0.80 to 0.84 (Table 20.1), providing evidence that there is about a five times increase in risk due to anthropogenic forcings. However, multi-decadal variability is clearly evident in the observations, as is stronger warming in ALL_P1 since the early-to-mid 1990s compared to the observations (Figs. 20.1e,f). This indicates that there is a likely role for natural variability in the NEP. Varying the trend period (all ending in 2014), the impact of multidecadal variability on NEP SST trends is evident when compared to the WTP (Supplementary Figs. S20.4a–d). For the WTP, a FAR value of one is obtained for a trend period longer than 25 years. For the NEP, a maximum FAR value (0.90–0.98, a 10–50-fold increase in risk) coincides with a trend from the early 1970s, and smaller values for shorter and longer periods.

We next conduct a similar attribution analysis of extreme 2014 annual SST anomalies. Distributions of all modeled SST anomalies

Table 20.1. Probability of occurrence exceeding the observed 2014 annual and boreal summer (JJA) mean long-term trend and extreme SST anomalies in the western tropical Pacific (WTP) and northeast Pacific (NEP) Ocean regions. The fraction of attributable risk is calculated as $FAR_{ALL\_PI} = 1 - P_{CTL\_P0} / P_{ALL\_PI}$ and $FAR_{GHG\_PI} = 1 - P_{CTL\_P0} / P_{GHG\_PI}$.

	Observations	CTL_P0	ALL_PI	GHG_PI
Trend in WTP Ann/JJA SST	0.62°/0.62°C 62 yr ⁻¹	0%/0%	50.79%/55.56% FAR = 1	100%/100% FAR = 1
Trend in NEP Ann/JJA SST	0.23°/0.24°C 62 yr ⁻¹	16.67%/15.31%	84.92%/83.33% FAR = 0.80/0.82	96.67%/96.67% FAR = 0.83/0.84
2014 WTP Ann/JJA SST anomaly	0.56°/0.62°C	0%/0%	2.79%/2.51% FAR = 1	24.72%/20.28% FAR = 1
2014 NEP Ann/JJA SST anomaly	1.42°/1.76°C	0.03%/0.03%	0.17%/0.49% FAR = 0.82/0.94	9.22%/8.89% FAR ≈ 1

internal variability given the small percentage of such anomalies occurring in ALL_PI. During summer, the corresponding FAR value is also one (Fig. 20.2e and Table 20.1). Even a threshold equal to the 1971–2000 climatological mean is greater than 10 times more likely due to human influence, highlighting the large shift of the mean state in the WTP from preindustrial levels (Supplementary Figs. S20.4e,h).

For the NEP, the record extreme 2014 annual (1.42°C) and summer (1.76°C) SST anomalies were greater than +3.5σ above the climatological mean (Figs. 20.2d,f). Modeled SST anomalies in CTL_P0, NAT_PI, and ALL_PI are centered on zero, with only a warm shift in GHG_PI. SST anomalies stronger than the 2014 event are extremely rare in CTL_P0, NAT_PI, and ALL_PI (Table 20.1). Corresponding FAR values with ALL_PI are 0.82 and 0.94 for annual and summer, respectively, representing 5–10 times more likely due to human influence. Probabilities increase to 9.22% and 8.89% in GHG_PI for annual and summer anomalies, with a FAR value essentially equal to one. However, there appears to be a likely role for natural variability on such SST anomalies in the NEP. Unlike the WTP, larger interannual variability in this region results in the FAR value varying considerably for different thresholds above the climatological mean (Supplementary Figs. 20.4f,i).

Sensitivity tests (see online supplemental material for full details) were conducted to assess robustness of the overall conclusions. These included model biases in natural internal variability, observed trend and anomaly uncertainty, and selection bias using the 2014 event for attribution. Conclusions for the WTP do not change despite models exhibiting slightly larger internal variability (Supplementary Figs. S20.5a,c and 20.6a), or if more conservative thresh-

olds (previous record or trends ending in 2013) are used (Supplementary Figs. S20.4a,c and e,h). For the NEP, scaling modeled variability up to better match observed variability reduces the FAR by no more than 0.1 (Supplementary Figs. S20.5b,d and S20.6b). Using a conservative threshold or trends ending in 2013 also reduces our confidence in the NEP conclusions (Supplementary Figs. S20.4b,d and f,i), but the 2014 anomalies are still significantly attributable to anthropogenic forcing. Additionally, choice of RCP experiments used for 2006–14 when constructing ALL_PI should not affect the main conclusions, as they do not diverge appreciably until the near-term future (Moss et al. 2010). It is also reported that solar irradiance is overestimated to a small degree in CMIP5 simulations (Schmidt et al. 2014); however, this will be only a small fraction of total forcings. Uncertainty arising from intermodel differences in climate sensitivity is also found to be small (Supplementary Fig. S20.7). The use of another observational SST dataset or extending the analysis period to cover the entire twentieth century do not change the main results (Supplementary Fig. S20.8).

Conclusions. Possible impacts of greenhouse gas increases on long-term changes and extreme 2014 record-breaking SSTs in the WTP and NEP are assessed based on the CMIP5 multimodel simulations, representing climate conditions with and without human influences. In the WTP, a strong long-term warming in SST can be explained only when greenhouse gas forcing is included, consistent with Funk and Hoell (2015). Modeled results suggest the record extreme 2014 annual and summer SST anomalies in this region are essentially attributable to anthropogenic forcing. For the NEP, the probability of SST

anomalies such as those observed during 2014 has become about five times as likely with human influences. However, owing to large variability on interannual to multidecadal time scales, there is evidence for the likely role of natural internal variability.

Regional extremes can be due to compounding effects of long-term warming coinciding with natural climate variability. The NEP provides an example of such concurrence. Spatial patterns of 2014 SST anomalies in the North Pacific resemble those observed during a warm phase of the Pacific decadal oscillation (PDO; Mantua et al. 1997) and/or negative phase of the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al. 2008; Chhak et al. 2009) (Supplementary Figs. S20.9a,b). Indeed, the PDO displayed an intense switch to positive in 2014, partly owing to the anomalously high SST anomalies in the NEP, and the NPGO was observed to be negative (Supplementary Figs. S20.9c,d). Both climate phenomena are associated with large anomalies in the NEP but not particularly associated with anomalies in the WTP. When such natural climate fluctuations act in conjunction with a warming background mean state, annual or seasonal regional extremes are highly likely to continue, resulting in extreme patterns similar to natural climate variability.

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Table 34.I. ANTHROPOGENIC INFLUENCE

ON EVENT STRENGTH †

	INCREASE	DECREASE	NOT FOUND OR UNCERTAIN
Heat	Australia (Ch. 31) Europe (Ch.13) S. Korea (Ch. 19)		Australia, Adelaide & Melbourne (Ch. 29) Australia, Brisbane (Ch.28)
Cold		Upper Midwest (Ch.3)	
Winter Storms and Snow			Eastern U.S. (Ch. 4) N. America (Ch. 6) N. Atlantic (Ch. 7)
Heavy Precipitation	Canada** (Ch. 5)		Jakarta**** (Ch. 26) United Kingdom*** (Ch. 10) New Zealand (Ch. 27)
Drought	E. Africa (Ch. 16) E. Africa* (Ch. 17) S. Levant (Ch. 14)		Middle East and S.W. Asia (Ch. 15) N.E. Asia (Ch. 21) Singapore (Ch. 25)
Tropical Cyclones			Gonzalo (Ch. 11) W. Pacific (Ch. 24)
Wildfires			California (Ch. 2)
Sea Surface Temperature	W. Tropical & N.E. Pacific (Ch. 20) N.W. Atlantic & N.E. Pacific (Ch. 13)		
Sea Level Pressure	S. Australia (Ch. 32)		
Sea Ice Extent			Antarctica (Ch. 33)

† Papers that did not investigate strength are not listed.

†† Papers that did not investigate likelihood are not listed.

* No influence on the likelihood of low rainfall, but human influences did result in higher temperatures and increased net incoming radiation at the surface over the region most affected by the drought.

** An increase in spring rainfall as well as extensive artificial pond drainage increased the risk of more frequent severe floods from the enhanced rainfall.

*** Evidence for human influence was found for greater risk of UK extreme rainfall during winter 2013/14 with time scales of 10 days

**** The study of Jakarta rainfall event of 2014 found a statistically significant increase in the probability of such rains over the last 115 years, though the study did not establish a cause.

	ON EVENT LIKELIHOOD ††			Total Number of Papers
	INCREASE	DECREASE	NOT FOUND OR UNCERTAIN	
Heat	Argentina (Ch. 9) Australia (Ch. 30, Ch. 31) Australia, Adelaide (Ch. 29) Australia, Brisbane (Ch. 28) Europe (Ch. 13) S. Korea (Ch. 19) China (Ch. 22)		Melbourne, Australia (Ch. 29)	7
Cold		Upper Midwest (Ch.3)		1
Winter Storms and Snow	Nepal (Ch. 18)		Eastern U.S. (Ch. 4) N. America (Ch. 6) N. Atlantic (Ch. 7)	4
Heavy Precipitation	Canada** (Ch. 5) New Zealand (Ch. 27)		Jakarta**** (Ch. 26) United Kingdom*** (Ch. 10) S. France (Ch. 12)	5
Drought	E. Africa (Ch. 16) S. Levant (Ch. 14)		Middle East and S.W. Asia (Ch. 15) E. Africa* (Ch. 17) N.E. Asia (Ch. 21) S. E. Brazil (Ch. 8) Singapore (Ch. 25)	7
Tropical Cyclones	Hawaii (Ch. 23)		Gonzalo (Ch. 11) W. Pacific (Ch. 24)	3
Wildfires	California (Ch. 2)			1
Sea Surface Temperature	W. Tropical & N.E. Pacific (Ch. 20) N.W. Atlantic & N.E. Pacific (Ch. 13)			2
Sea Level Pressure	S. Australia (Ch. 32)			1
Sea Ice Extent			Antarctica (Ch. 33)	1
TOTAL				32

† Papers that did not investigate strength are not listed.

†† Papers that did not investigate likelihood are not listed.

* No influence on the likelihood of low rainfall, but human influences did result in higher temperatures and increased net incoming radiation at the surface over the region most affected by the drought.

** An increase in spring rainfall as well as extensive artificial pond drainage increased the risk of more frequent severe floods from the enhanced rainfall.

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