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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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.

19. ANTHROPOGENIC INFLUENCE ON THE 2014 RECORD-HOT SPRING IN KOREA

SEUNG-KI MIN, YEON-HEE KIM, SEUNGMOK PAIK, MAENG-KI KIM, AND KYUNG-ON BOO

A comparison of observations and multiple global climate models indicates human influence has increased the chance of extreme hot springs in Korea such as the 2014 event by two to three times.

Introduction. During March–May (MAM) 2014 South Korea experienced the hottest spring days on record for the past 61 years. The observed 2014 MAM average daily maximum temperature ($T_{\max}$) reached 19.2°C , exceeding the 1971–2000 climatology by 1.7°C (Fig. 19.1a). This warming was evident at all weather stations across South Korea (Supplemental Fig. S19.1). Average minimum temperature ($T_{\min}$) was 9.1°C , the second highest on record, 1.6°C warmer than climatology. Average daily mean temperature (T_{mean}) was also the second warmest (13.8°C) behind only 1998. Due to the unusually warm spring weather, many spring flower festivals ran earlier than scheduled, indicating the dominant influence of temperature on plant phenology (Kim et al. 2015). Further, tropical nights (daily minimum temperature $>25^{\circ}\text{C}$; e.g., Choi et al. 2009) appeared in May for the first time over South Korea (Jeju and Gangneung stations) since meteorological observations began in the early 20th century.

Along with the 2014 extreme events, spring temperatures have been consistently increasing over the past 61 years with statistically significant trends in $T_{\max}$ (Fig. 19.1b). For most of 2014 MAM, T_{mean} exceeded the climatology, especially in the late March and late May (Fig. 19.1c). It is not surprising that the 2014 spring heat was in accord with the earliest start of summer on record (Fig. 19.1b), which was 22 May, 10 days earlier than climatology, 1 June. [Summer onset day is defined as a calendar date with over 20°C

in T_{mean} and 25°C in $T_{\max}$, obtained through applying a Butterworth low-pass filter to raw daily data with a cutoff period of 90-days (Kwon et al. 2007)]. Interestingly, the correlation between Korean $T_{\max}$ and the summer onset day is very strong ($r = -0.71$), indicating that a hot spring leads to an earlier onset of summer. The spatial correlation map (Fig. 19.1d) indicates that Korean spring temperature is closely related to spring temperatures over northeastern China, which also observed a warmer spring in 2014 (Supplemental Fig. S19.2).

A question might be raised whether, and how much, such warmer spring is due to human-induced greenhouse warming. Here, we conduct a quantitative attribution analysis of 2014 spring heat over Korea in the context of climate change. Anthropogenic contribution to extreme spring temperature is assessed by comparing the probability of the observed temperature and its long-term trend to those from coupled climate model simulations with and without human influences.

Data and Methods. We use $T_{\max}$, $T_{\min}$, and T_{mean} observations from 12 Korean weather stations for 1954–2014. We also use monthly surface air temperature (SAT) data from HadCRUT4 (Morice et al. 2012) to find a large-scale indicator of the Korean spring heat, utilizing an upscaling approach (Min et al. 2014). Global climate model outputs usually cannot capture spatial details of Korean climate due to relatively coarse resolution, so we use this large-scale indicator instead.

We use multimodel datasets available from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) experiments (see Supplemental Table S19.1) in order to assess the contribution of human influence to the observed spring heat. We use data from the “historical” experiment integrated with natural (due to changes in solar and volcanic activities) and anthropogenic forcings (due mainly

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FIG. 19.1. (a) Distribution of MAM mean Tmax anomalies (°C) observed at 12 stations over South Korea in 2014. Anomalies are with respect to 1971–2000 mean. (b) Time series of MAM mean Tmax (red, °C) and summer onset day (green) averaged over 12 stations for 1954–2014. Warming trends (gray straight lines) in Tmax (0.27°C decade⁻¹) and onset of summer (–1.6 day decade⁻¹) are statistically significant at 1% significance level based on the Mann-Kendall test. (c) Time series of Tmean in the spring of 2014. Red and blue shading indicate above normal and below normal, respectively. The black and red lines represent the Butterworth low-pass filtered Tmean and Tmax in 2014. The vertical green line represents the onset of summer in 2014. The horizontal gray lines indicate the 20°C (Tmean) and 25°C (Tmax) thresholds for summer onset date. (d) Spatial distribution of correlation coefficients between Korean Tmax and SAT calculated for 1954–2014. Box indicates an area selected as an indicator of Korean spring heat.

to increases in greenhouse gases and aerosols) for 1860–2005 and extend them to 2014 using data from RCP (Representative Concentration Pathway) 4.5 scenario simulations for 2006–14. We chose RCP4.5 scenario runs that provide the largest number of model samples because difference between RCP scenarios is very small until the near-term future (Moss et al. 2010). Subsequently, two 61-year periods are selected as 1860–1920 (ALL_P0), which is assumed to close to the pre-industrial period with negligible anthropogenic influence, and 1954–2014 (ALL_P1), which represents climate conditions with human influence. We also use datasets from the “historical-GHG” (greenhouse-gas only forcing) and “historical-Nat” (natural forcing only) experiments to examine contribution of the individual factors (note that the analysis period of these experiments is 1954–2012 because they end in 2012). Anomalies from all model runs are calculated relative to each 1971–2000 mean of ALL_P1 in order to consider climate response to different forcings.

so as to quantitatively estimate anthropogenic influence. Here, FAR is calculated as $FAR = 1 - (P_N/P_A)$, where P_N denotes the probability of exceeding the observed event (trends in SAT anomaly or 2014 SAT anomaly) occurring in natural unforced conditions (ALL_P0 or NAT_P1), and P_A represents the same probability estimated in anthropogenic forced conditions (ALL_P1 or GHG_P1). FAR uncertainty (5th–95th percentile) is estimated through bootstrap resampling.

Results. The observed SAT anomaly represents striking long-term warming (Fig. 19.2a) with a record high in 2014 (+1.8°C), tied with 1998. This SAT acts as a good predictor for the Korean spring Tmax with a correlation coefficient of 0.88. Modeled SAT anomalies are illustrated together in Fig. 19.2 for ALL_P0 (blue), ALL_P1 (green), GHG_P1 (red), and NAT_P1 (purple). Trends in ALL_P0 and NAT_P1 are very weak while GHG_P1 possesses stronger positive trends than observation (Fig. 19.2a). This

Next, in order to identify a large-scale SAT indicator for Korean spring temperature in general, we obtain a correlation map (Fig. 19.1d) between Korean Tmax and observed East Asian SAT for 1954–2014, both of which are MAM averages. We then choose a latitude–longitude box (30°–45°N and 110°–130°E) with strong correlation ($r > 0.7$) and calculate area-averaged SAT anomalies from observations and all CMIP5 simulations (referred to as “observed SAT anomaly” and “modeled SAT anomaly”, respectively). A similar local Tmax and large-scale SAT relationship is simulated by the models (Supplementary Fig. S19.3).

Using the fraction of attributable risk (FAR; Stott et al. 2004) approach, we evaluate the risk of long-term warming trends and 2014 spring heat wave in terms of anthropogenic forcing. The FAR approach compares the probability of extreme events occurring between a real world (with human influence) and a counterfactual world (without human influence),

suggests a dominant contribution of the greenhouse warming to the ALL_P1 trend considering that other anthropogenic forcing (mainly aerosols) will induce long-term cooling. The interannual variability of SAT anomaly is found to be reasonably well simulated by CMIP5 models with slight overestimation (Standard deviation of observed detrended SAT is 0.64°C . Multimodel mean of standard deviations of detrended SAT from ALL_P1 is 0.80°C with a 5th–95th percentile range of 0.60° – 1.03°C).

We first compare the trends of observed and modeled SAT anomaly using probability density functions (PDF) in Fig. 19.2b. The trend PDFs are constructed from linear trends from all ensemble members for each experiment (thin lines in Fig. 19.2a). While the observed trend (1.64°C per 61 years) exceeds the trends PDF of ALL_P0 and NAT_P1, it is positioned inside the trends PDF of ALL_P1 and located near the center of GHG_P1 distributions. Thus, fraction of risk of the observed SAT trend attributable to anthropogenic forcing is 100% ($\text{FAR} = 1$; Table 19.1) considering a negligible influence of natural forcing. According to various trend periods (all ending in 2014), a FAR value of 1 is obtained for a trend period longer than 40 years (Supplementary Fig. S19.4a).

For the recent 30-year period (1985–2014), the trends in SAT anomaly exceeding the observed trend (1°C per 30 years) is simulated in ALL_P0 (5.59% probability), ALL_P1 (37.19%), and GHG_P1 (33.33%) (Fig. 19.2c; Table 19.1). The corresponding FAR values of ALL_P1 and GHG_P1 relative to ALL_P0 are 0.85 and 0.83, respectively (about a six- to seven-time increase in risk). The slightly larger FAR in ALL_P1 than in GHG_P1 for the recent 30-year trends seems partly due to the NAT_P1 contribution to the ALL_P1 warming trend (i.e., recovery after volcanic cooling in the early decades; Supplementary Fig. S19.5).

We also compare the 2014 spring heat wave event using a similar method. The PDF distributions for the

FIG. 19.2. (a) Time series of SAT anomaly ($^{\circ}\text{C}$) from observation, ALL_P0, ALL_P1, GHG_P1, and NAT_P1. Black straight line represents the observed linear trend; thick colored lines indicate ensemble mean of each experiment. (b) Normalized PDF for trend in SAT anomaly ($^{\circ}\text{C } 61 \text{ yr}^{-1}$) from ALL_P0 (blue), ALL_P1 (green), GHG_P1 (red), and NAT_P1 (purple) in comparison with the observed trend (vertical black line) for the past 61 years (1954–2014). Colored vertical dotted lines indicates ensemble mean trends. (c) As in (b), but for the recent 30 years (1985–2014). (d) As in (b), but for SAT anomaly from models (all years) and the observed SAT anomaly in 2014 ($^{\circ}\text{C}$).

modeled SAT anomaly are displayed in Fig. 19.2d. The PDF distribution consists of all values of SAT anomalies during 61 years from all ensemble members for each experiment. SAT anomalies stronger than the observed 2014 event are extremely rare in ALL_P0 (0.91%) and NAT_P1 (0.73%). The chance of 2014-like extreme events increases to 2.49% and 17.74% in ALL_P1 and GHG_P1, respectively (Table 19.1). The corresponding FAR values with respect to ALL_P0 are 0.64 (5th–95th percentile range of 0.57–0.69) and 0.95 (5th–95th percentile range of 0.94–0.96), indicating a 2- to 3- and 20-time increase in risk due to human influence, respectively. The record extreme 2014 ($+1.8^{\circ}\text{C}$) SAT anomalies were greater than $+2\sigma$ above

Table 19.1. Probability of occurrence exceeding the observed trend in SAT anomaly and the observed 2014 SAT anomaly. The fraction of attributable risk is calculated as $FAR_{ALL_PI} = 1 - P_{ALL_P0}/P_{ALL_PI}$ and $FAR_{GHG_PI} = 1 - P_{ALL_P0}/P_{GHG_PI}$				
	Observations	ALL_P0	ALL_PI	GHG_PI
SAT anomaly Trend (61 years)	1.64 (°C 61 yr ⁻¹)	0%	3.31% FAR = 1	43.33% FAR = 1
SAT anomaly Trend (30 years)	1.00 (°C 30 yr ⁻¹)	5.59%	37.19% FAR = 0.85	33.33% FAR = 0.83
2014 spring SAT anomaly	1.8 (°C)	0.91%	2.49% FAR = 0.64 (0.57–0.69)	17.74% FAR = 0.95 (0.94–0.96)

the climatological mean. A relationship between hypothetical SAT anomaly and FAR (Supplementary Fig. S19.4b; Christidis et al. 2014) suggests more than a 10-time increase in risk when an SAT anomaly stronger than $+3\sigma$ is observed, for example.

We have also tested the sensitivity of FAR to the use of different model samples (Supplementary Fig. S19.6). The models are divided into two groups which have warm and cold biases relative to observed climatology (see Supplementary Table S19.1 for model lists). FAR values are similar between the two model groups (0.66 and 0.67, respectively), indicating that the FAR results are largely insensitive to the use of different model samples.

Conclusions. South Korea experienced the hottest spring and the earliest summer onset in 2014, and spring temperatures have been consistently increasing during the past 61 years. This study examines the possible impact of anthropogenic influence on the observed spring heat and warming trends by comparing CMIP5 multimodel experiments with and without human influences utilizing a large-scale SAT indicator of the Korean spring temperature. It is found that the observed SAT long-term trend is outside of the PDF of modeled natural and near-preindustrial simulations indicating that risk due to anthropogenic influence is 100% and that extreme hot springs like the 2014 event have increased two to three times due to human influence. Overall, our results show that greenhouse warming has contributed to warming trends in Korea spring temperature and an increasing risk of spring temperature extremes.

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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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