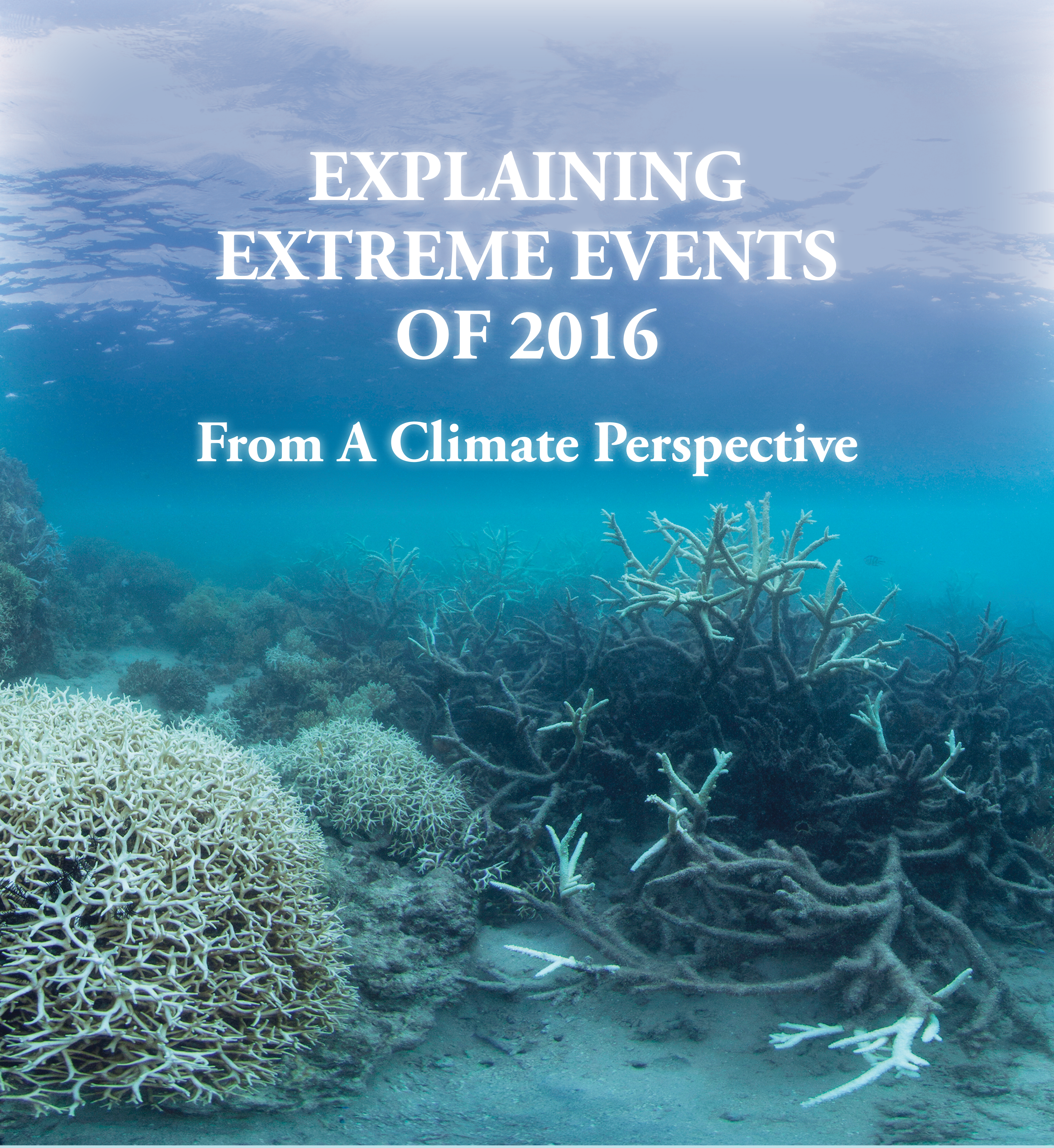

EXPLAINING EXTREME EVENTS OF 2016

From A Climate Perspective

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EXPLAINING EXTREME EVENTS OF 2016 FROM A CLIMATE PERSPECTIVE

Editors

Stephanie C. Herring, Nikolaos Christidis, Andrew Hoell, James P. Kossin,
Carl J. Schreck III, and Peter A. Stott

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ABSTRACT—Stephanie C. Herring, Nikolaos Christidi, Andrew Hoell, James P. Kossin, Carl J. Schreck III, and Peter A. Stott

This sixth edition of explaining extreme events of the previous year (2016) from a climate perspective is the first of these reports to find that some extreme events were not possible in a preindustrial climate. The events were the 2016 record global heat, the heat across Asia, as well as a marine heat wave off the coast of Alaska. While these results are novel, they were not unexpected. Climate attribution scientists have been predicting that eventually the influence of human-caused climate change would become sufficiently strong as to push events beyond the bounds of natural variability alone. It was also predicted that we would first observe this phenomenon for heat events where the climate change influence is most pronounced. Additional retrospective analysis will reveal if, in fact, these are the first events of their kind or were simply some of the first to be discovered.

Last year, the editors emphasized the need for additional papers in the area of "impacts attribution" that investigate whether climate change's influence on the extreme event can subsequently be directly tied to a change in risk of the socio-economic or environmental impacts. Several papers in this year's report address this challenge, including Great Barrier Reef bleaching, living marine resources in the Pacific, and ecosystem productivity on the Iberian Peninsula. This is an increase over the number of impact attribution papers than in the past, and are hopefully a sign that research in this area will continue to expand in the future.

Other extreme weather event types in this year's edition include ocean heat waves, forest fires, snow storms, and frost, as well as heavy precipitation, drought, and extreme heat and cold events over land. There were a number of marine heat waves examined in this year's report, and all but one found a role for climate change in increasing the severity of the events. While human-caused climate change caused China's cold winter to be less likely, it did not influence U.S. storm Jonas which hit the mid-Atlantic in winter 2016.

As in past years, the papers submitted to this report are selected prior to knowing the final results of whether human-caused climate change influenced the event. The editors have and will continue to support the publication of papers that find no role for human-caused climate change because of their scientific value in both assessing attribution methodologies and in enhancing our understanding of how climate change is, and is not, impacting extremes. In this report, twenty-one of the twenty-seven papers in this edition identified climate change as a significant driver of an event, while six did not. Of the 131 papers now examined in this report over the last six years, approximately 65% have identified a role for climate change, while about 35% have not found an appreciable effect.

Looking ahead, we hope to continue to see improvements in how we assess the influence of human-induced climate change on extremes and the continued inclusion of stakeholder needs to inform the growth of the field and how the results can be applied in decision making. While it represents a considerable challenge to provide robust results that are clearly communicated for stakeholders to use as part of their decision-making processes, these annual reports are increasingly showing their potential to help meet such growing needs.

I. INTRODUCTION TO EXPLAINING EXTREME EVENTS OF 2016 FROM A CLIMATE PERSPECTIVE

Stephanie C. Herring, Nikolaos Christidis, Andrew Hoell,
James P. Kossin, Carl J. Schreck III, and Peter A. Stott

Over the past six years, more than 130 peer-reviewed papers evaluating the potential connection between extreme weather and anthropogenic climate change have been presented in this annual special edition of the *Bulletin of the American Meteorological Society*. Of the roughly 89 papers that did identify a climate change signal in the authors' analysis of an extreme event, each found climate change had shifted the odds of an event happening. Prior to this year, however, none had determined that human-caused climate change was an essential factor in the occurrence of the event. In this year's report, for the first time, we present three new research papers that conclude the extreme magnitude of a particular weather event was not possible without the influence of human-caused climate change.

- In a paper analyzing the 2016 global heat record by NOAA scientist Tom Knutson et al., the authors concluded that record global warmth "was only possible due to substantial centennial-scale human-caused warming."
- Similarly, a study of the record heat over Asia led by Yukiko Imada of the Japanese Meteorological Agency found that the extreme warmth across Asia in 2016 "would not have been possible without climate change."
- In addition to these two papers looking at atmospheric temperatures, a team led by John Walsh of the University of Alaska determined that a large, persistent area of anomalously warm ocean water off the coast of Alaska (often referenced as "the Blob") found "no instances of 2016-like anomalies in the preindustrial climate" for sea surface temperatures in the Bering Sea.

These results are novel, and we would argue, significant for two reasons. First, it is important to note that climate scientists have been predicting that, based on the ongoing global warming of Earth's climate, the influence of human-caused climate change would at some point become sufficiently strong and emergent to push an extreme event beyond the bounds of natural variability alone. It was also anticipated that we would likely first see this result for heat events where the human-caused influences are most strongly observed. It is striking how quickly we are now starting to see such results, though their dependence on model-based estimates of natural variability in the absence of human-induced change will require ongoing validation of the time-of-emergence for extreme event magnitudes at local scales. Second, because of the small sample size of events shown in this report, it is possible that other temperature-related extreme events occurring in prior years may also have been impossible to achieve without human-induced climate change. Retrospective studies would be needed to explore this possibility. The 2016 results do not necessarily indicate that some climate threshold or tipping point has been reached.

It is helpful to consider the methodology used in these studies to understand the conclusions. Each used the commonly accepted event attribution technique of calculating the fraction of attributable risk (FAR) for the event, a statistical approach borrowed from epidemiology and public health, establishing the probability of the event happening with greenhouse gas emissions at current levels due to human activity. For heat events, this probability relies in large part on the observational record. This result is compared with model runs of a "control" world that only include natural forcing mechanisms and ignore the changes to atmospheric composition driven by human greenhouse gas emissions.

All three papers concluded that the FAR was 1, meaning that the event was not possible in the "control" planet, and only possible in a world with human-emitted greenhouse gases. It should also be recognized that although FAR = 1 in relation to a human-induced impact in these cases, other climate drivers that also affect the probability of such ex-

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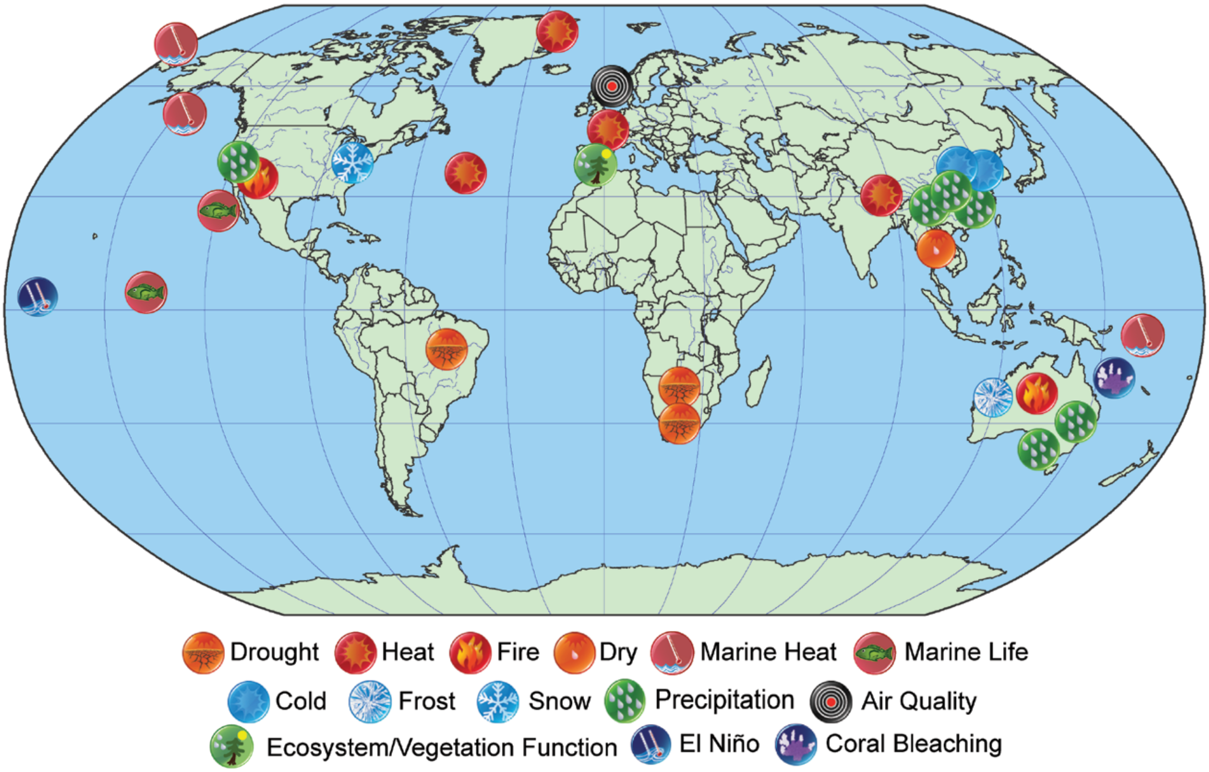

Fig. 1.1. Location and types of events analyzed in this publication.

tremes may have been major additional contributors to the likelihood of the event occurring. Each of these papers applied large model ensembles (CMIP5 for both the global heat and Alaska marine heat wave analyses and the atmospheric general circulation model MIROC5 for the Asia heat study) to determine the FAR for these events.

As in past years, this sixth edition of *Explaining Extreme Events from a Climate Perspective* includes studies of extreme events from around the world that did not find a role for climate change in influencing the magnitude or frequency of an event. It is important to note that papers are selected for consideration in this report by reviewing author proposals that do not indicate whether a role for climate change will or will not be found. Thus, there is no selection bias on the part of the editorial team toward one particular conclusion, and this publication prides itself as a venue that accepts papers without consideration for whether a role for climate change is found. This year there may be a slight bias toward events that do not find a signal relative to previous years because the editors have begun to limit the number of heat papers in the report which is the event type where a signal is most commonly found. Given that the majority of heat papers now use a widely established and accepted methodology, the scientific value of continuing to include a large number of heat studies began to seem limited.

Extreme weather event types included in this year's edition include ocean heat waves, forest fires, snow storms, and frost, as well as heavy precipitation, drought, and extreme heat and cold events over land. A number of papers also look at the impacts of extremes (Fig. 1.1). The Summary of Results Table (Table 1.1) gives readers a general overview of the results.

Twenty-one of the 27 papers in this current edition identified climate change as a significant driver of an event, while six did not. Of the 131 papers now examined in this report over the last six years, approximately 65% have identified a role for climate change, while about 35% have not found an appreciable effect.

Nevertheless, over the past six years, researchers have identified the robust influence of climate change on temperature-related extremes, making such high-temperature events quantifiably more intense and more frequent. The events studied by these 131 papers were not chosen randomly and may not be representative of all extreme events. They are concentrated mostly on the continents of North America, Europe, Asia, and Australia, so there remains an open question of how human-caused climate change may be influencing extreme weather in parts of the world that are not as well studied.

Last year, the editors called on scientists submitting research proposals to investigate potential links between an extreme event and its subsequent impact, and we were excited to see five research teams take on this challenge in this year's report. Lewis and Mallela concluded that the risk of the extreme Great Barrier Reef bleaching event was increased through anomalously high sea surface temperature and the accumulation of thermal stress caused by human-caused climate change. Jacox et al. and Brainard et al. both examined how high ocean temperatures caused in part by human-caused climate change impacted living marine resources like coral bleaching, reduced fish stocks, and a decrease in seabird counts in the California current and the equatorial Pacific, respectively. On land, Sippel et al. found that human-caused climate change is causing warmer winters on the Iberian Peninsula and, when coupled with a wet spring, drove higher ecosystem productivity in the region in 2016. However, these papers represent early approaches, and more work is needed to develop impact attribution methodologies.

As is always the case, we would caution that the results of any single study should not be interpreted as the final word on the matter for that event, nor be generalized to a broader class of extremes. For example, authors of these papers selected specific modeling approaches and made other choices about factors that are important in how the models replicate extreme events, such as terrestrial heat or sea surface temperatures. If other study designs were applied to these events, it is possible a different result would be reached. The importance of the methodological approach in attribution research is further discussed in the summary of this report (Stott et al.).

A big question raised by this collection of research is whether these findings undermine the axiom that "no event is caused by climate change alone and that natural variability always plays some role." The short answer is no. While several of the studied events were found not to be possible without climate change, natural variability still laid the foundation for the events to occur, and the authors acknowledge this in their papers. Extreme events are always the result of a cumulative set of factors. The building blocks that form the foundation of any event continue to include natural variability, with factors such as El Niño potentially adding to the strength of the event. These temperature-related extremes would likely still have been warm events even without human-caused climate change, but according to these analyses, the events could not have surpassed the extreme warm thresholds that they did without climate change. This was especially the case for the record-setting globally averaged temperature. At the global scale, the natural variations of Earth's temperature are increasingly seen to pale in comparison to the growing intensity of human-induced warming. Overall, human-caused climate change allowed them to pass a threshold that they could not otherwise have exceeded.

These papers also emphasize why clearer understanding of how human-caused climate change impacts extreme events is an important area of research. Retrospective analysis of previous extreme events may yield new insights into the history of human-caused climate change impacts, and we can expect to see insights into the extent and timing of the changes in the future.

Table 1.1. SUMMARY of RESULTS

	ANTHROPOGENIC INFLUENCE ON EVENT		
	INCREASE	**DECREASE**	**NOT FOUND OR UNCERTAIN**
Heat	Ch. 3: Global Ch. 7: Arctic Ch. 15: France Ch. 19: Asia		
Cold		Ch. 23: China Ch. 24: China	
Heat & Dryness	Ch. 25: Thailand		
Marine Heat	Ch. 4: Central Equatorial Pacific Ch. 5: Central Equatorial Pacific Ch. 6: Pacific Northwest Ch. 8: North Pacific Ocean/Alaska Ch. 9: North Pacific Ocean/Alaska Ch. 9: Australia		Ch. 4: Eastern Equatorial Pacific
Heavy Precipitation	Ch. 20: South China Ch. 21: China (Wuhan) Ch. 22: China (Yangtze River)		Ch. 10: California (failed rains) Ch. 26: Australia Ch. 27: Australia
Frost	Ch. 29: Australia		
Winter Storm			Ch. 11: Mid-Atlantic U.S. Storm "Jonas"
Drought	Ch. 17: Southern Africa Ch. 18: Southern Africa		Ch. 13: Brazil
Atmospheric Circulation			Ch. 15: Europe
Stagnant Air			Ch. 14: Western Europe
Wildfires	Ch. 12: Canada & Australia (Vapor Pressure Deficits)		
Coral Bleaching	Ch. 5: Central Equatorial Pacific Ch. 28: Great Barrier Reef		
Ecosystem Function		Ch. 5: Central Equatorial Pacific (Chl-***a*** and primary production, sea bird abundance, reef fish abundance) Ch. 18: Southern Africa (Crop Yields)	
El Niño	Ch. 18: Southern Africa		Ch. 4: Equatorial Pacific (Amplitude)
TOTAL	18	3	9

	METHOD USED	Total Events
Heat	Ch. 3: CMIP5 multimodel coupled model assessment with piCont, historicalNat, and historical forcings Ch. 7: CMIP5 multimodel coupled model assessment with piCont, historicalNat, and historical forcings Ch. 15: Flow analogues conditional on circulation types Ch. 19: MIROC-AGCM atmosphere only model conditioned on SST patterns	
Cold	Ch. 23: HadGEM3-A (GA6) atmosphere only model conditioned on SST and SIC for 2016 and data fitted to GEV distribution Ch. 24: CMIP5 multimodel coupled model assessment	
Heat & Dryness	Ch. 25: HadGEM3-A N216 Atmosphere only model conditioned on SST patterns	
Marine Heat	Ch. 4: SST observations; SGS and GEV distributions; modeling with LIM and CGCMs (NCAR CESM-LE and GFDL FLOR-FA) Ch. 5: Observational extrapolation (OISST, HadISST, ERSST v4) Ch. 6: Observational extrapolation; CMIP5 multimodel coupled model assessment Ch. 8: Observational extrapolation; CMIP5 multimodel coupled model assessment Ch. 9: Observational extrapolation; CMIP5 multimodel coupled model assessment	
Heavy Precipitation	Ch. 10: CAM5 AMIP atmosphere only model conditioned on SST patterns and CESM1 CMIP single coupled model assessment Ch. 20: Observational extrapolation; CMIP5 and CESM multimodel coupled model assessment; auto-regressive models Ch. 21: Observational extrapolation; HadGEM3-A atmosphere only model conditioned on SST patterns; CMIP5 multimodel coupled model assessment with ROF Ch. 22: Observational extrapolation, CMIP5 multimodel coupled model assessment Ch. 26: BoM seasonal forecast attribution system and seasonal forecasts Ch. 27: CMIP5 multimodel coupled model assessment	
Frost	Ch. 29: *weather@home* multimodel atmosphere only models conditioned on SST patterns; BoM seasonal forecast attribution system	
Winter Storm	Ch. 11: ECHAM5 atmosphere only model conditioned on SST patterns	
Drought	Ch. 13: Observational extrapolation; weather@home multimodel atmosphere only models conditioned on SST patterns; HadGEM3-A and CMIP5 multimodel coupled model assessent; hydrological modeling Ch. 17: Observational extrapolation; CMIP5 multimodel coupled model assessment; VIC land surface hdyrological model, optimal fingerprint method Ch. 18: Observational extrapolation; *weather@home* multimodel atmosphere only models conditioned on SSTs, CMIP5 multimodel coupled model assessment	
Atmospheric Circulation	Ch. 15: Flow analogues distances analysis conditioned on circulation types	
Stagnant Air	Ch. 14: Observational extrapolation; Multimodel atmosphere only models conditioned on SST patterns including: HadGEM3-A model; EURO-CORDEX ensemble; EC-EARTH+RACMO ensemble	
Wildfires	Ch. 12: HadAM3 atmospere only model conditioned on SSTs and SIC for 2015/16	
Coral Bleaching	Ch. 5: Observations from NOAA Pacific Reef Assessment and Monitoring Program surveys Ch. 28: CMIP5 multimodel coupled model assessment; Observations of climatic and environmental conditions (NASA GES DISC, HadCRUT4, NOAA OISSTV2)	
Ecosystem Function	Ch. 5: Observations of reef fish from NOAA Pacific Reef Assessment and Monitoring Program surveys; visual observations of seabirds from USFWS surveys. Ch. 18: Empirical yield/rainfall model	
El Niño	Ch. 4: SST observations; SGS and GEV distributions; modeling with LIM and CGCMs (NCAR CESM-LE and GFDL FLOR-FA) Ch. 18: Observational extrapolation; *weather@home* multimodel atmosphere only models conditioned on SSTs, CMIP5 multimodel coupled model assessment	
		30

ACRONYMS

AMIP: Atmospheric Model Intercomparison Project

BOM: Bureau of Meteorology, Australia

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

CESM: Community Earth System Model

CMIP: Coupled Model Intercomparison Project

GEV: Generalized extreme value

GFDL FLOR: Geophysical Fluid Dynamics Laboratory Forecast-Oriented Low Ocean Resolution

HadGEM3-A: Hadley Centre Global Environmental Model version 3-A

LIM: Linear inverse model

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

ROF: Regularized optimal fingerprinting

SGS: Stochastically-generated skewed

SIC: Sea ice concentration

SST: Sea Surface Temperature

USFWS: U.S. Fish and Wildlife Service

VIC: Variable infiltration capacity

weather@home: www.climateprediction.net/weatherathome/

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