

# **STUDY OF HEAT WAVES OVER INDIA**

**ARULALAN THANIGACHALAM**



**CENTRE FOR ATMOSPHERIC SCIENCES**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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# **STUDY OF HEAT WAVES OVER INDIA**

*by*

**ARULALAN THANIGACHALAM**

**CENTRE FOR ATMOSPHERIC SCIENCES**

Submitted

in fulfilment of the requirements of the degree of **DOCTOR OF PHILOSOPHY**

to the



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**Dedicated to My Family  
&  
My Teachers**

## **Certificate**

This is to certify that the thesis entitled "**Study of Heat Waves over India**" being submitted by **Mr. Arulalan Thanigachalam (Entry No : 2016ASZ8055)** to the **Indian Institute of Technology Delhi** for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bonafide research carried out by him. Mr. Arulalan Thanigachalam has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

New Delhi

July 2024

**Prof. Krishna AchutaRao**

Centre for Atmospheric Sciences  
Indian Institute of Technology Delhi  
New Delhi –110016, India

**Dr. Ashis Kumar Mitra**

Scientist-G & Head (Retd.)  
National Centre for Medium Range Weather Forecasting  
Ministry of Earth Sciences, Govt. India  
Noida, Uttar Pradesh – 201 309, India

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ARULALAN THANIGACHALAM

## Abstract

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6) highlights alarming climate projections for the Indian subcontinent, including a more variable monsoon, extreme rainfall, floods, droughts, heatwaves, and intensified tropical cyclones. India, highly vulnerable to climate events, faces yearly challenges impacting lives, infrastructure, agriculture, and the economy. Heatwaves, exacerbated by climate change, pose a significant threat, causing numerous deaths and economic losses. The AR6 findings reinforce the link between global warming levels and the intensification of extreme events, including heatwaves.

This study addresses the pressing concerns outlined in the AR6 regarding the escalating impacts of climate change on the Indian subcontinent. With a focus on heat waves, this study underscores the urgency of enhancing scientific understanding to inform effective adaptation planning and action. Numerous studies have documented the increasing frequency and duration of heat waves in different parts of India. The observed trends reveal a substantial impact on human health, agriculture, and overall mortality. Understanding the characteristics of heat waves is crucial for informed policy responses. India's current response involves Heat Action Plans that have been formulated by local and regional governments, but their effectiveness requires accurate heat wave forecasts. This thesis is focused on addressing the questions of how heat waves change in the future. This is investigated with the help of simulations of +1.5°C and +2°C warmer worlds designed to address the question of future changes in extreme weather. The mechanism of how the heat waves over Northwest India are triggered by atmospheric blocking events over North Atlantic through teleconnection is investigated for its robustness in future warmer worlds. In

order to inform adaptation to climate change, risk-based event attribution on a recent heat wave that occurred over India and Pakistan is carried out and, emphasizing the need for reliable forecasts, the forecast skill of state-of-art numerical weather prediction models for that heat event are analysed .

This study begins by analyzing past, present, and future heat wave conditions using operational definitions of heat events, such as "hot day," "heatwave," and "severe heatwave," employed by the India Meteorological Department. This allows for a meaningful comparison of future and past conditions and provides valuable insights for decision-makers. The methodology involves the identification of heat events of different categories in observations and bias corrected model output. The findings of this study reveal decreasing hot day duration but increasing heat wave duration in certain regions of India between 1951–2015. Future climates at +1.5°C and +2.0°C indicate a rise in frequency and duration of heat events, with shorter events 2-10 times more probable and longer duration events increasing by 10-30 times. The increased likelihood of heat waves in June and July poses additional risk due to higher moisture levels. A few recent heat waves that resulted in high mortality are taken as case studies to examine their characteristics in the two future climates. It is shown that the duration and area affected by the heat waves will most likely increase.

Next, this thesis investigates the influence of atmospheric blocking patterns and Rossby Waves on the heat events, particularly heat waves over Northwest India. Rossby Waves, exhibiting meridional expansion attributed to Arctic amplification, are linked to slower propagation and heat wave development. IPCC AR6 highlights robust trends in blocking frequency, showing increases

in specific regions and seasons. A quasi-stationary Rossby Wave pattern, characterized by anomalous cyclonic and anticyclonic flow, plays a crucial role in heat wave dynamics. This study explores teleconnections between atmospheric blocking over the North Atlantic and heatwaves in Northwest India, adopting a methodology to assess potential changes in teleconnections under future climate scenarios (+1.5°C and +2°C). The results suggest that specific Rossby wave patterns, such as those with wavenumbers 5 and 7, can induce simultaneous heat extremes in distinct regions. The findings highlight that atmospheric blocking events over the North Atlantic teleconnect with heat waves in Northwest India, with a 3-day lag, persisting in +1.5°C and +2°C future climates. Granger Causality tests confirm the continued influence of North Atlantic blocking on higher daily maximum temperature anomalies over Northwest India in warmer climates. The analysis of Rossby wave numbers (4-11) highlights that Rossby Waves 7 and 9 trigger anomalous blocking over North Atlantic, leading to increased heat events over Northwest India, and their higher frequency in earlier in the season (March and April) and more frequent and earlier heat events over Northwest India.

Next, well established event attribution techniques were employed to understand the contribution of human-induced global warming to a specific heat event - the 2022 heat wave over South Asia. Despite La Niña conditions contributing to a slightly lower global temperature, 2022 marked the fifth warmest year on record globally. The study delves into the unprecedented and prolonged heat wave experienced in North India and Southern Pakistan from March to May 2022, with significant impacts on public health and agriculture (specifically the wheat crop), glacial lake outbursts, and forest fires. This study finds that the 2022 event (March-April observed daily maximum temperature) had a return period of ~1-in-100 years and that human-caused climate

change made this heat wave about 1°C hotter and 30 times more likely in the current, 2022 climate, as compared to the 1.2°C cooler, pre-industrial climate.

Finally, this thesis also conducts a comprehensive analysis of the prediction skills of several state-of-the-art numerical weather prediction models for the 2022 heat wave. The results show that the multi-model mean gives better forecast skills on prediction of heat waves during March-April 2022.

Overall, the findings discussed in the thesis warn of heat waves that will occur earlier in the season in the future and last longer over a larger area. This is an insight for the government's preparedness measures, including Heat Action Plans, early warning systems, and healthcare strategies in India, offering a tangible basis for decision-makers and emphasizing the significance of actionable climate science in the face of evolving climate challenges.

## शोध-सार

इंटर-गवर्नमेंट पैनल ऑन क्लाइमेट चेंज की छठी मूल्यांकन रिपोर्ट (ए.आर. 6) भारतीय उपमहाद्वीप के लिए चिंतनीय जलवायु अनुमानों पर प्रकाश डालती है, जिसमें अधिक परिवर्तनशील मानसून, अत्यधिक वर्षा, बाढ़, सूखा, ऊष्ण-लहर और तीव्र उष्णकटिबंधीय चक्रवात शामिल हैं। भारत, जलवायु परिवर्तन आधारित घटनाओं के प्रति अत्यधिक संवेदनशील है और जीवन सम्बन्धी, बुनियादी ढांचे, कृषि और अर्थव्यवस्था को प्रभावित करने वाली चुनौतियों का प्रतिवर्ष सामना करता है। भारतीय उपमहाद्वीप पर जलवायु परिवर्तन के कारण बढ़ी ऊष्ण-लहर एक एक गंभीर खतरा पैदा करती है, जिसके कारण जीवन क्षति तथा आर्थिक नुकसान होता है। ए.आर. 6 रिपोर्ट के निष्कर्ष वैश्विक तापमान वृद्धि के स्तर और ऊष्ण-लहर सहित चरम घटनाओं की तीव्रता के बीच संबंध को मजबूत करते हैं।

यह शोध भारतीय उपमहाद्वीप पर जलवायु परिवर्तन के बढ़ते प्रभावों के संबंध में ए.आर. 6 रिपोर्ट में उल्लिखित गंभीर चिंताओं के समाधान को व्यक्त करता है। ऊष्ण-लहर पर केंद्रित यह अध्ययन प्रभावी अनुकूलन योजना और कार्रवाई को सूचित करने के लिए वैज्ञानिक सूझबूझ को बढ़ाने की तात्कालिकता को रेखांकित करता है। कई अध्ययनों के प्रलेख में भारत के विभिन्न हिस्सों में ऊष्ण-लहर की बढ़ती आवृत्ति और अवधि का वर्णन किया गया है। इन अध्ययनों में देखे गए रुझान मानव स्वास्थ्य, कृषि और समग्र मृत्यु दर पर प्रचुर प्रभाव दर्शाते हैं। इन प्रभावों द्वारा प्राप्त सूचनाओं की उचित प्रतिक्रियाओं के लिए ऊष्ण-लहर के विशिष्ट लक्षणों को समझना महत्वपूर्ण है। भारत की वर्तमान कार्य योजनाओं में हीट एक्शन योजनाएं शामिल हैं जो स्थानीय और क्षेत्रीय सरकारों द्वारा तैयार

की गई हैं, लेकिन उनकी प्रभावशीलता के लिए सटीक ऊष्ण-लहर पूर्वानुमान तकनीक विकसित करने की आवश्यकता है। यह शोध इस सवाल पर केंद्रित है कि भविष्य में ऊष्ण-लहर के लक्षण कैसे बदलते हैं। इसकी जांच +1.5°C और +2°C उष्ण वैश्विक तापमान के अनुकरण के मदद से की गई है, जिसे भविष्य में मौसम में अत्यधिक होने वाले बदलावों के सवाल का समाधान करने के लिए अभिकल्पित किया गया है। उत्तर-पश्चिमी भारतीय क्षेत्रों के ऊपर बहने वाली ऊष्ण-लहर कैसे उत्तरी अटलांटिक वायुमंडल द्वारा उत्पन्न व प्रेरित होती है , इसकी जाँच इस दूर-संयोजन के माध्यम से की जा रही है। जलवायु परिवर्तन के अनुकूलन को सूचित करने के लिए, भारत और पाकिस्तान में हाल ही में हुई ऊष्ण-लहर पर जोखिम-आधारित घटना देखी गयी है और, विश्वसनीय पूर्वानुमानों की आवश्यकता पर जोर देते हुए, अत्याधुनिक संख्यात्मक मौसम पूर्वानुमान मॉडल्स का पूर्वानुमान कौशल का उपयोग किया गया तथा ऊष्ण-लहर आधारित घटना का विश्लेषण किया जाता है।

यह अध्ययन भारत मौसम विज्ञान विभाग द्वारा नियोजित परिभाषाओं जैसे "गर्म दिन," "ऊष्ण-लहर" और "गंभीर ऊष्ण-लहर" का उपयोग करके अतीत, वर्तमान और भविष्य की ऊष्ण-लहर स्थितियों का विश्लेषण करता है। यह भूत व भविष्य की स्थितियों का तुलनात्मक अध्ययन करके निर्णय कर्ताओं के लिए मूल्यवान अंतर्दृष्टि प्रदान करता है। इसकी कार्यप्रणाली में अवलोकनों और पूर्वाग्रह सुधारित मॉडल आउटपुट में विभिन्न श्रेणियों की तापीय घटनाओं की पहचान शामिल है। इस अध्ययन के निष्कर्षों से पता चलता है कि 1951-2015 के बीच भारत के कुछ क्षेत्रों में गर्म दिन की अवधि कम हो रही है लेकिन ऊष्ण-लहर की अवधि बढ़ रही है। भविष्य की जलवायु +1.5°C और +2.0°C पर आधारित ताप-घटनाओं की आवृत्ति और अवधि में वृद्धि का संकेत देती है, छोटी घटनाओं की संभावना 2-10 गुना अधिक होती है और लंबी अवधि की घटनाओं की संभावना 10-30 गुना तक बढ़ जाती है।

नमी के उच्च स्तर के कारण जून और जुलाई में ऊष्ण-लहर की संभावना बढ़ने से अतिरिक्त जोखिम पैदा होता है। हाल की कुछ ऊष्ण-लहरें जिनके परिणामस्वरूप उच्च मृत्यु दरें देखी गई हैं, उन्हें भविष्य में होने वाले जलवायु परिवर्तनों में ऊष्ण-लहर के विशिष्ट लक्षणों की जाँच करने के लिए केस स्टडी के रूप में लिया गया है। इस केस स्टडी के माध्यम से देखा गया है कि लेकिन ऊष्ण-लहर से प्रभावित होने की अवधि और क्षेत्र में सबसे अधिक वृद्धि होने की संभावना है।

इसके अतिरिक्त, यह शोध प्रबंध गर्मी की घटनाओं, विशेष रूप से उत्तर-पश्चिमी भारत में ऊष्ण-लहर पर वायुमंडलीय अवरोधन पैटर्न और रॉस्बी तरंगों के प्रभाव की जांच करती है। रॉस्बी तरंगें, जो आर्कटिक प्रवर्धन के लिए जिम्मेदार मेरिडियनल (देशांतरीय) विस्तार को प्रदर्शित करती हैं, धीमी गति से प्रसार और ऊष्ण-लहर के विकास से जुड़ी हैं। आईपीसीसी ए.आर. 6 विशिष्ट क्षेत्रों और मौसमों में वृद्धि दिखाते हुए, अवरोधन आवृत्ति में मजबूत रुझानों को उजागर करता है। एक अर्ध-स्थिर रॉस्बी वेव पैटर्न, जो विषम चक्रवाती और प्रतिचक्रवाती प्रवाह की विशेषता है, ऊष्ण-लहर की गतिशीलता में एक महत्वपूर्ण भूमिका निभाता है। यह अध्याय भविष्य के जलवायु परिदृश्यों (+1.5°C और +2°C) के तहत दूर-संयोजन में संभावित परिवर्तनों का आकलन करने के लिए एक पद्धति को अपनाते हुए, उत्तरी अटलांटिक पर वायुमंडलीय अवरोध और उत्तर-पश्चिम भारत में ऊष्ण-लहर के बीच दूर-संयोजन की खोज करता है। निष्कर्ष बताते हैं कि विशिष्ट रॉस्बी तरंग पैटर्न, जैसे कि तरंग संख्या 5 और 7, अलग-अलग क्षेत्रों में एक साथ गर्मी की चरम सीमा को प्रेरित कर सकते हैं, साथ ही इस बात पर प्रकाश डालते हैं कि उत्तरी अटलांटिक पर वायुमंडलीय अवरोधन घटनाएं उत्तर-पश्चिम भारत में ऊष्ण-लहर के साथ 3 दिन के अंतराल के साथ जुड़ती हैं, जो भविष्य के मौसम में +1.5°C और +2°C तक बनी रहती हैं। ग्रेंजर कॉजैलिटी परीक्षण गर्म जलवायु में उत्तर पश्चिम भारत में

उच्च दैनिक अधिकतम तापमान विसंगतियों पर उत्तरी अटलांटिक अवरोध के निरंतर प्रभाव की पुष्टि करते हैं। रॉसबी तरंग संख्याओं (4-11) का विश्लेषण बताता है कि रॉसबी तरंग 7 और 9 उत्तर अटलांटिक क्षेत्रों पर विशिष्ट अवरोधन को प्रेरित करते हैं, जिससे उत्तर - पश्चिमी भारतीय क्षेत्रों में ऊष्ण-लहर की संभावनाएं अधिक होती हैं, और यह मार्च-अप्रैल माह के प्रारंभिक दिनों में अधिक होते हैं।

इसके बाद, दक्षिण एशिया में 2022 की ऊष्ण-लहर - में मानव-प्रेरित भूमंडलीय ऊष्मीकरण के योगदान को समझने के लिए अच्छी तरह से स्थापित ईवेंट एट्रिब्यूशन तकनीकों का उपयोग किया गया था। वैश्विक तापमान को कम करने वाली ला नीना स्थितियों के बावजूद, 2022 विश्व स्तर पर रिकॉर्ड पांचवां सबसे गर्म वर्ष रहा है। यह अध्ययन मार्च से मई 2022 तक उत्तर भारत और दक्षिणी पाकिस्तान में अनुभव की गई अभूतपूर्व और लंबे समय तक चलने वाली ऊष्ण-लहर पर प्रकाश डालता है, जिसका सार्वजनिक स्वास्थ्य और कृषि (विशेष रूप से गेहूं की फसल), हिमनद झील के विस्फोट और जंगल की आग पर महत्वपूर्ण प्रभाव पड़ा है। इस अध्ययन से पता चलता है कि 2022 की घटना (मार्च-अप्रैल में दैनिक अधिकतम तापमान देखा गया) की वापसी अवधि लगभग 100 में 1 वर्ष थी और मानव-जनित जलवायु परिवर्तन ने इस ऊष्ण-लहर को पूर्व-औद्योगिक जलवायु जो सामान्यतः 1.2 डिग्री सेल्सियस, की तुलना में वर्तमान, 2022 की जलवायु, को, लगभग 1 डिग्री सेल्सियस अधिक गर्म और 30 गुना अधिक संभावित बना दिया।

अंत में, यह शोध 2022 की ऊष्ण-लहर के लिए कई अत्याधुनिक संख्यात्मक मौसम भविष्यवाणी मॉडल के पूर्वानुमान कौशल का व्यापक विश्लेषण भी करती है। इस शोध प्रबंध के परिणाम बताते हैं कि मल्टी-मॉडल माध्य मार्च-अप्रैल 2022 के दौरान ऊष्ण-लहर की भविष्यवाणी पर बेहतर पूर्वानुमान देता है।

कुल मिलाकर, इस शोध प्रबंध में चर्चित निष्कर्ष भविष्य में होने वाली ऊष्ण-लहर की घटनाओं की चेतावनी देती है, जिसकी भविष्य एक बड़े क्षेत्र में लंबे समय तक घटित होने की संभावना है। यह भारत में हीट एक्शन प्लान, प्रारंभिक चेतावनी प्रणाली और स्वास्थ्य देखभाल रणनीतियों सहित सरकार की तैयारियों के उपायों के लिए एक अंतर्दृष्टि है, जो निर्णय लेने वालों के लिए एक ठोस आधार प्रदान करता है और उभरती जलवायु चुनौतियों के सामने कार्यवाही योग्य जलवायु विज्ञान के महत्व पर जोर देता है।

## Table of Contents

<b>Certificate</b>	<b>I</b>
<b>Acknowledgements</b>	<b>II</b>
<b>Abstract</b>	<b>IV</b>
<b>List of Figures</b>	<b>XVII</b>
<b>List of Tables</b>	<b>XXV</b>
<b>Chapter 1: Introduction</b>	<b>1 – 17</b>
1.1 Background	2
1.2 Extreme Weather Events	4
1.3 Observed Heat Waves in India	7
1.4 Heatwaves in India - Global Teleconnections	10
1.5 Heat Waves in India - Attribution to Climate Change	12
1.6 Heat Waves in India – Predictions	15
1.7 Scientific Questions	16
1.8 Thesis objectives and structure	16
1.9 Structure of the thesis	17
<b>Chapter 2: Heat waves over India under 1.5°C and 2°C warming Projections</b>	<b>18 – 52</b>
2.1 Introduction	19
2.2 Data and Methods	23
2.2.1 Datasets used: Observations and Models	23
2.2.2 Methods	25
2.2.2.1 Identification of heatwave categories using the gridded dataset	25

2.2.2.2 Observations and Models: Daily climatology and distribution	28
2.2.2.3 Model Bias Correction	29
2.3 Results	30
2.3.1 Model Validation	30
2.3.1.1 Observed heat events	30
2.3.1.2 Comparison of model simulations and observations	34
2.3.2 Probability of Heat Events in Historical and Future Climates	37
2.3.3 Large heat wave events in the past and the future of such events	40
2.4 Discussion	48
2.5 Summary and conclusions	51
<b>Chapter 3: The Role of Atmospheric Blocking Teleconnections</b>	<b>53 – 96</b>
3.1 Introduction	54
3.2 Data and Methods	57
3.2.1 Datasets used: Observation and Models	57
3.2.2 Methods	57
3.2.2.1 Identification of atmospheric blocking over North Atlantic and heat waves over Northern India	57
3.2.2.2 Observations and Models: Daily climatology and distribution	58
3.2.2.3 Model Bias Correction	59
3.2.2.4 Model Mean Error	59
3.2.2.5 Teleconnection of North Atlantic blocking to anomalous TMAX over Northwest India : Granger Causality Test	61
3.2.2.6 Identification of Rossby Wave Events	64
3.2.2.7 Rossby Wave Events Coincident Analysis	68

3.3 Results	71
3.3.1 Observed North Atlantic Blocking Teleconnections to Heat Waves Over Northern India	71
3.3.2 Model Simulated Future Blocking and Teleconnections	77
3.3.3 Teleconnection Mechanism - Rossby Waves	86
3.4 Summary and conclusions	94
<b>Chapter 4: Attributing and Predicting Heat Waves Over India</b>	<b>97 – 152</b>
4.1 Introduction	98
4.2 Data and Methods	103
4.2.1 Datasets used: Observations and Models	103
4.2.2 Risk-based Attribution method	106
4.2.3 Model Forecast Verification through Skill Scores	107
4.3 Results	110
4.3.1 Observed heat wave during March 2022	110
4.3.2 Attribution - Case study of the heat wave in 2022	112
4.3.3 Prediction Skills for the 2022 Heat Wave	120
4.3.3.1 Validation and Forecast Evaluation of TIGGE Models	120
4.3.4 Operational Ensemble Model Forecast Skills	138
4.4 Discussion	146
4.4.1 Attribution of the heat wave of 2022	146
4.4.2 Prediction of the heat wave of 2022	147
4.5 Summary and conclusions	150

<b>Chapter 5: Summary and Scope for Future Work</b>	<b>153 – 162</b>
5.1 Conclusions	154
5.2 Scope for Future Work	162
<b>References</b>	<b>163 – 176</b>
<b>List of Acronyms</b>	177
<b>Curriculum Vitae</b>	179

## List of Figures

- 1.1** Linear trends spanning from 1960 to 2018 are depicted in a) annual maximum daily maximum temperature (TXx); b) annual minimum daily minimum temperature (TNn); and c) the annual count of days when the daily maximum temperature exceeds its 90<sup>th</sup> percentile from a reference period of 1961-1990 (TX90p). These trends are based on the HadEX3 dataset, and calculations are limited to grid points with at least 66% of annual values during the specified period, extending to at least 2009. Regions lacking sufficient data are represented in grey. The absence of overlay indicates regions where the trends are statistically significant at the  $p = 0.1$  level, while crosses denote regions with non-significant trends. Figure Source: IPCC AR6 (Seneviratne et al. 2021 Figure 11.9). **6**
- 2.1** Schematic diagram represents the criteria A, B, and C defined by Joseph et al., (2018) is shown in panel (a), and non-overlapping of events for Hot Day, Heat Wave, and Sever Heatwave defined in this study are shown in panel (b). **27**
- 2.2** Total number of Heatwave events (annual) over (a) Safdarjung, New Delhi, (b) Jaipur, Rajasthan, and (c) Penra, Chhattisgarh from 1969-2015 using IMD's station-based definition applied to station data, IMD's station-based definition applied to 1°x1° gridded observations and Joseph et al., (2018) definition applied to 1°x1° gridded observations. **27**
- 2.3** The average annual mean duration (days) and its trend (days/decade) of HD events (panels a, d), HW events (panels b, e), and SHW events (panels c, f) are shown for the IMD gridded observation from 1951-2015. Trends significant at 95% level (using one-tailed t-test) are stippled. Gray shading represents grid cells that do not satisfy the criteria for HD, HW or SHW conditions. **30**
- 2.4** The average number of annual heat events and trend in the number of heat events (per decade) over India for HD (panels a, d), HW (panels b, d), and SWH (panels c, f) in the IMD observations for the 1951-2015 period. Trends significant at 95% level (using one-tailed, t-test) are stippled. Grey shading shows grid cells that do not satisfy the criteria of HD, HW, or SHW conditions. **31**
- 2.5** The annual mean duration of Hot days and Heatwaves with trend line during 1951-2015 for 6 different grid cells (a-f) which are shown as red dots in (g)). The slope and intercept numeric values (with sign) are shown at the top of each subpanel. **32**
- 2.6** The total number of events of Hot days and Heatwaves category with trend line during 1951-2015 for 6 different grid cells (a-f) which are shown as red dots in (g)). The slope and intercept numeric values (with sign) are shown at the top of each subpanel. **33**
- 2.7** Mean Error of daily TMAX between IMD observation and HAPPI model (rows) historical simulations before bias correction. This was calculated by taking **34**

the difference (model minus observation) during individual months (March to August, columns) of 2006-2015, then averaged over time before averaging over 100 ensemble members of each model. Note the difference in the color scale of Figures 2.7 and 2.8.

- 2.8** Mean Error of daily TMAX between IMD observation and HAPPI model (rows) historical simulations after bias correction. This was calculated by taking the difference (model minus observation) during individual months (March to August, columns) of 2006-2015, then averaged over time before averaging over 100 ensemble members for each model. Bias correction was carried out using the Empirical Quantile Mapping (EQM) method (See section 2.2.2.3). **35**
- 2.9** Total number of heat event days during 2006-2015 is shown for HD (first-row), HW (middle-row), SHW (third-row) in the IMD gridded dataset (first-column), the ensemble mean of bias corrected historical simulations of individual HAPPI models (second to sixth column). The Taylor diagram in each row (last-column) shows the statistics for each of the models with reference to the IMD dataset. Gray color represents grid cells that do not satisfy the HD/HW/SHW criteria. **36**
- 2.10** Probability of heat event days (HW or SHW category) in the 500 member multi-model ensemble for individual months of April-July (columns) for the Historical period 2006-2015 (top-row), +1.5°C future (middle-row), and +2.0°C future simulations (bottom-row). **39**
- 2.11** Probability ratio of heat events (HW or SHW category) of 3, 5, 7, and 9 days duration (columns) are computed for +1.5°C and +2.0°C futures (rows) with respect to historical simulation (2006-2015). The sky blue color indicates reduced probability of events in the future simulations whereas the violet color indicates grid cells that do not experience such events in the historical period but do so in the future (i.e. probability ratio is infinity). The probabilities of historical, +1.5°C and +2.0°C simulations from which the probability ratios are computed are shown in Figure 2.10. **40**
- 2.12** Duration (in days) when HW or SHW criteria were met during the large heat events of 2009, 2010, 2012, 2013, 2014, and 2015 (a-f) calculated from IMD gridded data. These particular years were chosen based on mortality exceeding 1000 (see Table 2.3). The state boundaries within India are shown overlaid. The spatial extent of each event is represented by the number of grid cells shown in brackets in each panel. **42**
- 2.13** Same as in Figure 2.12 but showing the start date of each observed event (at individual grid cells). The end of each event can be calculated by adding the durations shown in Figure 2.12. **43**
- 2.14** Joint exceedance frequency of HW or SHW events for different durations and corresponding daily maximum temperature, over grid cells of the large event **44**

regions shown in Figure 2.12 (columns). Duration is calculated as consecutive days meeting the HW or SHW criteria during March to August in observation (2006-2015, top-row), from the HAPPI simulations of historical (second-row), +1.5°C Future (third-row), and +2.0°C Future (bottom-row). Gray color represents zero frequency.

- 2.15** Frequency of HW or SHW events for different durations in all grid cells of the event region (shown in Figure 2.12 a-f) corresponding to years 2009, 2010, 2012, 2013, 2014, and 2015. Duration is calculated for consecutive days meeting the HW or SHW criteria during March to August in IMD observation (2006-2015, marked in black asterisks), 500 ensemble members (100 members of 5 models) from the HAPPI multi-model ensemble historical (2006-2015, marked in brown circles), +1.5°C (blue circles), and +2.0°C (red circles). Since there is only one “realization” of the observed, the frequency of observed values has been multiplied by 500 to match the sample sizes from model simulations. The extent of each event in the observation is represented by the number of grid cells shown in brackets in each panel where each grid cell represents 1°x1° resolution. **46**
- 2.16** As in Figure 2.15, but for temperature instead of duration. The maximum temperature during individual events (consecutive days of HW or SHW category) in all grid cells forming the observed events are counted. Since there is only one “realization” of the observed, the frequency of observed values has been multiplied by 500 to match the sample sizes from model simulations. **47**
- 2.17** Relative frequency of HW or SHW events for different durations and area fractions of recent large events (shown in Figure 2.12) corresponding to years 2009, 2010, 2012, 2013, 2014, and 2015 (columns). The ensemble average relative frequency from 500 HAPPI simulations are shown for historical (top-row), +1.5°C Future (middle-row), and +2.0°C Future (bottom-row). **48**
- 3.1** Daily Time series of normalized anomalies of (a) ERA5 reanalysis Geopotential height at 500 hPa (Zg500) over North Atlantic area average over 50°N-75°N and 40°W-20°E and (b) IMD observed TMAX over Northwest India area average over 21°N-30°N and 71°E-80°E, during March-June months of 1979 to 2018. The positive TMAX anomalies over Northwest India preceded by positive Zg500 over the North Atlantic by one week or less are marked in vertical pink colored lines. The thin red horizontal line marked in both panels indicates unit normalized anomalies. **58**
- 3.2** Mean Error of daily Geopotential height (meter) at 500 hPa over North Atlantic between ERA5 reanalysis and HAPPI model (rows) historical simulations before bias correction. This was calculated by taking the difference (model minus observation) during individual months (March to June, columns) of 2006-2015, then averaged over time before averaging over 100 ensemble members of each model. **60**

- 3.3** Mean Error of daily Geopotential height at 500 hPa over North Atlantic between ERA5 reanalysis and HAPPI model (rows) historical simulations after bias correction. This was calculated by taking the difference (model minus observation) during individual months (March to June, columns) of 2006-2015, then averaged over time before averaging over 100 ensemble members for each model. Bias correction was carried out using the Empirical Quantile Mapping (EQM) method. Note the difference between the color scales of Figures 3.2 and 3.3. **61**
- 3.4** Probability density of the phase positions of waves 4 to 11 during March-June based on weekly averaged ERA5 meridional wind fields at 500 hPa (1979 to 2018). Probability densities of weeks with high wave amplitudes (exceeds threshold of  $1.5\sigma(A)$ , red solid line) are compared with all remaining weeks (mean in black solid line, mean  $\pm \sigma$  range marked in gray shadings). The maximum for the active Rossby wave density is marked with a red dashed vertical line with pink shading representing the  $\pm\pi/4$  range around the maximum. **65**
- 3.5** Composite events map of ERA5 reanalysis (a) Geopotential height at 500 hPa (Zg500) anomalies (meter), (b) IMD observed TMAX anomalies ( $^{\circ}\text{C}$ ) over Northwest India, and (c) correlation between Zg500 and TMAX anomalies are shown in top, bottom left, and bottom right subplots, respectively. Composite events defined as when IMD observed TMAX over Northwest India events (TMAX normalized anomalies  $> 1$ ) preceded by ERA5 Zg500 over North Atlantic events (Zg500 normalized anomalies  $> 1$ ), during March-June of 1979 to 2018 period. All these values are significant at 95% confidence level (student t-test 1-tailed test). North Atlantic region ( $50^{\circ}\text{N}$ - $75^{\circ}\text{N}$  and  $40^{\circ}\text{W}$ - $20^{\circ}\text{E}$ ) is marked in black colored box in subplot (a) and Northwest India region ( $21^{\circ}\text{N}$ - $30^{\circ}\text{N}$  and  $71^{\circ}\text{E}$ - $80^{\circ}\text{E}$ ) is marked in blue colored box in subplots (b) and (c). **72**
- 3.6** Number of event days of IMD observed TMAX over Northwest India (bottom panel), ERA5 reanalysis Geopotential height at 500 hPa (Zg500) over North Atlantic (middle panel), and TMAX over Northwest India events preceded by ERA5 Zg500 over North Atlantic (top panel), during March-June months of 1979 to 2018. **73**
- 3.7** Number of blocking event days (when normalized Zg500 anomaly is greater than 1) over the North Atlantic in the 5 HAPPI models. Standard deviation (in days) is plotted against the mean of number of event days in each March-June season. Historical simulations (2006 to 2015) are shown in brown open circles (100 members) and the mean of 100 members as a filled brown circle. The analogous values for the  $+1.5^{\circ}\text{C}$  and  $+2^{\circ}\text{C}$  future simulations are shown in blue and red circles respectively. The ERA5 reanalysis (2006 to 2015) value is shown as a filled black circle. **78**
- 3.8** Same as in figure 3.7, but for TMAX over Northwest India. The IMD Observed TMAX (2006 to 2015) value is shown as a filled black circle. **79**

- 3.9** Same as in figure 3.7, but when TMAX events over Northwest India are preceded by blocking events (Zg500) over North Atlantic. The IMD Observed TMAX over Northwest India preceded by the ERA5 reanalysis Zg500 over North Atlantic (2006 to 2015) is shown as a filled black circle. **80**
- 3.10** Granger Causality Statistics of CCCma-CanAM4 model for Historical, +1.5°C and +2°C future simulations. Results are based on MAMJ season for a 10-year period, at 1 to 5 days lag. The lags of 1-5 days are shown in filled and open symbols, representing significant and non-significant p-values. The p-values for TMAX events over Northwest India Granger Causing blocking events over North Atlantic are plotted against the p-values for blocking over North Atlantic Granger Cause TMAX events over Northwest India. Note log scale used for both axes and the black dashed lines corresponds to a p-value of 0.05. When the null hypothesis H0: TMAX over Northwest India Granger Causes blocking over the North Atlantic is rejected and the alternate hypothesis H1: Zg500 over North Atlantic Granger Cause TMAX over Northwest India is accepted at 0.05 significance level (values in the top-left quadrant formed by the dashed lines), they are denoted by filled color symbols. Non-significant p-values are shown as open color symbols. The total number of samples for each of the 5 lags where the alternate hypothesis (H1) is accepted is shown in text below each subplot. The red dashed line marked in the Historical subplot correspond to a p-value (0.034) of ERA5 reanalysis period from 2006-2015 (marked in black filled circle) which rejected the null hypothesis H0 at 3 days lag with 0.05 significant level. **82**
- 3.11** Same as in figure 3.10, but for ETH-CAM4 model. **83**
- 3.12** Same as in figure 3.10, but for the MIROC-MIROC5 model. **83**
- 3.13** Same as in figure 3.10, but for MPI-M-ECHAM6-3-LR model. **84**
- 3.14** Same as in figure 3.10, but for the NCC-NorESM1 model. **84**
- 3.15** An idealized depiction of the March-June circulation when (a) Rossby Wave-5 and (b) Rossby Wave-9 from the ERA5 reanalysis (1979-2018) is in its preferred phase with the width and position of the maximum (brown dotted line and maximum  $\pm \sigma$  range marked in brown shadings) reflecting values shown in figure 3.4 (b and f). The shadings depict the composite of weekly averaged ERA5 TMAX ( $^{\circ}\text{C}$ ) during the corresponding Rossby Waves. Hatching indicates values significant at 95% confidence level. The North Atlantic region (50°N-75°N and 40°W-20°E) is demarcated with a black box and the Northwest India region (21°N-30°N and 71°E-80°E) is shown as a white box. **87**
- 3.16** Heat map of ECA trigger coincidence rates of amplified waves from 4 to 9 conditions with blocking events (ERA5 reanalysis Zg500 normalized anomaly as X-axis) over the North Atlantic region (Spatial extent as a fraction on the Y-axis). The numbers in each box refer to the amplification factor by which wave events **89**

amplify the respective blocking events relative to non-event weeks. Statistical significance of the coincidence rates at the 99% (95%) confidence level is marked with a white (cyan) dot. The waves 4, 7, and 9 have the highest ECA coincidence rates and amplification factors  $> 1$ .

- 3.17** Same as in figure 3.16, but for normalized anomalies of IMD TMAX over Northwest India. Rossby waves were computed from ERA5 reanalysis and compared with IMD observed TMAX during respective wave number weeks. The waves 6, 7, and 9 are having highest ECA coincidence rates and amplification factors  $> 1$ . **90**
- 3.18** Mean Frequency (and probability) of weekly Rossby Waves (for wave numbers 4 to 9) from 5 HAPPI models (500 ensemble members) in the Historical,  $+1.5^{\circ}\text{C}$  and  $+2^{\circ}\text{C}$  simulations (10 years each), during individual months between March to June and the whole season. The error bars represent standard deviation obtained from 500 ensemble members, with statistical significance at 95% confidence level, by a Monte Carlo method with random shuffling of events in time ( $N = 1000$ ). **91**
- 3.19** Probability density function of daily TMAX values over Northwest India during Rossby Wave activity for wave numbers 4-9 during March to June from 5 HAPPI models with 100 ensemble members each for the Historical (blue),  $+1.5^{\circ}\text{C}$  (orange) and  $+2^{\circ}\text{C}$  (red) simulations. The TMAX probability density functions during Rossby Wave activity (solid lines) are to be compared against the probability density with no Rossby Wave activity (dashed lines). **93**
- 4.1** Weekly mean of TMAX ( $^{\circ}\text{C}$ ) observed during the 8 weeks of March and April 2022 in the CPC Observations. The study region is highlighted by the blue polygon within each panel. **111**
- 4.2** Same as Figure 4.1, but for daily maximum temperature anomaly of CPC Observation. Daily climatology is computed for the 1981 to 2010 period. **111**
- 4.3** Trends in observed daily maximum temperature TMAX ( $^{\circ}\text{C}$ ) averaged over March–April from the (a) CPC and (b) IMD datasets, of the years 1979–2022. Stippling indicates trends that are significant at the 10% significance level. The ‘study region’ is highlighted by the blue polygon within each panel plots (a and b). Time series of area-averaged over the ‘study region’ and further average of March–April months of observed daily TMAX (shown by the red line) along with the ten-year running mean (shown by the green line) based on the (c) CPC (1979-2022) and (d) IMD datasets (1951-2022). Area average of IMD observation was computed over for the Indian part of the region only within the study region, and ignored data points over outside India where it does not have any observed data. **113**
- 4.4** Comparison of TMAX ( $^{\circ}\text{C}$ ) CPC Observation on 15<sup>th</sup> March 2022 and lead day-7 forecast from the TIGGE multi models (contributed institute-models namely BOM-UM, ECCO-GDPS, ECMWF-IFS, IMD-GFS, JMA-GSM, KMA-UM, NCEP-GFS, **121**

NCMRWF-UM and UKMO-UM – a total of 9 Global atmospheric models) and multi model ensemble mean (MME-Mean), and multi model ensemble median (MME-Median), whose initial condition (IC) dated on 09<sup>th</sup> March 2022 and forecasts valid on 15<sup>th</sup> March 2022. The study region is highlighted by the blue polygon within each panel plot.

- 4.5** Comparison of daily TMAX (°C) weighted area averaged over the ‘study region – blue polygone in Figure 4.4’ of CPC Observation and 9 TIGGE models forecast, along with its multi model ensemble mean (MME-Mean), median (MME-Median) for lead days from 1 to 10 during March-April 2022. **122**
- 4.6** Spatial pattern Correlation Coefficient of daily TMAX (°C) over the ‘study region – blue polygone in Figure 4.4’ between CPC Observation and 9 TIGGE models forecast, along with its multi model ensemble mean (MME-Mean), median (MME-Median) for lead days from 1 to 10 during March-April 2022. **124**
- 4.7** Spatial pattern Root Mean Square Error (RMSE) of daily TMAX (°C) over the ‘study region – blue polygone in Figure 4.4’ between CPC Observation and 9 TIGGE models forecast, along with its multi model ensemble mean (MME-Mean), median (MME-Median) for lead days from 1 to 10 during March-April 2022. **125**
- 4.8** Taylor diagram of spatio-temporal pattern stats of correlation, RMSE, normalized standard deviation 9 TIGGE model forecasts, MME-Mean, MME-Median, 5<sup>th</sup> percentiles, and 95<sup>th</sup> percentiles compared against CPC Observation for week-2 (8-15 March 2022) over the study region. **126**
- 4.9** Same as Figure 4.8, but for week-4 during 24-31 March 2022. **127**
- 4.10** Same as Figure 4.8, but for week-6 during 8-15 April 2022. **128**
- 4.11** Same as Figure 4.8, but for week-8 during 24-30 April 2022. **129**
- 4.12** Comparison of Bias Score (y-axis) of spatial and temporal daily TMAX for 5 different threshold ( $\geq 37^{\circ}\text{C}$ ,  $\geq 38^{\circ}\text{C}$ ,  $\geq 39^{\circ}\text{C}$ ,  $\geq 40^{\circ}\text{C}$ ,  $\geq 41^{\circ}\text{C}$ ) between CPC Observed data and 9 TIGGE model forecasts, multi model ensemble mean (MME-Mean), median (MME-Median) for all forecast lead days from 1 to 10 (x-axis) during 4 weeks in March 2022. Perfect Bias score is 1. **131**
- 4.13** Same as Figure 4.12, but for the 4 weeks in April 2022 (columns) and for thresholds of  $39^{\circ}\text{C}$ - $43^{\circ}\text{C}$  (rows). **132**
- 4.14** Probability of Detection (POD) of spatial and temporal daily TMAX for 5 different thresholds ( $37^{\circ}\text{C}$ - $41^{\circ}\text{C}$ ) for the 9 TIGGE model forecasts, multi model ensemble mean (MME-Mean) and median (MME-Median) for all forecast leads from 1 to 10 (x-axis) during 4 weeks in March 2022. Perfect POD score is 1. **133**

- 4.15** Same as Figure 4.14, but for Probability of False Detection (POFD). Perfect POFD score is 0. **135**
- 4.16** False Alarm Ratio (FAR) of spatial and temporal daily TMAX for 5 different threshold (39°C-43°C) in 9 TIGGE model forecasts, multi-model ensemble mean (MME-Mean) and median (MME-Median) for all forecast lead days from 1 to 10 (x-axis) during 4 weeks in April 2022. Perfect FAR score is 0. **136**
- 4.17** Same as Figure 4.16, but for Equitable Threat Scores. Perfect Equitable Threat Score is 1. **137**
- 4.18** Comparison of TMAX (°C) in CPC Observations (a) on 15<sup>th</sup> March 2022 with forecasts at lead day-1, lead day-3, lead day-5 and lead day-7 from NCMRWF's Unified Model Ensemble Prediction System – NEPS (global atmospheric model with 23 ensemble members). The ensemble mean (NEPS-Mean), and ensemble median (NEPS-Median) forecasts valid for 15<sup>th</sup> March 2022 whose initial conditions (Ics) are from 15<sup>th</sup> March, 13<sup>th</sup> March, 11<sup>th</sup> March, and 09<sup>th</sup> March, respectively are shown. The study region is outlined in blue within each panel plot. **139**
- 4.19** CPC Observation showing areas of TMAX  $\geq 40^{\circ}\text{C}$  on 15<sup>th</sup> March 2022 (a) and probability of TMAX (threshold  $\geq 40^{\circ}\text{C}$ ) forecasts valid on 15<sup>th</sup> March 2022 at lead days 1 to 7 (b) – (h) from the NEPS (23 ensemble members), whose initial conditions are from 09<sup>th</sup> to 15<sup>th</sup> March 2022, and forecasts compared with. The study region is shown in blue outline. **140**
- 4.20** Taylor Diagram showing spatio-temporal pattern statistics (correlation, RMSE, normalized standard deviation) for the ensemble of 23 members of NEPS (from 1 to 7 days lead), for the 8-weeks (March-April 2022). **141**
- 4.21** Comparison of Probability of Detection (y-axis) of spatial and temporal daily TMAX for 5 different threshold ( $\geq 37^{\circ}\text{C}$ ,  $\geq 38^{\circ}\text{C}$ ,  $\geq 39^{\circ}\text{C}$ ,  $\geq 40^{\circ}\text{C}$ ,  $\geq 41^{\circ}\text{C}$ ) between CPC Observed data and NEPS model forecasts with its 23 members, its mean (NEPS-Mean), and its median (NEPS-Median) for all forecast lead days from 1 to 7(x-axis) during 4 weeks in March 2022. Perfect Probability of Detection score is 1. **142**
- 4.22** Same as Figure 4.21, but for Probability of False Detection (POFD). Perfect POFD score is 0. **143**
- 4.23** False Alarm Ratios of spatial and temporal daily TMAX for 5 different thresholds (39°C-43°C) in NEPS forecasts with mean (NEPS-Mean), and median (NEPS-Median) of 23 members, for all lead times from 1 to 7 days during the 4 weeks of March 2022. The perfect FAR score is 0. **144**
- 4.24** Same as in Figure 4.23, but for Equitable Threat Scores. The perfect Equitable Threat Score is 1. **145**

## List of Tables

- 2.1** List of participating institutions, models, resolution, and number of ensemble members for the historical (2006-2015), +1.5°C (10-years), and +2.0°C (10-years) experiments in the HAPPI project database (Mitchell et al. 2017). **24**
- 2.2** Comparison of IMD’s operational criteria to identify heatwave, severe heatwave, and warm night for station observations (left column) and the Joseph et al., (2018) criteria to identify hot day, heatwave, and severe heatwave for gridded data. **26**
- 2.3** List of years and mortality caused by heat stroke in India. Source: The National Disaster Management Authority (NDMA 2019). **40**
- 3.1** Total number of Rossby wave events of ERA5 reanalysis during March-June season of 1979 to 2018 (40 years period) for wave numbers 4 to 11, along with amplitudes (max, mean, 5<sup>th</sup> and 95<sup>th</sup> percentiles) during wave events weeks and non-wave events weeks. **66**
- 3.2** Total number of Rossby wave events of ERA5 reanalysis during March-June season of 2006 to 2015 (10 years period) for wave numbers 4 to 11, compared against 5 HAPPI models and its multi model mean (HAPPI-MME-Mean) with Historical simulations (2006 to 2015, 10 years period, averaged across 100 ensemble members). In each cell, the mean number of Rossby wave events (averaged across 100 ensemble members) in +1.5°C and +2°C future simulations (10 years period) is given inside the brackets. **67**
- 3.3** Granger Causality test statistics teleconnection relations between anomalies of TMAX over Northwest India and Geopotential height at 500 hPa over North Atlantic, during March to June of 1979 to 2018. Probability (>F) is computed from an F distribution. Lag is the number of days. \* indicates value is significant at less than 0.05 level. **73**
- 3.4** IMD TMAX over Northwest India events preceded by ERA5 Zg500 over North Atlantic - Number of event days (Values are same as in Figure 3.6 (a)) Versus Granger Causality test statistics Versus ECA Coincidence Trigger test statistics teleconnection relations between anomalies of ERA5 Zg500 over North Atlantic and IMD TMAX over Northwest India during March to June season of individual years from 1979 to 2018. The P-value of the Granger Causality test Probability (>F) is computed from an F distribution. Significant p-values of Granger Causality at less than 0.05 (0.1) level are indicated by \* (#) symbol. Non-significant Granger Causality from lags 1 to 5 days is marked by a double hyphen (--) symbol. **76**

- 3.5** Number of ensemble members for which H1 (i.e. Zg500 over North Atlantic Granger Cause TMAX over Northwest India) is accepted at 0.05 significance level for each HAPPI model for historical, +1.5°C, and +2°C future simulations (March-June season, 10 years, 100 ensembles) at each lagged days from 1 to 5, respectively. These values are marked in Figures 3.10 to 3.14. **85**
- 4.1** List of Global Numerical Weather Prediction (NWP) models/institutions participating in the TIGGE project database by contributing 7 to 15 days lead forecasts with a large number of ensemble members. GDPS – Global Deterministic Prediction System, GEM – Global Environmental Multiscale Model, GFS – Global Forecasting System, GSM – Global Spectrum Model, IFS – Integrated Forecasting System, UM – Unified Model are the NWP model families. All these models were regridded to 0.5°x0.5° to compare with observations. The two major models run operationally in India are indicated by a \*. **105**
- 4.2** A 2x2 contingency table –fter Wilks (1995) for evaluation of dichotomous (Yes/No) forecasts. Elements in the cells are the counts of forecast-observation pairs. Using the combination of A, B, C, and D, the forecast evaluation skill scores are computed. **107**
- 4.3** Summary of trend-fitting analysis performed for four combinations of data length and domain from the CPC and IMD datasets. Including the magnitude of the event, the estimated standard deviation (sigma), return period of the event in the 2022 climate (Return Period 2022) and in the hypothetical pre-industrial climate that is 1.2°C cooler (Return Period -1.2°C), the change in intensity ( $\Delta I$ ) and the probability ratio (PR), including their uncertainty. **116**
- 4.4** Probability ratio (PR) and change in intensity ( $\Delta I$ ) in the present day climate when compared with a counterfactual climate (hypothetical pre-industrial climate that was 1.2°C cooler than the current climate) from observations and HAPPI models that have Natural forcings only simulations and passed the validation tests. The best estimate for PR and  $\Delta I$ , between the 2022 climate and the 1.2 °C cooler climate, is given in numeric value along with uncertainties marked within parentheses (5- 95% Confidence Intervals). (b) Projected probability ratio and change in intensity in the +2°C warmer climate compared with present-day climate for models that passed the validation tests. The best estimate for PR and  $\Delta I$ , between the 2022 climate and the +2°C warmer climate, is given in numeric value along with uncertainties marked within parentheses (5- 95% Confidence Intervals). **119**