Global Challenges of Extreme Climate Events: Scientific Understanding, Impact Assessment and Response Strategies

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Abstract This study takes "ocean heat waves" as a typical case to study the scientific definition, driving mechanisms, multi-dimensional impacts, and response strategies of extreme climate events. The definition of extreme events requires a comprehensive consideration of statistical thresholds and social impacts. It is mainly driven by global warming caused by human emissions of greenhouse gases, and is also influenced by the interaction of natural variations such as ENSO. Extreme events cause systematic and cascading impacts on human health, infrastructure, agricultural economy, and ecosystems (especially marine ecosystems). Advanced technologies such as satellite remote sensing, climate models, and artificial intelligence have significantly enhanced their monitoring and prediction capabilities. However, effective responses still require a parallel strategy of mitigation and adaptation, and international cooperation is strengthened through the framework of the *Paris Agreement*.

Key words Extreme climate events; Ocean heat waves; Global warming; Composite events; Climate resilience; Adaptation strategies

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In the context of the continuous warming of the global climate system, the frequency, intensity, spatial extent, and duration of extreme climate events have shown a significant increase trend, which has become one of the most severe challenges faced by the global society in the 21st century[1]. From superstorms that sweep through coastal cities to prolonged droughts that lead to large-scale reduction of food production, and to extreme heat waves and marine heat waves (MHWs) that threaten lives, these events are no longer distant theoretical predictions but have increasingly become the "new normal" that affects human health, economic stability, infrastructure security, and ecosystem balance. Marine heat waves are extreme high-temperature events occurring in the ocean, and its research has rapidly become a frontier hotspot in the past decade, providing a valuable perspective window for understanding the physical mechanisms, ecological impacts, and response strategies of extreme climate events. This paper takes ocean heat waves as an example to systematically analyze the scientific connotation, driving mechanisms, global distribution, multi-dimensional impacts, advanced technologies, and global strategies of extreme climate events, so as to provide a cognitive framework for interdisciplinary research and comprehensive risk governance.

1 Scientific definition of extreme climate events: a case of ocean heat waves

The scientific understanding of an extreme climate event serves as the foundation for effective responses, and its definition itself is a complex issue with multiple dimensions.

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1.1 Multi-dimensional core of the definition: statistical thresholds and disaster impacts The definition of extreme climate events typically revolves around three core aspects: rarity, intensity, and impact. The most commonly used quantitative method at present is based on statistical thresholds. For instance, an ocean heat wave is defined as an abnormal warming event where the sea surface temperature has exceeded the 90th percentile threshold of the local historical average (usually, the base period is 30 years.) for 5 consecutive days at least. This definition was systematically proposed by Hobday *et al.*, emphasizes the persistence, relative extremity, and seasonal adjustment of the event, and has become an international standard[2]. At the same time, the definition based on impact is equally important: even if an event is not statistically the most extreme, it is still regarded as an extreme event if it causes significant social, economic or ecological losses. For example, the ocean heat wave "Ningaloo Niño" in Western Australia in 2011 led to large-scale coral bleaching and fishing closures, and it is a typical case with high impact[3].

1.2 Classification framework: from simple variables to complex systems Extreme climate events exhibit diversity and complexity. Ocean heat waves can be classified as extreme events of atmospheric/climate variables, but their formation is often a composite event involving the synergy of atmospheric forcing, ocean advection, and climate modes (e. g. ENSO), and their impacts are often amplified[4]. Based on duration, ocean heat waves, which are mostly chronic events, last for several weeks or several months (such as the "Blob" event in the Northeast Pacific), and cause cumulative and lagging effects on the ecosystem, so the harm is particularly severe[5].

2 Driving mechanism and global pattern: interweaving of human-induced forcing and natural variability

The occurrence of extreme climate events is the result of complex interactions within the Earth's climate system. The driving factors can be classified into natural and human-induced factors, in which human activities have become the dominant force in intensifying the trend.

2.1 Dominant mechanism: amplification effect of global warming Since the Industrial Revolution, global warming caused by emissions of human-induced greenhouse gas has significantly amplified the frequency, intensity, and duration of extreme events through two physical mechanisms: thermodynamic effects (atmospheric water-holding capacity increases by about 7%/℃, which exacerbates heavy precipitation; the intensity of heat waves is directly elevated) and dynamic effects (changes in the atmospheric circulation lead to the stagnation of the weather system)[1].

2.2 Modulation factors and global patterns Natural climate variability, such as the El Niño-Southern Oscillation (ENSO), plays a significant modulation role in the occurrence of regional extreme events[4]. The high-intensity areas of ocean heat waves are mainly distributed in the extension zones of the western boundary currents (*e. g.* the Kuroshio and the gulf stream) and the central-eastern Pacific Ocean of the equator, while the duration of the events in the central-eastern Pacific Ocean of the equator was the longest. Observational data confirm that global extreme events happen frequently, strongly and simultaneously. During 1925 – 2016, the frequency of global ocean heat waves increased by 34%, and the duration rose by 17%[6]. The development of attribution science further confirms that human-induced climate change has significantly increased the possibility of major ocean heat wave events such as the global-scale ocean extreme warming in 2016[7].

3 Multidimensional impact: from human society to natural ecosystem

Extreme climate events pose extensive and profound systemic threats to human society and natural ecosystems through both direct and indirect means.

3.1 Challenges to Human Health and Infrastructure Extreme events directly cause casualties, and have indirect health impacts through changing the environment for disease vectors, triggering mental health problems and threatening food security (due to damage to agriculture and fisheries)[8]. Meanwhile, key infrastructure (energy, transportation, water supply, *etc.*) is exceptionally vulnerable in the face of increasingly frequent extreme shocks. Its damage can trigger chain reactions and amplify social crises.

3.2 Disruptive impacts on the global economy and the ecosystem Extreme events pose systemic risks to the global economy, affecting agriculture, supply chains, and coastal urban economy[9]. Ocean heat waves have a direct impact on fisheries, aquaculture, and coastal tourism. More profoundly, ocean heatwaves are a key driving factor of global coral reef bleaching and death, algal forest decline, and seagrass bed reduction[10]. They also lead to dramatic changes in fish community structure and geographical migration, directly resulting in the depletion of commercial fishery resources. Frequent and intense ocean heat waves may push coral reefs and other ecosystems beyond their resilience "critical point", and cause irreversible degradation and transforming them from important blue carbon sinks into carbon sources, further exacerbating climate change[11].

4 Technology empowerment: progress in monitoring, simulation and prediction

Technological progress is the core driving force for enhancing the understanding and risk management capability of extreme climate events.

4.1 "Sky – ground" collaborative three-dimensional monitoring network The modern observation system relies on the integration of diverse data. Satellite remote sensing (such as OISST data of NOAA) provides key parameters such as sea surface temperature with global coverage and long-term sequences[12]. The on-site observation network (such as Argo buoys) offers high-resolution data of ocean profiles, and is indispensable for capturing subsurface ocean heat waves and understanding physical mechanisms[13].

4.2 From global scenarios to regional predictions The simulation results of global climate models indicate that in the scenario of continuous global warming, the frequency, intensity, and duration of ocean heat waves in the future will significantly increase. Under high emission scenarios, some sea areas may even face a nearly "permanent" state of ocean heat waves[14]. To apply global-scale information to regional risk assessment, downscaling techniques serve as the key bridge connecting macroscopic scenarios with local impacts.

4.3 Integrated application of artificial intelligence and emerging technologies Artificial intelligence and machine learning are transforming the methods of predicting and responding to extreme climate events. Deep learning models have demonstrated the potential to outperform traditional numerical models in weather forecasting[15]. Machine learning approaches also show great potential in the early detection and prediction of ocean heat waves. Moreover, digital twin technology can be used to simulate the responses of key infrastructure or ecosystems to extreme climate scenarios, thereby optimizing adaptation plans.

5 Global response strategies: mitigation, adaptation and international collaborative governance

To address the increasingly severe risks of extreme climate events, it is necessary to adopt a dual-track strategy of mitigation and adaptation, and rely on strong global cooperation.

5.1 Mitigation and adaptation: indispensable dual paths Mitigation is the fundamental solution, and aims to limit the global warming extent by reducing emissions of greenhouse gases rapidly and deeply. Adaptation, as a practical measure, means taking proactive measures to adjust and reduce vulnerability in response to the already occurred and inevitable climate impacts. For ocean heat waves, specific adaptation measures include establishing ecosystem-based fishery management, protecting and restoring resilient ecosystems, developing climate insurance, strengthening community early warning, and so forth[10].

5.2 International governance framework and key challenges

The *Paris Agreement* serves as the cornerstone of global climate governance, sets a long-term goal of keeping global temperature increase below 2 ℃ and striving to limit it to 1.5 ℃, and elevates adaptation to an equally important position as mitigation[1]. However, global responses still face significant challenges: there is a huge gap between current commitments to national emission reduction and the actions required to achieve the target of temperature control; there is a severe shortage of funds for adaptation actions; there are complex issues such as scientific uncertainties in the adaptation decisions at the local level[9].

6 Conclusions and outlooks

This paper takes ocean heat waves as a thread to systematically expound the scientific understanding, global impact, and response strategies of extreme climate events. Solid scientific evidence indicates that in the context of global warming dominated by human activities, extreme climate events are becoming more frequent, intense, persistent, and widespread.

Looking to the future, addressing the challenges of extreme climate events requires a profound transformation of the social and economic system. This demands that the international community, with unprecedented determination and urgency, accelerates global energy and industrial transformation to achieve deep emission reduction. At the same time, climate adaptation and resilience building, especially natural-based solutions targeted at specific risks such as ocean heat waves, must be comprehensively and fairly integrated into global and local planning and decisions at all levels. This is not only about environmental protection, but also a core issue for ensuring global food security, economic stability, and social equity. Only through firm, coordinated, and inclusive global actions can humanity build a safe, sustainable, and resilient future for all species in the already changing climate.

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