Climate Change Science

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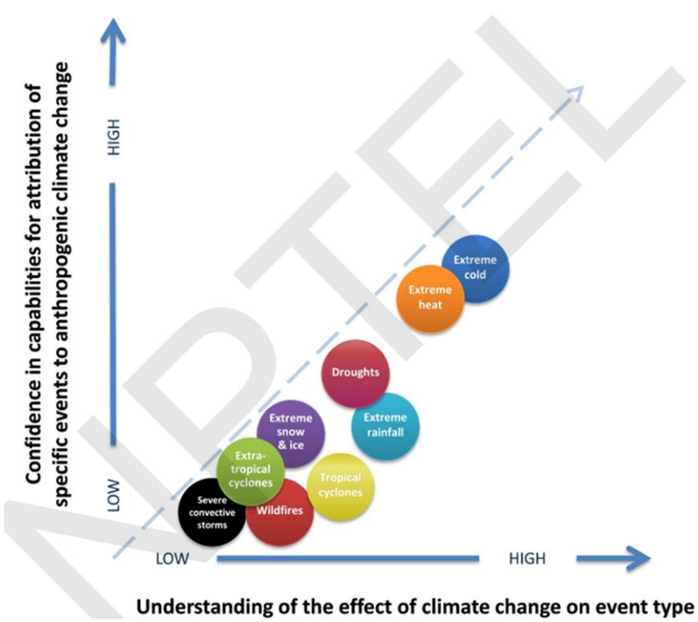
Lecture 52
Extreme Events

In the previous lecture, we focused on how reliable climate models are in predicting future climate, particularly global temperature. However, beyond predictions, most people are more concerned about how climate change will directly affect their lives. One important concern is abrupt climate change, which refers to climate shifts that happen more quickly than expected, disrupting ecosystems and societies. Such events have occurred in the past - for example, the Younger Dryas and Bolling-Allerod periods, which were sudden climatic shifts likely triggered by melting of the Greenland Ice Sheet and changes in ocean circulation.

Because of these possibilities, and the increasing number of extreme weather events such as heatwaves, floods, and intense storms, there is growing public concern about the impacts of climate change. Books and reports often highlight these events as signs of a changing climate. In this lecture, the focus is on reviewing the actual evidence of climate change impacts - what has already happened and what trends are emerging globally - helping us understand the real-world effects of a warming planet.



Our ability to understand and predict the impacts of climate change varies significantly depending on the type of extreme event. Among these, extreme heat and cold events are the best understood. Scientists have clearly observed that the overall temperature distribution is shifting to the right, meaning that higher temperatures are becoming more frequent. This is a direct and well-established consequence of rising greenhouse gas concentrations, particularly carbon dioxide. Climate models can simulate these changes accurately, and we can confidently attribute the increased frequency and intensity of heatwaves to global warming. Because we understand this link well, governments and communities can plan adaptation strategies such as building heat-resilient infrastructure or issuing heat alerts to reduce risks and impacts.

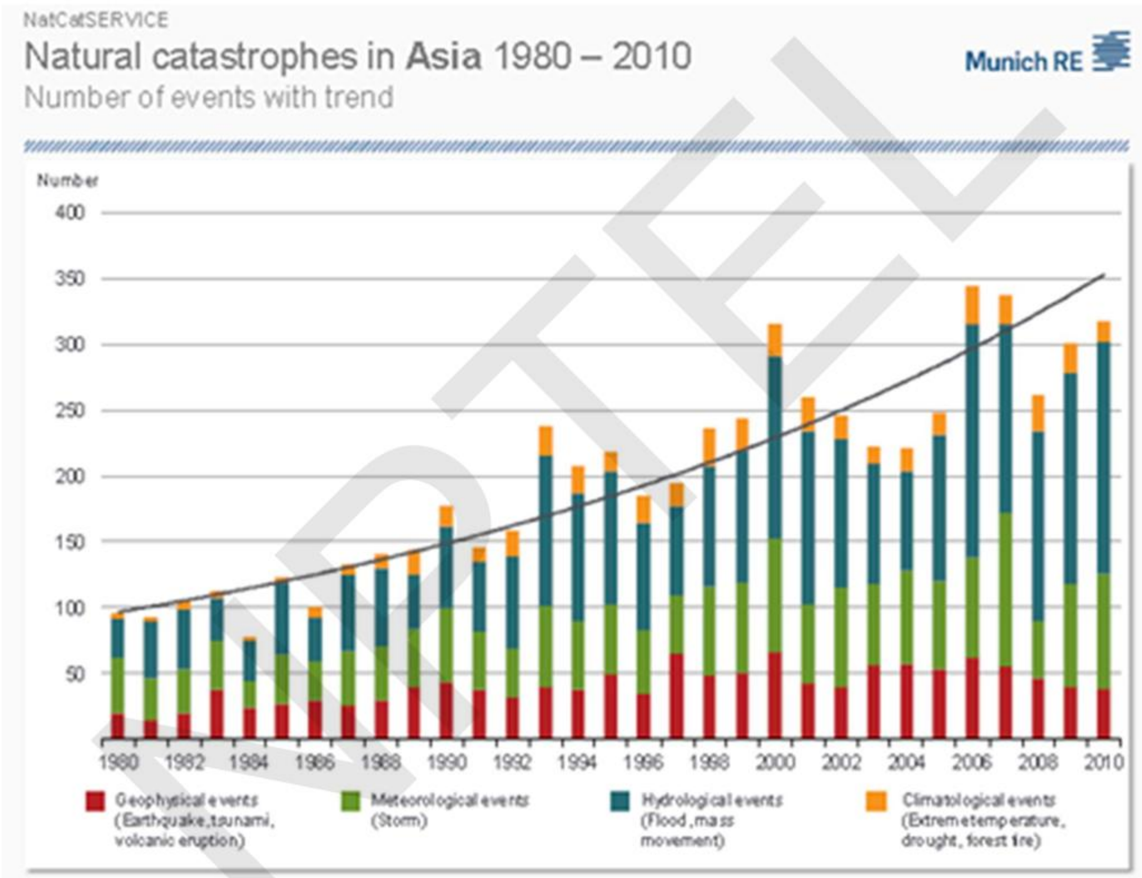
In contrast, the understanding and attribution of events such as droughts and floods due to extreme rainfall are more challenging. These events are often influenced by local and regional factors, including topography, land use, and atmospheric circulation patterns, which are not captured well in global climate models, especially those with coarser resolutions. While some long-term trends in precipitation can be attributed to climate change, it's still difficult to say with high certainty whether a specific flood or drought was caused by increased greenhouse gases. This uncertainty makes it harder to plan for and adapt to such events with the same level of confidence.

Even more difficult are extreme weather events that are highly localized and short-lived, such as tropical cyclones, wildfires, severe thunderstorms, and extreme snowfall. These events depend on a complex mix of atmospheric and surface conditions, including sea surface temperatures, wind shear, humidity, vegetation cover, and human factors like land management. Because of their complexity and variability, our models struggle to simulate these phenomena accurately. As a result, attributing their occurrence or intensity directly to climate change is often not possible with high confidence.

This variation in our scientific confidence has important policy and planning implications. For example, if we know that extreme heat will become more common, we can prepare health systems, modify urban design, and issue public warnings. But if we are uncertain about the future frequency of floods or cyclones in a specific region, it's much harder to make informed investment decisions. Therefore, it's essential to understand where science is strong, like in predicting heatwaves, and where uncertainties remain, so that society can focus efforts and resources effectively.

Let us now consider how climate-related impacts affect human lives. Insurance companies, who track these events closely due to their financial implications, have documented some alarming statistics. Over the past 20 years, approximately 1.65 billion people have been affected by floods, and about 1.43 billion by droughts. These two hazards stand out as major sources of human suffering, yet our ability to predict them accurately over the long term remains limited. While forecasts for the upcoming week may be possible, predicting floods or droughts a year or a decade in advance is still highly uncertain.

Severe thunderstorms have also had a massive impact, affecting nearly 700 million people in the same period. In contrast, earthquakes, though feared by many, affect relatively fewer people since they are localized to specific tectonic zones. Similarly, volcanoes, landslides, and extreme temperatures have affected around 100 million people, but among these, extreme temperatures are more predictable—so adaptation measures are more feasible for such events.

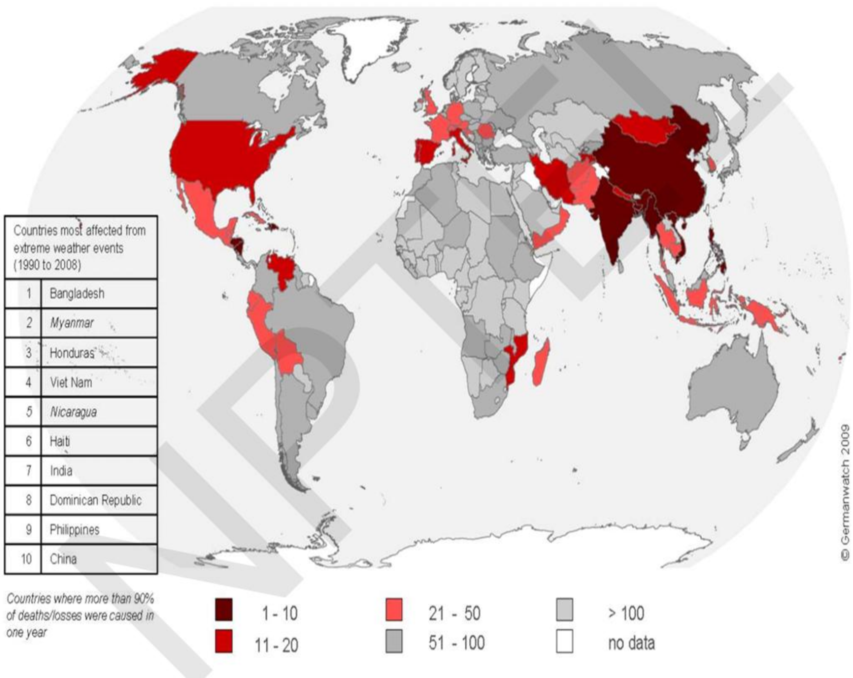


Insurance companies like Munich RE have compiled extensive records, showing a dramatic rise in natural catastrophes. In 1980, there were about 100 events per year, which increased to around 300–350 per year by 2010, a threefold rise in just three decades. This trend is expected to continue or worsen as the climate crisis deepens.

Looking closely at the types of natural disasters, the hydrological events (like floods) and meteorological events (like storms and heatwaves) dominate. These are closely linked to atmospheric temperature and weather patterns, and thus, to climate change. In contrast, geophysical events such as earthquakes and volcanic eruptions show no such trend, because they are not influenced by atmospheric temperature or greenhouse gases. CO_2

increases do not cause more earthquakes or volcanic eruptions, as those events are governed by deep Earth processes like plate tectonics and mantle dynamics.

Climate-related events such as floods, droughts, storms, and extreme heat are becoming more frequent and more damaging, and they have direct implications for human lives and economic systems. While some of these are predictable and allow for adaptation, many remain uncertain making the challenge of climate resilience even more complex.



The countries most affected by extreme weather events are primarily India and China. This is largely due to their high population and high population density, which make them more vulnerable to natural disasters. Both countries regularly experience droughts, floods, and extreme temperatures, which disrupt lives and economies on a massive scale.

In comparison, many other countries face less impact, either because they have lower population densities or because they are less frequently exposed to such a wide range of extreme weather events. Therefore, India and China remain among the most climate-vulnerable regions in the world.

To understand the impact of climate change, it's important to look at how the temperature distribution has changed over time. In the past, the distribution of temperatures was centered around a certain mean, shown in blue. Due to global warming, this entire distribution has shifted to the right, as shown in red. This rightward shift indicates an increase in the average global temperature, a fundamental change caused by rising greenhouse gases.

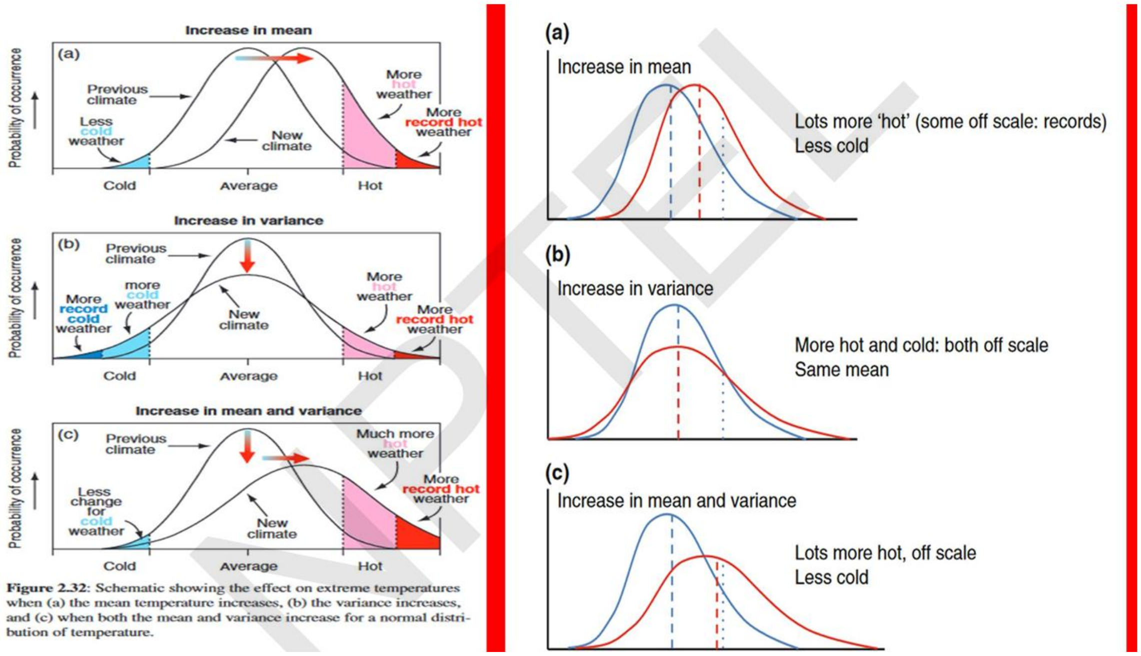
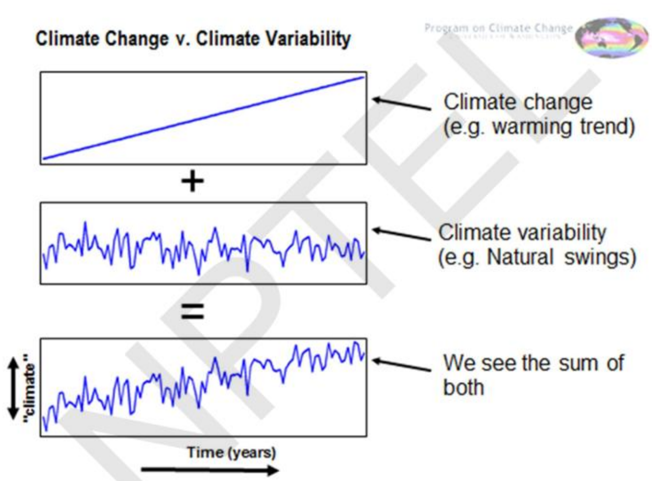


Figure 2.32: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature.

However, that's not the only change. Along with the shift in the mean, there is also a change in the variance of the distribution. A change in variance means that the distribution becomes wider and flatter, indicating greater variability in temperatures. This means that extremes, particularly heatwaves, are becoming more frequent and more intense, even if the average temperature only changes slightly.

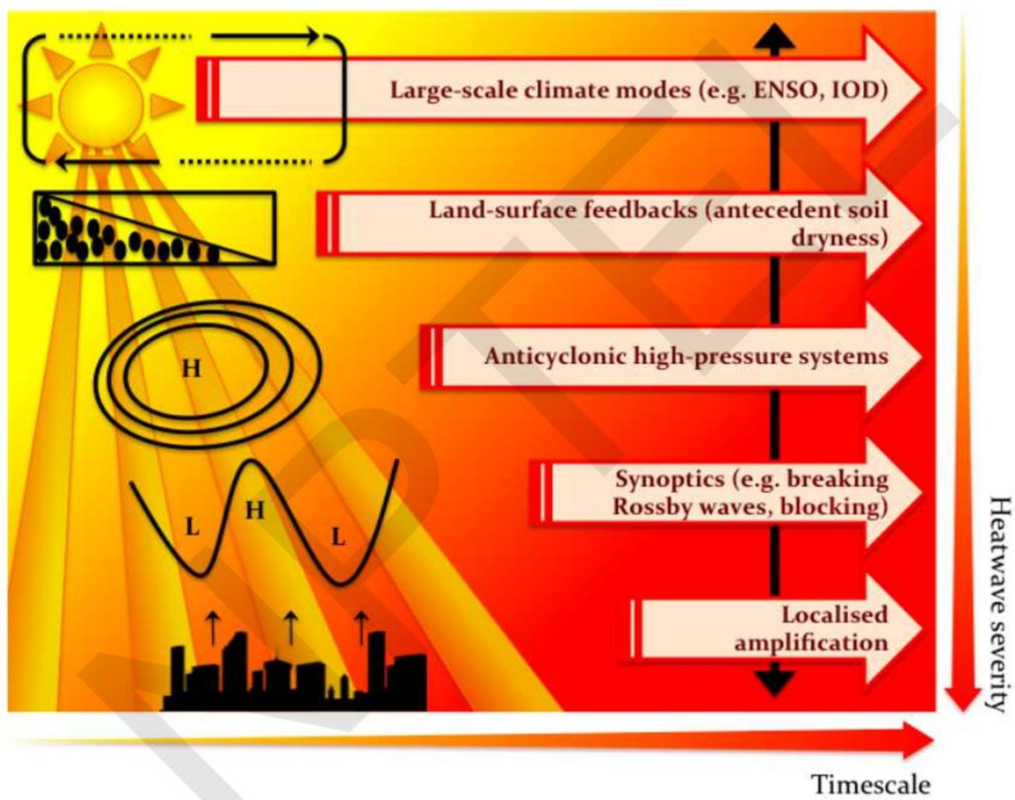
In reality, both the mean shift and increased variance occur together. As a result, we now see many more extreme temperature events, such as heatwaves, than we did in the past. This combined effect is clearly illustrated in the graphs being discussed: a simplified version shows the basic concept, while a more detailed graph provides quantitative evidence and explanation of these changes.



Today's climate-related changes arise from a combination of two key factors: long-term global warming and natural climate variability. Long-term global warming is primarily caused by human-induced increases in greenhouse gases like carbon dioxide. On the other hand, natural climate variability such as year-to-year fluctuations or decadal patterns occurs due to natural processes and is not something we can control.

It is important to distinguish between the two. Climate change can be mitigated by reducing CO_2 emissions and changing human activities. But natural variability must be adapted to, as it has always been part of Earth's climate system. Historically, humans have managed this variability for thousands of years through strategies like migration. For example, in India, when drought struck one region, communities would move to another region until conditions improved.

However, today's world is vastly different. The global population has increased from less than 1 billion to over 8 billion, and densely populated regions now limit the ability to migrate in response to climate events. In a country like India, with over 1.4 billion people, large-scale relocation in response to droughts or floods is no longer feasible. This makes adaptation much more challenging in the face of both climate change and natural variability.

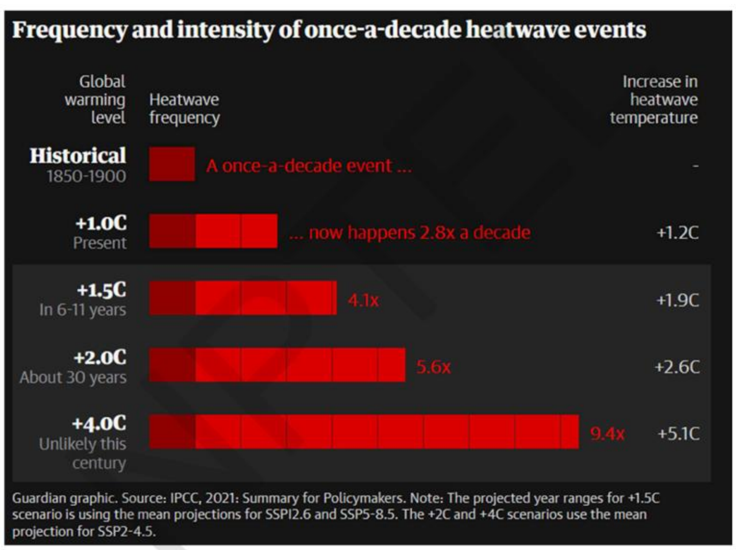


Heatwaves are becoming increasingly common and intense due to a mix of natural climate variability and human-induced changes. They can arise from large-scale phenomena like El Niño, which causes periodic warming in the Pacific Ocean roughly every four years. This alters global weather patterns, increasing the likelihood of heatwaves. Additionally, low seasonal rainfall can lead to dry soil, reducing evaporation and further heating the land surface. Another cause is stationary high-pressure systems, especially in regions like Europe, where such blocking events trap heat over the same area for days. Urbanization also contributes by amplifying local temperatures through the heat island effect.

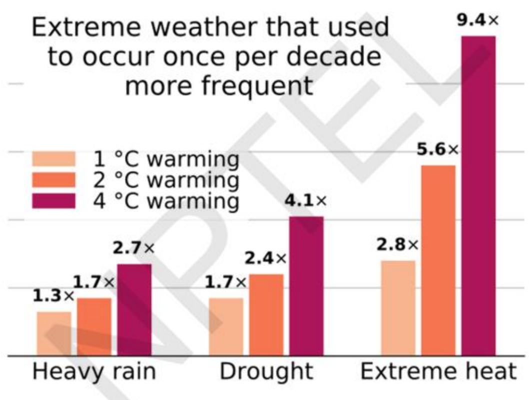
These combined factors have led to a dramatic rise in heatwave frequency and severity. According to United Nations estimates, around 12,000 people currently die each year due to heatwaves. However, the World Health Organization projects that by 2050, this number could rise to over 255,000 deaths annually, a more than 20-fold increase. Early forecasting of heatwaves, at least a week in advance can help reduce the risk and support adaptation strategies.

This growing threat is backed by strong evidence. For instance, studies by James Hansen and colleagues showed that the global area affected by unusually hot summer temperatures has increased by 50 times over the past 50 years.

In India, this trend is clearly visible. Previously, one or two short heatwaves occurred during the pre-monsoon season. Now, four or five heatwaves may occur, lasting longer up to a week. Moreover, heatwaves that typically started in May are now seen as early as April, and the hottest day of the season is becoming even hotter. These patterns strongly point to the influence of global warming, emphasizing the need for both mitigation and adaptation efforts.



The IPCC has expanded on the findings by Hansen regarding extreme heat events, offering a clearer picture of how their frequency will increase with global warming. Historically, once-in-a-decade heatwaves are now happening more than three times per decade. If the global mean temperature rises by 1.5°C, such events could occur four times per decade. At 2°C warming, they may happen nearly six times, and at 4°C, every year could see a major heatwave. This trend is well understood and robustly projected, highlighting the urgent need for adaptation strategies.



The IPCC also presents this data in the form of bar charts shown above comparing three key types of extreme events, heatwaves, droughts, and heavy rainfall, under various levels of warming. When global temperatures rise by 4°C, extreme heat events could increase by 10 times, droughts could become 4 times more frequent, and heavy rainfall events could be nearly 3 times more common.

While extreme heat shows the most dramatic numerical increase, droughts are arguably more impactful, especially for agriculture, water availability, and livelihoods. Likewise, a threefold rise in floods can have devastating consequences on infrastructure and displacement. These projections underline the multi-dimensional risks posed by climate change, making both mitigation and adaptation critical priorities.

In its 2001 report, the IPCC warned that the greatest increase in heat stress would not occur in the tropics, as commonly assumed, but rather in the mid- to high-latitude regions, especially in urban areas with non-adapted infrastructure and limited air conditioning. This prediction materialized two decades later during the June 2021 heatwave in North America, which severely impacted Canada and several northern U.S. states.

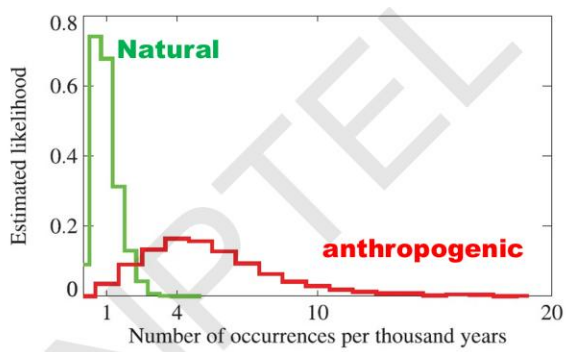
These regions, lying between 40°N and 60°N, were historically unaccustomed to extreme heat. As a result, homes were designed to retain heat and minimize cold air infiltration, often with poor ventilation and no cooling systems. When unprecedented temperatures struck in 2021, nearly 800 people died, many due to heat-related illnesses. This tragedy demonstrated that the IPCC's projections were both accurate and timely, yet poorly heeded.

The event stands as a stark example of how delayed adaptation and a false sense of geographic immunity can lead to severe consequences. It highlights the importance of acting on scientific warnings, especially in areas previously considered safe from extreme heat.

Climate change made North America's deadly heatwave 150 times more likely

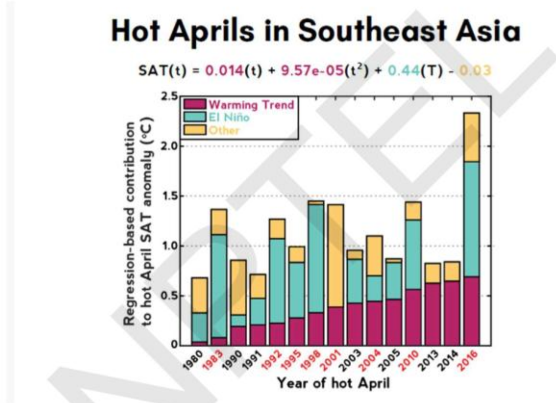
In Lytton, British Columbia, during the June 2021 heatwave, a record-breaking temperature of 49.6°C was observed, the highest ever recorded in Canada. Climate model studies have shown that this extreme event became 150 times more likely due to the increase in atmospheric CO_2, making it a clear example of how global warming amplifies heatwave risks.

This effect can also be visualized through temperature distribution graphs. Under natural climate variability, the probability of extremely rare events like a once-in-1000-years heatwave is very low. However, with the rise in CO_2 levels, the temperature distribution not only shifts to the right (indicating warmer averages) but also becomes flatter, indicating higher variability. This means that extreme heat events that were once considered very rare (e.g., one in a thousand years) are now expected to happen once in a hundred years or more frequently.



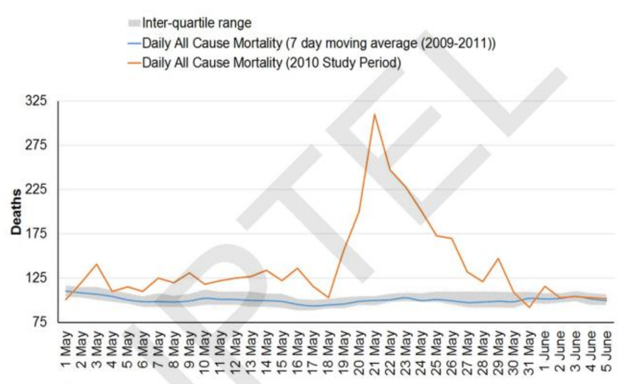
Likely hood of European summer temperatures exceeding 1.6 C above 1961-1990 average

An example of this trend was the deadly European heatwave in 2003, which caused thousands of deaths. Today, due to climate change, such extreme events are no longer rare anomalies but are becoming part of a new normal. This underlines the urgent need for climate adaptation strategies, especially in regions not historically exposed to such extremes.



K.Thirumalai, NATURE COMMUNICATIONS | 8:15531 | DOI: 10.1038/ncomms15531

A study by Kaustubh Thirumalai and colleagues, published in *Nature Communications*, highlights how extreme heat events in Southeast Asia are increasingly driven by a combination of natural and human-induced factors. Specifically, the researchers analyzed the unusually hot April temperatures in the region and separated the contributions from long-term warming due to carbon dioxide, short-term events like El Niño, and other local causes. For example, in 2016, a strong El Niño coincided with elevated CO_2 levels, making the heatwave much more intense than it would have been from El Niño alone. In contrast, similar heat events in earlier years like 1980 were mainly caused by natural variability, with little contribution from global warming. This shift over time shows that human-caused climate change is now playing a significant role in amplifying heatwaves. The study warns that as CO_2 levels continue to rise, Southeast Asia will face more frequent and severe heat events, especially during El Niño years. This emphasizes the urgent need for better forecasting, early warning systems, and stronger adaptation measures in the region.



Azhar GS, Mavalankar D, Nori-Sarma A, Rajiva A, Dutta P, Jaiswal A, et al. 2014 Heat-Related Mortality in India: Excess All-Cause Mortality Associated with the 2010 Ahmedabad Heat Wave. PLoS ONE 9(3): e91831.

An important example of heatwave impact and adaptive response comes from Ahmedabad, India. On May 20, 2010, the city experienced an intense heatwave that led to approximately 250 excess deaths beyond the usual daily average, as documented by

Azhar and colleagues. This spike in mortality was attributed to a sudden rise in temperature and the lack of preparedness among the population to cope with extreme heat. In response, the Ahmedabad Municipal Corporation, in collaboration with the Indian Institute of Public Health, Gandhinagar, and the U.S.-based Natural Resources Defense Council, launched India's first Heat Action Plan in 2013. This plan aimed to reduce the health impacts of future heatwaves through early warnings, public awareness, and community support measures. Since its implementation, it is estimated to have prevented over 1,000 deaths annually.

However, this approach is particularly effective for dry heatwaves, such as those experienced in Ahmedabad, where high temperatures are not accompanied by high humidity. Strategies like staying hydrated, using wet cloths, and improving ventilation can provide significant relief. In contrast, moist heatwaves—characterized by high temperature and high humidity—pose a greater threat, especially in coastal regions, where physiological cooling through sweating becomes ineffective. In such conditions, the risk to human health escalates, and the only effective adaptation often involves access to air-conditioned spaces. The growing occurrence of such moist heatwaves in Asia presents a more complex challenge, which will be explored further in the following lecture.