Climate Change Science
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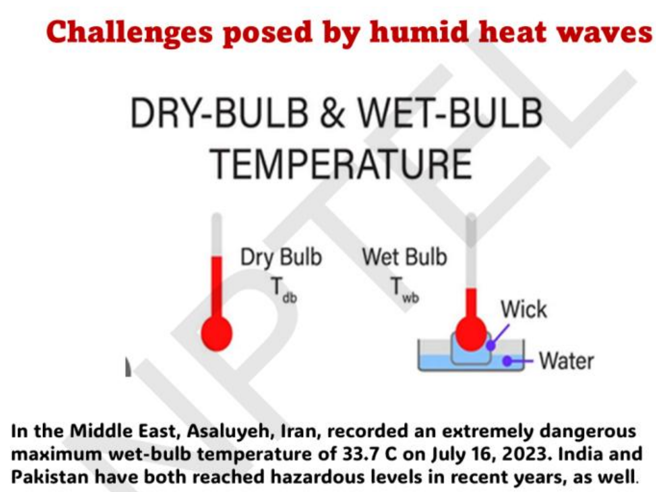
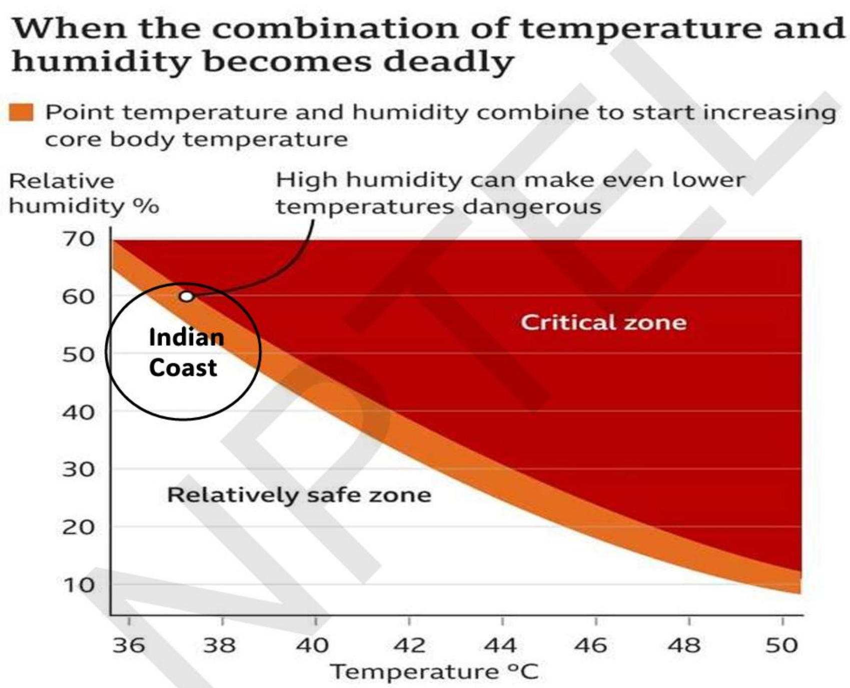
Lecture 53
Humid Heat Waves

In the previous lecture, the focus was on the impacts of climate change, with heatwaves highlighted as one of the most immediate and visible consequences. A notable example discussed was the severe heatwave in Ahmedabad in May 2010, during which approximately 200 excess deaths were recorded compared to the average mortality rate. This event exemplifies what is termed a dry heatwave, a heatwave caused by high temperatures but accompanied by low humidity. In such conditions, effective adaptation strategies can significantly reduce mortality. Following this event, the Ahmedabad Municipal Corporation implemented a proactive Heat Action Plan in 2013. This plan included public awareness campaigns, early warning systems, and community outreach measures. Since its implementation, it is estimated to have saved around 1,000 lives annually. The success of such a plan hinges on the manageable nature of dry heatwaves, where simple measures like drinking plenty of water, staying in shaded or ventilated areas, and using wet clothes or fans can effectively lower the risk of heat-related illnesses.



In addition to dry heatwaves, there is a more dangerous and challenging form known as moist heatwaves, where both temperature and humidity are high. In such conditions, it is not enough to only monitor the dry bulb temperature (the regular air temperature); one must also consider the wet bulb temperature measured using a thermometer wrapped in a moist cloth. This is crucial because the body's natural cooling mechanism relies on the evaporation of sweat. In a dry heatwave, evaporation occurs efficiently, helping to regulate body temperature. However, during a moist heatwave, high humidity severely limits this evaporation. As a result, the body struggles to cool itself even if water is consumed or wet clothes are used. This makes moist heatwaves significantly more dangerous, especially in coastal or tropical regions, where high humidity is common. Traditional coping strategies are less effective, and the risk of heat-related illnesses increases substantially.

This issue of moist heatwaves and their danger was explored in detail by Sherwood and Huber in a 2010 paper. They highlighted that there is a natural limit to human adaptability to heat stress, especially in regions with high humidity like coastal areas. As both temperature and humidity rise, the body's ability to regulate its internal temperature becomes compromised. At a certain point, people will no longer be able to maintain a safe core body temperature of 37°C. This is critical because the human brain functions like a computer. It must be kept cool to work properly. If the brain temperature rises above this limit, it can lead to severe health consequences or even death. Unlike dry heatwaves, where simple solutions like hydration and evaporation help, moist heatwaves present a situation with no easy remedy.



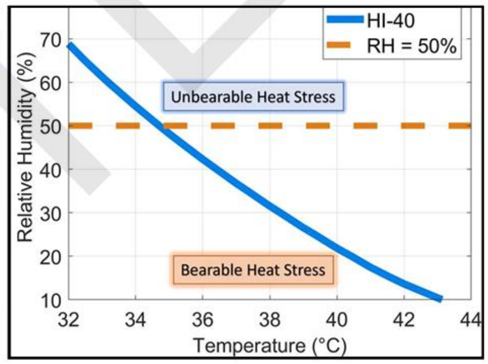
In India, several regions are already experiencing conditions close to the danger zone with temperatures around 38°C combined with relative humidity near 50%. This combination is critical because it pushes the human body beyond its ability to maintain a core temperature of 37°C, increasing the risk of heat-related deaths. When conditions move from the orange to red zone in the heat-humidity chart, survival without external cooling becomes nearly impossible. In such cases, the only effective solution is access to air conditioning. This means that measures like the Ahmedabad Heat Action Plan, effective in dry heat conditions, would not be sufficient in humid coastal areas. This presents a serious and growing challenge for many tropical, coastal countries under climate change.

Heat Index (HI)

HI is an empirical index that considers both ambient temperature and relative humidity and determines the thermal comfort of a person undertaking minimal work under shade

National Weather Service (NWS), USA HI Classification Chart

Classification	Heat Index (◦C)	Effect on the body
Caution	26°C - 32°C	Fatigue possible with prolonged exposure and/or physical activity
Extreme Caution	32°C - 41°C	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	41°C - 51°C	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme Danger	52°C or higher	Heat stroke is highly likely



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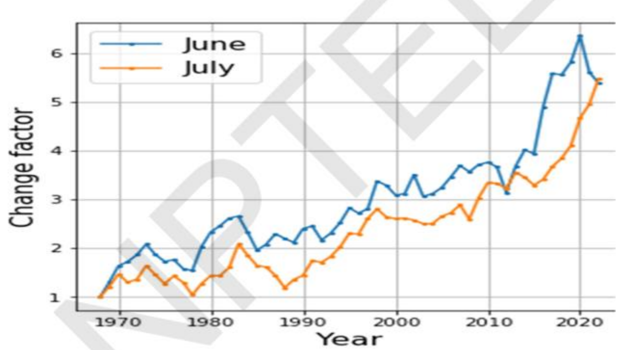
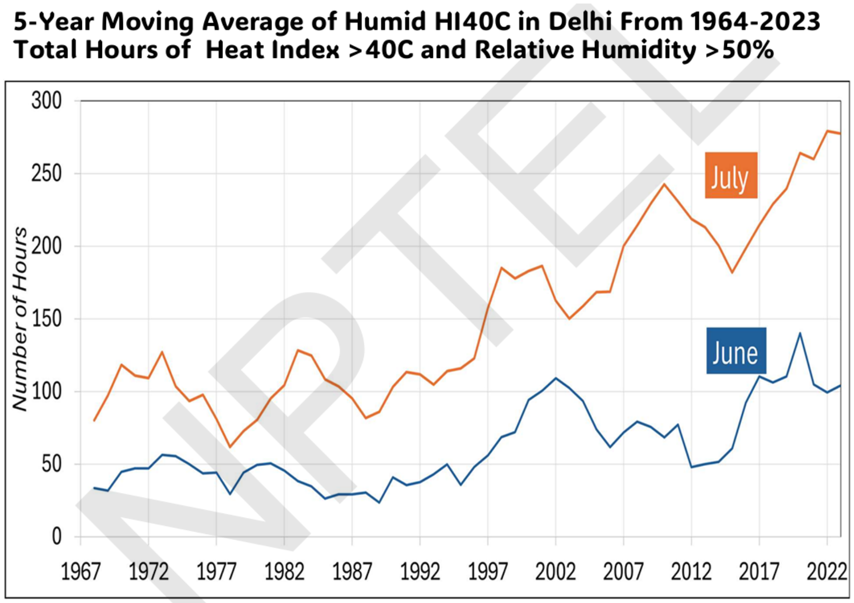
The National Weather Service in the United States has studied this issue and introduced the concept of the heat index, which takes into account both air temperature and relative humidity to assess how hot it feels to the human body. On a heat index chart, temperature is plotted against humidity, and a critical threshold is identified by a blue line. Conditions below this line are generally manageable through simple precautions like hydration and ventilation. However, once the combination of temperature and humidity crosses this line, typically around 35°C with 50% humidity, the human body struggles to regulate internal temperature. Beyond this threshold, heat stress becomes dangerous, and air conditioning becomes the only viable solution to maintain safety and prevent heat-related illnesses.

5-Year Moving Average HI40C (Heat Index >40C) Hours*Grid from 1964 to 2022 Over India

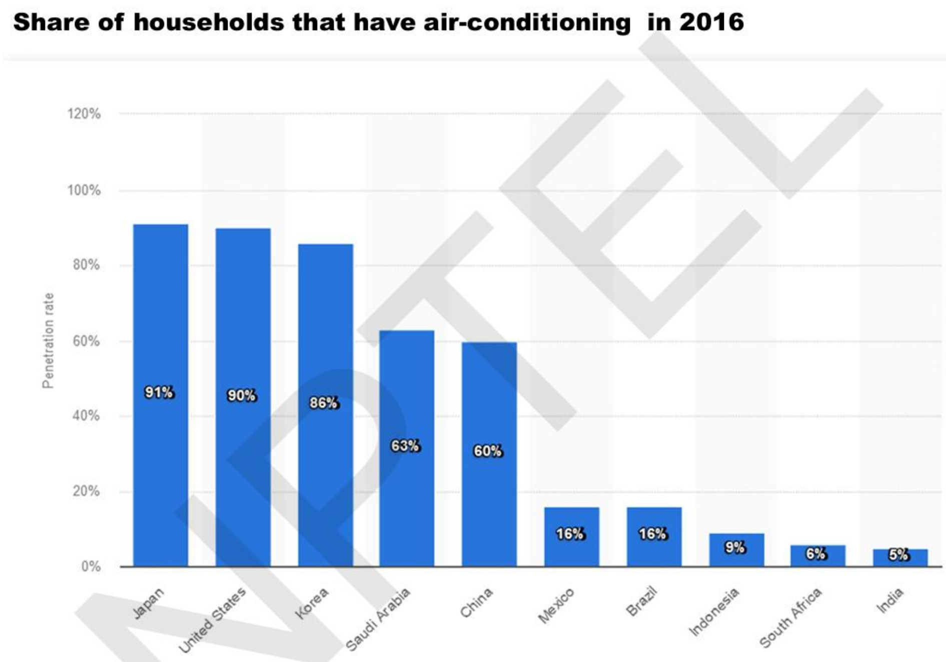


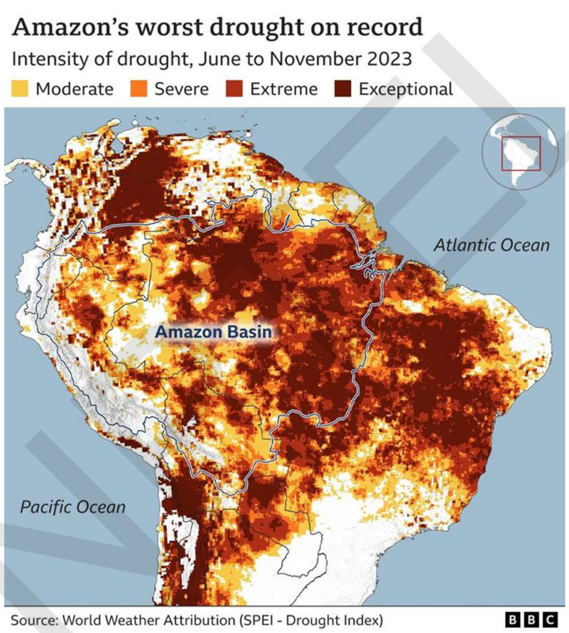
Recent estimates show that the number of hours and geographic areas in India experiencing a heat index above 40°C has increased significantly by nearly sixfold in the months of June and July, when compared to data from 1964. This dramatic rise indicates that extreme heat conditions are no longer rare, but are becoming a regular part of summer in many parts of the country. A heat index above 40°C represents a level of combined heat and humidity that poses serious risks to human health, especially in the absence of access to cooling infrastructure. Unlike dry heatwaves, moist heatwaves leave fewer options for adaptation, with air conditioning often being the only effective solution. As climate change intensifies, such events are expected to become more frequent and widespread over the next 40 years, raising urgent concerns about how densely populated and economically diverse countries like India will cope with the growing threat of moist heat stress.



An example from Delhi highlights the growing severity of moist heatwaves. While June has not seen a drastic increase in high heat index hours, July, following the onset of the monsoon, has shown a sharp rise. In 1969, Delhi experienced around 100 hours of dangerous heat index levels in July; by 2022, this number had tripled to nearly 300 hours. This upward trend is projected to continue due to global warming. The impact of such conditions is not limited to health risks like heatstroke or death; even before fatal thresholds are reached, productivity losses become significant. Outdoor workers particularly those in agriculture, construction, and uncooled factory settings will find it increasingly difficult to work during daytime hours. Their ability to work safely and efficiently will decline, suggesting the need for changes in work schedules, such as shifting to early morning or evening hours, to minimize exposure to high heat and humidity.

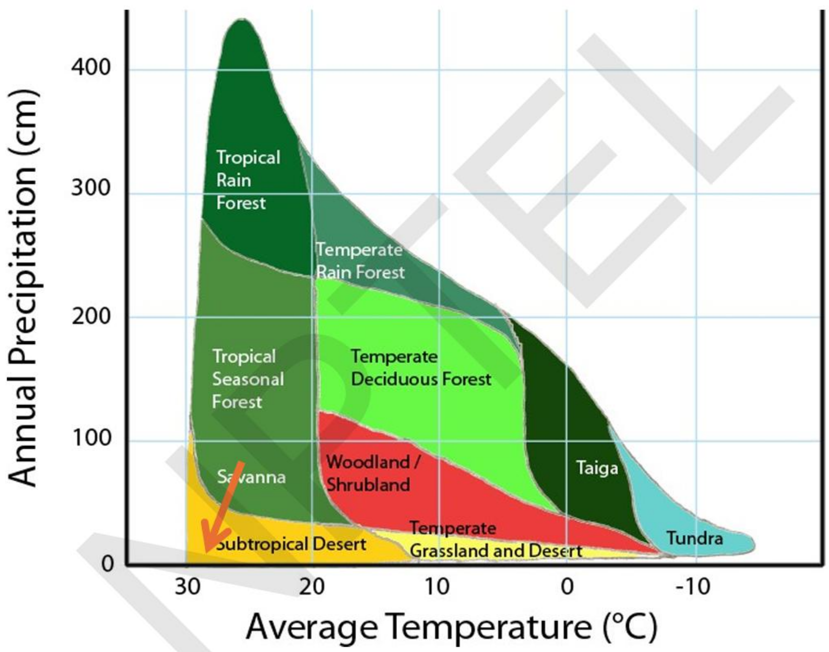
Data from 2016 on household air conditioning access highlights a stark global disparity. In advanced countries, nearly 90% of households have air conditioning, while China stands at around 60%. In contrast, India has only about 5% of households equipped with air conditioners. Similar low access is seen in South Africa and Indonesia. This indicates a major vulnerability: countries in the Global South, which are already prone to humid heatwaves, face a severe challenge in coping with rising temperatures. Without widespread access to cooling, millions remain exposed to dangerous heat stress, making adaptation and infrastructure planning a critical priority.





In addition to heatwaves, droughts are another major consequence of climate change. A drought occurs when there is a prolonged period with little or no rainfall, but it's not just rainfall that matters. The Standardized Precipitation-Evaporation Index (SPEI) is used to assess drought conditions more accurately because it considers both rainfall and evaporation.

A striking example occurred in the Amazon basin in Brazil between June and November 2023, when the region experienced an exceptionally long drought. High temperatures during this period increased evaporation, reducing soil moisture even if rainfall was close to average. This is critical for agriculture: even when rainfall is adequate, high temperatures can dry out the soil, leading to plant stress and crop failure. Thus, understanding drought requires looking at the combined effects of precipitation and temperature-driven evaporation.



This observation is crucial when viewed through the lens of the Köppen climate classification, a widely used system that categorizes global climates based on long-term patterns of temperature and rainfall. According to this classification, India presently falls largely within the savannah-type climate region, characterized by an average annual rainfall of around 100 cm and a mean temperature of approximately 25°C. However, with ongoing global warming, this climatic balance is at risk.

If the temperature rises by 3 to 5 degrees Celsius and there is even a modest decline in rainfall, India's climate in many regions could shift toward a subtropical desert type. This transformation would represent a dramatic ecological change. For instance, the arid desert-like conditions of Rajasthan could expand and encroach upon more southern and central states such as Maharashtra, Gujarat, and Karnataka. Such a shift would pose serious challenges for agriculture, water security, and livelihoods, as these regions are not currently equipped to handle arid conditions. Thus, monitoring and adapting to these potential shifts in climate zones is essential for long-term sustainability planning.

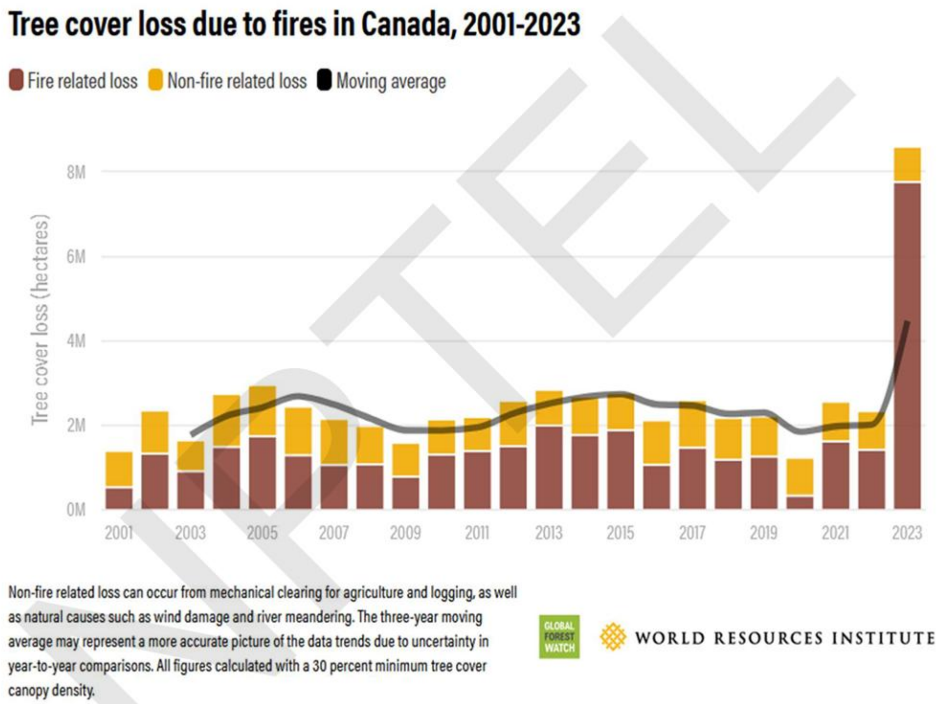
Apart from affecting human beings, the combination of high heat and humidity in the tropics is now beginning to challenge the survival of mammals as well. Many animals, especially larger ones, are reaching their physiological limits under current climatic extremes. For instance, during the 2010 heatwave in the U.S., there was a noticeable drop in milk production from dairy cows, leading to an estimated economic loss of over $1 billion. This highlights that extreme weather events are not only a threat to life but also carry significant economic consequences through their impact on livestock productivity.

In Kenya, the Maasai herders, who have lived in harmony with nature for thousands of years, are now observing that cows and buffaloes are struggling to survive in the rising heat, while goats are comparatively more resilient. This is explained by basic thermodynamics: smaller animals have a higher surface area-to-volume ratio, which allows for more efficient heat dissipation. Larger animals like cows, and even more so elephants, generate more heat relative to the area available to release it, making them vulnerable in hotter climates.

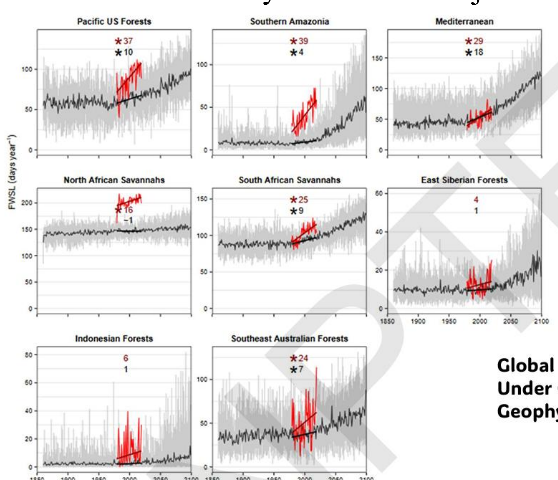
This vulnerability is not theoretical. In May 2024, monkeys in Mexico were reported to have died from heatstroke during an intense heatwave. Such incidents underscore the real and immediate risks of global warming for wildlife, particularly large mammals like elephants, tigers, lions, and leopards. These animals are less able to cope with rising temperatures and prolonged heat events, which could lead to population declines and ecological imbalance. Unfortunately, the threat to wildlife from climate-induced heat stress has not received the policy attention it urgently deserves

In recent years, forest fires have emerged as a major climate-related threat, especially over the past decade. As temperatures rise and rainfall declines, forests become drier and more flammable, increasing the risk of massive fires. The presence of dry vegetation serves as abundant fuel, and ignition can come from natural sources like lightning or human activities. However, forest fires are complex phenomena influenced not just by temperature but also by wind speed, duration of drought, and the quality of forest management. This makes it difficult to quantify the exact contribution of climate change, though its aggravating role is undeniable.

A recent study projects that by the end of this century, there will be at least 30 more days annually that cross the critical fire risk threshold on every continent. This highlights the growing global risk of forest fires due to climate change. Once these fires reach a certain scale, human intervention becomes nearly impossible. Traditional firefighting methods like water sprays or firebreaks are ineffective against large, fast-moving blazes. Devastating fires have already been witnessed in Canada, California, and Russia, engulfing millions of hectares. These incidents not only destroy ecosystems but also release enormous amounts of carbon dioxide, further exacerbating global warming in a dangerous feedback loop.



The above graph shows tree cover loss due to forest fires and non-forest fire causes during the last 22 years. We see a big jump in the year 2023 as Canada had a tree cover loss of 8 million hectares that year due to a major forest fire.



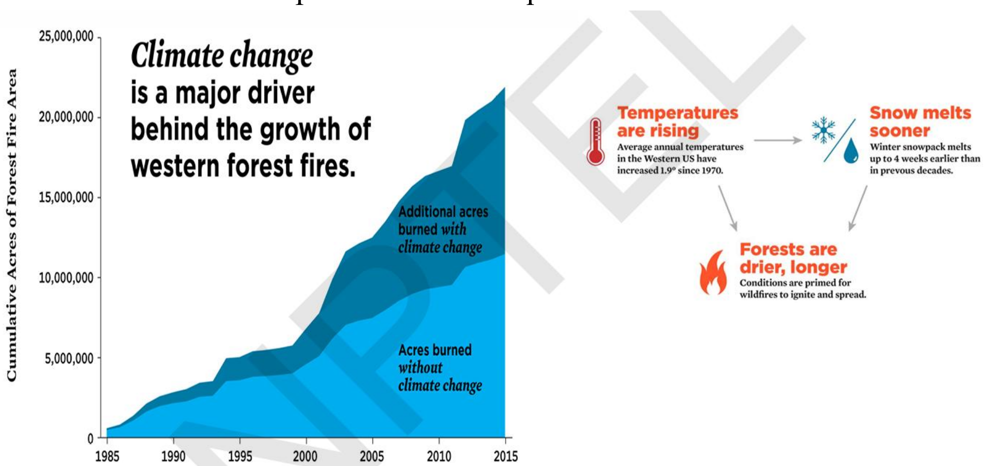
Global and Regional Trends and Drivers of Fire Under Climate Change Jones et al., Review of Geophysics, 2022,10.1029/2020RG000726

Figure 3. Time series of global and regional estimates of mean fire weather season length (FWSL) from ERA5 (thin red lines; Hersbach et al., 2020; Vitolo et al., 2020) and CMIP5 models running RCP8.5 (gray lines; Abatzoglou et al., 2019). Thin black lines mark the multi-model mean estimate from the CMIP5 models. Linear trends in the period 1979–2019 are shown for the ERA5 (thick red lines) and CMIP5 (thick black lines), with corresponding numbers marking the change in annual FWSL during the period (the slope integrated over the period 1979–2019) and corresponding asterisks denoting significant changes at the 95% confidence interval. Differences between modeled and observed FWSL can be explained by differences in the resolution of the models (2.5°) versus the observations (0.25°), since FWSL is partly determined by the maximum value FWI and this is reduced through spatial averaging.

Researchers have analysed global and regional trends contributing to the increasing incidence and severity of forest fires, and the findings are alarming. Certain regions such as the Pacific coast of the United States and the Amazon basin are witnessing a rapid extension of the fire season, far beyond historical norms. This means that the window of time during which conditions are favourable for fires is growing longer, increasing both the likelihood and intensity of fire outbreaks.

What is particularly concerning is the discrepancy between observed trends and model projections. In many cases, the actual rate of increase in fire activity (represented by the red line) is outpacing the predictions made by climate models (represented by the black line). This suggests that climate models may have underestimated the speed and magnitude of changes in fire-prone conditions. In effect, real-world impacts are unfolding more rapidly and severely than previously anticipated, serving as a stark warning of escalating fire risks under continued global warming.

About 15 years ago, during an Indo-Russian workshop on climate change held in Cochin, Russian scientists suggested that Russia might benefit from global warming, since large portions of the country are currently too cold for agriculture. They believed that rising temperatures could open up new areas for cultivation. However, this optimism proved to be short-sighted. Just a year later, Russia experienced a severe heatwave that resulted in a significant number of deaths in Moscow and massive forest fires. These fires grew beyond the capacity of human control and had to be extinguished by natural forces like rainfall and shifting weather patterns, not by firefighting efforts. This incident served as a stark reminder that even countries perceived to be "winners" of climate change are not immune to its extreme and unpredictable consequences.



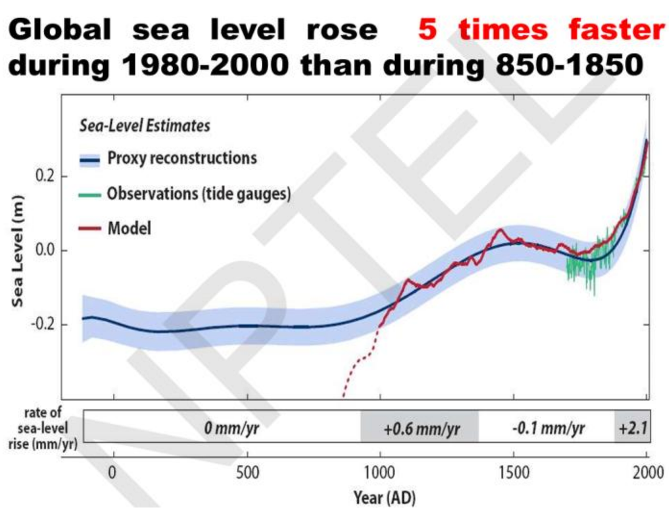
The impact of climate change on forest fires is now clearly evident, as shown in the above graph comparing the cumulative area burned under normal conditions (due to natural or human causes unrelated to climate change) with the additional area burned specifically due to climate change. This additional burning is driven by factors like rising temperatures, earlier snowmelt, drier forest conditions, and longer drought periods.

A striking example of how far-reaching the consequences can be is the 2023 Canadian forest fires, which led to a severe air pollution event in New York City, located hundreds of kilometers away. The smoke from the fires travelled across national borders, creating hazardous air quality far beyond the original fire zones. This illustrates that forest fires induced by climate change are not just a local issue, but can cause regional or even international crises.

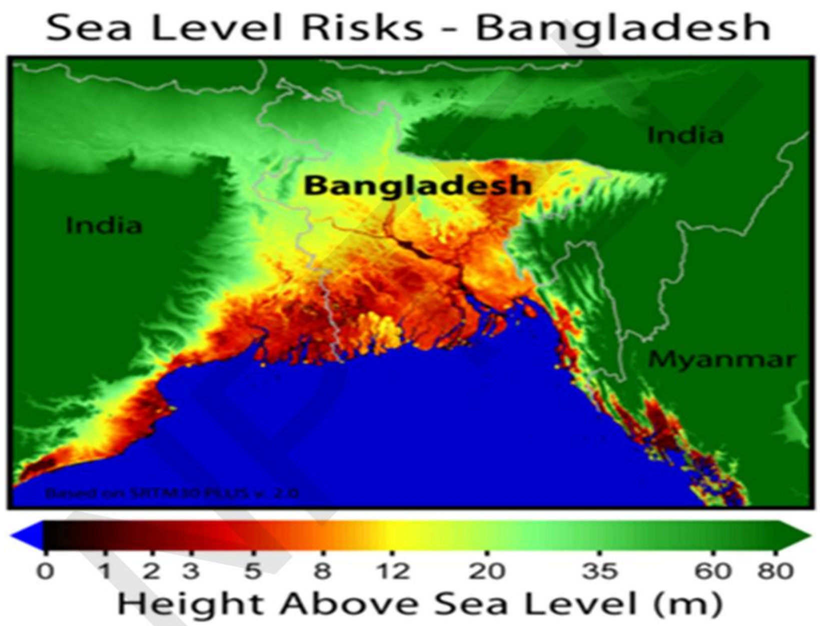
Another catastrophic example is the Australian bushfires in the past five years, which led to the death of an estimated 1 billion animals. This number emphasizes the enormous toll on biodiversity, affecting ecosystems at an unprecedented scale.

Overall, climate change-driven forest fires represent a grave and escalating global threat, not only in terms of human health, infrastructure, and cross-border air quality, but also in terms of irreversible ecological damage and mass wildlife loss. It reinforces the urgent responsibility of human societies, who have largely caused climate change, to take meaningful action to mitigate these growing disasters.

One of the most serious long-term consequences of climate change is sea level rise. As global temperatures increase, so do ocean temperatures. This warming causes thermal expansion of seawater, which leads to a gradual rise in sea level. In addition, melting of land-based glaciers and ice sheets contributes significant volumes of freshwater into the oceans. Together, these processes are causing the sea level to rise at an average rate of about 3 mm per year. While this may seem small, over a century it translates to a rise of at least 30 cm, and projections by the IPCC suggest that sea level rise could reach up to 1 meter by 2100, especially under high emissions scenarios. Such an increase would severely threaten low-lying coastal regions across the tropics and beyond, displacing populations and damaging infrastructure.



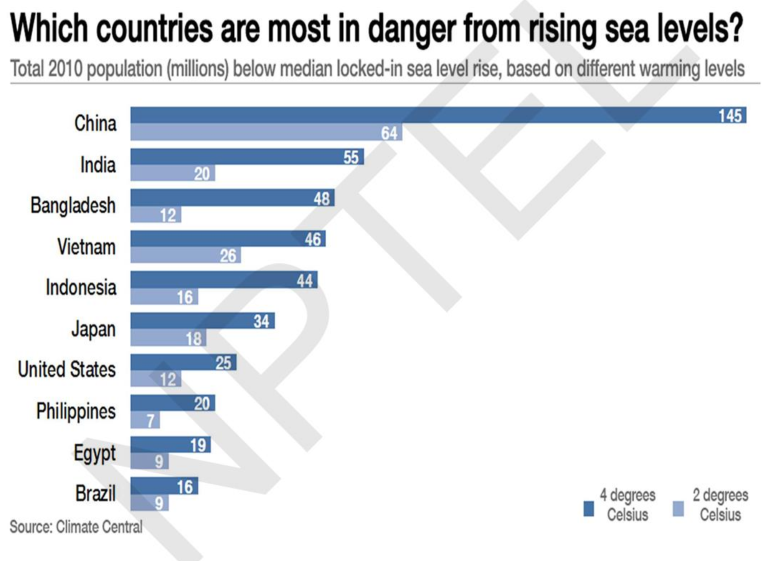
Historical records also reinforce the urgency of this issue. Reconstructions from proxy data, tide gauge measurements, and climate models all indicate that while sea level rose slowly in earlier centuries with a slight decline about 500 years ago, it has accelerated rapidly in the past 50 years. The current rate of rise is approximately five times faster than the average over the last millennium, clearly pointing to the intensifying impact of human-induced climate change. This trend, if unchecked, could reshape coastlines and ecosystems worldwide.



Sea level rise poses a critical threat to densely populated and low-lying regions such as eastern India and Bangladesh. Much of the land in coastal Odisha, West Bengal, and Bangladesh lies only 1 to 2 metres above current sea level. Even a modest rise in sea level on the order of 30 cm to 1 m over the next century could lead to widespread inundation of these regions, rendering large tracts of land uninhabitable.

Moreover, the impact is compounded by the region's vulnerability to tropical cyclones, which strike several times a year. Cyclones are typically accompanied by storm surges, which are temporary but powerful rises in sea level caused by strong winds and low pressure. When combined with an elevated baseline sea level, storm surges can flood inland areas more easily, increasing the frequency and severity of flooding in major cities like Kolkata and Dhaka. While these risks may not fully materialize in the next decade, the long-term outlook over the next century calls for urgent planning and adaptation to protect both populations and infrastructure.

Countries most at risk from sea level rise are predominantly located in Asia, where large populations live in low-lying coastal regions. For a 2°C global temperature rise, an estimated 64 million people in China and 20 million in India are at risk. If warming reaches 4°C, the number of people affected nearly doubles, underscoring the scale of the threat. Other vulnerable countries include Bangladesh, Vietnam, Indonesia, and Japan, where densely populated deltas and coastal cities face significant risks of flooding and permanent submersion.



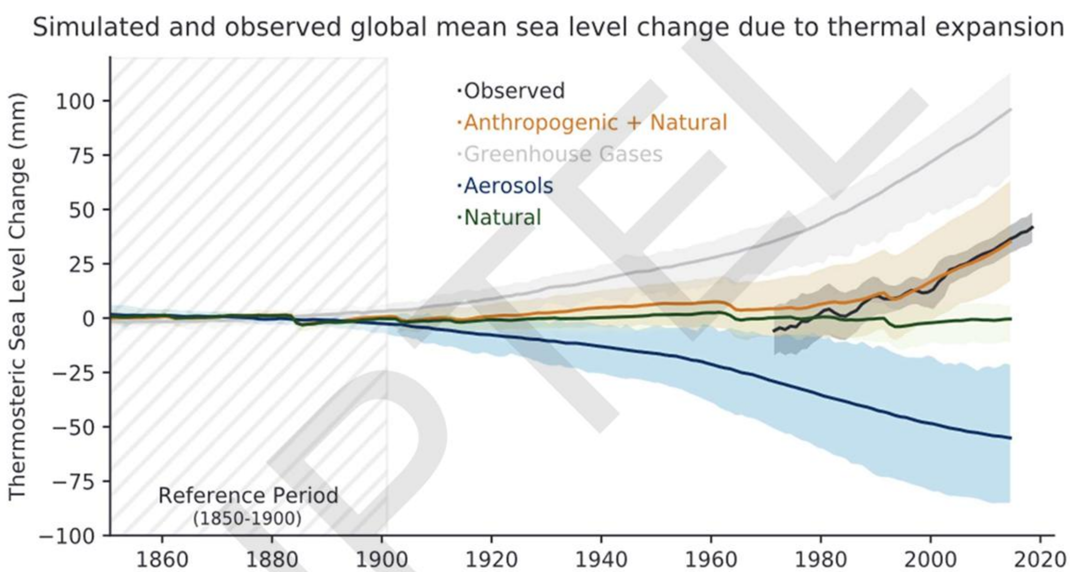
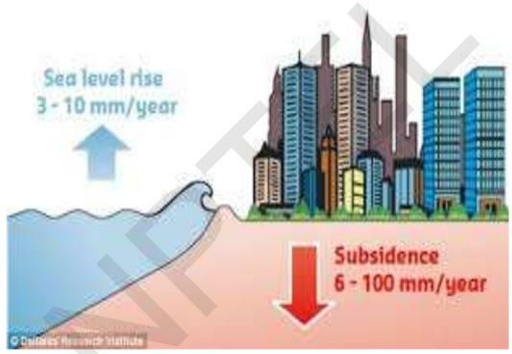


Figure 3.29 | Simulated and observed global mean sea level change due to thermal expansion for CMIP6 models and observations relative to the baseline period 1850–1900. Historical simulations are shown in brown, natural only in green, greenhouse gas only in grey, and aerosol only in blue (multi-model means shown as thick lines, and shaded ranges between the 5th and 95th percentile). The best estimate observations (black solid line) for the period of 1971–2018, along with *very likely* ranges (black shading) are from Section 2.3.3.1 and are shifted to match the multi-model mean of the historical simulations for the 1995–2014 period. Further details on data sources and processing are available in the chapter data table (Table 3.SM.1).

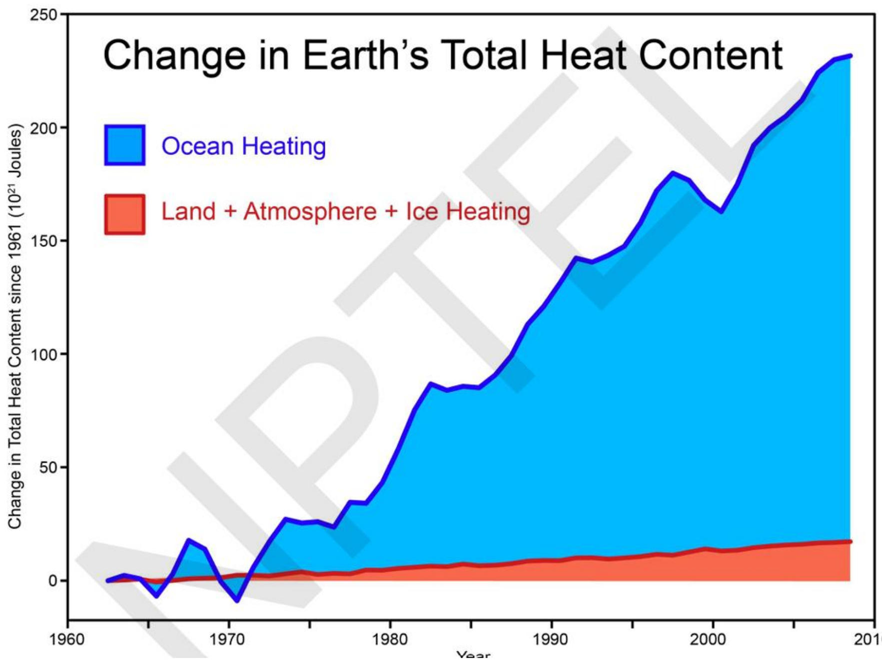
In terms of causation, both anthropogenic and natural factors contribute to sea level rise. Observations (black line) match closely with climate model projections that include both human-induced greenhouse gases and natural variability (orange line). However, models considering only greenhouse gases (grey line) predict a faster rise than observed. The slower observed rise is partly due to aerosols, which have a cooling effect and have moderated the temperature increase. But as aerosol pollution is reduced, a likely outcome of cleaner air policies, global temperatures will rise more rapidly, leading to an accelerated rate of sea level rise. This underscores a key message from the IPCC: air pollution controls may have the unintended effect of amplifying climate change impacts like sea level rise in the coming decades.



In addition to rising sea levels, land subsidence presents another serious complication for India, particularly in eastern regions like West Bengal and Bangladesh. This phenomenon, where land sinks over time, is largely driven by excessive groundwater extraction. When groundwater is pumped out in large quantities, the soil structure weakens and compacts, leading to the ground collapsing. This process can cause land to subside at a rate faster than sea level rise caused by global warming.

India, being the largest extractor of groundwater in the world, faces a significant risk from this dual threat. The combined effect of land subsidence and sea level rise dramatically increases the likelihood of coastal inundation, especially in low-lying areas. In such cases, even a modest rise in sea level can lead to severe flooding and loss of habitable or arable land. Thus, managing groundwater extraction is just as critical as addressing climate change to protect vulnerable coastal regions in the coming decades.

Coastal regions such as parts of Mumbai are expected to face inundation by 2050, just 25 years from now, due to the combined effects of sea level rise and land subsidence. Similar threats exist for coastal areas in Odisha, West Bengal, and Bangladesh, where low-lying land is highly vulnerable. The dual impact of rising seas from global warming and sinking land from excessive groundwater extraction significantly increases the risk of flooding and permanent submergence. This presents a serious long-term challenge that cannot be ignored. One of the key strategies to address this threat includes planning for the resettlement of populations to higher, safer areas. Proactive adaptation measures will be crucial to protect lives, livelihoods, and infrastructure in these regions.



The primary reason for rising sea levels is that the ocean is absorbing the majority of the excess heat trapped by greenhouse gases like carbon dioxide. While land absorbs only a small fraction of this heat, the ocean, due to its large volume and efficient mixing, acts as a major heat sink. This heat absorption leads to thermal expansion of seawater and accelerates the melting of glaciers, both contributing to sea level rise. As a result, sea level rise has emerged as a significant consequence of climate change. This lecture concludes with this discussion, and the next lecture will focus on extreme rainfall events, which have become increasingly frequent and intense in recent decades.