Climate Change Science
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Lecture – 54
Extreme rainfall

In this lecture, we will talk about another impact of climate change and global warming, which is extreme rainfall. Many countries in the world, including India, have seen a large increase in extreme rainfall. By extreme rainfall, I mean rainfall above 100 millimeters per day. This kind of rainfall causes flooding and lots of damage.

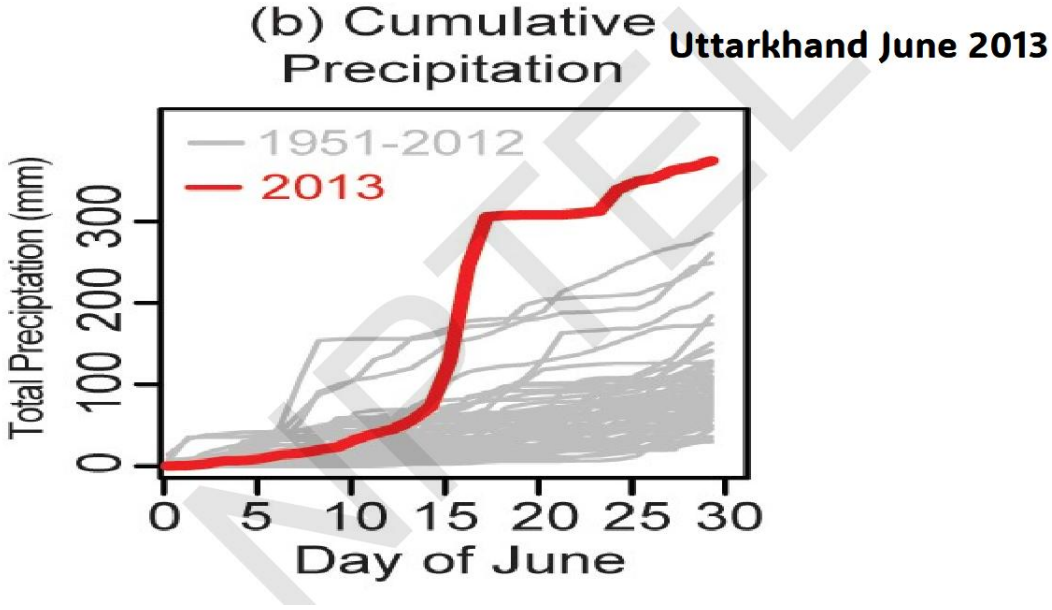
Now, this increase in extreme rainfall is due to three reasons. One is, of course, global warming. As the temperature rises, humidity increases. There is more moisture in the air. So, when conditions are appropriate, this water vapor will condense and fall. Secondly, we have seen that aerosols also contribute to extreme rainfall because they affect the number of liquid droplets and ice particles in the atmosphere. So, aerosols also contribute to extreme rainfall. Thirdly, most of the world is becoming more urban. Urban areas are hotter than the surrounding rural areas because they contain more concrete, which absorbs and stores heat. Typically, urban areas are around 3º to 4º warmer than the surrounding rural regions. This combination of urban heating, aerosols, and global warming is causing an increase in extreme rainfall in cities, and many cities are facing serious threats of flooding.

Extreme rainfall influenced by
Global Warming
Aerosols
Urban heat island

In USA, the number of cities facing threat of flooding will increase from 100 to 700in the next 50 years

In the United States, it is predicted that the number of cities at risk of flooding due to high rainfall will increase from 100 to 700—seven times more—in the next 50 years. We saw an example of extreme rainfall in Mumbai on July 26, 2005, when the amount of rainfall in one day was 942 millimeters. To give some perspective, in most years, Bangalore's total rainfall is not more than 900 millimeters. So, one year's rainfall in Bangalore fell in one day in Mumbai. This was an unprecedented event, and you can see in the picture shown below that it flooded most roads in Mumbai for a day and completely brought the airport to a standstill. These kinds of events are going to increase.

Another extreme rainfall event occurred in June 2013 in Uttarakhand. Suddenly, around the 14th and 15th of June, extremely heavy rainfall occurred, unseen in the previous 60 years. You can see that the rainfall in June 2013 was unusually high compared to the cumulative rainfall in previous Junes (please refer to the graph shown below). It caused major flooding and the deaths of a large number of tourists who had come to Uttarakhand for the summer.



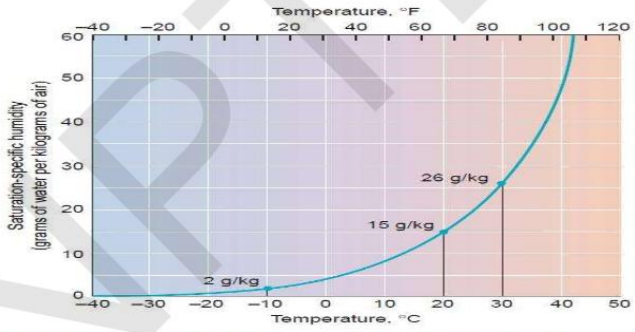
Why does extreme rainfall occur? You must remember that humidity in the atmosphere increases exponentially with temperature. This follows the well-known Clausius-Clapeyron equation in thermodynamics, which states that the ability of air to hold moisture increases with temperature. In the graph shown below, you can see that from 20º to 30ºC, the amount of humidity in the atmosphere increases by 11 grams per kilogram for just a 10ºC increase. This additional moisture

held in the atmosphere will cause more rainfall. Secondly, rainfall is also proportional to the total amount of water vapor in the atmospheric column.

Why are extreme rainfall events increasing rapidly?

1.An exponential increase of humidity with temperature

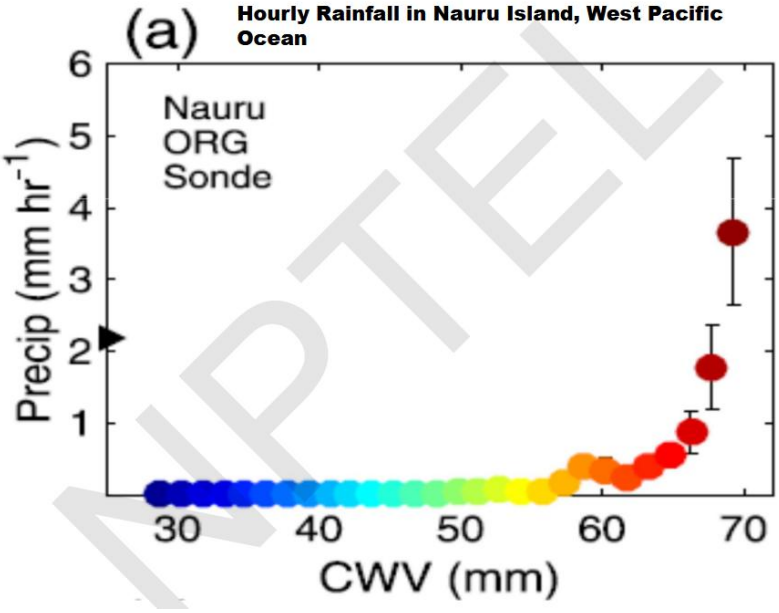
2. Non-linear increase of rainfall with humidity



4.6 Saturation-specific humidity and temperature

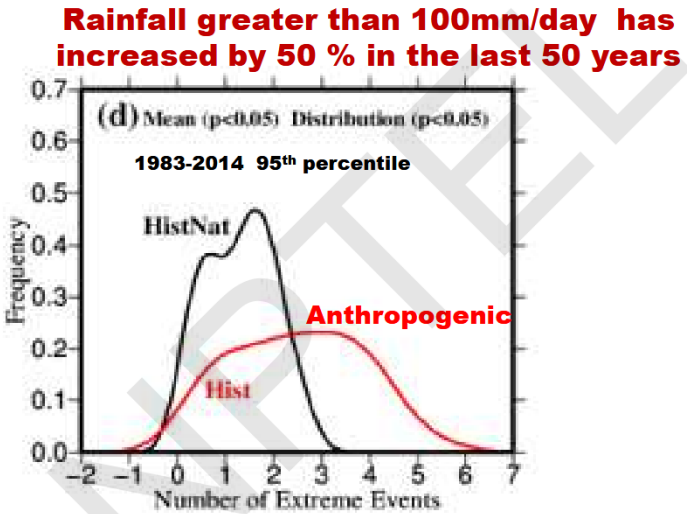
The maximum specific humidity a mass of air can have—the saturation-specific humidity—increases sharply with rising temperature.

If you integrate the water vapor from the surface to the top of the atmosphere, it is called column water vapor. As that increases, rainfall increases sharply. This increase is exponential. This was measured on Nauru Island in the western Pacific Ocean. You can see that up to 60 millimeters (mm) of total water vapor, not much happens. Beyond 65 mm, the precipitation starts increasing and rises 4 to 5 times. This is rainfall in the graph below is shown in millimeters per hour.



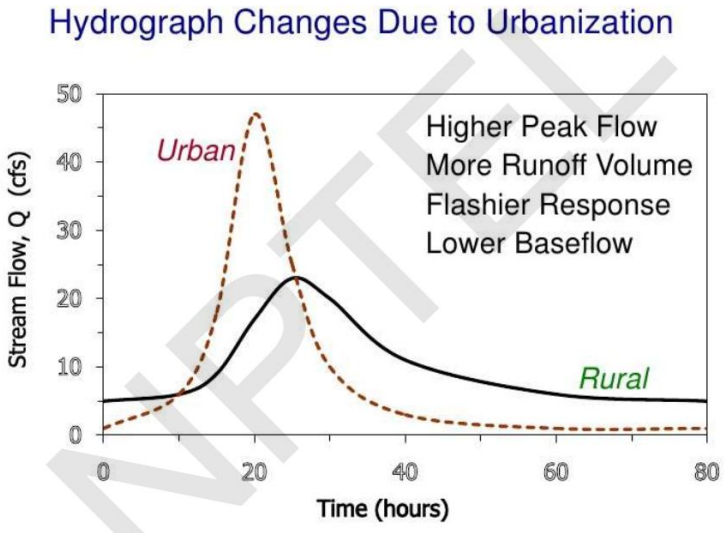
So, the combination of the exponential increase in humidity with temperature and the exponential increase in rainfall with water vapor has made extreme rainfall much more common today than it was 50 years ago. So, global warming has made the largest contribution to the increase in heavy rainfall events.

This is shown in a paper by Mukherjee and others, published in *Weather and Climate Extremes* about six years ago. The graph below shows the historical rainfall distribution and the number of extreme events, defined as rainfall above 100 millimeters per day, and then shows the data due to human-induced warming. You can see that previously, the number of extreme events per year was not more than three, which is very rare. Now, it is quite common.



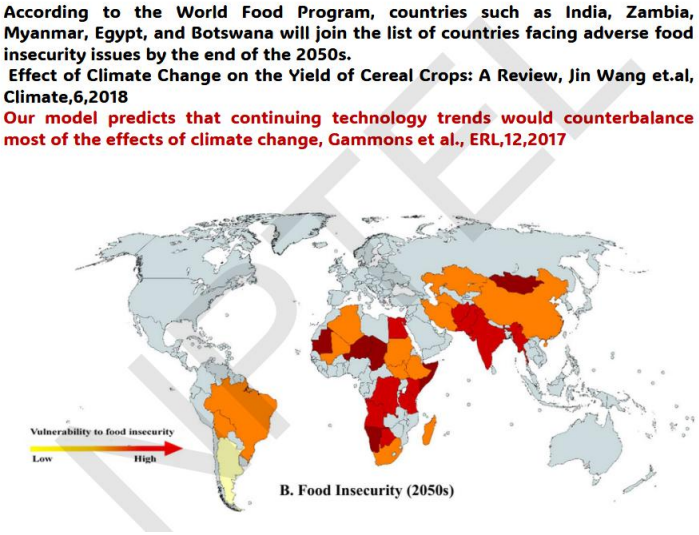
Mukherjee et al., Weather and Climate extremes , 2018

This change in distribution is what we are seeing in many parts of India and the rest of the world. This is something we must adapt to. It will continue to get worse over the next 50 years. In urban areas, in addition to the risk of higher extreme rainfall, the ground is also less pervious. That is, rainfall does not penetrate the ground because of concrete surfaces.



So, you can see that during very heavy rainfall, streamflow increases very rapidly and then decreases quickly, compared to surrounding rural areas. In rural areas, the soil can absorb moisture, and vegetation can store and release it slowly. But in urban areas, this cannot happen. So, floods in urban areas are increasing due to a combination of extreme rainfall and low porosity of the land. Again, this is a double jeopardy, caused by increased extreme rainfall and decreased porosity of urban surfaces.

Next, we come to agriculture. Climate change has a huge impact on agriculture because temperature affects plant growth and health. Researchers have analyzed the impact of global warming on the yields of cereal crops. A recent review by Jin Wang and others, published in *Climate* in 2018, shows that areas like India, China, Africa, and South America will experience lower crop yields compared to colder countries.

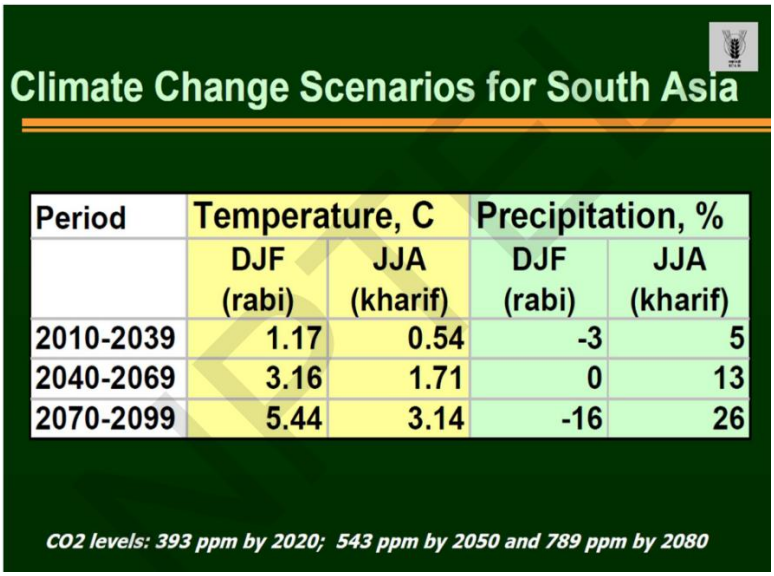


The plants we grow today in the tropics were selected based on climatic conditions that existed hundreds of years ago. Today, because of global warming, the same crops are no longer suitable for the new climate. Meanwhile, in colder countries like Russia, Europe, and America, the conditions are becoming more suitable for growing crops.

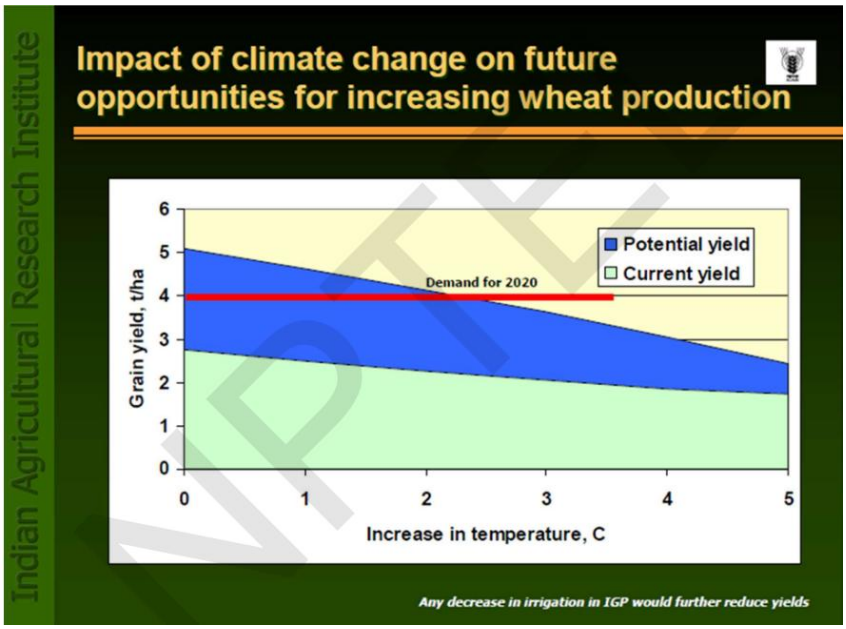
The Indian Agricultural Research Institute (IARI) has done a lot of research on this issue. Dr. P. K. Agarwal has provided insights showing that crop yields begin to decline with just 1ºC of warming, but in temperate climates, yields can continue increasing up to 3ºC of warming. So, present global warming is favorable for Europe, Russia, Canada, and North America—but unfavorable for India, Africa, and South America in the tropics. All data from IARI show that crop yield will go down. But there is very little information on what happens to fish and other livestock. I also pointed out that livestock will be affected by heat waves.

We have no data on pests and microbes. So, remember that as the climate changes, the types of pests and microbes that become more common are uncertain. There is still a lot of uncertainty about how agriculture will be affected because we do not yet know how pests and microbes will evolve during global warming.

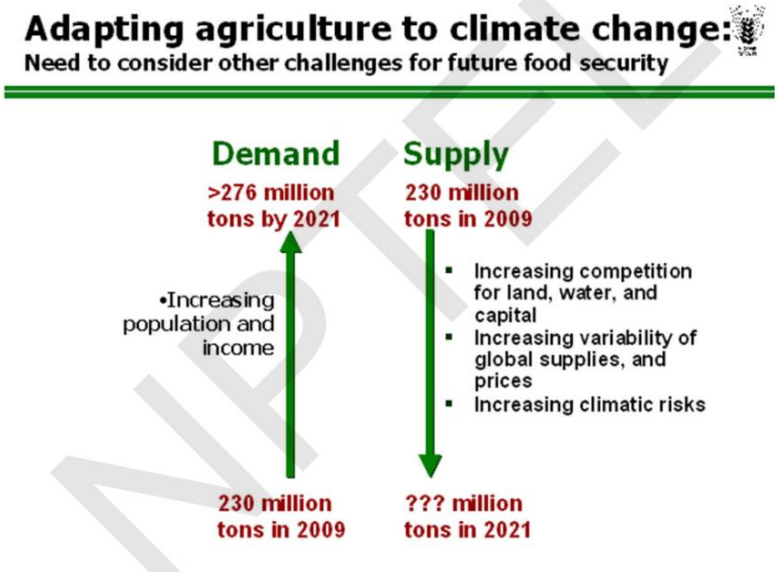
This data shows that during June, July, and August—the Kharif season—temperatures will go up slightly less than in the winter season. So, the increase in carbon dioxide will benefit photosynthesis somewhat. In some areas, monsoon rainfall may increase, but in winter, rainfall will decrease. We produce wheat mainly in the winter. During that time, rainfall will actually decline.



You can see that grain yield is going to go down as temperature increases (refer to the graph shown below). Even the theoretical potential yield—the maximum yield that can be calculated based on models—will decrease. But our demand in 2020 was already at a level of about 4 tons per hectare. With 3ºC of warming, our yield will fall below that demand. So, this is the concern of the IARI.

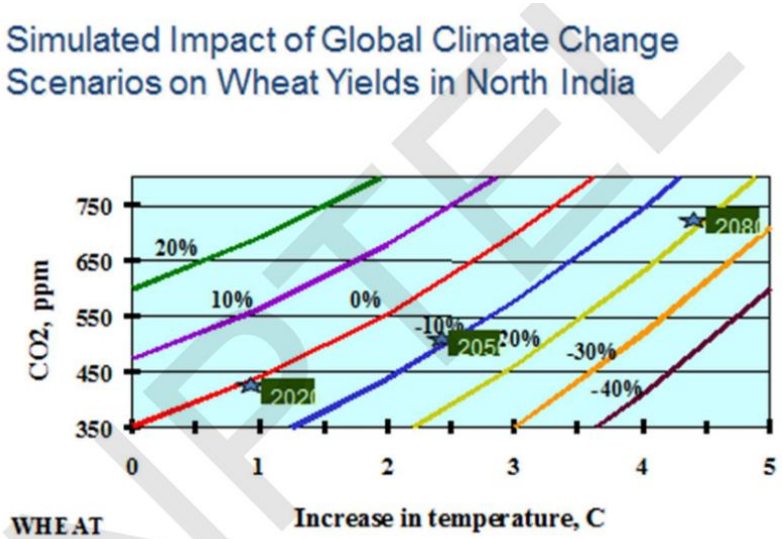


The challenge is that our demand is going to go up, and our supply is going to go down—unless we are able to increase our yield or manage the risks posed by climate change. Climate change has two different impacts on crop yield. As carbon dioxide goes up, photosynthesis increases, and yield can go up. But as temperature increases, yield will decrease.

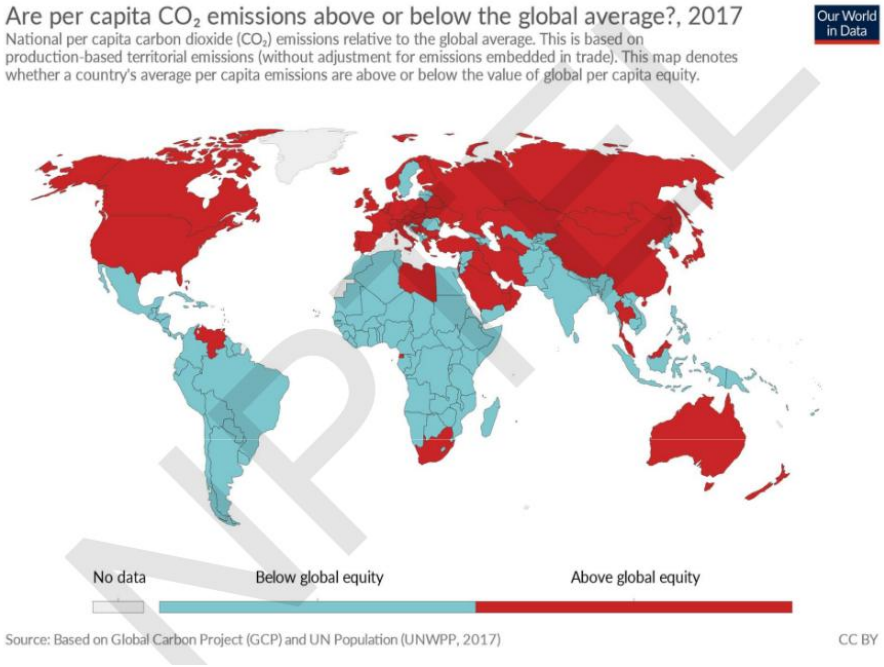


The diagram below shows the calculation for wheat. You can see that there is a very different impact from increased photosynthesis and decreased yield due to temperature. If the temperature goes up beyond 1ºC or 2ºC, the yield in North India will decline. So, this is a huge challenge for

India, which must be tackled by changing the variety of wheat and rice we grow or increasing the area under cultivation.

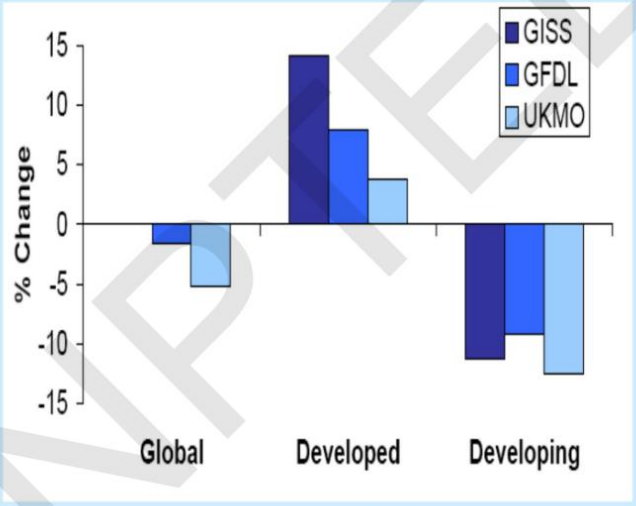


The problem is that global carbon dioxide emissions per capita are above the global average in all the developed countries of the world. In contrast, most developing countries have per capita CO_2 emissions below the global average. Unfortunately, the impact of climate change will be more severe in the developing world, while the developed world will benefit from the warming. This issue is a very serious matter of equity. That is, countries that contribute the least to climate change will be the most affected by global warming.



This concern was raised more than 30 years ago by Parry and Rosenzweig. They showed, using three models, that cereal production in developed countries may increase by around 5 to 15%, while in developing countries, it may reduce by around 10%. So, global warming is very unfair to the developing world because their crop yields are going to go down at a time when their populations are still rising.

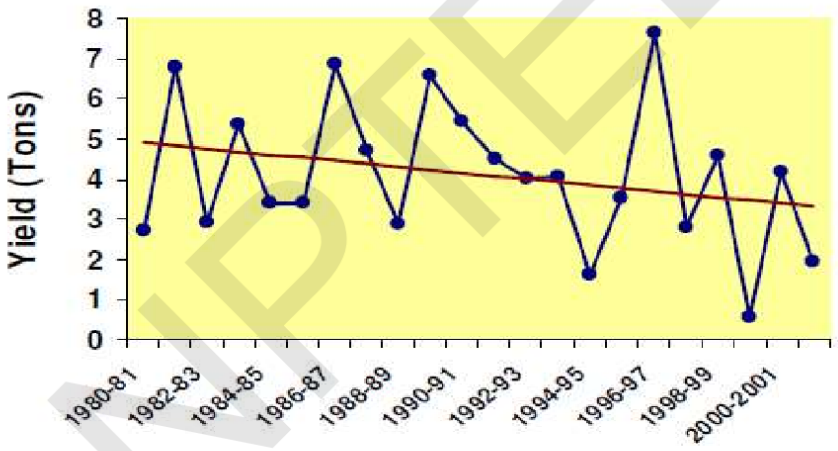
Figure 3.5 Change in cereal production in developed and developing countries for a doubling of carbon dioxide levels (equivalent to around 3°C of warming in models used) simulated with three climate models (GISS, GFDL and UKMO Hadley Centre)



Source: Parry *et al.* (2005) analysing data from Rosenzweig and Parry (1994)

In addition to rice and wheat, we should all worry about other crops. Here is an example of data on apples—specifically, apple yield in Himachal Pradesh.

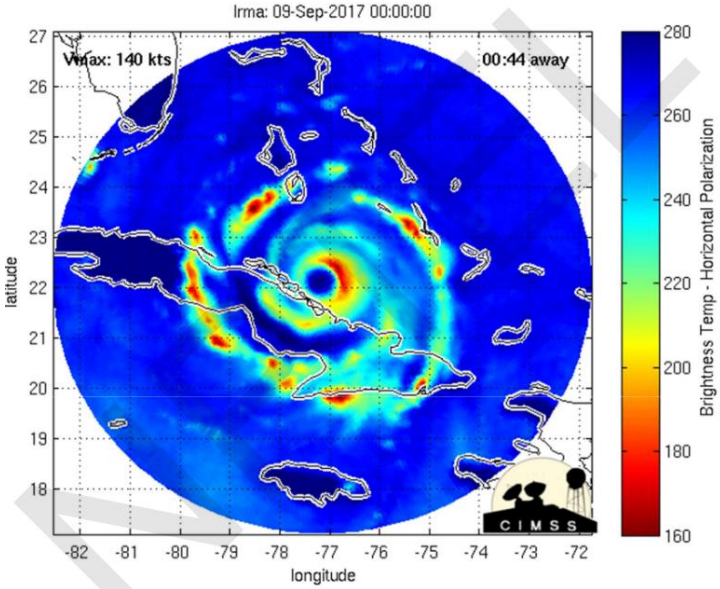
Decrease in yield of Apple in Himachal Pradesh
Apple growing areas in low altitude areas reduced by 77% between 1981 and 2007



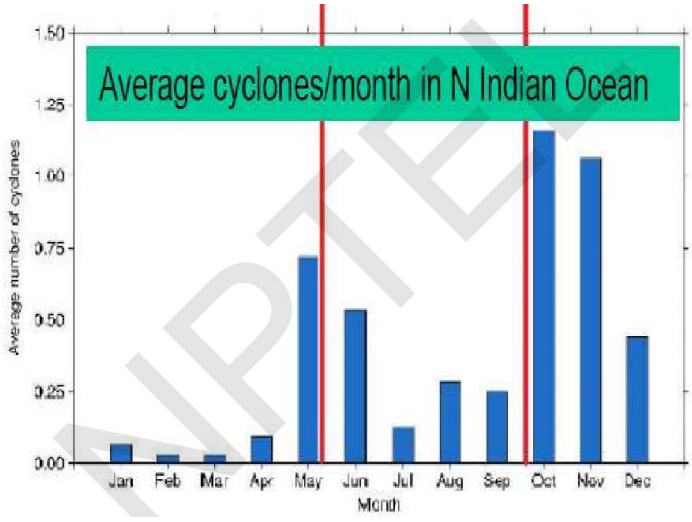
Bhagat, Rana, &Kalia, Global Climate Change and Indian Agriculture (ed. Aggarwal, P. K.), ICAR,2009

In apple-growing areas, the yield declined by 77% between 1981 and 2007. Over 26 years, the yield has gone down. Therefore, in Himachal, farmers are trying to move to higher altitudes for apple cultivation. But you can imagine there is a limit to how high one can go in the mountains. So, there will be serious consequences for the apple yield.

Now, the next major threat, of course, is cyclones. Cyclones are born primarily over the ocean. As they move over land—as shown in the figure below, over Florida and the Caribbean—they cause huge damage. The serious question is: Due to global warming, will the number of cyclones increase, and will their intensity also go up? We can now say with great confidence that intensity will increase because the energy for cyclones comes from the ocean. As ocean temperatures go up, there is more evaporation of water.



So, the intensity of cyclones will increase with global warming. But the number of cyclones—we are not so sure about, because that depends on various dynamical factors, the changes in which we cannot predict very accurately.



In India, cyclones occur either in the pre-monsoon or post-monsoon seasons. During the monsoon, cyclones are less frequent because there is a strong wind flow from the west over the Arabian Sea to India at the surface level, while at the upper level—above 5 kilometers—wind blows from the east. This wind shear (winds blowing in opposite directions at different levels) does not allow cyclones to form and grow. So, there are very few cyclones in the monsoon season, but there are many more in the post-monsoon season, like October, November, and early May.

The number of cyclones has shown a slight decrease, which may not be connected to global warming but to changes in weather patterns.

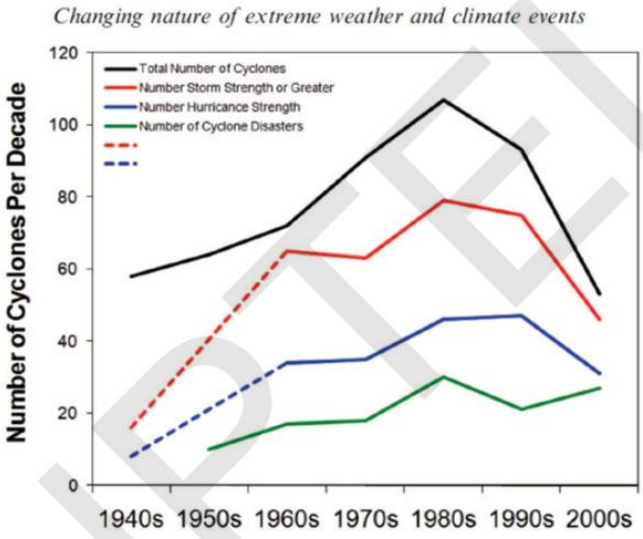


Figure 4. Reported number of cyclones in the southwest Pacific, 1940s–2000s; source: World Bank (2006) and Fiji Meteorological Service Tropical Cyclone Seasonal Summaries. Also shown is the number of cyclone-related disasters, by decade. Source: Rodriguez *et al*. (2009).

J. Hay and N. Mimura, Geomatics, Natural Hazards and Risk
Vol. 1, No. 1, March 2010, 3–18

However, the issue is not the number of cyclones but the number of intense cyclones. For example, the damage a cyclone causes when it comes ashore depends on its category. There are now hurricanes of category 5.

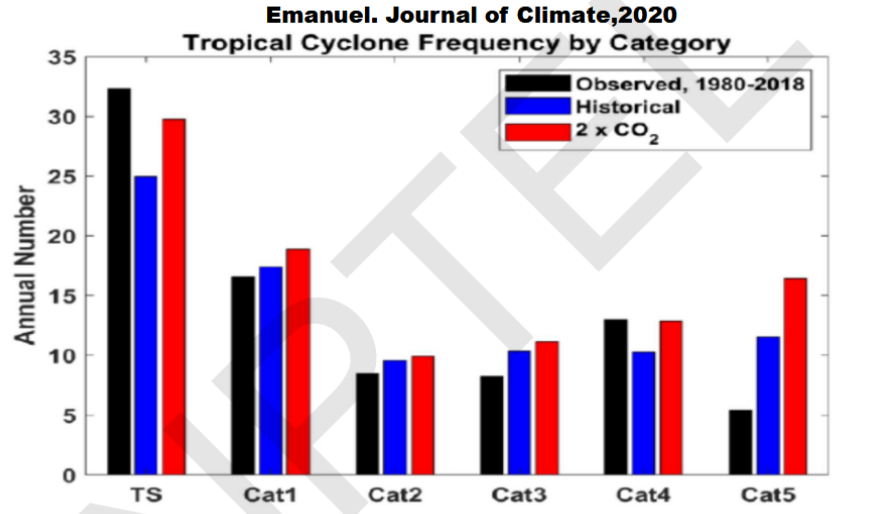
Hurricane Categories

Category	Speed Range(km/hr)
1	119-153
2	154-177
3	178-208
4	209-251
5	> 252

The terms *hurricane*, *cyclone*, and *typhoon* are interchangeable and are used in different parts of the world. We call it a cyclone. In the Pacific, it's called a typhoon. In America, it's called a hurricane. If a storm reaches category 4 or 5, that means wind speeds exceed 200 kilometers per hour. These are highly destructive. They cause huge damage and flooding. This is expected to increase with global warming.

This is shown by a paper by Emanuel, published in the *Journal of Climate*.

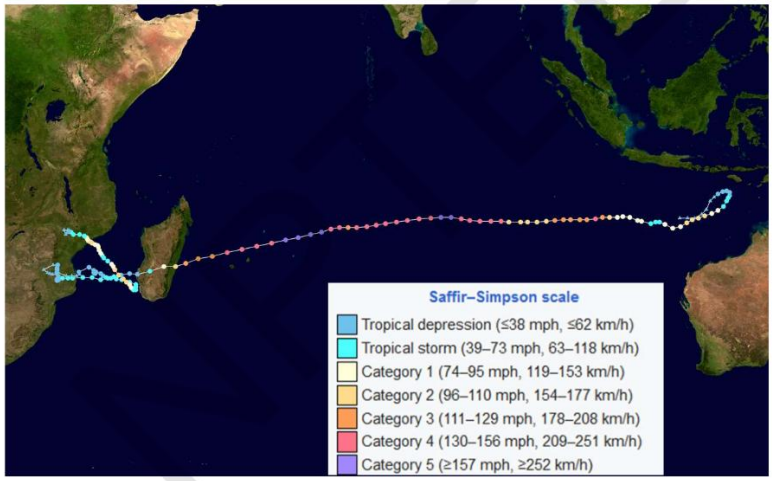
Global number of tropical cyclones by Saffir-Simpson category of lifetime maximum



intensity. Tropical storms here include only events with maximum intensities of at least 40 kts. Black indicates observed (IBTrACS) during the period 1980-2018, while downscaled events are shown in blue for the historical period and red from the linear regressions of trends in the $1\%\,yr^{-1}$

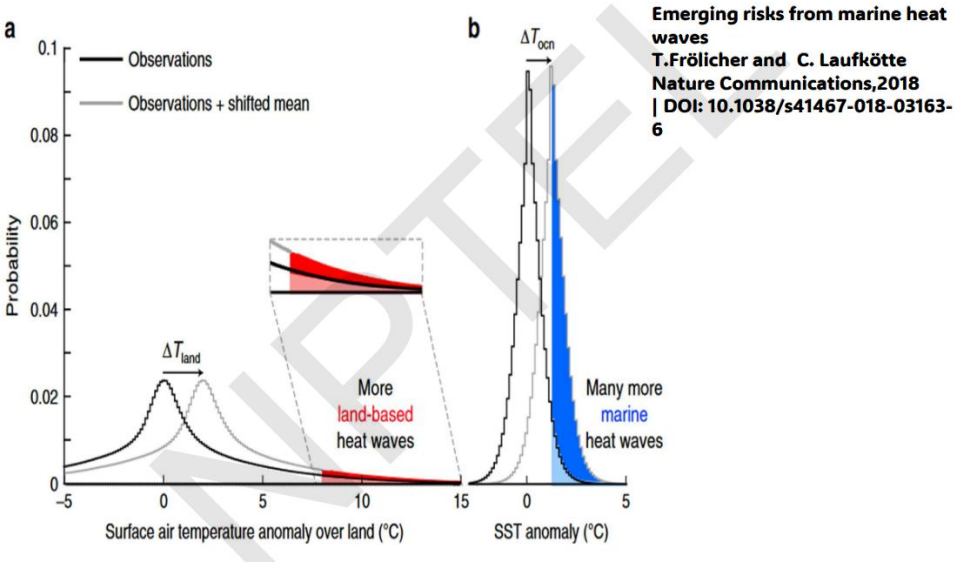
You can see that with the doubling of carbon dioxide, category 1, 2, 3, 4, and 5 cyclones will increase in the future compared to historical data. So, we have to learn to deal with these extreme cyclone events. Fortunately, because of improvements in weather forecasting models, we can now predict with greater accuracy where the cyclone will hit the land and what track it will follow.

Tropical cyclone Freddy 2023



In India, the number of deaths due to cyclones on the east coast has declined substantially because of better short-term cyclone forecasting. But the damage caused by cyclones cannot be prevented. That will continue to increase. Another risky aspect is that because oceans are warming rapidly, cyclones are behaving in ways they haven't before. For example, Cyclone Freddy, which started near Australia, lasted for about a month, intensifying as it crossed the southern Indian Ocean, passed Madagascar, entered Africa, and came back again. This kind of cyclone—with a life span of about a month—is very unusual and can cause a lot of catastrophe. Cyclones will appear in new areas, last longer, and be more intense. If they hit land, they will cause enormous damage.

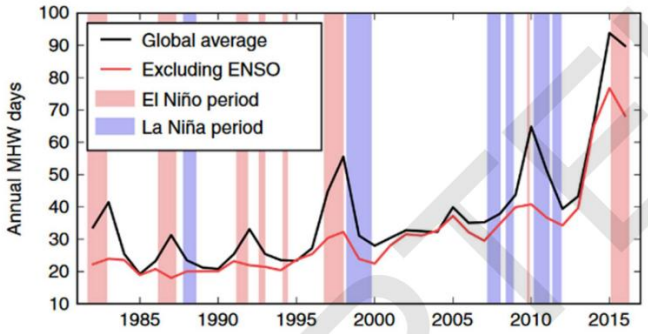
This is the future we have to deal with. As I mentioned, better short-term forecasting will save lives, but not property. Now, we are mostly concerned about human beings. But as oceans warm, marine animals face a huge threat. Marine heatwaves are making life very difficult for fish and other large marine mammals. Earlier, we saw that elephants face a major threat from global warming because they are large animals that cannot dissipate heat as effectively as smaller ones. The same is true for marine animals. Large animals like whales cannot cope with marine heatwaves because their ability to dissipate heat is limited.



Emerging risks from marine heat waves
T.Frölicher and C. Laufkötte
Nature Communications,2018
| DOI: 10.1038/s41467-018-03163-6

Here's an example of increasing marine heatwaves (please refer to the graph shown above). Over land, we saw a small increase in heatwaves, but over the ocean, it is much, much higher. From the past to the future, there is a sharp increase in marine heatwaves, which is going to seriously affect fish and other oceanic life.

This has been discussed in a recent paper in *Nature Communications* about the risk to marine animals.



E.C.J.Oliver et al., Nature Communications
DOI: 10.1038/s41467-018-03732-9
Mass mortality of marine invertebrates due to heat stress

Fig. 2 Total number of marine heatwave days globally. Globally averaged time series of total marine heatwave (MHW) days from NOAA OI SST over 1982–2016. The black line shows the globally averaged time series of total MHW days from NOAA OI SST over 1982–2016. The red line shows this metric after removing the signature of ENSO. The light red and blue shading indicate El Niño and La Niña periods, respectively, defined by periods exceeding ±1 s.d. of the MEI index for three consecutive months

The number of marine heatwave days has increased rapidly, and some of these are connected to El Niño events in the Pacific. During such events, marine heatwaves are much more intense, but even outside of El Niño years, the frequency and intensity of marine heatwaves are increasing. This phenomenon causes coral bleaching, fish mortality, and even the death of large marine mammals. It is a serious concern.

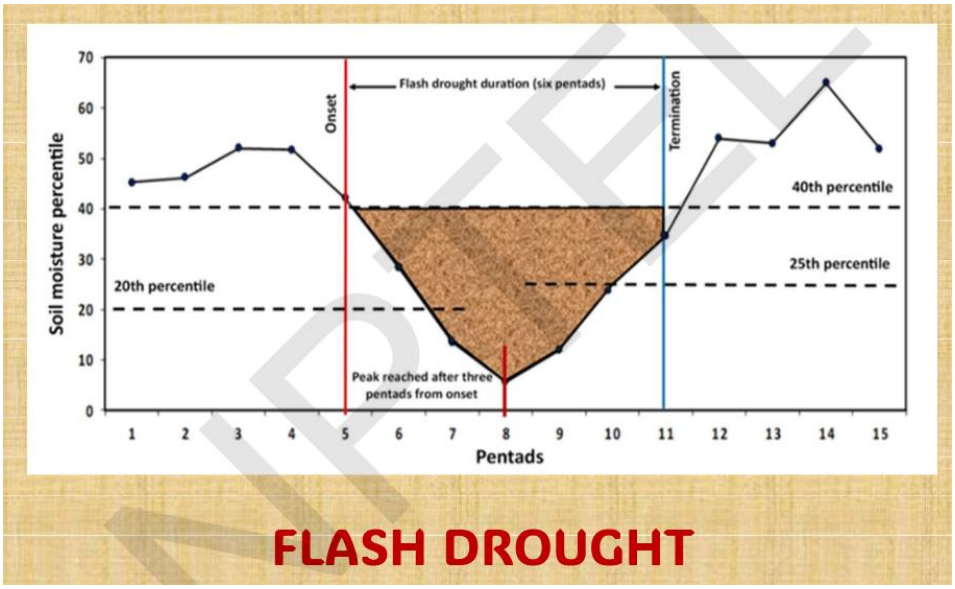
Now, in India, we experienced several serious and continuous heat waves between February and April 2022. Interestingly, this heatwave was not in May (which is more common), but occurred earlier in the year. As a result, it did not cause significant human casualties. However, it had a huge impact on agriculture. Heatwaves from February to April can reduce wheat yields in North India, as this is the season when wheat is grown.

South Asia faced five continuous heatwave spells that lasted about 35 days during late February and April 2022, affecting a large part of the region. The year 2022 heatwave was unprecedented that caused a deficit in soil moisture and crop yield.

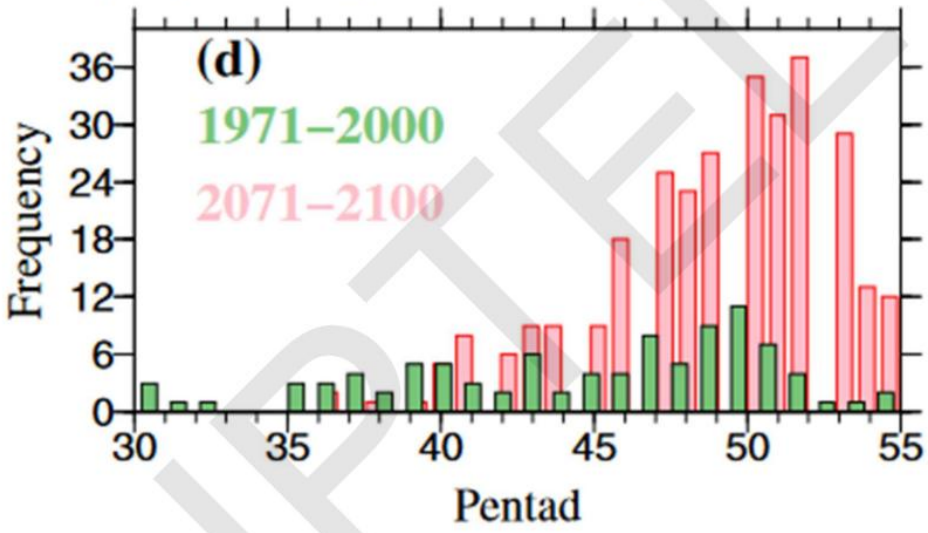
Vimal Mishra, IIT, Gandhinagar

Professor Vimal Mishra from IIT Gandhinagar has studied these impacts and warned that they could have serious consequences.

Due to rising land temperatures, there is now a new phenomenon called flash drought. Flash droughts are short-term droughts, lasting for 5 to 10 days, and are caused not only by low rainfall but also by high temperatures. Because of the higher temperatures, evaporation increases rapidly, drying out the soil and plant roots. Flash droughts, therefore, result from a combination of reduced rainfall and increased heat.



The frequency of flash droughts that occurred during the monsoon season

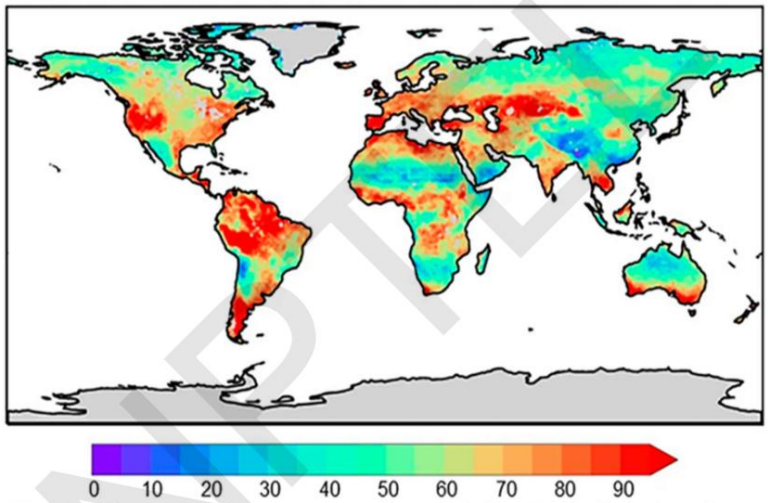


Mishra, V., Aadhar, S. & Mahto, S.S. Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India. npj Clim Atmos Sci 4, 1 (2021)

These flash droughts pose a major threat to agricultural yield. This has been documented by Professor Mishra and his group. They have shown that between 1970 and 2000, there was only a small increase in flash drought frequency. However, in projections for the next 100 years, flash droughts are expected to occur two to four times more frequently. This is a very serious issue.

The Indian Council of Agricultural Research (ICAR) published a report on the 2022 heatwave, its impact, and how to respond. So, this is an issue, especially for India, during the February-April period. These heat waves may not severely affect humans directly, but they have a huge impact on agriculture.

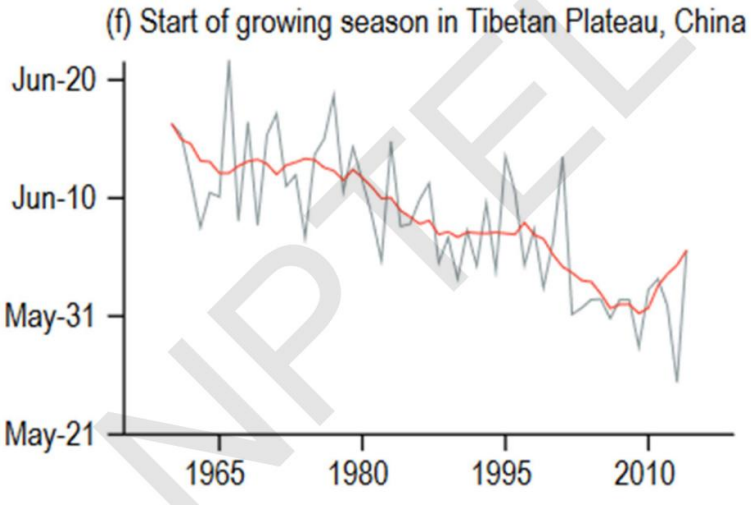
Globally, the total number of flash droughts—caused by either heatwaves or rainfall deficits—is expected to increase across Europe, America, Africa, and South America. In the 28-year period from 2020, there were 90 flash droughts recorded in parts of the Amazon.



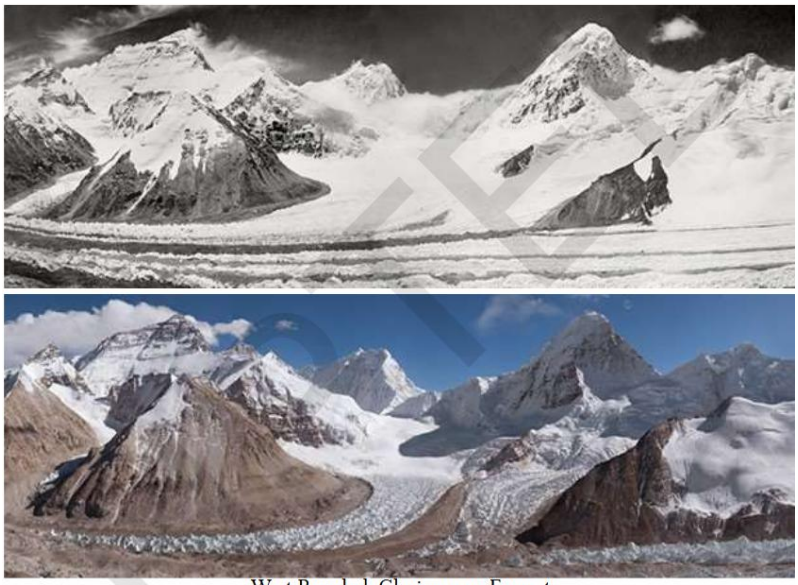
Total numbers of both heat wave and precipitation deficit flash droughts during the period 2000-2020. Detection method based on soil moisture percentile changes using modelled data. From Qing *et al.* (2022).

Now, climate change is also increasing the length of the growing season. Take the Tibetan Plateau, for instance. The growing season, which started around June 15 in 1965, has gradually shifted earlier—by about 15 days—by 2010. This is another significant impact of climate change. While

humans can try to adapt to this shift, animals must also adjust. Birds and other species are being forced to adapt to changing seasonal patterns due to global warming.

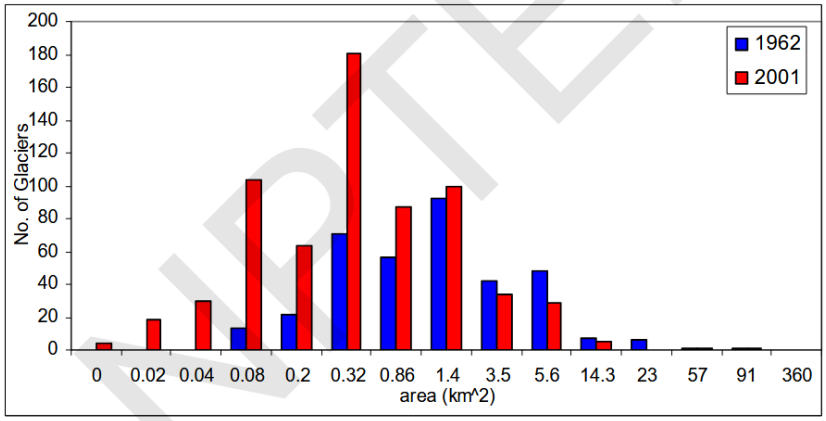


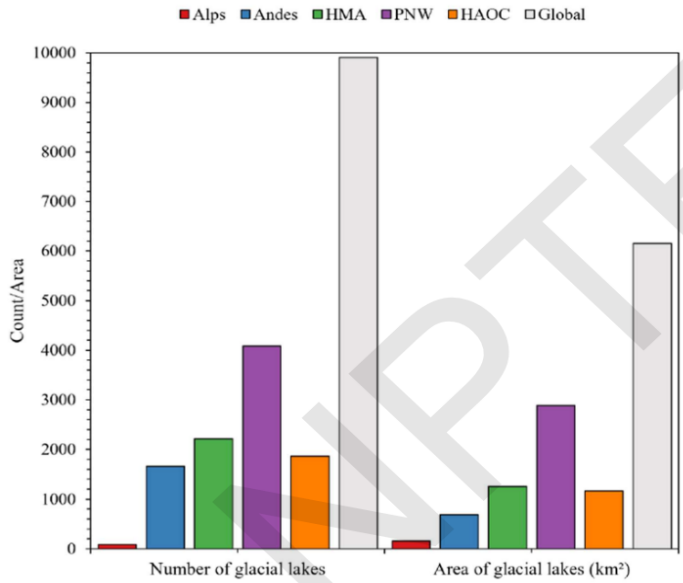
Perhaps the biggest visible impact of climate change is the melting of glaciers. Shown below is a photo comparison of the West Rongbuk Glacier near Mount Everest. One photograph was taken in 1921, and the other in 2009. Over this 80-year period, the glacier has retreated significantly, exposing large areas that were once covered with ice.



West Rongbuk Glacier, near Everest
1921 and 2009

Professor Kulkarni from our center has documented the fragmentation of glaciers in the Chenab Basin in Himachal Pradesh. Between 1962 and 2001, the larger glaciers have declined, and the number of smaller glaciers has increased. In other words, big glaciers are breaking into many smaller ones. The number of small glaciers has gone up dramatically, while large glaciers have declined.





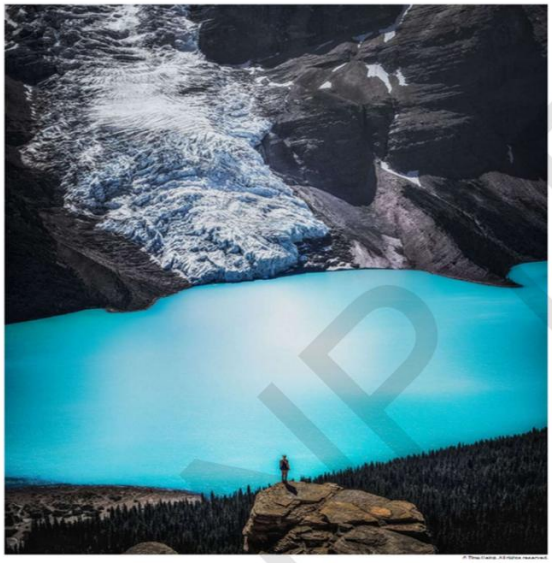
ID	Number of glacial lakes	Area of glacial lakes (km²)	Normalised Condition Score
Alps	87	159.51	0.041
Andes	1662	686.87	0.334
HMA	2211	1256.09	0.405
PNW	4083	2884.05	1.000
HAOC	1862	1166.09	0.447
Global	9905	6152.60	

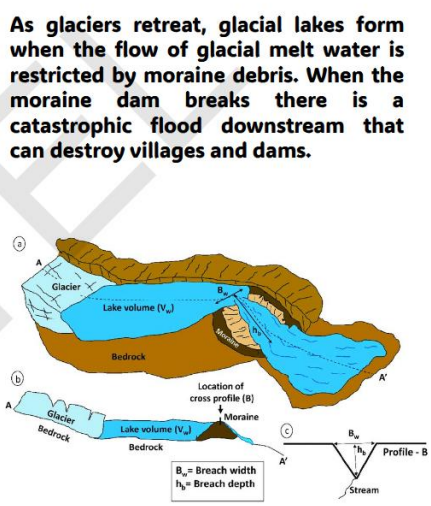
One serious consequence of glacier retreat is the formation of glacial lakes. When glaciers retreat, the melting ice collects to form lakes. These are called glacial lakes. A large number of such lakes have now formed in mountain regions around the world. For example, in the Indian and Asian Himalayas, there are about 2,000 glacial lakes, covering an area of 1,256 square kilometers.

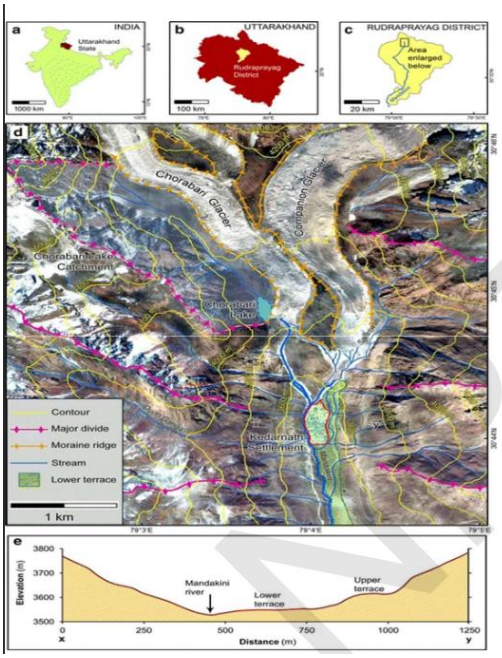
Here is an example of such a glacier retreat that resulted in a lake. The glacier leaves behind a moraine, which is debris pushed forward by the glacier. This moraine acts like a dam, holding the water in the lake. But over time, this moraine dam becomes weak. When it breaks, the lake water suddenly floods downstream. This is called a Glacial Lake Outburst Flood (GLOF).

GLOFs are a serious issue in the Himalayas. A large number of lakes have formed due to glacial retreat, and many moraine dams are at risk of breaking. One major GLOF event occurred in 2013 near the Chorabari Glacier, just north of the Kedarnath temple. During the extreme rainfall event

in June 2013, this glacial lake burst, causing massive damage to the Kedarnath temple and surrounding areas and killing thousands of pilgrims.







More recently, on October 7, 2023, another major GLOF event occurred in Sikkim. A dam on the Teesta River in Sikkim was completely damaged during this event. This is a major concern, not just because of the loss of life, but also because many dams built in the Himalayas are now under threat due to glacial lake outburst floods.

GLOF at Sikkim: The Teesta III dam was developed at the cost of Rs.14,000 crore was destroyed

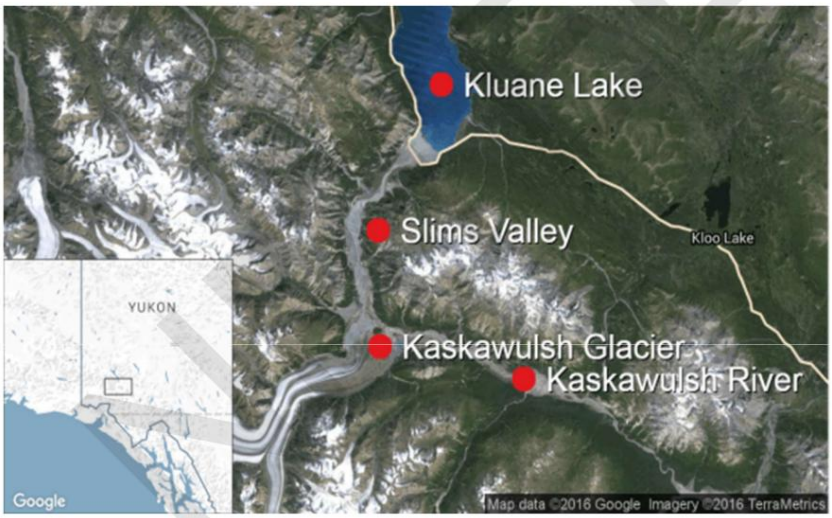
Now, climate change can also alter the course of rivers in these glacier-fed regions. This actually happened in Canada, in the Yukon area. Many people may not have heard about it because the region is sparsely populated and didn't suffer significant human loss. But it was a dramatic event: a glacier that was feeding two rivers—one flowing southward to the Pacific Ocean, the other northward to the Arctic Ocean—retreated. As a result, one of the rivers completely dried up within a couple of days because the glacier stopped supplying meltwater to it. The flow was redirected entirely into the other river.

Climate change causes glacial river in Yukon to change direction

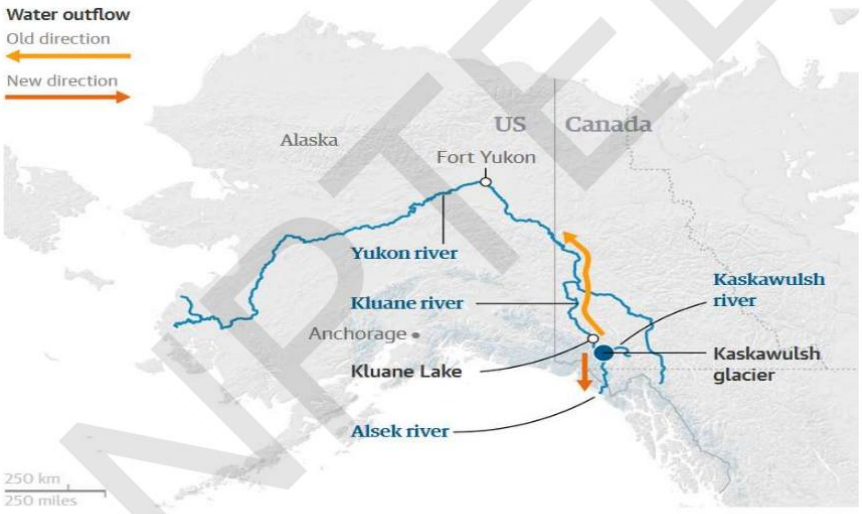
Glacier retreated so much that its meltwater switched course, in an event not documented in modern times

Because people don't live in that area, it didn't cause much damage. But imagine if something like this happened in India, where rivers are lifelines to millions. If a major river stops flowing due to glacier retreat, the consequences would be catastrophic.

Receding glacier causes immense Canadian river to vanish in four days Instead of flowing north 19 kilometres from the glacier's toe into Kluane Lake (and ultimately, the Bering Sea), that melt water is now draining eastward via the Kaskawulsh River towards the Pacific Ocean



Receding glacier causes immense Canadian river to vanish in four days



Guardian graphic | Source: Nature Geoscience

Ancient never-before-seen viruses discovered locked up in Tibetan glacier

Another hidden risk associated with glacial retreat is the release of ancient viruses. This is a new and emerging threat. One such event occurred in Kazakhstan, where 200,000 saiga antelopes died due to a virus infection, believed to be triggered by rising temperatures. This was documented by veterinarians from the Royal Veterinary College in London. As permafrost and glaciers melt, they can potentially release unknown microbes and viruses that have been dormant for centuries or even millennia.

More than 200,000 Saiga antelope died of a virulent infection in 3 weeks in May 2015 in Kazakhstan.

The threat posed by new bacteria and viruses cannot be taken lightly anymore. More than 200,000 Saiga antelope died of a virulent infection over a 3-week period in May 2015 in Kazakhstan.

Analysis by Richard Kock at the Royal Veterinary College in London identified a bacterium which caused extensive internal bleeding. This bacterium does not normally affect the antelope. They found that the attack by bacteria occurred when the daily temperatures and humidity levels were high. Hence there is a link between climate change and the virulence of a pathogen

Our ability to tackle climate change depends on three main factors: the hazard itself (e.g., floods, droughts, heatwaves, GLOFs), our vulnerability (e.g., where we live, how exposed we are), and our adaptive capacity (e.g., technology, policies, preparedness). When these three factors come together, the risk due to climate change becomes substantial.

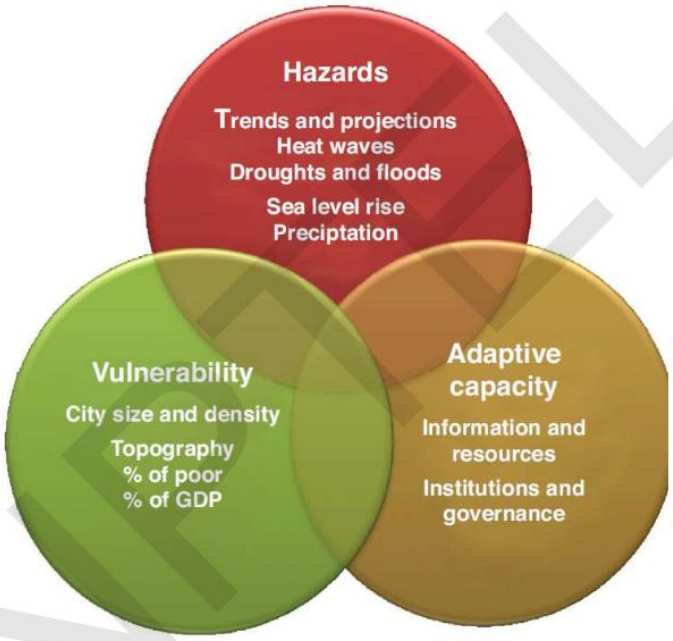


Figure 1: *Urban climate change vulnerability and risk assessment framework.*

Source: Mehrotra et al. (2009).

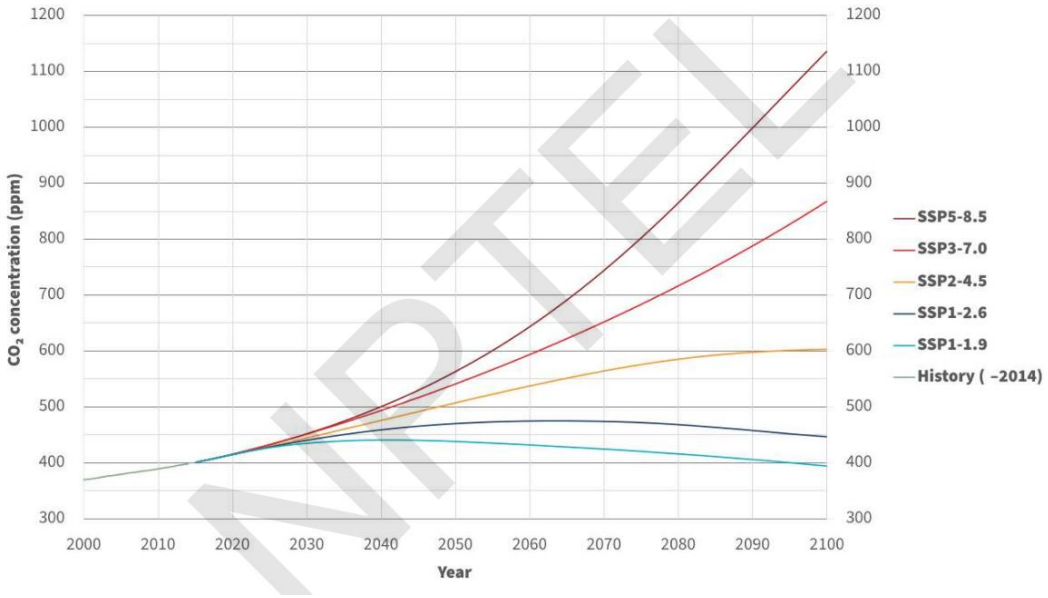


Figure. Shared Socioeconomic Pathways

With this, I will conclude my discussion on the impact of climate change. I will discuss the impact of climate change on the monsoon in my next lecture. Thank you.