Climate Change Science
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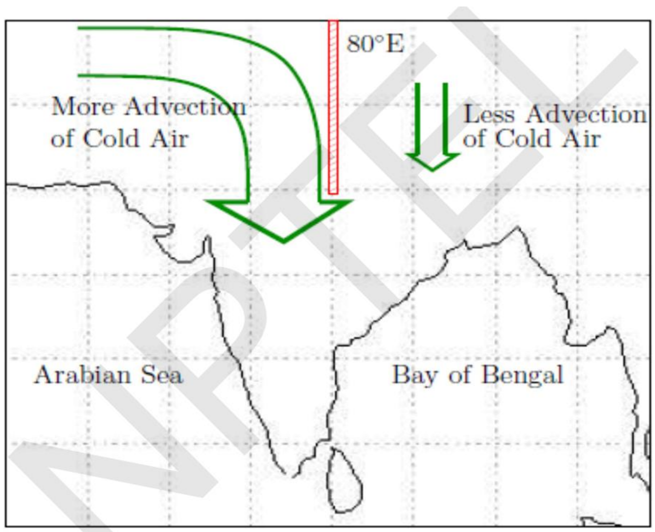
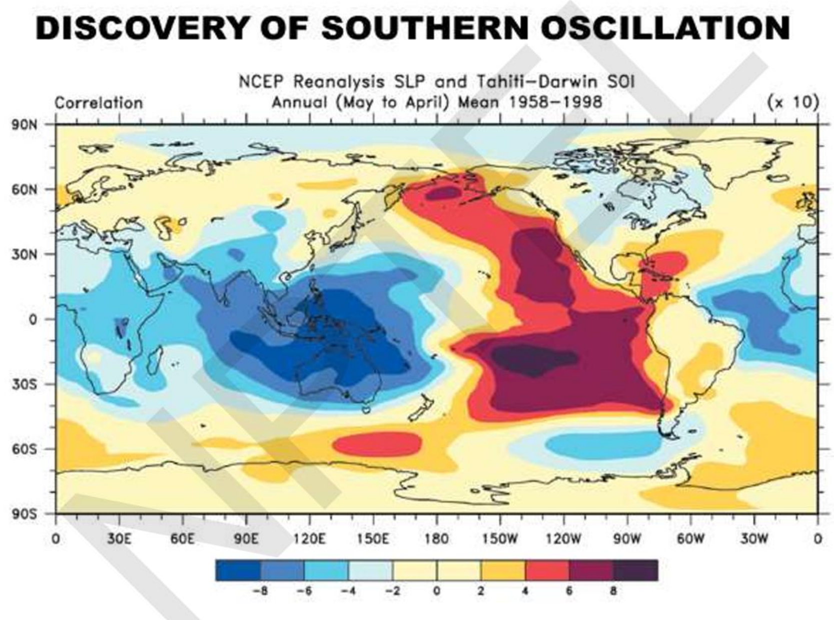
Lecture 56
Simulation of Monsoon

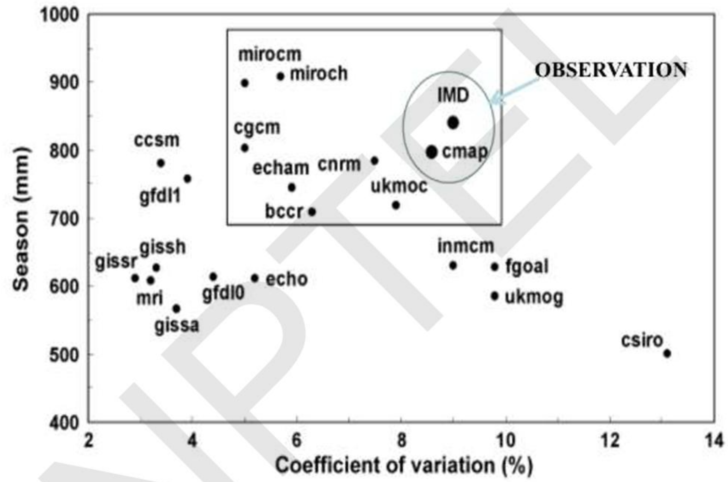


In the previous lecture, the discussion centered on the role of water vapor in the Indian monsoon system. A crucial factor influencing the monsoon is India's unique geography, particularly the presence of the towering Himalayan Mountain range in the north. These mountains, including the Tibetan Plateau and peaks like Mount Everest, act as a formidable barrier, preventing the incursion of cold, dry air from the mid-latitudes into the Indian subcontinent. This contrasts with regions like the Sahara, which lack such mountainous barriers; consequently, the African monsoon does not extend as far north, since cold, dry air from Europe can penetrate more easily. In India, not only do the eastern Himalayas play a protective role, but even the mountains to the west of 80°E longitude such as the Karakoram and ranges in Kashmir are important. Climate model experiments have shown that removing these western mountains weakens monsoon rainfall over India. Thus, the orographic features of the Indian subcontinent are vital in shielding it from cold air advection, allowing the monsoon to reach as far north as 25°N, compared to only about 15°N in the Sahara region.

In addition to the influence of local land-sea temperature contrasts, the Indian monsoon is significantly affected by remote oceanic influences from the Pacific, Atlantic, and Indian Oceans. One of the earliest and most well-known connections was discovered nearly a century ago by Sir Gilbert Walker, who identified a link between atmospheric pressure fluctuations in the Pacific Ocean and the Indian monsoon. This phenomenon, known as the Southern Oscillation, involves an oscillation of pressure between Tahiti (in the central Pacific) and Darwin (in northern Australia). These pressure variations are closely tied to ocean temperatures below. When the eastern Pacific is unusually warm, the associated rising air shifts towards that region, altering atmospheric circulation patterns. Conversely, when the eastern Pacific is cooler, rising air is more concentrated near Australia. This shifting of atmospheric convection between the eastern and western Pacific influences the monsoon's behaviour over India. Thus, the Pacific Ocean exerts a remote but powerful control over Indian monsoon variability through complex ocean-atmosphere interactions.



To understand the complex dynamics of the Indian monsoon and global climate systems, scientists use climate models that simulate the Earth's atmosphere and oceans. These models divide the Earth into a three-dimensional grid of small segments, over which the fundamental physical laws are applied. These include the conservation of energy, mass, and momentum (Newton’s laws), as well as radiation heat transfer. The models numerically integrate these equations over time to simulate the movement of winds, the transport of moisture, and the processes that lead to rainfall over regions like India. There are two main types of models: atmospheric models and coupled models. Atmospheric models focus solely on the atmosphere and require sea surface temperatures to be supplied as input. Coupled models, on the other hand, solve the equations for both the atmosphere and the ocean together, making them more complex but also more realistic for long-term climate simulations. Both types of models are essential tools in understanding the Indian monsoon and predicting its behavior.



Kripalani et al, Theor &App. Clim, 2007 43

When climate models attempt to predict the Indian monsoon rainfall, they often fall short of accurately simulating both the mean and its variability. Observations show that the average monsoon rainfall over India from June to September is around 880 mm, with a year-to-year variation of about 9 to 10 percent, referred to as the coefficient of variation. However, current models struggle to replicate this observed behavior. While some models simulate low average rainfall with low variability, others show low rainfall with high variability, none closely match the observed data. Despite significant improvements in model accuracy over the past 40 years, especially in simulating various aspects of the climate system, reproducing the mean and interannual variability of Indian monsoon rainfall remains a persistent and complex challenge.

Preethi et al. , Climate Dynamics,2010

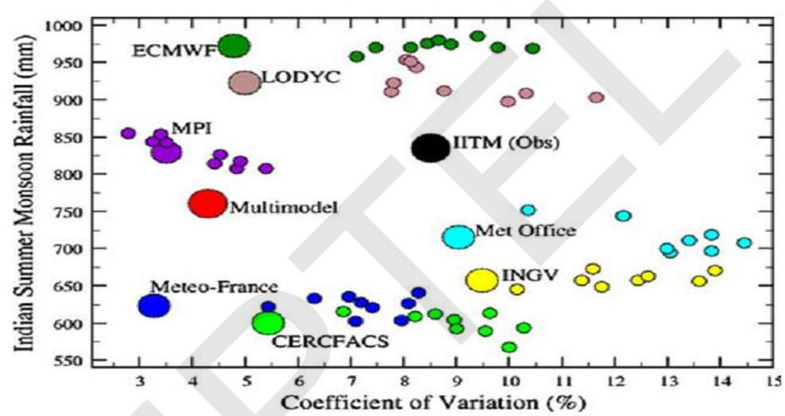
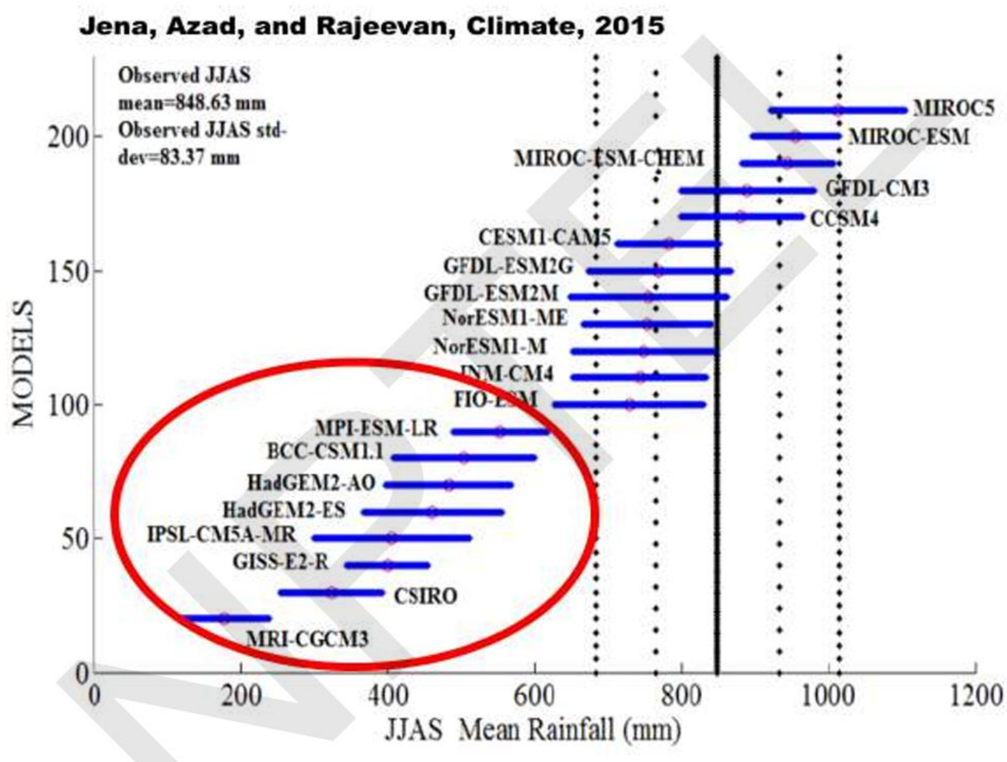


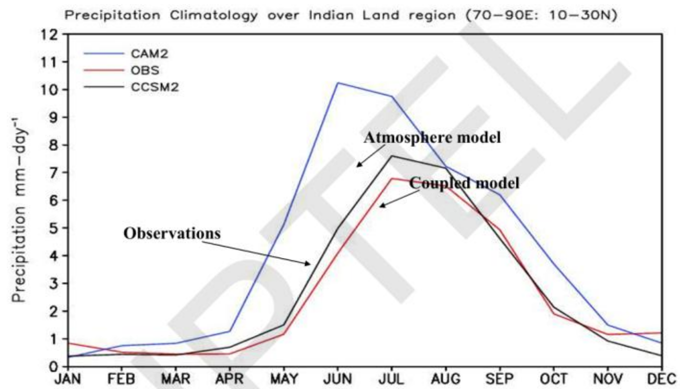
Fig. 3 Scatter plot of ISMR (mm) and CV (%) from observation (IITM Rainfall) and DEMETER model simulations, based on the data from 1980 to 2001. Observation is denoted by *black color*. The 7 different models are represented in *different colors* and the MME in *red color*. For each model, *smaller circle* denotes ensemble members and the ensemble mean is denoted by *bigger circle*

More recent model simulations continue to show that accurately capturing the Indian monsoon remains a significant challenge. When comparing model outputs with observed rainfall, particularly in terms of both the mean and year-to-year variability, no model aligns well with the observations. In these comparisons, the observed mean rainfall and its variability serve as a reference point. Each small dot represents an individual simulation from a climate model, while the larger dot indicates the ensemble mean, the average of all these simulations. Despite advancements in model resolution and physics, neither the ensemble mean nor any individual simulation successfully reproduces the observed rainfall characteristics over India. This persistent discrepancy highlights the complexities involved in simulating the Indian monsoon, particularly due to its sensitivity to a range of interacting processes such as land-sea contrasts, topography, and remote oceanic influences. Improving model performance in this region remains an active area of research in climate science.



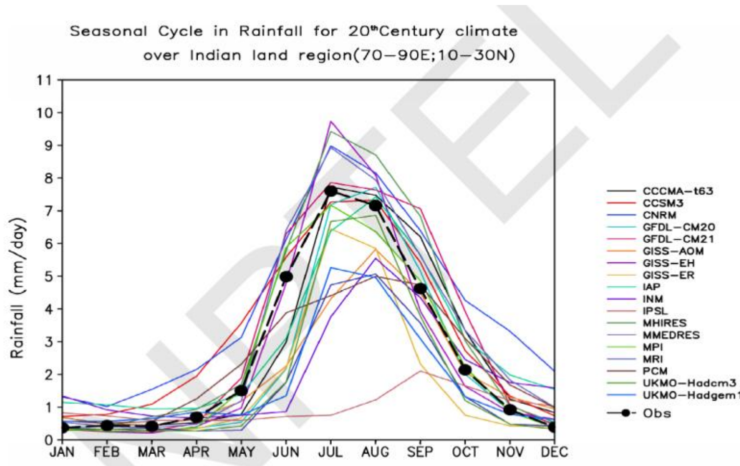
To highlight the discrepancies more clearly, a plot was created showing various climate models along one axis and their corresponding simulated mean rainfall on the other. The observed mean rainfall during the Indian monsoon season is approximately 880 mm. However, the comparison reveals that most models underestimate this value, resulting in simulations that are too dry. A few models overestimate it, producing rainfall amounts that are too wet. Importantly, none of the models come close to simulating the observed mean rainfall of around 850–880 mm. This clearly illustrates the ongoing difficulty climate models face in accurately capturing the magnitude of Indian monsoon rainfall.

A comparison of seasonal rainfall cycles from two models - CAM2, an atmospheric model, and CCSM2, a coupled model - against observations showed that while CAM2 produced excessive rainfall, CCSM2 appeared to match observations more closely.

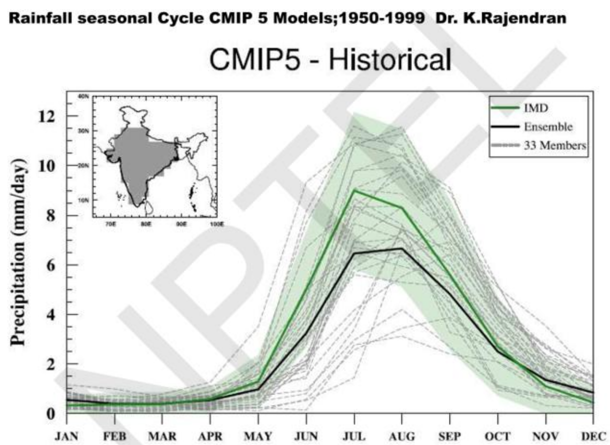


Coupled Model simulation more realistic than AGCM simulation (with observed SST) why?

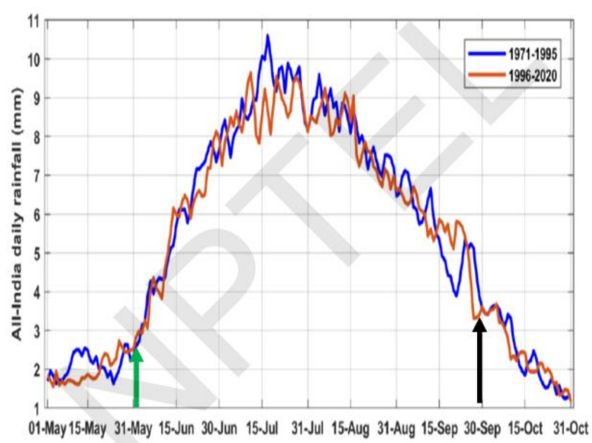
Initially, this result seemed promising. However, further analysis revealed that the agreement in CCSM2 was due to a compensating error: while the atmospheric component (particularly cloud processes) caused excessive rainfall in CAM2, the sea surface temperatures in CCSM2 were too low. These two opposing errors offset each other, resulting in seemingly accurate rainfall in the coupled model. This serves as a cautionary example that models can produce correct results for the wrong reasons. Hence, it is essential to examine both the atmospheric and oceanic components of models individually to ensure that the simulated processes are physically realistic. This example illustrates the importance of critically evaluating model performance beyond just surface-level agreement with observations.



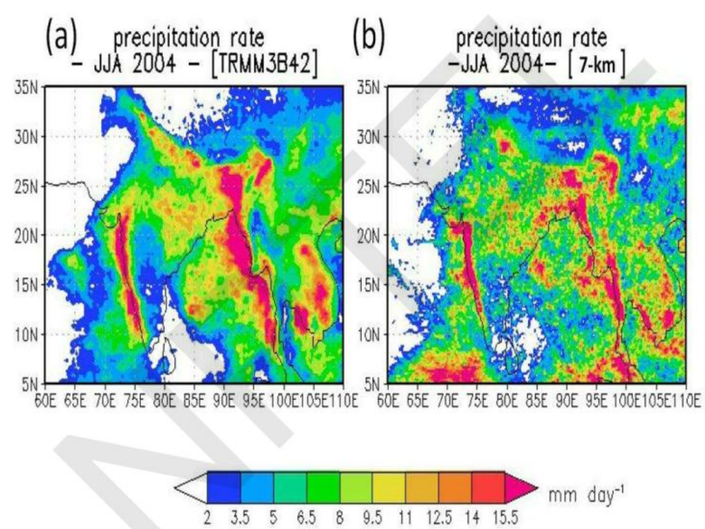
The above figure shows another example showcasing how different climate models simulate the seasonal cycle of rainfall over India. In these comparisons, the black line represents observed rainfall, while the colored lines correspond to various models. It becomes evident that very few models accurately capture the observed seasonal cycle. Most models significantly underestimate the rainfall, producing results that are too dry, while a few overestimate it, making the simulations excessively wet. More importantly, almost none of the models are able to reproduce the correct shape or timing of the seasonal cycle, which is critical for understanding and predicting the monsoon. This persistent mismatch between model simulations and observations highlights an unresolved challenge in climate modeling, particularly with respect to simulating the Indian monsoon's timing, intensity, and variability.



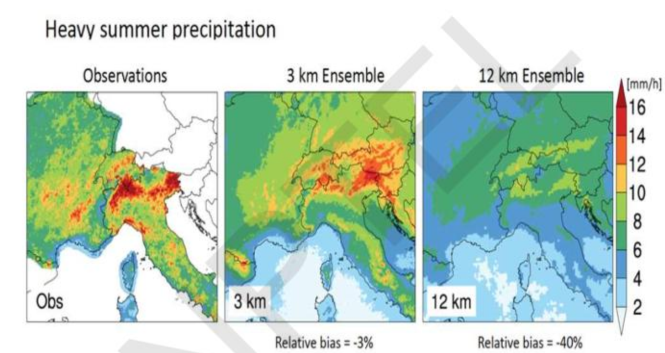
The above figure shows the seasonal cycle of rainfall over India from CMIP5. Here too, we find some models which are too dry, while some are too wet. Very few models get the correct seasonal cycle.



Many people claim that climate change has altered the seasonal cycle of the Indian monsoon. However, this is not supported by data at the all-India level. When comparing 50 years of monsoon rainfall data, specifically the first 25 years (1971–1995) with the most recent 25 years (1996–2020), the overall seasonal cycle remains largely unchanged. Although there may be slight variations on a few days, the general pattern and timing of rainfall have remained consistent. While localized changes might have occurred in specific regions such as the Northeast, Western Ghats, or Rajasthan, these do not reflect a shift in the broader all-India monsoon pattern.

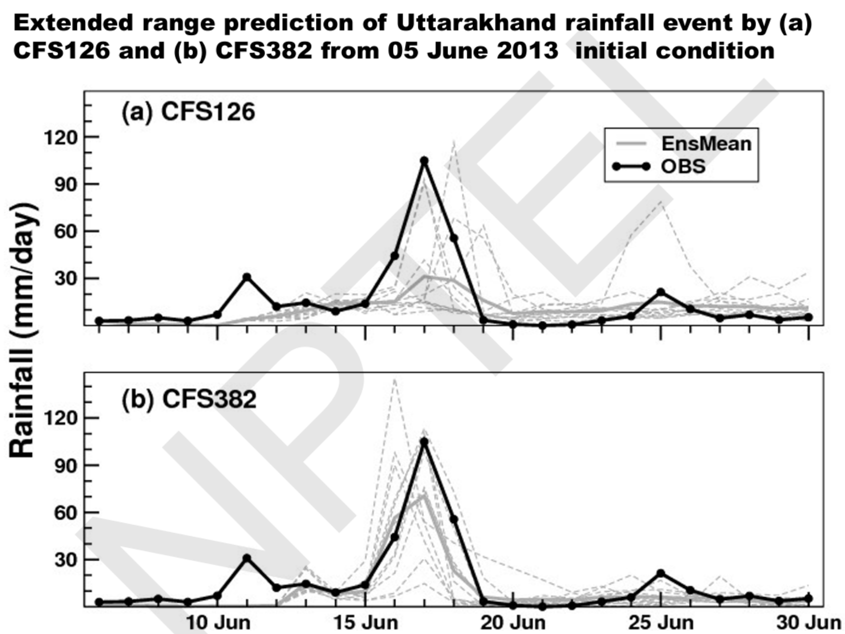


While climate models still face challenges, there is promising progress as well. A notable example comes from a high-resolution Japanese climate model with a spatial resolution of 7 kilometers, which was able to simulate the spatial pattern of rainfall quite accurately when compared with observations from the TRMM (Tropical Rainfall Measurement Mission) satellite, which uses radar to measure rainfall. In contrast, most of the models used in IPCC assessments currently operate at a coarser resolution of about 50 by 50 kilometers. The Japanese model's superior performance is possible because it is run only for short periods, typically a few months. Running such a high-resolution model for longer periods, for like a century, requires computational resources that are not yet widely available. However, with expected advancements in computational power over the next decade, it will become feasible to run global climate models at much higher resolutions. This will lead to significant improvements in the accuracy of rainfall simulations, particularly over complex regions like the Indian monsoon zone.



Heavy summer precipitation represented by 3km and 12km models for the Alpine region. Credit: Nikolina Ban.

To emphasize the critical role of model resolution in accurately predicting heavy rainfall events, a comparative study was conducted over the Alpine region in Europe. This analysis involved simulations from two climate models, one with a resolution of 12 km × 12 km and another with a finer resolution of 3 km × 3 km, alongside observational data. The results clearly demonstrated that the 3 km model significantly outperformed the 12 km model in capturing the short-term rainfall intensity and spatial distribution. Specifically, the 3 km resolution was essential to accurately simulate high-intensity rainfall events, such as those exceeding 16 mm per hour. This finding underscores the necessity of running high-resolution models to realistically capture extreme weather phenomena. Although current computational limitations restrict our ability to run such fine-scale models over long time periods or large domains, rapid advancements in computing technology are expected to make this feasible in the coming years. As a result, the accuracy of climate predictions, especially for extreme rainfall events, will greatly improve with the adoption of finer model resolutions.



A striking example that highlights the importance of high-resolution models is the extreme rainfall event that occurred in Uttarakhand in June 2013, which caused devastating floods and massive loss of life, particularly in Kedarnath where many pilgrims had gathered. In a model simulation of this event, the observed rainfall is shown in black, while the ensemble mean output from a coarse-resolution model (with approximately 50 km horizontal resolution) is shown in grey. The low-resolution model significantly underestimates the rainfall, capturing only about 30 mm per day, whereas actual observations indicate rainfall closer to 120 mm per day. However, when the same model is run at a higher resolution, about three times finer, it is able to simulate much higher rainfall amounts, though still slightly below the observed peak. This clearly demonstrates that capturing the complex mountainous terrain of Uttarakhand, which strongly influences localized rainfall, requires much higher spatial resolution in climate models. As computational capacity increases in the coming years, enabling widespread use of high-resolution simulations, the accuracy of forecasts for such extreme events is expected to improve substantially.

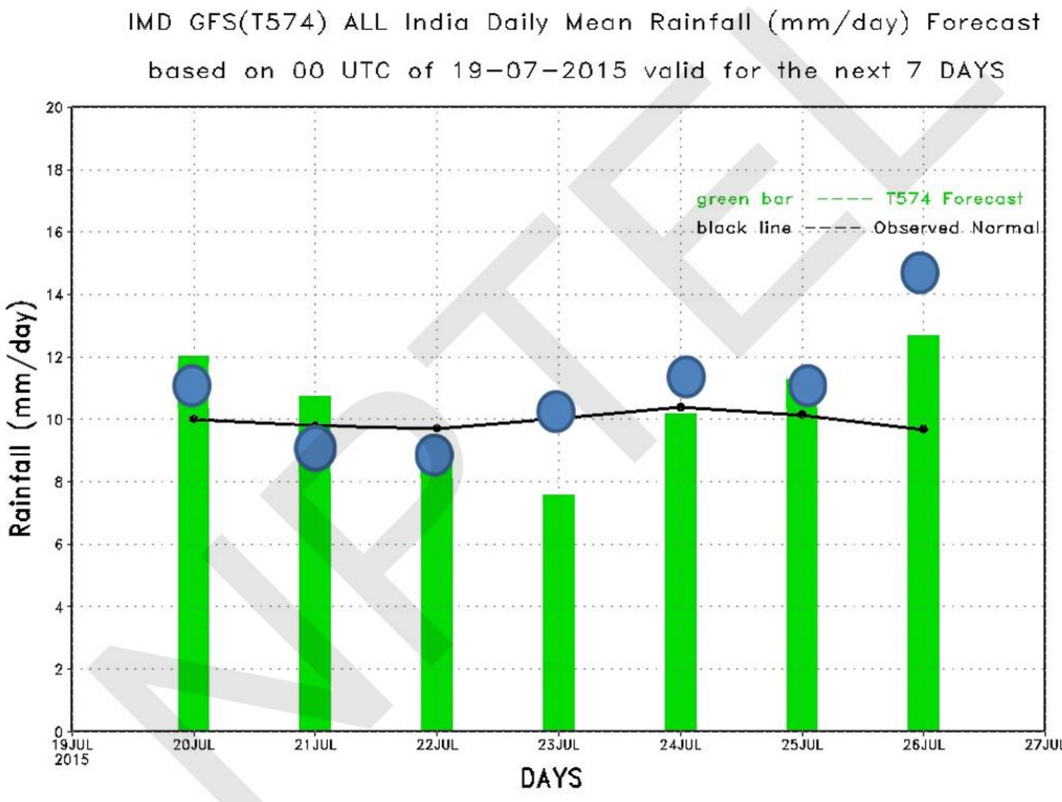
An important limitation in predicting future regional climate, especially over the medium term, stems from the uncertainty in initial conditions - a point emphasized by Hawkins et al., in their paper published in *Climate Dynamics* in 2015. Despite the availability of satellite data and ground-based observations, the initial state of the climate system cannot be perfectly captured, leading to an inherent, irreducible uncertainty. This uncertainty significantly affects predictions of regional climate changes, especially over decadal time scales. As a result, attempts to forecast rainfall or other regional climate variables for the next 10 to 20 years are often unreliable, since the signal of long-term climate change is typically masked by the noise of internal climate variability. Thus, any confident claims of regional rainfall trends over such time horizons are scientifically unfounded. This issue is exemplified in the simulation of the 2013 Kedarnath extreme rainfall event, where an atmospheric model (GFS) coupled with an ocean model (MOM version 4) was employed. The model incorporated atmospheric and oceanic initial conditions and showed promising results for short-term forecasts: 3-day forecasts were reasonably accurate and trustworthy, 7-day forecasts showed moderate reliability, and 15-day forecasts were improving but still faced challenges, particularly in capturing intense rainfall events. Forecasts beyond 30 days remain highly uncertain. However, there is optimism that as model resolution increases and computing power advances, these limitations will gradually be mitigated.

One of the key reasons for the dramatic improvement in climate and weather models over the past two decades is the advancement of data assimilation techniques. Data assimilation refers to the process of integrating observational data with model forecasts to estimate the most accurate current state of the atmosphere. This approach addresses the fundamental challenge that while we have many observations, they are not available everywhere, especially over oceans and remote regions.

To overcome this, models incorporate available satellite and ground-based observations, and in regions with sparse data, model outputs are used as proxies. The combination of these diverse sources produces a far more accurate and dynamically consistent initial condition for the model.

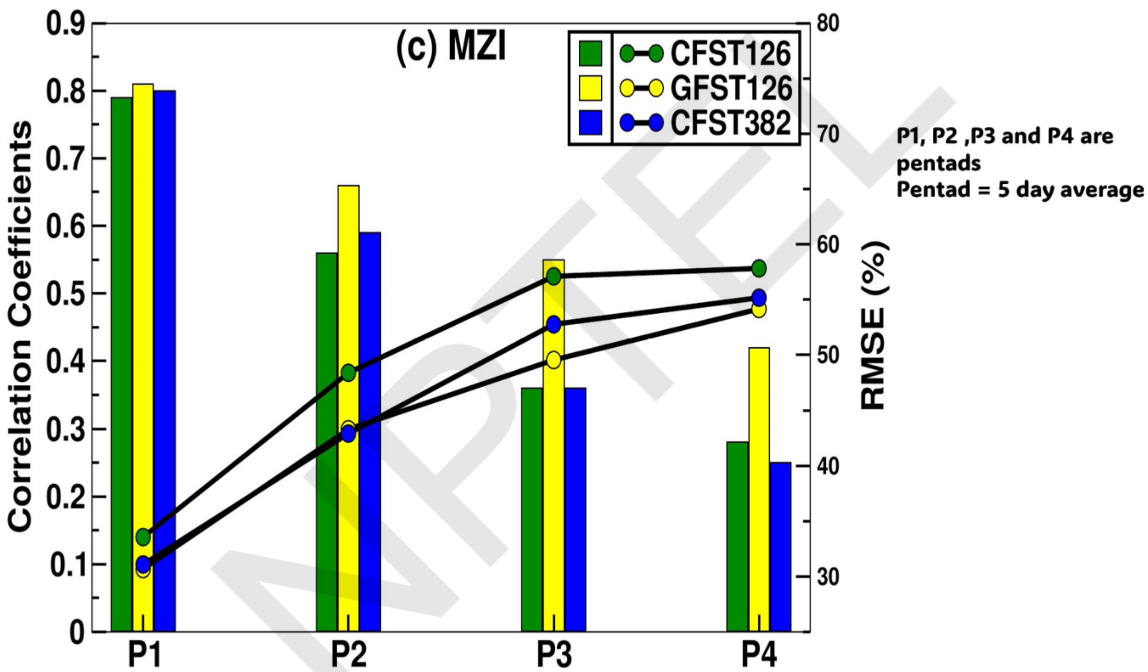
Today's operational forecast systems assimilate an enormous volume of data, often ranging from 30 to 50 million individual pieces of information per update cycle. These include satellite radiances, radar reflectivity, radiosonde measurements, surface observations, and aircraft reports, among others. The exponential growth in satellite-based observations, in particular, has significantly enhanced the quality of initial conditions, leading to major improvements in short- and medium-range forecasts.

This growing capacity for high-resolution, data-rich initialization is one of the most powerful enablers of model accuracy today and will continue to drive progress as observational networks and assimilation algorithms become even more sophisticated.

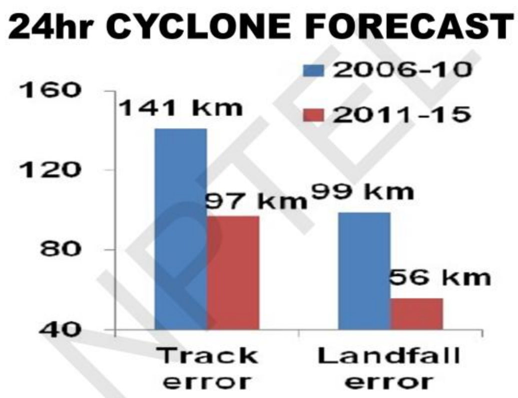


The above figure is an example illustrating the performance of a modern weather prediction model in forecasting all-India monsoon rainfall. The model, as mentioned earlier, provides forecasts up to seven days in advance. In this case, the forecasted rainfall is shown in green, while the observed rainfall is represented in blue. The comparison reveals that the model performs quite well for short-term forecasts. Up to three days, the forecast closely matches the observed rainfall, indicating high reliability in near-term predictions. From day four onwards, a slight discrepancy begins to emerge where the model underpredicts rainfall compared to observations on day four. However, despite such deviations, the overall forecast skill remains reasonably strong even up to seven days. This demonstrates the growing competence of models in capturing the general trends of monsoon rainfall over India on a weekly timescale, owing to improvements in model physics, resolution, and data assimilation techniques.

The correlation between forecasted and observed monsoon rainfall provides a clear picture of how forecast skill declines with lead time. In the example shown in the below figure, forecasts are evaluated in terms of pentads (five-day averages) with increasing pentad numbers indicating longer forecast horizons. For Pentad 1 (the first five days), the correlation between model predictions and observations is quite high, around 0.8, indicating strong forecast skill. In Pentad 2 (days 6–10), the correlation drops to about 0.6, showing a moderate decrease in accuracy. By Pentad 3 (days 11–15), the correlation further reduces to around 0.4, and in Pentad 4 (days 16–20), it drops to roughly 0.3, suggesting limited predictive ability at this range. This pattern holds across different models—whether coupled or purely atmospheric. The takeaway is that current models perform reliably for short-term forecasts (up to a week), are moderately accurate for medium-range forecasts (up to two weeks), but become less dependable beyond that. However, with improvements in model resolution and computational capacity, forecast skill is expected to improve significantly, even for longer lead times.



Weather forecast models have significantly advanced in cyclone prediction, especially in terms of track forecasting. The primary goal in cyclone forecasting is to accurately predict where the cyclone will make landfall. Fifteen years ago, the average error in predicting the cyclone track was approximately 140 kilometers. Today, that error has reduced to less than 100 kilometers, and in some cases, as low as 56 kilometers. This remarkable improvement allows authorities to more precisely identify the likely landfall location and efficiently evacuate only those in immediate danger, rather than relocating large populations unnecessarily. Being able to forecast the cyclone track within a 50-kilometer margin greatly enhances disaster preparedness and minimizes disruption. This progress stands out as one of the major achievements of modern weather prediction systems.



IMD PREDICTIONS 2021

	FORECAST		ACTUAL
ALL INDIA JJAS	96% TO 104%	✓	98%
JUNE	92 % to 108%	X	110%
JULY	94% to 106%	X	93%
AUGUST	94 to 105%	X	76%
AUGUST +SEPTEMBER	95 to 105 %	✓	100%
NW INDIA	92% TO 108%	✓	96%
NE INDIA	below 95%	✓	87%
CENTRAL INDIA	greater than 106%	X	101%
SOUTH INDIA	93% TO 107%	X	110%

The above example highlights the strengths and limitations of current seasonal forecasting by the India Meteorological Department (IMD). For the all-India average monsoon rainfall over June to September, the seasonal forecast was quite accurate. The predicted range was between 96% to 104% of the long-term average, and the actual value was 98%, indicating a strong seasonal mean forecast. However, the performance for individual months was less reliable. The forecast for June was incorrect, July was slightly off, and August was notably poor, though September was well predicted. At the regional scale, forecasts were good for Northwest and Northeast India, but less accurate for Central and Southern India. These discrepancies highlight the challenges in monthly and regional predictions. Nevertheless, significant improvements are expected over the next decade as forecasting models transition to higher resolutions, which will help capture finer-scale processes more accurately.

A major limitation of current climate and weather models is their inability to accurately represent the wide variety of cloud types present during the monsoon season. These include deep convective clouds, shallow cumulus, mid-level clouds, and high-altitude ice clouds. Each of these plays a significant role in monsoon dynamics and rainfall distribution, but due to coarse model resolution and simplified cloud parameterizations, they are poorly simulated. This inadequacy affects the accuracy of monsoon forecasts. However, as computational capabilities improve and models begin to operate at higher resolutions, the representation of these cloud processes is expected to become more realistic.

Additionally, aerosols present another complex challenge in modeling the monsoon. Aerosols affect the monsoon system primarily by modifying the Earth's radiative balance. Most aerosols scatter incoming solar radiation, leading to surface cooling, which tends to suppress monsoon rainfall. However, the type of aerosol is critical. Reflective aerosols like sulphates and sea salt primarily cool the surface and atmosphere, reducing the availability of water vapor and stabilizing the atmosphere, which weakens convection and leads to less rainfall. In contrast, absorbing aerosols such as black carbon (soot) and dust heat the atmosphere by absorbing sunlight, potentially destabilizing it in certain layers and altering monsoon circulation patterns. This distinction means that the net effect of aerosols on monsoon rainfall is region-specific and depends on the composition of the aerosol mix. Currently, many polluted regions, especially those with high sulphate concentrations, are experiencing reduced rainfall due to these cooling and stabilizing effects.

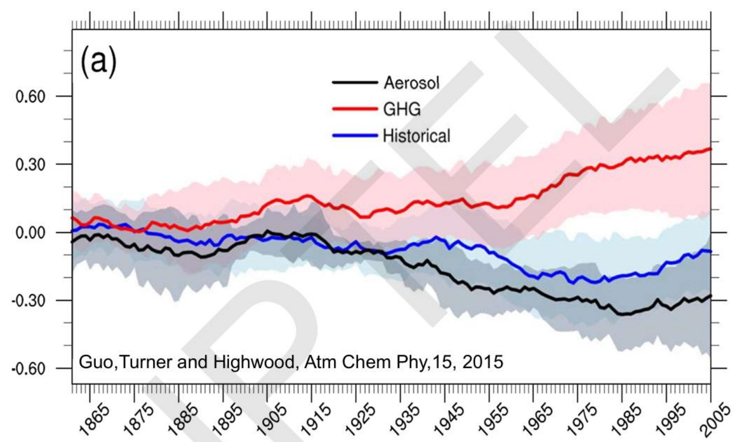


Figure 1. (a) JJAS rainfall from 1861–2005 averaged over South Asia (10–35° N, 70–90° E) in the CMIP5 all-forcings historical experiment (blue), GHG-only historical experiment (red) and the aerosol-only historical experiment (black). The thick

This interaction between greenhouse gases and aerosols on monsoon rainfall can be effectively illustrated through long-term climate model simulations. Over the past 140 years, models show that the presence of greenhouse gases alone tends to slightly enhance monsoon rainfall due to global warming and increased atmospheric moisture. However, when only aerosols are considered, particularly sulphate aerosols that cool the surface and stabilize the atmosphere, models indicate a decline in monsoon rainfall. When both greenhouse gases and aerosols are included in the simulations, the overall trend shows a modest decrease in rainfall, revealing that the aerosol-induced suppression has so far outweighed the greenhouse-induced intensification.

This suggests that the observed weakening of the Indian monsoon in recent decades is largely attributable to aerosol emissions, which have a stronger short-term regional cooling effect than the warming influence of greenhouse gases. However, looking ahead, as greenhouse gas concentrations continue to rise and aerosol emissions are potentially reduced due to air quality regulations, the warming influence is expected to become more dominant. This shift implies a likely future intensification of the monsoon, driven primarily by the strengthening greenhouse effect.

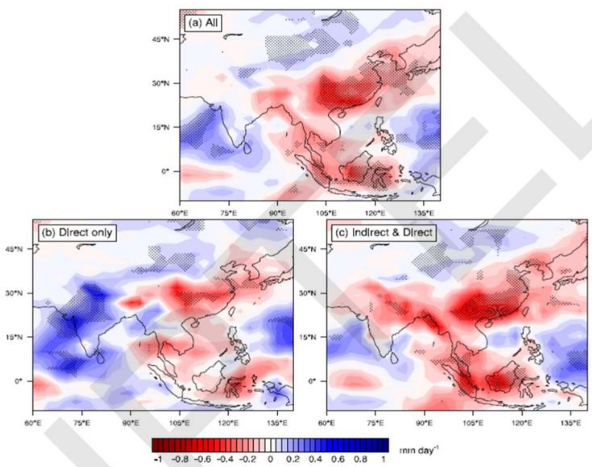


Figure 3. Changes of JJAS rainfall between present-day and pre-industrial periods (1986–2005 minus 1861–1880) in MME-means of the CMIP5 all-forcings historical experiment: **(a)** all 24 CMIP5

Guo et al., Atm Chem and Physics 2015

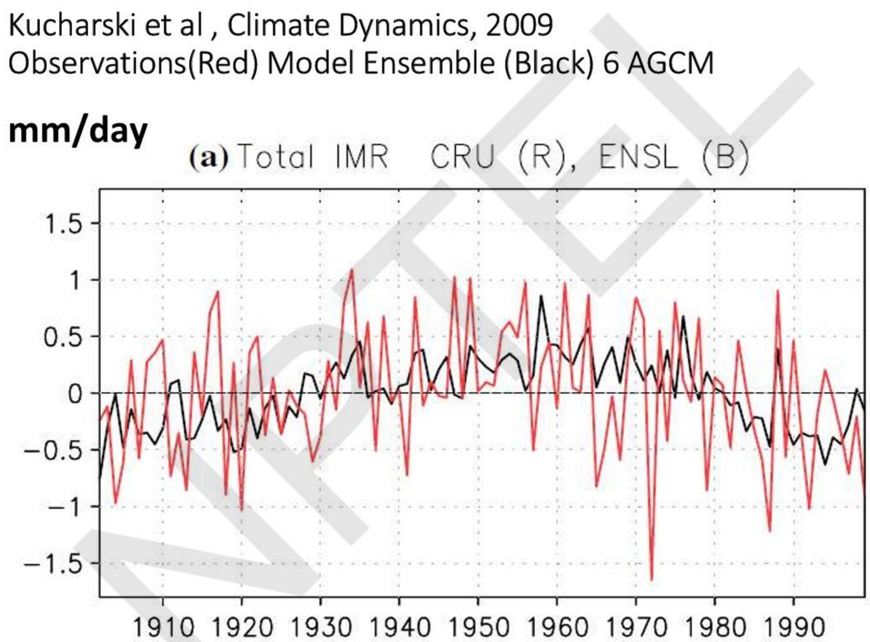
The above study reinforces the significant role of aerosols in modulating Indian monsoon rainfall, especially highlighting the distinction between their direct and indirect effects.

The total aerosol effect, shown in panel (a), results in an overall reduction in rainfall over India. When considering only the direct effect, that is, the scattering and absorption of solar radiation by aerosols, the models surprisingly show a slight increase in rainfall over India. This occurs because absorbing aerosols like black carbon can heat the lower atmosphere and potentially enhance convection in some regions.

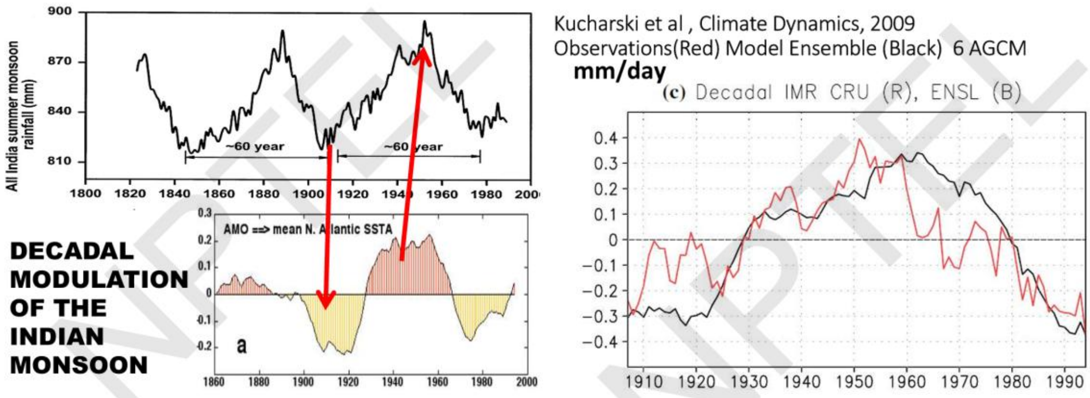
However, when both direct and indirect effects are included, particularly the indirect effects involving aerosol interactions with clouds (such as changes in cloud droplet number, size, and lifetime), the outcome is reversed: the Indian subcontinent experiences reduced rainfall or drought conditions. The indirect effects tend to stabilize the atmosphere and suppress convective activity by making clouds more reflective and longer-lasting, but less likely to precipitate.

Thus, this study underscores that the dominant mechanism causing recent declines in Indian monsoon rainfall is the indirect aerosol effect on clouds, not merely their radiative impact.

Importantly, if stringent air pollution control policies are enacted in India, reducing sulphate and other anthropogenic aerosol emissions, this would mitigate the cooling and stabilizing effects of aerosols. As a result, rainfall is likely to increase, especially as greenhouse gas-induced warming continues to intensify the hydrological cycle.



So far, the discussion has explored the variability of monsoon rainfall on daily, weekly, and annual timescales. We now turn attention to decadal variations. A set of forecasts generated by six atmospheric models, which use prescribed ocean temperatures rather than interactively simulating ocean dynamics, reveals some key insights. When comparing the ensemble mean of the models (black line) with observed rainfall data from the Climate Research Unit (CRU) in East Anglia (red line), it becomes evident that the models struggle to accurately capture year-to-year (interannual) variability. This suggests that current atmospheric-only models are limited in their ability to predict annual fluctuations in monsoon rainfall, and further improvement is needed.



However, when the same model outputs are averaged over 10 to 20 years, they succeed in reproducing observed decadal patterns. This is because monsoon rainfall exhibits strong decadal variability, largely driven by long-term changes in the Atlantic and Pacific Oceans. By smoothing out short-term fluctuations, the models more effectively capture broader climatic trends.

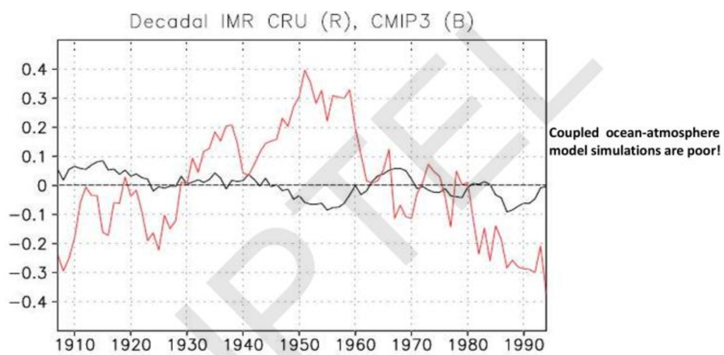
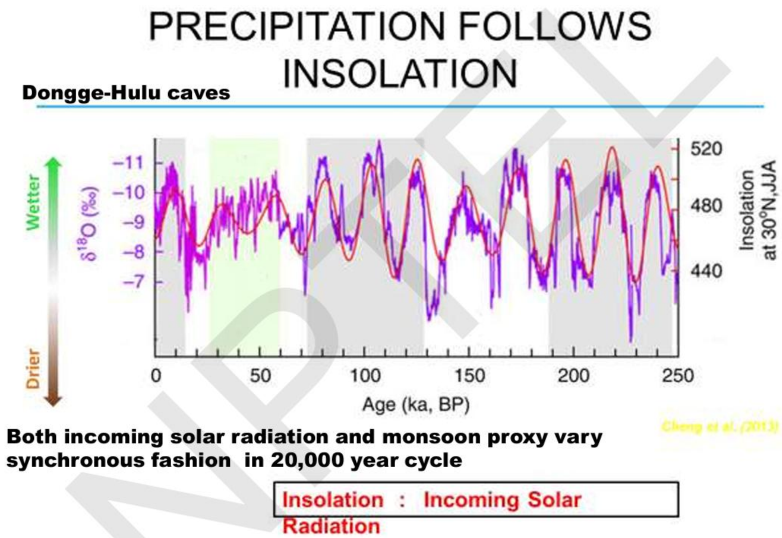


Fig. 5 Time series of 11-year running mean IMR anomalies of CRU data (*red*) and the ensemble mean of a selection of CMIP3 models (*black*). The units are mm/day

In contrast, when coupled models are used, the performance deteriorates. The black line representing coupled model simulations deviates significantly from the observed CRU data in red. This is attributed to persistent issues in coupled models, particularly a cold sea surface temperature bias, which affects their ability to accurately simulate both inter-annual and decadal monsoon variability. Thus, while atmospheric-only models show some skill in capturing long-term changes when averaged, coupled models still require substantial improvement to effectively represent monsoon dynamics.

To understand the long-term behaviour of the Indian monsoon, it is essential to go beyond the instrumental rainfall records of the last 150 years. These records, derived from rain gauge measurements, are relatively short in the context of climate variability and are insufficient to capture the full range of natural influences on monsoon dynamics, particularly those driven by changes in the Pacific, Atlantic, and Indian Oceans over longer timescales. For this reason, scientists turn to paleoclimate proxies, such as speleothems, which are mineral deposits found in caves (e.g., stalagmites and stalactites).

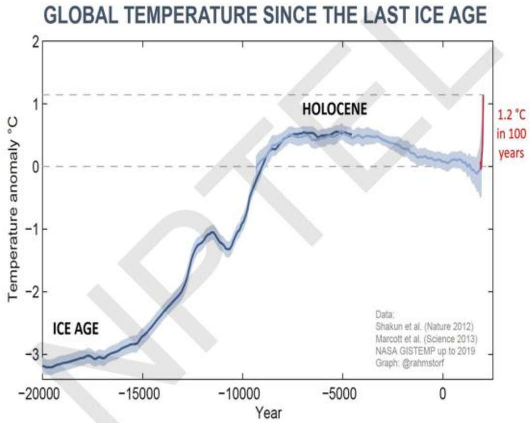
These formations grow layer by layer and preserve isotopic signatures that are indicative of past rainfall patterns.

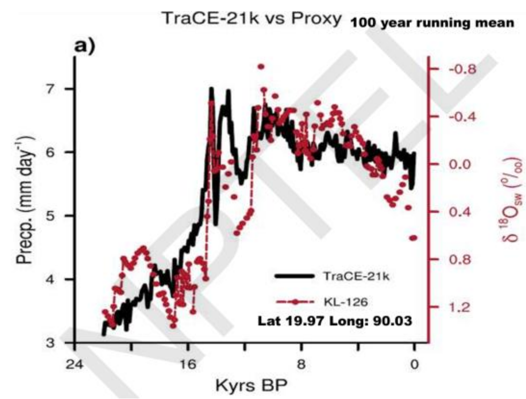


Using speleothem records, researchers have reconstructed monsoon variability over the past 20,000 years. One well-studied dataset comes from the Dongge - Hulu caves in China, where speleothem data has been compared with variations in incoming solar radiation (insolation) at 30°N latitude. Over these long timescales, there is a strong correspondence between solar insolation and monsoon intensity, suggesting that, on orbital (20,000-year) timescales, solar radiation is the primary driver of monsoon variability.

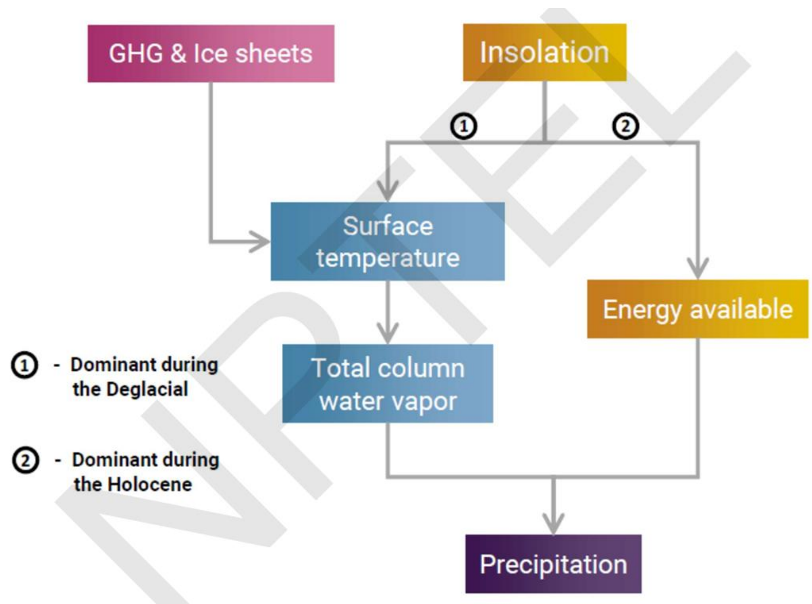
However, as we move to shorter timescales, ranging from centuries (100–1,000 years) to decades, monsoon dynamics become increasingly complex. At the centennial scale, both solar insolation and atmospheric water vapor become influential. At the decadal scale, additional factors such as vertical profile of water vapour, cloud processes, and ocean-atmosphere interactions start playing a significant role. Thus, as the temporal resolution becomes finer, more variables interact, making the system more intricate and challenging to model. This highlights the importance of incorporating paleoclimate data into model training to improve simulations across all relevant timescales.

Over the past 20,000 years, climate models like the TraCE simulation have done a fairly good job of reproducing large-scale changes in global temperature and monsoon rainfall. During the Last Glacial Maximum (LGM), temperatures were lower, and monsoon rainfall was about 4 mm/day. As the Earth warmed, rainfall increased. This trend is seen in both model simulations (black line) and proxy data from things like cave deposits and ice cores (red line), though they don't match perfectly due to uncertainties in proxy data.

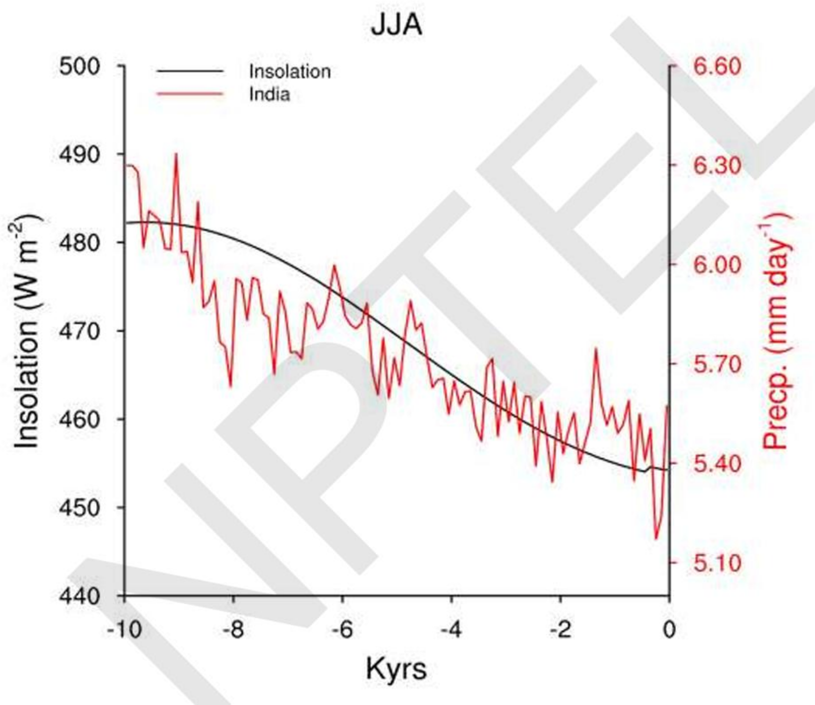




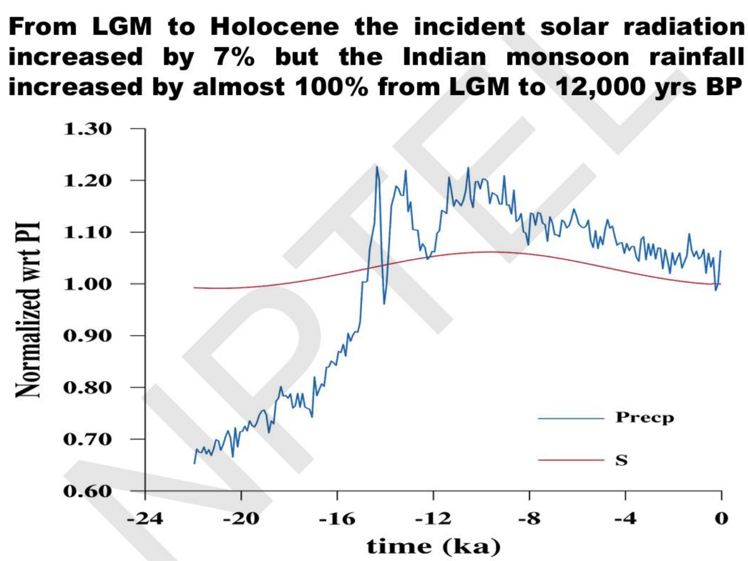
The models are better at capturing long-term trends, averaged over 100 years or more, rather than year-to-year variations. A simple model helps explain this by using a water balance approach: precipitation minus evaporation equals the net energy input and is influenced by water vapour levels. This relationship shows how greenhouse gases, by increasing water vapour and altering energy balance, affect long-term rainfall patterns.



Now it is well understood how greenhouse gases influence water vapor and rainfall. Greenhouse gases warm the atmosphere, which increases its capacity to hold water vapor, a key driver of the hydrological cycle. However, the exact impact on rainfall patterns depends on various factors like atmospheric stability, cloud dynamics, and regional climate conditions. To understand how these factors affected the monsoon in the past, scientists have used a combination of proxy data such as speleothems and ice cores and observational records. This integrated approach has allowed researchers to reconstruct historical monsoon behavior and better understand the long-term influence of greenhouse gases on rainfall.



An example of rainfall simulation over the last 10,000 years shows a clear decreasing trend in rainfall, which aligns with a similar decline in incoming solar radiation. This indicates that the reduction in solar radiation over time has had a direct impact on weakening the monsoon. The close correspondence between the two trends supports the idea that incoming radiation is a key driver of long-term changes in rainfall patterns.



This model clearly shows that while the variation in solar radiation over the last 10,000 years is small, it still influences rainfall. The decline in rainfall during the last 8000-year period corresponds to the slight decrease in sunlight. However, to accurately match observations, especially in period between 22,000-14,000 years ago, we need to include more than just incoming radiation. The model must also account for factors like water vapor and vertical moisture transport. Only when all these components are included does the model successfully reproduce the observed rainfall trends.

To conclude, current weather models provide reliable rainfall forecasts up to three days in advance. Seasonal forecasts (like for the monsoon season) are gradually improving but remain a challenge, especially at the monthly and regional scales. Forecasting rainfall a year ahead is still extremely difficult.

On longer timescales, decadal variability is better captured by atmospheric models (with prescribed ocean temperatures), whereas coupled models (with interactive oceans) struggle due to issues like cold biases. We've also understood that water vapor and incoming solar radiation are key drivers of monsoon variability across time.

Looking ahead, most models project an increase in monsoon rainfall during the 21st century, primarily due to rising greenhouse gases and water vapor. However, aerosols, especially reflective ones like sulphates, may offset this increase and even contribute to more frequent droughts.

Finally, a critical but uncertain factor is the potential weakening of the Atlantic Meridional Overturning Circulation (AMOC), which could lead to a sharp decline in Indian monsoon rainfall, a topic that will be discussed in the final lecture.