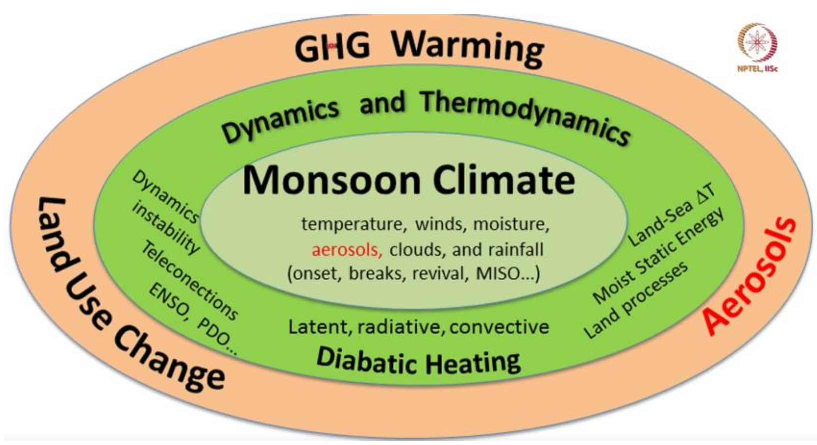
Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bangalore

Lecture – 55
Monsoons

In today's lecture, we are going to talk about the impact of climate change on monsoons. All of you realize that this is a very important issue because India is a country with 1.4 billion people, and our agriculture depends on the monsoon rainfall from June to September primarily. Already in the last 75 years, our population has gone up more than four times. So, the per capita availability of water has already gone down by a factor of four. So, on account of climate change, if the monsoon rainfall decreases, then we as a country will be in serious trouble.

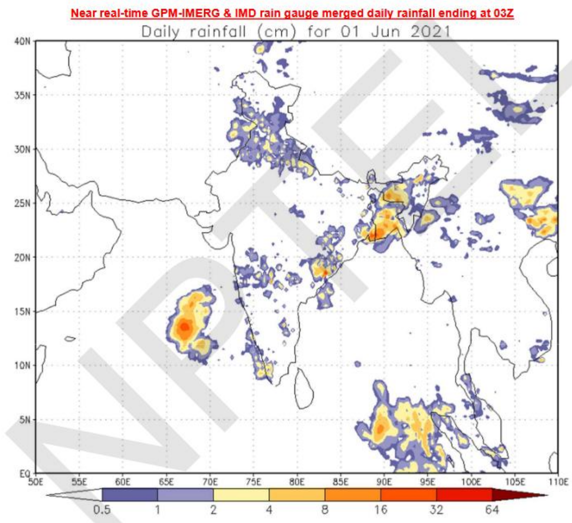
So, it is important to understand what the consequences of climate change on the monsoon are. This is a difficult topic because the monsoon is a complex system influenced by the sea surface temperature around India—the Arabian Sea, Bay of Bengal, and Southern Indian Ocean—as well as what is happening in the Atlantic Ocean and the Pacific Ocean. So, year-to-year, the monsoon rainfall keeps changing.

Our understanding of the monsoon has improved a lot in the last 60 years on account of lots of observations and satellite data. But still, our ability to predict how the monsoon will change on account of human-induced changes like carbon dioxide increase and aerosols is not completely understood. Before I go into climate change, I want to clarify some issues about the monsoon itself.



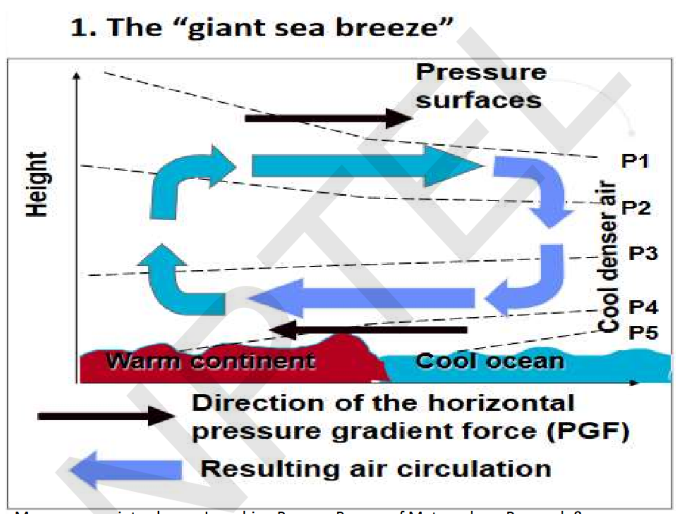
The monsoon is influenced by greenhouse gas warming, definitely, and by changes in the circulation of the atmosphere called dynamics. It has a strong dependence on thermodynamics—temperature, humidity, and so on.

And it depends on how land use is changing the surface albedo of the Earth. And, of course, there is the impact of aerosols. So, all these are having an impact on monsoons, and the net effect can be complicated because some of them increase, some of them decrease, and the net effect may be one way or the other. Shown below is a snapshot of daily rainfall over India in the year 2021, and it is not regular. It fluctuates from day to day, and systems are coming from the Bay of Bengal, from the Equatorial Indian Ocean, and from the Arabian Sea. It is a very complex system.



The short-term forecast of rainfall now is quite good based on weather forecast models, but here our main focus will not be on the short-term forecast, but on long-term prediction—what will happen next year, or after 10 years, or after 50 years. That is the issue we are going to talk about.

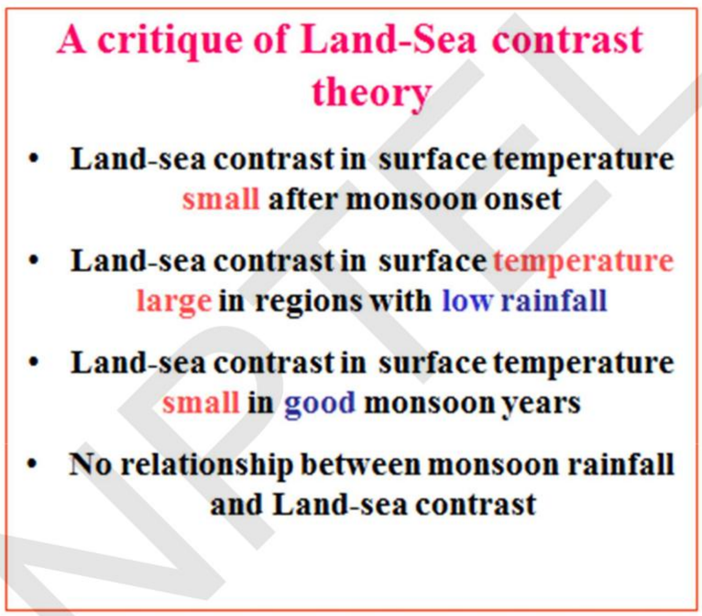
Now, I have to first make sure that some of the things you learnt in school have to be changed now, because normally, in many textbooks, they say the monsoon is like a giant land-sea breeze driven by the contrast between a hot continent and a cool ocean. This was an idea proposed almost 300 years ago, but this is wrong, and you will see why it is wrong. This is okay to understand coastal circulation.



Monsoons: an introduc.on Josephine Brown - Bureau of Meteorology, Research & Developmen

If you are in a coastal region, in the afternoon, the land heats up, the air becomes lighter, it rises, and cool, moist air comes from the ocean, and we have a circulation. This is a local circulation. It extends to the height of maybe one or two kilometers, that is all. This is called the land-sea breeze. All of you who have lived in coastal areas have experienced this, but this is not the monsoon. The monsoon is a much bigger system. As I said, it is influenced by the Pacific Ocean, the Atlantic Ocean, and so on. So, it is not a local land-sea breeze.

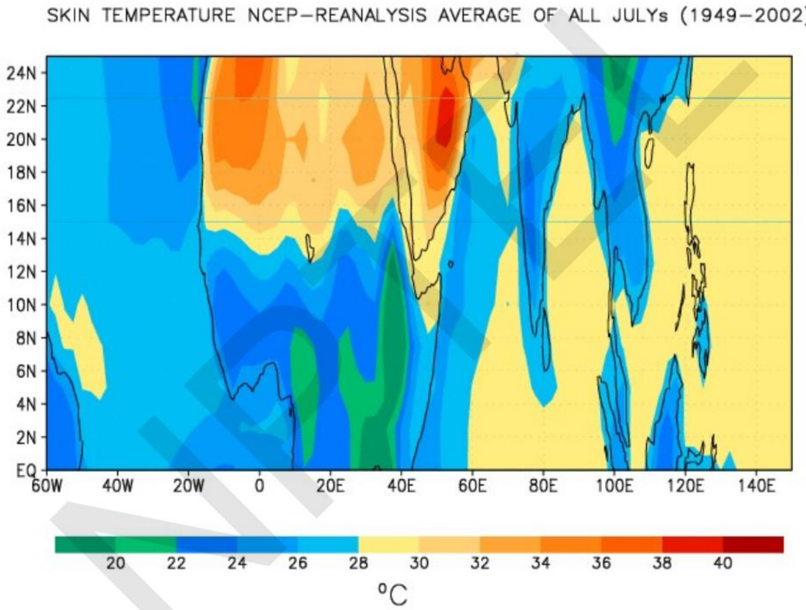
Now, why is the land-sea contrast theory not valid? I am talking about contrast in surface temperature. Because after the monsoon starts over India, the monsoon onset is around June. The difference in temperature between land and ocean becomes very small. The land becomes cooler by around 10 degrees, and then you do not see much change between land and ocean.



And you look at a place like the Sahara in Africa, where there is no rain, and it is very hot. The contrast between the Sahara and the surrounding Arabian Sea and Atlantic Ocean is very large, but there is no rainfall there. So, the land-sea contrast being high does not guarantee rainfall.

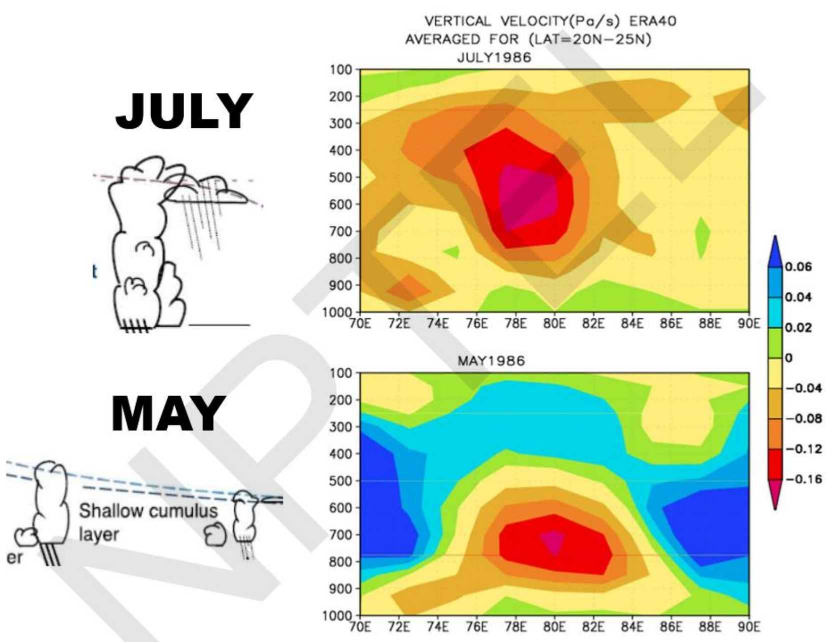
In India, in years when there is very good monsoon, rainfall is much above normal, and the temperature difference between land and ocean is smaller because the land cools more. In years when the monsoon rainfall is small, there is a drought, and the land-sea contrast is higher. So obviously, the land-sea contrast that we see during the monsoon is a consequence of rainfall, not a cause. So, the cause and the consequence should not be misunderstood. Land-sea contrast depends on rainfall. So, in a good rainfall year, the land-sea contrast is small. In a poor rainfall year, the land-sea contrast is large. So, land-sea contrast temperature is caused by monsoon rainfall and is not one which causes monsoon rainfall.

So, there is no relationship between the surface temperature of land over India and that of the ocean surrounding India and its rainfall. That can be shown clearly in the picture below.



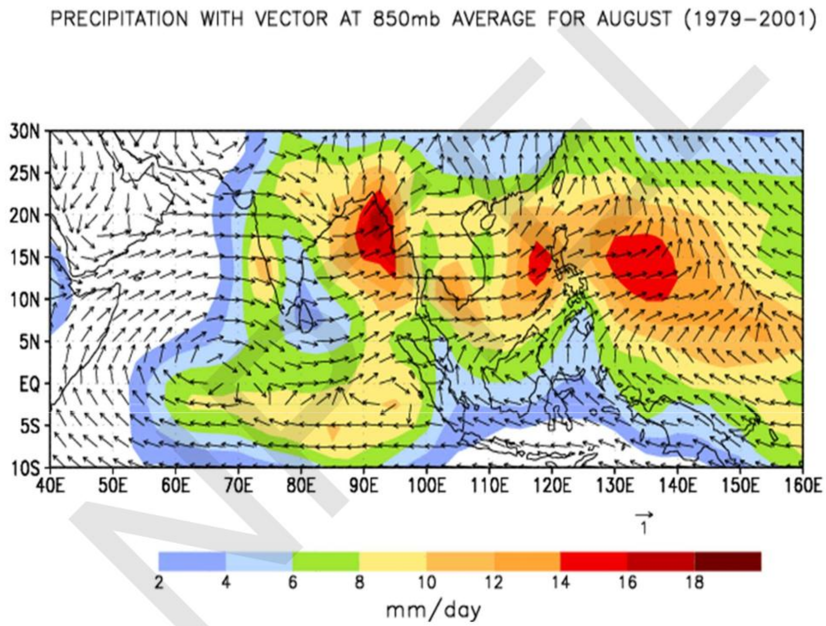
Look at the July surface temperature averaged over 50 years between 1949 and 2002. You see that the land is slightly colder than the surrounding ocean. So, land is not hotter than the ocean in July after the onset.

Now, if you look at the vertical structure, which is very important for the monsoon, you see a big difference between July and May. In May, the land is hot, and there is a land-sea breeze, especially in South India, and that causes an upward motion.



That upward motion is there only up to a height of over 2 kilometers. That is not the monsoon. That is local circulation driven by land-sea contrast. But in July, the vertical motion extends up to 5 to 6 kilometers, and that is the real monsoon circulation. This is the local circulation in May, and in July, we have monsoon circulation. You see the difference in the kind of clouds we have. We have deep clouds during the monsoon, and before the monsoon, we have shallow clouds which go up to 2 or 3 kilometers.

Now, if you look at the August rainfall in Asia, you see the highest rainfall is not over land, it is over the ocean—the Bay of Bengal and the West Pacific.



So, quite clearly, the circulation that drives the monsoon is not due to the temperature difference between land and ocean, which is very small anyway, but the ocean is the one that plays the important role.

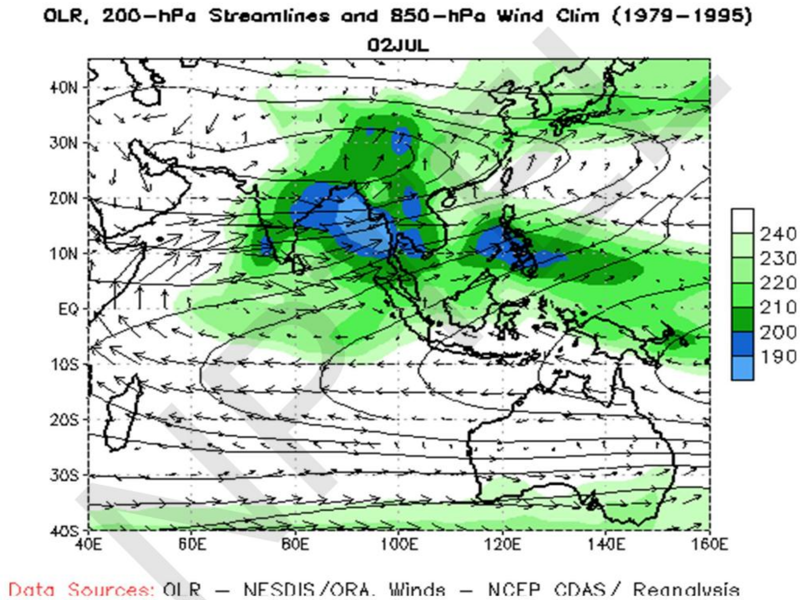
The best way this is explained is by Clift and Plumb in their book *The Asian Monsoon*. It says that the ocean stores the solar radiation because there is a thick mixed layer where the ocean is well mixed up to about 50 meters or 100 meters thick. What is important is the land-sea contrast in heat storage. Land cannot store heat. The ocean can store heat. That is what makes a big difference in the monsoon circulation. So, this difference is very important, but not surface temperature.

All the energy input for the monsoons is from the sun, but the way this energy finds its way into the atmosphere is very different for continental and oceanic regions (from Clift and Plumb, The Asian Monsoon , 2008)

In the ocean , solar radiation is stored in the upper mixed layer and released slowly over the next few months

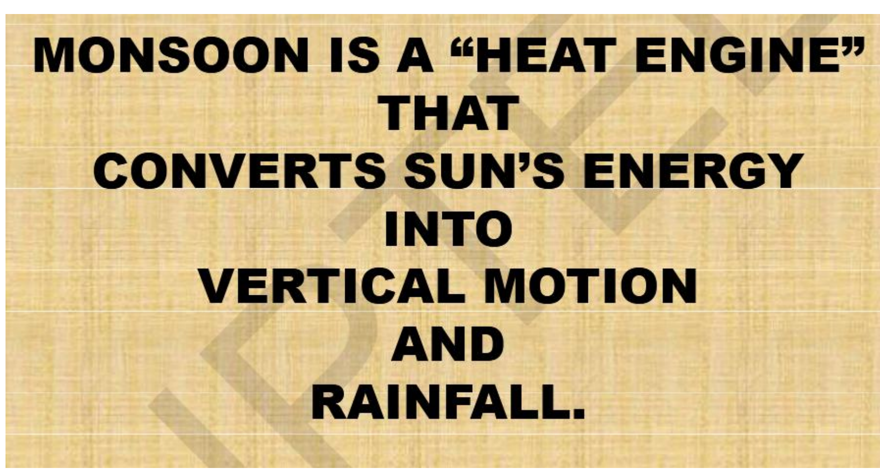
Land-sea contrast in heat storage more important than land-sea contrast in temperature

Now, here is a snapshot of the temperature of the cloud top obtained from a satellite, called outgoing longwave radiation—you know that name. In January: it is over Indonesia, and it gradually moves by May into the Bay of Bengal, then comes over India in July–August, and then goes back.



So, the monsoon clouds move between Indonesia and India. That is a southeast-to-northwest movement of the clouds. It is not north–south; it is moving from Indonesia towards India throughout the year. This is the annual cycle being shown here. You can see that Indonesia is the place where the clouds are in January, and they move gradually by May into the Bay of Bengal, then into India. They stay over India for some time and then go back to the Bay of Bengal and back to Indonesia. The cycle repeats. So, this shows that the temperature of the Indian Ocean and West Pacific Ocean plays a very important role in the way these monsoon clouds move.

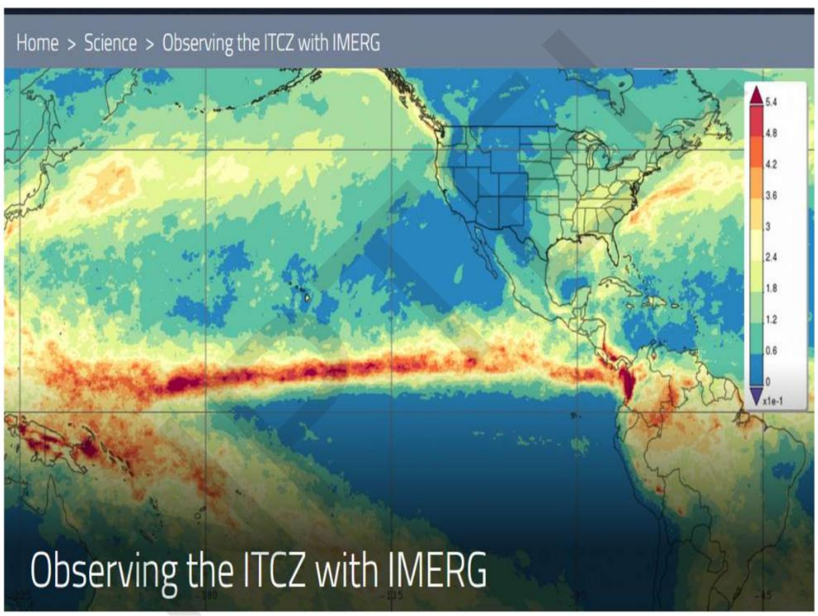
Now, to move away from this land–sea contrast theory, which we know is wrong, a new approach has been proposed based on the energy budget.



This idea is that the monsoon is a giant heat engine. The monsoon takes the heat stored in the ocean, and that heat causes evaporation of water vapour, which enters the atmosphere, condenses there, and when it does so, it sets up circulation. So, the monsoon is a heat engine which converts the solar energy stored in the ocean into the kinetic energy of the monsoon. The monsoon is a mechanism that converts solar heat into kinetic energy through the condensation of water vapour in the atmosphere after it evaporates from the ocean. So, the ocean is very important, and the Sun is very important—not the land–sea contrast.

The monsoon is a heat engine, and all of you have heard about the heat engine idea in thermodynamics—the famous Carnot cycle, Carnot engine. The monsoon is a Carnot engine which operates between the warm surface of the ocean and the cold atmosphere at a height of about 5 kilometers. In the monsoon heat engine, the heat source is the surface of the ocean, and the heat sink, where condensation occurs, is at the height of 5 kilometers, which is much colder than the ocean. The ocean may be at around 300 K, while at the height of 5 kilometers, the temperature is more like 270 K, less than the freezing point of water.

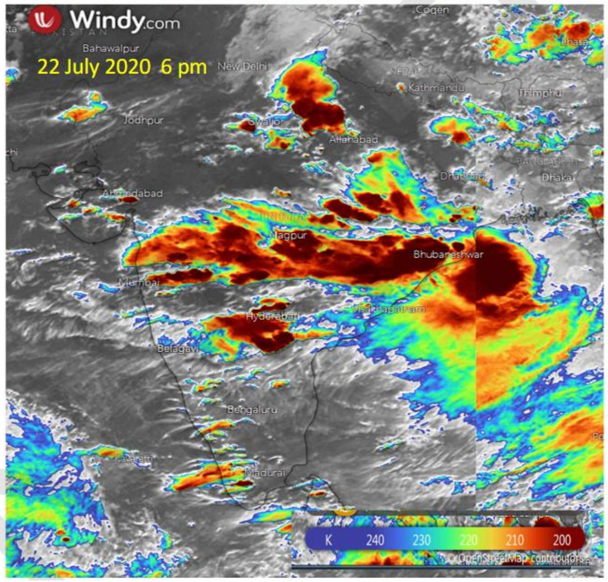
Now, to understand this concept of the monsoon, you must look at satellite data. Only satellite data gave us the true idea of what the monsoon is.



So, we look at the Pacific Ocean, which is the largest ocean in the world. There is an east–west oriented cloud band from the coast of Central America all the way to Indonesia. This is rainfall in millimetres per day. So, this east-west-oriented band is what is called the Intertropical Convergence Zone (ITCZ). That is the zone where air converges from the north and south—intertropical—and it comes to this region, and that is what forms the rain band. Now, over the ocean, this rain band moves a little, but over land, it moves much more.

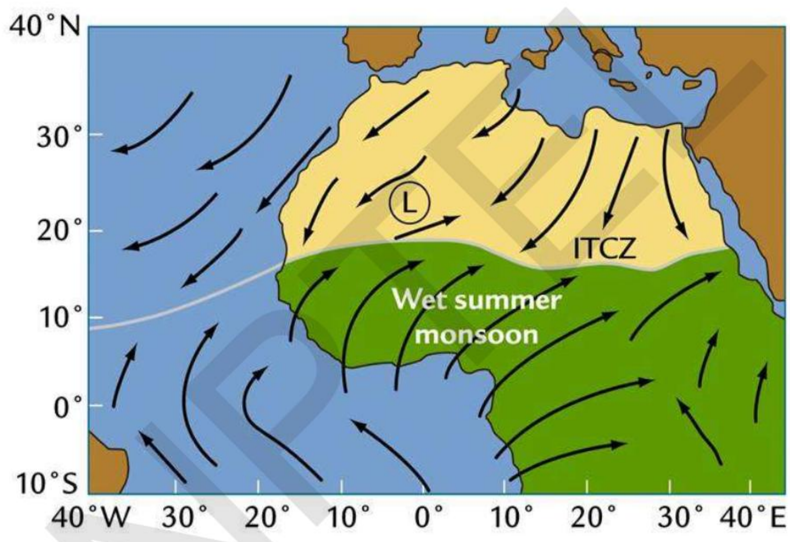
Now look at India in the month of July (the picture shown below), at the peak of the monsoon season: this east–west-oriented cloud band is located between Bhubaneswar and Mumbai. You do not see it every day—you have to average over many days to see this kind of picture.

Inter-Tropical Convergence Zones(ITCZ)
East-West oriented cloud band



So, this east-west-oriented band comes over India in summer, but in winter, it goes to the south of India. It remains there in winter and comes over India in summer.

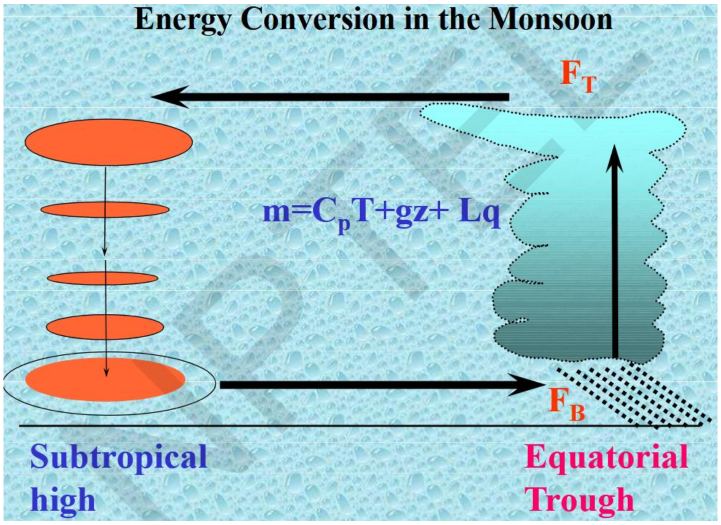
In Africa, this east-west-oriented band goes up to 15°N.



A Northern hemisphere summer

To the north, there is the Sahara Desert. So, hot, dry air comes from the desert and moisture from the equator comes up, and they meet along the ITCZ. So, this is the concept of the monsoon that is now considered more relevant.

So, what happens in the monsoon is that water vapour evaporates—both from land and ocean—condenses through deep clouds, and that air which rises ultimately sinks in the southern Indian Ocean and forms a high-pressure area there because the air descends. So, this is how the monsoon circulation works. In the figure shown below, there is India (equatorial trough), and there is the southern Indian Ocean (subtropical high), and the circulation occurs between them.

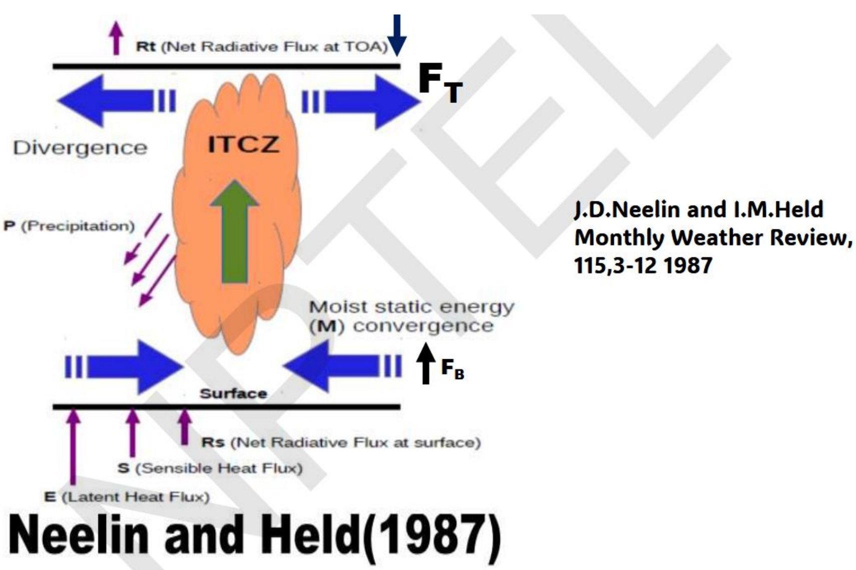


The quantity that is very important to understand here is called moist static energy (m).

$$m = C_pT + gz + Lq$$

It's the sum of:

- What all of us know as enthalpy or specific heat of air (C_p) × temperature (T), which is sensible heat (C_pT),
- The potential energy of the air (because as it rises under Earth's gravity (g), it gains potential energy, gz where z denotes the height),
- And the latent heat, which will be released when condensation occurs (Lq).



The above figure shows the concept of the ITCZ that was proposed by David Neelin and Isaac Held about 40 years ago. It describes how air converges at the surface, rises, releases heat, and then goes out on either side. The amount of energy available in this column is what drives the monsoon circulation.

In this column, solar energy comes at the top—that is F_T, and heat is radiated by the ground—that is F_B. The total amount of energy available will be F_T - F_B, which is the net radiation at the top of the atmosphere. We discussed this earlier when we looked at the global mean temperature. The same idea can be adopted for local conditions.

Now, we can integrate this equation of energy conservation from the surface to the top of the atmosphere.

ENERGY CONSERVATION EQUATION

$$\int \omega \, [\partial m/\partial p^*] \, \partial p^* = [F_B - F_T]$$

MOISTURE CONSERVATION EQUATION

$$\int \omega \, [\partial q/\partial p^*] \, \partial p^* = [E - P]$$

F_B & F_T Heat fluxes at bottom & top

E = Evaporation P = Precipitation

m=moist static energy=$C_PT+gZ+Lq$

Here

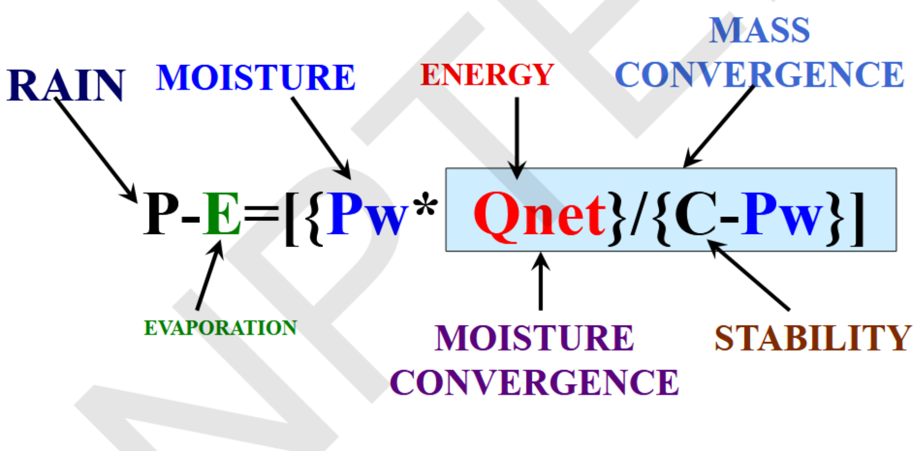
- ω is the vertical velocity,
- $\frac{\partial m}{\partial p^*}$ is the vertical gradient of moist static energy,
- ∂p^* is pressure, integrated vertically,
- F_B is the flux at the bottom, and F_T is the flux at the top.

We can also write the moisture conservation equation, which describes how moisture is conserved as vapour condenses into rain and falls down. Again, it's an integral:

- ω is vertical velocity,
- q is specific humidity,
- The integral $\int \omega \left[\frac{\partial q}{\partial p^*}\right] \partial p^*$ gives you evaporation - precipitation [E–P].

These are the two main equations that control the monsoon. So, the important quantities are evaporation (E), precipitation (P), and moist static energy (m).

Now, if you simplify the equation by making an assumption about the vertical velocity profile, you get a very neat, simple equation that says: Rainfall minus evaporation is equal to total water vapour in the column.



You integrate the water vapour from the surface to the top of the atmosphere. When you integrate, you get water vapour in kg/m^2—this is called column water vapour (Pw). And Qnet is the net radiation at the top of the atmosphere, which we discussed earlier and which you can obtain from satellite data. C is a quantity that is a measure of the vertical profile of temperature and moisture. We call it the stability term. It controls how far the air can rise.

$$P - E = \frac{P_w\, Q_{net}}{C - P_w}$$

So, we have a simple equation that connects:

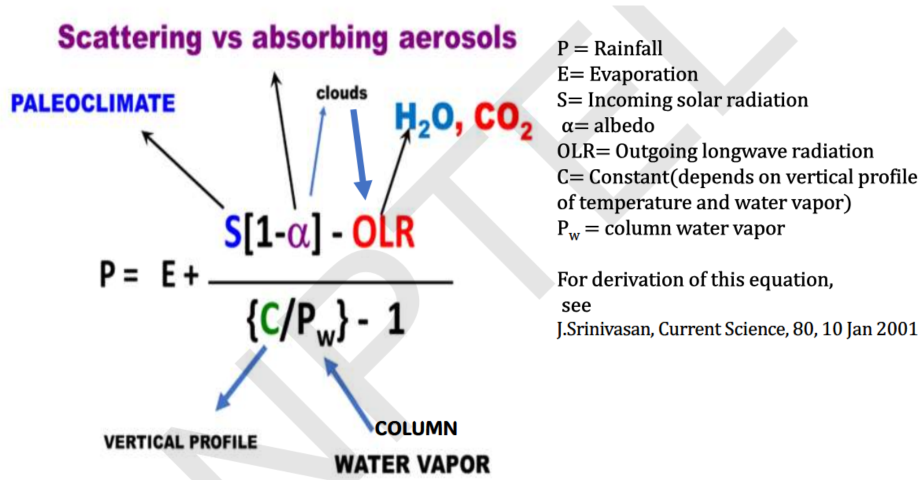
- Rainfall (P),
- Evaporation (E),
- Total water vapour (Pw),
- And total energy available (Qnet).

A very important point about this concept is that if the total energy available (Qnet) is not positive, then P - E is negative. That means the area is not a source of moisture, but a sink of moisture, like the Sahara. So, for you to have monsoon rainfall in the summer season, Qnet must be positive. We will show that in the next few slides.

Now, if you split the term Qnet into components:

$$Q_{net} = S[1 - \alpha] - OLR$$

- Incoming radiation as solar radiation (S), which we know changes over geological time scales;
- The absorbed part (1 – α), where α albedo is the reflectivity of the surface. Albedo is affected by scattering and absorbing aerosols, which we have already discussed. It is also affected by clouds;
- And clouds also affect the outgoing longwave radiation (OLR). Under clear skies, the OLR (outgoing longwave radiation) is affected by water vapour and carbon dioxide as well.

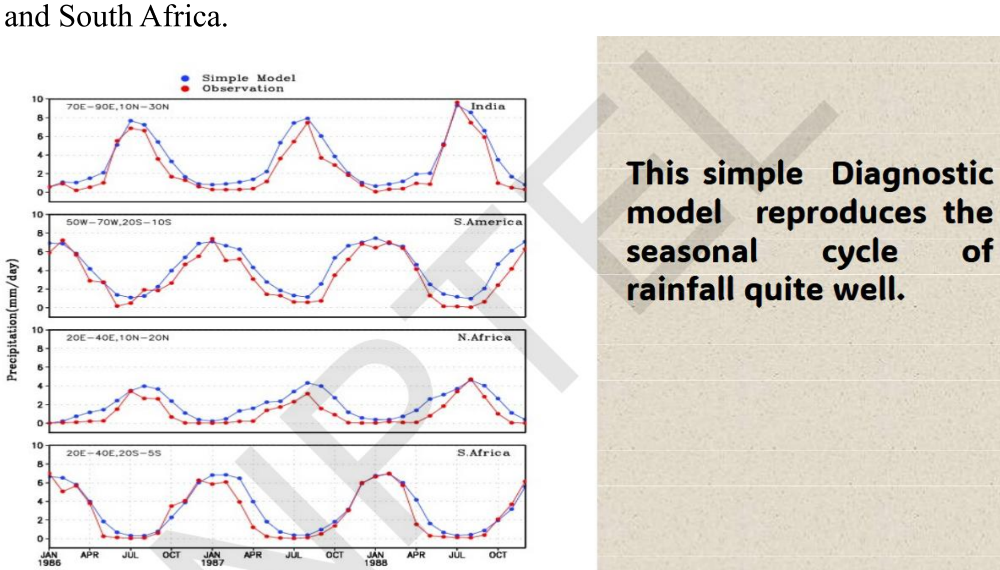


So, clearly in the numerator (Qnet), all these terms are affected by:

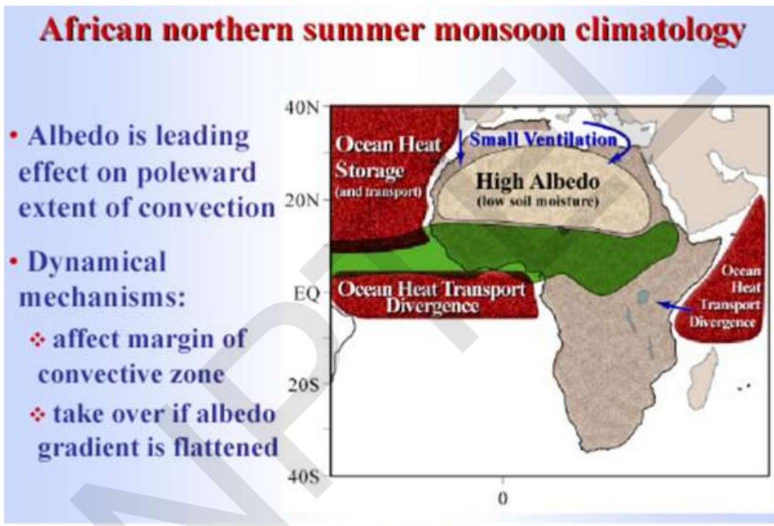
- The greenhouse effect of water vapour and CO_2,
- The greenhouse effect of clouds,
- The effect of clouds on albedo,
- The effect of aerosols on albedo,
- And the incoming solar radiation.

All of these were discussed earlier under climate change. All these will affect monsoon rainfall. In the denominator of the equation, we have terms controlled by the vertical profile of temperature and humidity. The most important term here is total water vapour (Pw) in kg/m². If you want to see the derivation, you can look at my paper published around 23 years ago in *Current Science*—it's available online and can be downloaded (J Srinivasan. "A simple thermodynamic model for seasonal variation of monsoon rainfall". In: Current Science (2001), pp. 73–77).

This simple model reproduces the seasonal cycle of rainfall over India, South America, North Africa, and South Africa.



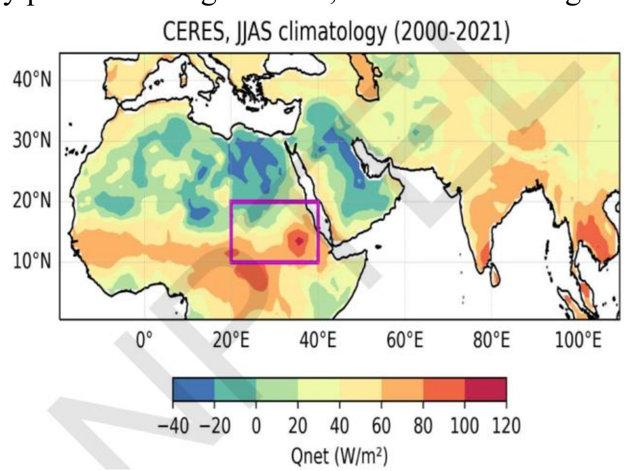
You can see that the seasonal cycle is different in South Africa and South America compared to India and North Africa, because the Qnet incoming radiation has a different cycle in South Africa compared to India. So, this model is useful, but remember—it is a diagnostic model. This model cannot predict what the rainfall will be next month or next year. It can only tell you what rainfall will be if you know the total water vapour, Qnet, and other variables. So, it is a model useful to understand the monsoon, not to predict it. Now, this model will also explain why, in Africa, rainfall does not extend beyond 15°N, while in India, rainfall goes up to 25°N, all the way to Punjab and Haryana.



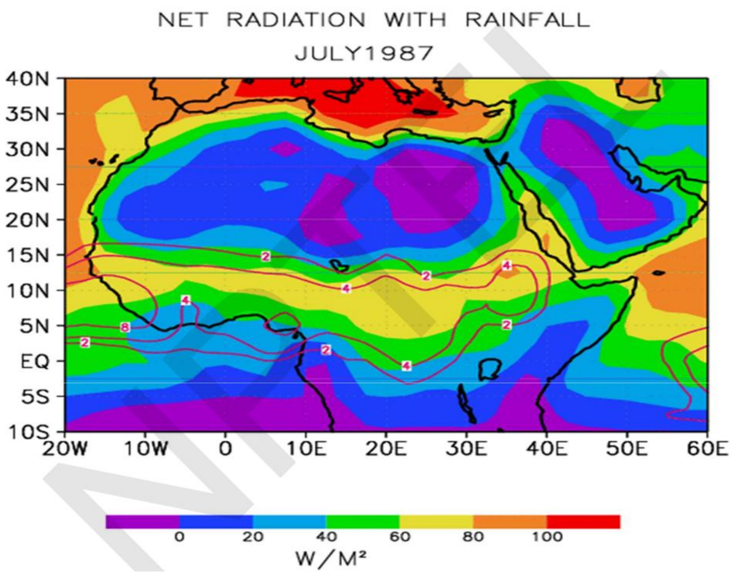
David Neelin, University of California at Los Angeles

In Africa, rainfall is restricted to around 15°N because there is a large desert—the Sahara—whose albedo is so high that Qnet at the top of the atmosphere is negative. Once Qnet is negative, we saw from that equation that P - E is negative—that is, rainfall cannot exceed evaporation. So, rainfall is very low, and evaporation dominates.

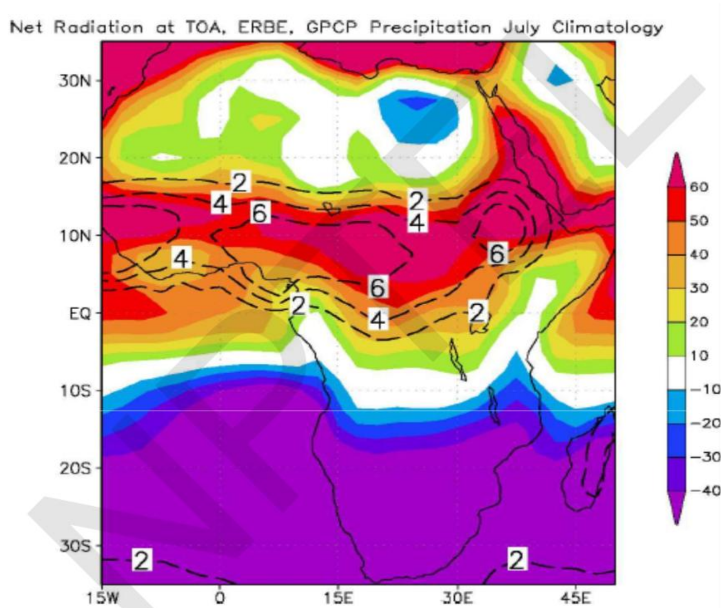
This is shown clearly using CERES satellite data (figure shown below), which measures Qnet. If you look at the June–July–August average, you will see that most of the Sahara has Qnet values that are either slightly positive or negative. So, it cannot have large rainfall.



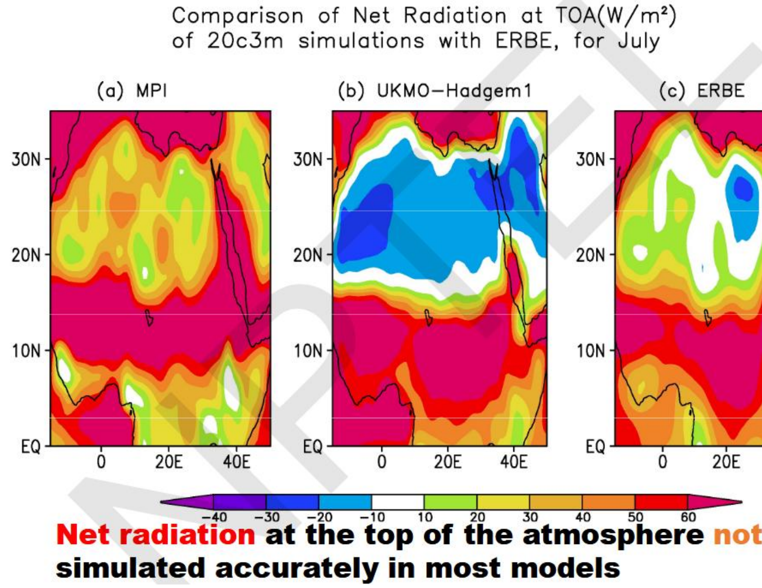
In comparison, at the same latitude over India, we have 40–50 W/m² of net incoming radiation. That is what gives India a strong monsoon. At the same latitude, Africa has no monsoon. So, remember the very important role played by Qnet, which is governed by surface albedo. If India were to become a desert like the Sahara, there would be no monsoon. So, you have to keep that in mind when discussing the impact of climate change on the monsoon. Remember that in Africa, the highest rainfall occurs around 10°N, where Qnet is very high. This is the reason why there is a lot of rainfall there. Now, to make this point even more clear, I'm showing you Qnet again (in the figure below) and highlighting the small positive and high negative values, and showing the contours of rainfall in mm per day in July 1987.



You see clearly—all the contours of rainfall, 2 mm and above, are in regions where Qnet is positive, not negative. Where Qnet is negative, there is no rainfall. That is the key point. Over Saudi Arabia, for example, there is no rain because Qnet is negative. This is again highlighted with one more graph shown below, showing more clearly the relationship between Q_net and rainfall.

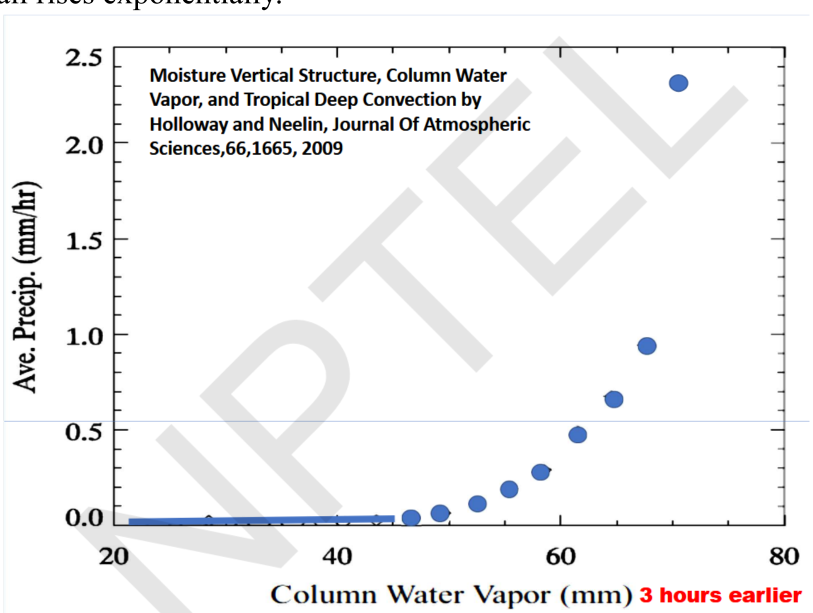


Now, climate models that simulate monsoon rainfall—some of them do not perform well.



For example, if we look at the UK Met Office (UKMO) model called Hadgem1, it has negative Qnet over a large portion of North Africa—more negative than what is observed. So, this model will perform somewhat worse than the MPI model, which has somewhat higher Qnet than the observations. The MPI model will simulate rainfall going further north than the UKMO model.

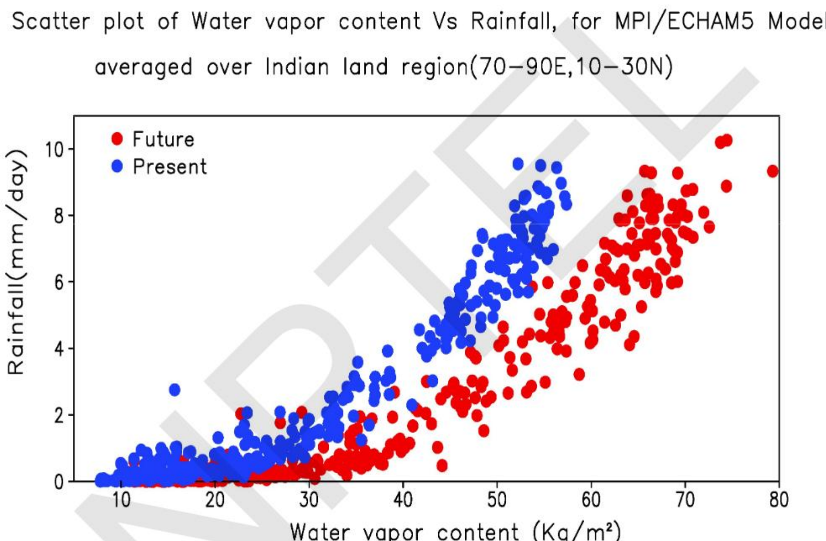
So, it is very important to correctly simulate the net radiation (Qnet) at the top of the atmosphere in order to get rainfall predictions correctly. Now, rainfall also depends on water vapour, according to the simple model I proposed. If you plot the column-mean water vapour at any location against rainfall—as shown by the paper by Holloway and Neelin—you'll see that when the column water vapour is 40 mm (or 40 kg/m²), you don't get much rain. It has to rise sufficiently above 40 mm, and then rainfall rises exponentially.



Keep this in mind: the relationship between rainfall and water vapour is highly non-linear—it is exponential in character. So, a small increase in water vapour causes a large increase in rainfall. This partly explains why we are getting more extreme rainfall in recent years, because due to global warming, the temperature has gone up. When the temperature goes up, there is more moisture in the air. When there is more moisture, there is more rainfall. And that relationship is not linear, but highly non-linear. Keep that issue in your mind.

This is shown more clearly in the plot shown below. We are showing the relationship between rainfall and water vapour from a climate model:

- For the present climate (in blue),
- And for the future climate (in red).

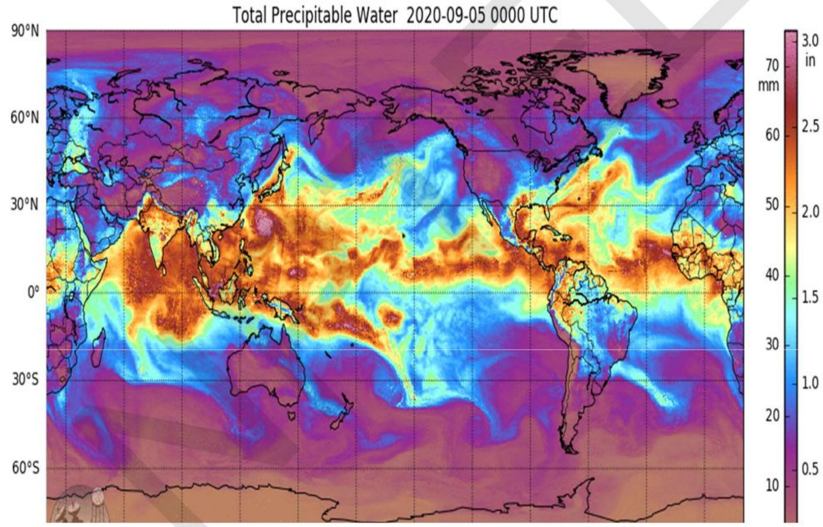


The increase in water vapor in 21st century comparable to increase from LGM to Holocene

Notice that the entire curve shifts to the right due to climate change. But also notice that for the same amount of water vapour, there is less rainfall in the future than in the present. So, although water vapour has increased, rainfall may not always increase, because the vertical variation of temperature and humidity controls how much rainfall occurs—and that changes with global warming. So, this must be kept in mind.

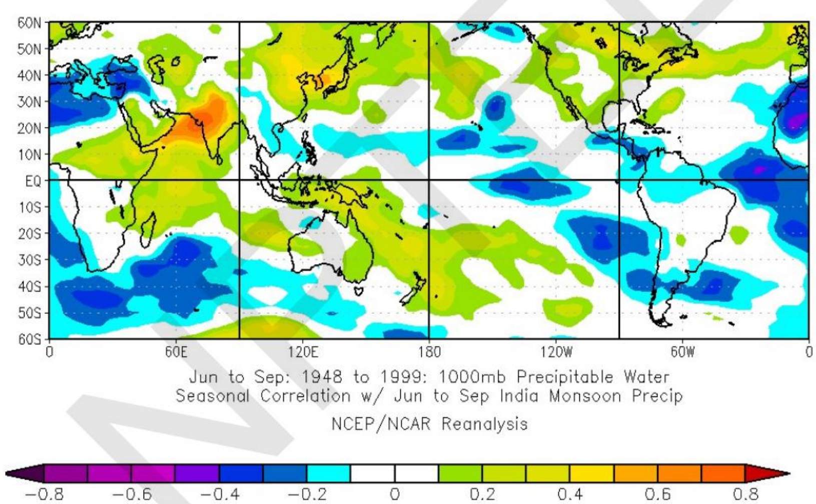
Now, shown below is a snapshot of water vapour in the month of September 2020. It shows you that the source of water vapour for India is the Southern Indian Ocean, Arabian Sea, and Bay of Bengal. These are the places where water vapour is concentrated. That water vapour has to be transported into India, and this happens through the winds over the Arabian Sea, which control rainfall here. In the Pacific Ocean, you can see that the ITCZ (Intertropical Convergence Zone) is stuck around 5°N. It does not move much northward. This is true in both the Atlantic and Pacific Oceans—the oceanic ITCZ remains relatively fixed. But in India, the ITCZ moves northward over land and also affects East Asia.

MIMIC-TPW2 is an experimental global product of total precipitable water (TPW), using morphological compositing of the MIRS retrieval from several available operational microwave-frequency sensors http://tropic.ssec.wisc.edu/real-time/mtpw2/



Now, in India, the water vapour is brought in by winds blowing from the Arabian Sea to India.

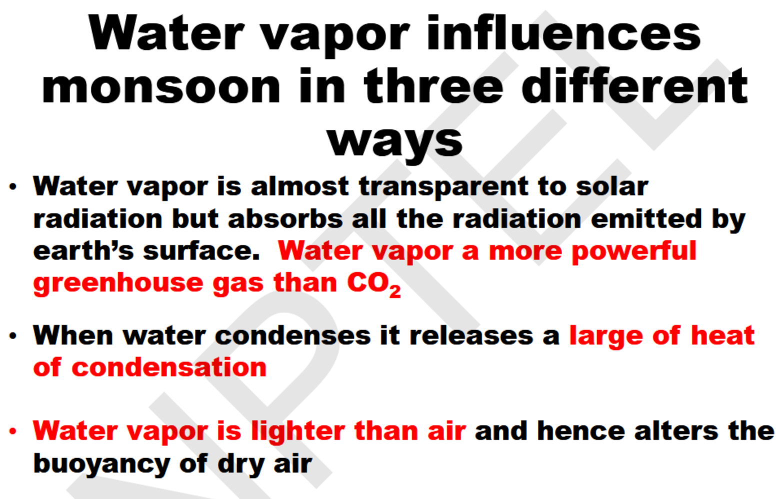
Winds blowing from Arabian sea control the water vapor over India



So, when you look at the correlation between rainfall over India and water vapour around the world, you see the highest correlation is with Arabian Sea water vapour, because the winds are coming from there, not from the Bay of Bengal. There is a big difference between the Bay of Bengal and the Arabian Sea in terms of their role. The winds that bring rain into the Indian subcontinent come primarily from the Arabian Sea, not the Bay of Bengal.

Let me conclude this talk by saying that water vapour influences the monsoon in three important ways:

1. Radiative Effect: Water vapour is transparent to solar radiation but absorbs outgoing longwave radiation emitted from the surface. So, it traps heat and acts as a powerful greenhouse gas.
2. Latent Heat Release: When water vapour condenses, it releases latent heat, which contributes to vertical motion and monsoon circulation.
3. Buoyancy: Water vapour has a molecular weight of 18 g/mol, compared to 29 g/mol for dry air. So, moist air is lighter, more buoyant, and rises more easily.



So, water vapour plays a very complex role in monsoon dynamics through radiative trapping, latent heat release, and buoyancy effects. This must be kept in mind when trying to understand the impact of climate change on the monsoon.

We will continue this lecture in the next class. Thank you.