Climate Change Science
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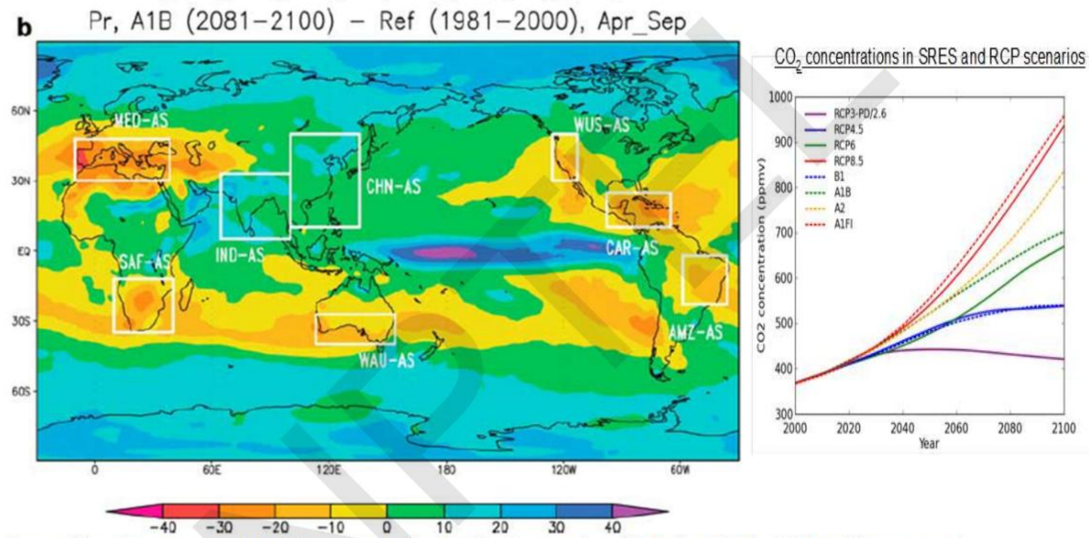
Lecture – 50
The impact of model resolution



Ensemble average precipitation change in April–September (AS), for 2081–2100 with respect to 1980–1999 in the A1B scenario. .Units are % of 1980–1999 value. F.Giorgi and X.Bi, GEOPHYSICAL RESEARCH LETTERS,36,2009

So, at the end of the last lecture, I showed this result demonstrating how rainfall will change on account of the increase in carbon dioxide during the last 20 years of this century as compared to the last 20 years of the last century. During the period April to September, you see a very clear signal of an increase in the tropical regions of Africa, India, China, and the Equatorial Pacific, but a decline in the mid-latitudes of America, the Amazon region, the Middle East, North Africa, South Africa, and also Australia.

This is a very interesting result, but I pointed out that we should be careful about it. This may not happen in the next 20 or 30 years, because the changes imposed by increasing carbon dioxide will occur along with natural decadal variation of rainfall due to energy exchange between the ocean and the atmosphere. So, natural decadal variability will show some changes. These predictions of the model can only be trusted if you look at data from 2081 to 2100.

Looking at the above picture, you cannot say what will happen between 2031 and 2050. So, for that, Giorgi and Bi came up with a quantity called the time of emergence. The time of emergence of the impact of increasing CO_2 will be different in different parts of the world.

Time of emergence (TOE) of GHG-forced precipitation change hot-spots

Table 2. PSPOTS From Figure 1, Their Latitudinal and Longitudinal Extent (Land Only), and Their TOE for the B1, A1B and A2 IPCC Emission Scenarios[a]

PSPOT	Latitude	Longitude	TOE-B1	TOE-A1B	TOE-A2
NEU-OM	50 N – 70 N	10.5 W – 40.5 E	<2020	<2020	<2020
MED-AS	30 N – 48 N	10.5 W – 38.5 E	2061	2035	2034
MED-OM	25 N – 43 N	10.5 W – 40.5 E	2035	2031	2038
NAS-OM	35 N – 70 N	85.5 E – 140.5 E	<2020	<2020	<2020
CHN-AS	10 N – 50 N	100.5 E – 140.5 E	2048	2048	2061
IND-AS	5 N – 33 N	64.5 E – 100.5 E	2072	2054	2066
EAF-OM	5 S – 12 N	27.5 E – 52.5 E	2046	2035	2029
SAF-AS	35 S – 12 S	9.5 E – 40.5 E	>2100	2046	>2100
NAM-OM	40 N – 70 N	170.5 W – 49.5 W	<2020	<2020	<2020
WUS-AS	30 N – 50 N	125.5 W – 112.5 W	>2100	>2100	2093
CAM-OM	15 N – 35 N	121.5 W – 97.5 W	>2100	>2100	2067
CAR-AS	10 N – 25 N	97.5 W – 64.5 W	>2100	2049	2077
AMZ-AS	23 S – 2 S	58.5 W – 35.5 W	>2100	>2100	>2100
WAU-AS	40 S – 27 S	113.5 E – 154.5 E	>2100	>2100	>2100

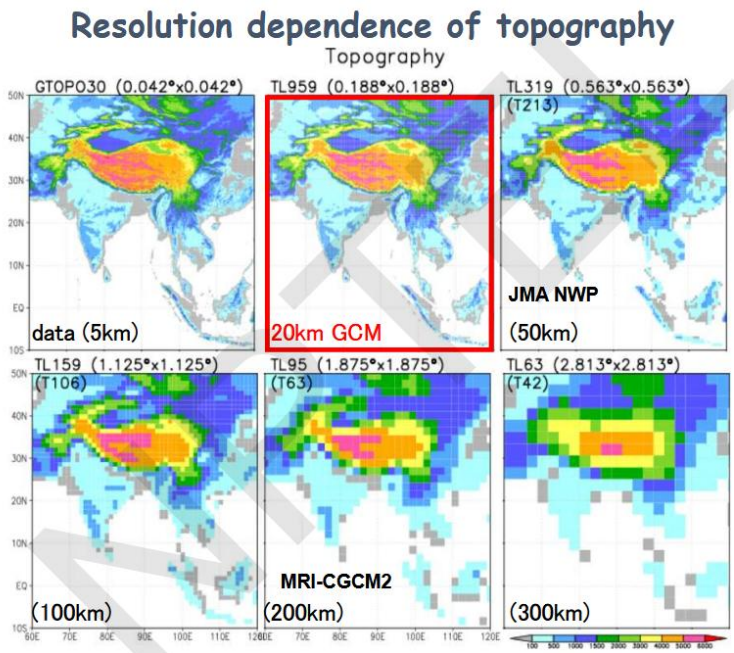
[a]AS is April–September, OM is October–March.

As far as India is concerned, their results show that around 2050 is when we can be confident that some of these predictions of the climate model may come true. Before that, the variations in our climate will be a combination of the impact of CO_2 and the natural decadal climate variability. That is why it is not wise to look at each extreme event occurring in India or other countries and say it is due to climate change, because climate change is occurring in the context of natural climate variation. Right now, both are playing a role, and one cannot say one is more important than the other. This fact is sometimes forgotten by our media and also by many NGOs—non-governmental organizations—which are trying to create awareness about climate change.

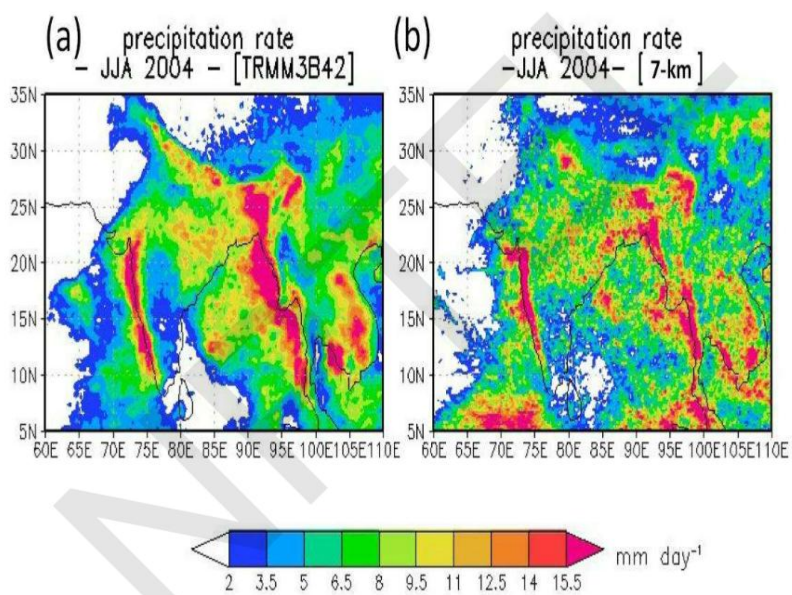
We also tend to sometimes exaggerate some of the predictions of climate models. We need to be careful. So, I want those of you who are taking the course to be clearly aware that our ability to predict the impact of increasing carbon dioxide cannot be trusted in the next 20 years because natural climate variation on a decadal scale has the same amplitude as the prediction by the climate model about the impact of increasing CO_2. So, you have to keep that in mind.

Now, another important issue with climate models is that in a country like India, where we have the Western Ghats—small mountains—and the big mountain ranges of the Himalayas and Tibet, most models, whose resolution is typically 0.5° by 0.5°, do not resolve some of these mountains correctly. Some of the models are even at 100-kilometer resolution, and they would not get the Western Ghats accurately.

For example, in the Western Ghats, all of you know that in Kerala, there is a gap called the Palghat Gap, where the Western Ghats are not present, and the air rushes through those gaps. Those areas are very suitable for windmills. So, most of the windmills in Tamil Nadu are located in the Palghat Gap. But the model will not be able to capture the impact of the Palghat Gap if the model resolution is 100 by 100 kilometers. Only when you go to 50 by 50 km, 20 by 20 km, or 4 by 4 km will you be able to resolve the Palghat Gap. So, if you want to trust the prediction of climate models about rainfall over the Western Ghats or the Himalayas, you need to be careful. You should choose a model that has a high resolution.

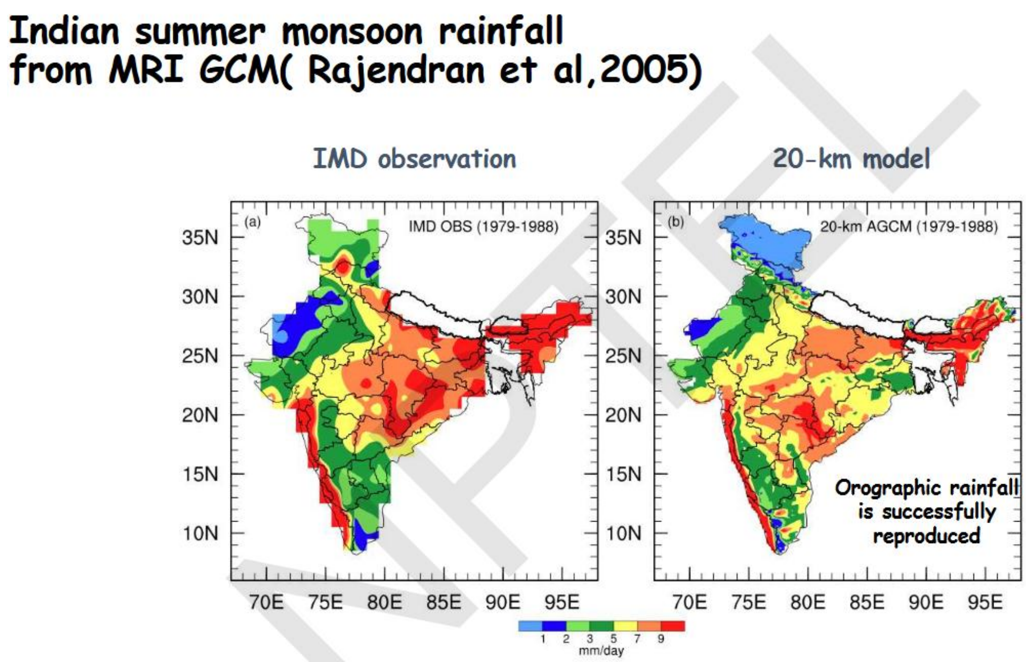


This I will take up when I talk about monsoons a little later. Here, you can see that a model developed with Japan called NICAM—the model simulation is shown on the right (refer to the picture below)—has a resolution of 7 kilometers by 7 kilometers. It is very, very high resolution.



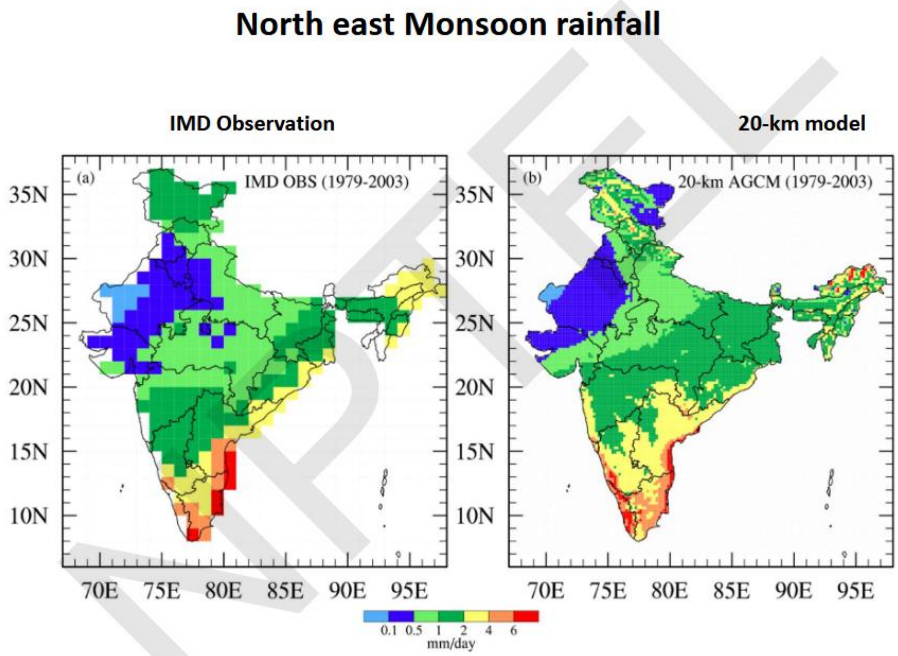
On the left-hand side is an observation from a satellite called TRMM, Tropical Rainfall Measurement Mission. You see that this model simulation of rainfall over the Western Ghats, as well as the Burmese mountains, is very good, but that requires 7 kilometers. Most of the models used today to predict climate change do not have this resolution. The IPCC results, which have been put out over the last 20 years, are based on models whose resolutions are typically 50 by 50 or 100 by 100 kilometers. They cannot be trusted to get the rainfall correctly over the Himalayas or the Western Ghats. But you can see that once you get a high-resolution model running, its simulation is very realistic. This shows that there is promise that in the next 10 to 20 years, as computers become more powerful and faster, model simulation of rainfall near mountains like the Western Ghats and Himalayas will improve substantially.

Now, to highlight that, I am showing a simulation made more than 20 years ago in Japan. This is the MRI model (in the picture shown below, right-hand side plot) of the Japanese forecasting center. One of our students who did his PhD thesis at our center in IISc went there for postdoctoral research. He simulated the 10-year mean rainfall over India using this model with a resolution of 20 kilometers and compared it with the observations of the India Meteorological Department (IMD).



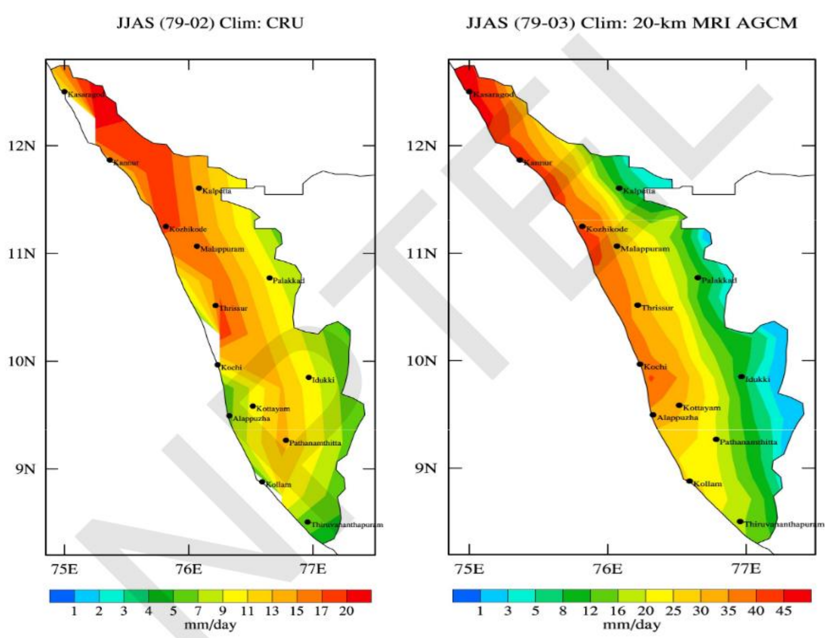
You can see the model performs extremely well. It correctly simulates the high rainfall over the Western Ghats, the high rainfall in Uttarakhand, and the high rainfall in northeast India, which has lots of mountains, along with the spatial pattern of rainfall over the Indo-Gangetic plain and the rain shadow in Karnataka to the east of the Western Ghats.

So, I would say this model, with a 20-kilometer resolution and work done almost 20 years ago, is quite good. Not only does the model simulate the June–July–August–September rainfall (summer monsoon), it also simulates the winter monsoon correctly. You can see the pattern is quite good (please refer to the spatial plot shown below).

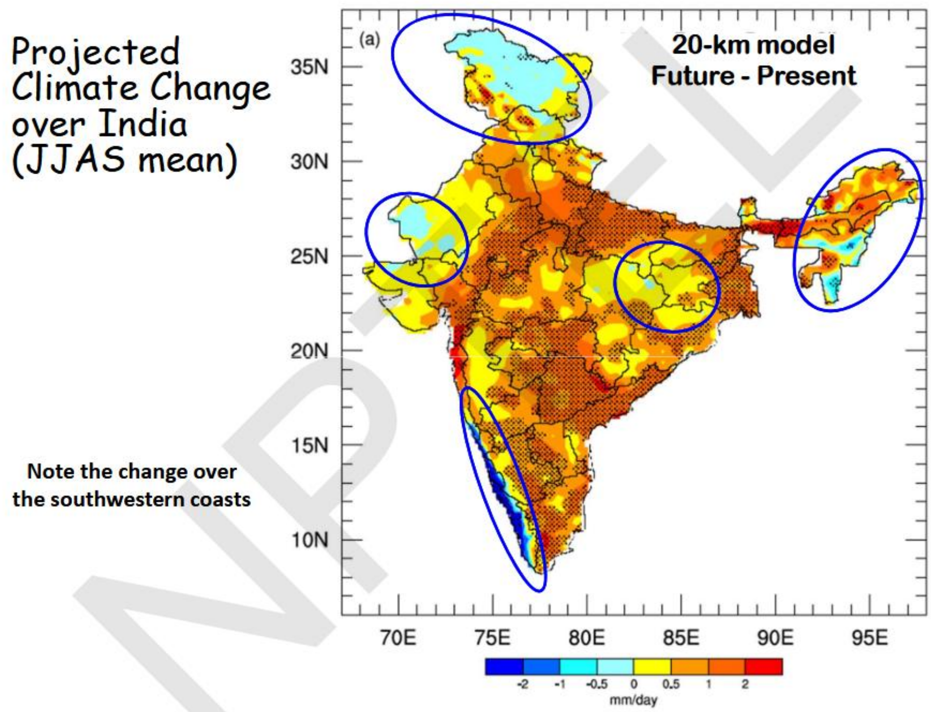


So, I would say a 20-kilometer model can be trusted to produce the spatial pattern of Indian rainfall quite well. But I want you to remember that models like CMIP5 and CMIP6 do not have this resolution. They are typically 50 or 100 kilometers. So, those models cannot be fully trusted to capture the spatial pattern of rainfall over areas like India, where mountains play an important role.

Now, to highlight this even better, I am showing you the 20-year average rainfall—June, July, August, September—as observed in the left-hand side figure shown below and as simulated by the 20 km resolution model.



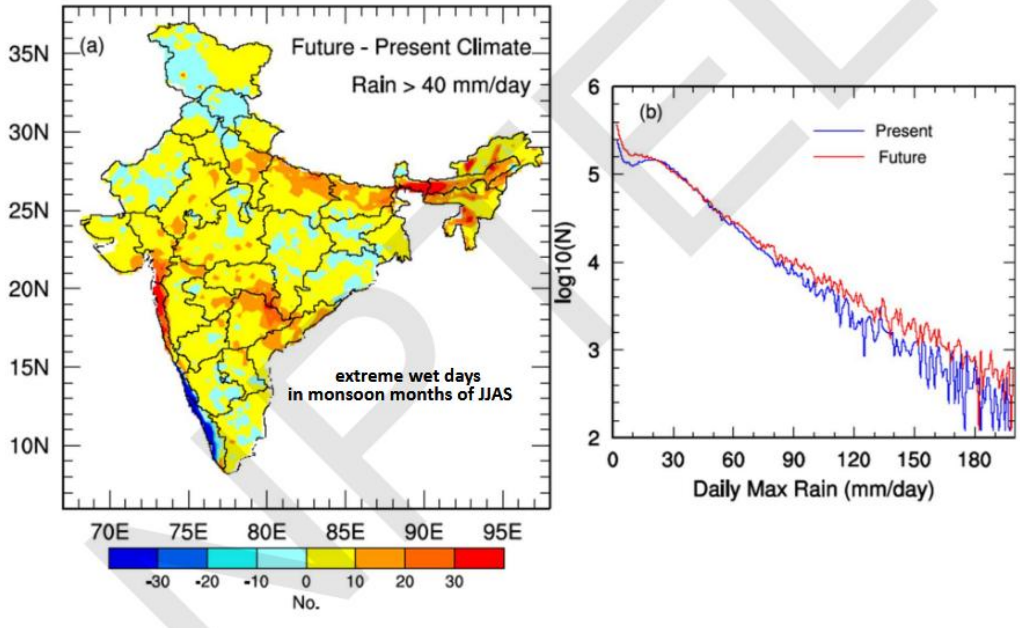
It is quite good. It gets the gradient very accurately and clearly shows the need for a 20 km resolution model to correctly forecast rainfall over the Western Ghats in Kerala. So, this is a very important requirement. If you want to predict future climate change over Kerala, you have to use a model with a resolution of 20 kilometers. Now, what does this model predict about the future?



In this model, the future refers to the last 20 years of this century, compared to 1981 to 2000. This model says that most of India's rainfall will go up.

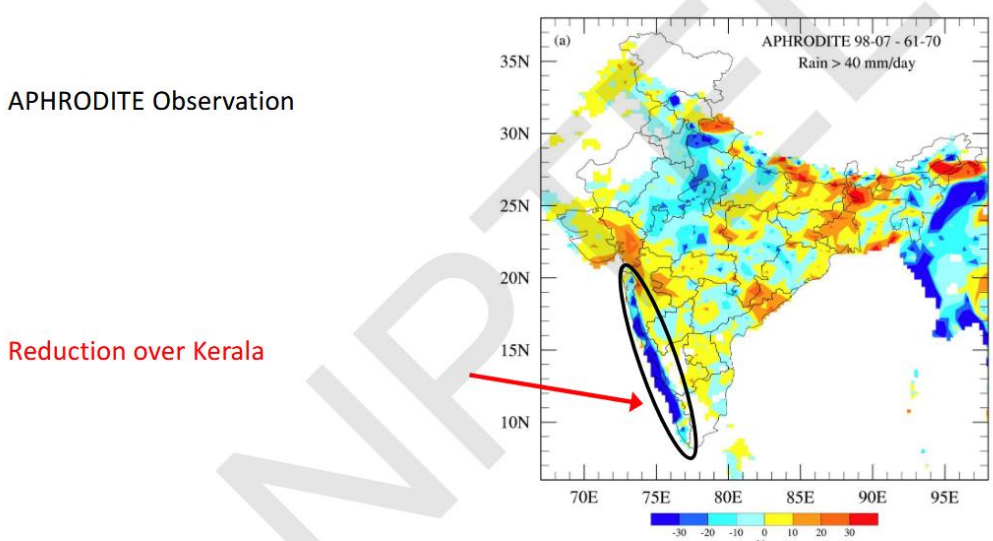
We are confident—these hatch lines show that we are confident. But the same model shows rainfall will decline over Kerala and in some parts of northeast India. Now, this was never shown by any other model because the other models had resolutions of typically 50 or 100 kilometers, and they did not capture the orography of the Western Ghats correctly. So, they did not show this decline. This decline is occurring because the jet that comes over India during the monsoon has shifted due to climate change. When the shift occurs, rainfall increases over the Western Ghats in Maharashtra but declines over Kerala. So, this is a unique prediction of this model, thanks to its high resolution.

The model also shows that extreme rainfall—rainfall above 40 mm per day (in the picture shown below), which causes heavy flooding in many urban areas of India—is going to increase in this region, Central India, while it will decline over Kerala. And this prediction, on a logarithmic scale of the occurrence of rainfall versus daily maximum rainfall, shows that in the future there will be more extreme rainfall than at present.



So, this is a cause for concern because extreme rainfall will do a lot of damage, both to agriculture and to many human settlements. The fact that rainfall above 90 mm per day will increase in the future climate compared to the present climate—as shown here in blue (please refer to the right-hand side graph in the picture above)—indicates that we need to adapt to the possibility of much more extreme rainfall in the future on account of climate change.

Now, what I just showed you is also seen in actual observation: there has been a decline in extreme rainfall over Kerala in the period 1998 to 2011 compared to the period 1960 to 1970. There has been a decline in extreme rainfall in the Western Ghats and some increase over West Bengal, Bihar, and parts of Bangladesh. But the challenge we face is that most models used right now do not have the resolution to predict rainfall on a scale that people need.



When we talk about the impact of climate change, you must remember that people are interested in the impact in *their* area, not in the global mean. Global mean models are doing fine, but that is only to check that the models are running properly. What we need is information about rainfall increase over Bangalore, New York, or London at a scale of, say, 20 by 20 kilometers. But that is not easy because models do not have that resolution. So, what people have done is develop a very popular method called statistical downscaling. It is a method in which you take the output of a model—at much coarser resolution—and statistically relate it to what may happen at higher resolution.

The demand for prediction of climate change at district level has made statistical downscaling fashionable

"The key uncertainty in statistical downscaling is due to the uncertainty in synoptic scale circulation pattern simulated by the parent models or the reanalysis data employed in developing the statistical relations"

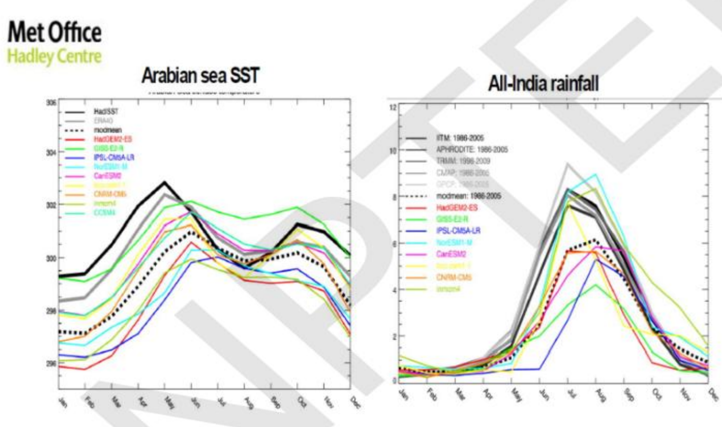
Shashikanth et al., Journal of Hydrology, October 2014

Now, this paper by Shashikanth and others, published in the *Journal of Hydrology* 10 years ago, warns that there is a large uncertainty in the circulation patterns in the models used for downscaling. So, we cannot totally trust the prediction of climate models on a regional scale. Keep that in mind, because I find many people look at the output from these models and make dire predictions about what may happen in the future. But you have to be careful about statistical downscaling because it is not that accurate. This must be kept in mind.

Now, one of the reasons these models are not doing well over India is the cold bias of the ocean. We discussed the cold bias about 20 minutes ago, and a good example is shown here.

- Similar pattern and timing of cold Arabian Sea SST bias seen in CMIP5 models
- Weak monsoon rainfall, particularly at beginning of monsoon, problem in almost all CMIP5 models

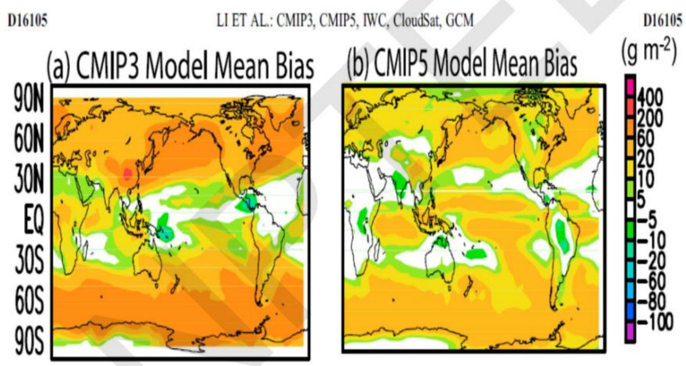
R.Levine



In the Arabian Sea, black (please refer to the graph shown above) is the observed seasonal cycle of temperature, and all the green and other colored lines represent various models. The model mean is shown as the black dotted line. What you see is that most models in the months of April, May, and June predict a temperature that is around 2 degrees lower than observed, which is a serious problem. The same models ultimately produce too little rainfall. So, you can clearly see that the cold bias in the Arabian Sea will have an adverse impact on rainfall over India.

So, models have to try very hard to improve their ability to forecast Arabian Sea temperatures accurately if they want to get the rainfall over India correctly. This is a study by Levine and highlighted by the Met Office. You can see this is a serious issue. Now, what is the bias in the ice water path? It is shown here for both CMIP3 and CMIP5, and you can see that the model ice water path is too high at higher latitudes and still too low in the lower latitudes. So, whether you take CMIP5 or CMIP3, it does not matter—models have a bias. They produce too little ice, and so one cannot trust these models completely.

Bias in ICE water path



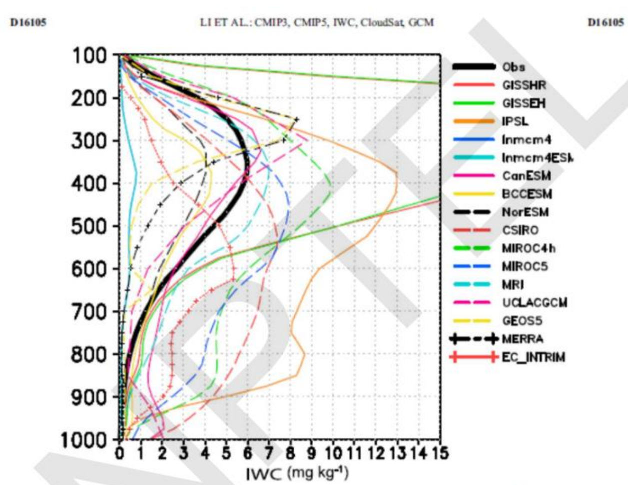
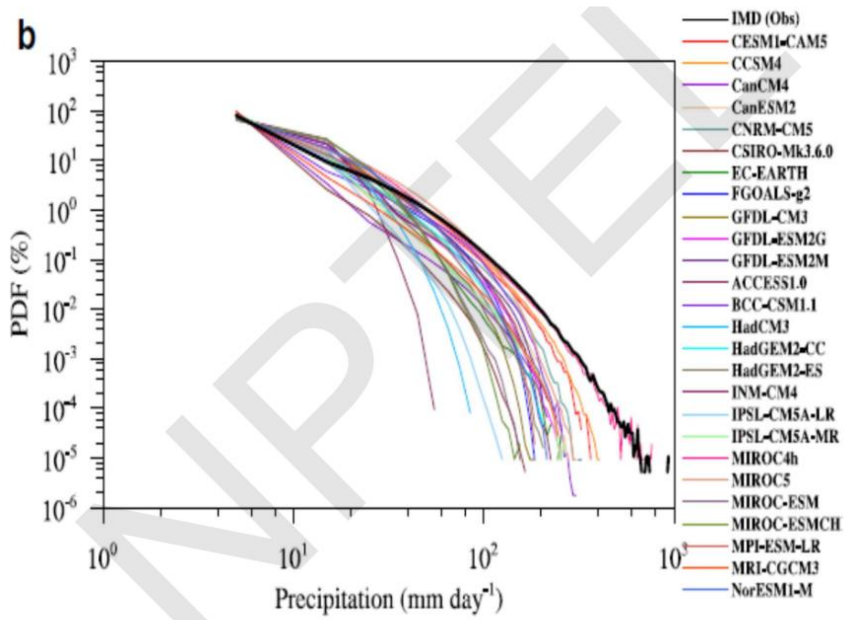
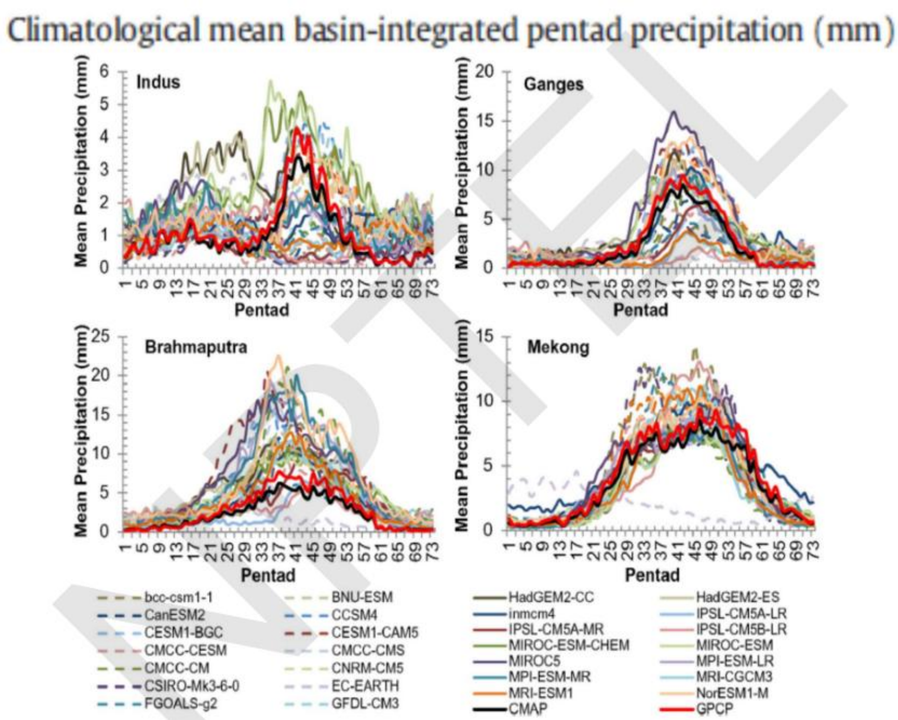


Figure 9. Globally averaged (80°N–80°S), annual mean, vertical CIWC profiles (mg kg^{-1}) from the CMIP5 GCMs, UCLA CGCM, GEOS5 AGCM, EC Interim and MERRA reanalyses, as well as the observed estimate (thick black profile). Note that the CNRM-CM5 CGCM CIWC is not available from the CMIP5 data portal at the time.

Now, here is a graph showing the vertical structure of ice fraction. The solid black line is the observed value, and the various colored lines represent the models. You can see that approximately half the models predict too high an ice fraction. You can't do much about it, because we saw earlier that ice fraction is a serious issue in climate models. Now, how about rainfall? In the below picture, black represents the observed rainfall rate.



What the models show is that the common climate models represent rainfall reasonably well at low rainfall rates, but at high rainfall rates, they are very inadequate. So, this problem has not yet been resolved—why models are not able to capture heavy rainfall regimes. We'll look at this a little later—why the models are doing poorly at high rainfall rates. Here is the pentad rainfall from June to September in many models, along with observations.



You can see that the prediction of most models for rainfall over the Indus, Ganga, Brahmaputra, and Mekong is actually high compared to what is observed. So, we need to improve the models in order to get this discharge accurately. Now, the Indian Meteorological Department has been running the CFSv2 at high resolution. What are the models saying? At the top is the model simulation compared to the Indian Meteorological Department's data. The model is showing too many clouds, and you can see that these two models are mentioned here.

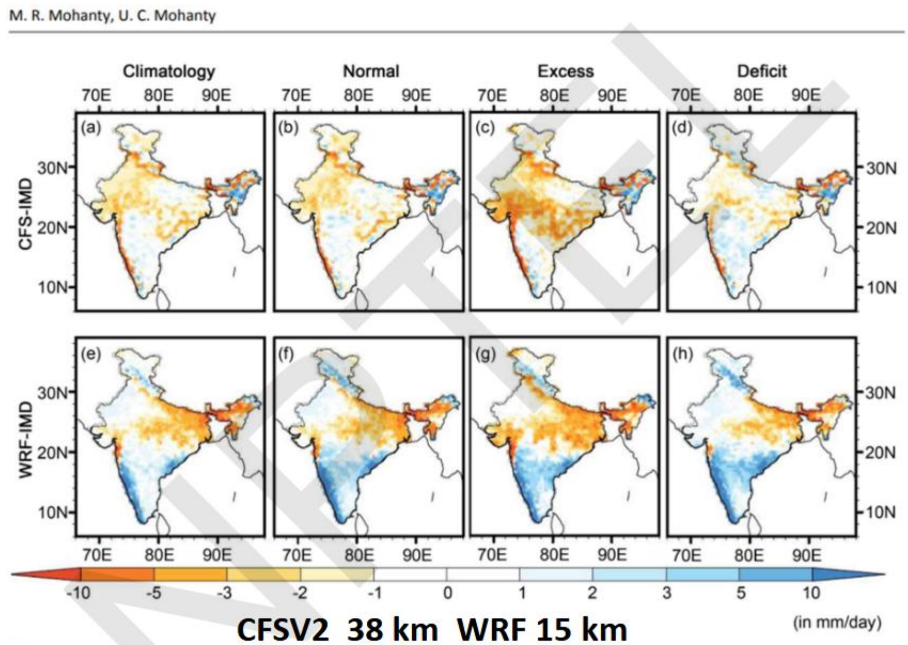


Figure 2. Mean rainfall bias (in mm/day) averaged (a) over the hindcast period of 1982-2008 and that of the composite (b) normal (c) excess and (d) deficit monsoon seasons as observed in IMD. Panels (e)-(h) and (i)-(l) are same as (a)-(d) but as simulated by

One is the regular CFSv2, which has a resolution of 38 kilometers, and the other is the WRF rainfall model. Now, let us look at Sahel rainfall.

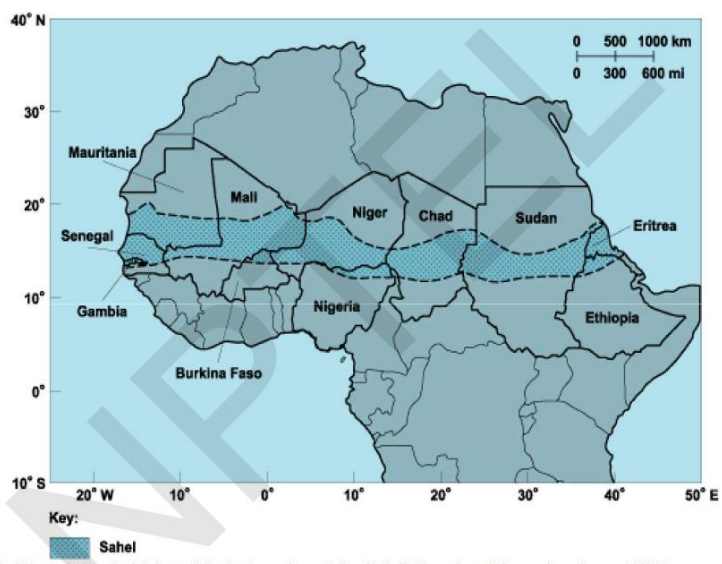


Figure 1: Map of North Africa with the location of the Sahel. Reprinted from Aondover (2008).

The Sahel rainfall is very important because in the African Sahel region—shown there by hatched lines—rainfall declined dramatically in the 1960s, leading to a major drought in Mali, Niger, Chad, and Sudan. So, there was a lot of debate about what caused this decrease. But now, in the 1980s, the rainfall has revived.

So, models are trying to see how they can simulate the decline in rainfall in the 1960s and the increase in the 1980s. One of the models discussed by Giannini shows that the model's observation is not bad over the Sahel. The Sahel is this east–west oriented region over Africa, and it has been experiencing drought.

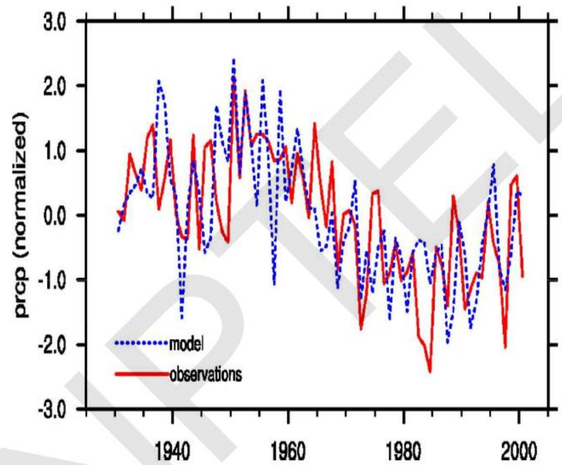


Figure 3: Index of Sahel rainfall variability from July-September from the years 1930-2000, displaying observed and modelled values. Reprinted from Giannini et al. (2003).

The model shows that rainfall, when normalized, declines from the 1950s to the 1980s and increases after the 1980s. Now, here is a picture from satellite data showing how, because of the increase in rainfall between 1982 and 2003, the greenery in Africa has increased. This is a change in the Normalized Difference Vegetation Index (NDVI).

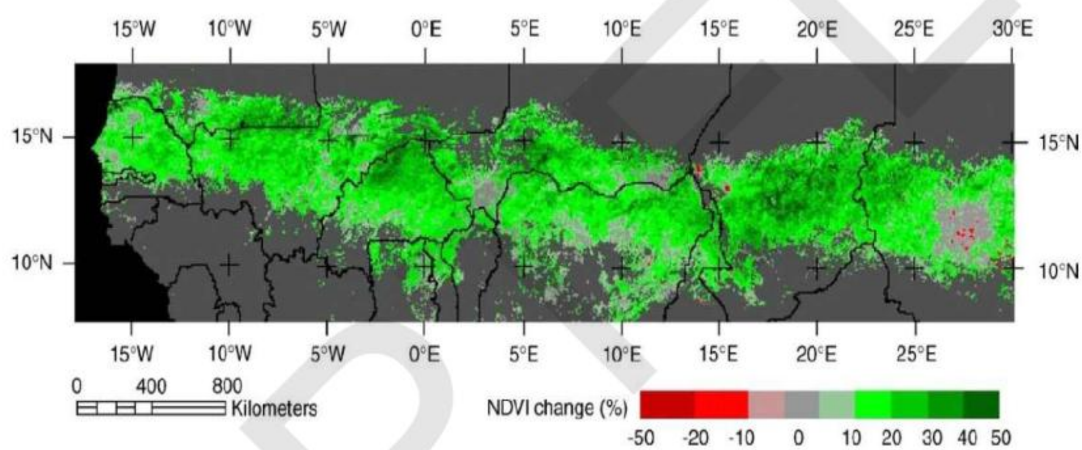


Figure 8: Trends in vegetation greenness, expressed as NDVI changes in percent during the time period 1982-2003, derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite data. Reprinted from Herrmann et al. (2005).

This is a satellite-based estimate of the amount of greenery on the surface of the Earth, obtained from satellite data—specifically, the Advanced Very High Resolution Radiometer (AVHRR). It shows that all the way from 15° West to 25° East, in the period from 1982 to 2003, there has been an increase in NDVI, which means it has become greener.

So, we need to understand what caused the decrease in rainfall from 1960 to 1980 in the Sahel, and what caused the increase in rainfall in the period 1982 to 2003. This is an important puzzle. This was modeled by Zeng et al. in 1999. They compared the simulation with observations, shown by the black lines. The simulation for the period 1980 to 1999 is shown as white dotted lines.

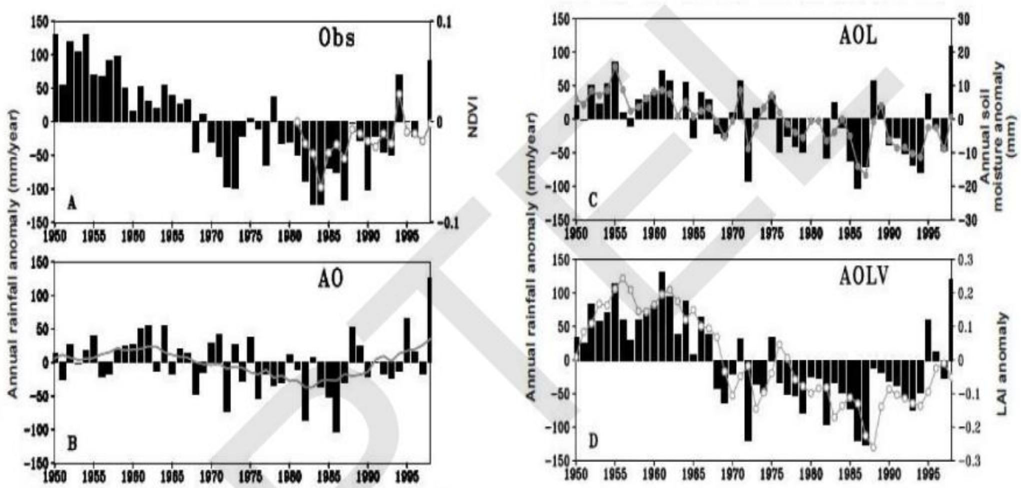


Figure 5: Rainfall anomalies (vertical bars) from 1950-1998 over the West African Sahel (13°N-20°N, 15°W-20°W). A: Observations, B: Model forced only with SSTs; soil moisture is fixed and vegetation is non-interactive, C: Model additionally forced with interactive soil moisture; vegetation remains non-interactive, D: Fully coupled model with additional interactive vegetation. Also plotted (connected circles) are for A: NDVI, C: simulated soil moisture anomaly, D: simulated LAI anomaly. All anomalies relative to 1950-1998, except the NDVI which is relative to 1981. Adapted from Zeng et al. (1999).

And what do you see? What you see is that if you use only an atmosphere–ocean model, then the model does not show any decline. The grey line is the model simulation, and the black line is the observation. So, the model does not reproduce the decline that is seen in the observation. Here, the black lines represent each year, and the solid line shows the decadal variation. You can see that the coupled atmosphere–ocean model (AO) does not capture the decline well. There is some indication, but it is not very good.

If you go to the atmosphere–ocean model with land added (AOL), there is a slight improvement. But if you add dynamic vegetation into the model, then it correctly simulates the change. This is the point made by the paper—that if you want to capture the decadal variation in the Sahel, you need not only a good atmosphere–ocean model, but also a good land model that includes land albedo, and more importantly, dynamic vegetation (AOLV), where greenery responds to rainfall.

This is a very important result obtained by Zeng et al., showing the importance of land vegetation dynamically interacting with rainfall. The AOLV (Atmosphere–Ocean–Land–Vegetation) model correctly simulates what is observed in the rainfall data. Now, many models are correctly simulating this for the 1950 to 2000 period—they are correctly simulating the decline in that period as observed and as simulated. So, things are improving in the models. Here, we are showing regional climate model simulations correctly reproducing the mean rainfall during 2003, the five-year average observed, and the model-simulated.

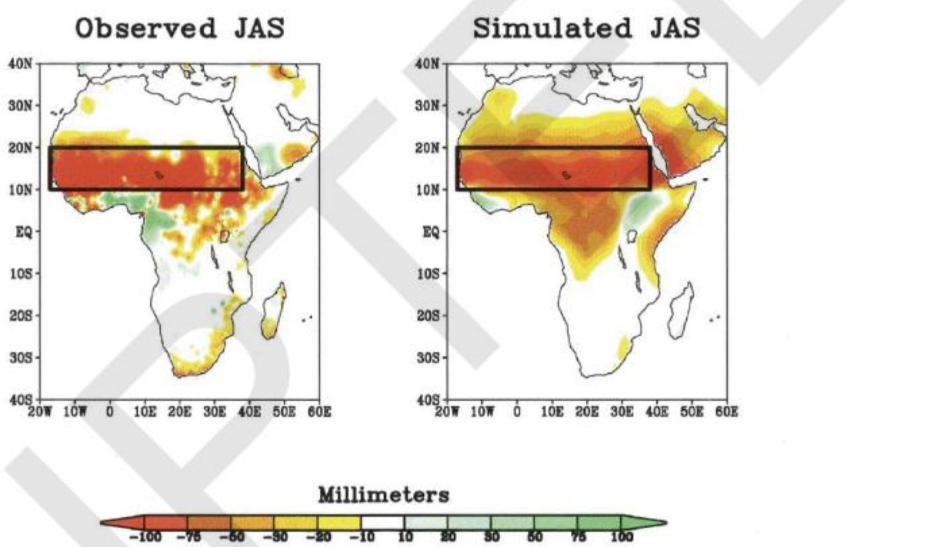


Figure 4: Observed and simulated JAS total seasonal precipitation change in mm over the time period 1950-1999. Simulations as a response to global SST forcings, mean of five different AGCMs. Reprinted from Hoerling et al. (2006).

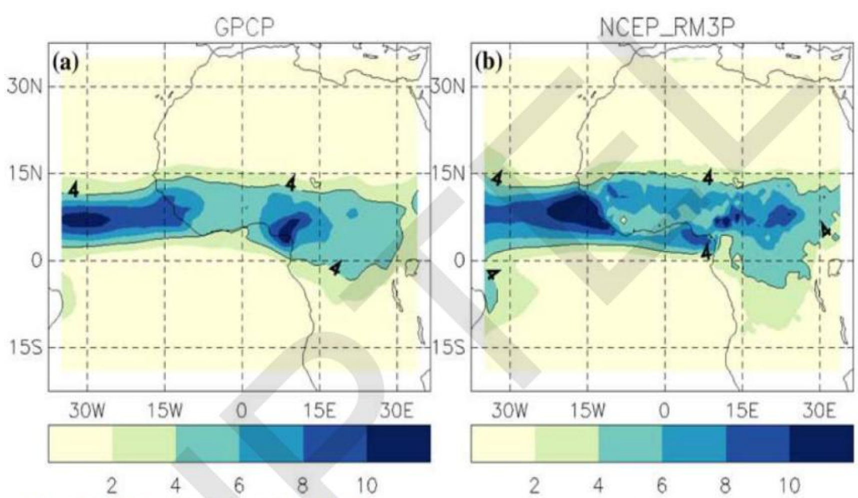


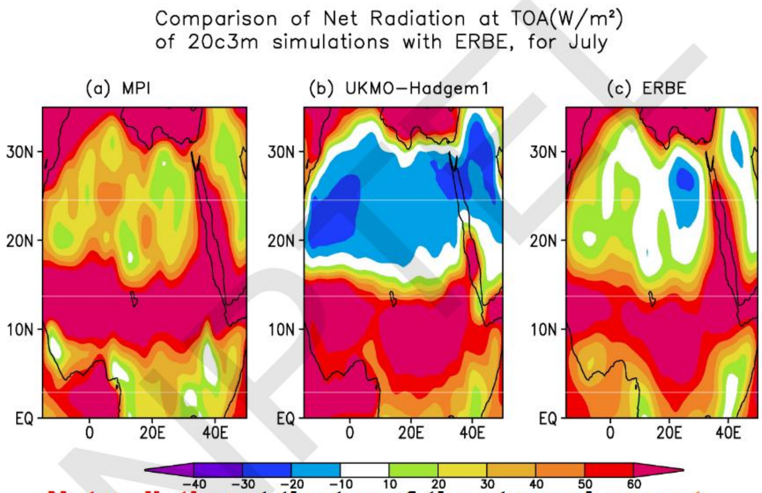
Fig. 5 Mean May–October rainfall rates in mm/day for **a** GPCP dataset, **b** the NCEP_RM3P experiment, **c** the difference NCEP_RM3P minus GPCP at 1° × 1° horizontal resolution. All data are averaged over the years 2000, 2003–2007

Impact of soil moisture initialisation and lateral boundary conditions on regional climate model simulations of the West African Monsoon

W. Moufouma-Okia · D. P. Rowell

Climate Dynamics,, 2009

So, the models are improving quite rapidly. Now, why the models sometimes do not perform well is highlighted by this comparison of the net radiation at the top of the atmosphere. This is observed from the ERBE satellite.



Net radiation at the top of the atmosphere not simulated accurately in most models

There is negative radiation over the Sahara and positive radiation over 10° to 15° North. The UK Met Office model correctly reproduces this pattern, although it is a little too negative over the Sahara. But the MPI (Max Planck Institute) model from Hamburg does not even show the negative sign here. This means it would tend to produce too much rainfall over Africa, because it does not reproduce the correct net radiation at the top of the atmosphere, which is the energy input into the monsoon model.

Now, if you look at aerosols—the role of aerosols, which we discussed earlier in our lectures—the annual mean visible aerosol optical depth from 2001 to 2005 using MODIS is shown along with the CMIP5 model output from 2005, and the difference between them.

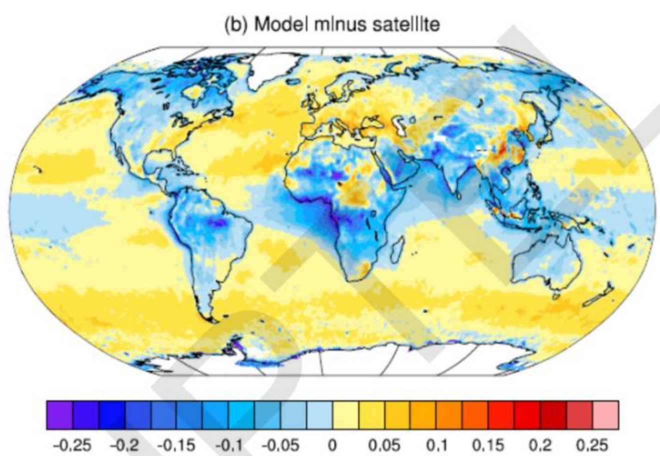


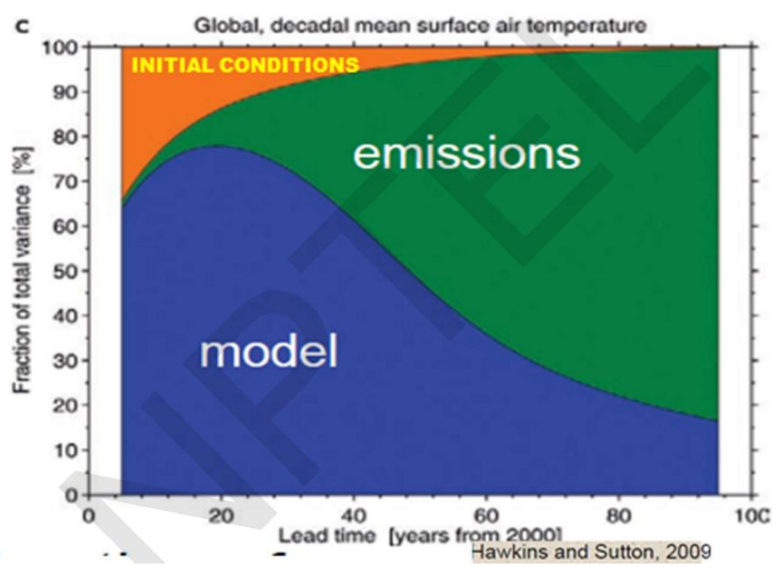
Figure 9.28 | (a): Annual mean visible aerosol optical depth (AOD) for 2001 through 2005 using the Moderate Resolution Imaging Spectrometer (MODIS) version 5 satellite retrievals for ocean regions (Remer et al., 2008) with corrections (Zhang et al., 2008a; The model outputs for 2001 through 2005 are from 21 CMIP5 models

What you see is that the differences are very large and negative over India and southern Africa, and too positive over Europe. That is, the model is producing too high aerosol concentrations over Europe and too low aerosol concentrations over India, South Africa, and South America. This shows that aerosol models are having some difficulty. This is partly because accurate data was not available before the year 2000.

Only after satellites came did we have accurate estimates of aerosol concentrations over many regions of the world, especially tropical regions. So, aerosols were not correctly modeled in these simulations. I want you to remember that when you look at model simulations, there is a cascade of uncertainty.

"Cascade of Uncertainity"
Scenario Uncertainty
Model Uncertainty
Downscaling Uncertainity
Impact model Uncertainity

First, there is the scenario—we have to predict how CO_2 and aerosols will change in the next 50 years. We have already seen that models have uncertainty due to clouds and aerosols. Then, if we take the model and downscale it to a higher resolution using a statistical scheme, that introduces further uncertainty. And finally, if we use it to predict floods in a hydrological model, that adds another layer of uncertainty. So, there is a cascade of uncertainty.



We need to be very careful in trying to believe the output of models without proper validation. That is the message I want to give at the end of this lecture. We will continue this discussion in the next lecture. As we look at model output from now to 100 years into the future, we need to ask: Where is the uncertainty largest? Is it in the initial condition? Is it in the emissions? Or is it in the model itself?

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