Climate Change Science
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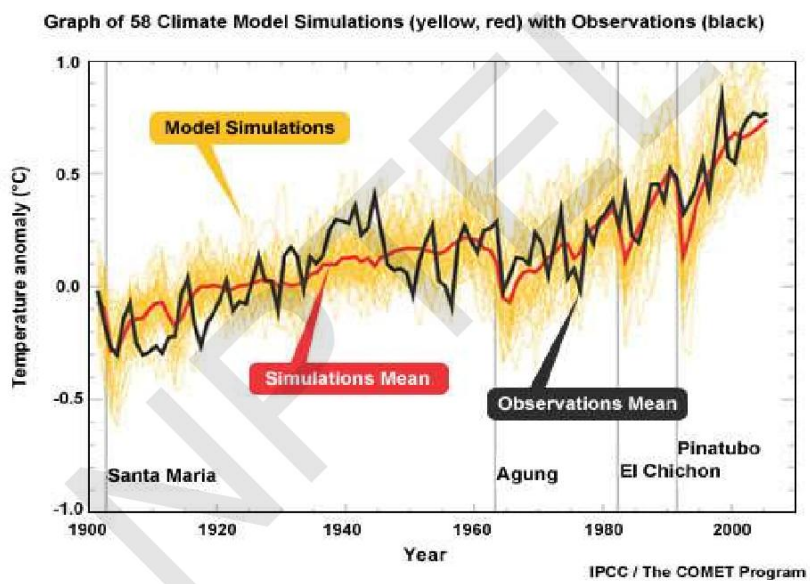
Lecture – 48
How good is the model simulation

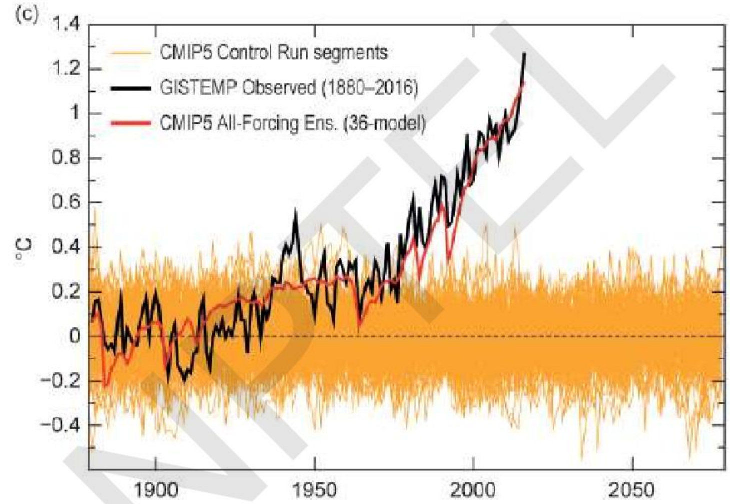


In the last lecture, I was telling you about this picture, a very important graph showing that the multi-model mean simulates more or less the warming trend of the Earth when compared to the observation in black. But it can go wrong in individual years. In years where there was a major eruption of a volcano, it can go wrong, or in some years, you can see here, the Earth warmed much more, but the model did not capture that. This is not because of El Niño. This is because most of the heat that is trapped by carbon dioxide due to the greenhouse effect is stored in the ocean. Ninety percent of the heat is trapped in the ocean because the ocean has a lot of heat storage capacity.

Now, in some years, that heat comes out in the Pacific Ocean through a phenomenon called El Niño in the Pacific. So, if that heat comes out, then the temperature of the Earth increases in that one year. The model is not able to simulate that accurately because that is something happening in that one year. In spite of all the wonderful progress we have had, we are still not very accurate in getting an estimate of where the ocean stores heat and how that heat ultimately comes out into the atmosphere.

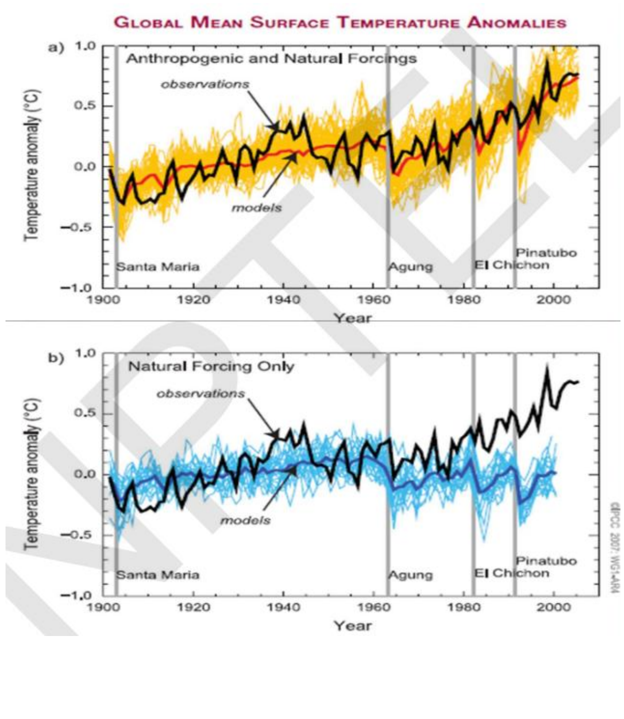
So, do not trust the model for giving the right answer in any one year. For example, last year we had 1.5 ºC global mean temperature above normal. No model got that prediction right. They said it would be 1.1–1.2 ºC; it came out as 1.5 ºC. So, this kind of problem will come, but the aim of these models is not to get the global mean temperature correctly in any one year. That is not the aim.

The aim is to get the long-term trend, and that is correct. You can see the long-term trend is perfectly correct in the model, although not good for a particular year. So, keep that in mind when you evaluate models.



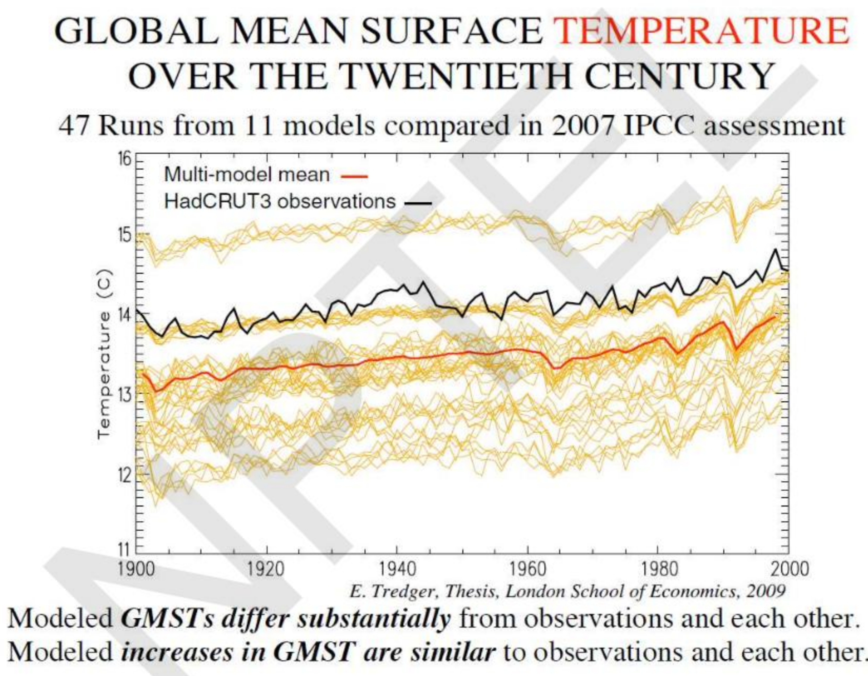
Knutson et al., Bulletin of the American Meteorological Society, December 2017

The same model, when you keep carbon dioxide constant at 280 parts per million, shows clearly—this is the simulation with carbon dioxide kept constant, the so-called control run—then the temperature does not change. It changes by 0.2º year to year, but in the long term, there is no change. So, this is the purpose of the model. The model was built to predict the trend in the temperature of the Earth over the next 100 years, and that trend is captured very nicely between 1960 and 2016. So, that is the purpose of the model, and it serves the purpose correctly. But if we ask for any one year, it will not be right. So, keep that in mind for any valid models.



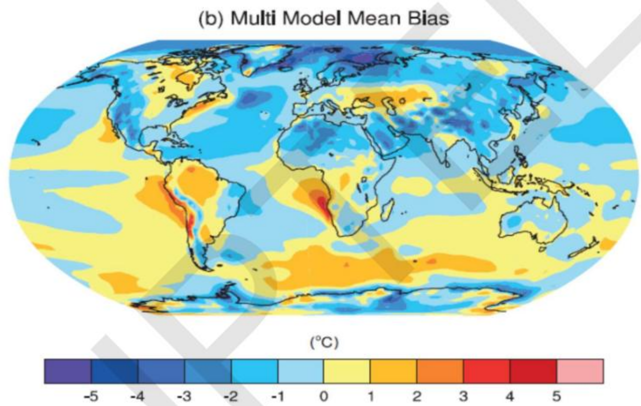
This result (the graph shown above) I have shown many times, but I have to repeat it to remind you that if you include all the effects of volcanoes and CO_2 increase, you get the increase. But if you only include volcano and solar variation, but not the CO_2 increase—so-called natural forcing—then the model does not show that warming. So, we can be very confident that the warming of the last 60 years was solely due to the increase in carbon dioxide. There is no doubt about that. In the last report of the IPCC, they said very clearly that we are virtually certain that the warming we have seen in the last 60 years is due to the increase in carbon dioxide. Now, if you look at any one model, they are not that good.

Here is an example of the multi-model mean, with various models. You can see there is one model that is getting 15 ºC, another model getting 14 ºC, and another model getting 13 ºC.



So, there are variations. Some models do not tune it to 15 ºC. They let it be at 14 ºC or 13 ºC. For example, in one case, they are saying from a Hadley Center observation, the global mean is 14 ºC. I would actually assume 15 ºC, but that depends on which temperature you are talking about. Are you talking about the skin temperature of the Earth or the temperature at the height where the measurement is made, about 2 meters? That also depends on that. But the key point to understand is that various models give various temperatures. Not all of them agree with what observations are given. So, global mean surface temperature differs substantially from observations and from each other.

The other problem models have is when we look at the spatial pattern. If we look at the 2-meter height air temperature over the world and compare it to observation, this is the average of many models minus observation. You can see that models are too cold in the Arctic and Antarctic and in many oceans. And in some parts of the ocean, they are too warm also.

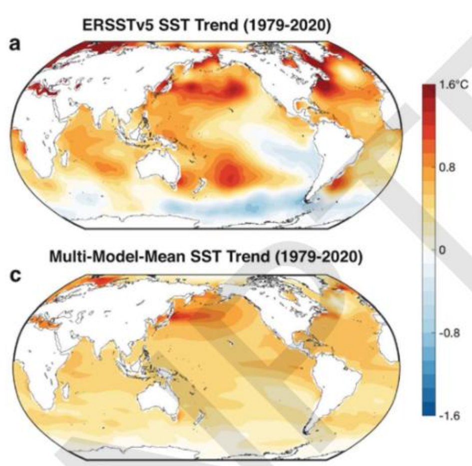


Annual-mean surface (2 m) air temperature (°C) for the period 1980–2005.

So, there are problems in the model in terms of not the global mean temperature, but local temperature. So, you do not expect the model to give you the right value of a local temperature because that is governed by many, many factors, not all of which are correctly modeled. So, you must be aware of the generally cold bias in ocean models and a warm bias near the coastline. This problem has not yet been resolved. This is partly due to model resolution. Right near the coast, cold water from the depth of the ocean comes up. It's called upwelling.

It comes out here, right here. Now, to simulate that correctly, you need a model resolution of about a kilometer because these upwelling regions are very narrow. So, if you do not have a resolution to capture the intensity of the upwelling, you will not get the right temperature. So, this problem is there. It is not easy to solve, but the global mean is correct.

Now, the other thing which is not so good is what was pointed out recently about the trend. Forget about the actual value on one day. You do not worry about it. You want to know the trend over the last 40 years, which is what is shown here.



Wills, R. C. J., Dong, Y., Proistosecu, C., Armour, K. C., & Battisti, D. S. (2022). Systematic climate model biases in the large-scale patterns of recent sea-surface temperature and sea-level pressure change. Geophysical Research Letters, 49, e2022GL100011. https://doi.org/10.1029/2022GL100011

This is the observed trend in the sea surface temperature. This is the multi-model mean. It is much lower than the observed, especially in the southern hemisphere and in the Atlantic Ocean. So, this is a serious issue because the model is not showing the warming that is seen in the observation by satellite data. The model is showing much less warming. We do not know the precise reason. It could be due to ice-melting processes or mixing in the ocean. So many possibilities are there, but the trend in ocean temperature does not follow what is observed. But the global mean looks okay.

Papalexiou et al, Earth's Futurehttps://doi.org/10.1029/2020EF001667

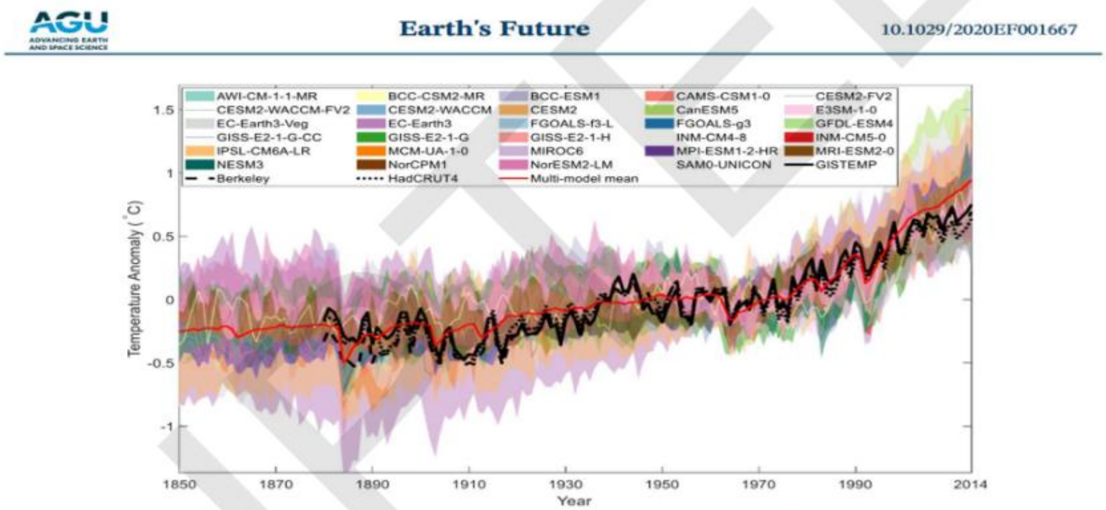
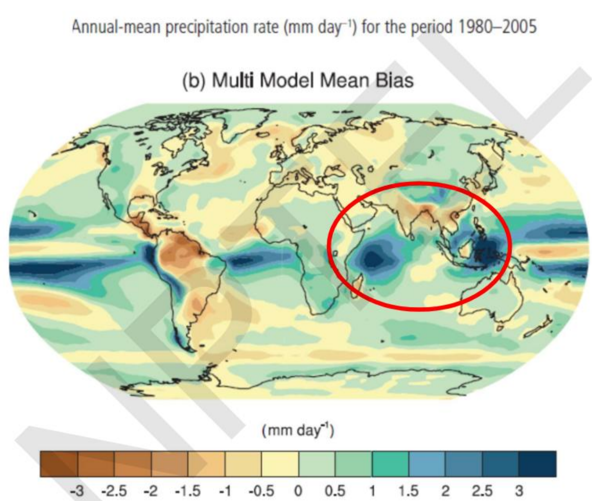


Figure 1. Observed and CMIP6 simulated anomalies of global mean surface temperature. Shaded area shows the ensemble of models with more than one simulation, and for models with one simulation are shown as thin lines, multi-model mean (thick red line) and historical observations from GISTEMP (thick black line), Berkeley Earth (dashed black line), and HadCRUT4 (dotted black line). Anomalies are estimated for the 1951–1980 baseline period.

There is another study recently published that shows that many models are compared, and the black line is the observation. You can see that the multi-model mean in red and the black line is the temperature from the Goddard Institute. The dotted line is the temperature from the UK Met Office. They are all quite close to each other, and the model simulation in red is good, more or less, except in a few decades. So, the multi-model is good, but locally it is not good.

Now, the next problem is rainfall, because rainfall is very important for us human beings.



You want the right amount of rain for agriculture. At the same time, you do not want too much rain because it causes flooding. You can see that in a multi-model bias—that is, the difference between multi-model mean minus what is observed—there is a large error of the order of 2 mm per day. That is a very large error near Indonesia and near the African equatorial region.

And over South America, the rainfall is too low. Same thing in India. So, these models do not get the monsoon rainfall accurately, which I will talk about in some depth in one of the later lectures. They estimate too high a rainfall over the ocean. So, this problem has not yet been solved. This is related to the way clouds are modeled. We know there are deficiencies. We have discussed that. In spite of various groups trying various techniques, ultimately, the multi-model mean does not get a small bias. It has a large bias. There are people who are concerned about it. They are saying if the multi-model mean has a bias, the common practice is to do bias correction. Take the model rainfall, let's say over India. Many models predict too low rainfall over India. So, you correct for it. You add some value so that you get the present value.

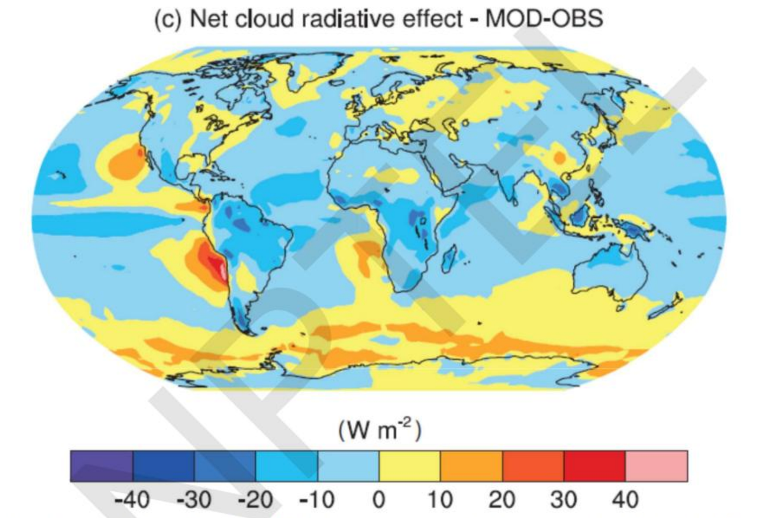
Bias Correcting Climate Change Simulations - a Critical Review by Douglas Maraun
Curr Clim Change Rep (2016) 2:211–220

The most crucial assumption underlying bias correction is that the driving dynamical model skillfully simulates the processes relevant for the output to be corrected. For climate change simulations, this implies that also the changes of these processes are plausibly simulated. Bias correction is a mere statistical post-processing and cannot overcome fundamental errors in a climate model.

Assessment of Bias Assumptions for Climate Models
Christian Kerkhoff et al, Journal of Climate, 27,2014 https://doi.org/10.1175/JCLI-D-13-00716.1
It is generally not correct to assume that model biases are independent of the climate state. These biases are generally significant in comparison to projected climate changes;

So, when looking at the future change, you compare it to the present. So, the fact that the model is not doing well in the present climate is not accounted for, because you are looking at the difference between future and present. But it is important to remember that bias correction is not safe because biases are generally significant in comparison to the change. For example, I have seen in many models, when you double CO_2, you get an increase in rainfall, but that increase is less than the model's bias in the present climate.

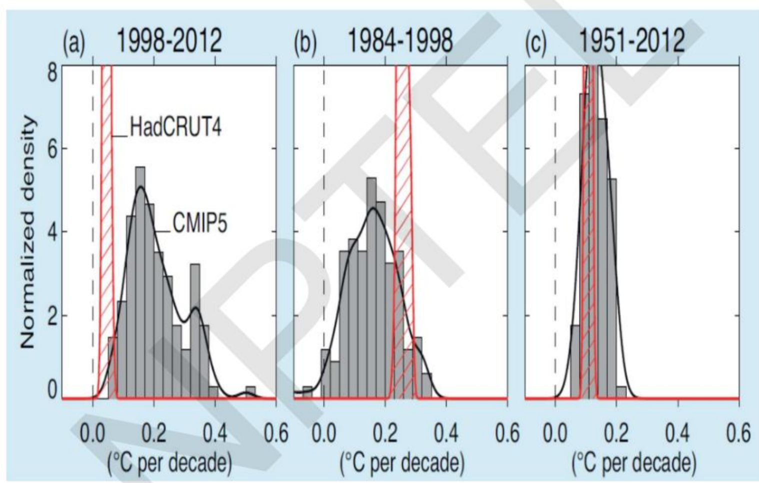
So, if a model has a bias of one millimeter per day in the present climate, and it predicts a future increase of one millimeter, one cannot be too sure that it is correct. The other, of course, is the effect of clouds. Clouds are very important in the Earth's climate. They control the Earth's climate. So, we want to know what the net cloud radiative effect is. How far does a cloud cool the Earth? We all know that in the present climate, the presence of clouds reduces the temperature of the Earth because it reflects solar radiation. So, the net cloud radiative effect is negative in the observation (please refer to the spatial plot shown below), but the model's net cloud radiative effect, when compared to observation at all points of the globe, shows a large difference—especially over regions where the model was too warm, where SST was too high. You can see it is a big difference. So, this is a problem we cannot completely avoid.



Annual-mean cloud radiative effects of the CMIP5 models compared against the Clouds and the Earth's Radiant Energy System

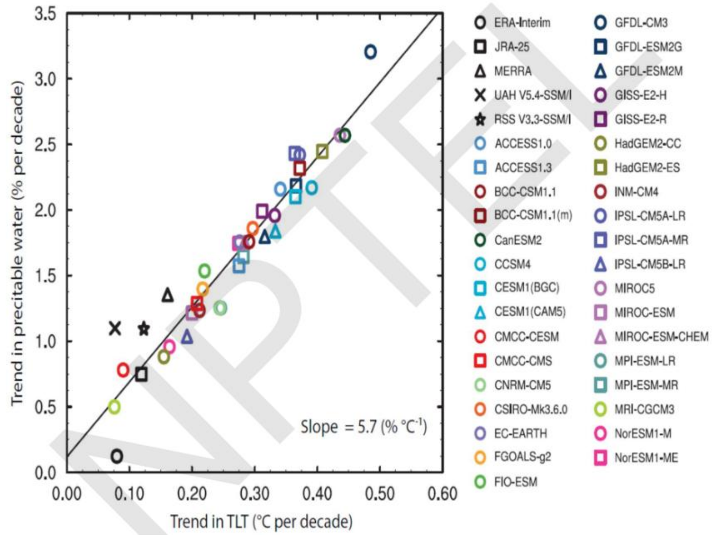
Now, you look at the decadal trend.

Decadal trend in Global Mean temperature



I said that the model trends are not accurate. You can see that in this decade, 1998 to 2012, the model temperature (CMIP5) increase was higher than the observed (HadCRUT4). But if you look at a different decade—15 years—the model warming is less than the observed. But if you look at a longer period of 60 years, then they are very close. So again, you cannot trust the model to get the correct global warming trend in any one decade. In one period, it was showing less warming; here it is showing more warming. But if we combine these two and look at a long-term trend, it is correct. Suppose a model says that in the next 10 years, the temperature will go up by 0.2º—you cannot be 100 % sure because within the model, you can see there is a large spread.

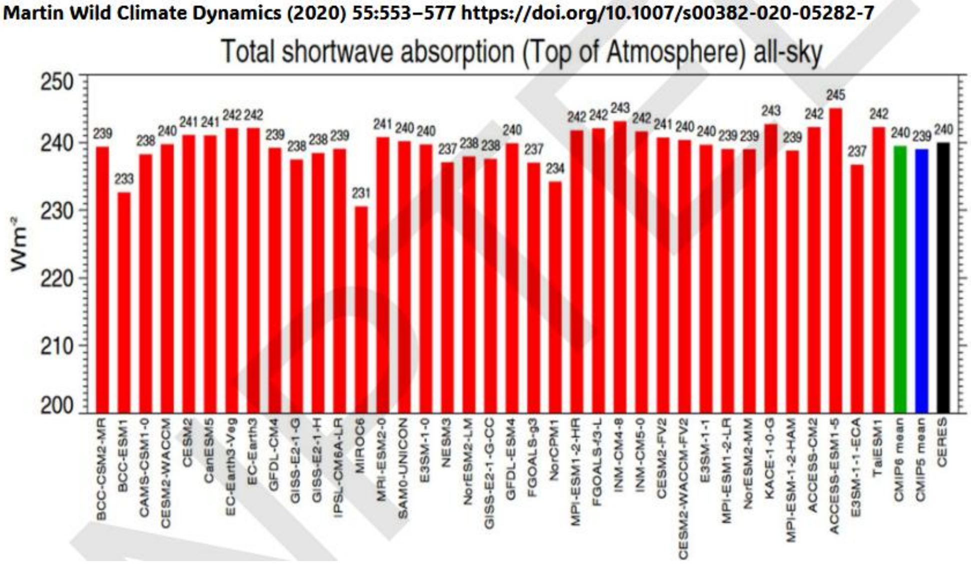
Not all models show 0.2º increase; some show much higher, some show much lower. So, there is a spread among models, plus our confidence in the models to predict the warming in the next decade is not very good. But we are sure about what will happen in the next 100 years.

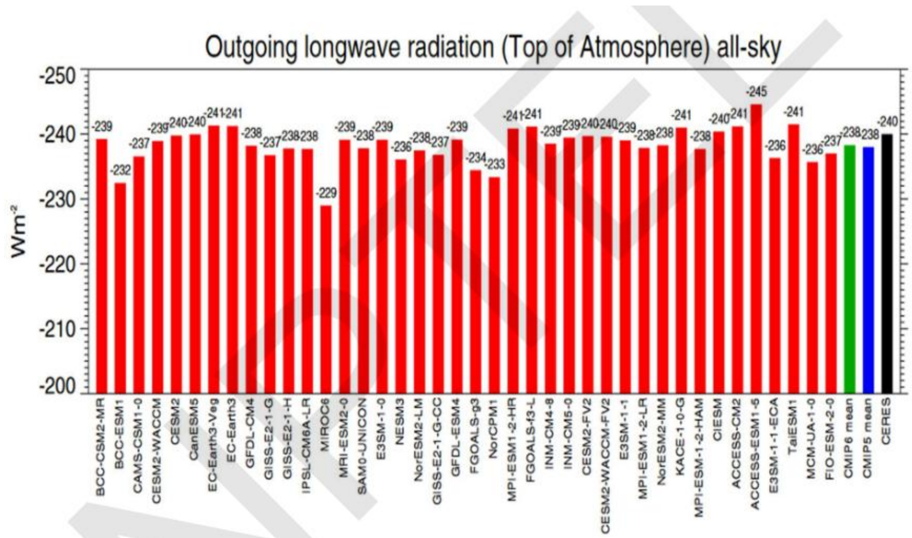


Now, here is the comparison between the trend in temperature in the lower troposphere (TLT)—that is, let us say 0 to 5 kilometers—and the amount of water vapor in the column, called precipitable water. How much water will you get when you condense that water vapor into the ground, and see how much it is. You can see that the increase in water vapor per decade is of the order of 1 to 3%. It follows the increase in low tropospheric temperature of the atmosphere. So, you can see that the model's increase in water vapor in the column is closely linked to how the troposphere is warming. So, you have to get that right because that will control rainfall.

Now, let us come to how the models are tuned. Most models are tuned to ensure that total shortwave absorption as measured at the top of the atmosphere is 240 W/m^2. You know that from one satellite dataset and two other models. So, most models are around 240 W/m^2 because they are tuned, they are adjusted to get 240 W/m^2 because that is the correct answer.

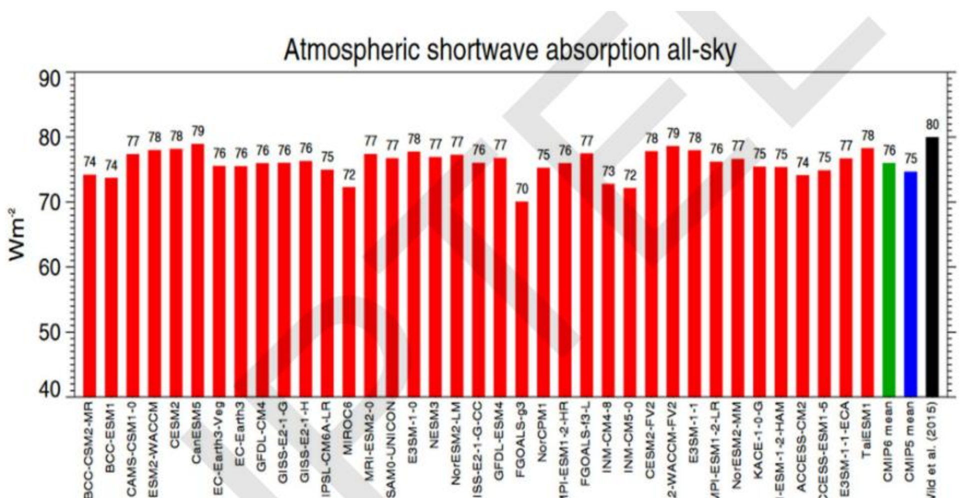
Martin Wild Climate Dynamics (2020) 55:553–577 https://doi.org/10.1007/s00382-020-05282-7



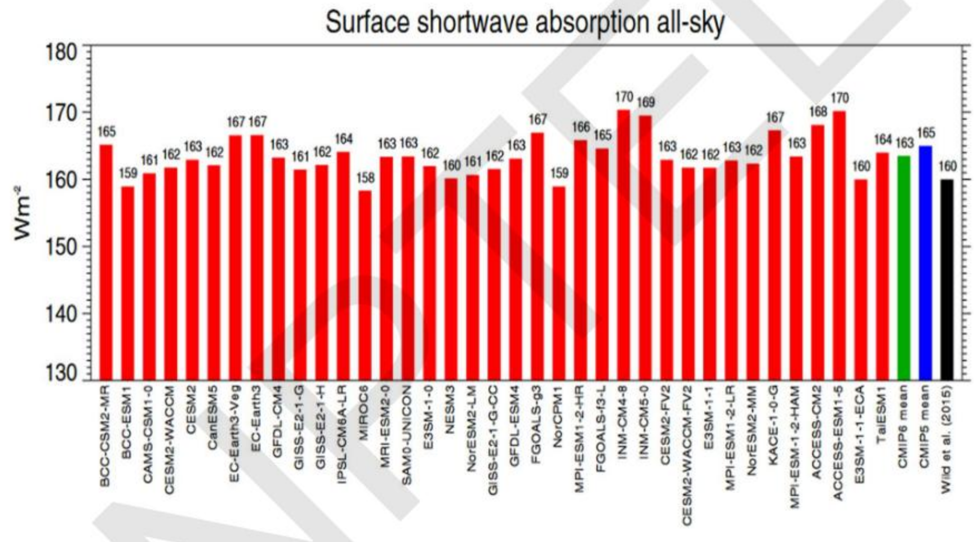


Same thing for OLR—outgoing longwave radiation. We know it is around 240 W/m^2, measured, shown in black value here. All the models are tuned, and if you average all of them, you get 238, which is quite close to 240. Some models are quite low—229; some are 245—but if you average all of them, you get 240.

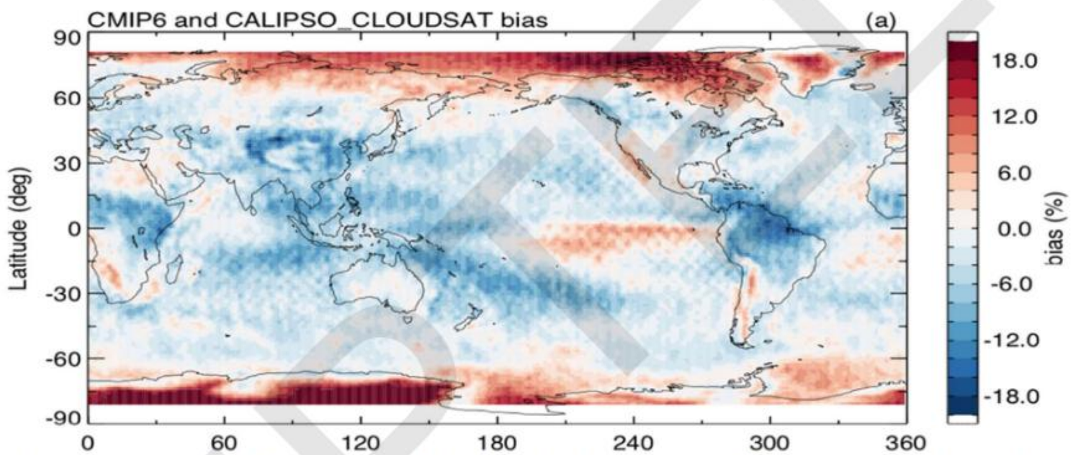
Now, how about shortwave absorption? It is a very important parameter: how much radiation the atmosphere absorbs from the Sun. It is around 80 W/m^2—remember that. The climate model mean is around 75 W/m^2, and various models show a range of 70 to 79 W/m^2. So, these are numbers within the error bar of observation, and these are coming out right because models are tuned.



Next, we have surface absorption (in the figure shown below), which you remember was around 160 W/m^2, and most models are between 160 and 170 W/m^2. So, these numbers all look good because, globally, the models have been tuned to get these numbers correctly.



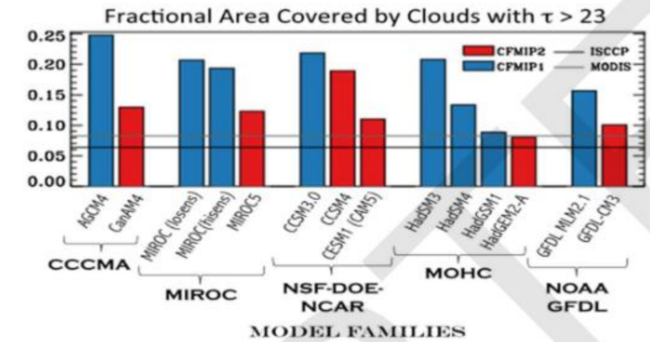
Now, let us look at the spatial pattern. Here is a comparison between total cloud fraction over a 5-year period as obtained from the satellite CALIPSO and CLOUDSAT, both put together, two satellites, and compared with CMIP6 multi-model mean.



Contour plot of bias between CMIP6 and CALCLD cloud fractions over the period from July 2006 to February 2011. The CMIP6 ensemble shows an increasing trend, but the CMIP5 shows a decreasing trend in TCF values
P.P.Vignesh et al., Earth and Space Science, 7,2020, e2019EA000975. https://doi.org/10.1029/2019EA000975

When you calculate, model minus observed value, you see the model predicts too high a cloud in the polar regions and too low a cloud in most of the tropics, except in the equatorial Pacific here. Models have problems in terms of percentage difference between total cloud fraction measured by satellite and obtained from models. So, there is an error of the order of 10 % plus or minus.

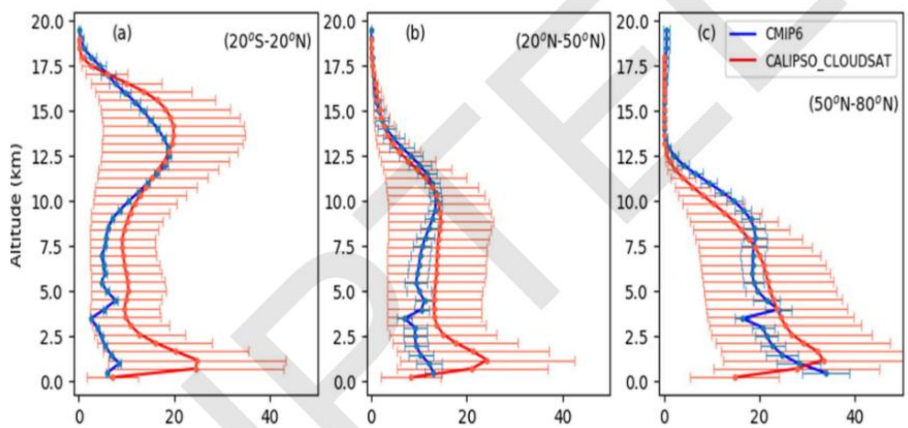
Here is another graph (shown below) comparing the global mean for thick clouds with optical thickness above 23. You can see that over a period of time, the difference between model and observation is coming down—not dramatically, but it has come down.



S.A.Klein et al., JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, 118, 1329–1342, doi:10.1002/jgrd.50141, 2013

Figure 4. Fractional area in the domain 60ºS–60ºN covered by clouds with $\tau > 23$ for selected model families and observations. Models are plotted so as to illustrate progress in reducing the overestimate of optically thick cloud over time by ordering models from earliest to latest (left to right) within families. In models for which progress can be tracked, the amount of optically thick cloud has been reduced between model generations, making them more consistent with observations.

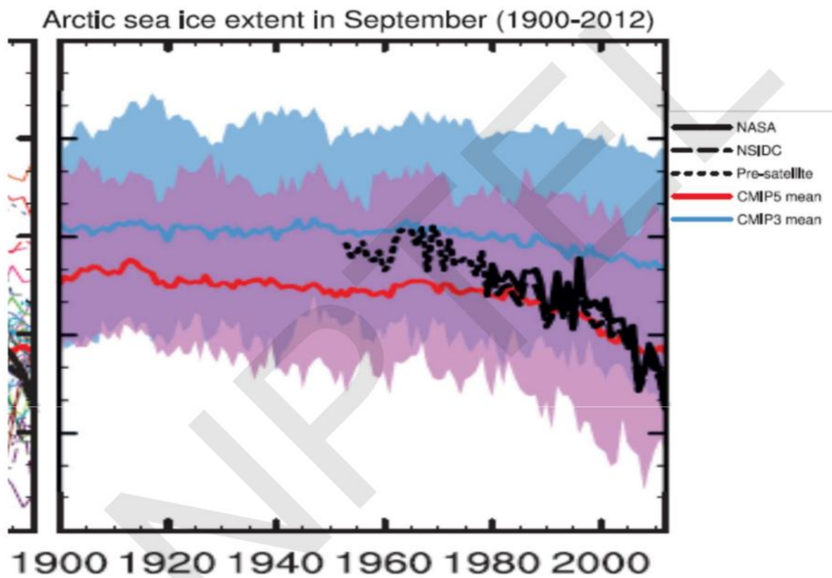
Now let us look at the vertical variation of clouds.



Mean vertical height profiles of cloud fraction of CMIP6 and CALCLD observations during the period from July 2006 to February 2011

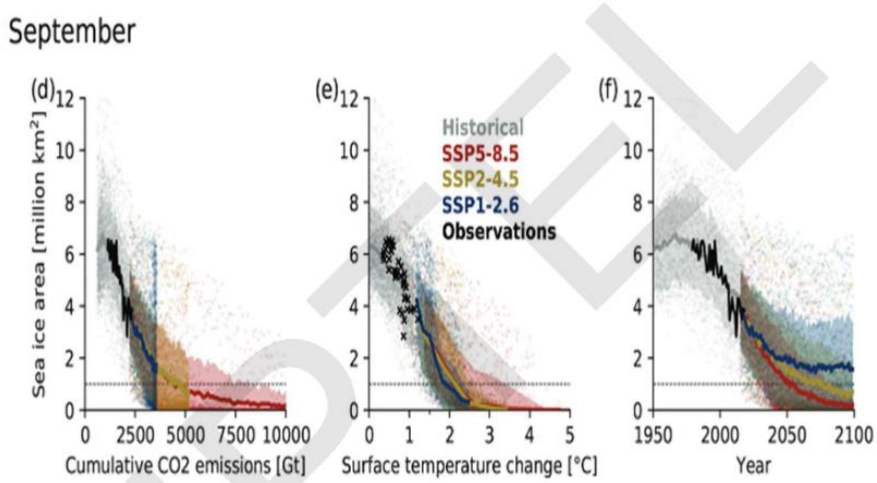
Here, the red is the satellite measurement, blue is the multi-model mean, and you can see clearly that the major error is near the surface. The shallow cloud at a height of 1 kilometer is not modeled by CMIP6. You can see clearly in the northern hemisphere, middle altitude; in the region, 20º to 50º N; and the 50º - 80º N region. In all of them, the model-simulated cloud fraction is less than observed. So, this is a challenge—we have not yet solved it.

Now, another important parameter, if you recall, is the melting of the Arctic sea ice, which we are concerned about because that controls our climate.



So, here the black line is observation from the satellite data as obtained by NASA and the NSIDC, a government organization under the U.S. government. The red and the blue lines are two different model simulations. You can see the more recent model, CMIP5, seems to agree about the Arctic ice extent in comparison to the blue, which is an older model.

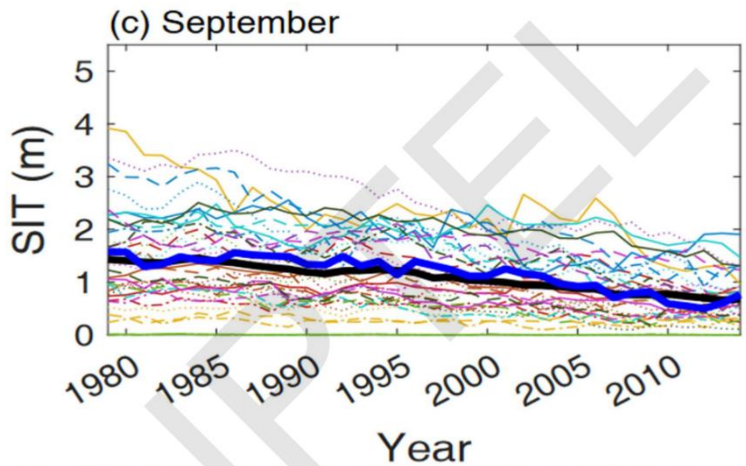
This is the month of September, and I am comparing more recent simulations.



Notz, D., & SIMIP Community (2020).Arctic sea ice in CMIP6. Geophysical Research Letters, 47, e2019GL086749. https://doi.org/10.1029/2019GL086749

You can see here—focus on surface temperature, the middle graph—you can see that it is quite good. The model simulations and the observations are quite close to each other.

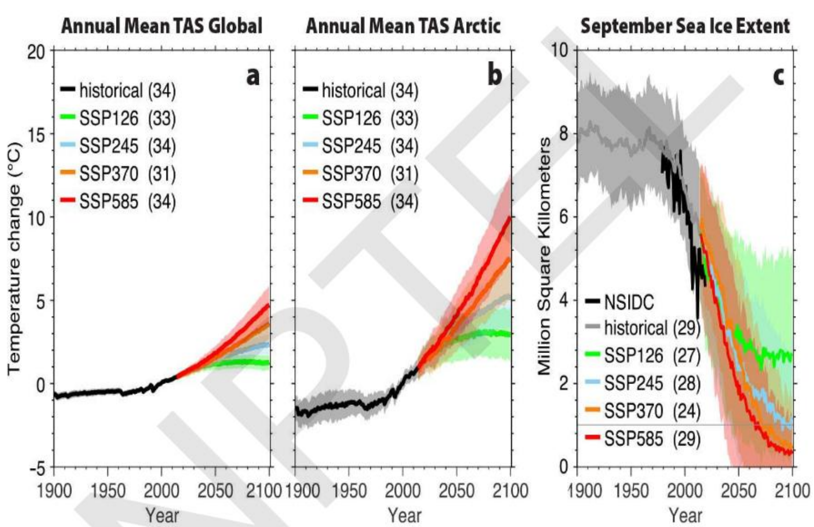
Now, we look at ice thickness (in the graph shown below). Now, ice thickness is a tough parameter to model—the thickness of ice.



Chen, L. Y., R. H. Wu, Q. Shu, C. Min, Q. H. Yang, and B. Han, 2023: The Arctic sea ice thickness change inCMIP6's historical simulations. Adv. Atmos. Sci., 40(12), 2331–2343, https://doi.org/10.1007/s00376-022-1460-4.

Shown here are two different estimates of the sea ice thickness and the simulations of the models. They are not that great—wide variation in sea ice thickness, all the way from 3 meters to 0.5 meters—and that is a parameter not easy to model.

Here is another example of the Arctic Sea ice, again showing that the models are improving now. The sea ice extent—black is the historical data—then you have the model simulation.



https://tos.org/oceanography/article/arctic-research-at-pmel-from-sea-ice-to-the-stratosphere

Here is another example of the winter sea ice from March to May in the Northern Hemisphere (shown below)—not just the Arctic, the entire Northern Hemisphere. You can see that different models are giving different answers. Some models are saying that by 2100, the amount of winter sea ice will come down dramatically, while others are not showing that much.

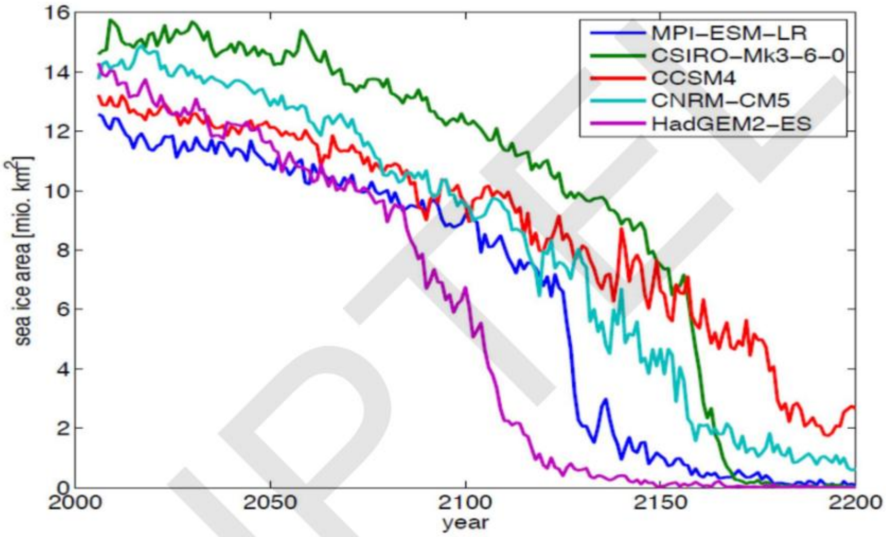


Fig. S1 Evolution of winter sea-ice area (mean over March to May) in the Northern Hemisphere in RCP8.5 simulations for the five models discussed under type-4 change.

Here is another example showing the Arctic Sea ice in September—various simulations—and some do not show any change.

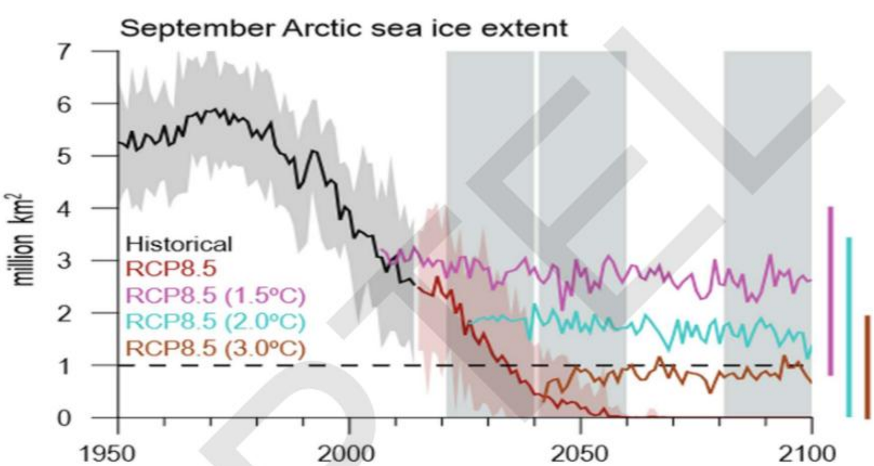
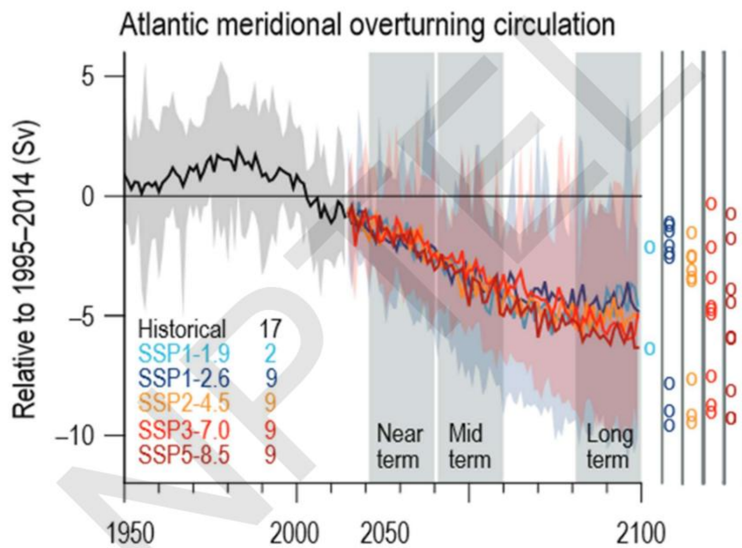


Figure 4.5 | Arctic sea ice extent in September in a large initial-condition ensemble of observationally-constrained simulations of an Earth system model (CanESM2). The black and red curves are averages over twenty simulations following historical forcings to 2015 and RCP8.5 extensions to 2100. The other curves are averages of over 20 simulations each after global surface air temperature has been stabilized at the indicated degree of global mean warming relative to 1850–1900. The bars to the right are the minimum to maximum ranges over 2081–2100 (Sigmond et al., 2018). The horizontal dashed line indicates a practically sea ice-free Arctic. Further details on data sources and processing are available in the chapter data table (Table 4.SM.1).

It is only 1.5 degrees warming. If the warming goes up, they definitely show that if it is 3 degrees warming, the sea ice will almost disappear in the Arctic. So, these are the predictions, but not very accurate.

This is the Atlantic Meridional Overturning Circulation (AMOC), which we discussed a lot because that has an effect on future climate.



We have data only from 17 years. Beyond that, the models agree as to what rate the circulation will change in response to global warming.

Now, the other thing which is very important is: as the carbon dioxide is absorbed by the ocean, it will become more and more acidic.

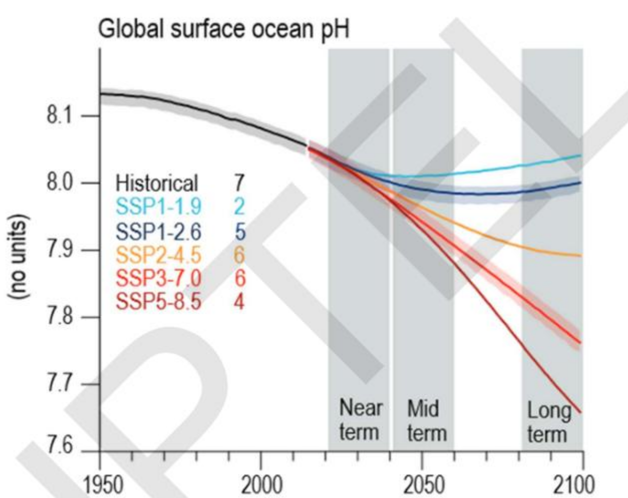
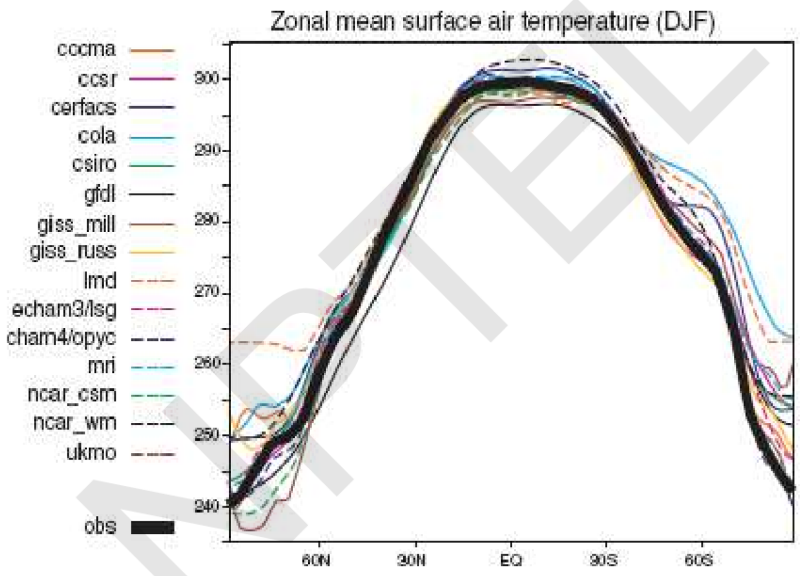


Figure 4.8 | Global average surface ocean pH. The shadings around the SSP1-2.6 and SSP5-7.0 curves are the 5–95% ranges across those ensembles. The numbers inside each panel are the number of model simulations. Results are from concentration-driven simulations. Further details on data sources and processing are available in the chapter data table (Table 4.SM.1).

Right now, it is alkaline—it is above 8—and at some point, in the near future, it will cross 8 completely. So, it will become acidic. Because if it is acidic, it is a huge problem for us because most marine animals cannot handle an acidic ocean. It will cause a lot of problems.

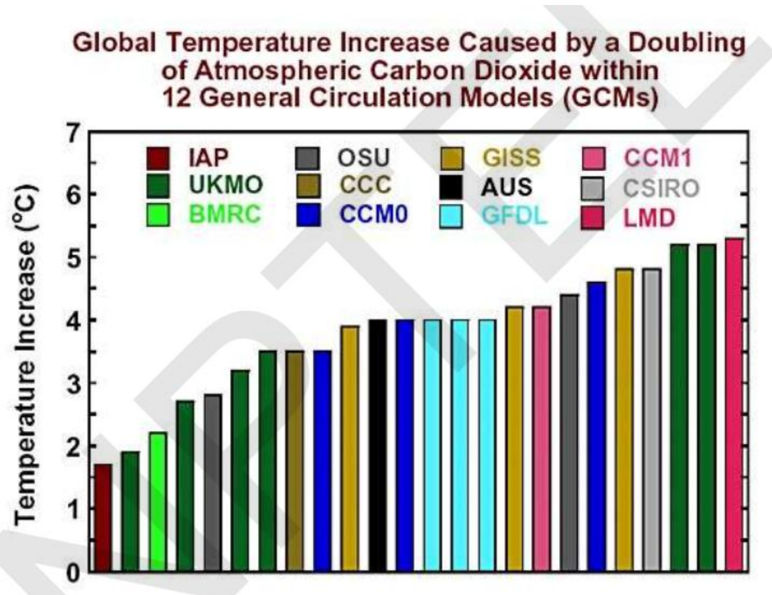
So, we need to see how to limit the CO_2 emission. Only when you limit it will it be under control. If you go on business as usual, you are going to get a lot of warming. So, this is an important point that has been made—that we have to work hard in the next 30 years to ensure that carbon dioxide usage is reduced. You can see that if you want to prevent rapid decline in pH and a catastrophic impact on ocean life, we have to follow a more gradual path of decline.

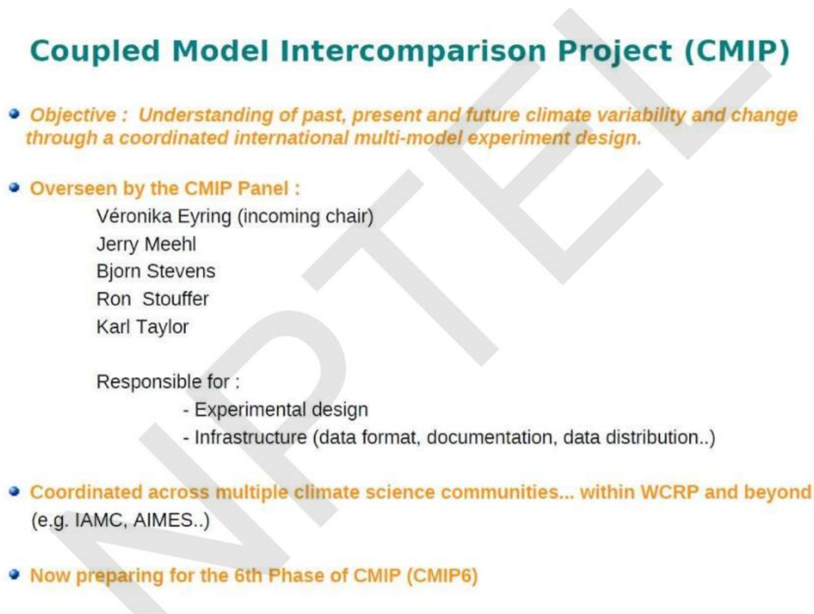
Now, although I have criticized the model, you see that the meridional gradient in the temperature in these models is quite good.



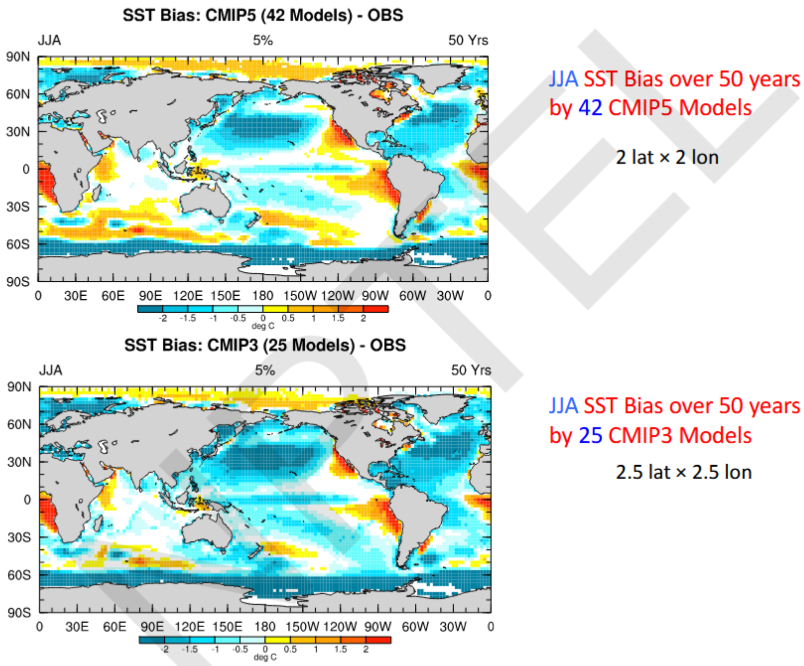
The black line is observation, and various models are shown in dotted and solid-colored lines. You can see that around the tropics, the models currently reproduce the temperature variation in the tropics quite well, and this shows the tropical temperature. But you can see that in the northern polar region and in the southern polar region, the temperature does not go down to the same extent as the observation. So, that is a fact—we have to live with that. In the polar region, we are not doing well, because modeling of those ice sheets is not easy.

Now, this figure (given below) I showed earlier: when you double carbon dioxide, models do not agree on the total change. They are anywhere from 1.5 to 5 ºC warming. This problem has not yet converged. So, that is why you have to worry about the future climate. So, this Coupled Model Intercomparison Project is very important—CMIP—which helped the IPCC to make plans. So, these models are very important. They still have bias over the ocean.

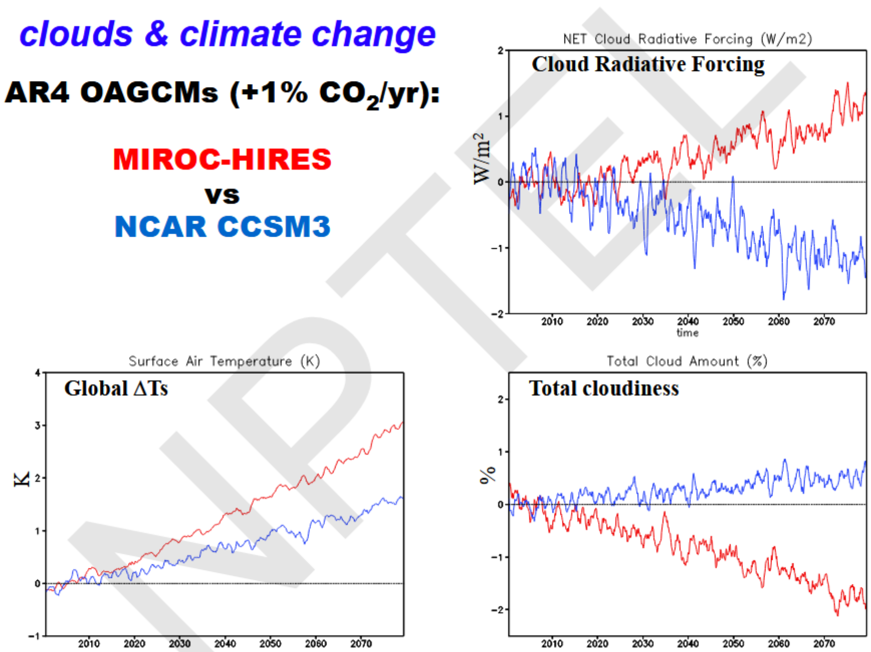




For example, here is a comparison of June–July–August SST between CMIP5 simulation and CMIP3 simulation (shown below). You can see a large difference here over the Indian Ocean, especially. This problem has to be fixed before you can trust the simulation over Africa.

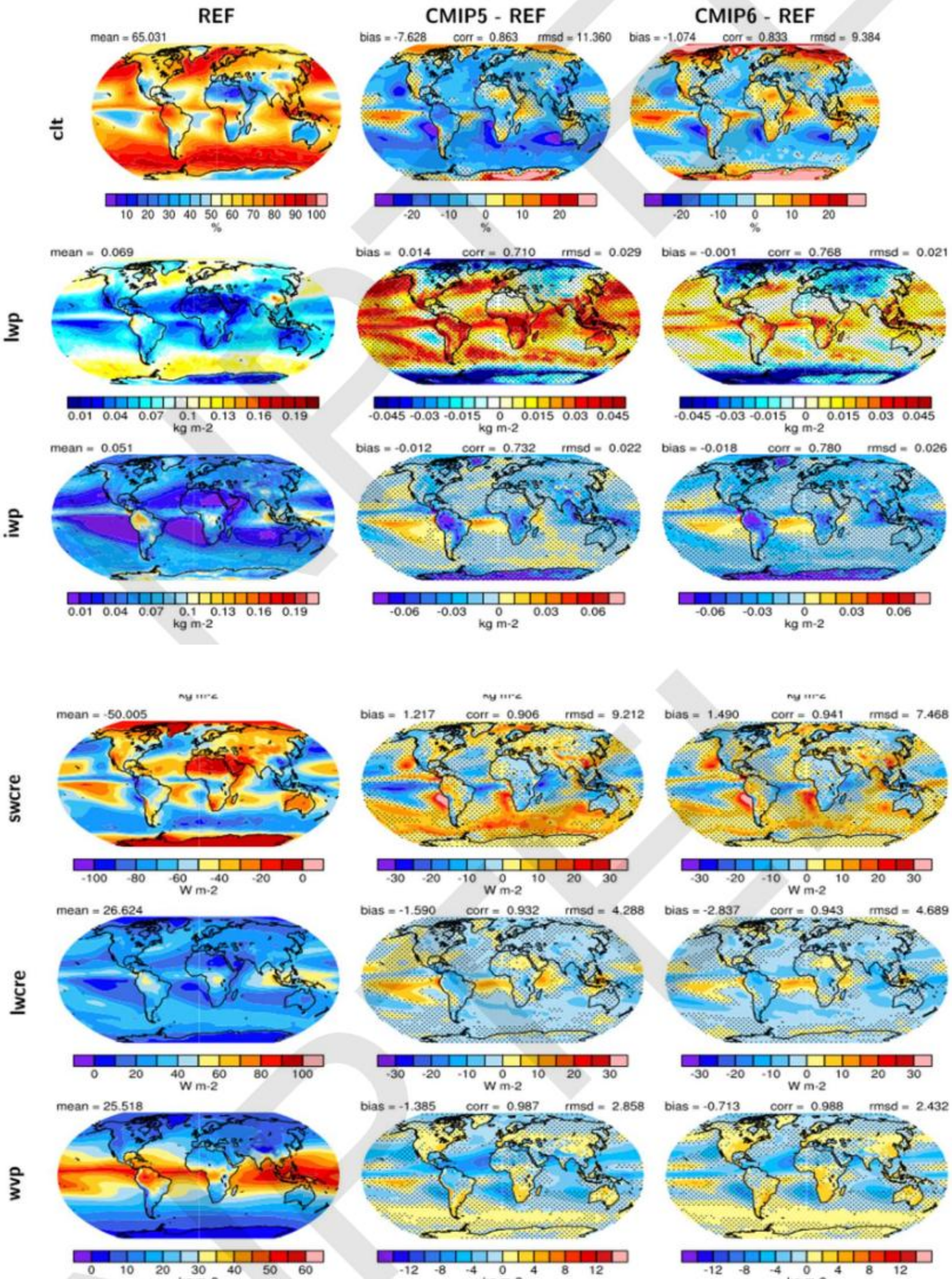


So, this figure I have already shown you—I will not repeat it.



Now, here is a comparison between cloud thickness in the figure shown below—observation, old model, and new model—and simulation, in which liquid water path (that is very important—how much liquid is in your path).

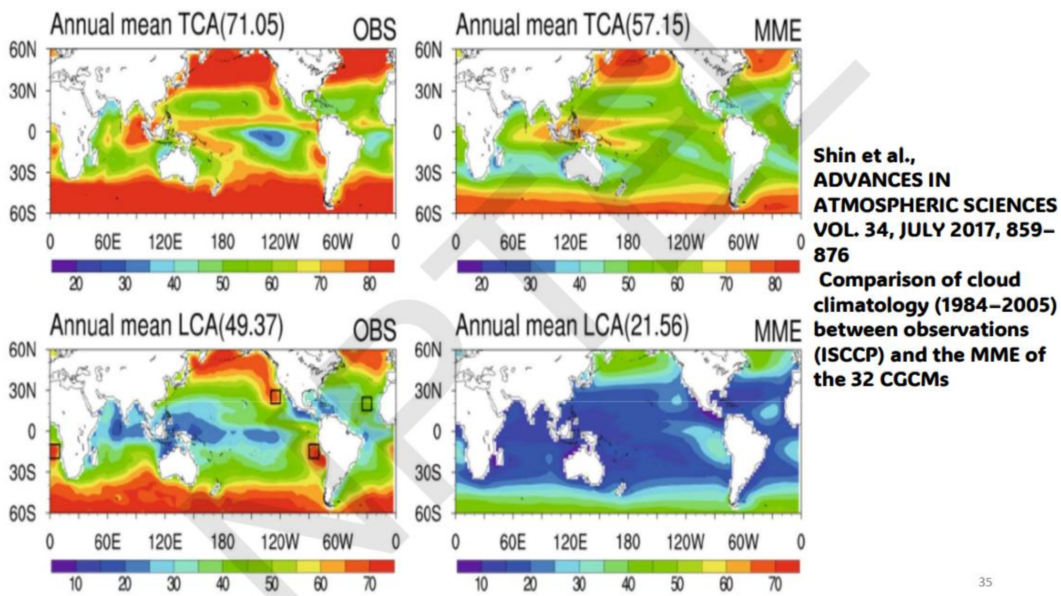
The 20-yr means (i.e., 1986–2005) for CMIP5 and 1995–2014 for CMIP6



The 20-yr annual averages (models) of total cloud cover (clt), liquid water path (lwp), ice water path (iwp), TOA shortwave (swcre) and longwave (lwcre) cloud radiative effects, and water vapor path (wvp), shown from top to bottom. (left) Observational reference datasets (multiobs means) and the differences of the (center) CMIP5 and (right) CMIP6 multimodel means to the observational reference dataset. Differences that are smaller than the observational uncertainty estimate calculated from interannual variability and variability across individual observational datasets

So, we know simulation is not so good for liquid water path. You can see that the liquid water path is not so good. So, mainly, many of the cloud parameters are not correctly simulated by the cloud parameters. So, you can see the shortwave cloud optical thickness, shortwave radiative effect, and the main water vapor content.

Now, here is the comparison between total cloud amount by a group, which compares ISCCP and 32 GCMs over a period of 20 years.



You can see that total cloud amount is 71 in the observation, and in the model it is 57. Huge difference. So, this is not a problem for any model. Same thing with low cloud—models, much worse. The low cloud amount is too low in the polar latitudes in comparison to observations.

Even in the tropics, the low cloud is too low, and in the higher latitudes, the model is giving much lower cloud. So, this problem is there, which is still being resolved, and I will continue the discussion in the next lecture.