**Climate Change Science**
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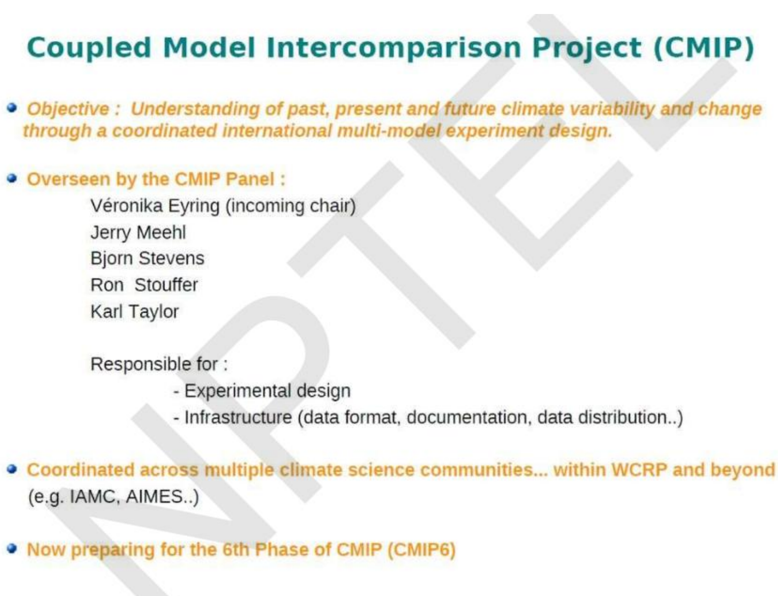
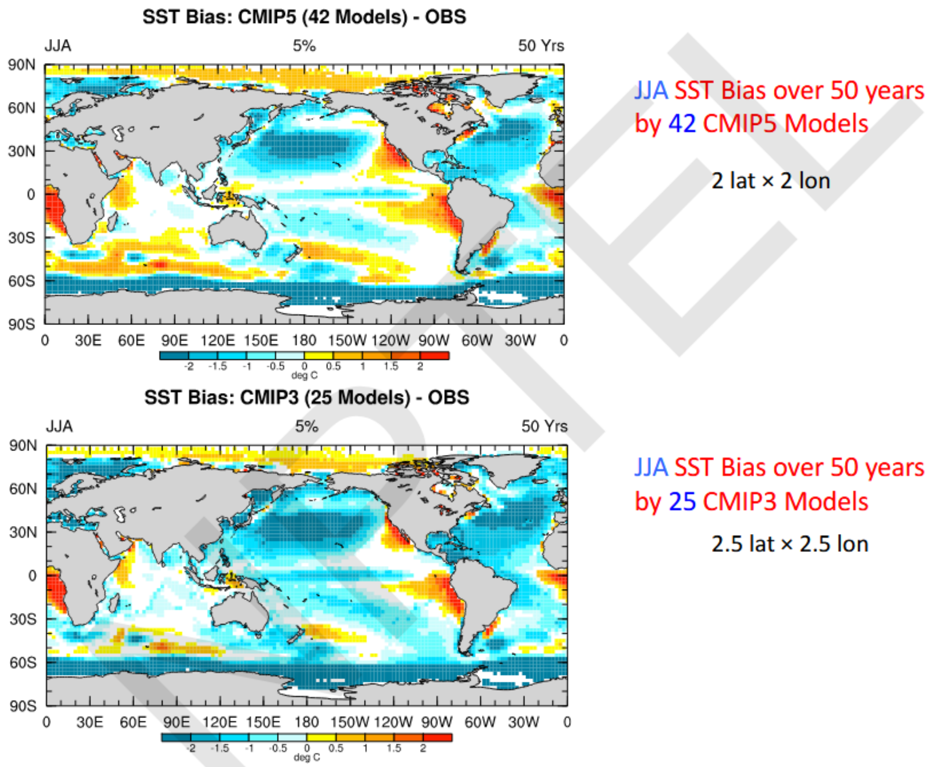
**Lecture – 49**
**Model biases**

In the last lecture, we talked about the use of climate models to predict how the climate will change in the future. But, in order to trust the climate model's ability to predict the future, we need to know how well it predicts the present climate. So, this has been the goal of the Climate Model Intercomparison Project, CMIP. In this project, a large number of groups that have climate models run the same scenario for the present climate and the future climate. Then, you compare all these models to see how well they agree with each other and how much they differ.




From these comparisons, we get an idea about how good or how bad the models are. The first example I discussed—and which I will repeat because it is important—is the major problem that the coupled models have, which is called the SST bias. That is, the temperature of the ocean is less than what is observed.

You can see two versions of the CMIP series. CMIP3 is the old one, and CMIP5 is the more recent one. Averaged over 50 years, we see that there is a huge negative cold bias in the Pacific Ocean. So, this is a serious issue because it has not really changed between these two series, CMIP3 and CMIP5.

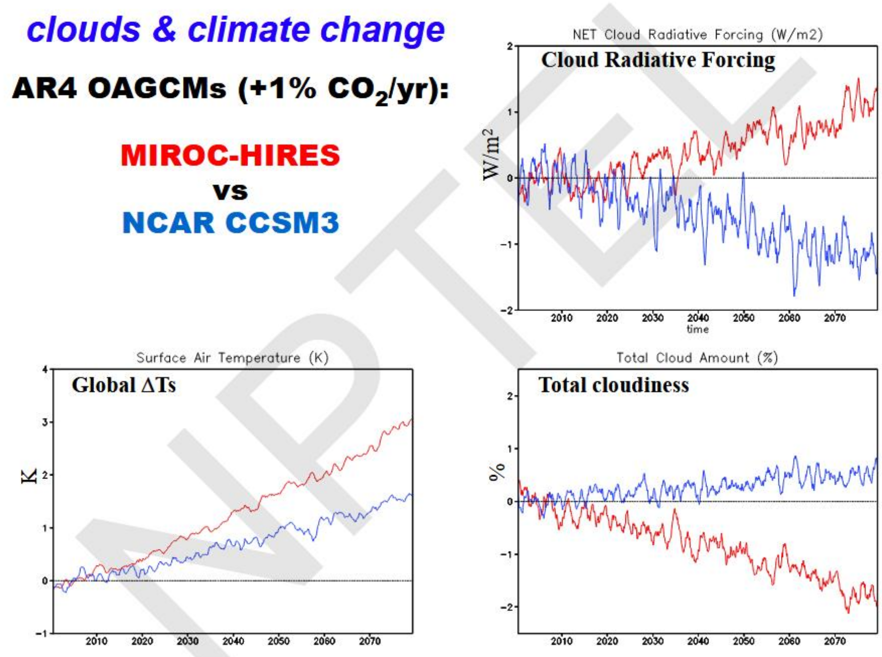



A lot of work has been done to improve models, but this particular problem of a large negative bias over the mid-latitude Pacific Ocean has not been solved. Now, the reasons are many. The transfer of heat from the ocean to the atmosphere is mediated by the wind speed in the atmosphere and the temperature difference between the ocean surface and the atmosphere next to it. This coupling between ocean and atmosphere cannot be specified—it evolves as the model is integrated. So, all we can say is that there is some problem in these models—in all of them, not just one model.

They tend to have very cold ocean temperatures in the mid-latitude Pacific as well as mid-latitude Atlantic. In addition, you also see that along the coastline of Africa, the west of Africa, and the west coast of South America, there is a warm bias—that is, the model-predicted sea surface temperature is larger than the observed. Now, we know why this happens: the model resolutions are not high enough to correctly capture the upwelling—that is, upward velocity in the ocean, which brings cold water from below to the surface and is very critical for the climate. That is not captured in these models because the model resolution is not high enough. This coastal upwelling occurs over a very narrow region, and to capture that, you need very high resolution close to the coast.

If you do not capture that, you will have these warm biases. This error will be reduced as the resolution of the model keeps increasing with improvements in computer power. But this large bias in the middle of the Pacific Ocean is a serious issue because it cannot be blamed on resolution—this error is over a large region. While the warm bias is confined to very close to the coast, the cold bias is very large. So, this issue is still being researched. Research is ongoing to figure out why it is happening.

Now, why do you have to worry about all this? Because you can see that two different models—one from Japan (MIROC), the other from the USA (NCAR)—simulated the impact of doubling $CO_2$ at the rate of 1 percent per year. By 2080, the MIROC model shows a 3-degree warming, while the NCAR shows 1.5. This difference can be clearly related to the difference in cloudiness.



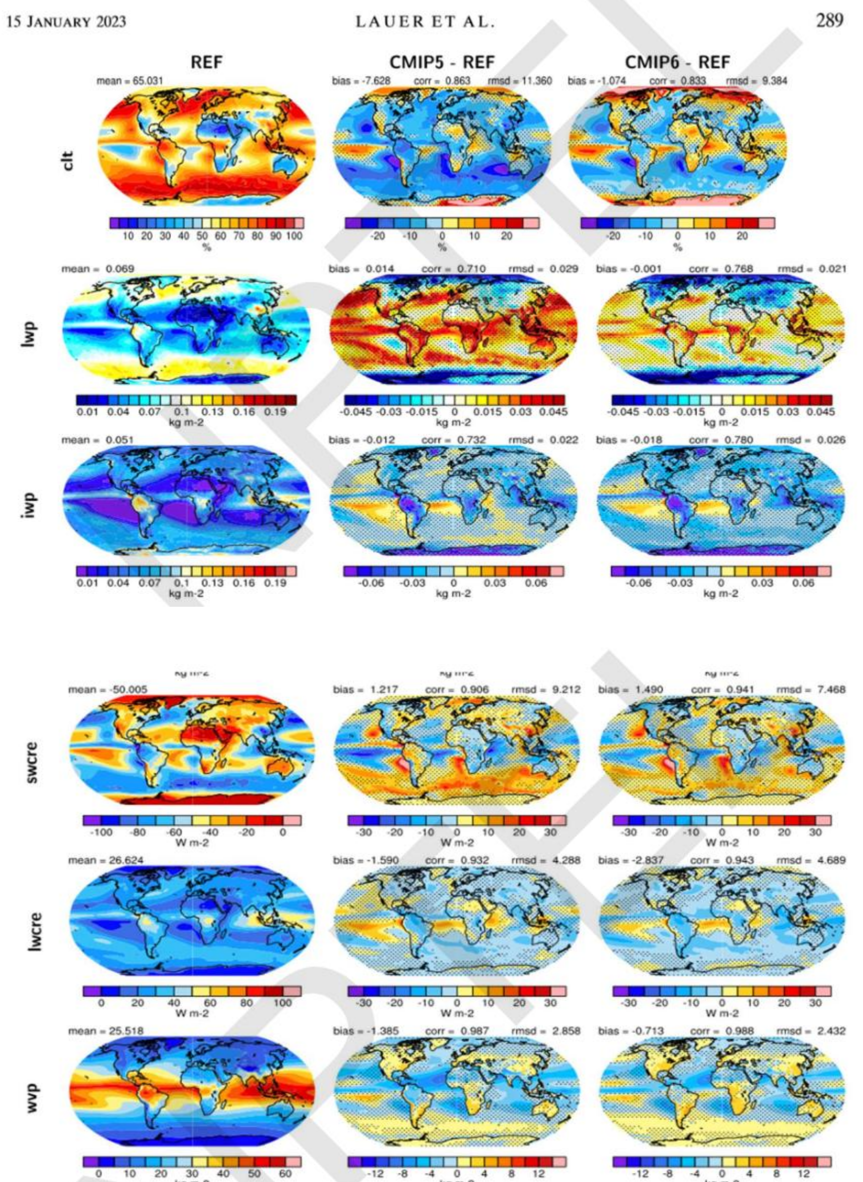

In the MIROC model, the cloudiness decreased by about 2 percent, while in the NCAR model it increased. As you recall, even a 1 percent change in cloudiness has a big impact on the energy budget because clouds reflect radiation to space. If your model predicts too high a cloud, the temperature will go down. If the model shows a decrease in cloud, the temperature will go up. This is connected to cloud radiative forcing, which we discussed earlier in the course.

So, this particular slide shows clearly how sensitive our ability to predict future warming of global mean temperature is to the correct prediction of the change in cloudiness. Now, that problem has not been solved yet because clouds come in a variety of forms—we have discussed that before: cirrus, cumulus, shallow, deep. The models are not capturing these clouds accurately because models do not predict clouds from first principles. Since the model resolution is not very high, clouds are added empirically in these climate models. Therefore, there is a large difference between different models that use different empirical data to model clouds.

This can also be seen in the total cloud as observed. In the figure shown below, we have the annual mean and what is produced in CMIP5 and a more recent model, CMIP6, compared to the observation. You can see that the total cloud amount is lower in most of the models—it is an average of many models—and this has not changed much from CMIP5 to CMIP6. There is a clear problem at the polar regions—the cloudiness is too high—and in the tropical region, the cloudiness is too low.

So, this problem has not yet been solved. If you relate that to the liquid water path—the total amount of liquid water from the surface to the top of the atmosphere—you see that the liquid water path is too high in CMIP5, and it is somewhat reduced in CMIP6, but still positive. The liquid water path is too low in the polar regions. How about ice water path? Ice water path in both CMIP5 and CMIP6 shows a lower ice water path than observed. So, this issue of the amount of liquid in the clouds and the amount of ice is still not well simulated. This impacts the shortwave cloud radiative effect and the longwave cloud radiative effect.

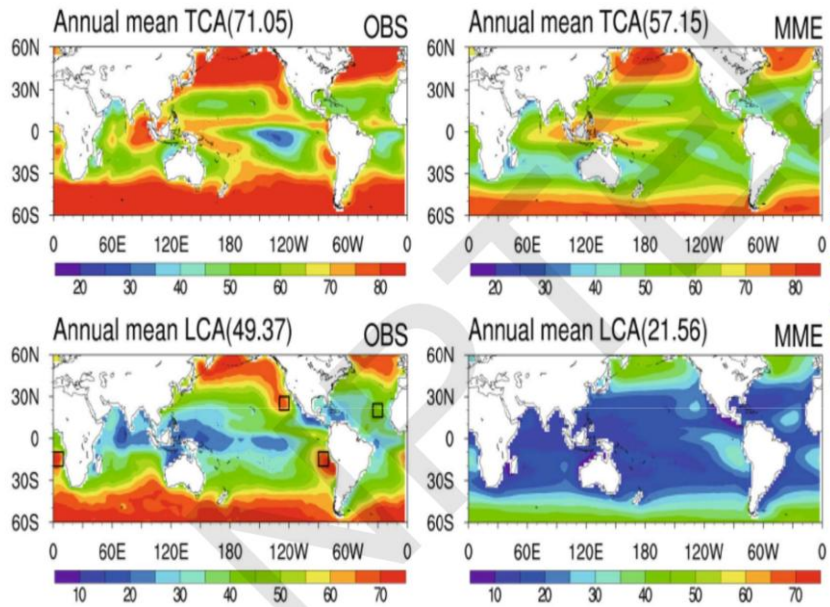
**The 20-yr means (i.e., 1986–2005) for CMIP5 and 1995–2014 for CMIP6**




**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**

Lastly, we see the total water vapor, which is a very important parameter for rainfall and radiation. You can see that over oceanic regions, the models have lower water vapor than observed, while over land regions, they are a little higher. So, this issue is to be remembered as something which is not yet completely resolved in climate models—clouds, ice water path, and liquid water path.

Now, here is a close-up comparison between 32 general circulation models. We are comparing only the clouds over oceans because the oceans form 70 percent of the globe.




**Shin et al., ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 34, JULY 2017, 859–876**

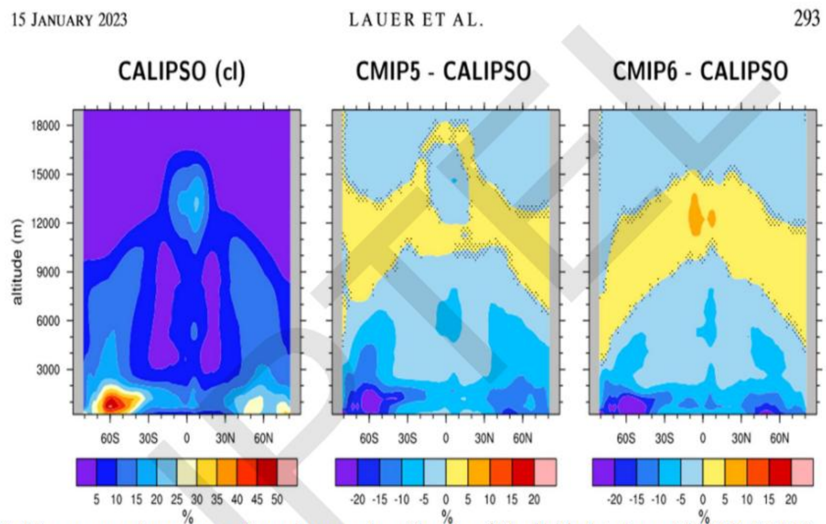
**Comparison of cloud climatology (1984–2005) between observations (ISCCP) and the MME of the 32 CGCMs**

We have to get everything right over oceans. You can see that on the left, observation shows that annual mean cloudiness (total cloud amount TCA) is 71 percent. The multi-model ensemble of 32 climate models shows that it is 57 percent. Although the spatial pattern is quite good—it looks quite similar—the total amount is wrong by 14 percent, which is very large. Even a 1 percent change in cloudiness has a huge impact on our climate.

A difference of 14 percent in the annual mean cloudiness is a very serious issue. Now, how about low cloud amount—that is, cloud near the boundary layer? You also find that the observed low cloud amount is 49 percent, while the modeled cloud amount in the multi-model ensemble of 32 models shows a huge difference. You can see that in the tropics, the models have lower cloud. The low cloud amounts are lower than observed, and so it is in the polar regions. Both in the polar region and the tropics, low cloud amounts are not correctly simulated.

So, this issue—until it is resolved—means we cannot be very confident about predicting regional climate. In the case of global climate, certain errors cancel out. As you have seen, models have correctly reproduced the increase in temperature from 1850 to 2023. We saw that earlier—global mean temperature. Based on this result, you should be concerned about the ability of the model to correctly predict sea surface temperature in certain parts of the world, because both the low cloud amount and the high cloud amount are not correctly reproduced.

The high cloud amount is not bad—the spatial pattern is okay, but the amount is wrong. The low cloud amount is wrong in total as well as in the pattern. Now let us look at the vertical structure.




Multiyear annual averages of zonal mean cloud fraction (%). (left) data from CALIPSO-GOCCP, as well as differences of the (center) CMIP5 (9 models) and (right) CMIP6 (7 models) multimodel mean

Today, we have satellite data using LIDAR, which is able to probe through the atmosphere using a laser. This is what the CALIPSO radar shows—our cloud percentage with height, global mean. This is from a paper by Lauer et al., published in January 2023. This is the difference between CMIP5 and CALIPSO, as well as CMIP6 and CALIPSO.

You can see that the models have too high a cloud fraction in the mid-troposphere and too low a cloud fraction near the surface. This issue is clearly highlighted here in the annual mean. We are not talking about even a particular month—we are talking about annual mean. In the annual mean, the model's low cloud amount is very different from CALIPSO. It is much lower, by as much as 20 percent.

So, all these results have been shown to remind you that we need to be very cautious about a model's ability to predict clouds as well as rainfall on a smaller scale. Global mean is fine—things do cancel out—but when you come to local, tropical, mid-latitude, and polar regions, you need to be very careful because models are not doing too well regarding local clouds and local rainfall.

Let us look at another comparison between CloudSat—another satellite, which had a radar—and CMIP6, CMIP5 with CloudSat (refer to figure below). Again, one sees a negative bias here of cloud liquid water. This is not cloud fraction—it is cloud liquid water.

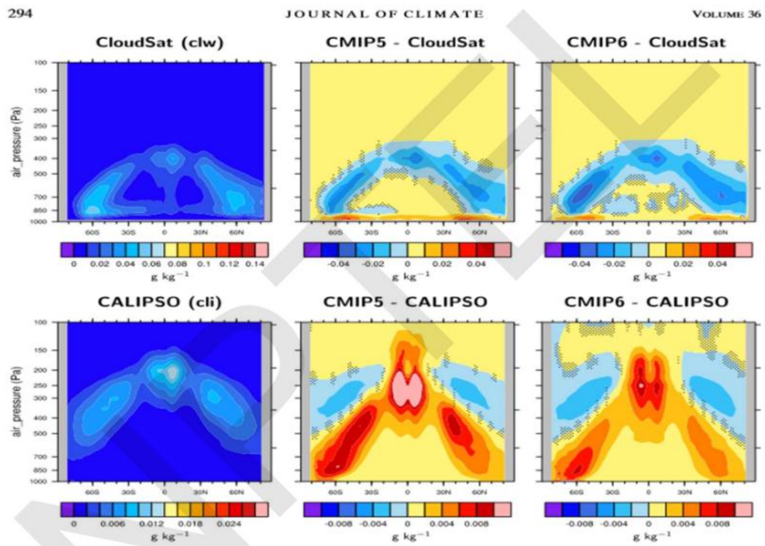
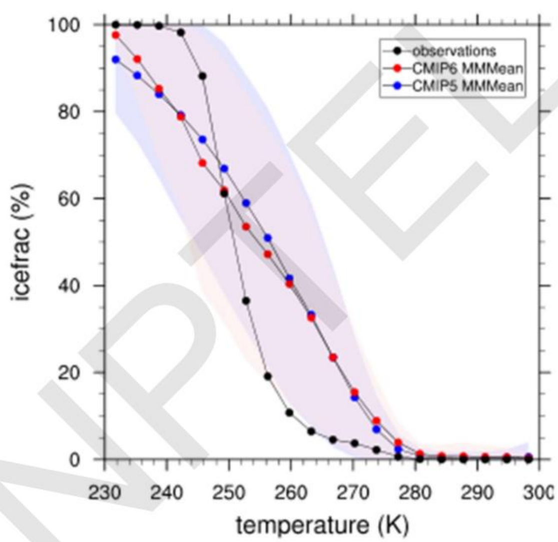



FIG. 4. The top row shows the multiyear annual average of (left) zonal mean cloud liquid water content (g $kg^{-1}$) from *CloudSat*-L2, and differences of the (center) CMIP5 (32 models) and (right) CMIP6 (28 models) multimodel mean compared with *CloudSat*. The bottom row shows (left) the zonal mean cloud ice water content (g $kg^{-1}$) from *CALIPSO*-ICECLOUD, and differences of the (center) CMIP5 (32 models) and (right) CMIP6 (27 models) multimodel mean compared with the *CALIPSO* data. Stippled differences are not statistically significant at a 95% confidence level.

So, the cloud liquid water in the models is lower than the observed, and it has not improved from CMIP5 to CMIP6. We expect some improvement as the models evolve in time, but here it has not happened. Other things have improved, but cloudiness and cloud liquid water still remain a challenge. The models are overpredicting the ice content in the mid-troposphere as well as at the lower level in the mid-latitude and polar regions. So, this is also an issue.

Ice cloud and water cloud are not being correctly predicted because of the way the model parameterizes clouds. Clouds are not being simulated from first principles. We are using some empirical model to convert the relative humidity and other parameters—which are simulated in the model—to calculate cloud liquid water and cloud ice. There is some lacuna in the models. To bring this out more clearly, here I am showing you the vertical variation of ice fraction as a function of temperature.



Now, look at the black line, which is the observation. You do expect that when you go to very low temperatures, you should have a very high ice fraction. Most of the condensation of water should go to ice, and that is what observation confirms. In the polar regions, for example, you would expect very high ice fraction, while in the tropics, when the surface temperature is between 280 and 300, you should expect very low ice fraction. Now, models correctly reproduce a low or zero ice fraction in the tropics. That is not surprising. But, as you go to low temperature, the way the ice fraction increases in the observation and the way it increases in the two models—CMIP5 and CMIP6—are very different.

The observation shows a rapid increase in ice fraction, approaching 50 percent by the time you get to 250 Kelvin, but the models show 50 percent only at around—I would say—260 or 255. As you go to even lower temperatures, the observations show a rapid increase in ice fraction, while the model shows a gradual increase. This is a very serious weakness in the models—that as the temperature goes below 250, the ice fraction should rapidly increase to 100 percent. So, this again shows a need for further improvement in the models in the way they model ice fraction. So, these weaknesses should be remembered when you try to understand the model's predictions about the future climate.

Now, the other thing very important to understand in models is the wind.

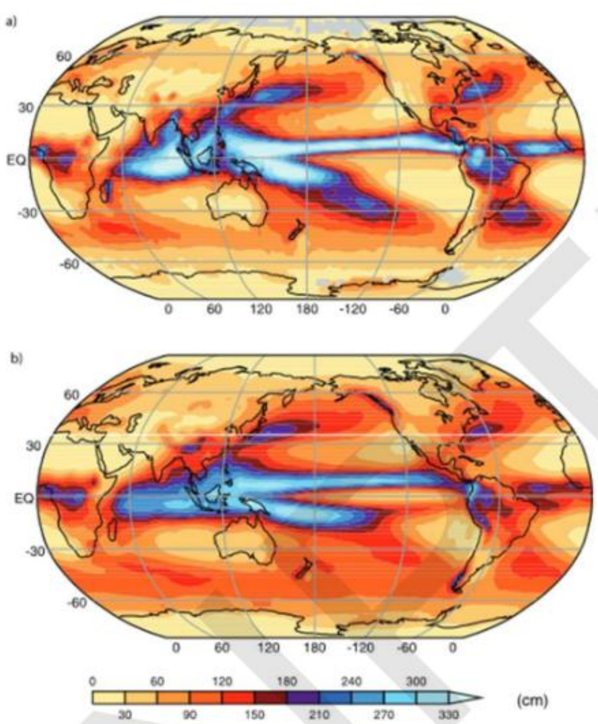



**Figure 8.5.** *Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. In (a), observations were not available for the grey regions. Results for individual models can be seen in Supplementary Material, Figure S8.9.*

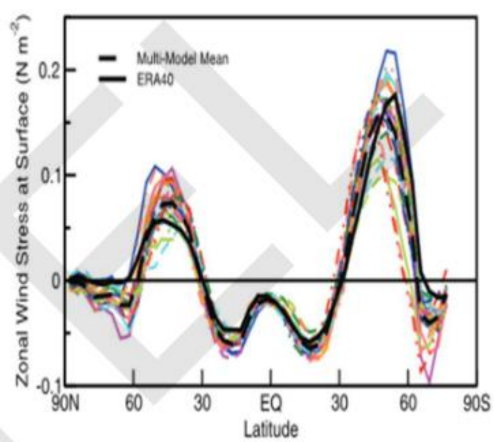



**Figure 8.7.** *Annual mean east-west component of wind stress zonally averaged over the oceans. The observationally constrained estimate is from the years 1980 to 1999 in the European Centre for Medium Range Weather Forecasts 40-year re-analysis (ERA40; Uppala et al., 2005), and the model climatologies are calculated for the same period in the 20th-century simulations in the MMD at PCMDI. The legend identifying individual models appears in Figure 8.4.*

Zonal and Meridional wind stress components are computed as:

$\tau_x = \rho_{air} C_D W^2 \sin\theta$ $\quad$ $\tau_y = \rho_{air} C_D W^2 \cos\theta$

Where,

$\rho$ is the density of air (1.2 kg/m$^3$).
$C_D$ is a dimensionless coefficient called **drag coefficient.**
**W** is the wind speed.
$\theta$ is the angle of the wind vector from true north.

The model winds at the lower level—that is, around 850 millibars—determine how much stress is imposed on the ocean. Remember that ocean circulation is driven both by changes in salinity and temperature inside the ocean—so-called thermohaline circulation—as well as by the stress imposed by the atmosphere on the ocean.

So, we want to know what the stress is, and that is defined right below here: stress in the zonal direction and in the meridional direction in terms of the wind speed $w$, the density of air $\rho_{air}$, the drag coefficient $C_0$, and, of course, the angle of the wind $\theta$ from the true north.

$$\tau_x = \rho_{air} c_0 w^2 \sin\theta$$

$$\tau_y = \rho_{air} c_0 w^2 \cos\theta$$

Now, we compare here—black is observation—and the dotted line is the multi-model mean. You can see that the models tend to overpredict the zonal wind stress both in the northern latitudes as well as in the southern latitudes. It is not that bad. In the northern latitude, the wind stress is too high. At the equatorial region—the tropical region—it is slightly low, but it is not too bad. So, this is critical, because if the model does not impose the correct wind stress at the ocean surface, the ocean circulation will not be realistic.

We saw how important the ocean circulation is to transport heat from the tropics to the polar regions. That is the only major mechanism we have in addition to atmospheric transport. If we do not do that correctly, the model will not correctly simulate the ocean circulation. On the left, we have the rainfall pattern. Annual mean observed is here; model is here—multi-model mean.

Overall, you can see it is quite good. In spite of all the errors in clouds and SST, it is good to know that in the big picture, the rainfall pattern looks quite good. The Intertropical Convergence Zone is correctly reproduced as being north of the equator in the annual mean. The South Pacific Convergence Zone is correctly reproduced here. But, the rainfall in the Indian Ocean—which is important for people in India—is somewhat lower than observed. And also, you can see that in the Bay of Bengal, the rainfall prediction is poor.

We will talk about this in more detail later because we will talk about the Indian monsoon and how well the Indian monsoon is simulated by climate models. But here, you can see it is not going to be too good, because in the Bay of Bengal, the model simulations are not too good.

Now, how about ocean circulation—ocean temperatures not at the surface but deep inside? Here, we are showing you the contours of the temperatures. The contours (in the figure below) show the time-mean observed potential temperature.

The potential temperature is the temperature a parcel would have if it were brought to the surface. That is called potential temperature, and it is zonally averaged over all ocean basins. That is the contour. The color shows the difference between simulated and observed, and you can see the cold bias near the surface and a warm bias deep inside.

Chapter 8 Climate Models and Their Evaluation

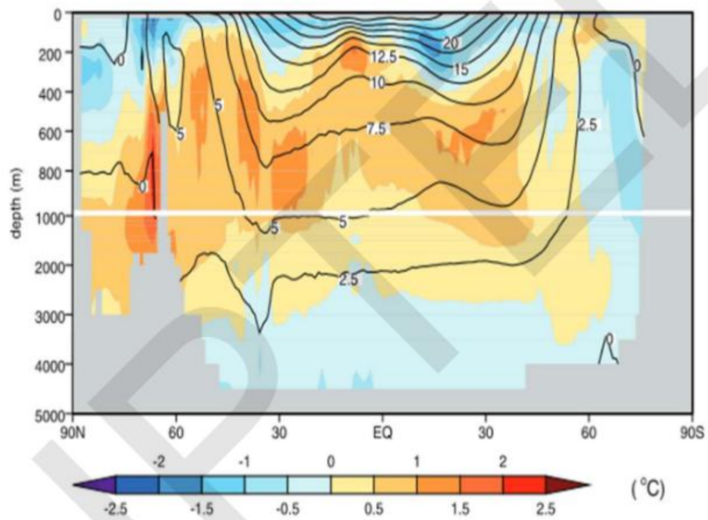



**Figure 8.9.** *Time-mean observed potential temperature (°C), zonally averaged over all ocean basins (labelled contours) and multi-model mean error in this field, simulated minus observed (colour-filled contours). The observations are from the 2004 World Ocean Atlas compiled by Levitus et al. (2005) for the period 1957 to 1990, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. Results for individual models can be seen in the Supplementary Material, Figure S8.12.*

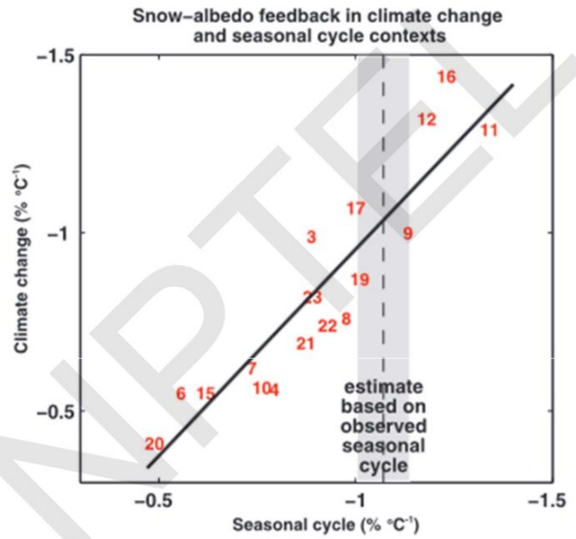
**Potential temperature is temperature that a water parcel would have if it were raised adiabatically from some depth to the sea surface without change in its salinity.**

This is an important problem, which has a significant effect on heat transport in the ocean. The models are too warm about 1 kilometer—or about 500 meters—below the surface and too cold at the surface. So, this is an important limitation in the climate model: at the surface, they are too cold, and deep inside, they are too warm. Now, the reason why models are not doing as well in the ocean as in the atmosphere is: you must remember that until recently, we did not have accurate data on the temperature of the ocean interior, not surface. On the surface, we had data from satellite, but deep inside the ocean, the only way we could get temperature was by sending sensors deep inside the ocean, and that is very costly and complicated. Only in the last 20 years have we had floats called Argo floats, which go inside the ocean and come back. We have data for the last 20 years, and before that, we had almost no data. So, this large error will be corrected, I am sure, in future models as we improve the model simulations.

What is the major reason for these large errors? One of the reasons is turbulence. In the ocean, the major cause of error is the modeling of turbulence, which we have not understood well because we do not have data—how turbulence changes from the surface (where turbulence is induced by the wind acting on the surface) to deep inside (where turbulence is governed by thermohaline circulation).

So, this issue is ongoing—research is happening, and one may expect some improvements in the coming years.

The second thing you have to worry about when you look at models is how well they simulate the seasonal cycle of temperature. Because if a model cannot simulate the seasonal cycle, that model cannot be trusted to predict climate change in the future.

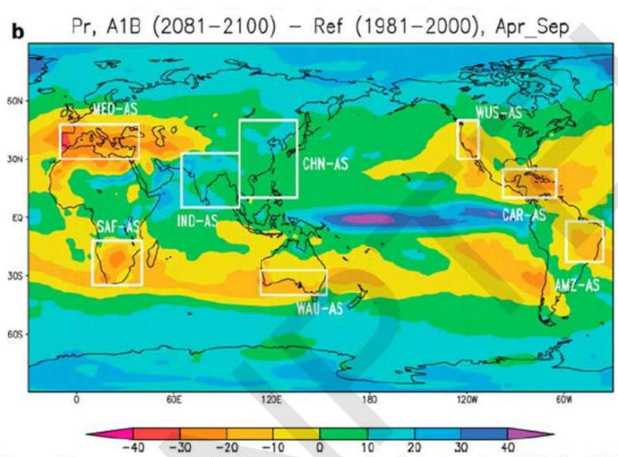


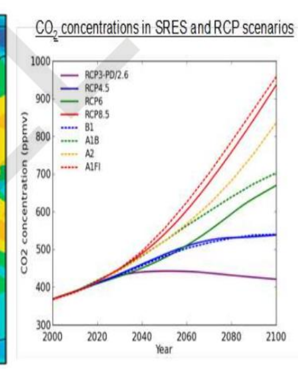



Here, we are showing the snow-albedo feedback during climate change and how it is related to the seasonal cycle of the snow cover. On the x-axis, there is the seasonal cycle in the snow cover as a function of temperature in different months, and on the y-axis is the change in snow-albedo feedback as warming occurs in the model.

If the model's seasonal cycle change in snow cover is close to the observed—which should be around here—then you can trust the model. You can see that among all the models shown here (about 23 models), I would say only three models have the seasonal cycle in snow-albedo change close to the observed. Some models give too high a value, while some models give too low values. So, we have a problem here, because only three of the 23 models have a seasonal cycle close to the observed. So, this issue is very serious because changes in snow and ice have an impact on albedo, and they impact global warming. So, this again needs to be improved.

Now, here is a paper by Giorgi and Bi showing the change in rainfall during 2081 to 2100—the last 20 years of this century—compared to the last 20 years of the last century, averaged over April to September, the monsoon season in the Northern Hemisphere.




**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**

What do we see? We see that models predict an increase in rainfall over India and China, an increase over the equatorial Pacific, and a decrease over the African region, the Mediterranean region, South Africa, the equatorial Pacific, and parts of America. So, this prediction is very interesting because some of these regions—especially the Americas and Africa—have experienced increases in drought.

So, this may indicate that the impact of climate change is already being seen in some of these regions. Now, this depends on which scenario you are simulating. Here in this paper, it is A1B. A1B is this green line. That is where the carbon dioxide concentration is increasing from 380 parts per million in 2000 to 700 parts per million, which is what is happening—the rate at which it is going now.

So, this is a scenario that will happen if we do nothing about $CO_2$ emissions. If that happens, this is the prediction: about a 10 to 20 percent decline in Africa—both North Africa and South Africa—and around a 10 to 15 percent increase in India and China, and a decline in Central America and the western part of North America. So, this is an indication that global warming may be causing these changes.

Now, in these models, if you want to understand how we can trust these simulations, you have to look at what is called the "time of emergence."

## 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.

Because all these models have interannual and interdecadal variation, which are part of the natural variation of the atmosphere-ocean system, you cannot trust the result totally unless you remove the natural variation from your simulation. In this paper, Giorgi and Bi are talking about—in this A1B scenario, which I showed you in the last slide—at what time the signal of the climate change due to $CO_2$ increase emerges above the natural year-to-year and decadal variation.

The numbers are all quite high. Take India, for example. If you look at India, only by 2050 can we be sure that the impact of $CO_2$ increase, above the natural variation, can be seen. So, until about 2050, you cannot be sure whether the change you are seeing is on account of $CO_2$ increase. This is the problem many people do not understand. Models do predict an increase in rainfall in India. But this need not be totally trusted until 2050, because there is natural climate variation due to the exchange of heat between ocean and atmosphere, which creates various decadal oscillations—called Pacific Decadal Oscillation, Antarctic Multidecadal Oscillation, and El Niño. All these oscillations are occurring year to year and decade to decade.

The impact of $CO_2$ increase will emerge as a signal only after about 2050 in many parts of the world. So, this must be remembered before people make dire predictions about what will happen in the next 10 to 20 years. We cannot do that because there is a lot of natural variation in these models. We will stop the lecture at this point. I will continue the discussion in the next lecture. Thank you.