Climate Change Science
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Lecture – 8
General Circulation Models

In the last lecture, we talked about model hierarchy. That is, we have so far covered a simple climate model for the global mean temperature; that is called the zero-dimensional model. If you want to get more details about how temperature varies with height or with latitude, you go to a one-dimensional model. We will cover a part of it later. Or if you want to capture both vertical and, let's say, latitude variations, then you can go to two-dimensional models.

Model Hierarchy

1 Zero dimension : global mean

2. One dimension:vert or horizontal

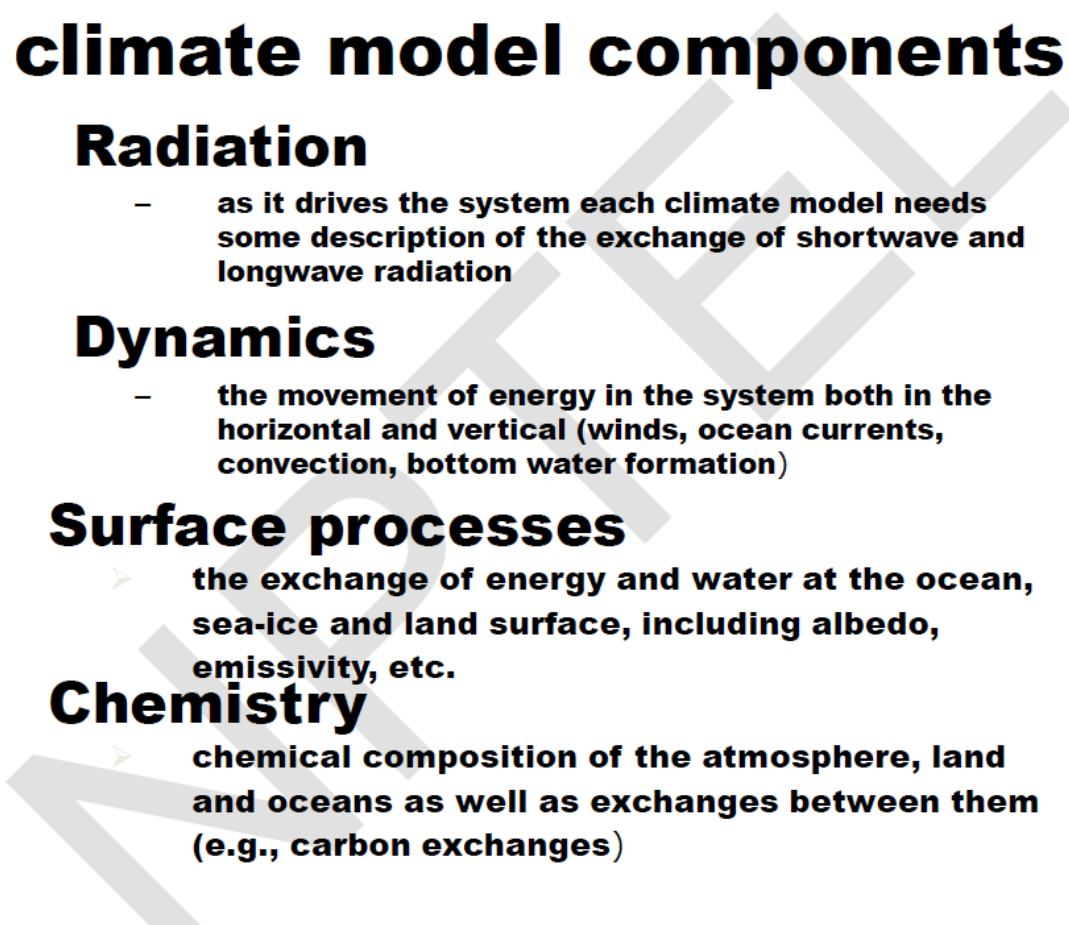
3. Two dimension: vert +one horz

4.Three dimesion : vert, lat, lon

5. Four dimesion: vert,lat,lon,time

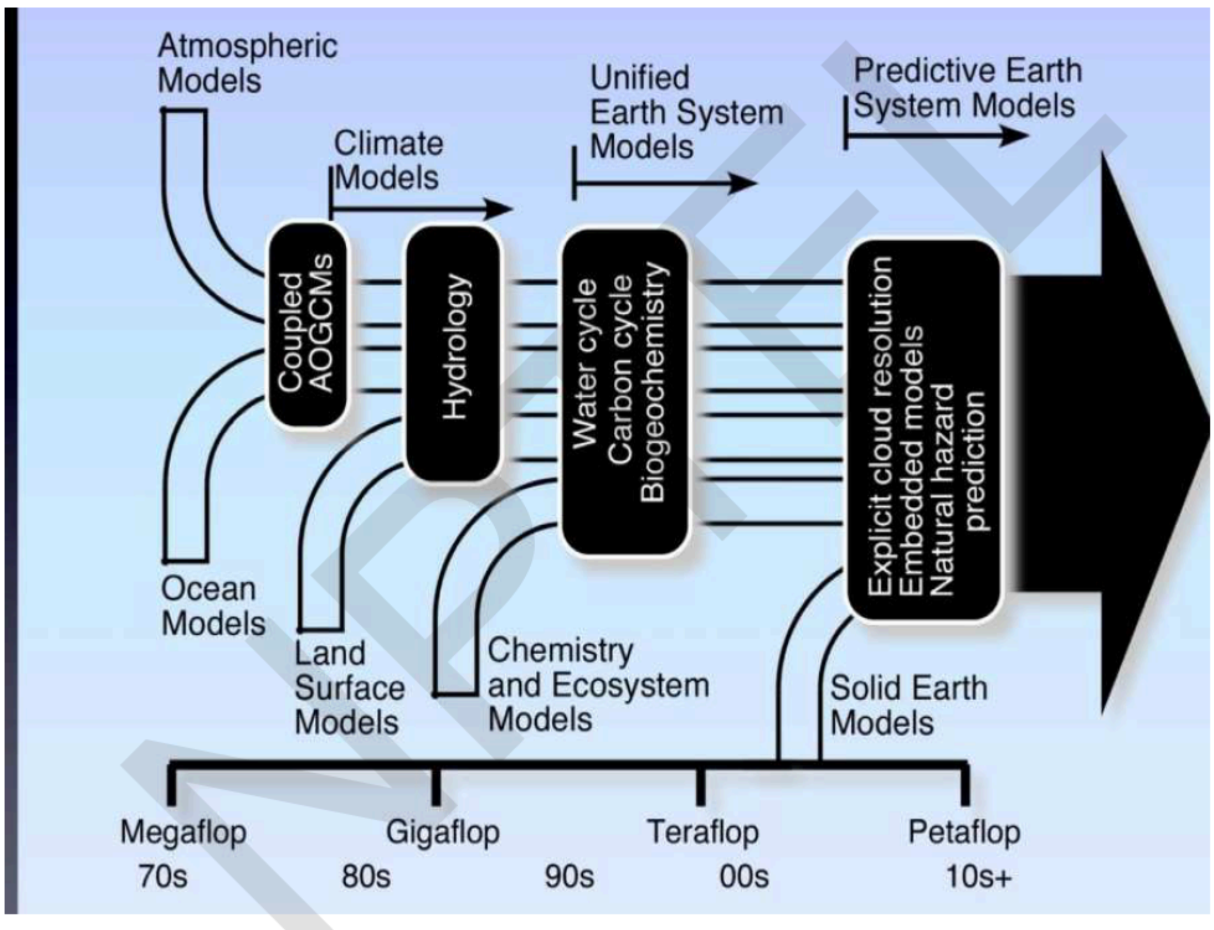
But ideally, you want to cover vertical, latitude, and longitude to get a global picture of how temperature is changing with height, latitude, and longitude. This is called the three-dimensional model, which can be integrated to a steady state. However, the most ambitious models are those in which you have vertical, latitude, longitude, and time. For example, you can have a model which starts at 1850 and integrates the model up to 2020, and then we see how the temperature of the Earth varies over time and how it responds to changes in incoming radiation, changes in carbon dioxide, and volcanic eruptions, for example. This is the most ambitious model. It is computationally very expensive and very complex. I wanted to show a few examples of this model in this lecture for you to get an idea of how these models are used.

Now, these models have lots of components. The first is radiation, which we already discussed in the last few lectures. So, you take into account radiation exchange in the vertical and in the horizontal, the role of clouds, the role of gases—all that is accounted for in the radiation module. The other part, which we have not discussed so far, is dynamics. In the Earth's atmosphere, winds move in the vertical, horizontal, latitude, and longitude directions, and they transport carbon dioxide and water vapor. All these have to be accounted for both in the ocean and in the atmosphere. So, this is computationally very expensive and is very important to understand how climate changes with latitude and height. Then, we also have to understand how energy is exchanged between the surface of the Earth—land as well as ocean—and the atmosphere. How does ice on land or ocean change the albedo? These are called surface processes. Finally, you need to understand atmospheric chemistry because in the Earth's atmosphere, due to natural processes, you have photosynthesis which consumes CO_2, combustion which releases CO_2, and CO_2 moves around the Earth due to winds.



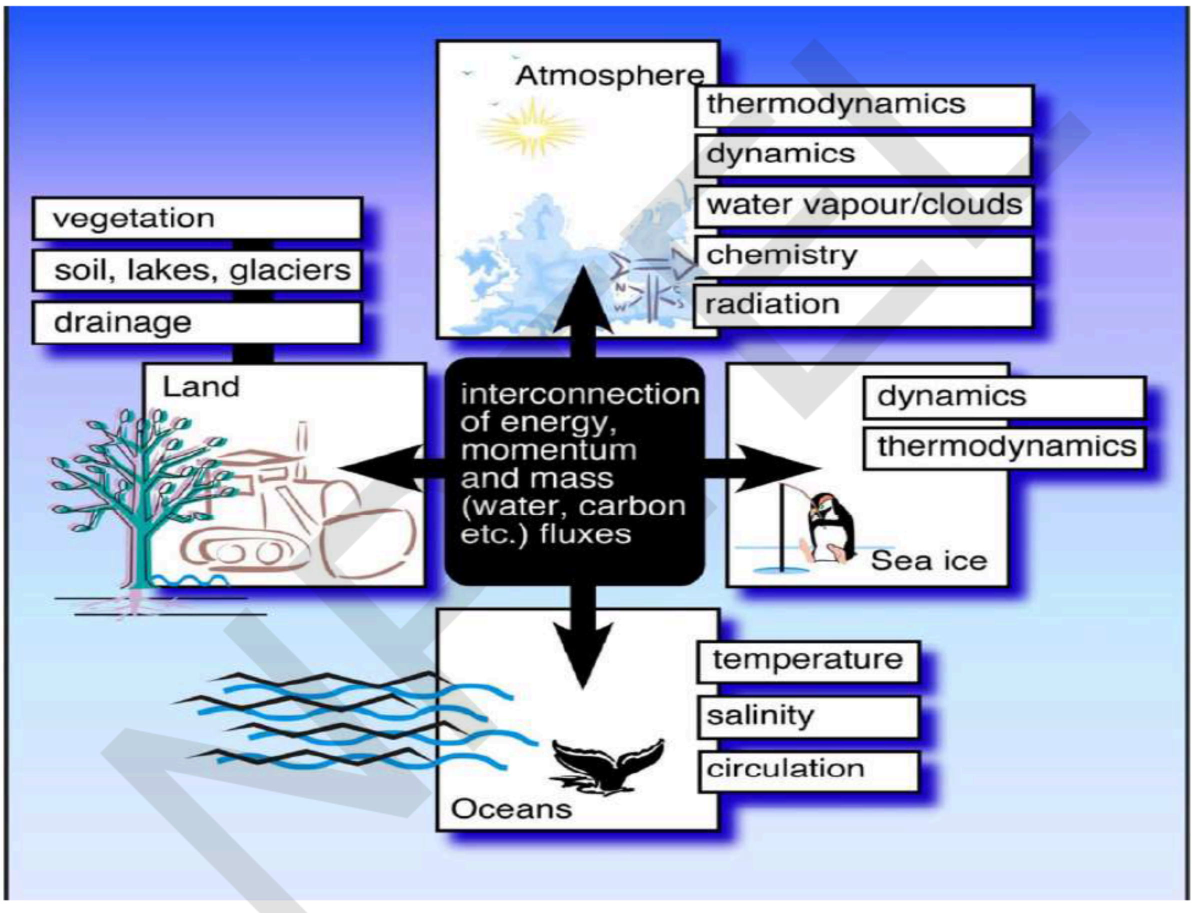
So, all these are in the chemistry module. You can see there are four major modules: radiation, dynamics, surface processes, and chemistry (both ocean and land and atmosphere). All these have to be combined to run the model. Now, this can be shown schematically as follows. The most common models are so-called coupled atmospheric–ocean general circulation models, which have both an atmospheric model and an ocean model. We call them climate models.

In addition, you must have hydrology, lakes, evaporation, and rivers; those are called land surface models. These two are combined and you have a water cycle, a carbon cycle, and biogeochemistry—what happens in the ocean, how the chemistry of the ocean changes. And chemistry and the ecosystem models are included. And all these, along with more modern ones which look at past climate, must take into account changes in geology, for example.



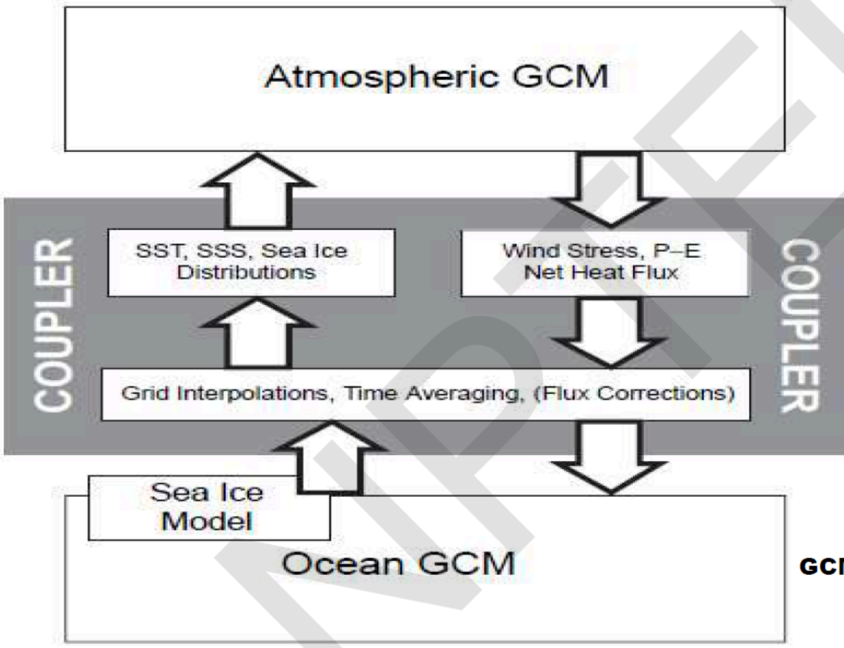
So, these are called Earth system models, which include everything. At the bottom, you can see the amount of computational effort it takes, from megaFLOPS to petaFLOPS. Some centers run these very complex models for hundreds of years to understand how geology interacts with Earth's climate. You must also understand that although there are individual models for land, atmosphere, thermodynamics, dynamics, and ocean, all these have to interact with each other. So, you have interfaces between land and sea ice, land and atmosphere, land and ocean.

This coupler, which couples all these different components, is very critical. It plays a very important role in ensuring that you have a realistic simulation of climate. Below is an example of how the coupler works in a simple case. You have an atmospheric model at the top and an ocean model at the bottom, which takes into account all the circulation that occurs due to winds and the atmosphere in the ocean. Then, we have to couple changes in the ocean to changes in the atmosphere through changes in sea surface temperature, sea surface salinity, sea ice, wind stress, wind acting on the ocean, rainfall minus evaporation, and heat transfer.



All these interact with the ocean and the atmosphere. This is a big challenge because the response time of the atmosphere is much smaller. The atmospheric mass is very low; the ocean is very massive—it is much, much more massive than the atmosphere because water has a density roughly a thousand times larger than air, and the ocean covers most of the Earth.

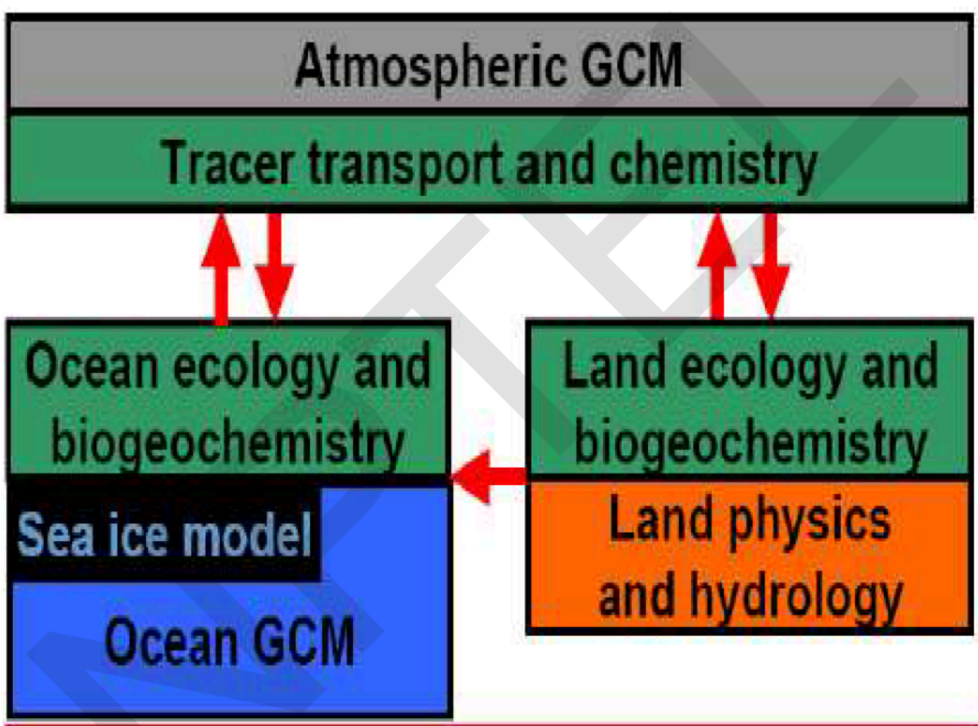
Since the response times of the two are very different, you have to ensure that they are coupled properly because one system—the atmosphere—is responding very rapidly, somewhat chaotically, while the ocean responds slowly. These challenges have been tackled, and now, today, models are able to interface these two correctly.



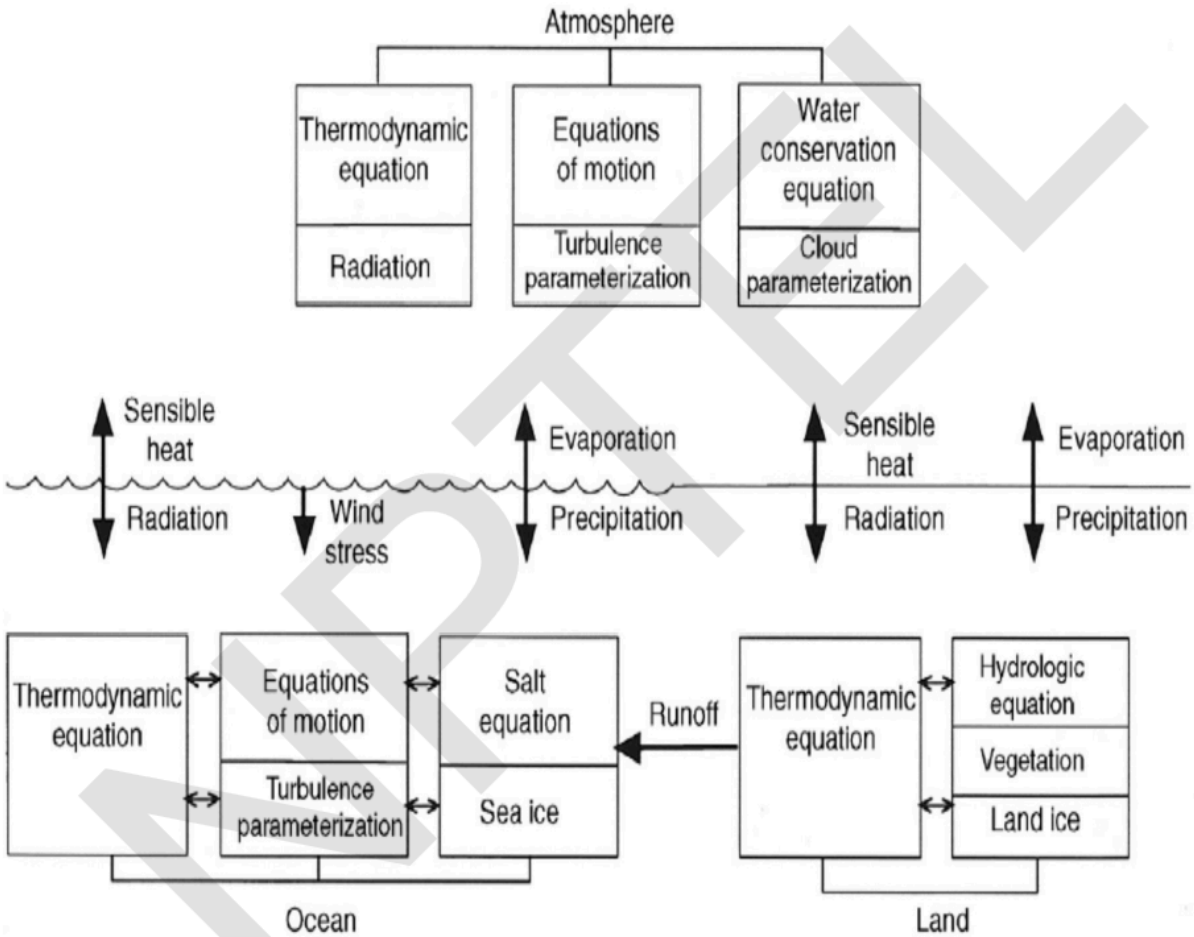
Response time of the atmosphere (which has lower mass) is much smaller than that of the ocean and hence the coupling between these two must be modelled properly

GCM=General Circulation model

So, you have an atmospheric GCM, you have a chemistry model that transports carbon dioxide and other gases, and the ocean contains biogeochemistry, sea ice, and the land contains land ecology, biogeochemistry, and physics, which takes into account changes in land albedo, vegetation, hydrology, lakes, rivers, and so on. All these are coupled in these models.



To show it another way, you have an atmosphere in which you have equations of thermodynamics and radiation, equations of motion—Newton's laws. You have to take care of turbulence, which is pretty complicated, so you approximate it; it is called parameterization. And you have to worry about water being converted from vapor to liquid to ice and becoming cloud. And this, as I mentioned earlier, is not well represented because clouds are very small. So, you have to approximate it, and that is called parameterization. All these have to interact with what is going on in the ocean below, through evaporation, rainfall, heat transfer from the ocean to the atmosphere from turbulent heat transport, and the atmosphere affects the ocean circulation through wind stress; then the rainwater has to run off from land into the ocean.



Particularly complicated interactions are going on, and all these are accounted for. Now, just to give you one example, in the case of the atmosphere, we have the east-west motion, so-called zonal wind. It takes into account the Coriolis force that acts on a rotating Earth, the pressure gradient, and various stresses, which act on it and affect the rate of change of velocity. The same applies in the north-south direction. In the vertical, normally we assume hydrostatics because the vertical motion of the atmosphere is very slow. So, in most situations, the atmosphere is in hydrostatic equilibrium, except when there is a strong system like a tornado or cyclone; then we have to change it slightly. But most of the time, for climate simulation, we assume hydrostatic balance.

Atmospheric model Component

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + F_\lambda$$ E-W wind

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial \phi} + F_\phi$$ N-S wind

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$ vertical balance

$$\frac{\partial \rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial \lambda}(\rho u) + \frac{\partial}{\partial \phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$ mass

$$c_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$ Temperature

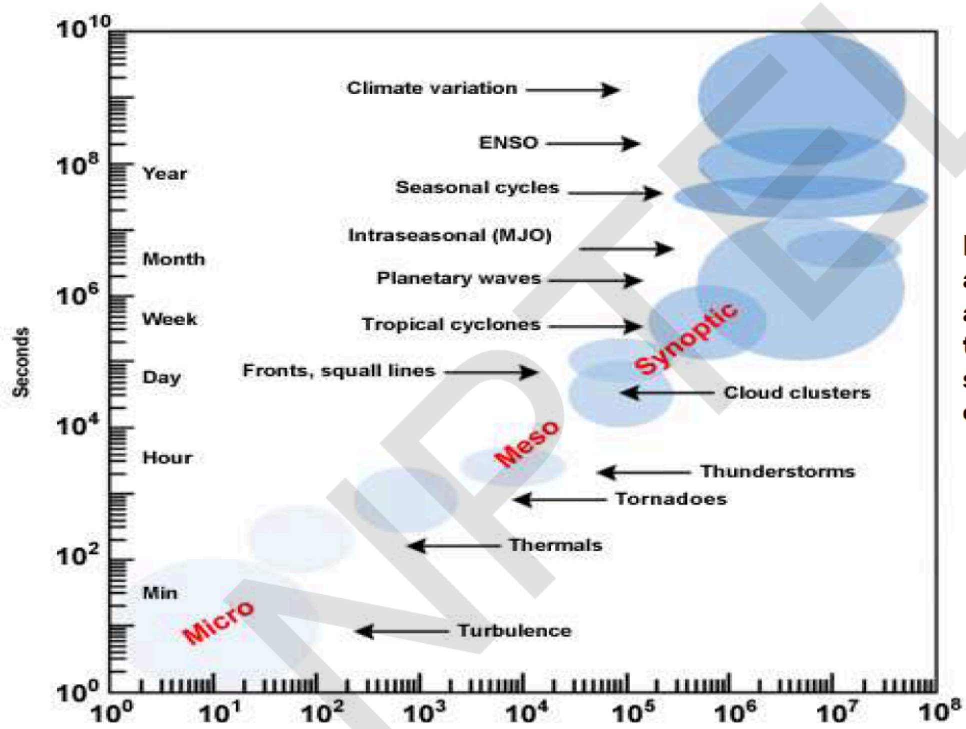
$$p = \rho RT$$ Ideal Gas

6 equations for 6 unknowns (u,v,w,T,p,ρ) - Moisture often added as 7th equation

Of course, mass conservation is very critical; the air moving in the horizontal and vertical directions has to conserve mass in every volume. Then, of course, there is energy conservation, and finally, the ideal gas law is used for the atmosphere. So, we have seven equations and seven unknowns that we integrate. This is one example of how complicated these models are. Because these models are so complicated, the model that you choose to understand a certain part of the Earth's climate system has to be chosen carefully, and it depends on the application.

The climate model has to be chosen carefully depending upon the application

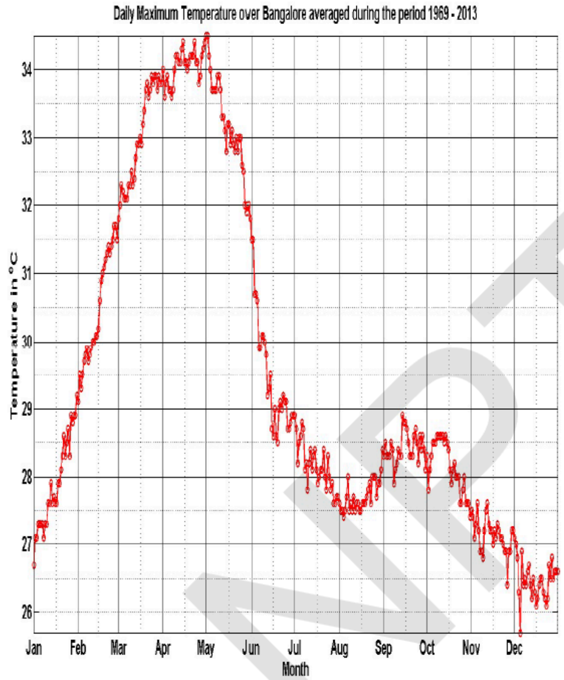
You cannot choose any model for any purpose. When you choose a model, you must ask what it is that you are trying to simulate. For that simulation, which components of the model are to be represented accurately and which can be approximated. This requires a lot of experience. Today, you can download many climate models from websites and run them, and many people do it, but if you choose the wrong model, you will get the wrong answer. So, you must be very careful in choosing your model and how you run it.

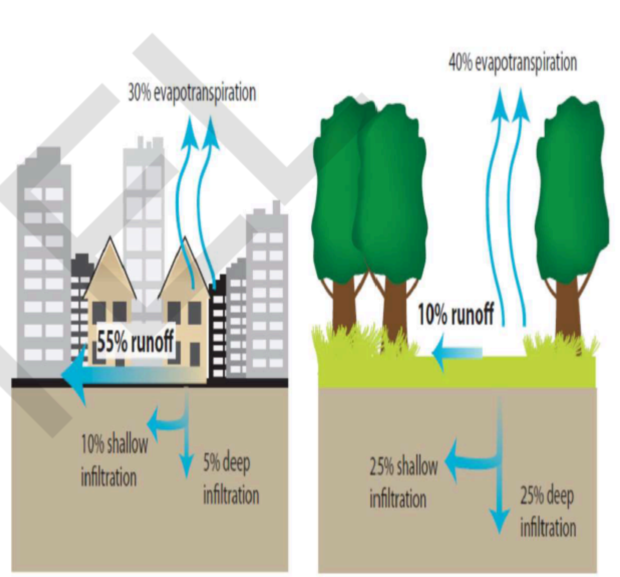


In the earth's atmosphere , ocean and cryosphere the time scales and spatial scales are closely coupled

For example, our model has (length) scales going from 1 meter to 10^8 meters and time scales from 1 second to 10^{10} seconds (many years). In the present course, our focus is on long-term climate. So, we look at scales of years and longer and spatial scales of thousands of kilometers. But if you are interested in a cyclone, then you have to be at that scale. If you are interested in a tornado, you have to go to a smaller scale. Thus, you have to choose your application, decide what time scale you want to simulate, and choose the appropriate model that takes that time scale along with the corresponding spatial scale. They are connected; they are not independent.

Just to give an example, suppose you want to simulate the climate of Bangalore. Bangalore has a very unique climate. It is somewhat cool in January, then the temperature rises rapidly, and by the time you come to April, it is very hot. It is not as hot compared to Chennai, but it is hot for those who live in Bangalore. Then it reaches a maximum around May, and then the clouds and rain come. It rapidly declines in temperature, and by the time we reach June and July, it becomes quite cool again and remains cool until about October. Then it cools further because we are in winter.





Highly developed urban areas (right), which are characterized by 75%-100% impervious surfaces, have less surface moisture available for evapotranspiration than natural ground cover, which has less than 10% impervious cover (left). This characteristic contributes to higher surface and air temperatures in urban areas.

If you want to simulate the temperature variation with season correctly, you need to model the fact that Bangalore has many buildings and urban areas, which affect the way water flows through the city. But there are also green areas like parks; here, you have to simulate the vegetation and how it affects runoff from rainfall. If you do not represent these things in your model, then you will not get the correct answer. The climate model you choose has to be appropriate to the application that you have in mind. You must spend a lot of time figuring out what the right model is for your purpose.

Let me give an example of what has been done with climate models over the last 30–40 years. People have simulated the climate of the last 100 years because if you want to predict what will happen in the future, you must be able to correctly predict the past—the immediate past, at least. So, you have to get the mean state correctly and understand how it varies over all these years. Many models have been run for the last 100 years to ensure that the model correctly simulates the climate of the Earth from 1850 to today. Then people have become more ambitious. They want to simulate the climate of the last 20,000 years (for example, the last glacial maximum) or even much longer periods, such as the last 1,000 years.

These simulations are now quite common because a lot of proxy data tells us what happened on Earth 1,000 or 10,000 years ago. We want to see whether our models are good enough to simulate past climate. Then, to understand complex climate models, you run idealized cases. You might suddenly increase CO_2 by a factor of 2 and see what happens, or suddenly add water near Greenland to see what will happen if ice melts rapidly in Greenland and how it affects the ocean circulation.

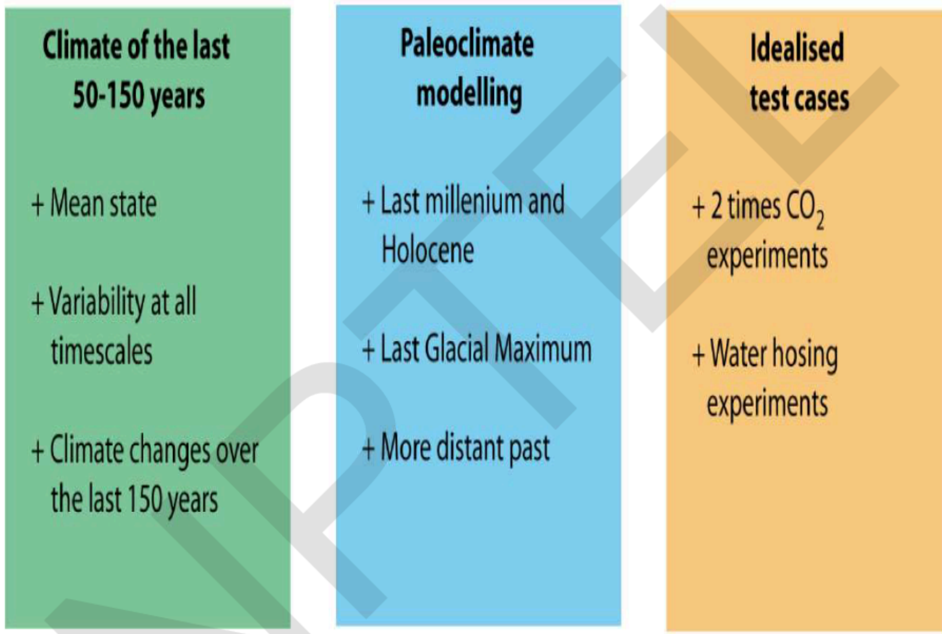
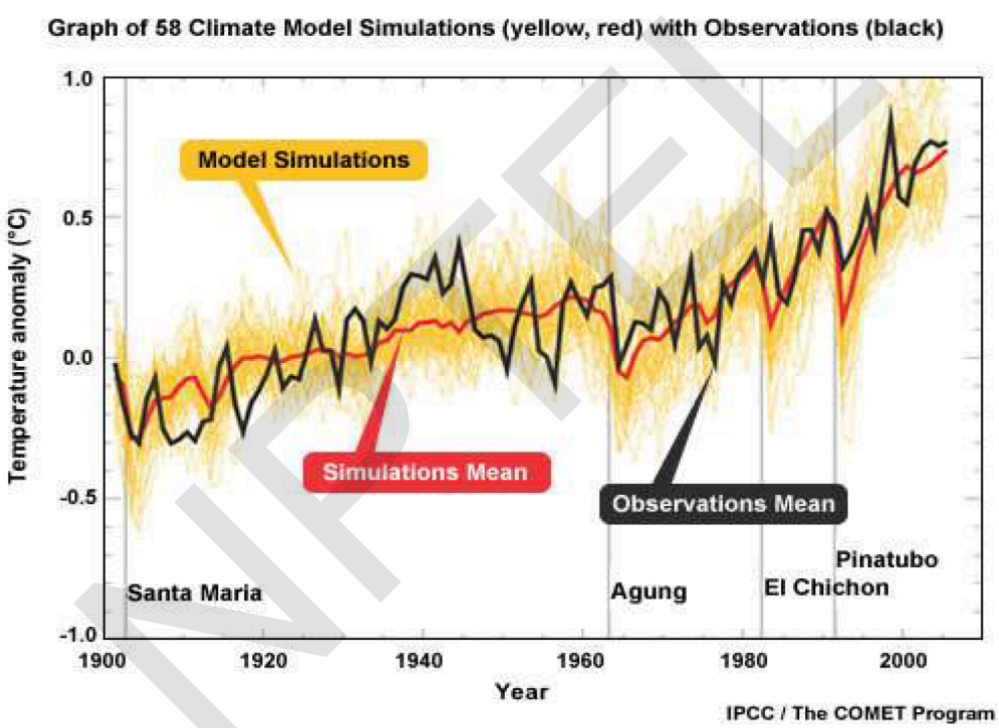


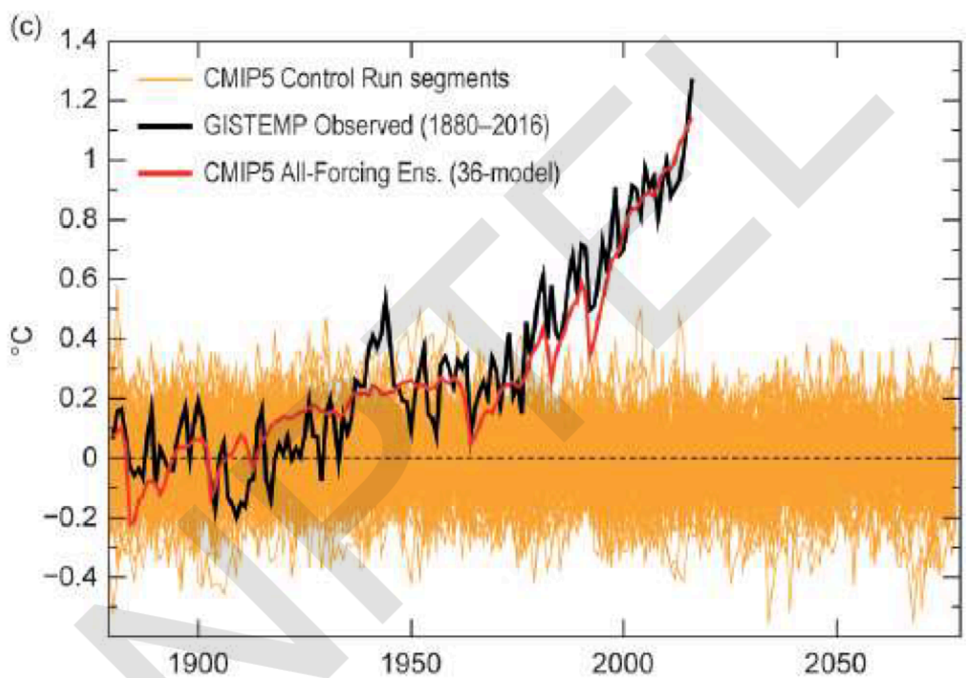
Figure 3.16: Classical tests performed on climate models.

These idealized models are run to understand specific aspects of the Earth's climate. There are all kinds of model simulations related to what you want to understand about the model. You have built a complex model, but it is a very complex beast, and you have to spend a lot of time understanding how the model behaves.



Now, to give you an example of what people have done, many models have been run for the last 100 years. There are about 58 climate model simulations (in the diagram shown above) over the last 100 years, and the small yellow lines represent many simulations from each model. The average of those is the red line, called the ensemble mean of all the simulations, and the black line is the observed global mean temperature. You can see that the models correctly simulate the warming of the last 100 years, but they do not capture the specifics of certain periods. Now, this lack of agreement over a few years may be due to model weaknesses or limitations, or it could also be because, in the past, we did not have many observations. Before 1960, there were not many observations, especially over the oceans. In the last 60 years, you can see the models are doing quite well, but there are still some periods where they are not so accurate. For example, when the volcano Pinatubo erupted in June 1991, the model simulation of the cooling was slightly too high compared to observations. This could be due to model limitations or because we did not input the correct data regarding the type and number of particles released by the volcano.

Also, remember that when you look at year-to-year variation, there is energy exchange between the ocean and the atmosphere. These are complex processes, and these models are not simulating them perfectly, although they are improving. You can see that the 40-year trend is correctly simulated, but any single year may show discrepancies. For example, the large warming observed in the late 1990s due to El Niño is not captured correctly by the models. What you must understand is that the models are quite good for global mean temperature over long time scales—10 years, 20 years, and so on—but not good for year-to-year variations. These models can be used to predict what will happen 50 years from now; global negotiations about climate change are based on these models, and for that purpose, they are acceptable. But if you want to know what will happen next year, the model may not be so good.

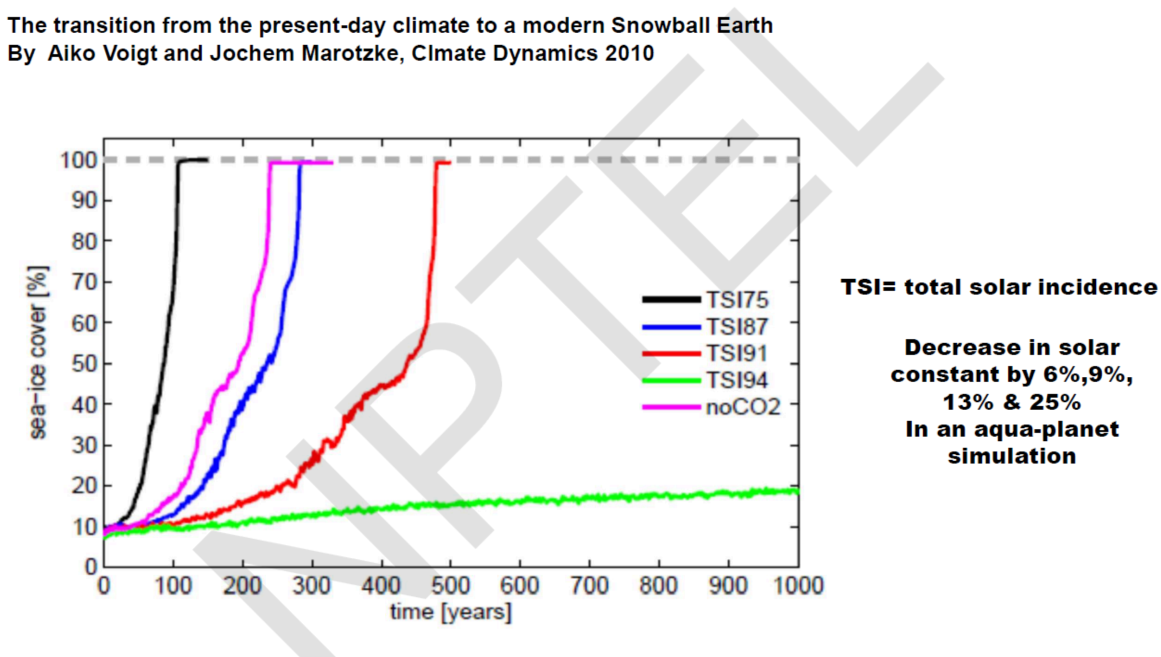


Knutson et al., Bulletin of the American Meteorological Society, December 2017

Now, to show how these models have been used by the Intergovernmental Panel on Climate Change (IPCC), here is an example of models (in the graph above) that took part in the so-called CMIP5 simulation, a coupled model intercomparison project in which many models ran the same type of simulation for comparison. The models were run twice: once without a change in CO_2, keeping CO_2 at the pre-industrial value of 280 parts per million for about 150 years, and then again with an increase in CO_2 as observed (the red line is the mean of 36 models, and the black line is the observation). You can see very clearly that when you run the model with an increase in CO_2, it correctly shows the large warming that has occurred in the last 70 years.

Do not look at year-to-year variation; look at the trend. It does very well, and the model also shows that if CO_2 had not increased and we did not have an industrial revolution, then the temperature would not have changed at all; it would have remained around plus or minus 0.2 degrees relative to the temperature in 1890. This model has been very useful to show clearly that the warming of about 1 degree in the last 100 years is mainly due to the increase in CO_2, and not due to any other natural causes. These models are useful for that purpose—testing a hypothesis.

I must tell you that 30 years ago, many people doubted whether the warming that is ongoing was due to human-induced climate change or natural causes. Today, we can say with great confidence that what we are seeing is a consequence of the increase in CO_2 caused by human actions. These models were used for that purpose, but the same model may not be good for predicting what will happen next year. You must understand both the strengths and limitations. Those who do not trust climate models say they cannot predict next year's temperature, but if your aim is to understand whether the increase in CO_2 is causing global warming, then you do not have to worry about next year's temperature; you have to worry about temperature change over the next 50 years. For that, these models are very good. Remember the subtle differences between applications: certain models are good for some applications, but not so good for others.



Now, I am going to give an example of some simulations done by Aiko Voigt and Jochem Marotzke from Germany, published in Climate Dynamics about 15 years ago, to show how Earth can go from its present climate to a snowball Earth if we change the incoming radiation. This is a thought experiment; it does not happen in the real world. We just aim to understand how sensitive the Earth's climate is to incoming radiation.

Here, TSI is the total solar irradiance coming in. "TSI75" means 25 percent below the present value of 1364 watts per meter square. If we reduce the solar incoming radiation by 25 percent, this model says that for an ocean-covered Earth—a simple model—within 100 years, the ocean becomes completely ice-covered. On the other hand, if you do not reduce the radiation that rapidly, but instead reduce it by only 6 percent, then the sea ice will change very slowly. Even after 1000 years, you will not see a rapid increase in sea ice. You can see the very big difference between a 6 percent change and a 25 percent change. In between, there are other cases: 9 percent, 13 percent, and the case of no CO_2 change. "No CO_2" means you keep the solar radiation constant but suddenly remove CO_2. If you remove CO_2, then within 200 years, Earth becomes completely ice-covered. I want you to remember this case because it shows the very important role played by carbon dioxide in the Earth's climate.

If we remove all the carbon dioxide from Earth—the 420 ppm that is there now—within 200 to 250 years Earth will be ice-covered. So, carbon dioxide is a very important part of the Earth's climate. Although we are concerned about increases beyond the normal value, CO_2 is necessary to have a stable climate in which we can practice agriculture. So, CO_2 is not a villain. The villain is that we are increasing CO_2 too rapidly. I want you to remember that if CO_2 is removed suddenly, Earth's climate will change rapidly; within 200 years, we will have an ice-covered Earth. This simulation was very useful to understand that. This is not a real Earth—it is only an ocean-covered Earth—but it gives you a lot of insight about the time scales by which Earth's climate can change, and the abrupt change in either incoming radiation or carbon dioxide.

Now, there are others who have done similar simulations. I am showing this only to illustrate how changes on Earth can be abrupt. As you go on reducing the incoming solar radiation by 1%, 2%, and so on, the ice cover increases slowly, and you can go up to 90% here. In about 700 years, Earth is 50% covered with ice (for an all-ocean Earth). But from a value of 0.90 you go to 0.89, and suddenly it jumps rapidly to 100%. This is called **bifurcation**. It shows that under certain conditions, the Earth's climate can change very rapidly. I want you to understand this unique feature. From one state to another, there is a slow change; from one state to another, the change is not very rapid; but then suddenly, it jumps—this is called the tipping point. We will talk about this more in the future, because as we are increasing CO_2 rapidly, there is concern that a tipping point might be reached beyond which the Earth's climate will change so rapidly that we can do nothing further. This is a very serious matter, and it must be understood by everyone to realize that we cannot afford to play around with Earth's climate, because there are situations where the Earth can suddenly jump from one state to another.

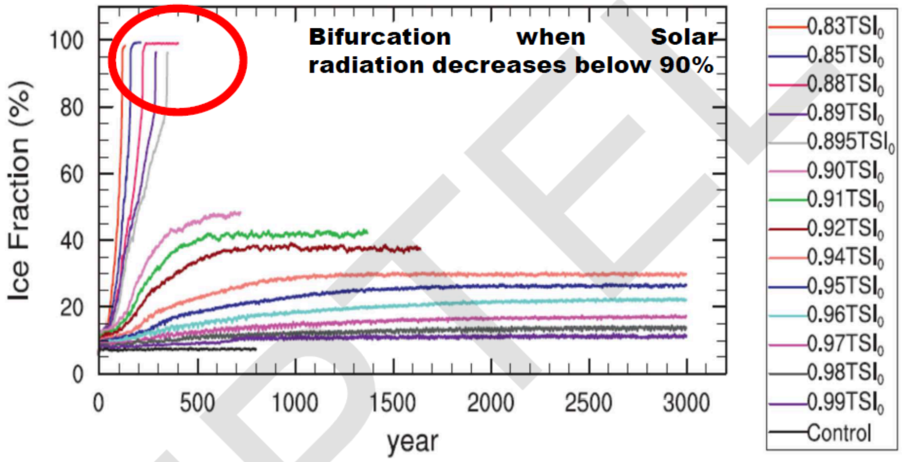


FIG. 2. Global- and annual-mean sea ice evolution in response to abrupt decreases of total solar irradiance. The present value (TSI_0) is 1367 W m^{-2}. In these experiments, the sea ice (snow) albedo is set as the CCSM3 default value: 0.50 (0.78).

Here is another example (see diagram below), which is very interesting: as you reduce the amount of carbon dioxide, you reach a point around 17.5 ppm when the climate suddenly starts going to an ice-covered state. Otherwise, if you change it to 70, 30, and so on, it stabilizes to ice cover on 50% of the Earth. But beyond some point, again suddenly, it starts increasing rapidly. This is called the runaway effect—once it reaches a tipping point, the change becomes rapid. I will discuss this in more detail when I discuss snowball Earth in a later lecture.

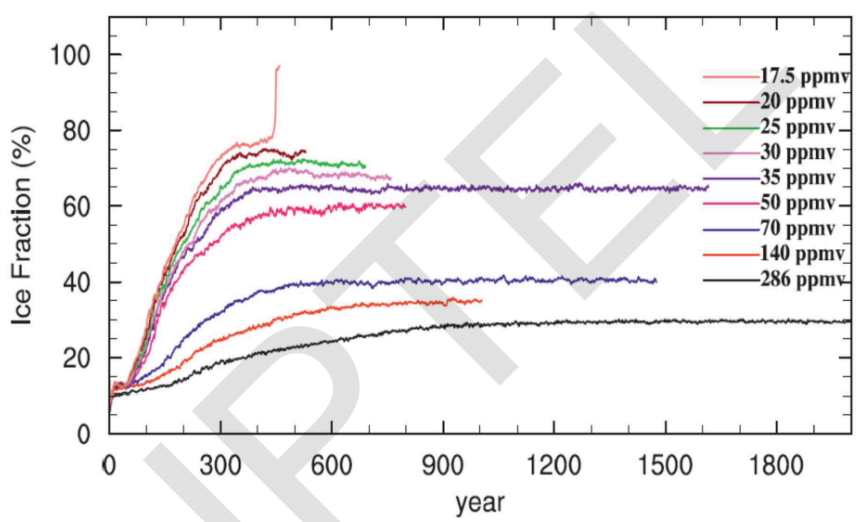


FIG. 3. Global- and annual-mean sea ice evolution in response to abrupt decreases of CO_2 concentration. Solar radiation is fixed at 94% of the present level. The sea ice (snow) albedo is 0.50 (0.78).

Snowball Earth can only happen under certain unusual conditions, and one of them is a very low carbon dioxide content. But I want you to appreciate that these changes occur over thousands of years, so they are slow and may not be an immediate worry. However, when the CO_2 content goes above a certain value, it suddenly leads to a snowball Earth. This point will be discussed further later.

Now, I want to discuss another extreme case, which was published recently (about 15 years ago) by Heinmann et al. in the journal Climate of the Past. This is called the Paleocene–Eocene Temperature Maximum. This period is very important because at that time, the CO_2 level was probably around 560 parts per million—double the pre-industrial value. On Earth, we are pushing towards that value because we are releasing a large amount of CO_2.

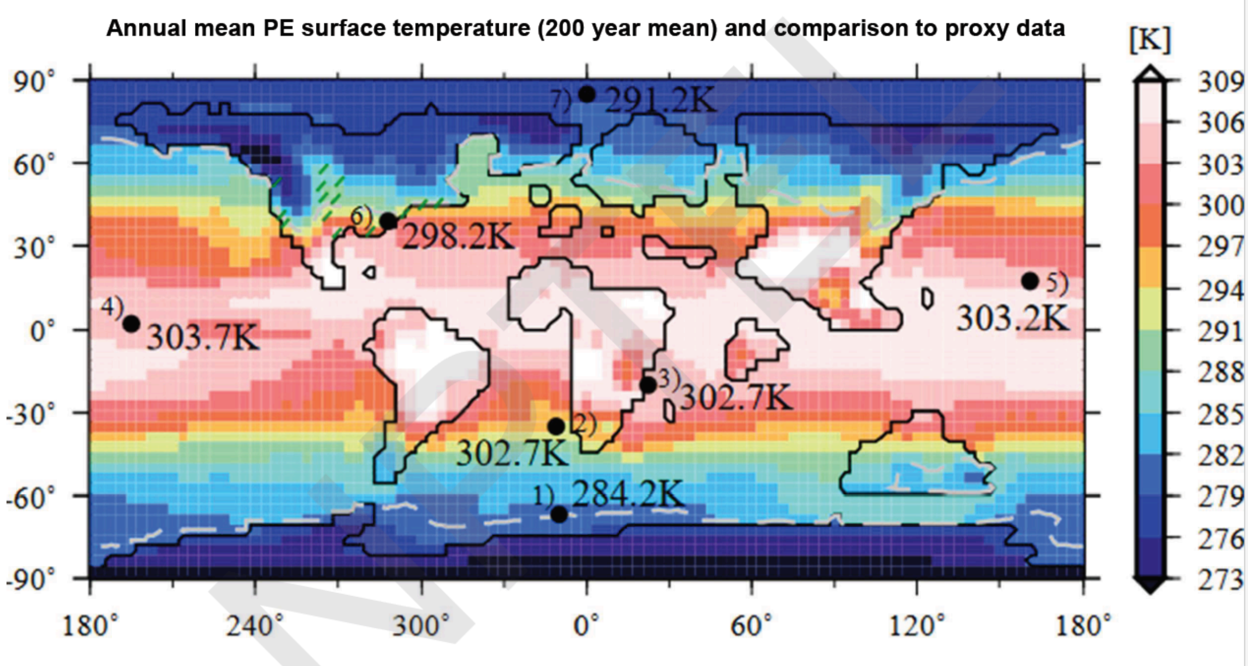
Paleocene-Eocene (PE) ~ 55million years ago
Heinmann et al. Climate of the Past,5, 2009

parameter	*PE*	*PR*
carbon dioxide concentration (pCO_2)	560 ppm	278 ppm
methane concentration (pCH_4)	0.8 ppm	0.65 ppm
nitrous oxide concentration (pN_2O)	0.288 ppm	0.27 ppm
total solar irradiance (S_0)	1367 W m^{-2}	1367 W m^{-2}
eccentricity of the Earth's orbit	0.0300	0.0167
obliquity or inclination of the Earth's axis	23.25^o	23.44^o
longitude of perihelion	270^o	283^o
land surface background albedo	0.16	0.25
sea surface albedo	0.07	0.07
vegetation ratio	0.6	0.4
leaf area index (LAI)	2.3	2.2
forest fraction	0.40	0.26
maximum field capacity of soil (single bucket water height)	1.2 m	0.6 m
FAO soil data flag (1~sand, 3~mud, 5~clay)	3	2.6
surface roughness length over land	1.6 m	1.6 m

So, it is good to know what will happen. They ran the model with the present climate at 278 ppm and a future climate of 560 ppm. All the other quantities were roughly the same. Various quantities are given here; you do not have to worry about them. They wanted to know if you suddenly increase CO_2 from 270 to 560, what kind of climate you will get. It will be similar to what happened in the past.

You must remember that 55 million years ago, Earth's geography was not the same as it is in the present. India was below the equator; Africa was not joined to Europe; South America and North

America were not connected. This model took care of all these geographical features, and the model simulated the climate 55 million years ago and compared it with proxy data.



Proxy data is obtained from sediments in ocean cores. These samples, taken from the present ocean floor, give us a rough idea of what the temperature was. Notice that although the numbers in the model simulation and those inferred from proxy data are not perfect, they are quite close.

This shows that the model's ability to simulate the climate 55 million years ago, when Earth had a CO_2 level of 560 parts per million, is quite realistic. These models are getting pretty accurate in simulating climate change due to increases in CO_2. I want you to remember that. Even though the models have performed well, we have to understand what caused those changes. It is not enough to say that the models have done well and I am very happy; the model may have gotten the right answer for the wrong reason. That can happen.

In the table below, you see the model albedo went from around 0.3 in the present climate (0.32 to 0.29, not much change, about 10%). The model surface albedo went down more because of the melting of ice from a warmer climate, and the climate was about nine degrees warmer. The effective emissivity, which I discussed in the last class, also went down substantially. This gives you some idea, but it is good to relate it to what we learned from the zero-dimensional model that we discussed. In that simple model, the left-hand side is the radiation absorbed from the Sun and the right-hand side is the radiation emitted to space. f is the effective emissivity. Based on all the model data, you can find out how much f changed, how much ρ changed, and how much each contributed to the temperature change.

parameter	*PE*	*PR*
surface temperature τ_s	297.0 K	287.6 K
mean surface pressure	985.5 hPa	985.5 hPa
mean sea level pressure (SLP)	1001 hPa	1012 hPa
potential temperature at SLP	298.4 K	289.9 K
planetary albedo α	0.292	0.318
clear sky planetary albedo α_c	0.133	0.173
surface albedo α_s	0.094	0.137
effective emissivity ϵ	0.541	0.585
clear sky effective emissivity ϵ_c	0.608	0.658
surface temperature $\tau_{s,ebm}$ (0-D)	298.0	289.5
surface temperature $\tau_{s,ebm}$ (1-D)	297.2	287.9
surface temperature $\tau_{s,ebm,c}$ (0-D)	304.9	295.7
longwave cloud radiative forcing (CRF)	29.6 Wm^{-2}	28.8 Wm^{-2}
upward longwave radiation at the surface $LW_s^{\uparrow}$	−445 $W\,m^{-2}$	−395 Wm^{-2}
shortwave CRF	−54.3 Wm^{-2}	−49.6 Wm^{-2}
total cloud cover	0.576	0.617
vertically integrated water vapour	45.3 $kg\,m^{-2}$	25.5 $kg\,m^{-2}$
spectrally filtered surface height h	141 m	231 m

The model showed a 9.5-degree warmer climate. If you run a simple energy balance model like those discussed in the last two lectures, you will not get the same answer; you will be off by about one degree. Now, we can ask whether the 8.5-degree change is due to a change in emissivity or due to a change in albedo. Based on the energy balance model, we can show that 5.7 Kelvin of the change is due to a change in effective emissivity, and 2.8 degrees is due to melting of ice and changes in albedo and clouds. We are able to understand, a little better, the complex changes that took place in terms of changes in the solar energy absorbed and the energy going to space. Clouds affected the albedo, and changes in ice cover and the amounts of water vapor and carbon dioxide also changed the effective emissivity.

Compared PEB to preindustrial simulation using 0-D EBM:

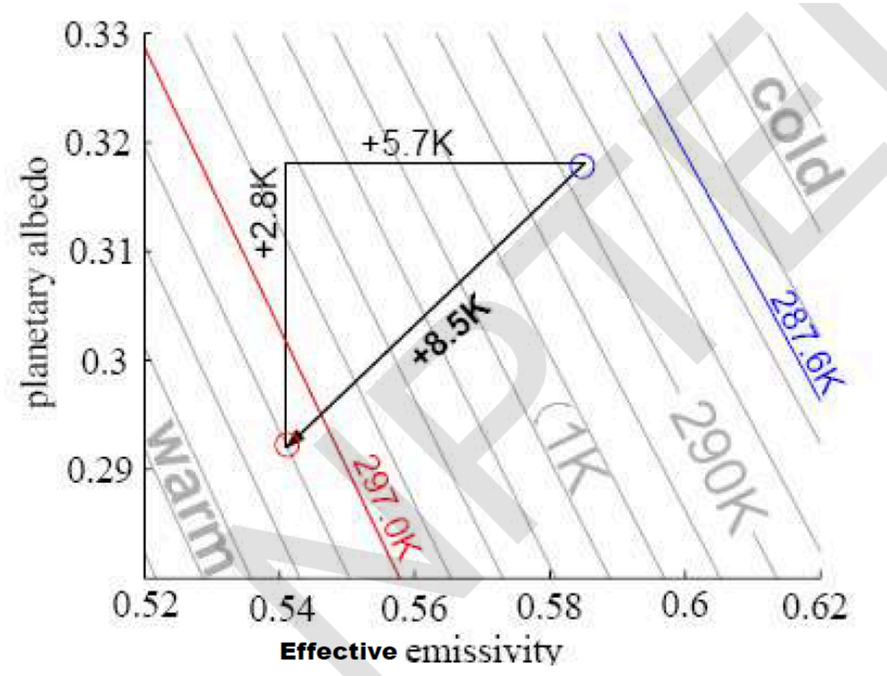
- PEB AOGCM run 9.4 K warmer than preindustrial
  EBM predicts 8.5 K
- +5.7 K due to emissivity change
  clouds have little effect (+0.2 K), CO_2 doubling (+1 K), rest water vapour, orography, ... (+4.5 K)
- +2.8 K due to planetary albedo change
  due to surface albedo change, clouds partly compensate the warming (-1 K)

Energy Balance Model

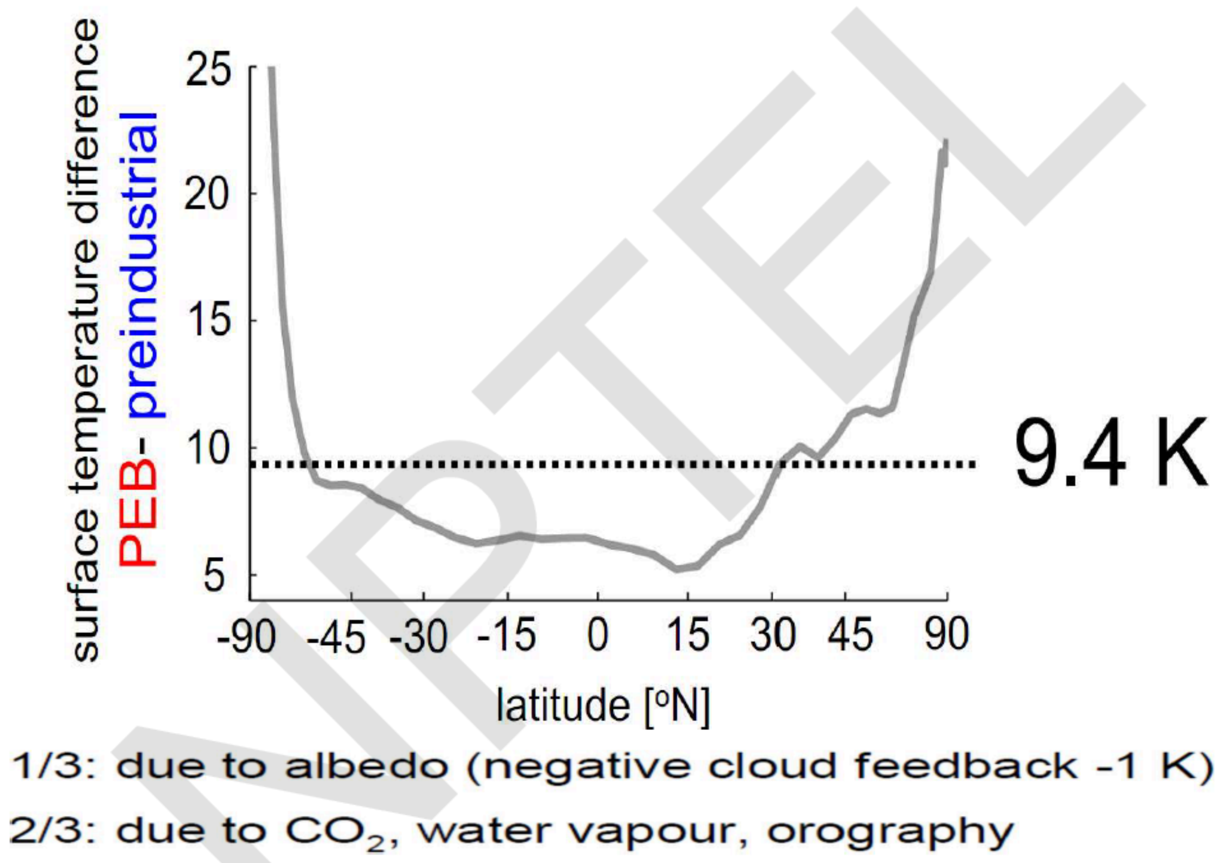
$$S/4(1-\rho) = f \sigma T_g^4$$

How much did the absorbed solar radiation and earth's emitted radiation during Paleocene-Eocene maximum?

That is best shown in a graphical diagram (below): effective emissivity on the x-axis and albedo (ρ) on the y-axis, with the present climate at about 288 Kelvin and the warmer climate that occurred 55 million years ago following a certain path. That path can be broken up into changes due to emissivity and changes due to albedo. What we see is that the change in emissivity is twice as important as the change in albedo, showing that atmospheric emission changes are very critical. This demonstrates that about two-thirds of the change is due to CO_2 and water vapor, and one-third is due to ice melting. I hope you appreciate that although the simple zero-dimensional model is very limited, it helps us to understand a complex model.

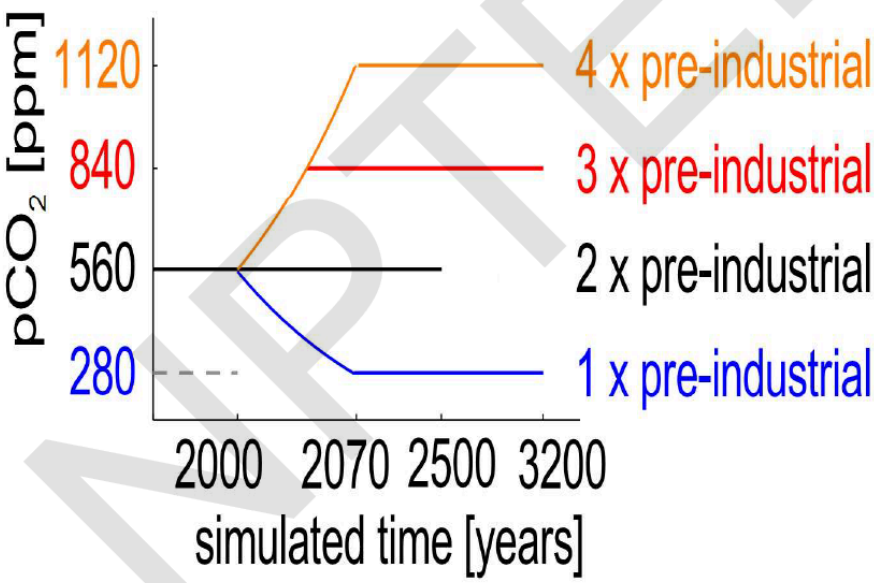


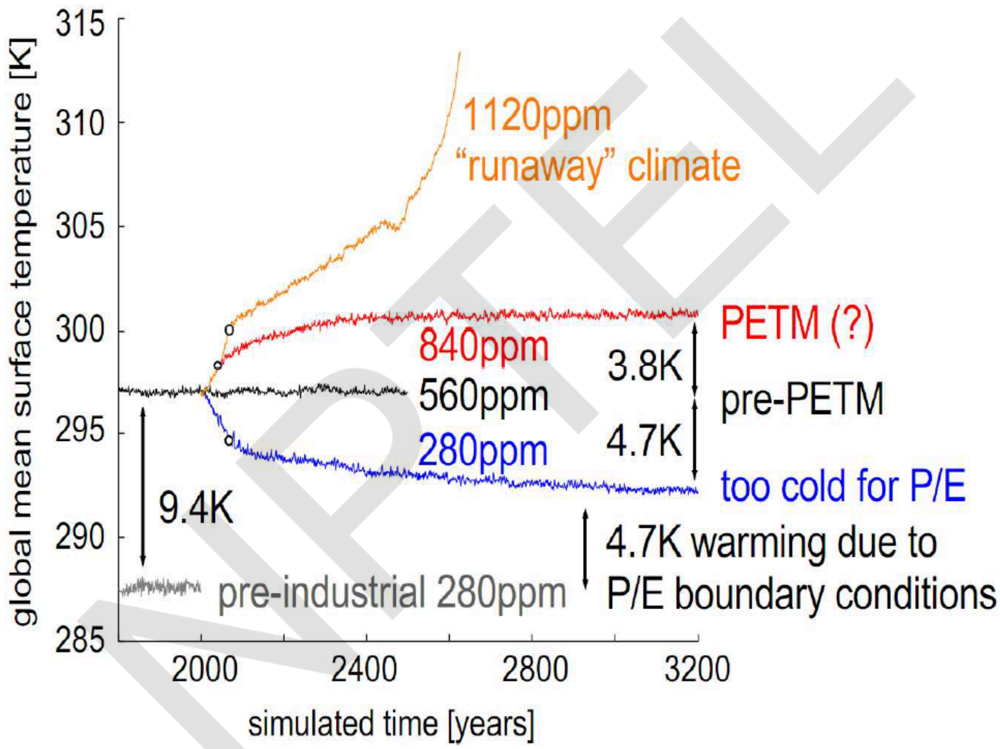
If we do not do that, if we do not understand the complex model, then it may have gotten the right result for the wrong reason. So, we have to use both a complex model and a simple model together to understand Earth's complex climate system. With that, I want to show one more result from this model: the difference between the past climate and the pre-industrial climate, that is, 1850, and how it changes with latitude**. Remember that when climate changes, the largest changes occur in the Antarctic and the Arctic, not in our region.** In our region, it may be a 3–4 degree change, but the Antarctic and Arctic will undergo changes of 20–30 degrees in temperature. For example, in Greenland or Siberia, the changes are on the order of 4 degrees Kelvin, while in our region they are 1 or 2 degrees. So, the models capture these changes with latitude quite well.



With that, I will conclude, and I will also show you that these models have been used to predict what happens if you change the CO_2 to four times the present amount, or three times, or two times, and what happens if it goes down from 560 to 280. All these scenarios have been simulated. One example shows that from 560 (the Paleocene climate), if you bring it down to 280, the temperature will go down to the present value. If you keep it constant, it remains the same. If it is at 840, it will approach the Paleocene–Eocene Temperature Maximum, but if we increase it to 1120, it will start increasing and enter a runaway greenhouse state, meaning the temperature will never stop increasing.

Paleocene/Eocene CO_2 sensitivity runs





This is a cause for concern, although this modeling is not easy. The model shows that we need to be careful—if we continue increasing CO_2, there is a possibility that Earth's climate will increase without bound and we may have no control over it.

On that note, I will conclude my discussion on this topic and move to the next lecture, where we will look at how different feedbacks in Earth's climate system will affect the climate. Thank you.