Climate Change Science
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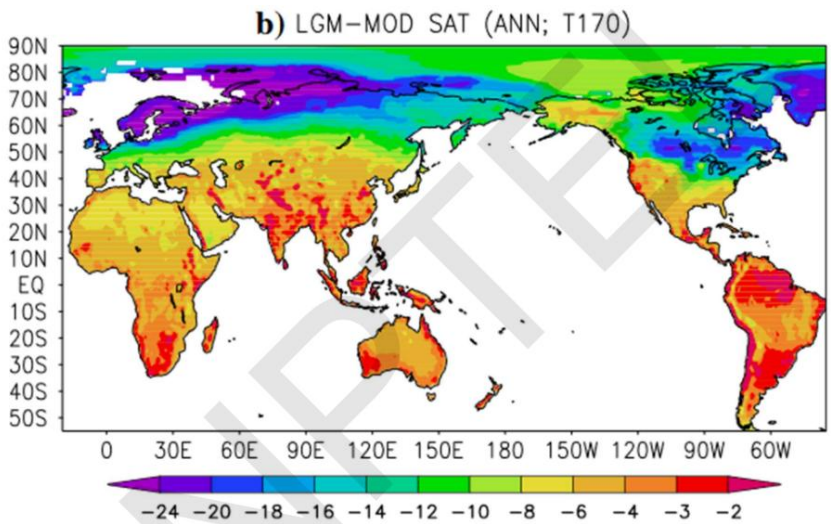
Lecture – 38
Simulation of glacial to interglacial

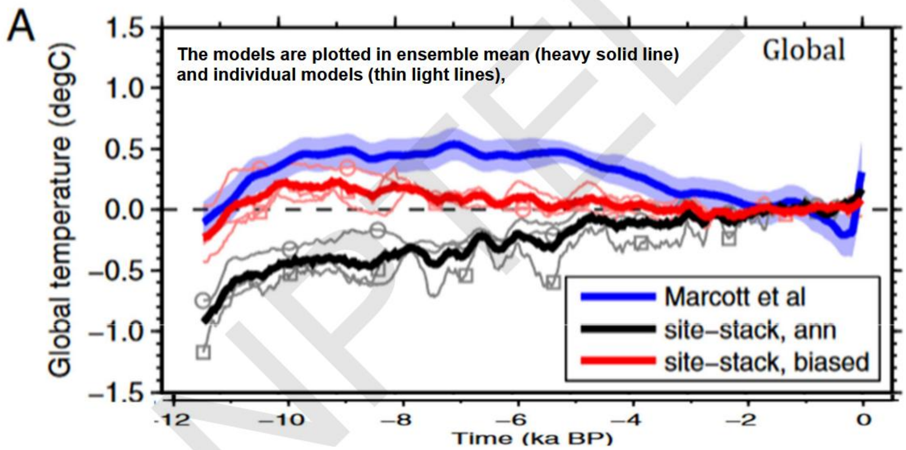
In the last lecture, we discussed the Shakun et al. paper, which looked at data from 80 different ice cores and ocean cores to develop a global mean temperature from proxy data and showed how it changed from the Last Glacial Maximum to today. We also saw that when we compare the model simulation by the NCAR model with proxy data, there were some differences.



The simulations were performed with the CCM3 atmospheric general circulation model.
High-resolution climate simulation of the last glacial maximum by S.J.Kim et al, Climate Dynamics,2008

These differences were there because the proxy data does not sample the whole globe. It only samples a part of the region. So, some errors are introduced of the order of half to one degree.

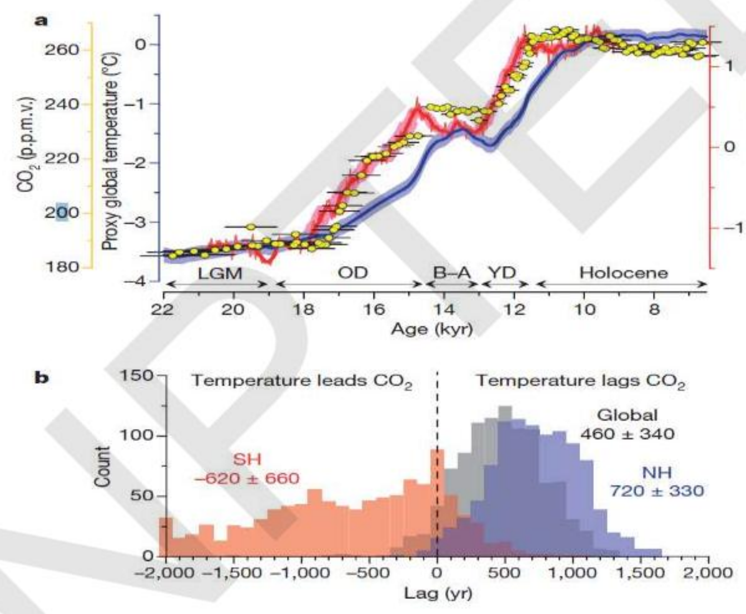
Now, this is shown in this graph shown below where the proxy data of Marcott et al. was compared with the model data, which used either the annual mean temperature or the seasonal mean temperature according to the proxies. You see there is a difference between annual mean and seasonal mean temperature. If you use seasonal mean, the model is closer to the observation. So, that shows that the proxy data does not necessarily sample the annual mean.



The above result shows that the proxies may not represent the annual mean but the conditions in a specific season

We go back to the original paper of Shakun and we see that the Antarctic started warming around 18,000 years ago.

The global proxy temperature stack (blue) as deviations from the early Holocene (11,5 – 6,5 kyr) mean, an Antarctic ice-core composite temp record (red), and atmospheric CO2 concentrations (yellow dots).



That Antarctic warming immediately caused the CO_2 to increase. The CO_2 increase was exactly following the temperature increase in Antarctica, but the global mean temperature lagged by around 800 years. This is because of the CO_2 increase due to the increase in Antarctic temperature. That CO_2 spread all over the globe because CO_2 gets well-mixed in the atmosphere and that causes warming of the Northern Hemisphere, but it will not occur immediately because the oceans have a large thermal inertia. They take a long time to respond to the greenhouse effect of CO_2, and that takes about around 800 years.

In the bottom graph (refer to the figure shown above), they have shown a distribution function of the global mean temperature, the Northern Hemisphere temperature, and the Southern Hemisphere temperature. You can see that the Southern Hemisphere temperature warming occurs earlier because Antarctica warmed earlier. The Northern Hemisphere warmed later, about 700 years later. So, when you calculate the global mean, global mean temperature warms around 500 years after the warming of the Southern Hemisphere. So, this is an important conclusion.

It shows clearly that the warming that occurred from 18,000 years ago to the present was on account of the increase in carbon dioxide coming out of the ocean, a greenhouse effect on Earth, which causes that warming—about 5ºC. This clearly proves that increase in CO_2 causes global warming. A lot of people have doubts whether CO_2 causes global warming or global warming causes CO_2 increase. This paper has clearly demonstrated that CO_2 warming occurred first in the past and the global mean followed. That means the CO_2 increase which has occurred in the last 100 years will continue to cause warming of the Earth for the next 1,000 years. That is the message from this paper.

The advantage of doing simulation is you can look at how the spatial pattern of simulation from the Last Glacial Maximum to today evolved. You see this graph showing the cooling that occurred during the Last Glacial Maximum.

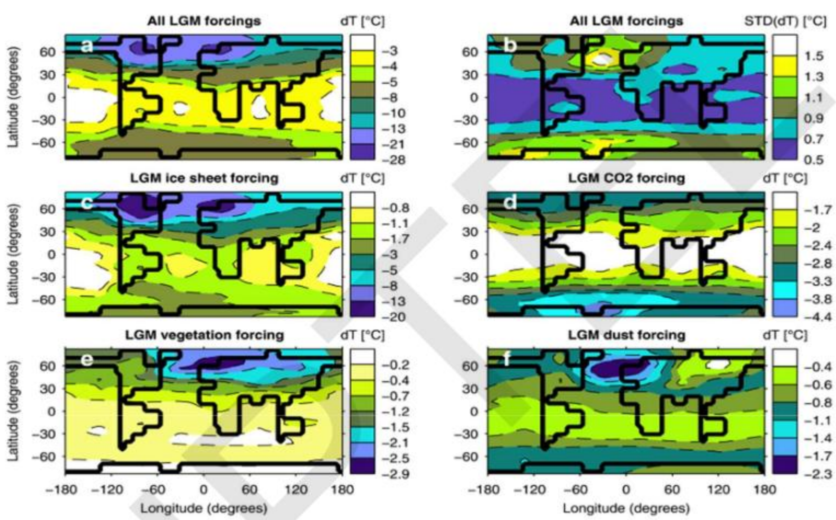
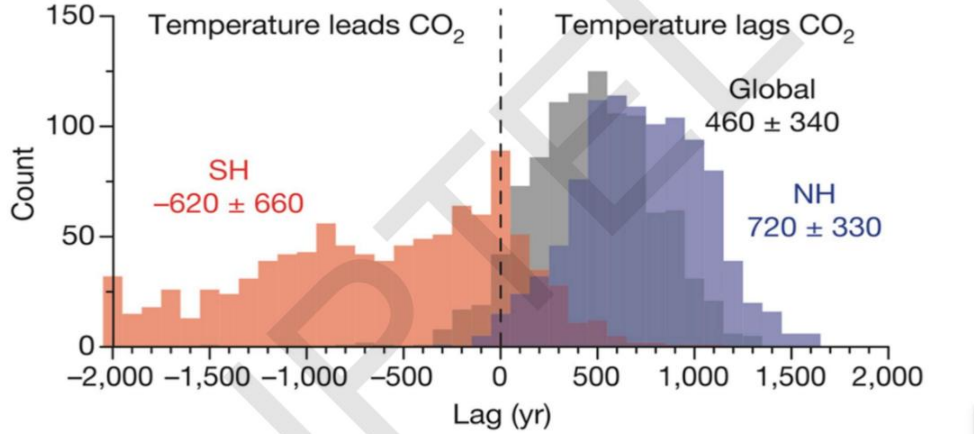


Figure 2. Annual surface air temperature anomaly (LGM minus pre-industrial) resulting from (a) the prescription of all main forcings; (b) the spread from the mean; and annual surface air temperature anomaly (LGM minus pre-industrial) resulting from (c) individual forcings of ice sheets, (d) CO_2, (e) vegetation and (f) dust. All data represent the mean values for the ensemble constrained by tropical SST proxy data.

How cold was the Last Glacial Maximum? By Von Deimling et. al., GRL,2006

The highest cooling was, of course, near Greenland and the Arctic. But suppose you use only CO_2 changes, you will not see much cooling. CO_2 would have decreased in the LGM, but it would have caused 1º of cooling, not 20º. If you include dust, which increases during the glacial maximum, there is some cooling—you can see that. If you include vegetation, because vegetation changes when climate changes, you see some effect. But only when you include ice sheet, you get the maximum cooling. When you add all these four, you see the maximum cooling here. So, this shows clearly that to reproduce the spatial pattern of warming all over the globe during the Last Glacial Maximum, you have to include the ice sheet to reproduce the Arctic cooling, but you also have to include all the other forcings to correctly reproduce the changes in temperature spatial pattern.



The lags between increases in atmospheric CO2 concentrations and temperature for the global (grey), northern hemisphere (NH; blue) and southern hemisphere (SH; red) proxy stacks over the period from 20,000 to 10,000 years befor

Now this is the same graph I showed last time comparing the fact that the Northern Hemisphere warmed much later than the Southern Hemisphere.

So, there is another example showing that carbon dioxide changes occurred earlier than temperature changes. There is a different dataset here, and they are able to show clearly that carbon dioxide started increasing 500 years before the global mean temperature.

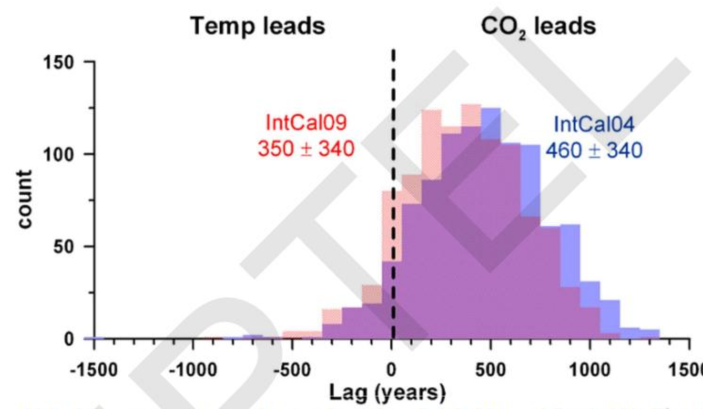
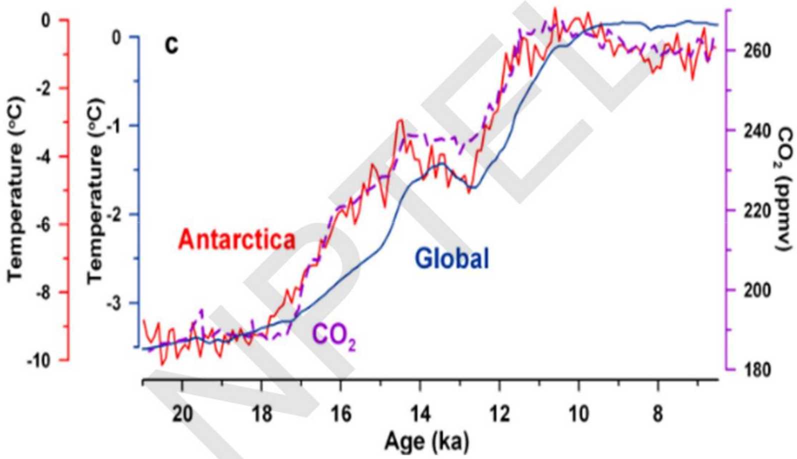
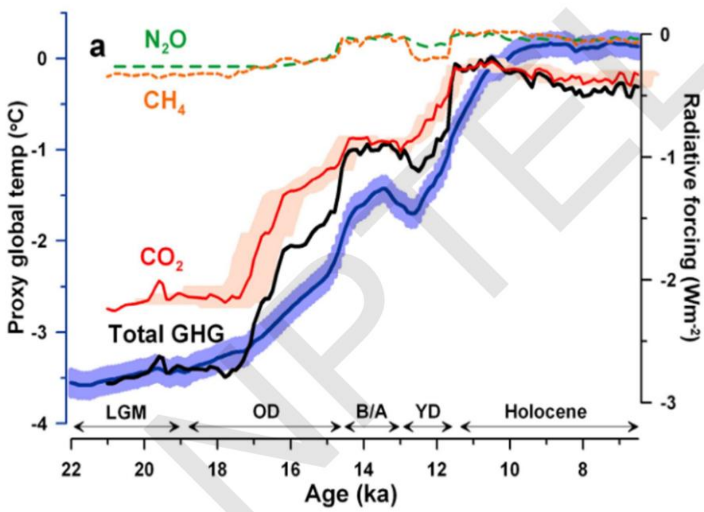


Figure S24: CO_2-temperature phasing based on IntCal04 and IntCal09. The phasing of CO_2 and the global proxy temperature stack based on the IntCal09 (red) and IntCal04 (blue) radiocarbon calibrations using lag correlations from 20-10 ka. The histograms show the result of 1000 realizations, perturbing the proxy records with age model and temperature uncertainties and the CO_2 record with age model errors. The mean and standard deviation of the histograms are given.

This is again the same graph from Shakun et al., in a simplified format, showing Antarctic temperature increased first, CO_2 followed it, and this was followed by global mean temperature.

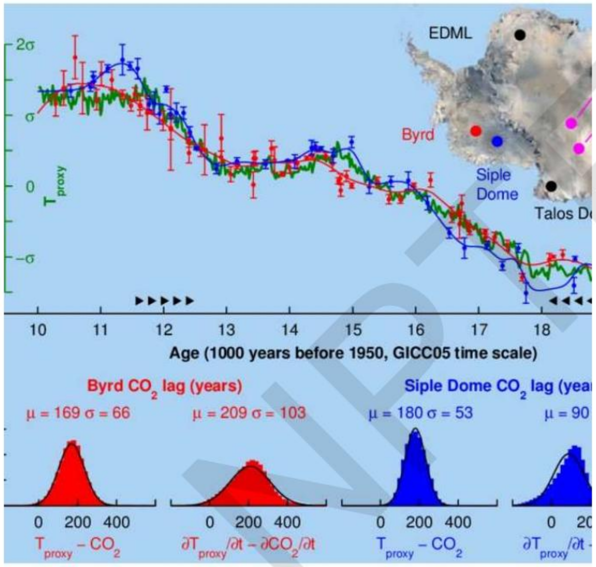


And here is an example showing how the greenhouse gases changed.



There is a change in CO_2, change in methane, change in nitrous oxide—all greenhouse gases. But note that the biggest change was CO_2. Methane and nitrous oxide changed, their impact on radiative forcing was about 0.5 watts per square meter. Its increase from LGM to today contributes to 2.5 watts per square meter. So, CO_2 is the dominant gas, but of course, methane and nitrous oxide add to it. That is why when you take CO_2 and add these two, you get much higher radiative forcing. And that radiative forcing was what led to this warming of the global temperature. So, you can explain the change in global temperature when you include both the changes in ice sheet and changes in the greenhouse gases over the last 20,000 years.

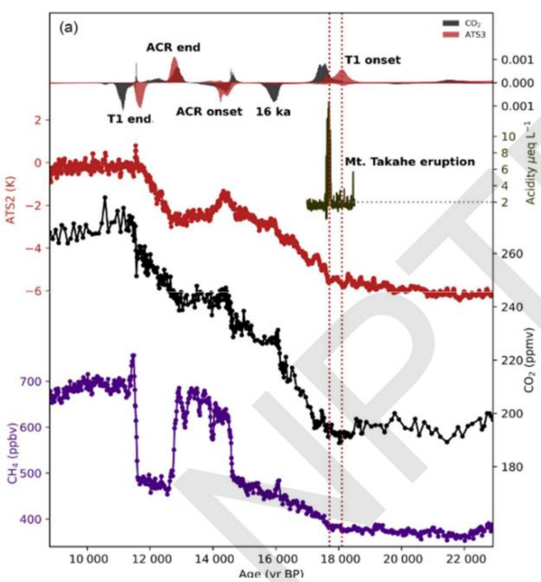
Now, there are other papers which have reproduced this result and they have taken samples of different ice cores. One is in Byrd, one is in Siple Dome and so on.



Pedro et al., Climate of the Past 8, 1213–1221, 2012

And they show that in this case, CO_2 changes occurred earlier by about 180 years in one location—that is, Siple Dome—and in the other it occurs at 169 (lag) years. Changes which are somewhat different, they are not identical. So, you must remember that when you take data from various sources, there will be some differences because we are depending on proxy data; it has its own conversion factor.

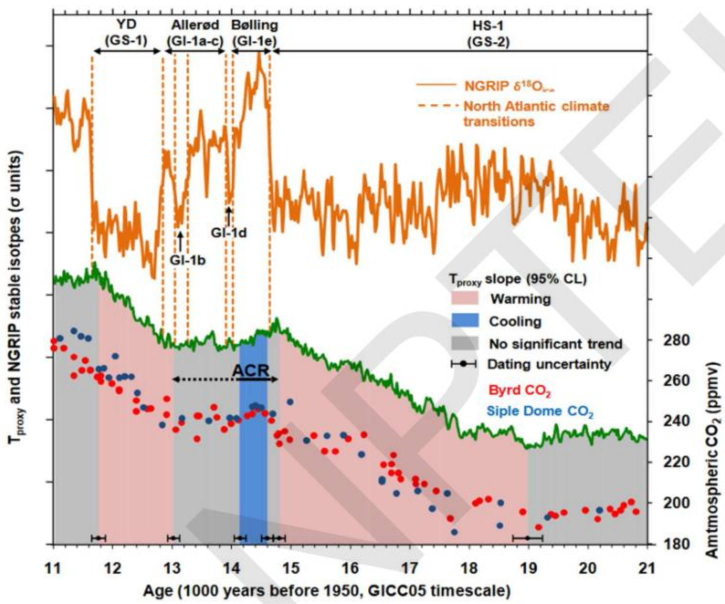
Now, one interesting thing I want to highlight is the fact that methane changes are much larger than changes in CO_2.



The last deglaciation, often referred to as glacial termination 1 (T1), offers a case study for a large global climatic change. The canonical interpretation of this apparent puzzle is that insolation acts as a pacemaker of climatic cycles and the amplitude of glacial–interglacial transitions is mainly driven by two strong climatic feedbacks: atmospheric CO2 and continental-ice-surface–albedo changes
J.C.Beeman etal., Clim. Past, 15, 913–926, 2019

As we came to the last glacial age, we saw a sharp change in methane, but carbon dioxide change is not that much. Same thing during the Younger Dryas event—methane drops dramatically, but not CO_2. So, you must remember that carbon dioxide and methane come from different places.

Methane comes from land—that is, large places where you have water on land and where methane is generated in these water bodies. Like today, we have methane generation in rice fields. Similarly, in the past, when the ice melted, the large areas covered with water generated methane. Methane responds very rapidly to temperature change because it is produced over land where water is present. So, you must remember that methane and CO_2 sources are different. Methane has biological sources. CO_2 does not have that many biological sources.



Significant warming and cooling trends in Tproxy are represented by coloured vertical bands, adopted from a previous study. Climate in the North Atlantic region is represented by the NorthGRIP ice core δ18O record . Changes in the slope of Tproxy are synchronous with climate transitions in the North Atlantic (vertical orange lines). The deglacial increase in CO2 occurs in two steps, corresponding to the significant warming trends in Tproxy (pink bands). A pause in the CO2 rise is aligned with a break in the warming trend (central grey band) during the Antarctic Cold Reversal (ACR). Within the core of the Antarctic Cold Reversal, significant cooling in Tproxy (dark blue band) coincides with an apparent decrease in CO2.

Now, in this above graph here, comparing the last 10,000 years from the LGM to 11,000 years ago, we are comparing data from Greenland, NGRIP, and data from Antarctica. I am showing this result to highlight the fact that changes in the Northern Hemisphere are much more dramatic than in the Southern Hemisphere, because the Northern Hemisphere contains land and the Southern Hemisphere is mainly ocean. So, the changes in the Southern Hemisphere are much smoother than the changes in the Northern Hemisphere. So, this must be kept in mind. The dramatic changes you saw during the Younger Dryas are not seen in Antarctica. It responds, but in a much more subdued fashion, in a smooth fashion.

The Atlantic Meridional Ocean Circulation changes associated with orbitally induced retreat of the Northern Hemisphere ice sheet is the most plausible explanation for the early Southern Hemisphere deglacial warming.

AMOC changes associated with an orbitally induced retreat of Northern Hemisphere ice sheets is the most plausible explanation for the early Southern Hemisphere deglacial warming and its lead over Northern Hemisphere temperature; the ensuing rise in atmospheric CO2 concentration provided the critical feedback on global deglaciation

So, the warming we saw in Antarctica can only be explained because the AMOC suddenly stopped because of the Heinrich event in the Northern Hemisphere. When AMOC stopped, a lot of heat was kept in the Southern Hemisphere and hence it warmed rapidly. That warming led to an increase in CO_2 in the whole globe. So, you must remember the complex interaction between changes in ocean circulation induced by AMOC, increase in CO_2 in the Southern Hemisphere, and finally the global mean temperature change. So, they are all linked in a very complex way and the Shakun et al. paper was able to decipher this complex interaction by looking at both proxy data as well as model simulation.

Now, we can briefly look at what is the radiative forcing caused by CO_2 and land albedo due to land ice.

Table 11.5

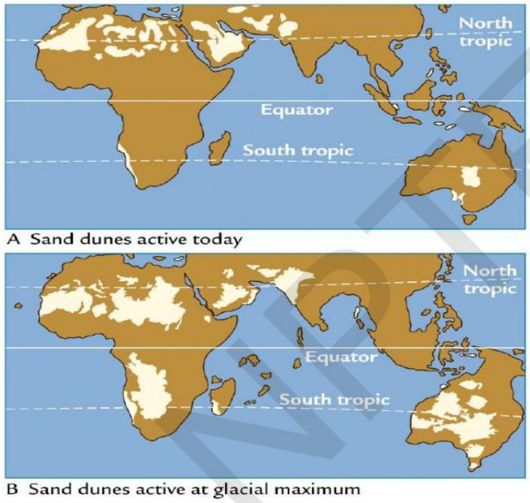
Direct Forcing of Radiative Energy Balance at Top of Atmosphere as a Result of Including Boundary Conditions and CO_2 Changes Estimated for Last Glacial Maximum

Control experiment	Perturbation	ΔR Global	ΔR N. Hem.	ΔR S. Hem.
E1	LGM distribution of continental ice	−0.88	−1.71	−0.06
E3	Atmospheric CO_2 reduced to 200 ppm	−1.28	−1.24	−1.31
E2	LGM distribution of land albedo	−0.67	−0.77	−0.58

Values are in W m^{-2} (N. Hem., S. Hem. = Northern, Southern Hemispheres). [Adapted from Broccoli and Manabe (1987), © Springer-Verlag.]

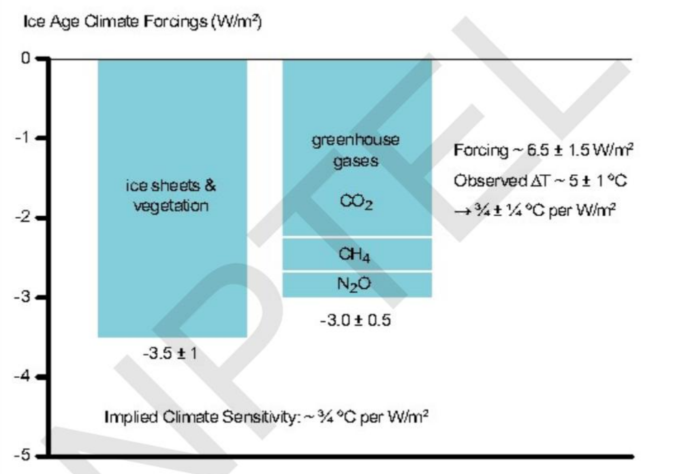
You can see that CO_2 is the dominant contribution: -1.28 W/m^2 cooling occurred because CO_2 declined. The land albedo contribution is there, but it is not as high as CO_2. So, between albedo and greenhouse effect, greenhouse effect is more important according to this data from Manabe.

Dust also made a contribution because during the Last Glacial Maximum, vegetation got reduced. So, deserts increased both in India and in Africa. Sand dunes spread all over the place.



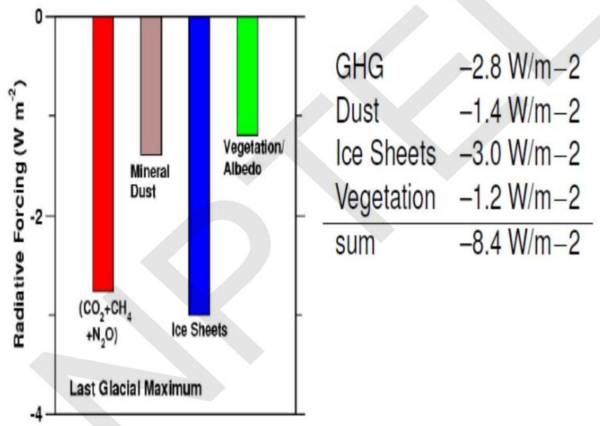
From Earth's Climate Past and Future by W.F.Ruddiman W. H. Freeman and Company New York

So, in the simulation, if you include only ice sheet and greenhouse gases, you may not get the full answer.



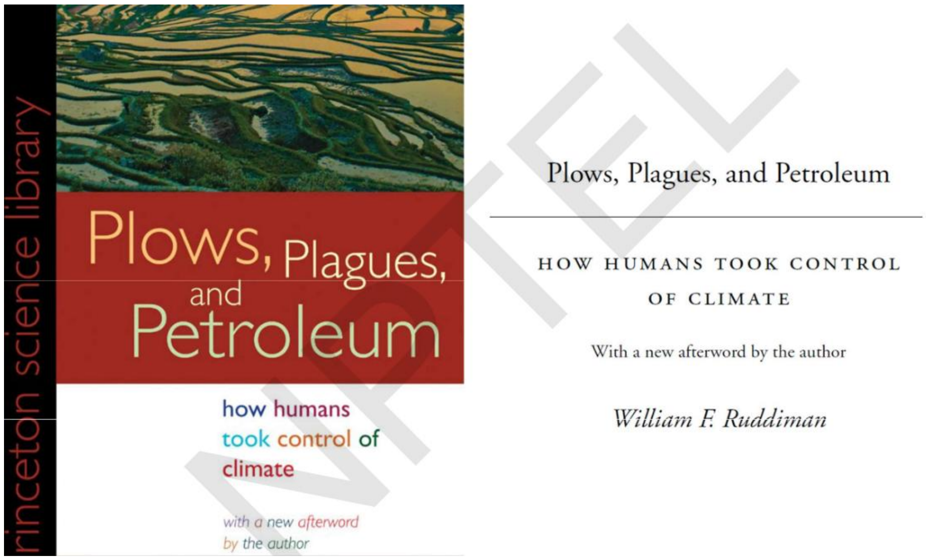
Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period. (Source: Hansen et al. 2008)

So, in the estimation given below, dust contributes -1.4 W/m^2; GHG is still dominant at 2.8 W/m^2; ice sheet contributes -3 W/m^2; and vegetation -1.2 W/m^2; and the total is -8.4 W/m^2 at LGM.



So, LGM had large cooling because of greenhouse gases, dust reflecting the solar radiation, ice sheet reflecting solar radiation, and vegetation also changing the albedo of the Earth.

We will continue the discussion now about what happened during the last 6,000 years based on a hypothesis by Professor Ruddiman. This is a very interesting hypothesis. Ruddiman has written a book called *Plows, Plagues, and Petroleum*.



Plows means conversion of forest into agricultural land, which changed albedo as well as caused more methane to come from rice fields. Plagues is when large numbers of human population decline because of pandemics, and once the human population decline, the agricultural land go back to forest. Finally, the discovery of petroleum 158 years ago caused a dramatic change in global temperature. Ruddiman talks about how humans took control of global climate gradually, starting from deforestation, rice cultivation, and finally to petroleum.

The Ruddiman hypothesis is that the global mean temperature should have declined from 8,000 years before present to today, because that is what happened in the previous interglacial events.

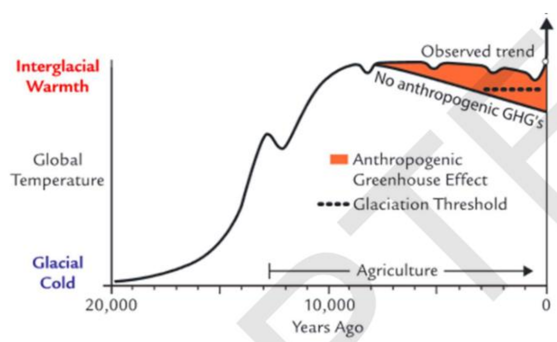


Figure 1. Schematic summary of two views of Holocene climate. Natural hypotheses regard the nearly stable observed climate trend as natural in origin, but the anthropogenic hypothesis claims that climate would have naturally cooled and passed the threshold for early glacial inception if anthropogenic greenhouse gas emissions had not offset most of a natural cooling.

Ruddiman, W. F., et al. (2016), Late Holocene climate: Natural or anthropogenic?, Rev. Geophys., 54, 93–118, doi:10.1002/2015RG000503

In the previous interglacial events, when the solar radiation started declining, the temperature declined—but on Earth, it has not happened. It has remained constant. So, this is a puzzle, and Ruddiman claims that this constant temperature that we enjoyed during the last 10,000 years is due to human interaction. Let us see what this hypothesis is.

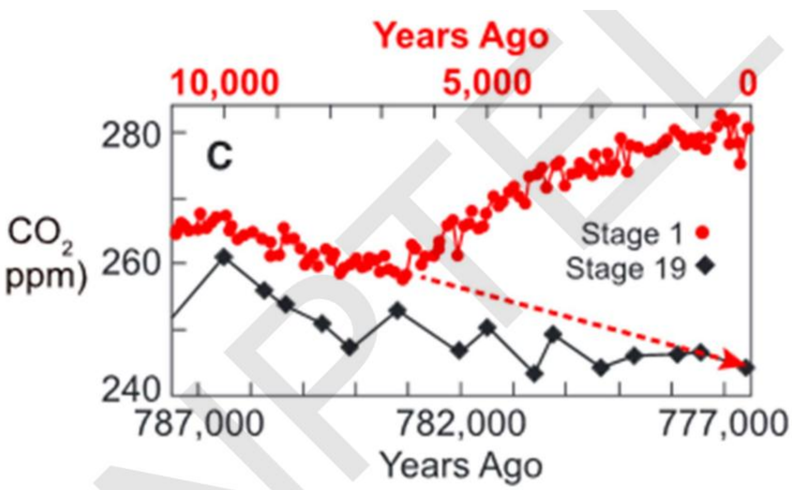
Table A3. Start and End of Deglaciations Based on *Lisiecki and Raymo* [2005]

Interglacial Stage	Start Years Ago	End Years Ago
1	17,000	7,000[a]
5	135,000	126,000
7	252,000	241,000
9	341,000	331,000
11	431,000	412,000
15	631,000	610,000[b]
17	718,000	700,000
19	794,000	784,000

[a]Based on glacial geologic evidence of the final melting of the Laurentide ice sheet.
[b]$\delta^{18}O$ decrease slows at 615,000 years ago but continues throughout stage 15.

Now, what Ruddiman does is he compares the deglaciation that occurred many times during the last 800,000 years. In the last 800,000 years, he has identified eight deglacial events. He compares them all with the last interglacial, which started 17,000 years ago.

So, here is one comparison he has made.



The red line is the period from 10,000 years before present to the present, while the black line is 78,000 years ago to 77,000 years ago—two 10,000-year periods separated by around 770,000 years. So, what is happening in the previous period, where human beings were not there, was that once the solar radiation started declining, the CO_2 started declining—from 260 to 240. Now, that did not happen in this interglacial. In the present Holocene, you see from around 6,000 years ago to the present, CO_2 increased from 260 to 280. Most people assume that this change is natural, but Professor Ruddiman disagrees. He thinks this change is because of human practice of agriculture that changed both the albedo of the land as well as the release of methane from rice fields.

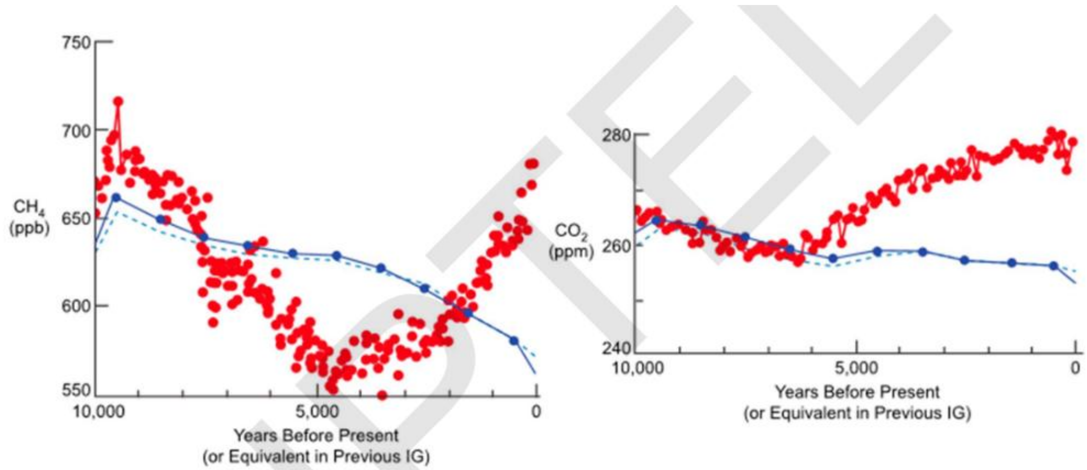


Figure A4. Stacked averages of CH_4 and CO_2 for previous interglaciations based on aligning the end of the previous deglaciations. Solid blue trend shows average with stage 15 omitted; dashed trend shows trend with stage 15 included.

Here is another example shown here—comparing all the previous interglacials we have the blue line—two different ways of doing it. And the change in methane in the last 10,000 years and change in CO_2 both do not follow what happened in the previous eight interglacials. So, this is a very interesting result where you are saying that the last 6,000 years are peculiar, because they do not follow the previous eight interglacial events, where, when the radiation started declining, the amount of methane and amount of CO_2 declined, because CO_2 and methane are linked to temperature. So, his point is that the fact that the present interglacial, from 6,000 years ago to present, the changes in methane and CO_2 are different from the previous eight interglacials implies that human beings have played some role.

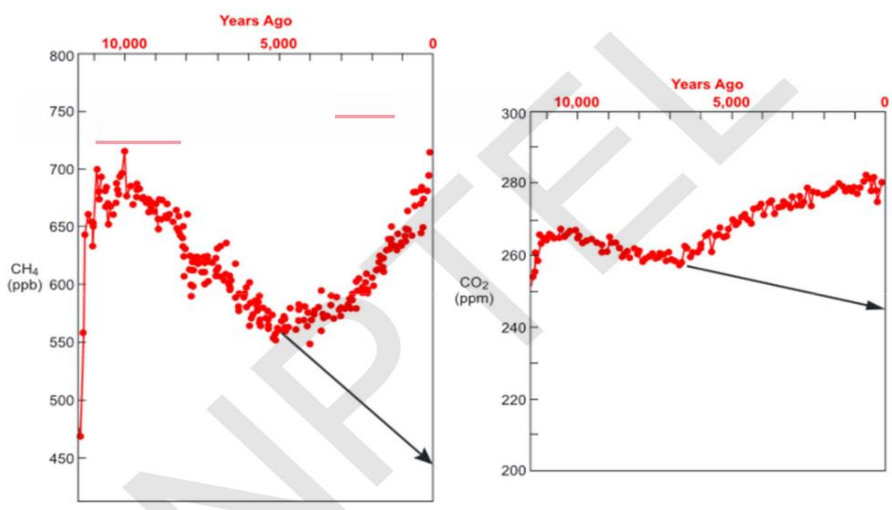


Figure B2. Linear projections (in black) of early Holocene CH_4 and CO_2 values forward to the industrial era (present day).

So, this is the argument. He is saying that we should have been going along this line (black arrow in the figure above) from 5,000 years ago to the present—the methane should have gone down from 550 parts per billion to 400 parts per billion. Instead of that, it increased to 700 parts per billion.

Same thing with CO_2. According to him, CO_2 should have declined to around 245 parts per million, but it increased to 280. So, he claimed that this increase in methane and CO_2 in the last 4,000 years is human-induced.

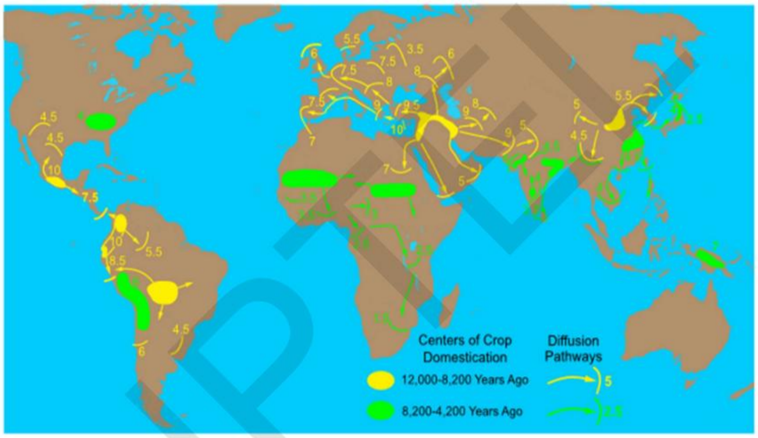


Figure 6. The spread of agricultural crops. Domesticated crops originated during the early Holocene from 12,000 to 8200 years ago and in the middle Holocene from 8200 to 4200 years ago [*Fuller et al.*, 2014; *Larson et al.*, 2014]. Numbers along dispersion pathways represent ages in thousands of years.

Now, this is the area that Ruddiman looks at from papers by Fuller and Larson—areas where agriculture cultivation started. The areas marked yellow were the times when cultivation started around 8,000 to 12,000 years ago, and the areas marked green were the areas where cultivation started from 4,000 to 8,000 years ago. You can see that China, the Middle East, and South America started earlier. And for Africa, India, and America, the cultivation and domestication occurred later.

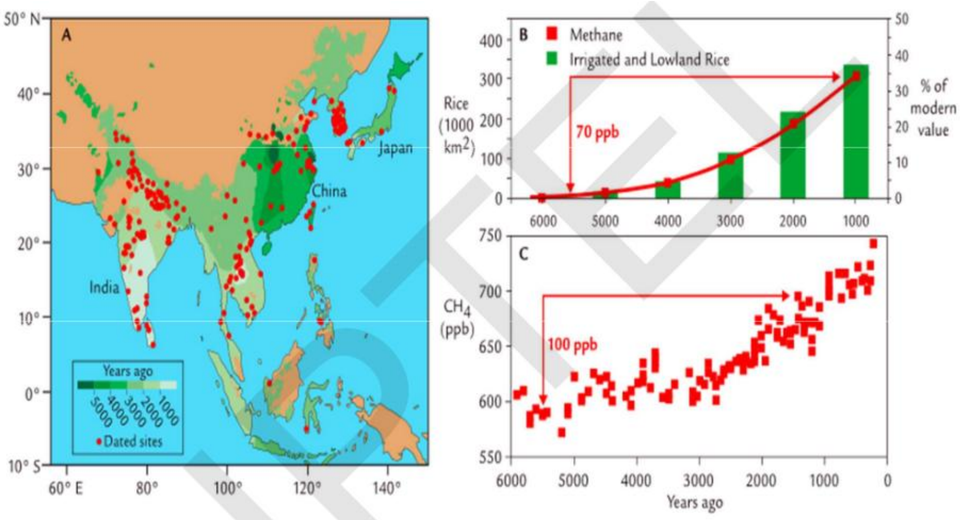


Figure 7. Estimated irrigated rice contribution to atmospheric methane during the late Holocene [*Fuller et al.*, 2011]. (a) Spread of rice farming across southern and southeastern Asia. (b) Estimated area of irrigated rice farming in Asia and contribution to atmospheric CH_4 concentrations, compared to (c) CH_4 concentrations at Dome C [*Monnin et al.*, 2001].

In the above figure, Ruddiman has estimated rice production and its contribution to methane. So, he estimates rice production areas as increasing from 1,000 km² to 3,000 km², and that increased methane by 70 parts per billion. That is the estimate.

Actually, the increase is around 100 parts. So, Ruddiman argues that the increase in rice cultivation in India and China contributed to the increase in methane.

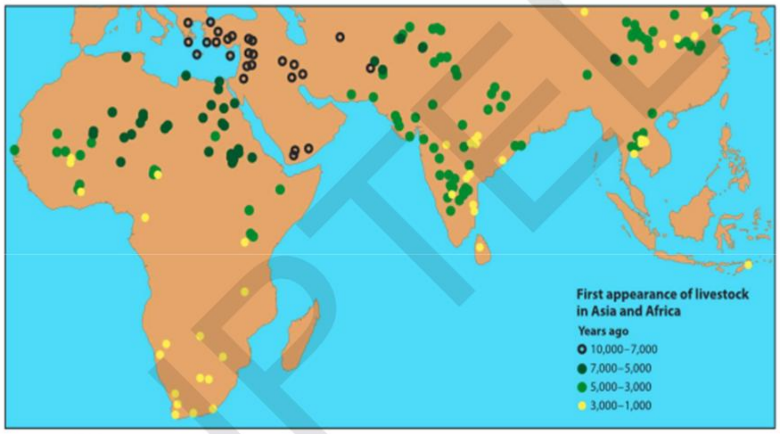
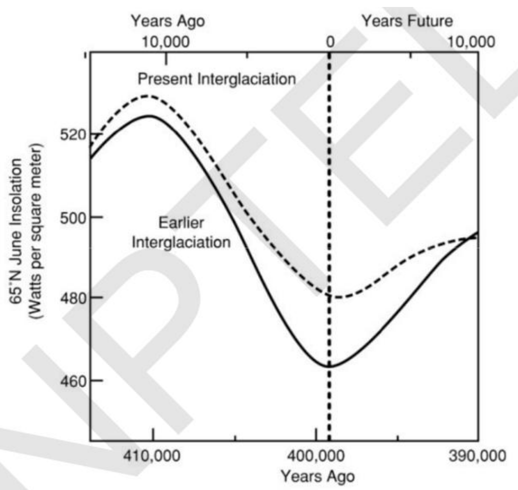
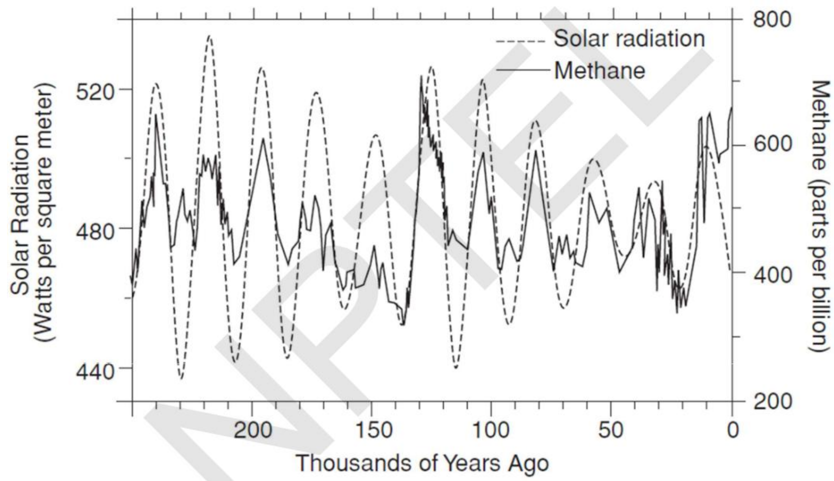


Figure 8. Radiocarbon-dated first appearance of livestock in Asia, Africa, and far southeastern Europe [*Fuller et al.*, 2011] with additions from *Boivin and Fuller* [2009], *Conolly et al.* [2011], and *Arbuckle* [2014].

And he also is able to locate when, in these old civilizations, livestock—that is, cow and sheep and other livestock—were domesticated. And these livestock emit methane—remember that. So, he is looking at 5,000 years ago to 3,000 years ago to 10,000 years ago—the discovery of livestock in fossils.



So, the point that Ruddiman is making is that the amount of radiation coming from 10,000 years ago to 1,000 years ago—the decline in solar radiation—was around 50 W/m^2 in the present deglaciation, while in the earlier deglaciation, it was around 70 W/m^2, slightly higher. So, I would argue that maybe that higher decline in solar radiation may have contributed to the reappearance of glaciers in the past. But in the present, the decline was less, so it may not have happened. But Ruddiman would not agree to it.



Here he compares the amount of methane in ice cores with solar radiation. You can see there are differences. In some periods, the methane change agrees with solar radiation; in others, it does not. So, this is a summary of what I said about Neolithic settlements, which changed the emission of methane in the past.

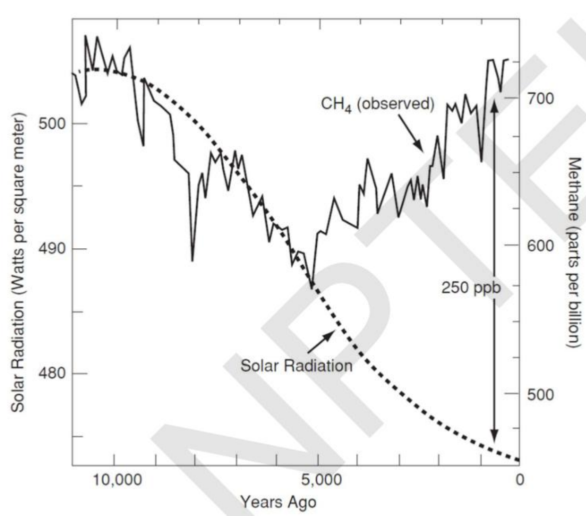
The Holocene, is characterized by an increase in atmospheric CO2 during the last 8000 years and an accelerating increase in atmospheric CH4 since 3000 years before present .

Anthropogenic land cover change (ALCC) has been proposed as a contributing factor. The clearing of natural vegetation for agriculture

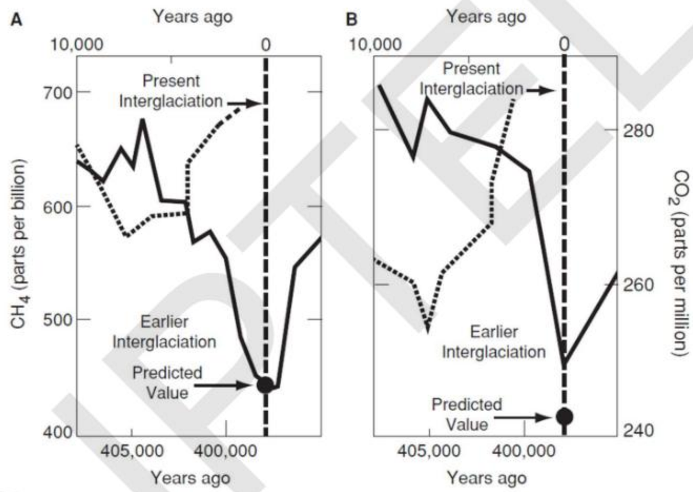
begins with the first neolithic settlements some ten thousand years before present . Well before the industrial era, ALCC could have affected climate and atmospheric chemistry through (i) carbon emissions (ii) changes albedo and (iii) changes in the emissions of non-CO2 greenhouse agents, carbon monoxide, and volatile organic carbon compounds

Stocker et al., Biogeosciences, 8, 69–88, 2011

According to Ruddiman: that if methane had not increased in the last 5,000 years, the decreased solar radiation would have triggered the next Ice Age.



So, he says the next Ice Age was averted because methane increased from around 400 parts per billion to 700 parts per billion.



11.3. During the interglaciation nearly 400,000 years ago, methane and CO_2 concentrations fell to natural values much lower than those reached during recent millennia.

Here again, he is comparing methane variation in the past 10,000 years to the previous interglaciation. There is a big difference both in methane and CO_2. So, it suggests that the increase in CO_2 and methane in the last 5,000 years is probably human-induced.

W.F. Ruddiman, J.S. Thomson / Quaternary Science Reviews 20 (2001) 1769–1777 1771

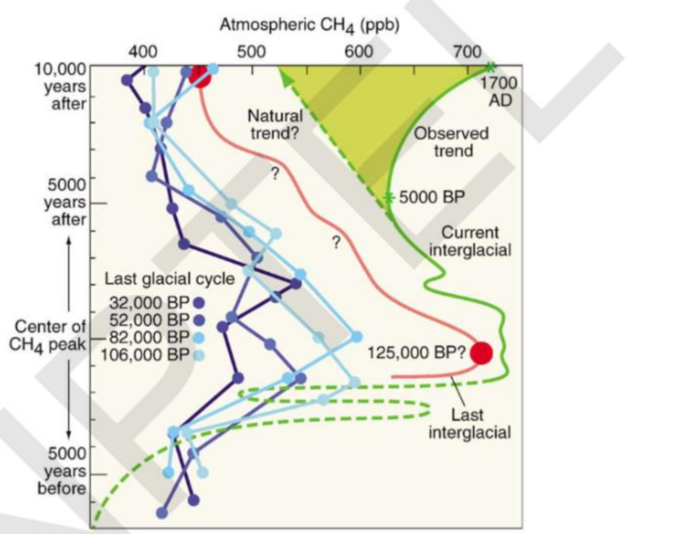


Fig. 2. Following the most recent natural (monsoon-driven) peak in atmospheric methane (far right), the level of atmospheric CH_4 initially followed a downward trend similar to previous peaks that had been driven by the same kind of orbital forcing (left), but methane concentrations after 5000 cal BP began a slow rise unprecedented in the earlier record. Dashed green line shows the hypothesized projection of the natural trend through recent centuries.

And he has compared all these examples with the last interglacial. In all previous interglacials, the methane declined, but in the present one, it has increased. So, he is comparing this with the previous interglacial.

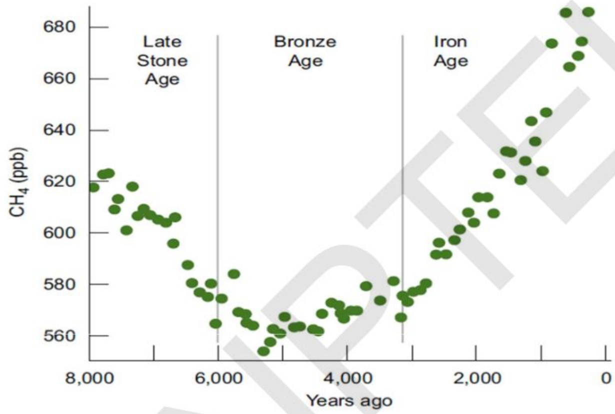


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Fig. 1. Holocene methane trend: Methane trends during the last 8000 years of the Holocene from Antarctic Dome C (EPICA Community members, 2004). The reversal of the downward trend near 5000 years ago and subsequent increase coincide with increased human agricultural activities during the Bronze and Iron Ages. In China, the Bronze Age began ~4500 years ago.

He relates it to the civilizations of the Late Stone Age, Bronze Age, and Iron Age, where they started cultivating crops. That is his major claim.

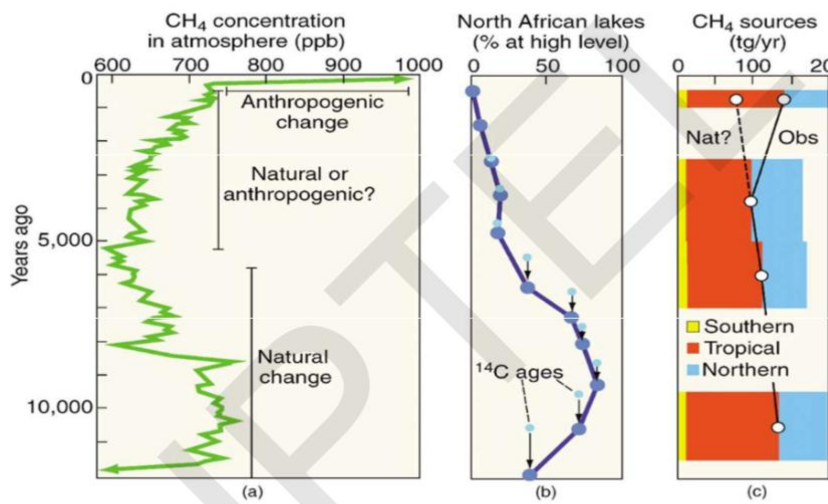


Fig. 1. Atmospheric methane variations from 12,000 to 5000 years ago (a) from Blunier et al., (1995) were primarily caused by monsoonal rains that filled tropical lakes and other wetlands (b) from Kutzbach and Street-Perrott, 1985. In contrast, the abrupt CH_4 rise after AD 1700 resulted from human activities. The intervening 100 ppb CH_4 increase from 5000 cal BP to AD 1700 occurred during a time of early anthropogenic influences, including irrigation of land for rice farming. Bar graphs (c) show estemated CH_4 inputs in tg/yr from boreal, tropical and southern hemisphere sources based on changing interhemispheric CH_4 gradients in ice cores (Chappellaz et al., 1997). Dashed-line projection shows hypothesized projection of the natural trend through recent centuries.

And here it is shown in terms of methane concentration. It is similar to the last figure.

The evidence of growing Arctic methane in the past 5,000 years comes from differences between the amount of methane trapped in the Arctic and the amount sealed in Greenland. So, the amount of methane in the Greenland Arctic is not the same, because in the Northern Hemisphere, there is a lot of permafrost in land regions.

The evidence against a growing Arctic source of methane in the last 5,000 years comes from differences between the amount of methane trapped in air from Antarctic ice versus the amount sealed in Greenland ice. Methane stays in the atmosphere for an average of about 10 years before it is converted to other gases. Because of this relatively quick removal, and because most methane sources are in the Northern Hemisphere (both in the tropics and the Arctic), more methane survives the trip to Greenland than makes it all the way to the South Pole. As a result, concentrations in Greenland ice average about 5–10% higher than those in Antarctic ice.

So, the methane concentration is higher by about 5 to 10 percent compared to Antarctica. So, that is all he talks about. So, this is a claim that rice cultivation contributes to methane.

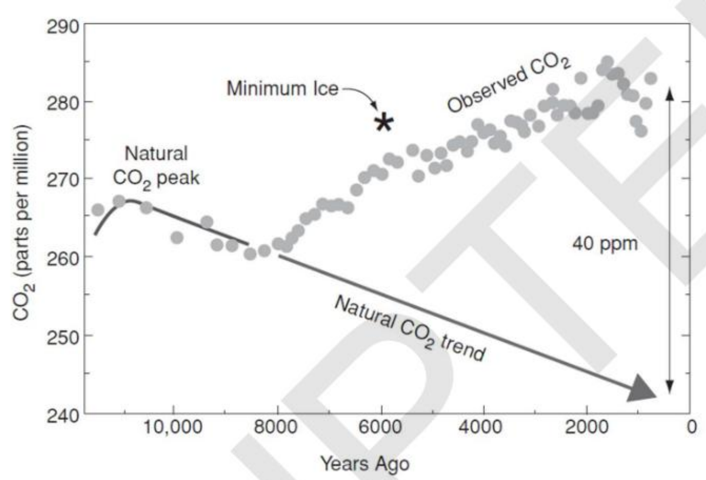
Then you look at all the sources of methane through agriculture and other sources.

Table 1
Estimated 1990 methane budget (in tg/year; IPCC, 1994)

Total CH_4 sources	530
Natural CH_4 sources	160
Wetlands	115
Termites	20
Oceans	10
Recent anthropogenic sources	140
Fossil fuels	100
Municipal landfills	40
Early anthropogenic sources[a]	230
Rice paddies	80
Livestock	60
Biomass burning	40
Animal waste	25
Domestic sewerage	25

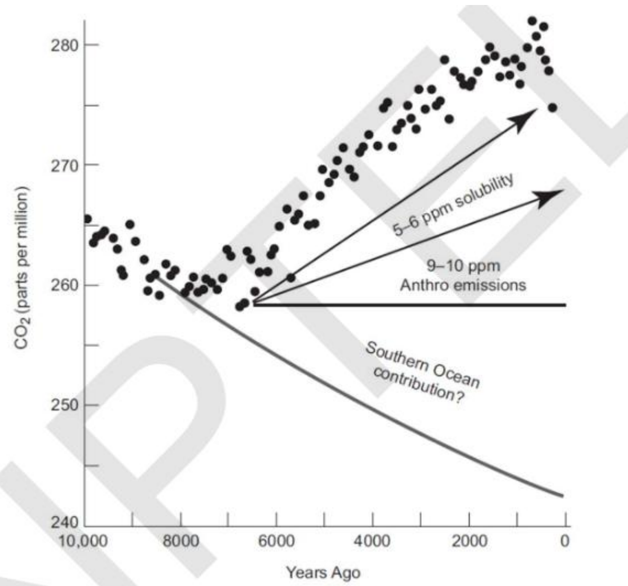
[a]Sources that could have been significant prior to the industrial revolution.

Of course, these days, fossil fuels dominate.



9.2. Natural processes caused the atmospheric CO_2 peak nearly 10,500 years ago and the subsequent decrease until 8,000 years ago, but humans have caused the anomalous CO_2 increase since that time.

His argument is that if CO_2 had naturally gone down in the last 6,000 years, it would have contributed to a new Ice Age.



A.6. A "pie-chart" representation of possible contributions to the anomalous CO_2 trend during the last 7,000 years from: warming of the deep ocean (resulting in decreased CO_2 solubility), direct anthropogenic emissions, and maintenance of anomalous warmth in the Southern Ocean.

So, he is trying to explain what are the differences between what should have happened and what has happened in terms of CO_2.

So, here is a summary of the role CO_2 and albedo played in the Last Glacial Maximum.

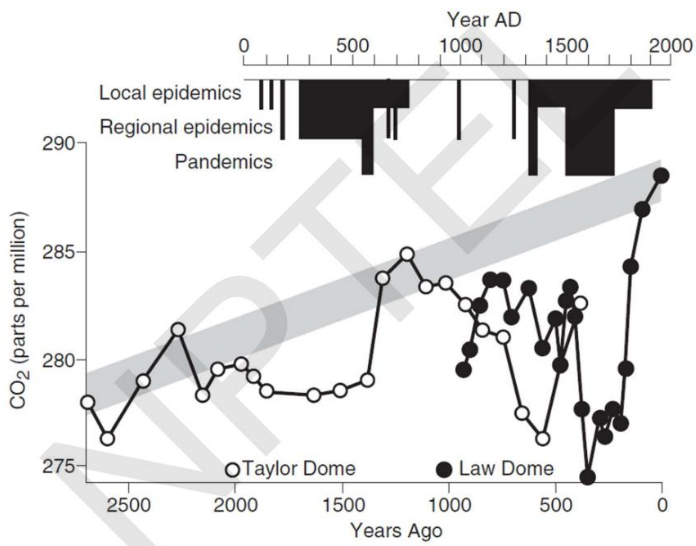
> **The means by which the ice sheets affect CO_2 levels is still debated, but two promising candidates have been identified. One hypothesis is that the dust generated on the continents by the ice sheets is blown to the ocean and fertilizes algae in the surface layers of the ocean. As the algae die, their carbon-rich tissue sinks to the sea floor, removing CO2 from the surface ocean and the atmosphere. The other hypothesis calls on large ice sheets to alter the circulation and chemistry of the deep ocean in such a way as to change the CO2 content of the atmosphere**

Ruddiman, based on his calculation, shows that human activities have increased the CO_2 concentration by around 40 ppm.

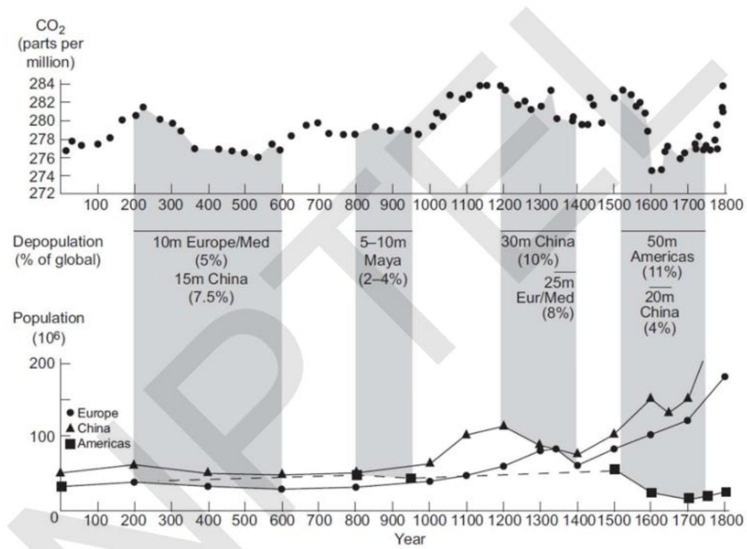
> **My calculations of forest clearance had suggested that more than 200 billion tons of carbon could have been emitted by human activities, an estimate that seemed reasonably close to the amount needed to explain the 40-ppm CO2 anomaly. But now a model simulation had been run that required a much larger amount of carbon to explain the CO2 anomaly—somewhere in the range of 550 to 700 billion tons. Because humans could not possibly have released that much carbon into the atmosphere in the last few thousand years, the authors of this paper concluded that human activities could not account for a 40-ppm CO2 anomaly. If so, my hypothesis must be flawed**

But there are other people who do not agree that this large increase would have happened. He attributes this to clearing the forest.

And then the other remark he makes is about the role of pandemics. He has historical data on how pandemics occurred in Europe and in China. And whenever the pandemic came over, he claims CO_2 was lower.



The CO_2 decline in the last 2,000 years, Ruddiman attributes to pandemics. This is a bit controversial because both the CO_2 data and the data on pandemics are not as accurate as you would like to have.



A.8. High-resolution CO_2 analyses from Law Dome Antarctica show CO_2 decreases that match episodes of mass human mortality caused by pandemics in Europe and the Americas and by civil strife in China.

So, he tries to relate the decline in CO_2 to pandemics, which I am not sure is that reliable. So, with that, I conclude the discussion on the Holocene based on Ruddiman's hypothesis. It is an interesting hypothesis, but we cannot be too sure that this actually happened. We need more data both on the human removal of forests and cultivation of rice to be convinced that human beings began to influence the global climate 5,000 years ago.

In IPCC, 1850 is considered as pre-industrial, where human impact on climate is small. So, all the discussion is about 1850 onwards. All the global negotiations compare global mean temperature with 1850. But, if you believe in Ruddiman, human impact started 5,000 years earlier. But, this is not proven yet. We will need more data to verify whether human beings really had an impact on global climate.

In the next lecture, we will look at an unusual event in the past called Snowball Earth, where the entire Earth was covered with ice. It is a unique time period, well before human beings came, which we will look at in the next lecture.