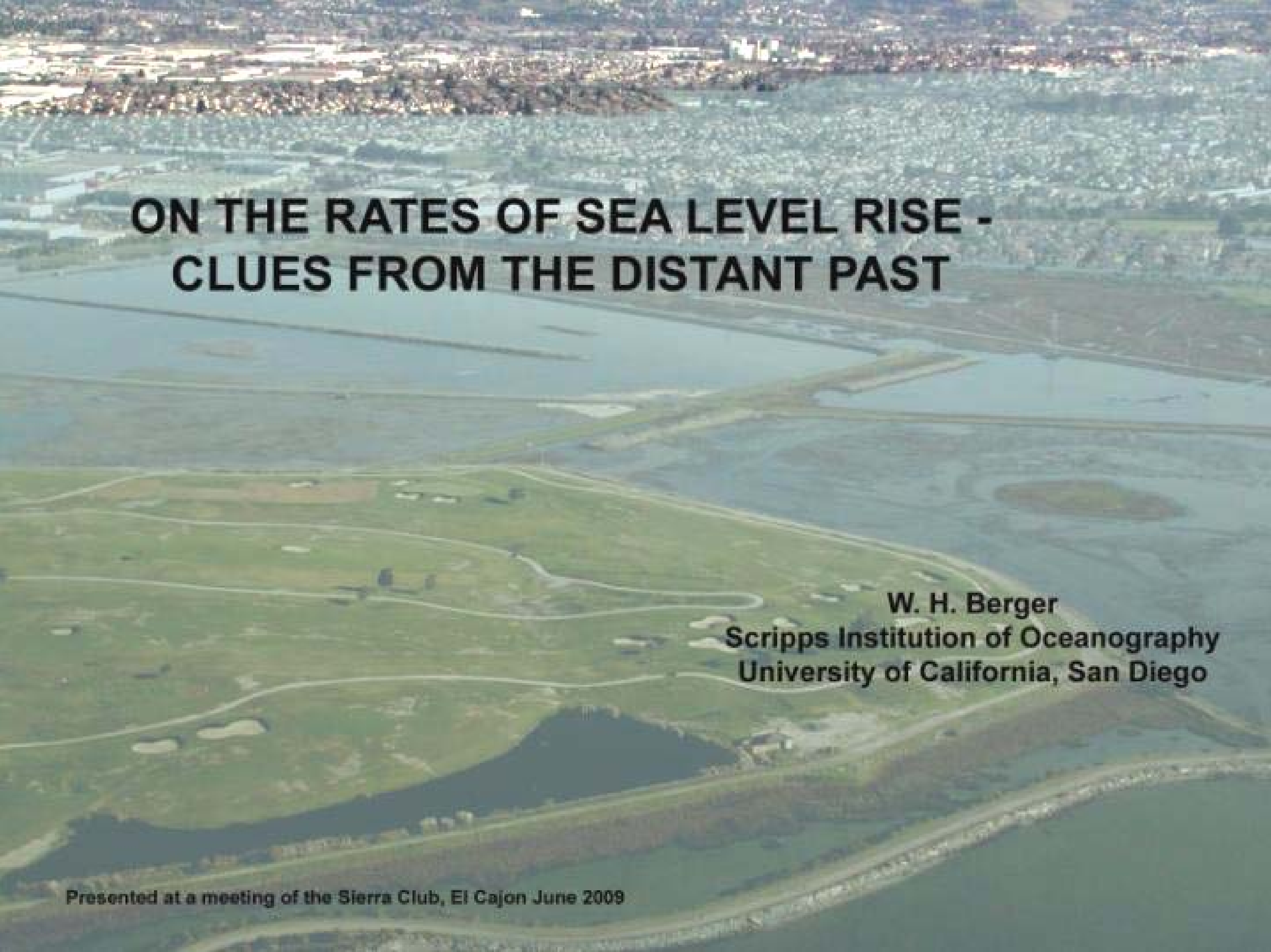

ON THE RATES OF SEA LEVEL RISE - CLUES FROM THE DISTANT PAST

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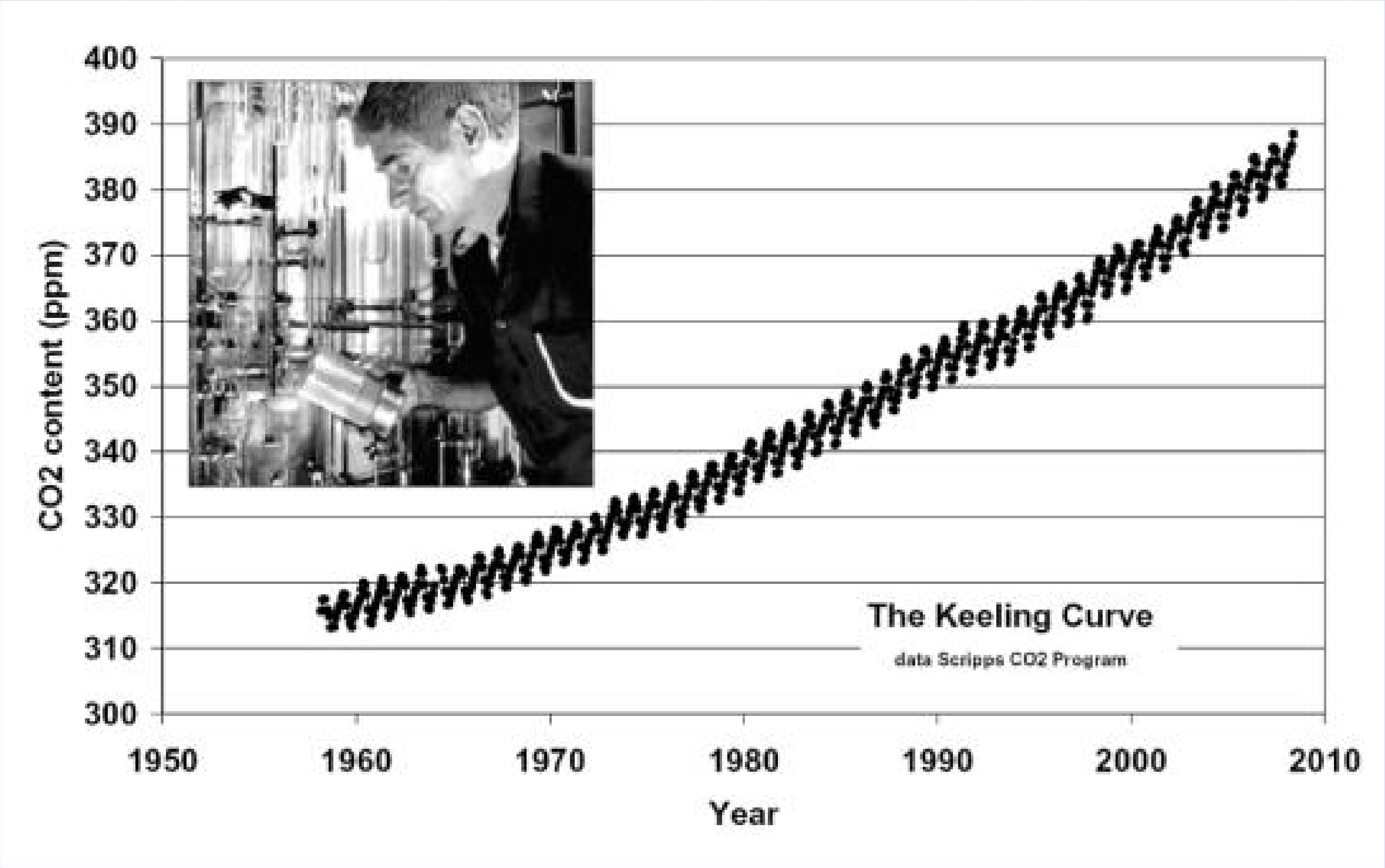
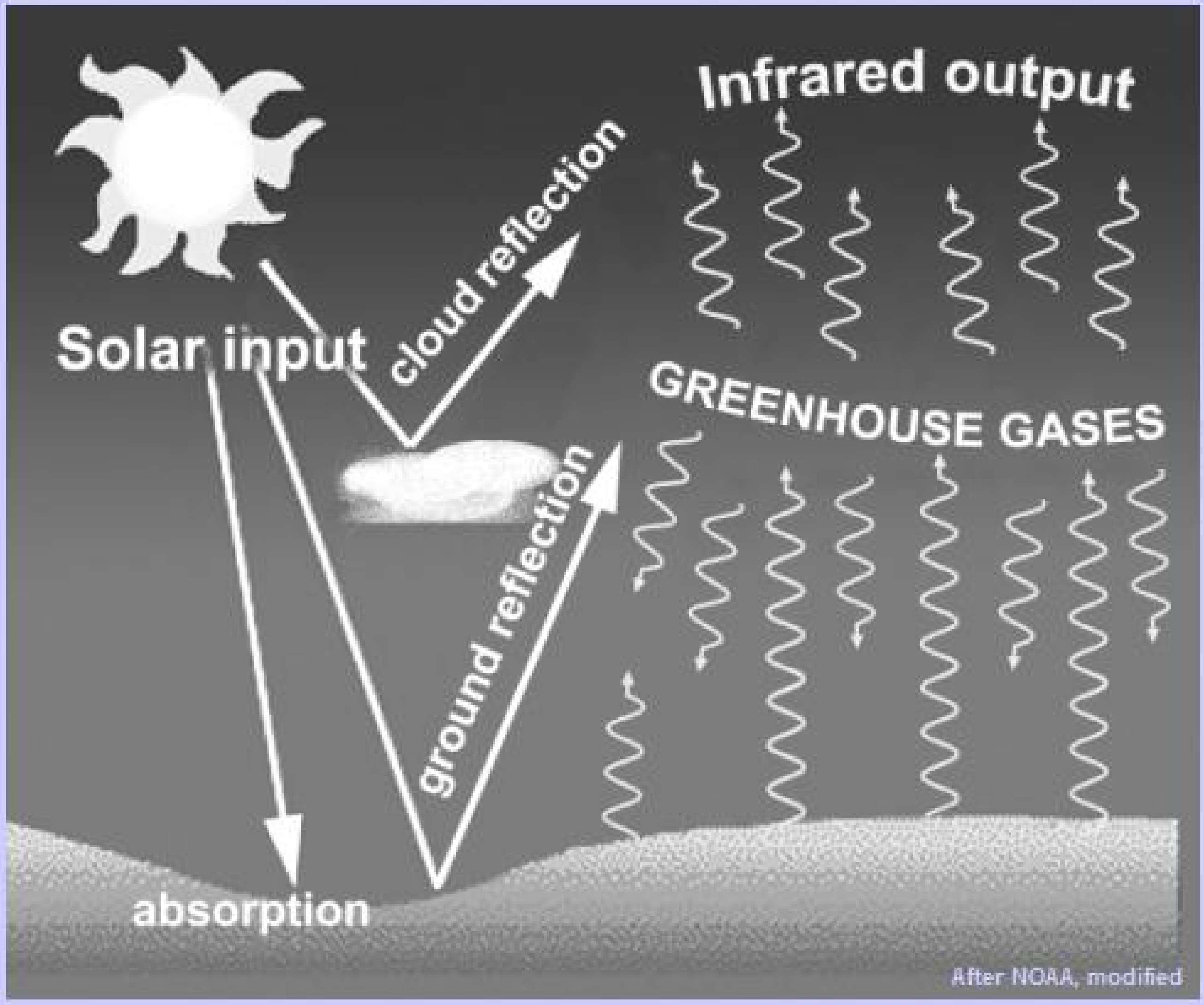
Presented at a meeting of the Sierra Club, El Cajon June 2009

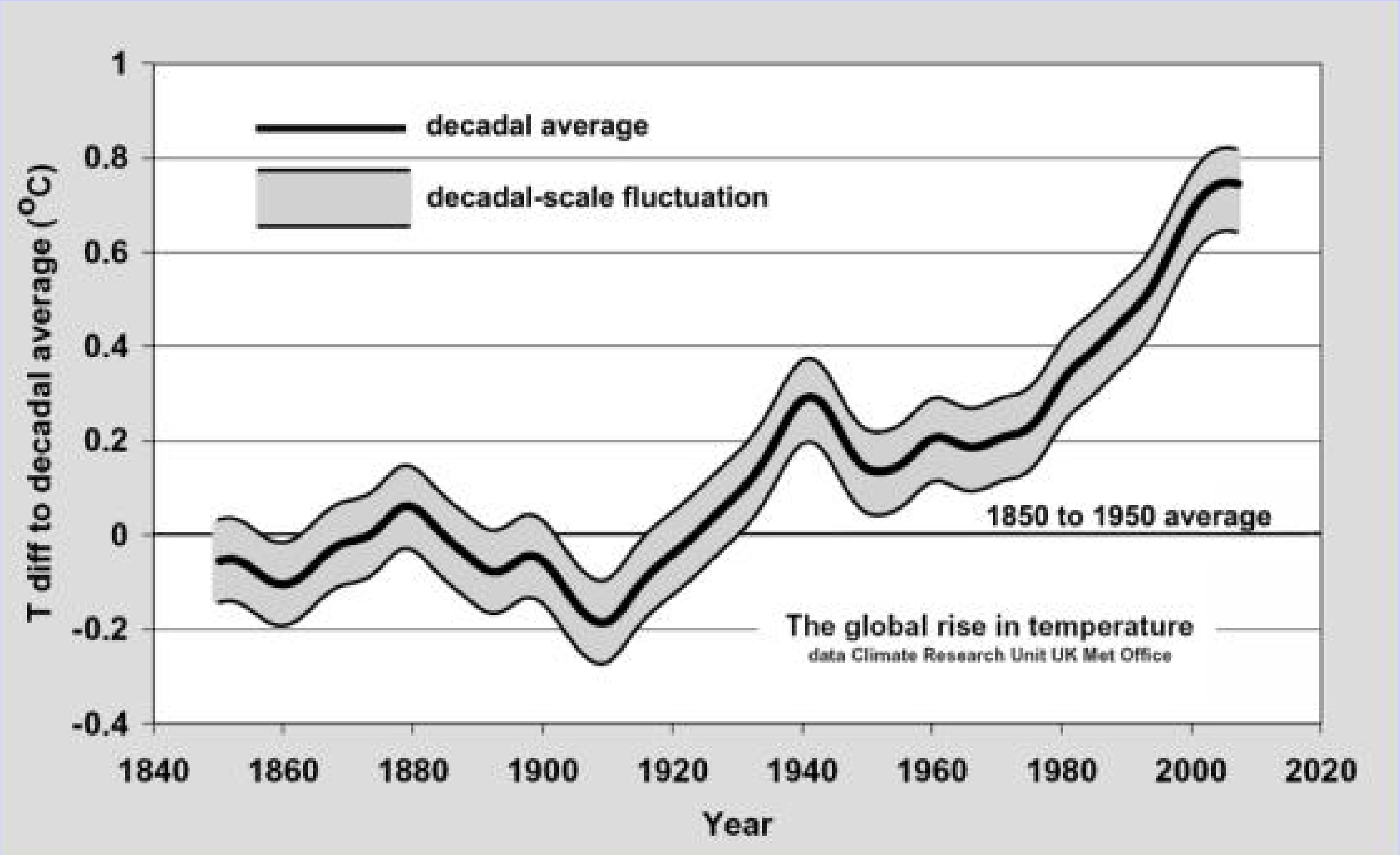


The 20th century has seen an inexorable rise of the trace gas carbon dioxide within the atmosphere. There is no end in sight regarding this rise.

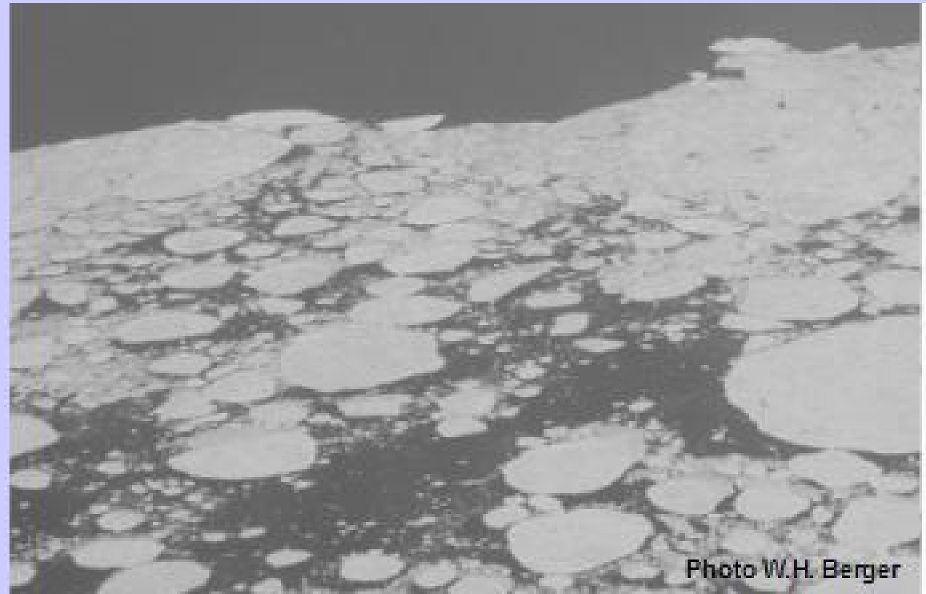
The rise is well documented, starting with measurements by Charles David Keeling (1928-2005), in the late 1950s, on samples taken on Mauna Loa.



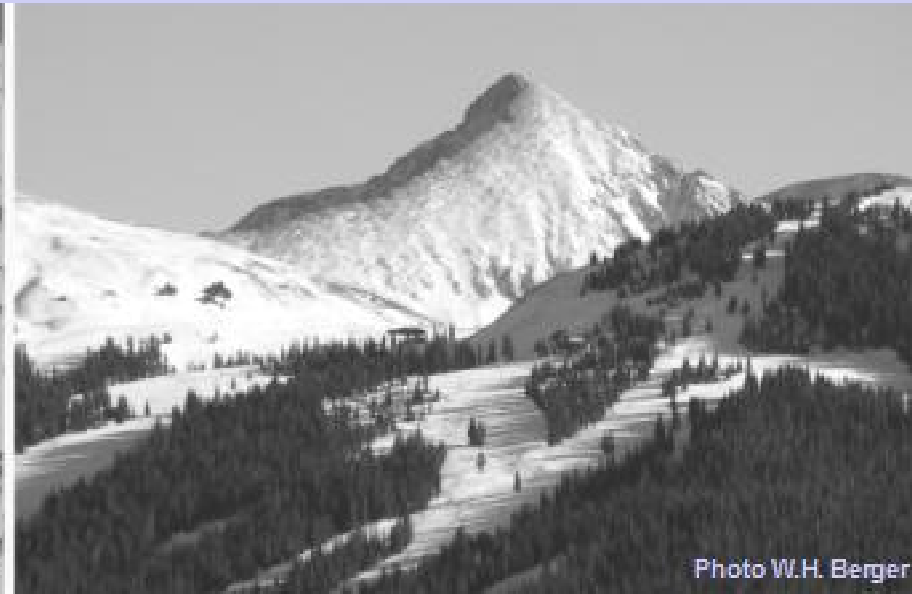
The addition of carbon dioxide to the atmosphere changes the radiation balance of Earth, by increasing the ability of the atmosphere to intercept outgoing infrared radiation. The ensuing warming increases the water vapor in the atmosphere, providing for additional warming.



The change in radiation balance wrought by adding carbon dioxide gives rise to an expectation that the lower atmosphere should warm. Such warming is indeed observed, especially since the middle of the last century. The reasons for the earlier warming are not clear. Some suggest an involvement of the sun, which seems reasonable. A finding that the climate is sensitive to small changes in the brightness of the sun would support the notion of strong sensitivity to a change in greenhouse gases.



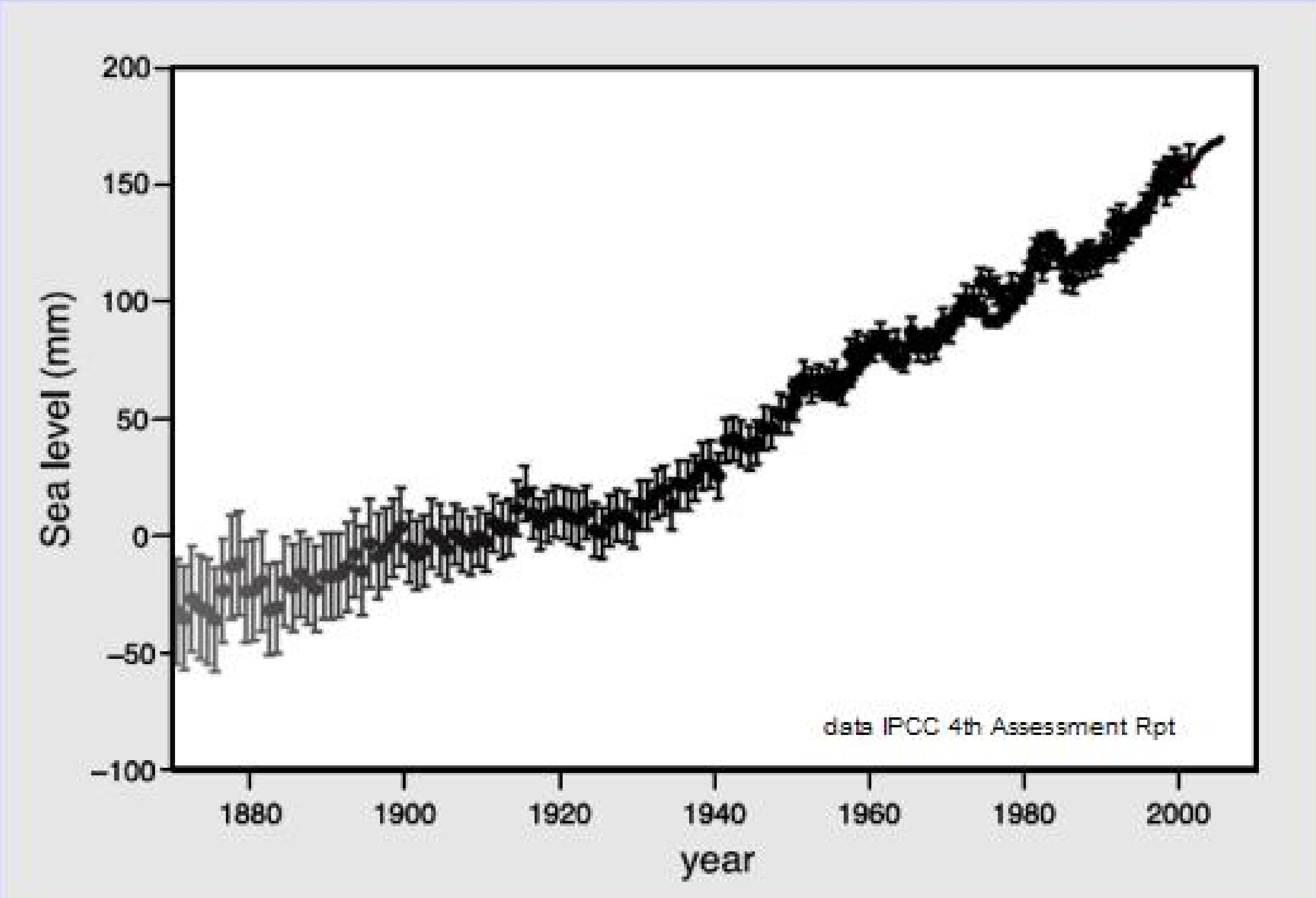
Labrador Sea



Colorado Rocky Mountains

Besides water vapor, there is another important positive feedback to a change in temperature: albedo change. During warming, snow and ice is removed in favor of dark surfaces: water and soil or plants.

This feedback works especially well in high latitudes and at high elevations, which explains the observation that changes are large in such regions, relative to other regions.



The general warming since the 19th century has been associated with a general rise of sea level, as measured by tide gages (and, lately, by satellite radar).

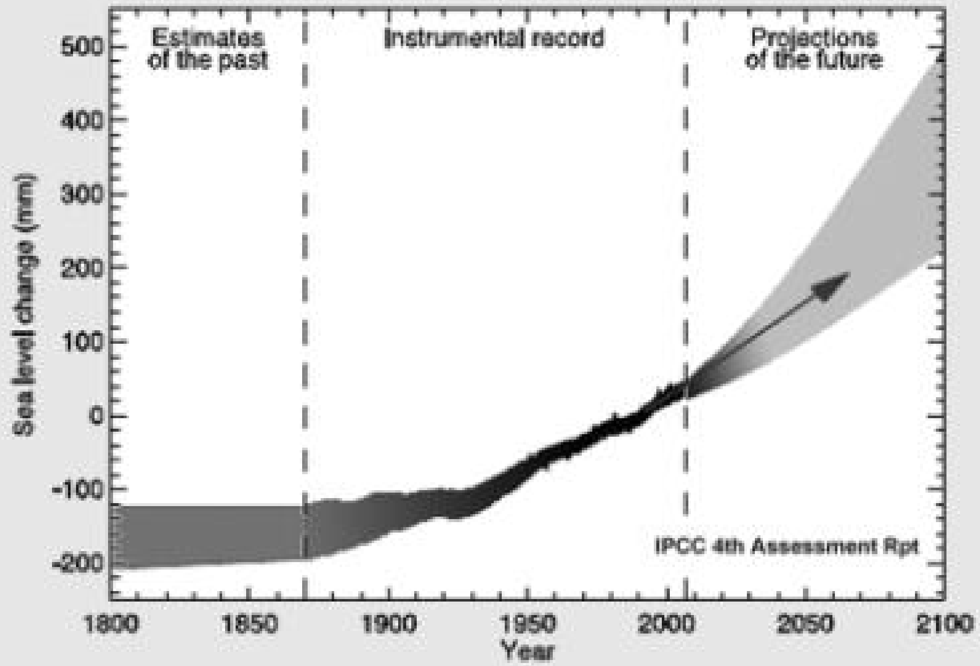
California

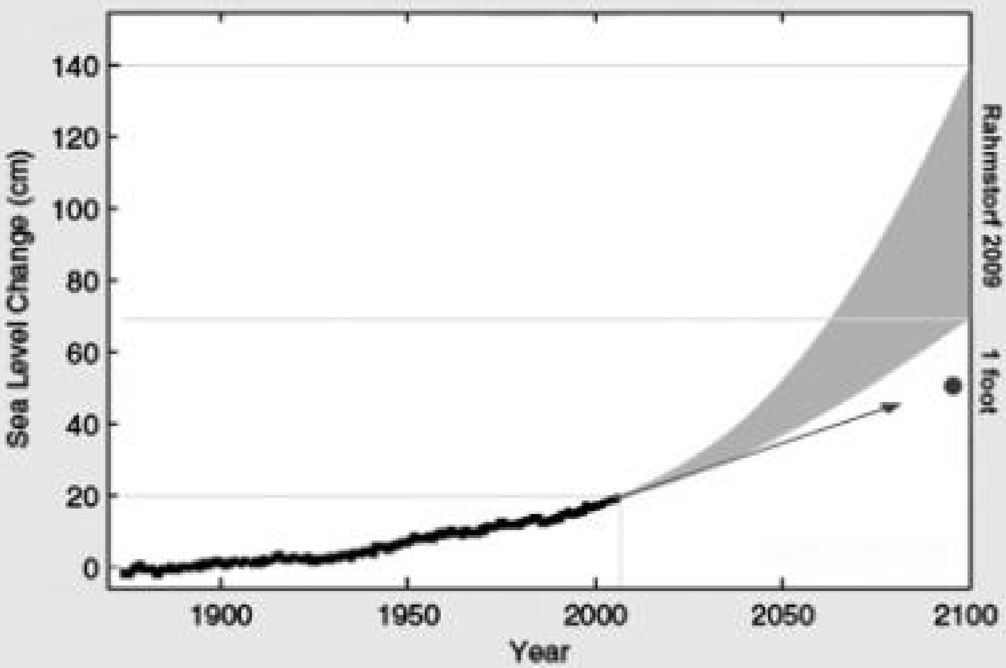
A rise in sea level has substantial sociologic and economic implications for many coastal regions of the United States of America, and for coastal communities throughout the world.

For the USA, threats are concentrated along the East Coast (>) where the land is commonly flat and near sea level, and along the Gulf Coast. In California, also, there are large regions vulnerable to sea level rise, with wetlands surrounded by settlements (^).

New York

Photo W.H. Berger





Just how much will sea level rise in the current century?

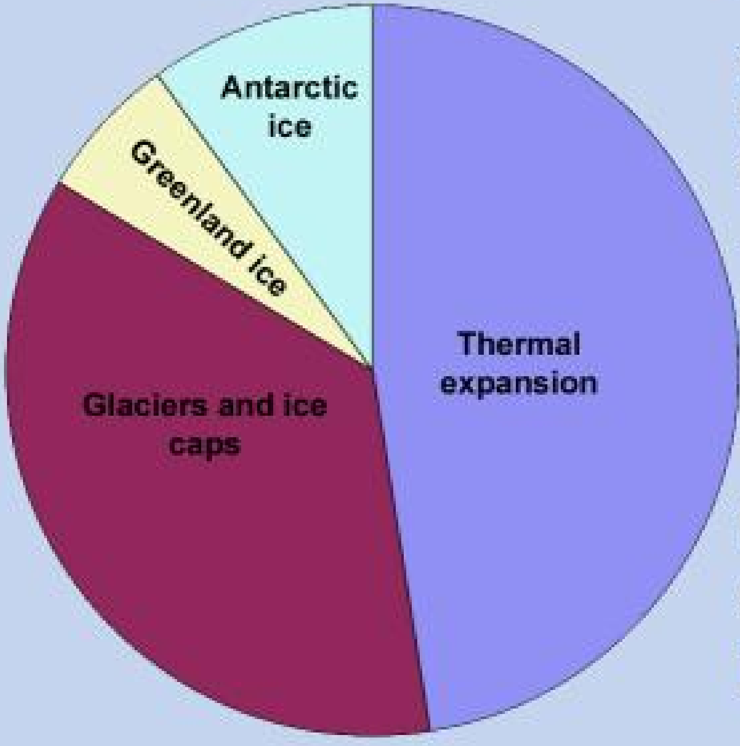
No one knows.

Guesses range widely. The Intergovernmental Panel for Climate Change (IPCC) suggests about 1 foot or so, based on linear extrapolation of the observed rise in the last decades of the 20th century (top panel).

Rahmstorf (2009) using IPCC's prediction range on warming and tying sea level rise to such warming, gets considerably higher values (lower panel).

Which approach is the more trustworthy?

This is not known. But it seems the IPCC method is conservative and likely provides a minimum value for the expected rise.

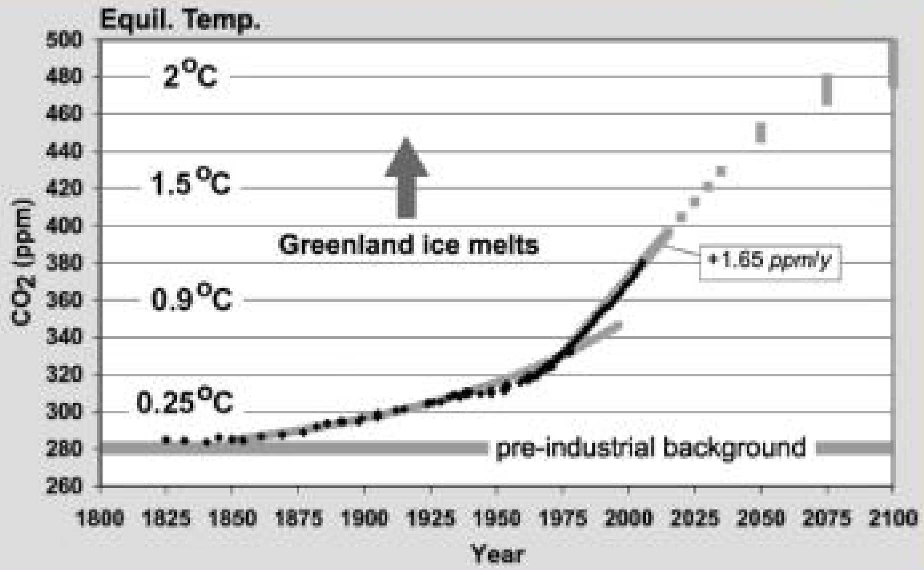


The fundamental assumption in Rahmstorf's approach - linking the rise in sea level to that in temperature - assumes that the mix of causes for the rise (<) stays roughly the same.

The dominant cause is thermal expansion of the water column. As the ocean warms, the water expands, and sea level rises.

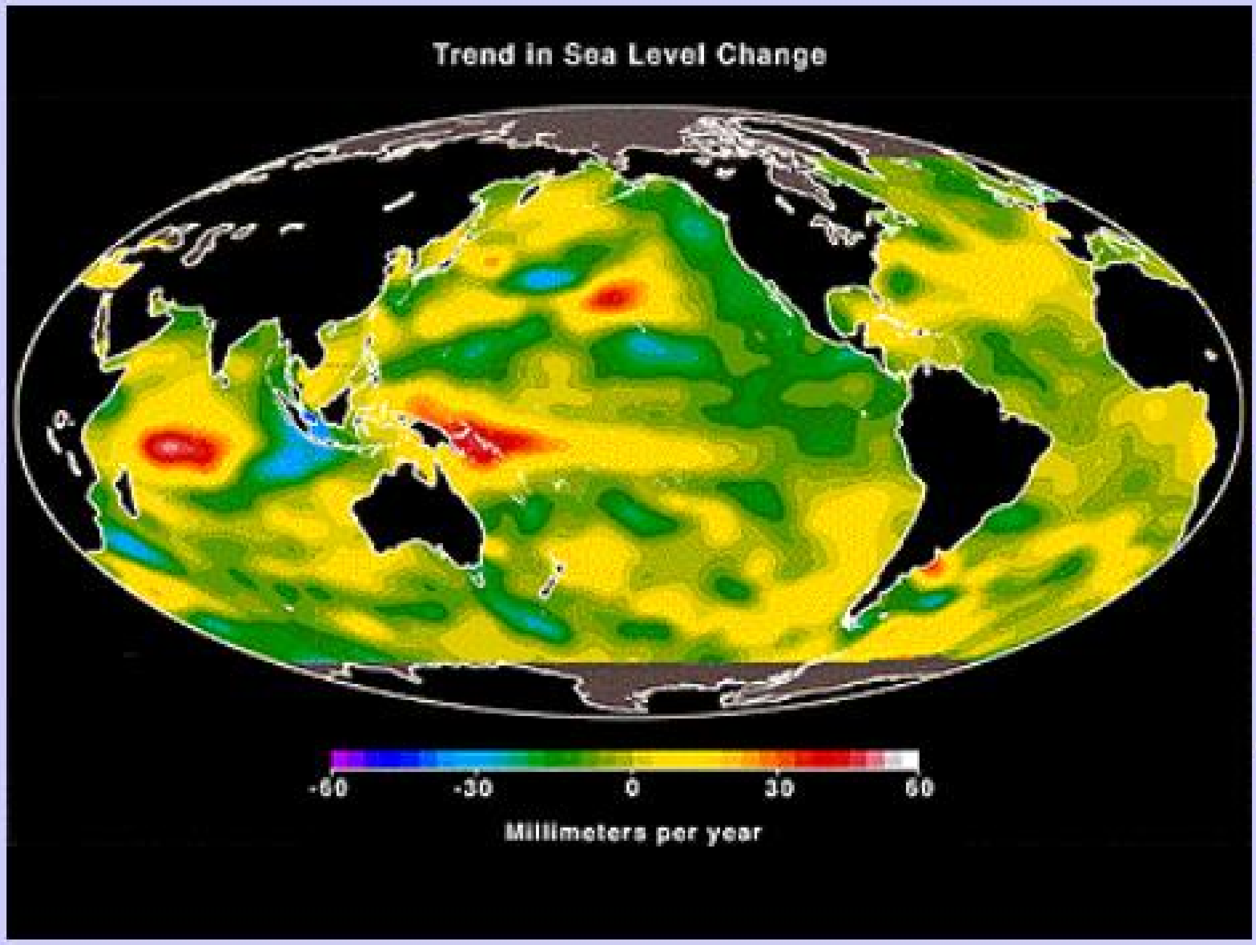
The second most important cause is input from glaciers and ice caps.

So far, apparently, the input from the melting of polar ice, if any, is modest.



But what if Greenland ice starts to melt in earnest?

Some think the process has already started. If so, it is likely to accelerate with warming. The resulting rise in sea level will help destabilize ice in the West Antarctic, by removing ice from shelves.



TOPEX-POSEIDON: Sealevel rise Dec92 to Aug95 NASA

When discussing sealevel rise we have to be aware that we are dealing with multi-decadal trends. For short runs (here: 32 months) the data are too noisy to yield trends. Note that the differences are typically ten times greater than the long-term trend.

Thus, when some self-described “skeptic” points to a recent “lowering” of sea level, he merely illustrates the difficulties encountered when dealing with trends in a noisy system. Similar problems arise when trying to establish trends in the stock market. Would you bet your pension on the call of the fellow next door, even if he is good at his business? Expert prediction is not infallible. But it is a lot more trustworthy than random opinion.

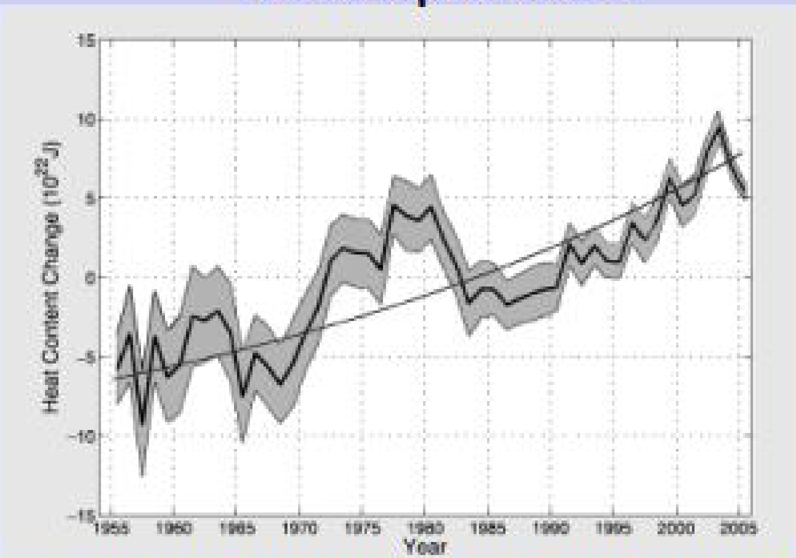
So, back to the experts at the IPCC. While they may not be infallible, their opinions are the best thing available.

Here is how they call the trends, and the causes for these trends. (I used this table for the pie diagram a couple of slides back.)

	Sea Level Rise (mm yr^{-1})	
Source	1961–2003	1993–2003
Thermal Expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and Ice Caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Sum	1.1 ± 0.5	2.8 ± 0.7
Observed	1.8 ± 0.5	
		3.1 ± 0.7
Difference (Observed –Sum)	0.7 ± 0.7	0.3 ± 1.0

Note that there is a perceived increase in the rise in the last years of the 20th century (and the first few of the 21st). Also note that the factor of increase is largest for the Greenland ice sheet. This means that the experts believe that the mix of causes is changing in favor of Greenland contributions.

To recapitulate ...



Source: IPCC, based on Levitus et al. 2000; trend fitted by eye.

The biggest factor is the heat uptake of the ocean (<), which results in the expansion of the water column.

The next biggest one is the contribution from the melting of glaciers and ice fields such as the Columbia ice field in the Canadian Rockies (<).

The meltwaters from polar regions (if any) are set to low values.

Projecting these same factors into the future yields estimates for the sealevel rise of around one foot (within a factor of two).

Glaciers have been melting since the middle of the 19th century, and this along with the recent rapid retreat has resulted in "ghost glaciers" outlined by moraines left behind (<) as seen everywhere in the Canadian Rockies and in Montana, for example.

The fact that melting started in the 19th century (around 1850) suggests that man-made warming is not the only factor at work. Changes in the solar brightness may be involved in the early melting. If so, it suggests that climate is rather sensitive to small changes in forcing factors.

A general retreat of mountain glaciers is observed almost everywhere. Here: in the Alps in Austria. The ski resort (Kaprun) is negatively impacted. The operator covers the ice with plastic liners to prevent melting before the skiing season starts. Large bulldozers bring ice downslope toward the entry points of the lifts.

The melting of mountain glaciers will continue as the planet warms. (Soon we shall have the "Glacier Memorial Park" in Montana.)

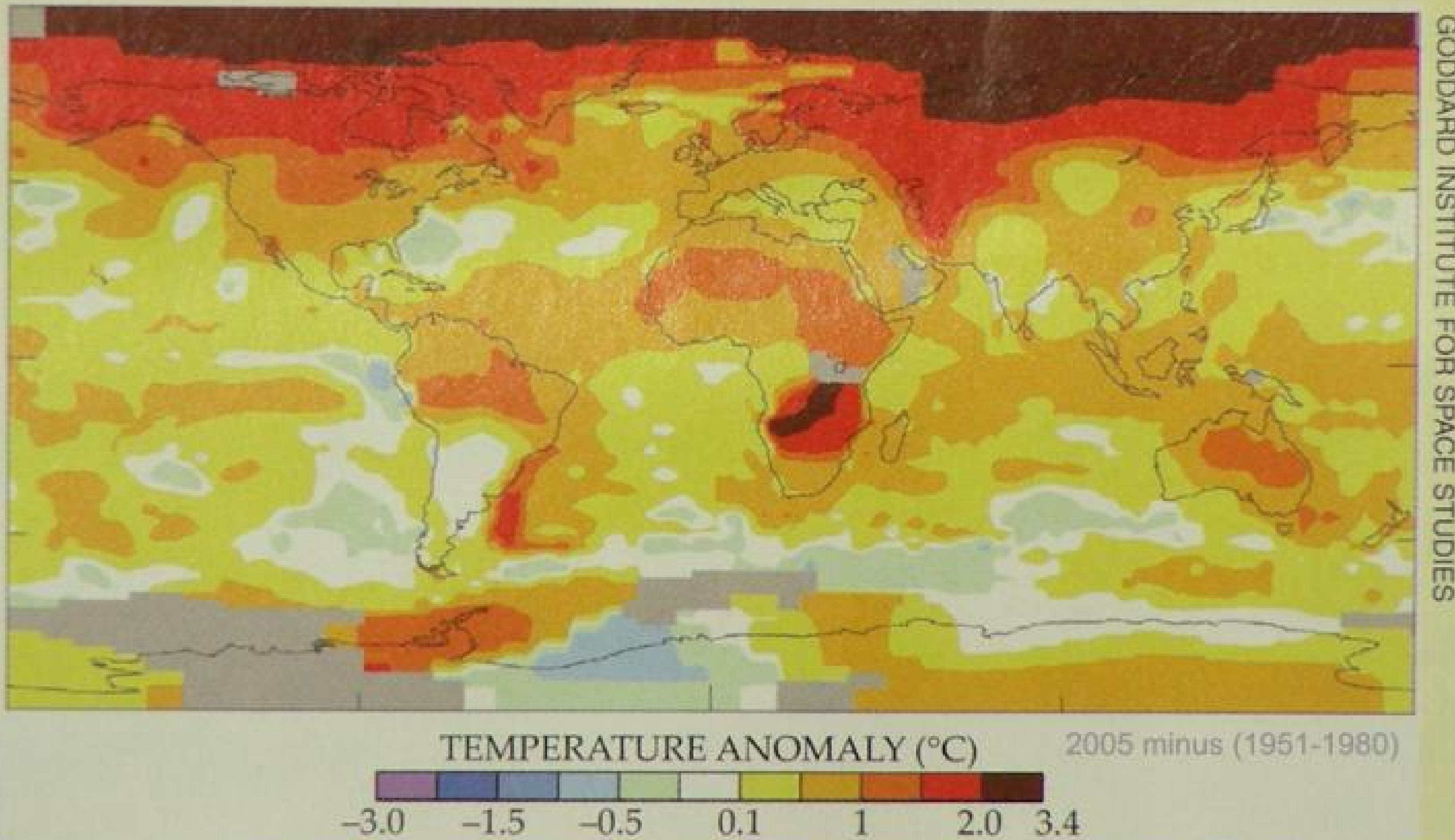
But this source will run out eventually and the sealevel rise it drives, for this century, will not exceed the rise already experienced by much.

The big elephants in the room are the vast ice masses in Greenland and in Antarctica (upper: Grld; lower: AA), as shown in the statistics from the US Geological Survey (below).

ICE MASSES AND POTENTIAL SEALEVEL RISE

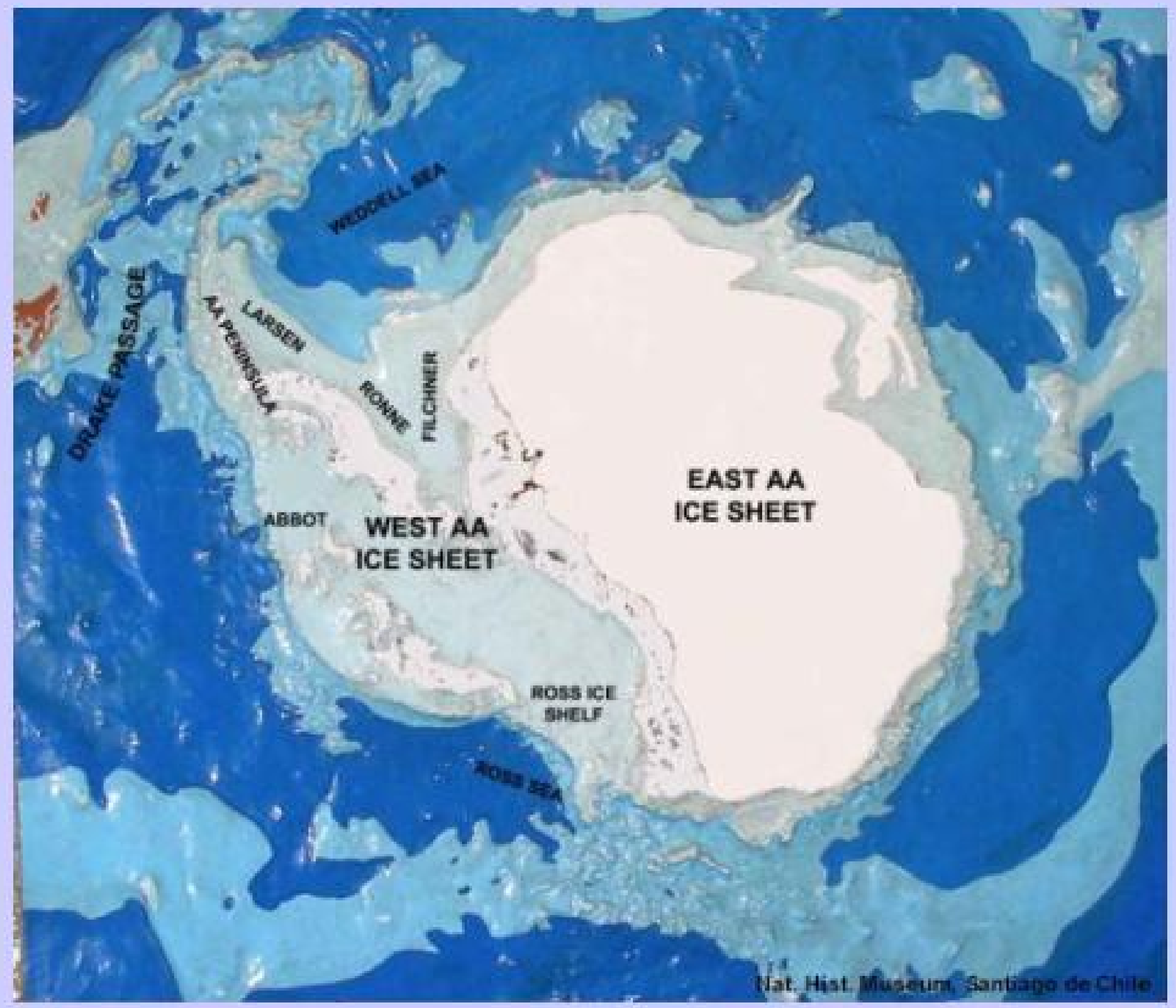
REGION	VOLUME (km^3)	SL EQUIVAL. (m)
MISC. GLACIERS	180,000	0.45
AA PENINSULA	227,100	0.46
GREENLAND	2,600,000	6.5
WEST ANTARCTICA	3,262,000	8.1
EAST ANTARCTICA	26,039,200	65

Serious melting has already started in Greenland, according to climate researchers at the University of Colorado in Boulder. (The graph shows the areas of summer melt during 2005.) It is possible that some portion of the melting is compensated by increased snowfall above the melting regions. Monitoring the mass balance of the Greenland ice is a focus of much ongoing research, and the final word is not in on this (nor is it likely to emerge soon). This is the reason why the IPCC did not attempt to guess future contributions from Greenland to the sealevel rise in their 4th Assessment Report.



Projections of global warming using mathematical climate models agree that northern high latitudes will warm faster than the rest of the world, and this agrees well with direct observations (^).

Obviously, this has implications for the stability of polar ice in Greenland.

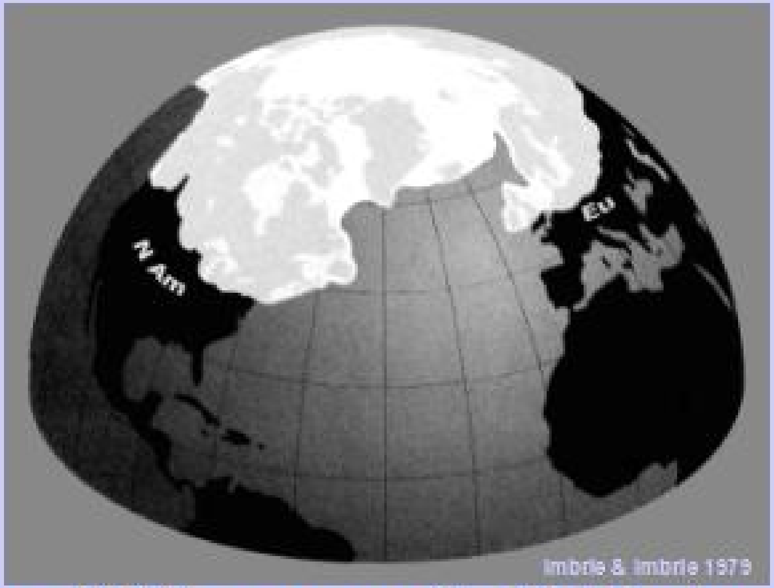


While the northern polar regions seem more vulnerable to warming, the southern ice masses cannot be ignored in assessing the risks of sealevel rise. The chief reason is that a rise of sea level will affect the stability of those ice sheets that are grounded below sea level (<light blue).

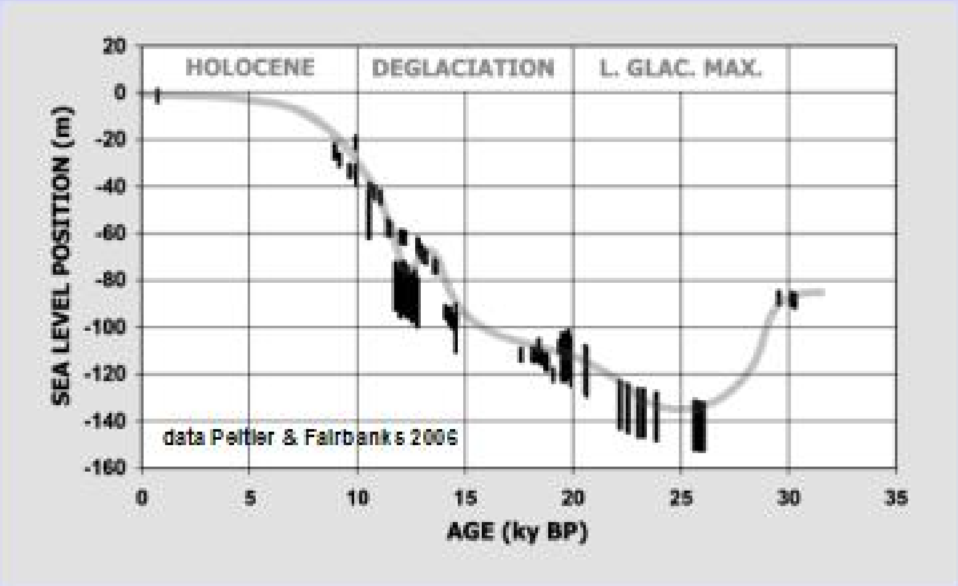
Destabilization of West Antarctic ice sheets could yield a sealevel rise of the same order as the rise driven by the melting of Greenland ice.

So, a linear extrapolation of sealevel rise into the future (as in the IPCC report) mainly reflects a combination of ignorance about the behavior of polar ice sheet, and a conservative approach to risk assessment. It does not reflect the actual risk associated with ongoing or anticipated warming. Because the situation is so unusual, there is no experience within the industrial age (the age of measurements) that we could fall back on to make predictions.

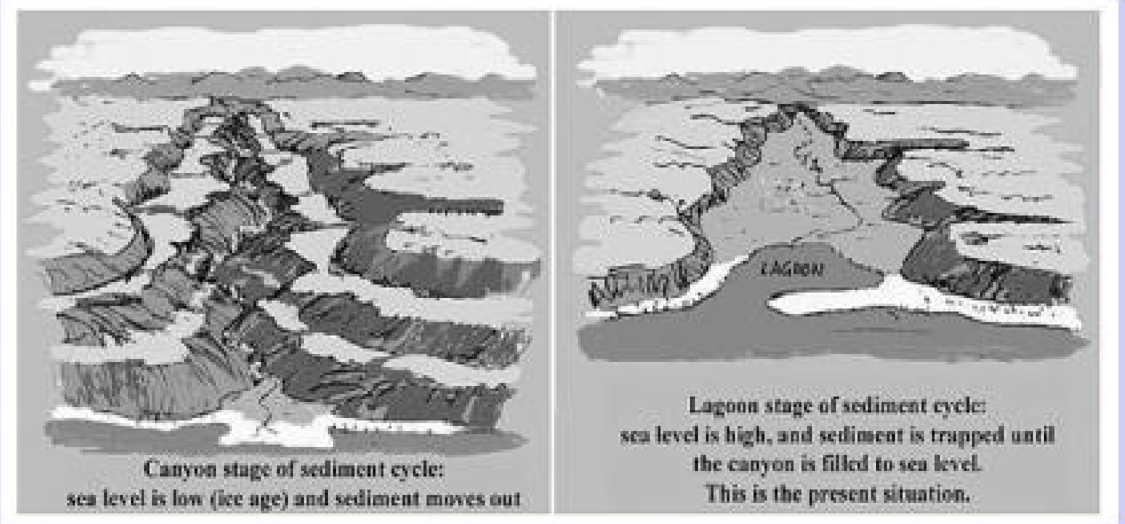
We need to turn to geologic experience, and in particular to geologic experience with collapsing ice sheets.



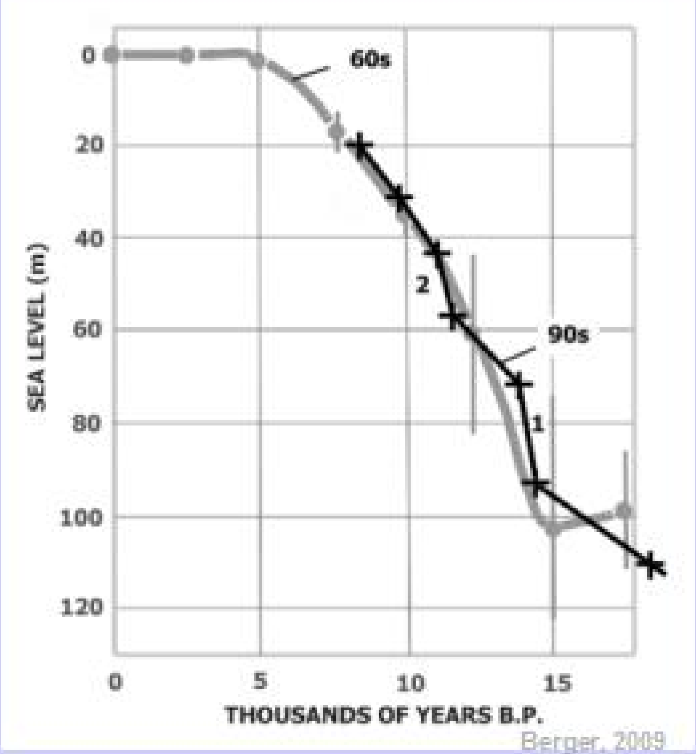
Some 20,000 years ago, the high North was covered with ice. Excepting Greenland, the ice vanished within 10,000 years.



Note that the rise of sea level was quite rapid, for at least 5,000 years, at >1m per century.



We are quite familiar with the landscape, along the shores of southern California, that resulted from the rise of sea level between 20,000 and 10,000 years ago.

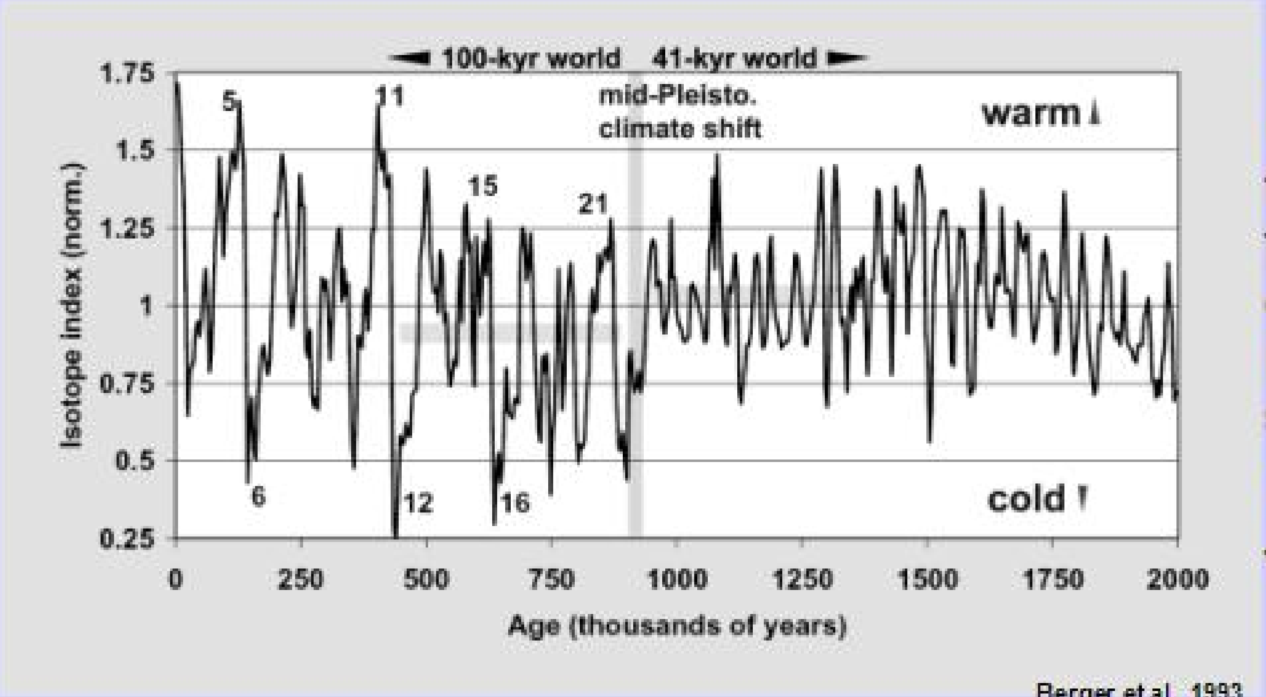


That this rise was quite rapid has been appreciated since the 1960s (<), although details only became available since 1989.

Clearly, when there is a lot of ice around (as during the last glacial maximum), sea level then can rise very rapidly whenever this ice melts.

What we would really like to know is how fast sea level can rise when the planet is already in an interglacial, with a sea level position close to the present one.

To get a statistically sound answer, we should look at the last 450,000 years for an answer. For this period, there are detailed data on the oxygen isotope composition of seawater, and the climate exhibited more or less regular behavior that is relevant to present conditions.



Berger et al., 1993

The record of oxygen isotopes in foraminifers for the last 2 million years, in the western equatorial Pacific. The numbers are "isotope stages."

The useful portion is the time since Stage 16.

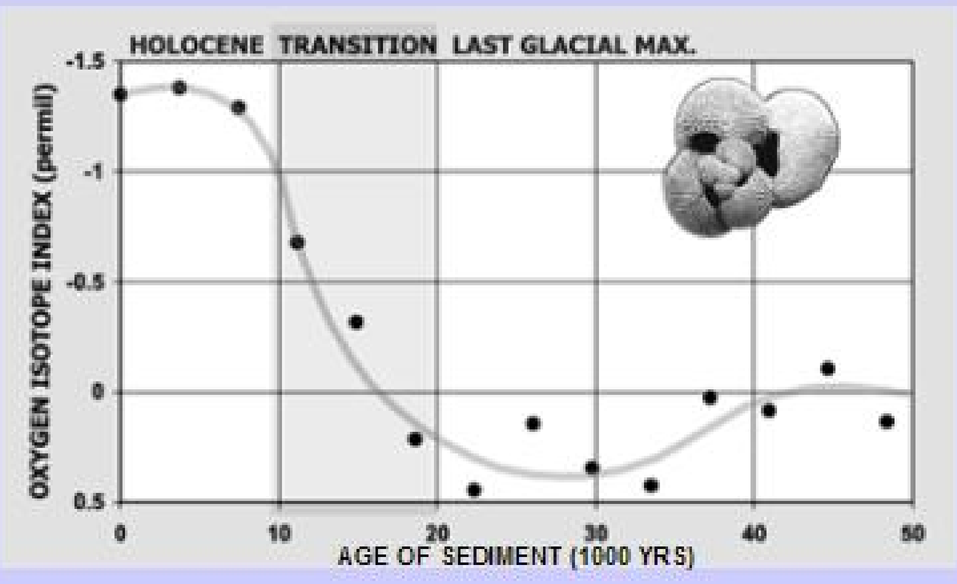
Cesare Emiliani in the 1950s. Courtesy U. Miami.

The oxygen isotopes are extracted from the shells of foraminifers, which consist of calcium carbonate (CaCO3), and thus contain plenty of oxygen atoms.

The two isotopes of interest are O16 and O18.

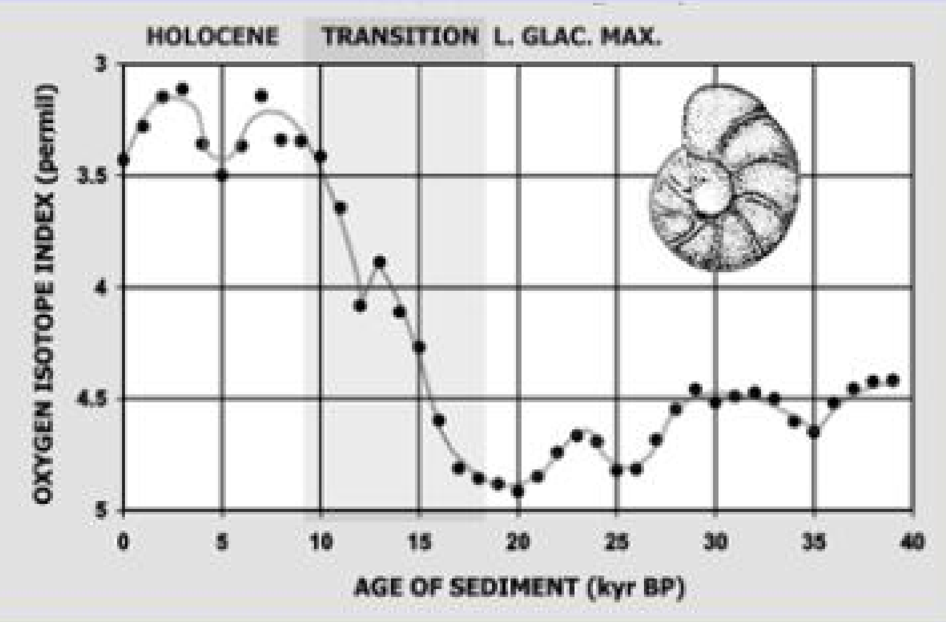
They change their ratio in response to temperature of precipitation. And also in response to the changing ratio within the ocean.

The link to sea level is as follows: whenever ice builds up in polar regions, it incorporates O16 preferentially, leaving relatively more O18 behind in the sea. Thus,



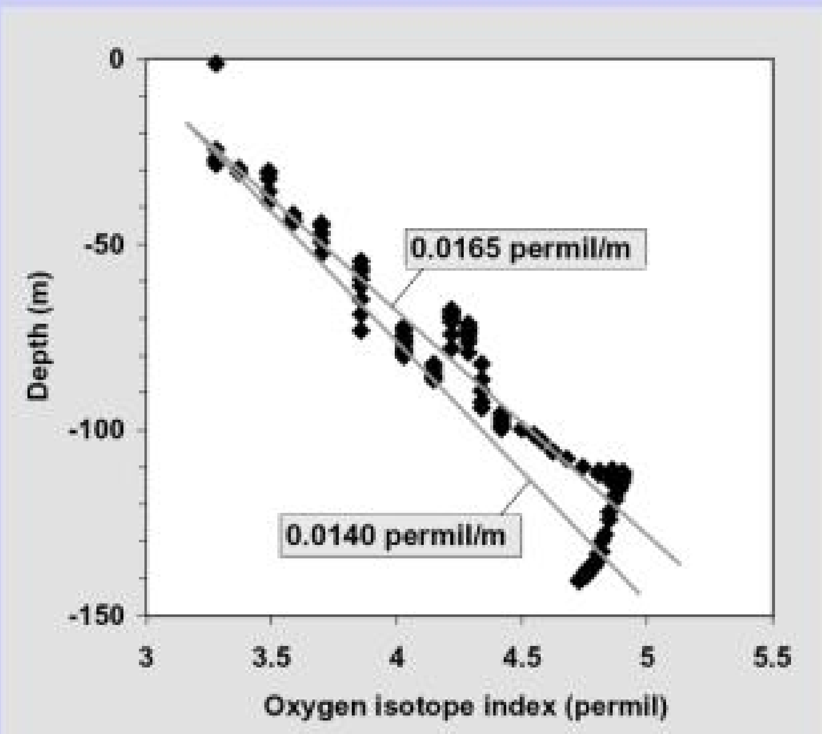
when sea level drops, the ratio within the foraminifers moves toward higher O18 values. Conversely, when it rises, the ratio moves toward lower O18 values (<).

The pioneer work in this sort of analysis was done by Cesare Emiliani (1922-1995). (He was mainly interested in the temperature change recorded in the isotope ratios.)

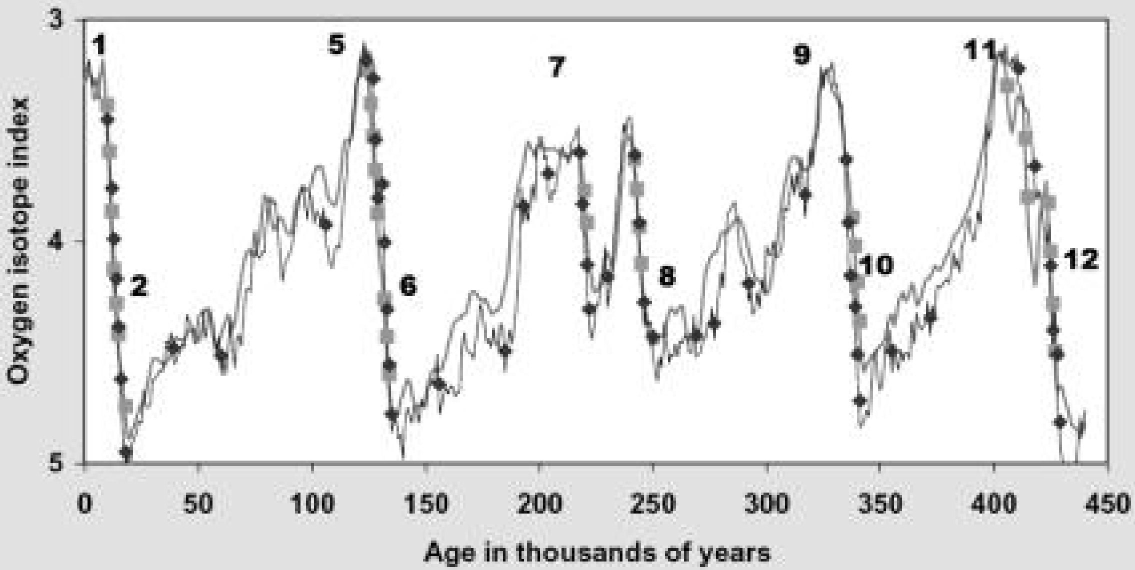


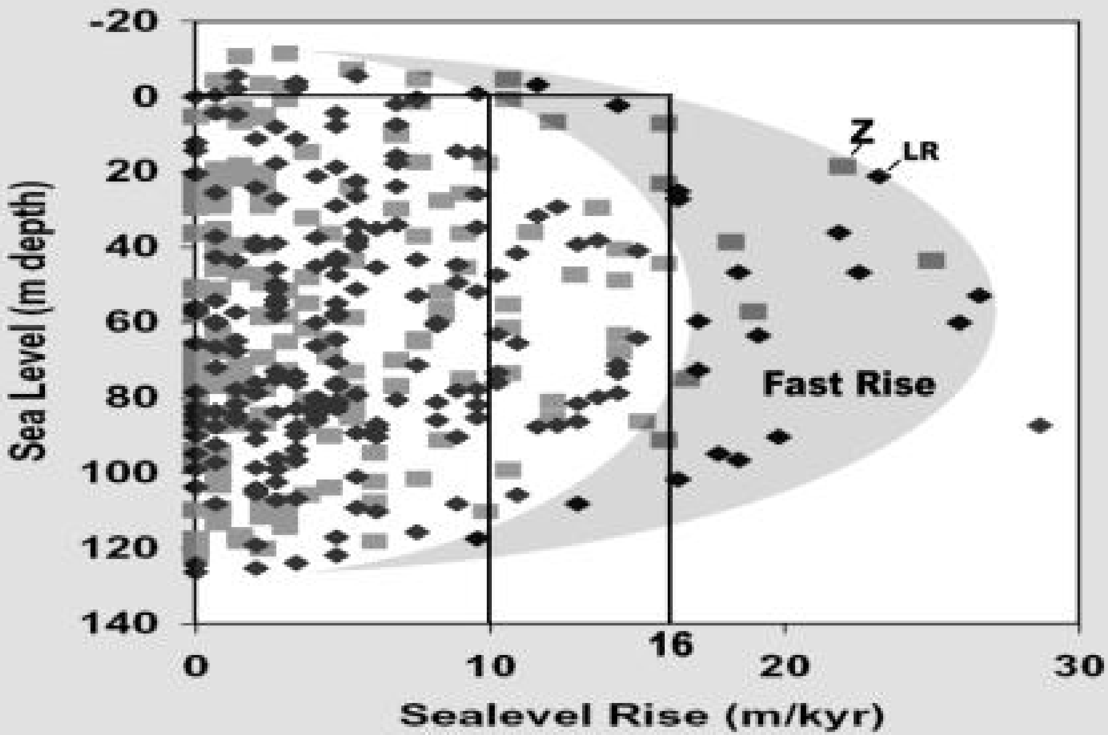
To minimize the interference from temperature change, and focus thereby on sealevel change, one uses benthic foraminifers living on the deep-sea floor. Here the temperature of the water changes only slightly (unlike in surface waters).

An example of what the record of the last ice collapse looks like in detail is given in the graph (based on data by Zachos et al., 2001).



We can find a conversion of isotope ratios to sealevel change by plotting the isotopes (top graph) against the corresponding depth in the Peltier and Fairbanks graph (4 slides back). Back in time (at greater depth), the uncertainties increase (since we don't know the temperature effect if any), but a value near 0.015 permil per meter of sealevel change is probably not far off.

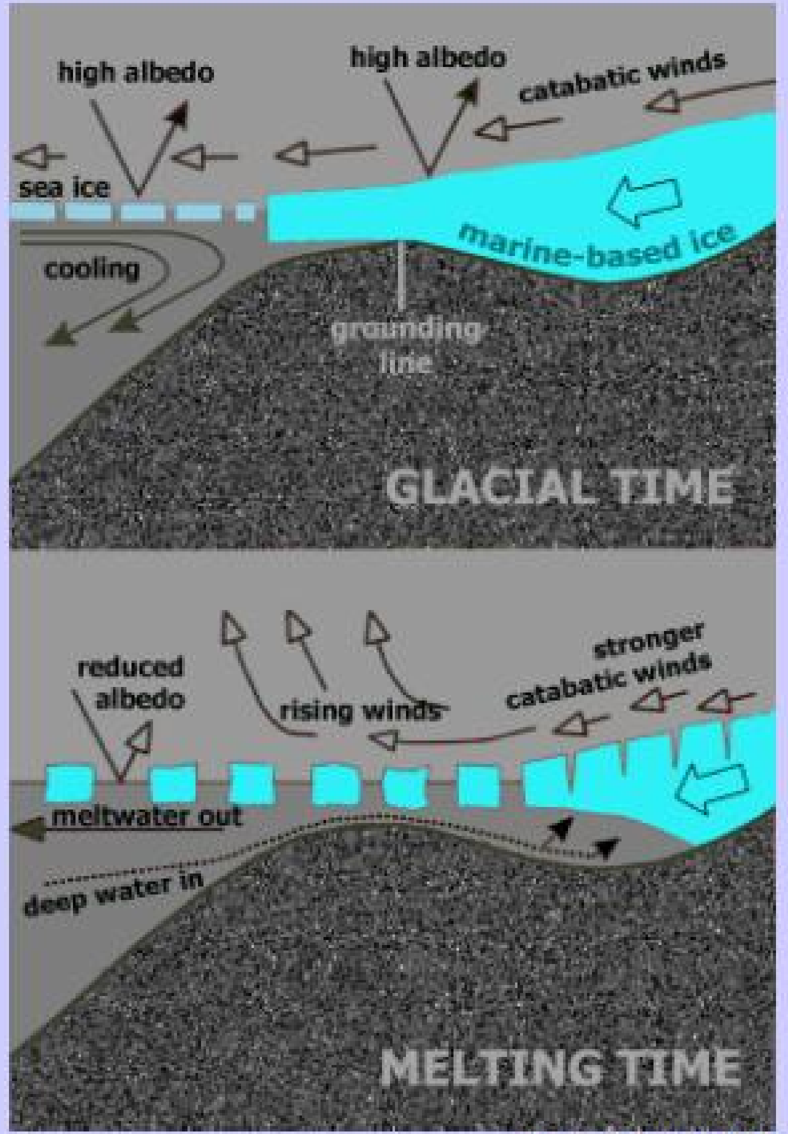




We next take the isotope record for the last 450,000 years, and extract all data points representing sealevel rise (<). Note that the rates of rise are commonly much greater than the rates of fall. Two detailed records are available, compiled from many sources, one by Zachos et al. (2001), and the other by Lisiecki & Raymo (2005).

Armed with the conversion factor, we convert isotope values to depth (present=0) and rates of change to sealevel rise. Since the resolution is on the millennium scale, we obtain change in sea level in terms of meters per 1000 years (x-axis). Rates are highest (26 m/kyr) when sea level is in intermediate positions(<), but still reaches values between 10 and 16 m/kyr for present sealevel positions (1 - 1.6 m per century).

Note that the rise has stopped, historically, near a sealevel 10 m higher than present.



Berger & Jansen 1995

Why are the rates of sealevel rise so much greater than the rates of fall?

The answer, presumably, is that ice tends to build up instability, and this factor comes into play when sea level rises. One important element of this instability is the fact that much of the ice is grounded below sea level. When sea level rises, such ice is lifted off its base in places, and water penetrates below the ice sheet, bringing heat, and carrying the ice away (<).

The removal of such marine-based ice removes the back-stop for ice that is grounded well above the sea level. Such ice will then flow more readily, driven by gravity.

Glaciers ending in the sea

There is a considerable amount of ice grounded below sea level, both in the Arctic (upper: Svalbard) and in the Antarctic (lower: Gerlache). As sea level rises, such ice masses tend to make bergs and drift away, making room for faster flow of ice higher up on the landward side.

Another aspect of instability is that when summer meltwater penetrates to the base of a moving ice mass, it can start a process of ice sliding downhill. It is then no longer the melting of the ice that matters for the mass balance, but the fact that there is mass wasting: large-scale movement of ice masses into the sea, where the melting is done by the heat available in seawater.

This all-important aspect of energy use is the reason why coal and petroleum resources are counted among the assets of a nation. Coal fueled the Industrial Revolution.

Coal occurs in layers, sandwiched between barren sediments.

Like in many other oil-rich places, petroleum in Colorado comes from Cretaceous shales. Such shales occur all along the Front Range right up into Canada. It is likely that the oil will be pumped long into the future. It brings wealth to the producers and their communities.

Questions arising

Can the rise of sea level be stopped?

This is unlikely. For one, our energy needs are enormous, and as long as coal and petroleum are the mainstay of energy generation, greenhouse gases will continue to build up and warming will proceed.

Can the rise of sea level be slowed?

Probably. We are now close to the upper limit of the historical range of sealevel position. By limiting the overall warming, we should attempt to take advantage of the apparent stability of this upper limit.

How high will sea level go?

Historically, it has gone 5 to 10 m above the present level, as far as this can be reconstructed. With serious warming, it might well go far beyond that (large ice masses are available in Antarctica).

How fast will it rise at most?

Historically, it has risen at around 1 inch per year at times of fast decay of ice. This is a millennial average, though!

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