Chapter 3

Measuring Temperature in the Distant Past

The Art of Developing Temperature Proxy Data

Proxy Measurements

When you first decide to look at temperatures from the distant past, the first thing you notice is that the number of available thermometer-based temperature records doesn't really stretch back all that far. There are a very few records from the late 1700's. Before that time there are none, because the thermometer as we know it was a new invention – new technology, if you will[1]. But if we're going to evaluate whether the *short term* global temperature behavior we are seeing today is truly abnormal in terms of longer term trends, we need data from much further back. It is the job of scientists from a number of different disciplines to come up with innovative ways to learn what those ancient temperatures were like. They do so by devising what are called "proxy" measurements. That is, they try to identify things in nature that; **a)** respond to different temperatures in slightly different ways, and **b)** store this information in some long term manner that we can retrieve through clever scientific detective work.

There are a number of temperature proxies in nature, and a number of problems with each of them. Let's take an example. A lot of readers have probably heard of tree ring data. Tree ring analysis is relatively easy to carry out. There's no digging, drilling or deep sea diving to perform, although getting to suitable trees may involve hiking into

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[1] The modern thermometer can be said to have been invented in the early 1700's with the addition of standard scales (Fahrenheit in 1724, Celsius in 1742) to the glass tubes being experiment with at the time. However, widespread usage really didn't begin until the late 1700's,

some pretty remote areas. When the appropriate tree is located, tree slices or cores are removed and then taken back to the lab for analysis. When sliced, scientists can see each separate year of the tree's growth as an individual ring.

Figure 3.1. Cross section of tree trunk showing rings associated with a number of different growth years. There are various reasons for the different widths of individual growth years.

In tree ring analysis (called, "dendroclimatology"), it is vital that every physical and geographical characteristic of the site be documented, including such things as slope of the land, soil/bedrock composition and even proximity to other trees (which all make a huge difference in tree ring growth). One frequently-repeated "fact" is that the warmer the climate in a given year, the wider will be the width of the ring. But this statement is grossly oversimplified. Tree ring growth is influenced by many other factors, such as the amount of precipitation that year, solar availability (sunlight and clouds), pests, competition from other trees, forest fires, soil nutrients, and even the annual duration of snow on the ground. In the end, all a tree ring can really tell us is whether the bio-geo-chemical-physical conditions during the various growing seasons were favorable to tree growth at that spot. This long list of extraneous factors brings about a great deal of subjectivity regarding what the width of the ring tells us specifically about temperature.

Worse – trees that qualify as good candidates for this type of proxy are relatively few and far between, so the density of the data network is extremely sparse. Generally, it is probably fair to say that tree rings are not the best historical temperature proxies. Other proxies such as isotopes in glaciers, coral, minerals and sediments are a much better choice[2]. We will probably spend the greatest amount of time in this chapter describing ice core data, since this information reaches hundreds of thousands of years into the past, is relatively accurate (for proxy data), and is available from many locations around the world. But before we get into a detailed discussion of ice cores, let's list a few of the other ways various scientists have tackled the temperature proxy problem.

Very crude estimates of temperatures from the past can be constructed from the direct measurement of temperatures inside boreholes drilled into the Earth's crust[3]. The correlation is found by looking at differences in the borehole temperatures and the *expected* change in temperature with depth (i.e., the "normal" geothermal gradient), which some feel can be interpreted in terms of past changes in temperature at the surface. However, in addition to being very rough approximations, these data are limited to just the last 150 years, or so, and we have thermometer data for that period (although the sparse network of thermometers for much of that time limits that source).

Another way of inferring temperature is by utilizing human historical evidence. Such evidence includes written accounts of the weather at various locales from private or public journals, hunting and fishing records, harvest dates and yields, dates/years when oceans or lakes failed to form ice, or dates/years when ice formed early and to a greater extent than normal on oceans or lakes, and so forth. The problem is that without actual

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[2] For more information on tree rings see: http://www.icogitate.com/~tree/treerings.ac04.htm

[3] For more information on borehole data see: http://www.geo.lsa.umich.edu/climate/.

temperature measurements, all we have to go on are essentially, localized, non-calibrated, anecdotal stories. This type of information is interesting and is often vital in *confirming* other proxy data (for example, historical human records confirm proxy data that detail a Medieval Warm Period and a Little Ice Age. Trieste 2008 Workshop Report on Documentary Data). But as a primary data source, this information is far too subjective to be useful by itself.

Temperature proxies can be derived from pollen grains washed or blown into lakes that accumulate as sediment. Obviously, different types of pollen in lake sediments reflect the vegetation that was present around the lake at a given point in time, and thus the climate conditions can be determined (within a broad range) that would favor given vegetation. These data are considered to be relatively low resolution[4]. Along this same vein, floral and faunal data[5], taken together, constitute another method for estimating historical temperatures. Most of this data set is made from preserved remains large enough to be visible without a microscope. They include plant and animal life (including insects) formerly living and growing in the region of concern. This information along with pollen data can be used to reconstruct a terrestrial environment of the past. Though the temperatures estimated using these techniques is quite subjective, the data can be combined with other proxy data to provide confirmation, or refutation of other results.

As water levels in lakes fluctuate with changes in moisture balance (precipitation minus evaporation) over time, so do the fossil shoreline deposits and other features that are indicators of past moisture balance as well as climate within the lake's basin. Stable

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[4] For more information see: http://www.ucar.edu/learn/1_2_2_10t.htm

[5] For more detailed information on this topic, see: http://www.ncdc.noaa.gov/paleo/fauna.html , http://www.ncdc.noaa.gov/paleo/plantmacros.html, or http://www.ncdc.noaa.gov/paleo/insect.html

oxygen isotope and trace metal analysis are the two primary means of reconstructing past climate histories from lakes. This is often considered a subset of paleoclimatology which will be described in more detail below.

There are a number of other esoteric proxy data sources for deriving general trends (e.g., lake level sedimentation information, silt and clay deposition, dust proxies, paleofire proxies, paleolimnology – i.e., reconstructing the paleo-environments of inland waters – and speleothem (cave deposit) proxies. There are multiple articles available on the internet on these topics, and most good internet articles have references to journal articles and/or books. But, for now, let's move on to a more detailed description of a proxy temperature method that involves long term, somewhat more accurate results; that of drilling-out and removing deep core samples from ice sheets and glaciers – glaciers that have been around for hundreds, or even hundreds of thousands, of years.

Glacial Ice Cores. Glacial ice core samples are narrow cylinders of ice that have been drilled from glaciers. They can be hundreds of meters long. Packed in these samples are thousands, or even hundreds of thousands, of layers of ice – each representing about a year of glaciation history.

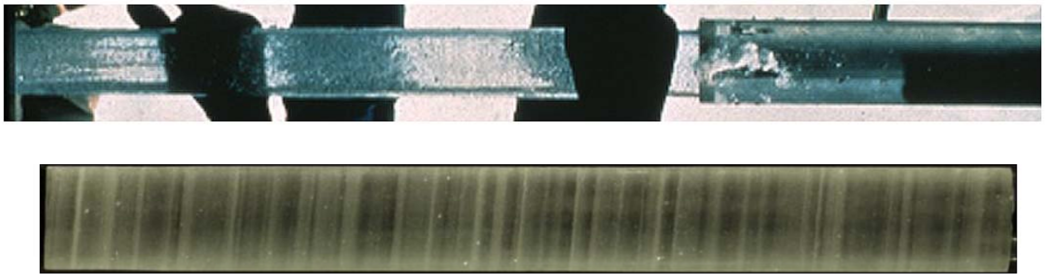
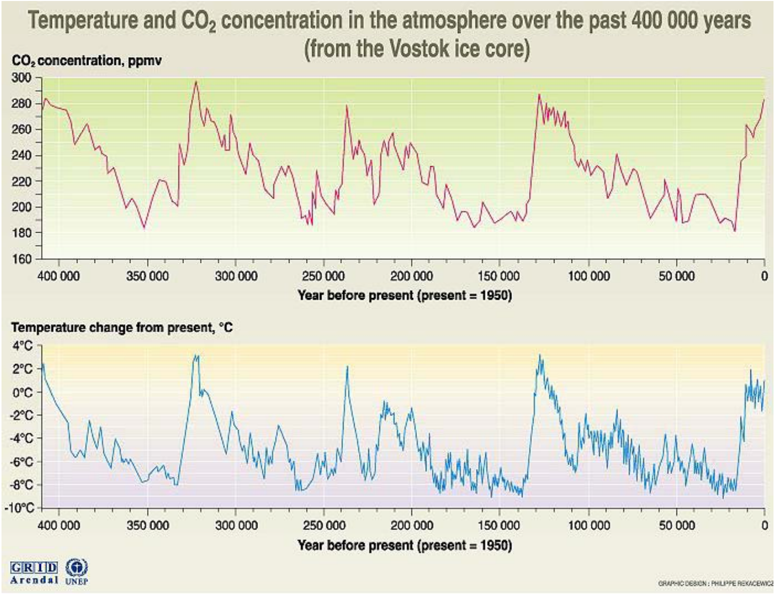


Figure 3.2 Upper – Ice core sample just taken from drill, Byrd Polar Research Center, Ohio State University (see: http://www.ncdc.noaa.gov/paleo/globalwarming/gallery.html). Lower: GISP2 ice core at 1837 meters depth with clearly visible annual layers. Image was produced at the National Ice Core Laboratory by employees of the United States Geological Survey.

Ice cores can be taken from locations not only over polar regions, but anywhere on earth where semi-permanent ice is present. There is fairly representative coverage worldwide. Many of the deepest samples come from regions such as Antarctica or Greenland, of course, but cores can be collected and analyzed from mid-latitudes in places such as Mt. Kilimanjaro, the Andes of Peru and Bolivia, the Himalayan plateau, and others. Ice cores can provide general information on temperature and greenhouse gases stretching back, in some cases, hundreds of thousands of years. Much more detailed information can be obtained for the past several thousand years from certain mid-latitude core samples, because there has been less time for the tremendous weight of the glacier to crush the critical layers of ice together. In addition to containing many chemical constituents that are deposited in snow, dust, or air bubbles, ice cores can reveal climatic variations that were as brief as a few years, or show general changes over periods as long as hundreds of thousands of years. Though the accuracy of the temperatures thus inferred *are no* *<u>better than</u>* ± 1.5°C, and become *<u>less accurate</u>* the further back in time we go, the data can be used to establish long term, *climatological* trends – which is precisely what we are trying to establish. Also, the more recent data can be calibrated to nearby thermometer data, and historical observations and thus provide a somewhat more accurate look at – say – the last couple of thousand years of human history. Recall the Vostok ice core data presented back in Chapter 1 that includes not only long term temperature trend information, but information on historical carbon dioxide concentrations, as well (Fig. 3.3)



Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

Figure 3.3. Data calculated from Vostok Ice core samples. Graphs as presented by Pettit et al. (1999)[6]*.* *<u>Top</u> – CO_2 concentration in parts per million (by volume) from 410,000 years ago (lt.) to the present (rt.).* *<u>Bottom</u> – Temperature change from 410,000 years ago to the present in degrees Celsius for the same time period as shown in top portion of figure. The time axis represents number of years before the present ending in 1950. Extensions to the year 2000 are available at* [*http://www.geocraft.com/WVFossils/last_400k_yrs.html*](http://www.geocraft.com/WVFossils/last_400k_yrs.html) .

To understand how ice core estimates are made, as well as how representative they might be in terms of climate, we now have to talk a little chemistry. There won't be a lot of it, and we're going to simplify the discussion *a lot*, but we want to describe enough to make the process paleoclimatologists use to make some of their estimates understandable to a certain extent. We'll simplify it enough to offend everyone – the lay reader will be offended (but please don't skip it), because it may still be a little difficult to follow. The true scientists (especially the chemists) will really be offended, because our description is too simplified. So no one will be complete happy here, but it will be over quickly. So let's give it a try.

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[6] Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., & Stievenard, M. (1999). Climate and Atmospheric History of the past 410,000 years from the Vostok Ice Core, Antarctica. *Nature*, *399*, 429-436

Okay, so most everyone has probably learned the following facts at some point. First, most people know that all matter is made up of atoms. An “atom” is composed of a central core called the nucleus, which – except in the case of simple hydrogen – contains protons and neutrons. There are also a number of negatively-charged particles called electrons (about equal to the number of protons) which spin and vibrate around the nucleus at some relatively great distance. There are lots of levels of complication, but for our purposes here, this is enough – protons, neutrons, and electrons.

Each of the individual protons and neutrons in the nucleus all have about the same mass, but a proton has a positive charge while a neutron has none. Electrons weigh a couple of thousand times less than the either the protons or the neutrons, so the mass of the atom is more than 99.99% contained in the nucleus. But the electrons do have a strong negative charge that pretty much offsets the positive charge on the much larger, positively charged protons. Anyway, the total mass of the atom is pretty much defined by the mass of protons and neutrons.

Another thing you might remember from high school or college is that each different element (such as oxygen, or iron) has a *specific number* of protons and neutrons in their nuclei. It’s what makes every element unique. So the atoms from different elements each have a unique mass. For example, oxygen normally has 8 protons and 8 neutrons (with 8 very tiny electrons vibrating around it at some distance). The so-called “atomic mass” is simply the sum of the protons and neutrons, which is 16 in this case. There is a scientific shorthand that designates the nature of the atom which gives the atomic mass as a superscript, followed by the elemental symbol. For common oxygen (symbol O), we shall designate the oxygen atom as ^{16}O.

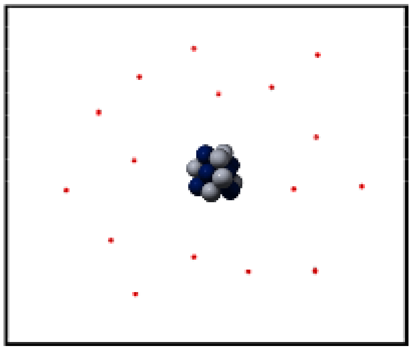

Figure 3.4. A simplified representation of an oxygen atom. Eight protons and8 neutrons are concentrated in the center (nucleus). Sixteen electrons are actually vibrating and rotating around this center. In a real atom, the electrons would be too small to see at this scale, and the distances from the nucleus would be much, much greater.

Okay, so moving on. The final point we hope most readers have learned (and remember) is that "molecules" are made up of two or more atoms bonded together. For example, a water molecule is composed of two atoms of hydrogen and one of oxygen. Its more simplified molecular designation is given as H_2O (you've heard of H-two-O). In the more complex, shorthand of science it can be more precisely described as $^{1}H_{2}{}^{16}O$. It looks complicated, but it's not. The first *superscript* in this formula tells us that the atomic mass for the hydrogen atom (H) is "1" (because normal hydrogen atoms have only a single proton, and no neutrons). The *subscript* "2" means there are two atoms of hydrogen in this molecule. There is also an oxygen atom which has the atomic mass of 16 (remember, that's 8 protons and 8 neutrons). There is only one oxygen atom per water molecule. When there's only one atom of a given type in a molecule, you can just drop the sub-one. It's implied. So $^{1}H_{2}{}^{16}O$.

Now for the last little bit of chemistry. Atoms actually come in slightly different varieties, and these varieties are called "isotopes." It may seem like this is never going to end, but stick it out a just a little bit longer, because this is the kicker for getting temperature information from ice cores.

Oxygen comes in heavy and light varieties. As we said, naturally occurring oxygen normally has 8 protons and 8 neutrons (more than 99% of the time in nature), but a very small percentage of oxygen atoms can also be found in nature that have 8 protons and 9 neutrons (so the designation is ^{17}O), or even 8 protons and 10 neutrons (^{18}O). These variations of oxygen only occur naturally in very small quantities, but they are very important.

Any combination of the stable isotopes of hydrogen and oxygen can combine in different ways to form water molecules. We will only be talking about two of them. First is the normal water molecule, $^{1}H_{2}{}^{16}O$. The *total* atomic mass in this case is 18; one oxygen atom with a mass of 16, plus 2 hydrogen atoms. The second is a variation designated $^{1}H_{2}{}^{18}O$. It has two regular hydrogen atoms and one of the O-18 oxygen isotopes (total atomic mass is 20). *For proxy temperature measurement, the ratio of the heavier isotope(^{18}O) to normal oxygen (that is, ^{16}O) in the air is what we're interested in, because this ratio varies with the climate.* And both varieties are found locked in ice.

The key to getting proxy temperature data from ice cores is that the second variety of water molecule has slightly more mass than the first, *and these molecules have slightly different properties – including slightly different evaporation and condensation rates – rates which are directly related to the temperature of the air at the time condensation occurs.* For example, as the air cools, the heavier molecules preferentially condense. By studying the oxygen isotopic ratio of ice that fell as rain or snow, paleoclimatologists can infer the temperature of the environment at the time condensation occurred. Reiterating – this characteristic of condensation provides <u>specific information</u> about the temperature of the air at the time that the precipitation formed. A few droplets can give us a hint, but with the millions of droplets involved in precipitation, we can get a statistically significant sampling of inferred air temperature by looking at the frozen precipitation in layers of the glacial ice core. There is also a formula that allows for inter-comparison of various samples. The result of this temperature formula is designated $\delta^{18}O$ (delta-18-O), and allows paleoclimatologists to estimate and compare the actual air temperature of condensation that formed at a given time all around the world[7].

Since the vast majority of individual years within ice cores are marked by softening or melting layers during each warm season, scientists can date the average warmth of most one year layers for many places around the globe. But for those years in which there was little melting or precipitation, there are also chemical reactions that take place in a snow layer when it interacts with the ultraviolet light from the sun. Since areas closer to the poles are dark for most or all of the day in winter, the deep ice cores from these regions can be accurately dated automatically using information on hydrogen peroxide concentration. These variations can also be detected in the shorter days in upper-mid-latitudes. This secondary method provides dating for those years in which little detectable melting may have occurred.

A number of other meteorological variables can also be inferred from these cores (such as CO_2 concentrations in trapped air bubbles), but we'll not discuss those here. Right now, we want to stay focused on temperature.

The nice thing about more recent times (i.e., the last few thousand, years) is that; 1) there is much less likelihood of two or more layers being crushed together, and 2) temperatures derived from ice core samples can be verified to some degree, by other

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[7] http://www.csa.com/discoveryguides/icecore/review.php

records. The ice core proxy temperature data can be compared to thermometer observations over the period they were available, or written historical accounts from any location near the sampled glacier. As noted, such reports may include accounts of cold winters, droughts, hot summers, etc. The Little Ice Age, for example, can be verified in any number of ways. It turns out that recent ice core temperatures are pretty good (say, ± 1.5-2.0^{o}C per year). In fact even longer term ice core data seem to match other temperature approximations to a reasonable degree, and can still be used to study trends when the errors become too large.

It is clear that ice core data are not as accurate as thermometer data (which in and of itself is not that great). They are probably not even as representative, since they only cover regions at or near glaciers. At the same time, remember that thermometer data only cover areas where civilization existed for most of the 200+ years since the invention of the thermometer. We believe that the ice core data show acceptably accurate temperature trends during more recent historical times (say the most recent 2500 years, or so) and acceptably accurate information on long term trends before that. But to reiterate, these data are not nearly as accurate as thermometer data (which aren't, remember, really all that representative a data set for global temperature in and of themselves).

Other δO^{18} proxy applications – Coral Reefs

Delta-O-18 techniques are also used as one of several methodologies in the analysis of coral reef data to obtain sea surface temperature proxies. The sea surface temperature can then be related back to air temperature (though only roughly so). With coral reef samples one can also look at trace metal ratios (such as strontium to calcium, or magnesium to calcium ratios) to derive sea surface temperature and salinity in the upper

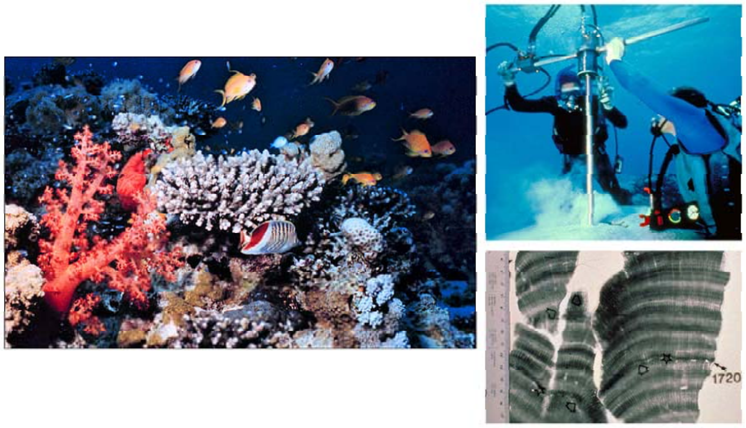

Figure 3.5 Left a beautiful coral reef in the Red Sea. Upper right – Scientists in SCUBA gear use a drill to extract a coral sample from Clipperton Atoll. Lower right – an x-ray image of coral samples from the Galapagos Islands clearly shows the banded growth pattern. Photo courtesy NOAA.

ocean environment. The results can be used to verify δO^{18} results. Lastly, the density and composition of coral can also be used to estimate temperature,[8] though these estimates involve a number of confounding variables. It turns out that coral reef growth varies with sea water temperature – the higher the sea water temperature, the more dense the coral. However, as in the case of tree rings, many other factors come into play, as well. Several attempts have been made to account for the confounding variables, but a plethora of problems still exist. These problems may not be as great as those associated with tree ring data, but they are significant. The final kicker is that data for this proxy is only available for about the last 200 to 300 years[9].

Another δO^{18} proxy application – ocean floor sediment samples

Sediment cores collected from the bottom of the sea can provide indirect air temperature information using $\delta^{18}O$ isotope ratios. In this case, the paleoclimatologists looks at the fossilized shells of tiny plankton-like creatures called foraminiferea. The

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[8] E.g., Beckman and Mahoney, 1998

[9] For more information see: http://www.ncdc.noaa.gov/paleo/reports/trieste2008/corals.pdf.

oxygen isotope composition ($\delta^{18}O$) of calcite from these shells is related to sea surface temperature at the time the shells formed. In addition, magnesium-to-calcium ratios in the calcite show a temperature dependence. The theory is that these creatures form near the surface at a certain sea temperature, then fall to the ocean floor over time, leaving behind a permanent record of historic sea temperatures – which are loosely related to air temperatures. Unfortunately, settling rates can be variable due to ocean currents and other, lesser, factors. Plus, settling rates are extremely slow for these tiny shells, so there can be mixing of many years before they actually make it all the way to the bottom. In the end, there is good news and bad news. The good news is that sediment layers contain much longer records than do ice core samples. The bad news is that it is nearly impossible to resolve the year-to-year differences that are possible with ice core data. The *resolution* for sediment cores is more likely on the order of hundreds of years, although the records cover several million years. In this sense, perhaps, ice core data and sediment cores sort of provide complimentary information.

Summary; Chapter 1 through Chapter 3

With these few examples of Science's efforts to develop proxy temperature information, we will close the entire discussion of how much we really know about measuring global mean temperature. We will do so with a brief summary.

The most successful times, historically, for the human race have been those brief periods of warmth that are sandwiched between much longer ice ages (Chapter 1). During the last ice age there is some evidence that our species was nearly eradicated.

The thermometer data which represent our best effort to construct a climatological data base historically have never been all that accurate (Chapter 2), nor have they been representative of the earth as a whole. And proxy-based temperature records from before that time (this chapter) are much worse than that, though ice core data are probably the best in that regard. Even the satellite observations which have been available over the past thirty years, and represent our most accurate global temperature record to date, are actually measuring different layers of the atmosphere and can only be used together only after serious calibrating assumptions have been applied (Chapter 2).

The alert reader might be wondering at this point why there is such a big fuss over a less than $1.2^{o}C$ temperature rise that has taken place over the recent 160 year period. Clearly one cannot justify any argument for global concern based on historical global temperatures. Even the most accurate data is not nearly accurate enough and the temperature change thus measured is small.

But if not temperature data, then what? On this note, we shall move on to the topics of greenhouse gases and computer modeling.