A modern Galileo thermometer. As the ambient temperature changes, the density of the water in the thermometer changes (decreasing as it gets warmer). Each glass sphere has a different density which is tuned to match the water density at a particular temperature (seen on the tag). If a sphere floats, that means it has a density that is less than the actual water density, and so the temperature is colder than the value on the tag. The actual temperature can be estimated as being between the temperature of the bottom floating sphere, and the top sphere that is not floating. In this image the temperature was between 66ºF and 70ºF (19 to 21ºC).

Chapter 1 -- Taking the Temperature of the Planet

Peter deMenocal

“The heat is on” - Glenn Frey

31 December, 1768: “No one can recall such a mild Autumn: the ground is as green as in the Spring, and today I have picked sufficient young nettles, dandelions, and other herbs to cook green cabbage tomorrow, which is New Year’s day.”

Colorful mixes of meteorology and domestic concerns are typical of weather diaries kept by diligent observers for centuries. This example, from the Stockholm Observatory in Sweden, is not unusual, but it does pose problems for those interested in climate change. For instance, exactly how mild was that autumn and how might it compare to autumn in 2007? To answer those questions and others like them, these qualitative descriptions are not sufficient—quantitative measures are required.

Galileo Galilei developed the first thermomete in the late 1500s. The “thermoscope”, as beautiful as it was imprecise, was an elegant liquid-filled glass cylinder hosting several colorful, sealed glass bulbs that rose and sank with changes in temperature as their density relative to the liquid changed. More accurate measurements became available two centuries later, when German physicist Daniel Fahrenheit developed the sealed mercury thermometer in 1714 and the temperature scale that bears his name. As with many scientific advances, this new way of reducing nature to numbers lead to a new way of viewing the climate. No longer was the difference between one year and another simply a qualitative change – warmer, cooler, wetter – but a difference that could be reliably quantified. These records gave rise to the statistics of weather and eventually to the possibility of detecting subtle changes in climate.

Armed with this new measurement device, weather stations were established in many European cities by the mid-1700s, marking the start of instrumental records of surface air temperature change. Some of the longest instrumental surface temperature records are from Central England (1659), Basel, Switzerland (1755) and indeed Stockholm (1756). These stations are very few in number but since they extend more or less continuously over 250 years, they have become extremely valuable in judging long term changes in climate. Maintained in the face of war, political upheaval and economic collapse. “neither rain, not sleet, nor gloom of night...” kept the many generations of observers from their appointed tasks.

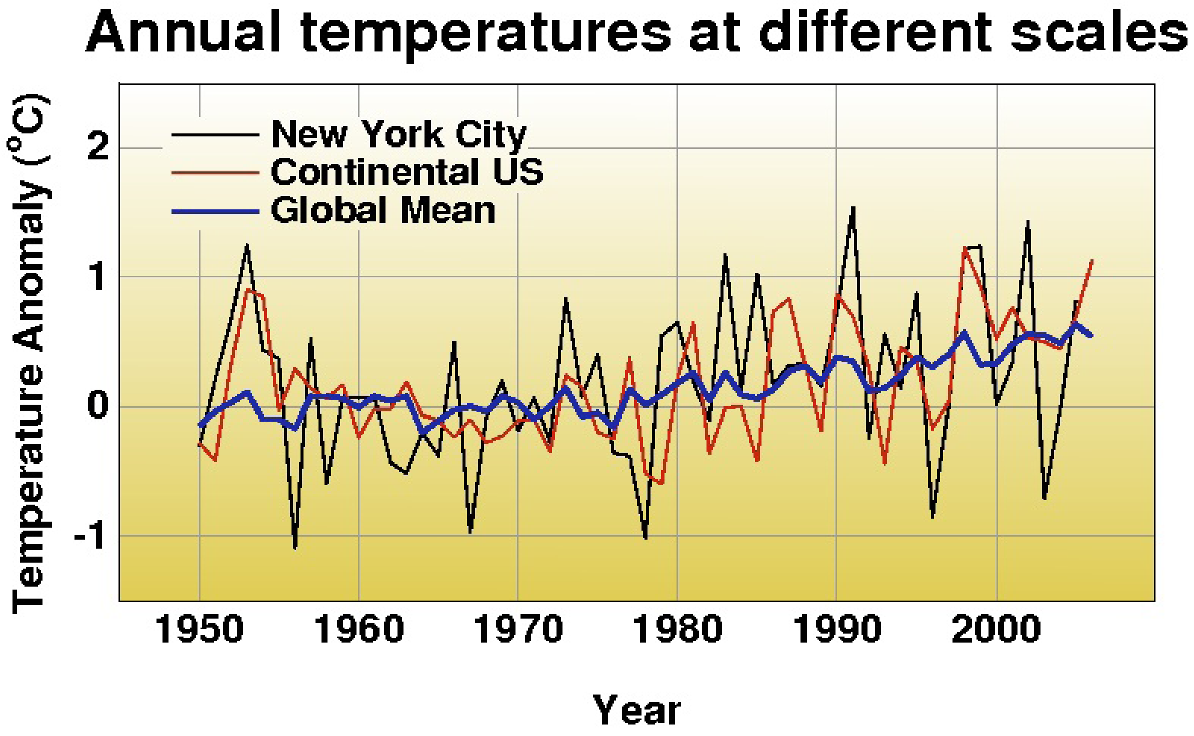
Since 1850 or so, a sufficiently large number of stations have covered about 80% of the globe, making it possible to have reliable estimates of the global surface temperature of the earth. Currently, thousands of meteorological stations gather data used to calculate changes in earth's surface air temperature year after year. However, it is difficult to put the data from these different stations together to and estimate historical global average temperature change. Each temperature station has its own "personality" complete with measurement gaps and other peculiarities such as the location of the site or the competence of the observer. These potential problems are often random, and so will average out in regional or global scale averages, although special care needs to be taken to account for station moves, instrumental changes and changes in the way that temperatures are taken (such as the time of day). Each of these factors can make a small difference in the mean temperature which could be misinterpreted as a climate trend if not accounted for.

One problem needs particular attention: temperature readings from some urban settings have had very localized warming trends over time. Cool natural vegetation cover is replaced by warmer streets and buildings, and industry and transport increase the local production of heat. This "urban heat island effect" can be felt in many cities and becomes stronger as cities grow. For instance, New York, Phoenix and Paris are all a couple of degrees warmer than their surrounding countryside. The local heat is real enough, but if these central city locations were assumed to represent a wide tract of countryside as well, that could contaminate the regional and global mean estimates. The effect can usually be isolated and removed by comparing a given urban temperature record with nearby rural records.

For assessing climate variations, we're most interested in temperature changes over time rather than absolute temperature – the 1ºC difference from last year is more relevant than whether today's temperature is 20ºC. So each records is standardized by subtracting the average temperature over a fixed base period (commonly 1951-1980, but the choice is arbitrary and makes no difference to the trends). The resulting temperature anomaly record expresses how temperature has changed relative to that common base period, and this process is repeated for all stations. The advantage of this approach is that anomalies in different locations are strongly correlated: if London has a warm summer, then Paris usually has one as well. Closely spaced stations can be used as a check on station problems (such as an undocumented move) and can increase confidence in the regional results.

So what do these records show? Most obviously they show that the atmosphere is a very dynamic place. Combined with the earth's rotation, variations in atmospheric pressure cause weather patterns to develop, swirl, and cast off waves of warmer or colder and wetter or drier conditions. These variations can cause large swings from week to week, season to season, and year to year. However, averaged over a continent or globally, these sorts of weather events, as impressive as they are locally, tend to cancel out. For the climate, weather variability is thus "noise" which obscures the underlying climate change. In New York City the standard deviation from one

A technician checks out the automated weather station on Bonaparte Point off Palmer Station on the Antarctica Peninsula.



The variations in average temperature vary more at a single location (New York City in this case) than they do over a continent or over the globe. In each case, temperatures are rising, but the signal of global warming is easiest to see at the largest scale.

month to another is around 2ºC (4ºF), from one year to another is 0.6ºC, while for the continental United States it is 0.4ºC, and for the global mean, 0.2ºC. The larger the area and the longer the period, the smaller the effect of weather.

But over the long term, climate changes can be seen through the noise. For instance, at the Stockholm weather station temperatures over the last two decades have been about 2°C/4ºF warmer than the 1951-1980 base period, and roughly 1ºC/2ºF warmer than the mild "nettles and dandelions" autumn of 1768 highlighted in the logbook excerpt above. Average temperatures in Stockholm in recent decades are the warmest they've been in over 250 years – even after accounting for the urban heat island. Note that this increase is much larger than the year to year variability. For the rest of the world, there is some variation in when the warmest temperatures occurred, but globally, temperatures have risen by about 0.8°C/1.4ºF over the last century to the warmest they've been over the whole record (starting in 1850). Most of this warming has taken place since the 1970s. The warming is stronger in the high northern latitudes than at the equator, higher over land than over ocean, and higher at night than during the day.

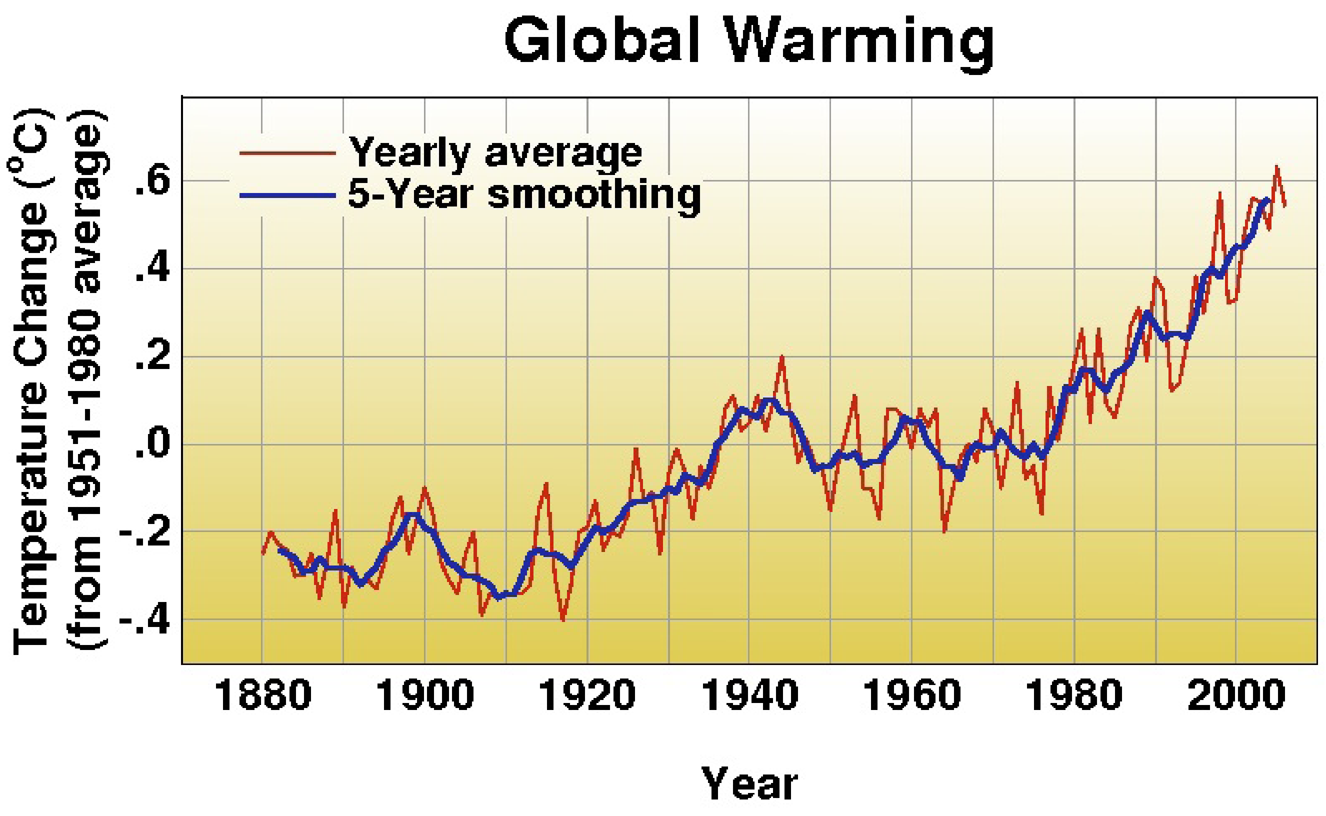
This modern instrumental trend is now well accepted by scientists because the record is now long enough and the warming is now so large that its reality is clear. The warming detected by this global array of instrument stations is also observed by many completely independent sources of information.

Oceans, boreholes and satellites

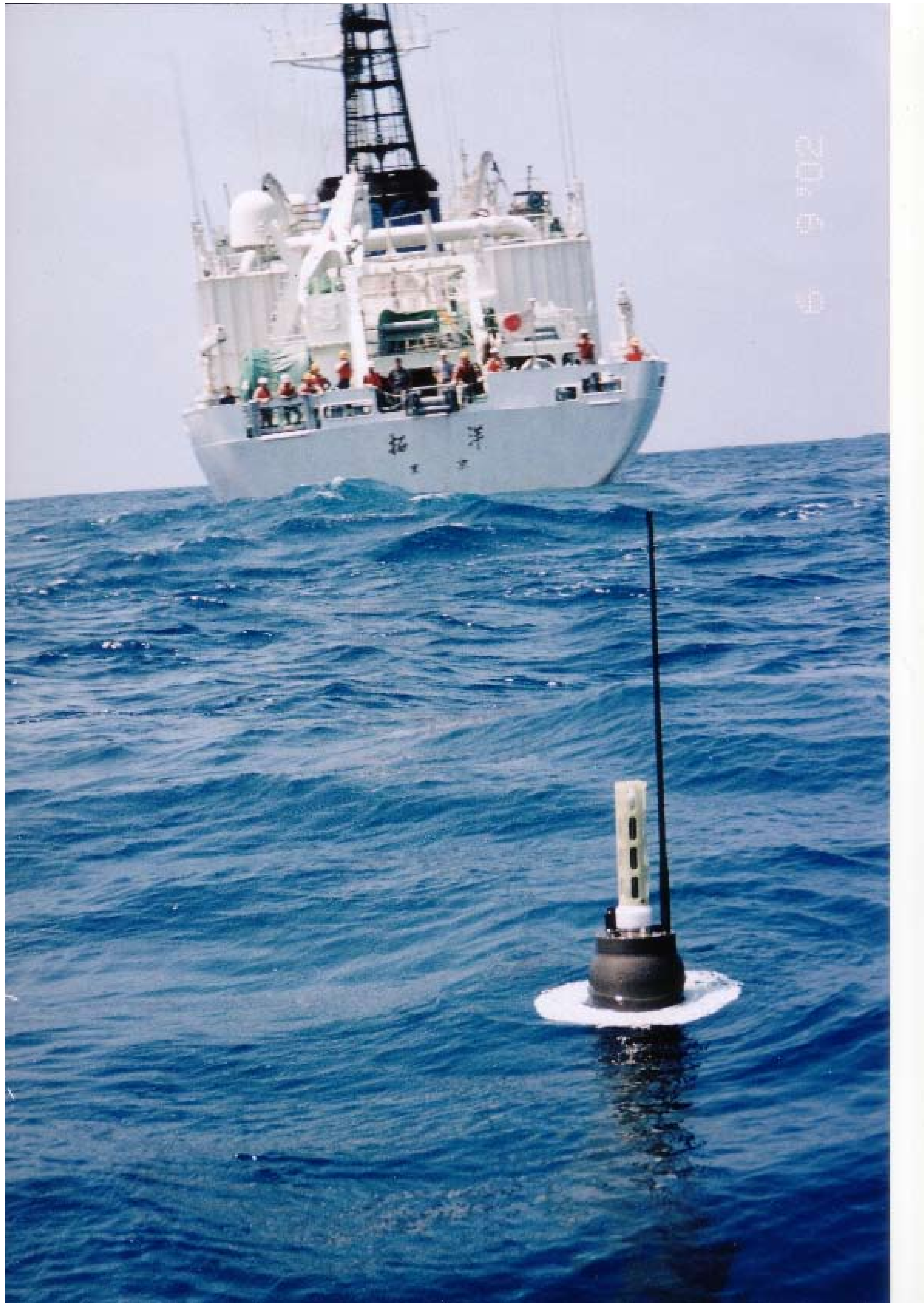
In just the last few years, oceanographers have demonstrated that the surface oceans have warmed by 0.1-0.2°C over the last fifty years or so. This warming is found not only at the surface, but has penetrated to an average water depth of 50-100m (150-300 feet). The measurement of water temperature is exceedingly precise and so this warming signal is well known, significant, and has been observed in every ocean basin. The oceans cover nearly 70 percent of the earth's surface and are very important to climate. It's not only their spatial coverage that is important, but the fact that water has a very large thermal inertia - it takes a long time to adjust to changes (see Chapter 3). On one hand, this implies measuring temperature changes in the ocean is difficult because the changes will be small, but on the other, if you see a global ocean warming, it's very significant.

Analyses of ocean temperature are based on millions of ocean temperature measurements made by ships sailing the world's oceans. Coverage in earlier decades was reasonable along well-traveled shipping lines, but quite sparse in the remoter areas of the ocean. Measurements became more widespread recently due to expanding fleets of commercial and passenger ships which routinely recorded the intake temperatures of seawater used to cool their engines. Over the years, their voyages have recorded ocean temperature changes for most regions of the world's oceans. An obvious limitation to this data is that some of the more remote areas (such as the South Pacific) have relatively few ship tracks and their temperature history is not well known.

In the early days, ocean temperatures were measured by dipping a canvas bucket over the side and taking a thermometer reading on deck. Getting a bucketful of water was a feat by itself as the ship would usually be moving



The changes in the global mean surface temperatures since 1880.



An Argo float floating in the Pacific Ocean shortly before recovery by the Japanese coastguard vessel Takuyo.

at full speed and some skill was needed to dip the bucket in without being pulled overboard. For a laugh, the old hands used to let the young, inexperienced sailors measure bucket temperatures. They would confidently go to the rail with their bucket wondering what the fuss was about. As the light canvas bucket skimmed the ocean surface, it immediately filled and became an impossibly heavy, jerking weight, pulled by the ship at full speed, and the poor deckhand would typically be dragged down along the ship's rail, their hands blisteringas they struggle to haul the simple canvas bucket back to the deck. Speaking from experience, this lesson is needed precisely once.

In the last few years, a technological innovation has given us the potential to deal with the sampling problem—obtaining near global, real-time measurements of world ocean temperatures, not only for the surface but the subsurface as well. Since 2000, a global array of 3000 drifting floats have been released into the world's oceans to autonomously measure, record, and report (via satellites) ocean temperatures. These Argo floats, named after Jason's ocean-going ship in ancient Greek legends, are about one meter (3 feet) long and drift with the ocean currents. Periodically, they sink below the surface by adjusting their buoyancy with an internal bladder and they record continuous measurements of ocean temperatures to depths of up to 2000m (6000 feet). They then float back up to the surface and wirelessly report the results back to a data center on land. The record from these devices is not yet long enough to completely specify the trends, but slowly and surely the gaps in coverage are being filled.

Geophysicists have also been trying to test directly whether the earth's surface rock layer is warming. If the earth's atmosphere is really warming then the upper ground surface should be warming too, and this heating should have gradually penetrated like a wave into the ground, albeit weakly and slowly, to a depth of many tens of meters.

In a deep hole (a borehole), drilled for a water well or any other reason, the temperature in that hole gets warmer and warmer the deeper down you go because the earth's interior is hot due to the decay of naturally radioactive elements. This "geothermal" heating gradient is normally very smooth and can be measured precisely using a special thermometer lowered down the hole. Surface temperature changes due to seasons are large, but since they only last for a few months the seasonal temperature wave only penetrates to a depth of a few meters below the surface before it is damped. But more persistent temperature changes penetrate to much deeper depths, several tens of meters in fact. The deeper you go, the larger the temperature perturbation needs to have been in order to be detectable — in some regions, it is still possible see cold signals associated with the last ice age, 20,000 years ago.

The exceptional warming trend in recent decades can be detected in borehole temperature profiles quite readily. The global warming signal measured in boreholes matches the instrumental record with warming apparent in almost every region. As with the instrumental data, the greatest borehole warming signals were observed in the high latitude and Arctic regions where temperatures have apparently risen several degrees above their long-term averages (see Chapter 2 for more details on polar amplification).

These days, measurements are no longer limited to ground (or below ground) observations. Since 1979, weather satellites have been orbiting the Earth measuring a whole spectrum of changes in radiation. An advantage of these satellite-based surface temperature measurements is that they can very nearly measure the entire globe in a few quick orbits. Satellites do not measure temperature directly, but by measuring the radiation at certain wavelengths that emanate from the atmosphere, usually in the microwave band, they can estimate the temperature of different layers of the atmosphere. Microwaves reflect the temperature of vibrating atmospheric oxygen molecules and are measured using “Microwave Sounding Unit” (MSU) sensors.

Over the satellite period (that is, since 1979), there have been about a dozen different satellites that had MSU units, and the records from each need to be tied together to give a climate trend. This can sometimes be tricky since each satellite’s orbit can drift, subtly changing the time of day any one reading is taken, and instruments themselves can degrade over time. However, despite that uncertainty, the trends from these satellites for the lower part of the atmosphere show very strong correlations and similar magnitudes to the trends seen at the ground.

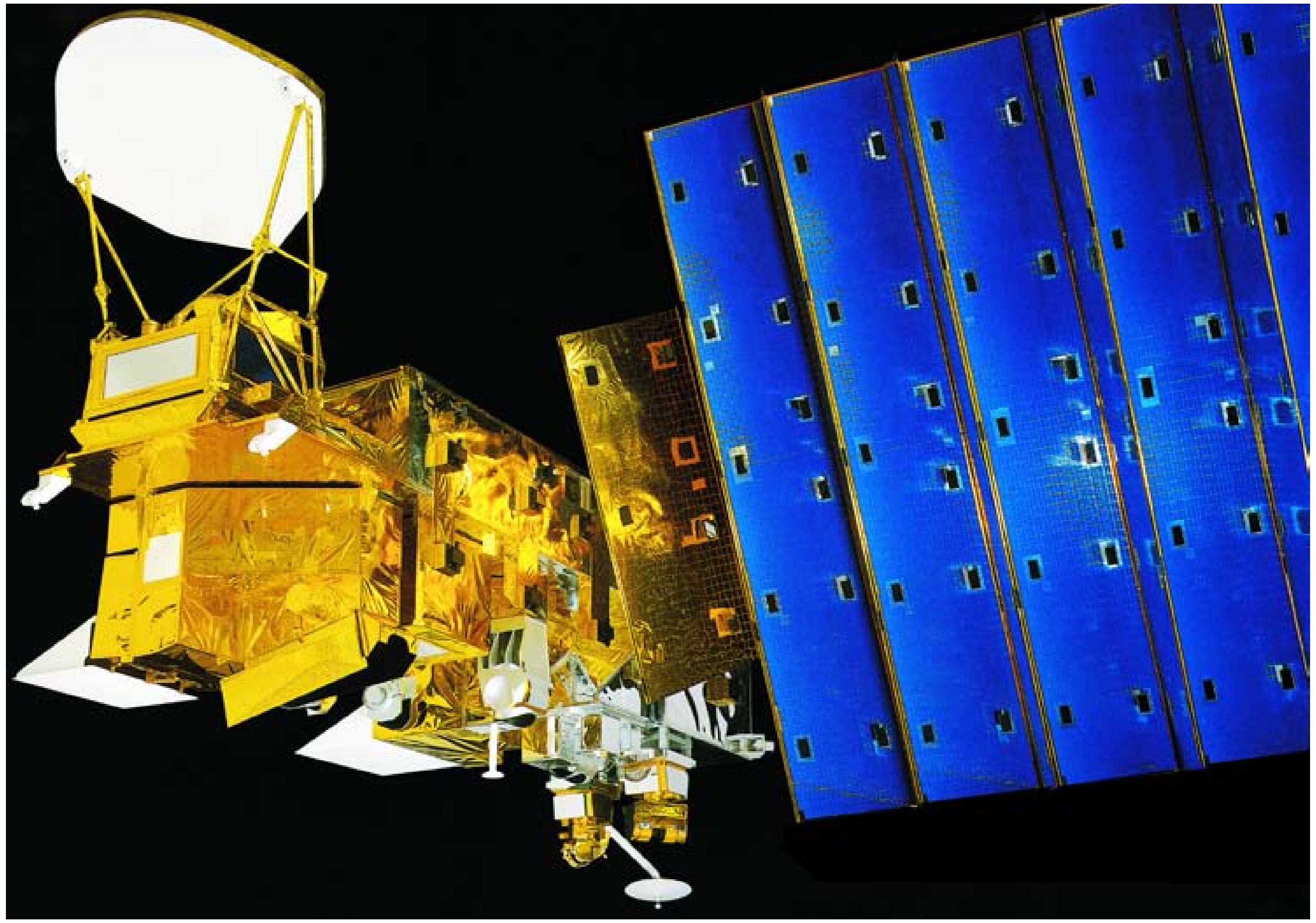
At slightly different wavelengths, these same satellite sensors have also been used to show that the stratosphere (at around 20 km altitude and higher) has been cooling significantly over the same time that the lower atmosphere has been warming. While this might at first reading seem contradictory, these opposing temperature trends between the upper and lower reaches of the atmosphere are an important fingerprint for the causes of these changes (but see Chapter 6 for the details).

Curiously, this upper atmospheric cooling means that the sky is, literally, falling. The upper layers are becoming more dense and contracting and so the stratosphere and the layers above it are slowly falling closer to earth. Chicken Little might not have approved, but there is a positive benefit in that it reduces the frictional drag on the satellites, and thus is helpfully prolonging the lifetimes of the very satellites that observe the phenomenon.

With these temperature changes have come dynamic changes in wind patterns. In both the northern and southern mid-latitudes, the westerly winds (which flow from west to east) in winter have been stronger in recent decades. This is changing the storm tracks, particularly in Europe where winter storms now track further north than during the 1950s or 1960s, leading to significant drying around the Mediterranean from Spain to the Middle East and even more rain in Scotland and coastal Norway. As if Bergen, where it already rains 250 days a year, really needs it...

Further back

One of the more challenging questions surrounding the current record surface temperatures is how unusual the current trends are in the broader long-term context. The challenge is that our observation period is really quite short relative to the long timescales of global climate changes. As we have observed, global thermometer read-



This is an artist’s rendering of NASA’s AQUA satellite that is currently in orbit as part of a constellation of 5 satellites with multiple sensors that are tracking ocean temperatures, clouds, surface winds, water vapour and air pollution from a low-Earth orbit that circles the Earth every 99 minutes.

Scientists Ed Cook and Rosanne D'Arrigo from the Tree Ring Laboratory at the Lamont-Doherty Earth Observatory of Columbia University.

ings only extend back 150 years, and ocean temperature and satellite-based records only reach back a paltry 50 or 30 years, respectively. As compelling and consistent as these temperature records are, they are still too short to assess the magnitude of natural variations in temperature, say, over the last several centuries or millennia.

Luckily there are reliable ways to do this using proxy records of past climate change. Proxy records are surrogate indicators of past climate changes which derive from natural recorders of climate variability, such as tree rings, corals, fossil pollen preserved in lake sediments, ocean sediments, clam shells and glacier movements. They aren't direct measures of temperature or rainfall, but they are so closely tied to them that changes in the proxy can give a strong clue to changes in climate.

An example of a proxy record is the use of tree rings to reconstruct past changes in temperature or rainfall. Temperature controls the growing season of some tree species in certain locations very closely. These trees lay down visible rings each year, with light, low density layers reflecting the warm season growth and dense, dark layers marking the cool season growth cessation. Since some trees live for hundreds of years and forests of trees represent a broad spectrum of ages, it's possible to take small borings into dozens of tree in a particular location and to build a single, composite tree ring record which documents changes in tree growth spanning many hundreds of years.

Tree rings are not the only biological proxy that has annual banding, corals in the tropical oceans produce a hard calcium carbonate skeleton which is also laid down in annual increments. The carbonate is made of constituents that the corals extract and precipitate from seawater that can be analyzed to determine the water temperature in which the coral grew. Some corals grow to be several meters in diameter and the skeleton can represent a virtual library of many hundreds of years of continuous coral growth in a single spot in the ocean.

A guiding principle in paleoclimate research - the science of reconstructing past climates using proxy measurements - is that proxies such as tree rings must be calibrated against observed variations of climate, and the resulting product must be validated against known historical changes. Only after climate proxies have been both calibrated and validated can the proxies be trusted to provide useful data for analyzing climates of the more distant, pre-instrumental past. Tree ring records have been particularly valuable for reconstructing past temperature changes before the instrumental record. Statistical methods are used to combine tree ring temperature estimates from different regions of the world to develop global temperature reconstructions that extend back up to 2000 years into the past.

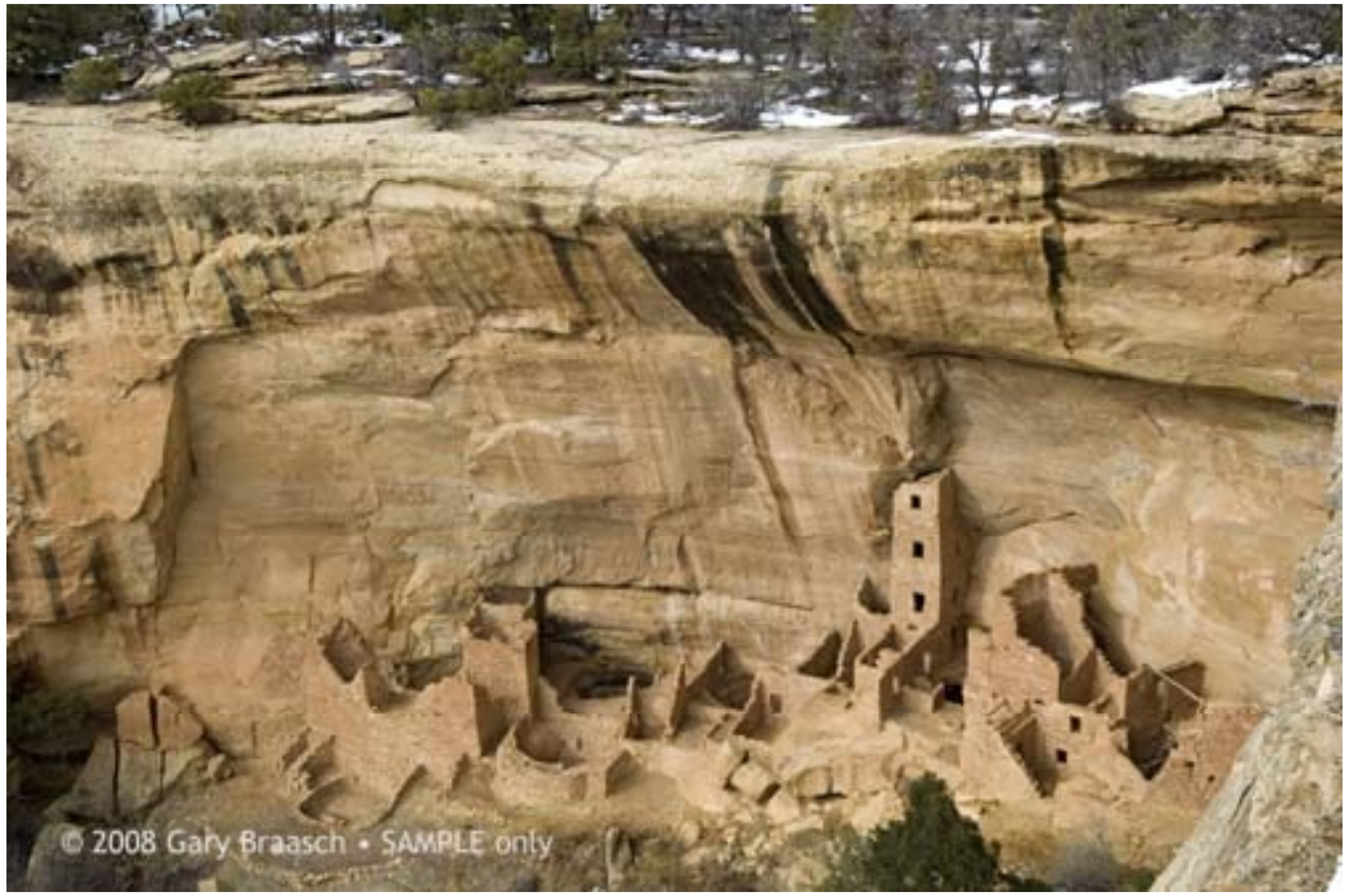
The accuracy degrades the further back one goes, but these studies have shown that modern temperatures are the warmest they've ever been in the last 400 years, and it's likely (though not absolutely certain) that we are in the warmest period globally in over a millennium. The increased uncertainty prior to 1600 CE is mainly a consequence of a reduced number of records that are available that are long enough; more and better data are definitely needed. Still, the temperature reconstructions suggest contemporary global warming is exceptional from even before the first instrumental measurements.

Medieval times in Europe appear to have been quite warm, but warm periods elsewhere don't seem to have happened at the same time, making the "Medieval Warm Period" a regional phenomenon. For contrast, coral records provide a very long baseline of past tropical Pacific variability that reaches back many centuries and show medieval times to have been characterized by cooler conditions. They also show "El Niño" events becoming both more frequent and more intense after the mid-1970s, including a dramatic and unprecedented freshening of the western tropical Pacific Ocean (see Chapter 3 for more details). Whether this is connected to the long term temperature rise or is just the 'noise' in a chaotic system is as yet uncertain.

The most interesting results from these reconstructions are not the simple headlines alluded to above, but the structure of the temperature and rainfall patterns in space and time. These can often be tied to documented changes in human societies and landscapes that are seen in art, oral histories or archeology. For instance, cold periods around the 14th and 17th centuries and lasting until the 19th Century, sometimes called the 'Little Ice Age' correspond to occasional Frost Fairs on the frozen Thames River where the citizens of London would drink, skate, play sports, and socialize. Some of the very long instrumental records also capture these cold periods – such as the "Year without a summer" in 1816 in the wake of the Tambora volcanic eruption. Going further back in time, drought reconstructions from tree ring records indicate that climate change may have been responsible for the disappearance of the Anasazi culture in the American southwest and the collapse of classical Mayan cultures in the Yucatan, Mexico.

Integrating Glaciers

Mountain glaciers are very useful indicators of climate change. Found on every continent and at almost every latitude, these "rivers of ice" slowly integrate over many years of weather and react mainly to long term changes. The presence of a glacier in a high mountain valley indicates that the long-term average rate of snowfall



Mesa Verde in Colorado is one of a number of Ancestral Puebloan sites in the Four Corners region of the American Southwest. The Square Tower House ruins were abandoned roughly 800 years ago at a time of severe drought.

The Brüggen Glacier in southern Chile is one of the largest outflow glaciers from the Southern Patagonian Ice Field. Unlike most glaciers worldwide it advanced significantly from 1945 to 1994. Since then the glacier has mostly stabilized.

exceeds the rate of snowmelt at that altitude. Moreover, air temperatures there must be on average below the freezing point of water. As anyone who has climbed even a modest mountain will have observed, it's colder at the top. The atmosphere is compressible, and the higher you go, the less air (and pressure) there is above you, so the air expands, cooling at the same time. This is the same effect (but in reverse) that you see as you pump air into a bicycle tire – it will warm up considerably. The atmosphere cools at a rate of about 7°Cper kilometer of altitude. So, if it's a comfortable 21°C (70°F) at sea level one might expect alpine glaciers to start at about three kilometers elevation.

More precisely, the existence of the glacier is determined by the delicate balance between snowfall accumulation on top in winter and melting that occurs at the lower elevation zone in front of the glacier (usually in summer). The melting zone is commonly marked by a terminal moraine, a massive, curving rock pile that marks the position where the flowing glacier disintegrates and drops its load of pebbles and rock that it has scraped from the valley. The Little Ice Age cooling events are marked by terminal moraines at levels roughly 300 meters below their present level in alpine glacier valleys across Europe and Scandinavia. This difference actually tells us roughly how much cooler it was during the Little Ice Age. Using the average atmospheric cooling rate with height mentioned above, the Little Ice Age in those regions works out to have been about 2°C (4°F) cooler than today. This is similar to the local cooling inferred from the proxy records like tree rings.

As one of the most visually compelling indicators of climate change, mountain glaciers have been melting and retreating at an accelerating rate in recent decades. This exceptional meltback is observed nearly everywhere around the globe where there are mountain glacier systems, from New Zealand to Patagonia, from Montana to Switzerland. Glaciologists are alarmed that the vast majority of well-documented glaciers are retreating at an accelerating pace, although there are a few exceptions to this general rule – usually in cases where the winter snowfall has compensated for the increased summer melt, for instance in Norway (see above). Like the recent rise in surface air temperatures, the magnitudes and rates of recent glacier melting also appear to be unprecedented, at least over the last 400 years.

Glaciers in the tropics have faired even worse. The tropics are warm and seasonality is low, but glaciers can form at high elevations on isolated plateaux and mountain peaks in the Andes, East Africa, the Himalayas and Papua New Guinea. At this elevation, temperature changes across the tropics are strongly coordinated, much more so than at the surface, and so coherent tropical glacier retreat is a likely sign of a long-term tropics-wide warming. Despite their precarious existence, the largest tropical glaciers are ancient, containing ice that is many thousands to tens of thousands of years old. These majestic tropical glaciers silently remind us that past climate swings over prior millennia were never large enough to have melted the glaciers away.

At present however, tropical glaciers, large and small and on all continents, are disappearing and they are melting away at an accelerating rate. The melting of the larger, older tropical glaciers is particularly troubling because they provide such obvious evidence that the modern, industrial-age warming is exceptional. Some glaciers appear to be rotting from the inside as melt waters trickle down through ice crevasses, whereas others seem to be literally evaporating away. For example, the small ice cap atop Mount Kilimanjaro, Tanzania has lost 80% of its mass already and Hemingway's "snows of Kilimanjaro" are expected to become just a memory in about a decade or so.

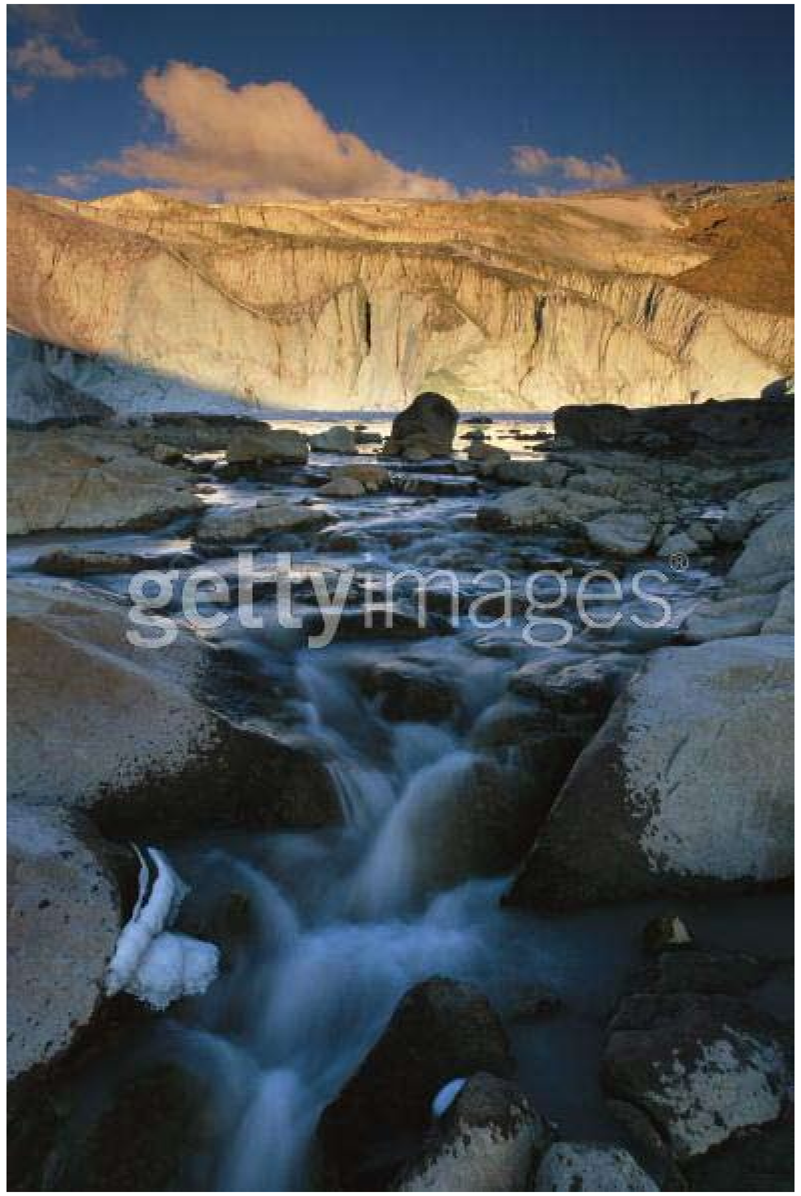
The largest tropical glaciers are found in Peru's Cordillera Blanca, or White Mountain Range. The Quelccaya ice cap is the largest tropical glacier, covering roughly 44 square kilometers. One of the largest glaciers flowing from this ice cap has been intensively studied and the best estimate now is that the glacier will be gone completely in about five years (by about 2012). The accelerating rate of tropical ice melting is a real concern here not only because the White Mountains will soon lose their moniker, but because the glaciers store water seasonally for agriculture and hydropower for tens of millions of people. Changes in that storage will exacerbate water stresses in summer in the lowlands.

Unequivocal warming

This collection of warming indicators demonstrates the reason why the recent IPCC assessment described the recent warming as "unequivocal". Warming is greatest in the Arctic, over land and at night. Nineteen of the warmest years on record have occurred within the last 25 years. The warmest years globally have been 1998 and 2005, with 2002, 2007 and 2003 close behind. The warmest decade has been the last 10 years. The warming is substantially more widespread than in any previous warm decade (such as the 1930s) and the rise appears to be exceptional on even longer time scales. The odds of this sort of clustering, if it occurred only by chance, would be less than one in a billion. It's almost like being the newcomer to a game of roulette and having your ball consistently land on the "1" pocket, spin after spin. It's exceedingly unlikely that the current warming trend is, well, not a trend.

How does modern warming fit into a broader, earth history perspective? The last time the earth was substantially warmer than this for a sustained period was about three million years ago, during the early Pliocene, when temperatures were about +3°C warmer and geological evidence shows that the Arctic was ice free, the Greenland ice sheet was nearly absent and sea levels were possibly 20 meters (over 60 feet) higher. Other more recent periods appear to have been slightly warmer, specifically the last 'interglacial' period around 125,000 years ago where Greenland temperatures might have been 3 to 5ºC warmer and sea level 4 to 6 meters higher.

The bottom line is that while the current warming is not unprecedented in all of Earth history, previous eras, clearly warmer than today, were accompanied by changes (particularly in sea level) that dwarf variations that we have so far seen.



A stream of glacial runoff from the Quelccaya ice cap in Peru.