Two Canadian Coastguard icebreakers unloading equipment to set up the SHEBA base camp on an ice floe in the Beaufort Sea in October 1997. The ice is 1.6 meters thick and floating over 2000 meters of deep water.

Chapter 7 Studying Climate
Gavin Schmidt and Peter deMenocal

"Write how the clouds are formed and how they dissolve and what it is that causes vapor to rise from the water of the Earth to the air..."
> - Leonardo Da Vinci

"The wind that blows is all that anybody knows"
> - Henry David Thoreau

From October 2000 to May 2001, dozens of scientists and graduate students could be found drifting on the sea ice in the Beaufort Sea, north of the Canadian Arctic. As well as spending a cold and isolated winter thousands of miles from home, the scientists also had to be constantly ready with a rifle to scare off any hungry polar bears who happened to wander into view. Rather than simply being the unfortunate victims of a shipwreck, most had actually volunteered to be there. What motivated them? And why should we care?

The study of climate is one of the most complex and lively branches in all of earth science. It is an amalgam of dozens of different fields: meteorology, oceanography, biology, chemistry, quantum physics, orbital mechanics and ecology. As one might expect, the scientists studying climate are as diverse as climate itself.

Climate scientists can be broadly split into four overlapping groups according to discipline. Some study the physical processes in the current climate system, others look for indications of how and why climates were different in the past, others document the impacts of change today, and some bring all of these elements together so that they might be able to say something about tomorrow. Each branch contributes something unique to the mix, and our understanding of climate change and its impacts owes something to each of these sub-fields.

Observers of Climate Processes

The Earth's climate is a huge interconnected system that ranges from the ocean floor to 100km above the surface of the Earth; from the frigid wastes of Antarctica to the lush tropical rainforests of the Amazon; from the scale of an individual cloud droplet to ocean gyres thousands of kilometers across. Some of these places and processes are easily accessible. But most are not, and so we need a large array of different techniques to probe them.

Climatology, as a discipline exists because all of these scales are relevant. But most processes are still studied

in a traditional reductionist way: researchers have become experts in trying to slice and dice the climate into more manageable bite-size pieces for study. None of those pieces are complete, but each measurement gives a different perspective on the system as a whole, which can then be integrated into a coherent picture.

The information that is most accessible is from the surface, and particularly on land, and that is typified by the networks of data gathering stations that have been developed to help in weather forecasting. These weather stations often consist of just a small screened box containing a thermometer and barometer (for measuring pressure) with an anemometer (for measuring winds) on the side. They feed their information directly to the national weather services in individual countries who then forward that data to the main central databases that are used by the weather forecasting centers like the National Weather Service in the US. Some of these stations provide the longest records of instrumental data which are some of the clearest measures of what has happened since about 1850 – the "instrumental period".

Long, coherent records are particularly prized; some individual records, such as at the Royal Observatory in Paris, go back 400 years to the invention of the mercury thermometer. Since the records are often in Latin or in archaic scripts, graduate students in history are often needed to transcribe the old handwritten records, and this process is still ongoing.

An important point to note is that the needs of weather forecasters and climatologists are subtly different. Weather forecasters need the most accurate and up-to-date information at all times while climatologists are interested in the statistics such as the averages and variability of that data. Moving weather stations around, or updating their equipment may help improve the weather forecast, but could play havoc with analyses of the long term climate trends, because those changes can introduce subtle biases in the climate record. For instance, a weather station in the center of a city often records the effects of increasing urbanization over time, which is not representative of a regional climate change (as discussed in Chapter 1). On the other hand, if a weather station moves location from the center of a city to a more rural airport site, that could introduce a spurious cooling jump into the record. In order then for this data to be useful for climate monitoring purposes, climatologists need to adjust for these kinds of effects. Those adjustments are determined through painstaking analysis of the written records, statistical tests and correlations with other nearby stations.

Meteorologists are also trying to get to the heart of what goes on higher in the atmosphere. The most complex processes take place at the level of individual cloud droplets and the aerosols that drift around the atmosphere. These processes determine when clouds form, how long they last, and whether they rain, thereby controlling the net effects of clouds on the climate system itself. A key uncertainty is the life cycle of the ice particles that make up high level cirrus clouds since they have both a reflective (cooling) and a greenhouse (warming) role. Knowing how they might change is a big determinant in whether cloud feedbacks to climate change will be positive or negative.
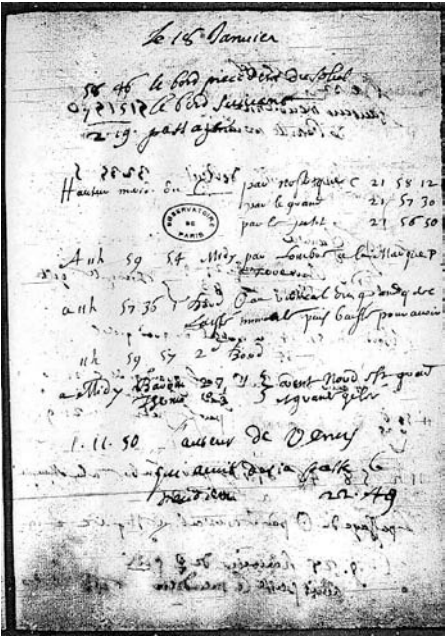
An original handwritten page from the Observatoire de Paris weather log book demonstrating the difficulty in dealing with older sources of data. Both handwriting and meteorological conventions need deciphering. The second image is an example of the collated data showing weather records during a crucial few days during the French Revolution.

High cirrus clouds over New York City. These clouds consist of small ice crystals and are 8 to 10 km high.

The perils of living on an ice floe. Constant movements of the ice driven by the winds would occasionally cause the ice to ridge - one ice floe crunching into another. Any equipment caught in between would be crushed and lost.

NASA's high altitude research plane, the WBS- 57, is one of the only ways to get data directly from the higher levels of the atmosphere (above 10 km or so), including the lower stratosphere where many key processes occur. The plane carries no passengers, and so instruments need to be designed to be extremely hardy (temperatures can drop to -80°C) and independent of any operator. The plane is often used in conjunction with measurements from the ground and from balloon-borne instruments to pin down what is going on in a particular air column. This is particularly useful for testing theories about radiation transfer and convection processes.

Ice is important for clouds, but it is also the overwhelming focus of scientists working in the high Arctic. During the Surface Heat Budget of the Arctic (SHEBA) project mentioned above, hundreds of oceanographers and polar specialists worked on dozens of measurements on the floating base camp. There, scientists measured the heat fluxes through the ice, the role of melt ponds in the reflectivity, and the interactions of oceans and clouds – all key parameters in controlling Arctic and global climate. Among the analyses made at SHEBA are fundamental studies on how the reflectivity of the snow and ice changes as a function of temperature and surface conditions, and how clouds and sea ice interact to control the heat balance of this crucial component of the climate system. None of this necessary knowledge could have been determined without individuals going to the Arctic to make the measurements themselves.

In both field experiments mentioned above, there was an unseen partner; the network of orbiting satellites that criss-cross the sky. Currently there are over 1000 functioning satellites in orbit – some are military, some are for global positioning systems. But many are Earth Observing systems, put there to measure the intensity of the light across the whole electromagnetic spectrum, recover information on clouds, water vapor, temperature, ozone, soil moisture and measure the amount of particles in the atmosphere. They probe variations in the ocean and ice surfaces with laser altimeters, and measure tiny variations of gravity due to seasonal and long-term changes in water storage. The great advantage of satellites is the global (or near-global) view they can provide. But satellites too have limitations. Cloud-viewing satellites, for instance, can not see lower clouds if they are underneath higher clouds. Satellites looking at aerosols often have problems picking them out if the land beneath is very heterogenous. Regardless of what they see, satellites send out a large continuous stream of data back toward Earth. On the receiving end, researchers have problems of data overload and spend most of their time trying to reduce the terabytes of incoming data into something more manageable. Sometimes a satellite's instruments suffer slow changes in the accuracy that

can be difficult to detect, although if there is an overlap with another similar satellite, this can be re-calibrated. Over time as well, the orbits of the satellites gradually slow and decay due to the very slight friction with the upper atmosphere. This too needs to be detected and adjusted for.

Because of their near-global reach, plans are continually being made to upgrade the satellite instruments and replace aging hardware. This process is very long and expensive; it can take a decade for a new measuring device to actually make it into orbit, and there have occasionally been gaps when instrumentals failed ahead of schedule before their replacement could be launched. These service gaps and the constant need for adjustments to correct for known problems mean that long term satellite-derived trends are at present, a supplement to, and not a complete replacement for, ground-based observations.

The top-down perspective of satellites is however very useful for the large scale context, and is in sharp contrast to the necessarily limited viewpoints of the ground observers. Since the satellite era began in earnest in 1979, the completeness of the observations has increased markedly. This bonanza is most noticeable in weather forecasts where accuracy improved dramatically when the satellite data began to be used in the forecasts. For climate models as well, the satellite data on solar activity, precipitation patterns, radiation fluxes at the top of the atmosphere and cloud variability, have all added unique ways to test and improve them.

Reconstructing Past Climate Change

The amounts of data being generated by the current observational networks and satellites are truly phenomenal, though still not sufficient for many purposes. They are incapable of providing a history of climate change prior to the beginning of the satellite era, or before the implementation of the weather station network in the late 19th Century. Without that longer term overview, it is impossible to place the current changes in context or to understand what the climate is capable of doing.

Information about past climates is buried in a multitude of archives, some well known (tree rings, pollen), some obscure (isotopes in stalagmites, pack rat middens, chemical biomarkers in ocean mud). Each can be analyzed to say something about temperature, rainfall, ocean or atmospheric circulation in different periods of the past.

The tree rings and corals mentioned in Chapter 1 have very clear annual bands, making them easy to date. There are plenty of other archives that lack such precision but are still invaluable for detecting climate

The launch for NASA's TERRA satellite in December 1999. TERRA is part of the A-train constellation of 5 satellites in low-Earth orbit that follow each other in the same orbit separated only by a few minutes. Measurements from TERRA include the Earth's radiation, aerosol amounts and concentrations of pollutants in the Earth's atmosphere. In particular, TERRA hosts the MODIS instrument which is used for a number of satellite images in this book.
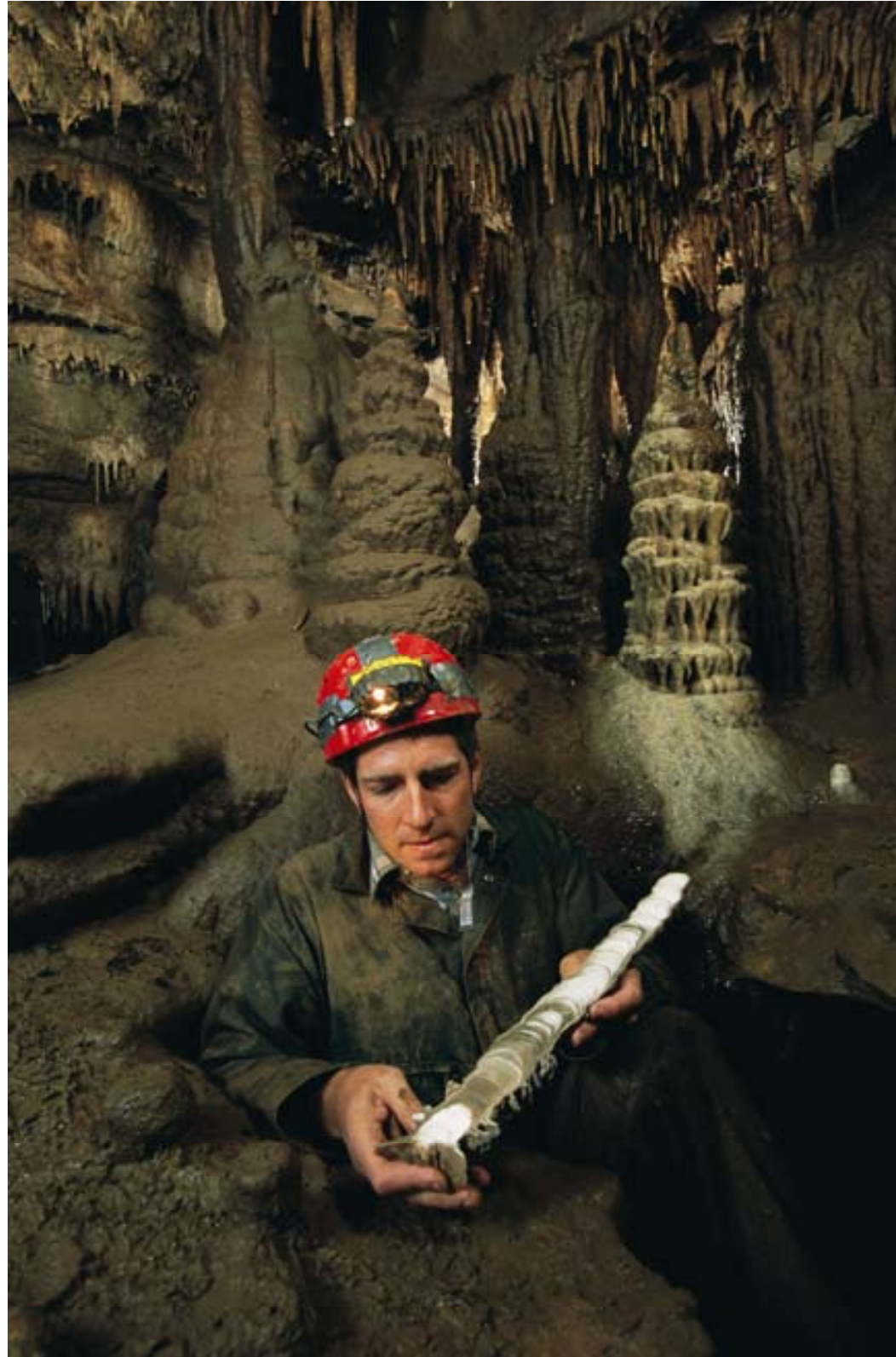
Jeff Dorale of the University of Iowa holds a stalagmite from Crevice Cave near Perryville, Missouri. Stalagmites hold a record of climate change in their layers that build up over time, revealed here after the stalagmite has been sliced in half. The record of oxygen isotopes in each layer tells us something about temperature and rainfall. The large stalagmite in the background is about 130,000 years old.

changes, both recently and further back in the past. One of the most promising is the study of cave deposits, usually stalagmites, which can be well dated using the decay series of uranium in the limestone.

Stalagmites form as ground water rich in dissolved minerals drips into a cave, where the minerals precipitate. They can grow quickly or very slowly, depending on location, and individual stalagmites can be decades to thousands of years old. Careful geochemical analyses of the limestone (calcium carbonate) layers can provide continuous, well-dated records of climate change in the cave region spanning millennia into the past. One of the most useful measurements is the ratio of oxygen isotopes in the carbonate, which derives from the isotope ratio in the water dripping into the cave.

Oxygen atoms come in a number of stable isotopes that differ in the number of particles in the nucleus. Chemically, the oxygen behaves the same way regardless of whether the nucleus holds 16, 17 or 18 protons and neutrons. But some physical processes differentiate between the heavier atoms and the lighter ones. For instance, during the evaporation of water (H_2O), water containing the lighter atoms (written $16O$) evaporates more readily compared to the heavier ones ($17O$ and $18O$). When a cloud condenses, heavier atoms form water droplets more readily than lighter ones. The isotopes in the rainfall contain heavier oxygen isotopes at first, i.e. a greater proportion of $17O$ or $18O$, and then progressively lighter ones, i.e. a greater proportion of $16O$, as more of the water vapor rains out. Changes in the isotopic ratio in the stalagmite over time can then be connected to changes in rainfall patterns and local temperatures. It's as if some oxygens were painted a different color. By looking at the eventual blend, we can work out how the proportions were mixed.

Since water is ubiquitous in our climate, there are many archives where water isotopes are recorded. Most directly, snow and ice falling on mountain glaciers and ice sheets carry with them information about the source and temperature of the water. As the snow accumulates, layers of ice form, each with their own isotopic signature, laying down a history of change. In the polar regions, the dominant effect is related to temperature; as it gets colder, there are less heavy atoms (because the colder air has lost more of its initial water vapor). In the tropical ice cores, the signal is more tightly tied to patterns of rainfall change.

The deeper you go into the ice, the older it will be. In the polar ice sheets, we find ice that is more than 100,000 years old in Greenland and at least 850,000 years old in the center of Antarctica. The pioneer cores were drilled

in Greenland in the 1980s. But it wasn't until the 1990s that two cores more than more than 3000 meters deep extracted at the Summit site (in the middle of the Greenland) really demonstrated the value of these archives. Drilled separately by US and European teams 30 km apart over a period of years, these cores were remarkably similar and told a story of large and dramatic changes. Particularly during the last age, these finding overturned widely held notions about the stability of past climates. Since the 1970s, conventional wisdom in the science community was that ancient climate change had been slow and driven predominantly by the changes in the orbit of the Earth. Measurements of the water isotopes, along with records of dust accumulation, and gases like methane trapped in air bubbles in the ice, demonstrated that temperature swings of tens of degrees could happen in decades with severe consequences for the climate across the hemisphere – the last time occurring around 12,000 years ago.

The most dramatic result from the study of ice cores is the strong connection between Antarctic temperatures and the concentration of CO_2 in ice core bubbles. CO_2 is not well preserved in Greenland cores because of the high and variable dust content that is a consequence of the amount of deserts in the Northern Hemisphere and Greenland's relatively southern location. But in Antarctica the snow is significantly cleaner. Scientists have managed to extract very accurate records of greenhouse gas concentrations through at least 800,000 years. Over eight glacial cycles driven by wobbles in the Earth's orbit, the temperatures and greenhouse gases have moved up and down in lockstep, with the CO_2 occasionally lagging slightly behind. Here we have prima facie evidence that climate affects the carbon cycle (as discussed in Chapter 6) but it also hints very strongly that greenhouse gas changes play a role in how cold the ice ages are. Calculations suggest that, in fact, decreases in CO_2, CH_4 and N_2O provide just under half the '"forcing" keeping the ice ages as frigid as they were. The other factors were the extent of the ice sheets, increased dust and decreased vegetation that collectively reflected more solar energy to space. The cycling and slight lag indicate that in these circumstances, the greenhouse gases are acting as feedbacks on the orbital forcing and then contributing to the temperature changes themselves. More fundamentally, this cycling implies that to a large extent climate is predictable, and given a similar configuration of external factors, the climate will come to a similar state.

Oxygen isotopes come up again in the layers of muddy sediment that accumulate in oceans and lakes the world over. This mud is made up of the slowly accumulating 'rain' of organic matter that falls from the productive surface layers, building up over thousands to millions of years. Sediment records are retrieved by taking specially equipped drill ships and drilling down hundreds of meters; in some cases, in water depths of more than 4 km, and in some very rough seas. Paleoceanographers take a small sample of the mud and pick through it using a microscope to find the calcium carbonate shells of specific species of small zooplankton, called foraminifera. Just like the stalagmites, the carbonate oxygen isotope ratio gives clues about past climate conditions; in this case the local temperature and water mass properties. In ideal cases, the bottom of a lake or isolated ocean basin is anoxic, that is, there is not enough mixing of surface water down to the depths to provide oxygen. Thus there is no marine life on the bottom and the sediment can accumulate in neat and undisturbed layers called lamina. These records have shown that the variability in the Greenland ice core can be seen mirrored as far afield as the West Coast of California near Santa Barbara, and in the Cariaco Basin near Venezuela.

Sylvia England processes an ice core from the West Antarctic Ice Sheet at the National Ice Core Lab in Denver Colorado. The core is sliced and diced before being sent to different labs for analysis of the gas in the bubbles, and the isotopes and dust in the ice.

A group of summer students from Columbia University taking a sediment core from the Manitou Marsh north of New York City. The mud they recover will be analyzed for pollen and charcoal (signatures of climate, human occupation and the history of local fires).

At different time scales, the ocean records can be a measure of ice ages waxing and waning, or the oscillations of ocean circulation on millennial time scales. Just as for ice cores there are many other relevant parameters that can be measured, each of which give another partial view of the climate in centuries and millennia past. For example, the accumulation of wind blown dust in some records off West Africa has offered a clear view of the rise and fall of the "Green Sahara". It is well known to any watchers of The English Patient that there are many areas in what is now the Saharan desert that used to have abundant water and wildlife, including hippos and crocodiles. Now these areas are sandy desert and the only obvious sign of these animals are in ancient petroglyphs etched into the rock. Dust from these dried lake beds is often blown out to sea by the winds where it ends up accumulating in the ocean sediment. During the wet period following the end of the last ice age, those lakes were full, and dust levels were much lower for many thousands of years. However, around 5,500 years ago, dust levels found in Atlantic sea-floor sediment cores shot up very quickly, indicating widespread drying and desertification. Up to today, the rains have never returned. We discuss the possible reasons for that below.

Lakes, bogs and ocean mud records contain a wealth of information about change in plant life as well. Climate scientists use these plant histories to validate the more indirect measures of climate change mentioned above. Pollen from each plant species is both small and unique. It is often airborne and, therefore, part of the dust that settles in lakes and oceans. From our research on plant communities today (see Chapter 5), we know which plant species are more heat or drought tolerant. Mapping the presence or absence of particular species at a given location over time yields a reasonably accurate portrait of the changes in the ecosystems there. In the Sudan, palynologists (those who study pollen) found that records taken from bogs and old lake beds also show a switch between tropical savanna to desert conditions today at the same time indicated by the dust records. Large increases in ragweed pollen coincide with the arrival of Europeans and their woodland clearances on the East Coast of the United States in the 17th Century. The expansion and contraction of range of the alpine flower Dryas octopetala shows the coming and eventual going of the great European ice sheets. Pollen histories are often not as quantitatively specific as isotope records (the connection between exact climate conditions and pollen distributions are a little fuzzy at times) and the layers are often less easy to date than ice cores. Yet pollen histories can reveal many subtle features about how ecosystems and the local environments respond to climate and other disturbances.

There are few limits on how far certain scientists will go to find clues about past climate. Some will root around in piles of plant material stored in desert caves by packrats. These small rodents solidify their nests into a midden with their highly viscous urine. Remarkably, in dry areas such as the Grand Canyon, these packrat mid-

dens can last for tens of thousands of years and contain within them pollen evidence for the local plant life and climatic conditions. They have shown that the American Southwest was much more heavily wooded a thousand years ago. It is the combination of this paleo-vegetation data, the tree ring records of drought mentioned in Chapter 1, and the insights from local archeology that then allows the histories of the local cultures to be pieced together.

In the tenth century, population started to rise in the Four Corners region of the Southwest as maize cultivation arrived from Mexico. The number and density of these Ancestral Pueblo settlements grew, as evidenced by the impressive multi-story cliff dwellings they left behind. However, near the peak of their cultural influence in the 12th and early 13th Century, many sites were abandoned. The coincidence in timing between this, the deforestation, the mega-droughts and the establishment of new sites closer to the Rio Grande valley suggests a strong two-way interaction between human culture and the environment. The forests likely fell victim to a combination of human activity and periodic droughts, and the ability to sustain such population densities likely relied on the forests themselves.

Tracking Ecosystem Impacts

Obvious signs of climate change include a change from one ecosystem to another and in the physical environment surrounding that changes. But careful measurements and clear understanding are needed to be able to link the ecological changes, such as plant disappearances, to the physical climate, such as the temperature and rainfall. This work can be extremely painstaking. Such detail is critical however and includes cataloging and quantifying bio-diversity in various ecological niches and tracking how that changes as a function of year to year variability and eventually long-term trends (as described in Chapter 5).

It appears to be a fact of nature that the most sensitive and fast changing components of the ecosystem are the smallest and hardest to observe such as insects, plankton and parasites. However, these are often key players in controlling the impacts of change on the larger scale species that we are more normally interested in, i.e. the impact of krill abundance on penguin colonies (see Chapter 2 and 5). This requires that long term ecosystem monitoring be very detailed if it is to be useful. In areas where careful long term studies have been done (such as in the cloud forests of Costa Rica, or the dry valleys in Antarctica), changes due to local and large scale climate change have been profound.

It is often only in hindsight that the value of long term records becomes clear, and it is remarkable that many of these records are due to the perseverance and work of only a few determined individuals. In any specific eco-

Camille Holmgren holding a packrat midden in a cave near San Simon, Arizona. The middens from the cave date to about 14,000 years ago, in the transistion period between the last ice age and the Holocene. Pollen from vegetation such as pinon pines and oaks were present at that time, indicating a wetter climate in that region than today.
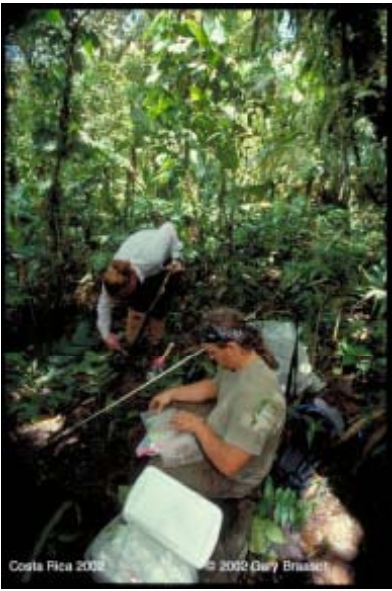
Boone Kauffman and colleague measuring the carbon storage in soils near the Monteverde Preserve in Costa Rico.

system, the impact of climate change will be very individual and thus difficult to generalize to the global scale. Since many ecosystems are not being monitored as closely as they could be, many changes are likely going unrecorded.

Modelers

There are multiple interlocking themes such as the basic cycles of energy and carbon that link the different communities of climate researchers. For instance, the water cycle links the water isotopes measured in the ice cores to the drought reconstructions from tree rings, to the ice measurements at SHEBA and the cloud forest habitat of amphibians in Costa Rica. How do such links get evaluated and quantified? This is where the climate modelers come in.

Some climate models are relatively simple, like models that try to encapsulate the gross energy budget of Earth's total inputs and outputs as discussed in Chapter 6. However, the most common models used to examine climate change on the decadal to centennial timescales are called coupled ocean-atmosphere General Circulation Models (GCMs). These GCMs are developed by around 15 modeling groups from around the world contain much of the physics of weather, ocean circulation and sea ice, all of which is tied together so that changes in one part of the simulated world have a multitude of effects on all the other components. Some newer models are even more complex. Earth System Models (ESMs) as well as including the physics of the GCMs, also simulate the interactions between aerosols, atmospheric chemistry, vegetation and ocean biology. The climate models are well known for the projections described in the IPCC reports (and in Chapter 8). These models involve huge numbers of processes that interact in complicated and non-linear ways. Their inherent complexity can make us uneasy if results are presented as answers that appear to come from a 'black box' whose inner workings are opaque. These are valid concerns, and so it is worth uncovering how scientists develop confidence in the projections of such climate models.

Climate modelers have set themselves a formidable task: To take our knowledge of the equations of fluid motion for winds and ocean currents, the physics of radiation through the atmosphere, and estimates of the effects of clouds, convection, the fluxes that connect the different physical components, and use that knowledge to understand the large scale features of the climate system and their response to external pressures. All these calculations must be done for a system whose key components are in constant motion. This idea to numerically predict weather was first formulated in the 1920s, but it wasn't until the 1960s that computers started to make the large scale calculations feasible. The essential concept is that the atmosphere can be divided up into small chunks (called grid-boxes) that are considered homogeneous and which interact with neighboring chunks through the winds, radiation and other processes. The smaller the chunk, the better the approximation. Since computational power has grown exponentially, so has the detail that can be included in these models.

Weather forecast models include a lot of detail for atmospheric processes, but climate models have to include much more. Climate models need descriptions of land, oceans, sea ice, and, more recently, interactive atmo-

In the early years of climate modeling, all instructions were input into the mainframe using punch cards. Each card was good for one line of code, and a whole program would take hundreds to thousands of cards, all in the exact right order. These cards were saved from an Amdahl V/6 machine used by NASA.
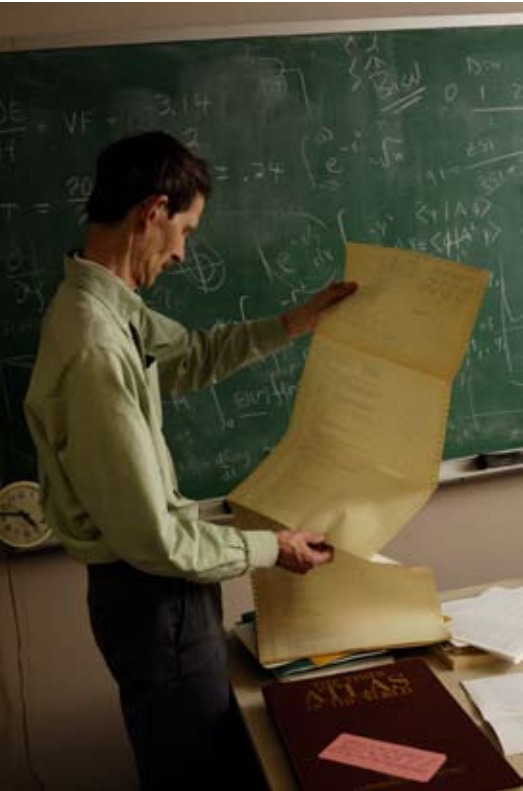
Gary Russell, a climate model developer with NASA, examining old output from an early 1980s era climate model. In the days before graphical displays, the only way to see model results was to read off the numbers.

Allegra LeGrande is typical of a new generation of climate scientists who are using the models to look at past-climate changes, incorporating atmospheric chemistry and isotopes modules for more direct comparisons with the observed data.

spheric aerosols, atmospheric chemistry, and representations of the carbon cycle.

One can divide the physics of climate that we need for models into three classes. First, we use aspects of fundamental physics, including the conservation of energy and mass, calculations of the Earth's orbit, and the distribution of the sun's energy over the Earth's seasons. These basic components are calculated with as much precision as the computers allow. Second, we use physics that is very well known in theory, but must be approximated in some way due to time constraints or complexity . Examples include how much radiation goes through the atmosphere or the specific equations of motion for particles moving within the ocean or atmosphere. Some details get lost, such as the specific absorption of radiation at one particular frequency, or the impact of small gust of wind. But the overall behavior of a system is well captured. Third, we use physics for which we only know empirically measured values. Such phenomena include the formula for calculating evaporation as a function of wind speed and humidity, which is derived from observations of the process in many different environments.

These empirical formulas are called parameterizations. The uncertainty in these formulas accounts for a lot of the differences between the models. However, much of the large scale behavior seen in models is robust and does not depend on the details of the parameterization. Why? Because much of the interesting behavior of the climate system is emergent. For instance, we have no formula for modeling a mid-latitude storm track across the North Atlantic, yet all models show one. The storm track emerges instead out of the complex interaction between the warm tropics, the cold poles and the certain properties of the equations of motion.

Why do scientists use such models? We do not use them just because they are complicated. Rather we use models because they have enough complexity to help explain enormous amounts of what we see in the real world. The confidence we have in the climate models, comes from successful tests they have passed in predicting what is seen in the real world.

So how does that get done? The testing happens at two distinct levels. At the first level individual process are tested; each parameterization, such as the formula for evaporation, can be checked against observations. As the observations improve, the parameterizations can too. At the second level, testing applies to large scale emergent properties; the seasonal cycle in tropical rainfall, the statistics of winter storms, or the response of the atmosphere to an El Niño event. These tests are not directly evaluating any particular part of the model, but rather, the combined effects of all of the components.

The most relevant tests for climate change purposes are those which use natural experiments such as the Mount Pinatubo eruption, to test the sensitivity of the climate to those forcings. There were many observed consequences of this eruption: we already mentioned the subsequent global cooling of about 0.5°C/1°F (Chap-

ter 6), but in addition there was warming in the stratosphere, a decrease in global water vapor, and an increase in westerly winter winds in the North Atlantic. Each of these changes also occur in climate models when we add the observed change in volcanic aerosols as the forcing.

Another example is the drying of the Sahara 5,000 years ago mentioned earlier. Theories suggest this was a natural phenomenon related to slow changes in the Earth's orbit. The key factor is that 6000 yrs ago summer in the Northern Hemisphere was warmer because the Earth was closest to the sun in July (rather than January as it is at present). This made the tropical rain bands move further north, making it easier for vegetation to grow. But complex vegetation dynamics created a non-linear trigger for rapid change (since there is a threshold of rainfall below which vegetation won't grow). Models do show this behavior as the orbit is changed.

The models are not perfect. For instance, the scale of key processes right on the equator is often smaller than the size of the ocean or atmosphere grid boxes. That makes it difficult to simulate El Niño events properly and gives rise to systematic biases in tropical rainfall where they tend to have excess rain on either side of the equator, but not on the equator itself. Yet, despite those problems, the models give very consistent answers for how sensitive climate is to increasing greenhouse gases, or the spatial patterns of ocean temperature variations. Over the last 20 years their match to observations has measurably improved, and as computer resources increase, that improvement is likely to continue.

The most important role for these models is their ability to quantify otherwise qualitative hypotheses and generate new ideas which can be tested against observations. They are extremely flexible tools, and though far from complete, the results so far have been surprisingly successful.

Observations of large scale climate as described above are partial and sometimes apparently contradictory. Climate models can help assess whether this might be because of weather 'noise' or if there is really a significant discrepancy. In that case, both the models and the data need be examined to see whether there is something wrong in the models, or, as is sometimes the case, there was a problem with the data. This works well for resolving current climate conundrums with the amount of observations now available, but this should be just as useful for the larger changes seen in the paleo-climate record. There are additional problems in that case since the interpretation of paleo-data is less clear than for modern measurements. However, coincidentally, many of the new processes now being included in the Earth System Models, such as dust or the carbon cycle, are also the processes that produce the changes recorded in the ice cores or ocean sediment. In one particular example, some models now contain the physics of water isotope fractionation and can be compared directly to the isotopic archives mentioned above. These comparisons allow us to test hypotheses for climate change over a much larger set of examples than was possible even ten years ago, and hence improve our confidence in the models.

The Lingua Franca of Climate Science

The interconnectedness of the climate system and its rise as a coherent field of study is a dominant and integrat-

August 30, 1984

August 8, 1991

These two photos show the Earth's horizon at sunset before and after the 1991 Mt. Pinatubo eruption. In the first picture, the atmosphere is relatively clean and the colors change smoothly above the tops of the thunderstorm clouds. In the second, two months after the eruption, two dark layers of sulfate aerosols at 20 to 25 km above the surface are clearly visible.

Operators on the US Coastguard Healy readying to take a deep sea sediment core. This Jumbo Piston Coring System can take a sediment sample of up to 100ft and works by dropping a 5000 pound lead weight, driving a steel pipe into the sediment.

ing force in Earth sciences. Climate science brings together researchers who drill in ice sheets with those who climb up into tropical forests, those who study cloud microphysics with those who observe deep ocean circulations, those who study plant genomes with those who rock formation. These experts in any other situation might never have had anything to do with each other.

However, we face numerous challenges in trying to communicate across disciplines. Specialized fields tend to have their own jargon, their own journals and their own debates about what is or is not important. Often the researchers specialized in a field will have developed a shorthand for describing a phenomenon - a description that may be at odds with how experts in a different field see that same phenomenon.

A good example of the challenges of multi-disciplinary science and how they can be met is the effort underway to understand the variability and dynamics of the North Atlantic thermohaline circulation (Chapter 3). This effort to understand ocean currents links physical oceanographers with paleo-climatologists and with modelers and theorists who all have separate perspectives derived from the tools and techniques that they use.

Physical oceanographers collect very high resolution data with timescales of a few minutes to a few years. This data is mostly gathered from research cruises and fixed moorings (a tethered line of instruments that go from the sea floor to the surface). The important signals measured relate to ocean eddies, the seasonal cycle and tides. Long term changes over a few decades are measured in tenths or hundredths of a degree. Paleoclimatologists use archives which go back thousands of years to the last ice age or further. They can see much larger changes, sometimes tens of degrees over that longer time span. However, they have a much coarser view in time with one data point every few decades at best, but more usually one data point per century or even longer. Meanwhile, modelers try to reconcile the "micro-data" gathered by physical oceanographers with the "macro-data" culled by paleoclimatologists. But computational limits mean that they cannot model the details as finely as can be seen in the present day observations, nor can they simulate thousands of years of ocean evolution.

Initial mismatches of perspective limited the opportunities for collaboration for many years. However, available observations can now stretch back decades. Meanwhile, some paleoclimatologists have switched their focus the recent Holocene period (the last 10,000 years) and some very high resolution ocean sediment data (down to individual years) is starting to become available. Finally, as computational resources have improved, the simulations of ocean variability now overlap with both direct observations and paleo-data. As a result, each of the groups has started to see merit in the others' techniques and conclusions (since these might now illuminate their own studies) and constructive engagement on theories of ocean change has become easier to achieve.

Consider the following example. About 8,000 years ago, the North Atlantic region experienced an episode of abrupt cooling. The leading hypothesis is that the rapid drainage of what had been a large ice-dammed lake into Hudson Bay reduced the density of the North Atlantic ocean and slowed the heat-transport of the thermohaline

circulation (see Chapter 3). The old lakeshore of Lake Agassiz, a precursor of the Great Lakes we know today, can still be seen through Ontario and Manitoba and can be dated to the same time. To see if this idea is correct, paleoceanographers have analyzed new ocean sediment data to provide evidence of ocean changes at the time. Modelers are trying to simulate the observed changes by adding the fresh water from the lake into their modeled North Atlantic and seeing what effect it has on the ocean density and circulation. The physical oceanographers are using their experience with the complexity of the modern ocean to interpret the paleo evidence and model results. The outcome has been a validation for both the idea and the models. The amount of water that was released when the lake drained is apparently sufficient to affect the circulation, and the temperature and rainfall changes that result match up with what is inferred from the proxy data. Since this episode is the most recent example of a significant shift in the North Atlantic circulation, it has a pivotal role to play in evaluating the importance of ocean circulation changes on climate. Effective collaborations on this topic thus lead directly to effective assessments of potential ocean circulation changes in the future.

More generally, the development of Earth System Models is forcing modeling centers to reach out beyond their core expertise and bring in people who are knowledgeable, for instance, about vegetation responses to climate. This both widens the flexibility of the new modeling tools to encompass a wider set of scientific questions and educates a new community about the usefulness of modeling at this scale. Possibly the most important new set of collaborations will focus on the role of ice sheets and their response to climate. Current GCMs assume that the response times for ice sheets are centuries or longer and so historically, they have not included a dynamic ice sheet component. Recent observations however indicate that ice sheet changes can happen much faster than previously supposed (see Chapter 2) and that uncertainty in that response is dominant in discussions of future sea level rise (see Chapter 8). There are multiple ongoing efforts to improve this situation, and many of the same disciplinary challenges (of scale, language and outlook) discussed above are apparent in this case as well. Given the history it is likely that those challenges will be met, and this will allow for a much deeper understanding of past, present, and future ice sheet development.

To answer our questions posed at the start of the chapter, scientists put themselves to so much trouble because they know how interconnected the system is. They know also that the answers we need can often only be sought after in inaccessible, cold, dirty and difficult environments. Perhaps surprisingly, getting this data is often fun.

A self-portrait of Ken Mankoff at the official South Pole monument in late 2007.