Abrupt Climate Changes: Past, Present and Future

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The Earth's tropical regions are very important for understanding current and past climate change as 50% of the Earth's surface lies between 30°N and 30°S, and it is these regions where most of the sun's energy that drives the climate system is absorbed. The tropics and subtropics are also the most populated regions on the planet. Paleoclimate records reveal that in the past, natural disruptions of the climate system driven by such processes as large explosive volcanic eruptions[1] and variations in the El Niño-Southern Oscillation[2] have affected the climate over much of the planet.[3] Changes in the vertical temperature profile in the tropics also affect the climate on large-spatial scales. While land surface temperatures and sea surface temperatures show great spatial variability, tropical temperatures are quite uniform at mid-tropospheric elevations where most glaciers and ice caps exist. Observational data before, during and after a major El Niño event demonstrate that within four months of its onset, the energy from the sea surface is distributed throughout the tropical mid-troposphere.[4] Thus, the observation that virtually all tropical regions are retreating[5] under the current climate regime strongly indicates that a large-scale warming of the Earth system is currently underway.

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[1] *See* Alan Robock, *Volcanic Eruptions and Climate*, 38 REVIEWS OF GEOPHYSICS 191 (2000), *available at* http://www.agu.org/journals/rg/rg0002/1998RG000054/pdf/1998 RG000054.pdf.

[2] Michael H. Glantz, *Currents of Change: El Nino's Impact on Climate and Society* (Cambridge University Press 1996).

[3] *Id.*

[4] John C. H. Chiang & Adam H. Sobel, *Tropical Tropospheric Temperature Variations Caused by ENSO and Their Influence on the Remote Tropical Climate*, 15 J. OF CLIMATE 2616 (Sept. 15, 2002).

[5] Mark B. Dyurgerov & Mark F. Meier, *Twentieth Century Climate Change: Evidence from Small Glaciers*, 97 PROCEEDINGS NAT'L ACAD. SCIENCES 1406, 1409 (2000), *available at* http://www.pnas.org/cgi/reprint/97/4/1406; *see also* Lonnie G. Thompson, Ellen Mosley-Thompson, Mary E. Davis, Ping-Nan Lin, K. Henderson & T.A. Mashiotta, *Tropical Glacier and Ice Core Evidence of Climate Change on Annual to Millennial Time Scales*, 59 CLIMATIC CHANGE 137 (2002), *available at* http://springerlink. metapress.com/content/t2302533h2415v45/fulltext.pdf; Johannes H. Oerlemans, *Extracting a Climate Signal from169 Glacier Records*, 308 SCIENCE 675, 675 (2005), *available at* http://www.sciencemag.org/cgi/reprint/308/5722/675.pdf.

One of the reasons that high-resolution tropical paleoclimate proxy records are lacking is simply the difficulty of obtaining the ice cores from remote and often very high elevation ice fields. Since 70–80% of the snowfall sustaining most tropical glaciers comes during the regional wet season, tropical ice cores generally contain distinct annual cycles in the stable isotopic ratios of oxygen and hydrogen and concentrations of dust and major ionic species. For most tropical ice fields south of the equator the wet season is centered from December to March, while north of the equator the wet season is generally centered from June to August.

The first long tropical ice cores were retrieved in 1983 from the Earth's largest tropical ice cap, Quelccaya, which is 5,670 meters above sea level (m ASL) in the southeastern Andes of Peru.[6] Because of its dome shape, it is very sensitive to the current increase in the elevation of the 0°C isotherm,[7] and it loses more mass per unit rise of the equilibrium line than steeper alpine glaciers.[8] This sensitivity makes Quelccaya an obvious choice for monitoring changes in both ice mass and ice-cover extent.[9] The retreat of its largest outlet glacier, Qori Kalis, has been evaluated by terrestrial photogrammetry since 1978. These observations, coupled with a map produced from aerial photographs taken in 1963, reveal the changes in ice area and volume over the last 42 years. A sequence of maps documents the rapid and accelerating retreat of the glacier front.[10] Over the last 14 years (1991-2005), Qori Kalis has retreated approximately 10 times faster (approximately 60 meters per year) than during the initial 15 year measurement period from 1963 to 1978 (approximately 6 meters per year). A small proglacial lake that first appeared in 1991 and covered approximately 6 hectares, has grown contemporaneously with the retreat of the ice front and now covers approximately 34 hectares.[11] On the basis of sonar observations in 2004, the lake is up to approximately 60 meters deep.[12] The accelerating rate of retreat of the Qori Kalis terminus is consistent

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[6] Lonnie G. Thompson, Ellen Mosley-Thompson, W. Dansgaard, P.M. Grootes. *The Little Ice-Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap*, 234 SCIENCE 361-64 (1986).

[7] Henry F. Diaz, Jon K. Eischeid, Chris Duncan, and Raymond S. Bradley. *Variability of Freezing Levels, Melting Season Indicators and Snow Cover for Selected High-Elevation and Continental Regions in the Last 50 Years*, 59 CLIMATIC CHANGE, 33–52 (2003), *available at* http://www.geo.umass.edu/faculty/bradley/diaz2003.pdf.

[8] Bryan G. Mark, Geoffrey O. Seltzer, Donald T. Rodbell, and Adam Y. Goodman, *Rates of Deglaciation during the Last Glaciation and Holocene in the Cordillera Vilcanota-Quelccaya Ice Cap Region,* 57 QUATERNARY RESEARCH 287-98 (2002), *available at* http://geog-www.sbs.ohio-state.edu/faculty/bmark/QRMarketal.pdf.

[9] Lonnie G. Thompson, Ellen Mosley-Thompson, Henry Brecher, Mary E. Davis, Blanca Leon, Don Les, Tracy Mashiotta, Ping-Nan Lin, and Keith Mountain, *Evidence of Abrupt Tropical Climate Change: Past and Present,* 103 PROCEEDINGS NAT'L ACAD. SCIENCES, 10536-43 (2006), *available at* http://www-bprc.mps.ohio-state.edu/Icecore/Abstracts/thompson_pnas_2006.pdf.

[10] *Id.* at Figure 1A.

[11] *Id.*

[12] *Id.*

with that observed for six other glaciers in the Cordillera Blanca that have been monitored by the power company ElectroPeru.[13]

The recent and rapid loss of ice on Quelccaya is characteristic of most low- and mid-latitude ice fields and is best typified by Kilimanjaro's three remaining ice fields that have persisted for at least 11,000 years, but have lost 82% of their areal extent since 1912.[14] Aerial photographs taken by Photomap (Nairobi, Kenya) for the Ohio State University team in January 2006 confirm the continued reduction of ice cover.[15]

The chemical and physical properties preserved within glaciers and ice caps also record climatic and environmental changes that provide a longer-term context for 20th century climate changes. Over the past three decades, the Ice Core Paleoclimate Research Group at the Byrd Polar Research Center has recovered cores from ice fields across Tibet and in the Andes. Various aspects of these records have been published, and only recently have they been integrated and published.[16] That paper[17] presents three lines of evidence for abrupt tropical climate change, both past and present. First, annually and decadally averaged oxygen isotopic ratios (^{18}O) and net mass-balance histories for the last 400 years and 2000 years, respectively, reveal that the current warming at high elevations in the mid-to low latitudes is unprecedented for at least the last two millennia.[18] Second, the continuing retreat of most mid-to low-latitude glaciers, many having persisted for thousands of years, signals a recent and abrupt change in the Earth's climate system.[19] Finally, rooted, soft-bodied wetland plants, now exposed along the margins of Quelccaya as the ice retreats, have been radiocarbon dated and when coupled with other widespread proxy evidence indicate an abrupt mid-Holocene climate event that marked the transition from early Holocene (pre-5000 years B.P.) conditions to cooler, late Holocene (post-5000 year) conditions.[20] This abrupt event (approximately 5100–5200 years B.P.) was widespread and spatially coherent through much of the tropics and was coincident with structural changes in several civilizations.[21] These three lines of evidence argue that the present warming and associated glacier retreat are unprecedented in some areas for at least 5,200 years. The ongoing global-scale, rapid retreat of mountain glaciers is not only contributing to global sea-level rise but also threatening freshwater supplies in many of the world's most populous regions.

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[13] Alcides Ames, *A Documentation of Glacier Tongue Variations and Lake Development in the Cordillera Blanca, Peru*, 34 Z.GLETSCHERK GLAZIAL 1–36. (This is ZEITSCHRIFT FÜR GLETSCHERKUNDE UND GLAZIALGEOLOGIE).

[14] Lonnie G. Thompson, et al., *Kilimanjaro Ice Core Records: Evidence of Holocene Climate in Tropical Africa*, 298 SCIENCE 589–93 (2002).

[15] Unpublished paper in preparation (on file with author).

[16] *See supra* note 9.

[17] *Id.*

[18] *Id.*

[19] *Id.*

[20] *Id.*

[21] *Id.*

This global array of ice-core records and glacier observations point to a few key points that we know with certainty: (1) glaciers are disappearing and as they disappear very valuable paleoclimate archives are being lost; (2) the loss of glaciers, often called the world's water towers, in many regions threatens the water resources that are critical for hydroelectric power production, crop irrigation, and municipal water supplies, and (3) at the regional scale, the loss of glaciers, particularly those that are well known such as Kilimanjaro (Tanzania) and Glacier National Park (U.S.), will have a direct impact on tourism and commerce. Moreover, the ice core records, coupled with observations of glacier mass loss, suggest that (1) glaciers, especially tropical glaciers, are "the canaries in the coal mine" for our global climate system as they integrate and respond to most of the key climatological variables, such as temperature, precipitation, cloudiness, humidity and radiation, and (2) the near global scale retreat of glaciers and ice fields at the beginning of the 21st century is strongly driven by increasing temperature although regional climate impacts such as desertification and deforestation may also play a role.

In 1915 Ernest Shackleton stated: "What the ice gets, the ice keeps," but today the retreating ice is giving up long-buried secrets. The burial of soft-bodied plants by the expanding margins of the Quelccaya ice cap mentioned above, as well as the abrupt onset of cool, wet conditions which resulted in the advancing glaciers in the Alps that covered and preserved the Tyrolean Ice man (or Ötzi), who is approximately 5,200 years old, as well as evidence of a sudden climate disruption at many other sites,[22] lead to two important conclusions: (1) during at least the last approximately 5,200 years the Quelccaya ice cap has not been smaller than it is today and (2) the widespread climate event at approximately 5,200 years B.P. was large and abrupt. If such an event were to occur today with a global population exceeding 6.5 billion people, it would have tremendous social and economic impacts. Such events raise some very important questions that humankind must address. These include: Does the abrupt cooling of the climate system at approximately 5,200 years BP mark the transition from the early Holocene warm period to the cooler late Holocene conditions? Do such abrupt (non-linear) events result from linear climate forcing? How might non-linear feedbacks alter the climate system? Is it possible to exceed a critical threshold? If so, should we be concerned about such a prospect in light of the ever-rising concentrations of carbon dioxide in our atmosphere. The 2006 average CO_2 concentration is currently approaching 382 parts per million,[23] a level not observed in the past 650,000 years in the EPICA ice core[24] from Dome C in Antarctica, the oldest ice core yet recovered and analyzed for gas composition.

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[22] *Id.* at Figure 1.

[23] *See* http://www.cmdl.noaa.gov/ccgg/trends/ (last visited Jan. 13, 2007).

[24] Lauren Augustin et al., *Eight Glacial Cycles from an Antarctic Ice Core*, 429 NATURE, 623 (2004).

Large, abrupt climate changes have repeatedly affected much, if not all, of the Earth. Available evidence suggests that abrupt climate changes are not only possible, but are likely in our future, with potentially large impacts on ecosystems and societies. Abrupt climate change can occur when gradual causes, both natural and human-induced, push the Earth system across a threshold. Societies and ecosystems respond more easily to slower and/or better-anticipated changes, so that the potential abruptness and unpredictability of the potential changes should be disquieting. We need to consider the patterns, magnitudes, mechanisms and impacts of abrupt climate changes, possible implications for the future, and where the critical knowledge gaps exist. Obtaining a global array of high-resolution (annual) records is the first step in documenting the abrupt events of the past. Increased knowledge that leads to better understanding is the best way to improve the effectiveness of any response, and research on abrupt climate change can help reduce vulnerabilities and increase adaptive capabilities.

Glacial ice now covers about 10% of the Earth's continental area.[25] Most of the ice (more than 28 million cubic kilometers) blankets Antarctica and Greenland, but around 180,000 cubic kilometers are locked in the mountain glaciers and ice caps of the world.[26] Potential sea level rise due to melting of all mountain glaciers and ice caps is estimated to be approximately 0.5 ± 0.1 meters[27] which would displace more than 100 million people. A very important question arises: Where would these people go?

This leads to three questions: (1) Who will pay? (2) What are our options? and (3) When will we take meaningful action on climate change issues? The first question is the easiest to answer. Initially those who will pay will be those who are least able to do so and least responsible for the change . . . the poor of the world! As to our options, they may be synthesized into three broad categories: (1) ignore the problem, for example, do nothing in particular and allow market forces to work toward a solution, (2) mitigate, for example, get actively evolved to mitigate the production of greenhouse gases, and thereby begin to reduce the future impact of the changes, and (3) adapt. In reality, adaptation to significant climate change is already built into our future.[28] The real question is whether market forces will be able to forge a new path for energy resources as well as improve the efficiency of our energy use. Eventually we will actively reduce our dependence on fossil fuels, because their limited supply will force us to do so. However, as the supply dwindles the demand will grow, intensifying global competition for resources and generating more political instability. Market forces alone will not produce the big switch in energy resources that is required if we are going to significantly reduce

[25] WILLIAM M. MARSH, EARTHSCAPE: A PHYSICAL GEOGRAPHY 475 (1987).

[26] J.M. Church, et al., *Changes in Sea Level*, CLIMATE CHANGE 2001: THE SCIENTIFIC BASIS. CONTRIBUTION OF WORKING GROUP I TO THE THIRD ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 648 (J.T. Houghton et al. eds., 2001).

[27] *Id.*

[28] James Hansen et al., *Earth's Energy Imbalance: Confirmation and Implications*, 308 SCIENCE 1431(2005).

our carbon dioxide emissions. A major challenge for us in the future will be managing the multiple risks that can be foreseen, as well as dealing with the inevitable surprises. For example, it is already too late to save the glaciers on the summit of Kilimanjaro, so the people living in this area must look to adaptation to ensure that alternative water supplies are available after the glaciers are gone and as their climate and environment changes.

A personal view: As I write this essay in my room at the Institute of Tibetan Plateau Research in Lhasa, Tibet, I must say that everything I have learned about human nature, while conducting more than 50 expeditions around the world, points to our innate ability to rise to our best in a crisis! This short word, crisis, has two characters in the Chinese language: wei and ji. Wei, as you might expect, means danger, while ji is a bit of a surprise, as it means opportunity. So in one of the oldest languages we see wisdom from an ancient culture that believed that crises bring opportunities to make things better. Two examples serve to make this point. In Ohio, the Cuyahoga River was so polluted that in 1959 and again in 1969 it caught fire as it flowed through Cleveland. The 1969 fire made national headlines and grew into a crisis that ended the debate as to whether the river should be cleaned up. The answer was obvious but the political will was lacking until the 1969 fire! Since then, the river has been cleaned up and it is now used by both boaters and anglers who catch walleye and pike.[29] Thus, it was not that we could not clean it up; it was simply that we did not have the political will to act until the consequences of our folly forced us to action. A second, larger-scale example comes from the history of soil conservation in the United States. Hugh H. Bennett is considered to be the 'father of soil conservation'. However, back in the 1920s there were many congressional debates about the failed farming practices in the U.S. and the need to change but there was no action. However, change came in the spring of 1935, when Hugh Bennett was in Washington, D.C. preparing for "yet another" congressional hearing on the subject. He knew that Chicago had just experienced a dust storm that dropped 12 million tons of dust from Oklahoma and that it was headed for Washington, D.C.. Bennett delayed the congressional hearing so that during his presentation the dust from Oklahoma fell on Washington and federal policies on soil conservation took an unprecedented 180 degree turn at that moment. The Soil Conservation Act, the first soil conservation act in the history of this or any other nation, was immediately passed by Congress and signed by the President on April 27, 1935.[30]

Unfortunately, the situation with increasing greenhouse gases is different from the local, regional and national problems described above. This is a long-term, global scale problem and the carbon dioxide released today will remain in the atmosphere, affecting our climate for an average of approximately 100 years. The

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[29] GEORGE TYLER MILLER, JR., SUSTAINING THE EARTH: AN INTEGRATED APPROACH 188 (Wadsworth ed., Int'l Thompson Publishing 1994).

[30] Hugh Hammond Bennet-Biography, http://www.soil.ncsu.edu/about/century/hugh.html (last visited Jan. 13, 2007).

atmospheric residence time of CO_2 ranges from 70 to 130 years.[31] Thus, if we continue to behave as we have in the past and wait for the first crisis then we will have built in a series of climate and environmental crises that we will have to address at the same time that we try to reduce further greenhouse gas emissions. Moreover, on the question of climate change, one might ask whether we have the institutions in place to deal with long-term issues like the current accumulation of anthropogenic greenhouse gas into our atmosphere. If we concede that, as so many times in the past, we will wait for the crisis before taking action, then the follow-on question is; What would that crisis have to be? Evidently it was neither the 2003 summer heat wave that killed approximately 35,000 people in Europe, nor the 2004 and 2005 hurricane seasons that plagued the United States.

To conclude on a positive note I believe that we can and will change our actions, because ultimately we will not have a choice in the matter. I have had the opportunity to work with multinational research teams in 15 countries and in some of the harshest environments on Earth. On mountain tops above 20,000 ft, it is cold, windy, oxygen is lacking and food is often in short supply, yet we focus on a goal and work together effectively to attain it. The OSU team has managed to do this over and over. Thus, I have no doubt that the global community can do what will be necessary once we are convinced of the threat and the necessity to address it. However, there is a very important quote from the Reverend Dr. Martin Luther King, Jr. that is directly relevant to global warming issue. It is paraphrased below:

> We are now faced with the fact that tomorrow is today. We are confronted with the fierce urgency of now. In this unfolding conundrum of life and history there is such a thing as being too late. Procrastination is still the thief of time. Life often leaves us standing bare, naked and dejected with lost opportunity. The 'tide in the affairs of men' does not remain at the flood; it ebbs. We may cry out desperately for time to pause in her passage, but time is deaf to every plea and rushes on. Over the bleached bones and jumbled residue of numerous civilizations are written the pathetic words: 'Too late . . .' [32]

For global warming, Nature is the time keeper. It is important that we all do what we can, and do it now![33]

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[31] *See* http://www.ecd.bnl.gov/steve/CDIAC_94/CDIAC.html (last visited Jan. 13, 2007).

[32] Rev. Martin Luther King, Jr., Address at a Meeting of Clergy and Laity Concerned about Vietnam (Apr. 4, 1967), *available at* http://www.oilempire.us/mlk.html.

[33] The OSU ice core records collected over the years and discussed in this paper were collected and analyzed with support from the NSF Paleoclimate and Earth System History Programs and the NOAA Paleoclimatology Program. This is Byrd Polar Research Center Contribution No. 1348.