The Impact of Global Warming on the Distribution of Rainfall: A Historical Perspective

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INTRODUCTION

The changes in rainfall to be generated by the ongoing rise in atmospheric CO₂ will likely have the greatest consequences for humans. This will be especially true for the Earth’s dry lands where water is already in short supply. Isaac Held, recipient of the 2012 BBVA climate prize, has predicted based on theory and model simulations that the tropics will get an even larger fraction of global rainfall and that this increase will be at the expense of the adjacent dry lands. Although simulations carried out in linked ocean-atmosphere models confirm Held’s prediction, they disagree widely regarding the details. Because of this, a group that I work with has set out to complement these simulations with evidence gleaned from past climate changes. By past, I mean changes that have occurred during the last 30 thousand years, a time period where radiocarbon dating allows us to correlate events occurring at different places on the planet. As shown in Figure 1, this period includes the Last Glacial Maximum (28 to 18 thousand years ago), the period of deglaciation (18 to 10 thousand years ago) and the Holocene interglaciation (last 10 thousand years). As I will show, two sets of millennium-long punctuations are particularly instructive. One is an oscillation centered at 14.5 thousand years ago (14.5 kyrs) and the other is the Medieval Warm–Little Ice Age oscillation in the latest Holocene.
Comparison of the records for the isotopic composition of ice from cores drilled through the Greenland and Antarctic ice caps. These records serve as proxies for local air temperature. Also shown are records of the methane content of the air trapped in the ice. As the methane is mixed pole to pole quite rapidly, its temporal variations allow the isotope records at the two ends of the planet to be tightly correlated. As can be seen, during the period of deglaciation air temperatures in the two polar regions were antiphased.

During the demise of the last glaciation, large and abrupt changes in the pattern of global rainfall occurred. These changes appear to have been driven by shifts in the latitude of the tropical rain belt induced by out-of-phase expansions and contractions of the sea ice extent in the two polar oceans. These changes are recorded in three archives: 1) the size of closed basin
lakes, 2) oxygen isotope composition of cave stalagmites, and 3) the ratio of soil debris to marine shells in continental margin sediments. These records make clear that 14.5 kyrs ago the Earth’s tropical rain belt underwent a dramatic northward shift. As a result, the Chinese monsoons strengthened and the southern fringe of Amazonia underwent a pronounced drying, as did the Middle East and the American West (see Figure 2).

**Figure 2**

Documented hydrologic changes that occurred about 14.5 kyrs ago and between the Medieval Warm (MW) and the Little Ice Age (LIA). As can be seen, the latter are in the opposite sense of the former. During the MW–LIA transition, the thermal equator and its associated rain belts were shifted to the south and at 14.5 kyrs, the thermal equator shifted to the north.

One might ask, what does this have to do with the next one hundred or so years? Simulations of the ongoing rise in the atmosphere’s CO$_2$ content show that the Northern Hemisphere will heat about twice as fast as the Southern Hemisphere. Hence, if, as the model simulations suggest, a doubling of CO$_2$ were to warm the Earth by 3.6°C, then the Northern Hemisphere would warm by about 4.8°C and the Southern by about 2.4°C. The extra warming in
the Northern Hemisphere would cause the thermal equator and its associated rain belts to move northward. The question then becomes whether rainfall changes that occurred 14.5 kyrs ago can be used as a guide to those to be generated by global warming.

Once again I turn to historical evidence to answer this question. It is based on rainfall changes that occurred during the Medieval Warm–Little Ice Age oscillation. In this case, the thermal equator appears to have moved to the south. Although the consequences were much smaller in magnitude, as outlined below, they were opposite in sign to those associated with the larger northward shift that occurred at the midpoint of the deglaciation. Since the forces driving these two shifts were quite different, their consistency strengthens the argument that global warming will bring about a repeat of the consequences of the northward shift of the thermal equator. And, of course, we all know that the annual north-south shifts in the position of the thermal equator create a pronounced rainfall seasonality.

**PRECIPITATION ARCHIVES**

The most dramatic and easily understood precipitation archive is the record of changes in the size of lakes that have no outlet to the sea. Of these, the Dead Sea and Great Salt Lake are the best known. The water that reaches them by direct rainfall and by river runoff is lost entirely by evaporation from the lake surface. Hence, at times when rainfall was greater (or evaporation smaller), the lakes increased in size and depth. As the ages of these raised shorelines can be determined by radioisotope dating, chronologies of past lake size can be constructed. The changes in lake size recorded by these abandoned shorelines are surprisingly large. During the Last Glacial Maximum, the Dead Sea was about four times larger and Great Salt Lake about eight times larger than prior to the Industrial Revolution (i.e., before human interference). So large were these lakes that it stretches credibility. Increased rainfall coupled with decreased evaporation fall way short of explaining these expansions.

It turns out that a very powerful amplifier mushrooms changes in rainfall into the observed very large responses in lake size. It involves the dependence of the fraction of rainfall that runs off from the landscape into rivers on the amount of rainfall. For the Great Salt Lake and the Dead Sea drainage basins, currently only about 10 percent makes it to rivers. The rest either evaporates from the soil or is transpired by plants. Were the precipitation in these areas to double, the fraction of runoff would increase by threefold (i.e., from 10 to about 30 percent). Hence, the lakes fed by these rivers would receive six times more water each year!

This powerful amplifier applies not only to closed basin lakes but also to manmade reservoirs and dams. As changes in rainwater input to the catchment basin will be greatly amplified, so too will the amounts of water available for irrigation and electrical power generation. To the extent that
agriculture in the world’s dry lands depends on river water captured in reservoirs, this amplification will increase the impacts of changes in rainfall. In the case of the Nile, these changes will not only impact Egypt’s food supply but also the amount of electrical power generated at Aswan.

Just before the 14.5 kyr northward shift of the rain belts, the Dead Sea and Great Salt Lake were at their maximum sizes. But, as Great Salt Lake had breached its outlet and was overflowing to the sea, it no longer recorded changes in rainfall. However, a number of other closed-basin lakes in the Great Basin of the western US recorded the conditions at this time (see example in Figure 3). A photo of one of these lakes is shown in Figure 4. They were all significantly larger than during the Last Glacial Maximum. At that time the combined area of all the lakes in the Great Basin was about 10 times that in 1850 AD (i.e., before the onset of agricultural diversions).

The response of these Great Basin lakes to the northward shift of the thermal equator was dramatic. They rapidly shrunk from their largest size to their smallest. The Dead Sea underwent a similar shrinkage. Further, the size of Lake Titicaca, a large closed basin lake situated in the northern part of Bolivia’s Altiplano had a similar time history. Fifteen thousand years ago it overflowed to the south creating a three-times-larger lake in the now dry “solar” of the southern Altiplano. Then about 14.5 kyr ago, this megalake dried up. This very wet to very dry transition is the result of a northward shift in the position of Amazonia (see Figure 5).

The record for East Africa’s Lake Victoria merits consideration. Today it overflows into a branch of the River Nile. But prior to the 14.5-kyr event, not only did it cease to overflow but surprisingly it dried up. Evidence for its desiccation comes from four sediment cores. Each bottoms out in a soil. The lake sediment resting on top of this soil has an age of about 14 kyr. Bursts of sound sent down from the lake surface bounce off this dense soil. In this way it was shown that the soil extended to the deepest part of the lake. Hence at the same time that the Dead Sea desiccated, dry Lake Victoria came back into being. This suggests that discharge of the River Nile was weak prior to the northward shift and became stronger afterward.

Less easily understood is the record kept in cave deposits. It is contained in the ratio of heavy oxygen ($^{18}$O) to light oxygen ($^{16}$O) in the calcite deposited on stalagmites. The oxygen isotope composition of the water dripping from the cave ceiling onto the stalagmites matches the annual average for local rain. Thus temporal changes in the isotopic composition of the cave calcite provide a record of those in rainfall above the cave. As monsoonal rain has a quite different isotopic composition than non-monsoonal rain, stalagmites record how the monsoons have changed in strength. An analogy involving the contrast between a drizzle and a thunderstorm will help to understand how this works. A drizzle involves the removal of only a very small fraction of the moisture contained in the parent cloud. A thunderstorm removes a very large fraction. The consequence is that the oxygen isotope composition of the thunderstorm water will be very close to that of the water vapor in the cloud. By contrast, as the vapor
pressure of heavy water ($\text{H}_2^{18}\text{O}$) is slightly less than that in light water ($\text{H}_2^{16}\text{O}$), the drizzle water will be enriched in the heavy isotope relative to the cloud. Monsoon rains are akin to thunderstorms, and non-monsoonal rains to drizzle. Hence, the variations with time in the isotopic composition of cave calcite (i.e., $\text{CaCO}_3$) are related to the fraction of the cave water supplied by monsoon rain.

Figure 3

Map showing the changes in size of Nevada's Lake Lahontan. As can be seen, when the first explorers arrived, four tiny remnants of this once large lake remained. One of these (the twin to Pyramid Lake) has since gone dry as the result of diversions of water for agriculture. Note that just prior to the 14.5-kyr northward shift of the thermal equator, the lake was even larger than it was during the Last Glacial Maximum.
Photo of Nevada’s Pyramid Lake. In the foreground is the pyramid formed by hot springs beneath the lake surface during episodes when the lake was much deeper than now. In the background is Anaho Island. As can be seen, it is ringed with shorelines formed when the lake was much larger and deeper. The highest of these shorelines is just below the island’s summit.

Current location of Amazonia (green) with respect to the seasonal boundaries of the tropical rain belt. Although narrow over the ocean, the rain belt is much broader over land. The red symbols show the locations of four records. Two—the triangle and circle—are for continental margin sediments; the third, a diamond, is for the lake on the Altiplano and the fourth, a square, is for a stalagmite in a now dry cave. Just prior to 14.5 kyrs ago, the rain belt shifted to the south of its present position bringing extra rainfall to the three southern locales. Then, at 14.5 kyrs it shifted back to the north.
Larry Edwards, an isotope geochemist at the University of Minnesota, pioneered the use of this archive. His entée was the development of a highly precise means for determining the age of cave calcites. It is based on $^{230}$Th, a 75 thousand-year half-life product of the radioactive decay of uranium. He hit pay dirt when he obtained oxygen isotope records for precisely dated stalagmites from Chinese caves. These records extend back several hundred thousand years. He found that the ratio of $\text{H}_2^{18}\text{O}$ to $\text{H}_2^{16}\text{O}$ slavishly follows the 20 thousand-year precession of the Earth’s spin axis. The impact of this cycle is to change summer insolation. What Edwards found is that during times when summer insolation in China was stronger than average, the contribution of monsoon rainfall was greater (see Figure 6).

Our interest lies in millennial-long departures from this cyclic behavior. As can be seen in the blow-up of the Chinese stalagmite record for the last 25 thousand years (Figure 6), the deglacial time interval is punctuated by departures from this smooth 20 thousand-year cycle. Of particular interest is the strong intensification of the monsoons centered at 14.5 kyrs ago. Thus, at the same time as the supply of water to lakes in western USA, the Middle East and the Altiplano plunged, monsoon rainfall in China became stronger.

Caves are ubiquitous. Hence, during the next couple of decades, the monsoonal record will be extended worldwide. Indeed, a cave in southern Brazil has already shown that the precession cycle is, as expected, the reverse of that in the Northern Hemisphere. I say “reverse” because at the times when summer insolation is stronger than average in the Northern Hemisphere, it is weaker than average in the Southern Hemisphere. As discussed below, during the Little Ice Age (1300 to 1850 AD) the monsoons in the Northern Hemisphere were somewhat stronger and those in the Southern Hemisphere somewhat weaker than average.

Rivers deliver the products of continental erosion to the sea. The greater their discharge, the more debris they carry. This material is largely deposited along the continental margins where it is mixed with the shells produced by marine plankton living in the overlying water. As the rain rate of shells remains more nearly constant with time than the widely varying supply of debris from rivers, the ratio of erosional debris to marine calcite in the sediment provides a qualitative measure of river discharge.
A comparison of the sediment record for the Atlantic margin off Brazil with that for the Caribbean margin off Venezuela provides convincing evidence for the northward shift of the Amazonian rain forest 14.5 kyrs ago. At this time, off Brazil, the ratio of continental silicate to marine carbonate underwent an abrupt tenfold decrease. By contrast, off Venezuela, the delivery of continental debris underwent a substantial increase.

Of interest in this connection is the record in a cave from the dry lands of eastern Brazil (see Figure 5). A burst of stalagmite growth occurred during the time of Lake Titicaca’s great expansion and came to a halt when this lake desiccated. The drying that terminated stalagmite growth is consistent with the large drop-off in river discharge into the adjacent Atlantic. Both were caused by the northward shift of the Amazonian rain belt.
Sonja Braas, *Forces 31*, 2003
WHAT DROVE THE NORTHWARD SHIFT?

As mentioned at the beginning of this chapter, the shifts in the position of the thermal equator were driven by alternating expansions and contractions of the extent of sea-ice cover in the two polar oceans. When the expanse of north polar sea ice became smaller, that in the south polar region became larger. This caused a net warming in the Northern Hemisphere and a net cooling in the Southern Hemisphere and, as a consequence, the thermal equator and its associated rain belts moved to the north.

The question then becomes what caused the flip-flops in sea-ice cover? The short answer is that the driver is what I refer to as the “bipolar ocean seesaw.” The long answer requires a bit of background regarding how the deep sea is “ventilated.” I say “ventilated” because it is equivalent to blowing fresh air into a stale room. The waters that sink from the surface into the interior of the ocean carry oxygen gas (i.e., O₂). They replace the in situ water that has become stale as the result of O₂ utilization by the creatures — large and small — that live down there.

The ocean is like a layer cake of waters of differing density. As these density differences are primarily related to temperature, the ocean becomes ever colder with depth. The coldest surface waters in the ocean are found in polar regions. Hence the deep sea is “ventilated” from these polar waters.

A complication to this otherwise simple story is that salt is a secondary densifier of sea water. Because of this, the waters destined to sink to the abyss must be both cold and salty. As we shall see, it is salt that drives the bipolar seesaw.

In today’s ocean, about half of the deep sea’s ventilation occurs in the northern Atlantic and about half in the Southern Ocean. The water sinking in the north flows down the deep Atlantic to the tip of Africa where it takes a sharp left and joins the rapidly flowing circum-Antarctic current. This current acts as a very efficient “Mixmaster” blending the Atlantic input with a roughly equal amount of deep water descending along the margins of the Antarctic continent. It is the mixture of these two waters that ventilates the deep Indian and Pacific Ocean.

14.5 kyrs ago the Earth’s tropical rain belt underwent a dramatic northward shift. As a result, the Chinese monsoons strengthened and the southern fringe of Amazonia underwent a pronounced drying, as did the Middle East and the American West.
Sonja Braas, Forces 11, 2002
Although interrupted by a few burps, this mode of deep-sea ventilation appears to have remained steady during the last 10 thousand years (i.e., the Holocene). However, this good behavior was absent during much of the last glacial period. The bad behavior was most pronounced during the period of deglaciation when war between the two deep-water sources was the rule rather than the exception.

Imagine what would happen if a large slug of fresh water were to be dumped into the northernmost Atlantic. It would dilute the salt content of the surface waters to the point where winter sinking could no longer occur. The northern Atlantic would become much like today’s Arctic and the northern Pacific where surface pooling of fresh water prevents deep-water production.

Now, if the north polar region was colder than it currently is, then in the aftermath of the flood, sea ice would form during the next winter. The reason this region is currently ice-free is that heat brought to the surface from the underlying water column prevents ice formation. If the region was covered in ice, solar radiation would be reflected by the ice back to space and the heat carried by any warm water reaching this area would be trapped beneath the ice. Instead of being warmed by the Sun and the Gulf Stream, northern Atlantic winters would be more akin to those in Siberia!

In order to understand what went on at the southern end of the ocean, we must consider what drives deep-sea ventilation. Just as the rate of ventilation of the stale air in a room depends on the strength of a fan, deep-sea ventilation depends on the rate at which heat from the warm upper ocean “diffuses” to the abyss. This heat reduces the density of the resident deep water and in this way creates a “density vacuum”, which allows polar surface waters to sink into the deep sea.

Now imagine what would happen if the northern Atlantic source waters were to be shut down by a flood of fresh water. Unless something boosted the rate of deep-water production in the Southern Ocean, the density vacuum created by the downward seepage of heat would not be filled. Although the details are not understood, there is evidence that the consequent readjustment of conditions in the Southern Ocean reduced the extent of its sea-ice cover. This warmed the Southern Hemisphere reinforcing the southward shift in the thermal equator.

One might ask, what was the origin of the fresh water necessary to squelch deep-water formation in the northern Atlantic? The answer is, of course, the huge ice caps in Canada and Scandinavia. During the course of the glacial period, destabilization of the several-kilometer-thick ice over Hudson Bay caused the ice sheet to collapse, sending an armada of icebergs through Hudson Straits into the northern Atlantic. The melting of these bergs provided the freshwater lid. Another source was lakes formed by the melting of the southern ice front. If the water in these lakes were to breach the ice dam that held them in place, huge amounts of water would escape to the sea.
Sonja Braas, *Forces 12*, 2002
We know from our paleo archives that once turned off, after a lapse of 700 years or so deep-water production in the northern Atlantic sprang back into action causing the sea ice to disappear and the Northern Hemisphere to warm. Perhaps a gradual build-up of salt resulting from a net export of water vapor through the atmosphere from the Atlantic to the Pacific led to this renewal or, perhaps it was something internal to the ocean. We are not sure. But from our records, we know that these turn-ons were abrupt. They happened over just a few years.

During the course of the last glacial period and its demise, the switching on and off of deep-water production in the northern Atlantic moved the thermal equator and its associated rain belt back and forth. I am focusing on the shift 14.5 kyrs ago because its consequences were the most dramatic and also the best documented.

**BUT IS THE 14.5-KYR SHIFT A RELIABLE ANALOGUE FOR WHAT IS TO COME?**

One could argue that the coming CO₂-induced shift will be quite a different “kettle of fish.” First of all, it will be gradual rather than abrupt. Second, even though the Arctic’s sea-ice cover is likely to disappear, there will be no corresponding growth of sea ice in the Southern Ocean. Third, there is unlikely to be a large-scale reorganization of the ocean’s circulation.

There is, however, evidence that supports the idea that we are in for a repeat of the rainfall shifts which occurred 14.5 kyrs ago. It comes from what is known as the Little Ice Age, a 500-year-long cold snap between about 1350 and 1850 AD. During this half millennium, sea-ice cover around Iceland increased, mountain glaciers in Europe and North America reached their largest size in the last 8 thousand years, and the tree line in Siberia retreated to the south. Based on measurements on ice cores from Greenland, the northern cap of our planet cooled by about 1°C. It is referred to as the Little Ice Age because the cooling was only about one-tenth that for the Big Ice Age (i.e., the Last Glacial Maximum). The Little Ice Age was preceded by a 400-year-long period known as the Medieval Warm. It was during this time interval that Eric the Red and his Viking band occupied southern Greenland.

Although smaller in amplitude, the Medieval Warm–Little Ice Age oscillation produced rainfall changes akin (but, in the opposite sense) to those that occurred 14.5 kyrs ago. Studies of sediment cores from small lakes on equatorial-zone Pacific islands suggest that the rain belt moved 500 miles to the south. This conclusion is based on the observation that although lakes on islands within the rain belt overflow to the sea, those on the islands outside its reaches are closed. The sediments in these two types of lake are very different. Hence, cores taken in these lakes record shifts in the latitude of the rain belt.

As shown in Figure 7, stalagmites from a Southern Hemisphere cave in Peru record a strengthening of the monsoons during the Little Ice Age, while those in a Northern Hemisphere
Sonja Braas, Forces 22, 2003
cave in China show a weakening. This is consistent with a southward shift of the thermal equator.

Evidence for changes in the sizes of closed basin lakes between the Medieval Warm and Little Ice Age has proven difficult to come by. As the drying that occurred during the 14.5-kyr northward shift, then it would be expected that these lakes increased in size from the Medieval Warm to the Little Ice Age. The problem is that if the shorelines formed during the Medieval Warm are currently underwater; hence, they are inaccessible for study. In any case, for the Dead Sea there is a suggestion of a pronounced Medieval Warm low stand but its timing is only roughly bracketed. Although no direct evidence exists on the Altiplano, the remains of settlements in the adjacent Atacama Desert suggest wetter conditions prevailed during at least part of the Little Ice Age.

In the case of the Great Basin Lakes, there is direct evidence for low stands of Walker Lake and Mono Lake during the Medieval Warm. The reason that they can be directly documented is that the manmade diversion of the streams feeding these lakes caused their levels to fall, exposing otherwise inaccessible shorelines. Scott Stine of the University of California found a way to directly document the timing of these low stands. He found stumps of Jeffrey Pine projecting above the surface on the West Walker River (see Figure 8). The stumps had more than 100 growth rings. As Jeffrey Pines cannot survive root submergence for even several weeks, these stumps document century-long periods when the river was dry. Radiocarbon measurements reveal that there were two such century-long droughts separated by a few decades. Stine went on to demonstrate corresponding drops in the level of Walker Lake. He did this by collecting the remains of woody plants from the shore zone exposed as a result of the diversion of the Walker River. He showed that during the two droughts the lake shrunk to less than half its pre-agriculture size.

Although little information exists regarding the history of closed basin lakes in China, one of my colleagues, Aaron Putnam, documented that China’s currently largely dry Lake Lop Nor occupied its largest shoreline during the Little Ice Age. It was roughly eight times larger at that time. Further, he radiocarbon-dated the wood from fossil poplar trees found between the dunes of China’s vast Taklamakan Desert, demonstrating that they grew during the Little Ice Age.

The warming of the Earth by manmade CO₂ will create large changes in water availability in the Earth’s dry lands. Yes, there will be winners as well as losers. However, if Isaac Held is correct, the winners will be a minority
So the suggestion is that all of the Northern Hemisphere dry lands lying poleward of the monsoon zone underwent a dry Medieval Warm to wet Little Ice Age change. However, as the evidence remains spotty, more research is needed to confirm this observation.

Although no major reorganization of ocean ventilation occurred during this oscillation, it appears that during the Little Ice Age, the wedge of Southern Ocean that underrides the deep water produced in the northern Atlantic was forced to retreat. Today, and during the Medieval Warm, this wedge extended all the way to Bermuda. During the Little Ice Age, it was absent. But, as were all its other impacts, this change in the ocean was small potatoes compared with those associated with the last glaciation.

There is no consensus as to what drove the Medieval Warm to Little Ice Age climate change. Based on the analysis of air trapped in bubbles in polar ice, we know that neither CO₂ nor any of the other greenhouse gases changed significantly. Modelers have attempted to blame the Little Ice Age cooling on a combination of excess volcanic activity and a weaker Sun, but in my opinion, their case is far from convincing. Instead, I suspect that this oscillation reflects changes of the heat budget of the ocean. So vast is the ocean’s heat content that a slight imbalance between its uptake and release of heat could easily produce the small Medieval Warm–Little Ice Age climate change. Perhaps during the Medieval Warm, the ocean was giving

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**Figure 7**

![Diagram showing stalagmite records for the last 2 kyrs. One is from China (green) and the other from Peru (blue). They look very similar until one notes that the scales are reversed. Hence, during the LIA, the monsoons were weaker in China and stronger in Peru. This is consistent with a southward shift of the thermal equator.](image-url)
off more heat than it absorbed and during the Little Ice Age, it absorbed more heat than it released.

Figure 8

Stumps projecting above the water in the West Walker River (see Figure 3 for location). Each stump has more than 100 growth rings. As Jeffrey Pine is killed by root immersion, this river must have been dry during the century-long growth period. Radiocarbon dating shows that there were two such century-long droughts separated by a few decades. Both fall within the bounds of the MW.
CONCLUSIONS

Based on the similarity between the consequences of the large northward shift of the thermal equator which occurred 14.5 kyrs ago and those associated with the much smaller southward shift which occurred during the Little Ice Age, I suspect that the northward shift to be generated by global warming will bring about similar changes in rainfall in the Earth’s dry lands. If so, the western United States and the Middle East will become drier. The Nile will receive more water. The Amazonian rain forest will shift to the north drying out eastern Brazil and the Bolivian Altiplano. China’s monsoons will strengthen. But I should be humble. The factors influencing where and how much it rains are highly complex. This is why the global models designed to predict these changes give such a wide range of results. But one thing is for sure. The warming of the Earth by manmade CO₂ will create large changes in water availability in the Earth’s dry lands. Yes, there will be winners as well as losers. However, if Isaac Held is correct, the winners will be a minority.
REFERENCES


Model simulations of the response of the Earth to the ongoing global warming predict that the Northern Hemisphere will heat up about twice as fast as the Southern Hemisphere. If so, the thermal equator will undergo a northward shift. By analogy to a shift that occurred about 14,500 years ago, this will strengthen monsoon rains in China, increase the discharge of the Nile, make more arid the dry lands in the 35 to 45°N latitude belt and shift Amazonia to the north. Evidence in support of this prediction comes from the small southward shift of the thermal equator that accompanied the transition from the Medieval Warm to the Little Ice Age.
Wallace Broecker is the Newberry Professor in the Department of Earth and Environmental Sciences at Columbia University and a scientist at Columbia’s Lamont-Doherty Earth Observatory. He is author of over 450 journal articles and 10 books, including the seminal textbook, *Tracers in the Sea*, which he co-authored with Tsung-Hung Peng, and his 2010 publication, *The Great Ocean Conveyor, Discovering the Trigger for Abrupt Climate Change*. Broecker has received numerous awards over his career, including the Crafoord Prize, the Vetlesen Prize, and the 2009 BBVA Foundation Frontiers of Knowledge Award. In 2008, he was awarded the Balzan Prize for outstanding achievement in science. He is a Fellow of the American Academy of Arts and Sciences and the National Academy of Sciences. He is also Foreign Member of the Royal Society, and a Fellow of the American and European Geophysical Unions.

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