"Hiatus" in Global Warming: Paradox and Complexity in Climate Science[a]

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Abstract

The strong *El Niño* event of 1998 marked a transition from the persistent growth in global temperature that had prevailed since the mid-1970s to slower irregular growth since the year 2000. This slowdown has been called a "hiatus." The slowdown occurred even though the growth in greenhouse gas concentrations accelerated after 1998. This apparent paradox has made the hiatus one of the principal public arguments against action on climate change. Two other apparent paradoxes exist. During the hiatus, when the global temperature was close to constant, the Arctic region was warming—and sea ice, land ice, and snow cover were retreating—faster than before. Furthermore extreme weather events were increasing in number and intensity.

In Part 1, this triple paradox is described, as well as the confusion sown in the public mind by the climate's apparently contrary behavior since 1998. In Part 2, the mechanisms to explain the change in surface warming rate that were re-examined and discarded by the climate science community are discussed. The remaining and best explanation is that the oceans began to bury the expected additional warming at depths inaccessible to the atmosphere around the year 2000 (Part 3). Since then, the Pacific Ocean has been in a prolonged cool state—a *La Niña*—that suppresses the global temperature, and *La Niña*-like

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Please see the *Author's Note* at the end of this paper for more information on significant works bearing on the hiatus and its manifestations that have been published since the final submission of the current paper.

weather patterns have prevailed around the world. In addition, around 2004 the mid-Atlantic region and the Southern Ocean also began to route ocean heat to depth.

Part 4 presents evidence that persistent retreat of Arctic sea ice began when the slowdown in temperature growth did; the retreat of sea ice and snow cover is directly related to the acceleration in the rate of Arctic warming. The rapid local warming has consequences for the global climate, one of which might be changes in the equator-to-pole atmospheric heat transport that can affect the frequency, location, and duration of extreme events at mid-latitudes. Part 5 presents evidence that the frequency of extreme weather events—heat waves especially—has increased at temperate latitudes since the hiatus started. There is, therefore, circumstantial evidence, if no rigorous proof, that all three paradoxes are related: they are indicators of a general reconfiguration of the climate system. In Part 6, statistical "teleconnections" between weather patterns at the equator and poles are described, as is the global heat flow system that is thought to account for them.

Part 7 summarizes the evidence indicating that the climate switched to a new state at hiatus onset. Part 8 explores the idea that the unexpectedly rapid sea ice retreat may be changing the thermal boundary conditions governing the equator-to-pole circulation of heat in the atmosphere, forcing the observed persistent *La Niña* bias, as well as the cyclone-anticlycone systems that are responsible for extreme events at mid-latitudes. Arctic warming also modifies the boundary conditions governing ocean heat transport and sequestration in the North Atlantic. A new metastable state that balances Arctic and greenhouse warming with forced ocean cooling might have been created. In Part 9, the implications for public communication and policy are addressed, particularly how global temperature is a misleading indicator of climate risk.

Part 1. Climate's Triple Paradox

T. H. Huxley once said that the greatest tragedy in science is the murder of beautiful theories by ugly facts. For climate scientists, this decade's ugly fact has been that the global average temperature seems not to have changed as much since 1998 as before, although about 28% of the Carbon Dioxide (CO2) added to the atmosphere by human activities, largely fossil fuel burning, has been added since 1998[b], and one would have naively expected the increased CO2 to lead to increased warming. This slowdown has been called, picturesquely but somewhat

b In 1700, the atmospheric CO2 concentration was 277 parts per million (ppm), and in March 2014, it was 401 ppm; industrial civilization has added 124 ppm, of which about 35 ppm (28%) was after 1998.

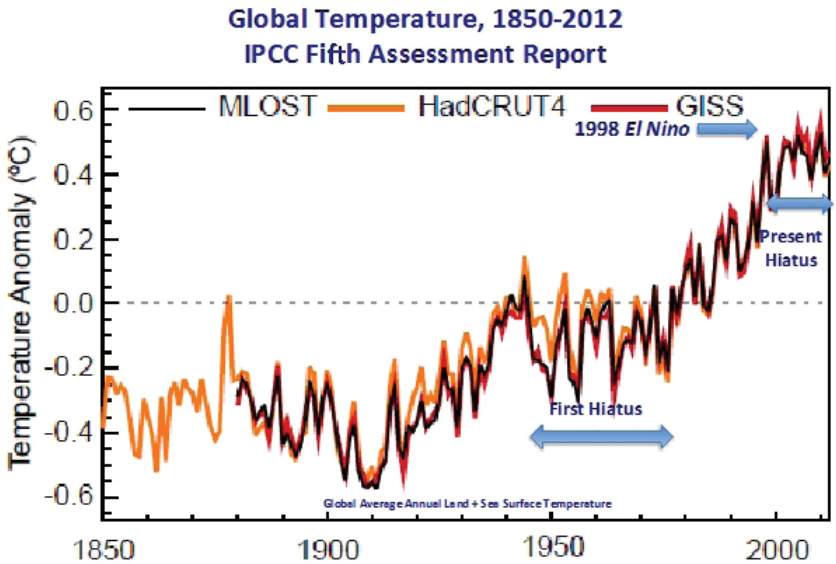

FIGURE 1. Global (land + ocean) temperature history taken from IPCC AR5 (2013). The temperature "anomaly" is the change in temperature relative to the 1850–2012 average, denoted as a dotted line. These curves derive from the three separate data compilations indicated at the top of the figure. They differ in the way they take into account such things as sampling bias. Additional annotation added by the author.

inaccurately, the "hiatus" in warming. Those opposed to action on climate change use the hiatus to argue that if the temperature isn't changing, there is no urgent reason to limit the use of fossil fuels.

Figure 1 shows the Intergovernmental Panel on Climate Change's (IPCC's) most recent version of what all the fuss is about. It shows the history of the global temperature calculated from measurements taken from 1850–2012 relative to the mean established over that period. There was persistent growth from the beginning of the 20th century until about 1945, a "first hiatus" between about 1945 and 1975, steady growth until the *El Niño* of 1997–1998, and the second hiatus in which we presently find ourselves.[c] There is a school of thought that says the only real outlier in this diagram is the large 1998 *El Niño*. If we excluded it, then the flattening of the curve would be less obvious, and

c My colleagues, Naomi Oreskes and Stefan Rahmstorf, have argued to me that the term "hiatus" is misleading, because people might take it as meaning that the global temperature has not changed at all since 1998, whereas in reality it has grown but at a different rate. I will sometimes use "slowdown" to acknowledge the validity of this point, but I will also continue to use "hiatus" as a kind of shorthand describing the period after 1998 because it has become so prominent in the public media, and the climate science community itself has come to use it as a term of art.

the temperature profile after 2000 could be made consistent within statistical error with the profile before the *El Niño*. If global temperature were the only data available, this position would be a natural one to take. However, other evidence indicates that a comprehensive transition in climate state occurred around 1998.

At first, the post-1998 slowdown in warming was of little concern to climate scientists. It wasn't yet a hiatus; it lay within the spread of outcomes of contemporary models of greenhouse warming. As time passed, and the global temperature failed to resume its previous rate of growth, they continued to express confidence that more robust warming would resume, but they got a little more uncomfortable. They began to emphasize that the growth rate had stalled at a record-high level, a level, moreover, that had been set by one of the largest *El Niño* warming events on record. They argued that the different temperature data sets couldn't track year-by-year changes accurately, but if averaged decade-by-decade, each was warmer than its predecessor (which is true).[d] They also said hiatuses happen: one occurred between 1945 and 1975, and hiatuses appear naturally in model forecasts. Some scientists pointed out, in terms only physicists could love, that the climate is a complex nonlinear system and as such is given to abrupt changes in behavior, this hiatus being one. Although this argument might be correct, it did not clarify the public debate.

As the hiatus wore on, it became one of the principal arguments, perhaps the principal argument, against action to limit the emissions of greenhouse gases. Why should we try to limit global warming when the world isn't even warming? This argument, first used for the 1945–1975 hiatus, can stall initiative in its tracks. To outsiders, the scientific response seemed more and more defensive, devious to some. It looked to skeptics as though the climate science community suffered from a mass delusion of its own making. How could it overlook the obvious fact that the global temperature was not changing?

The hiatus had continued beyond its tenth year when the world climate science community began to prepare the Fifth Assessment Report of the Intergovernmental Panel on Climate Change that would appear in 2013 (IPCC AR5, 2013). A sense of urgency took hold. There is nothing like a paradox with policy riding on its solution to stimulate scientific activity. An explosion of research followed on possible reasons for the hiatus, much of which was published, after the deadline to be included in IPCC AR5 and is therefore not discussed in that report. A more recent report prepared by the U.S. National Academy of Sciences and the Royal Society of London[1] updated the state of play.

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d Always keep in mind the hiatus is a period of unusual global warmth.

Several things had become clear. The scientific community had to tackle the issues raised by climate skeptics—and not just for political reasons. For example, there is abundant evidence in the paleo-climate record that volcanic explosions have an important short-term cooling effect and on occasion have triggered changes in climate regime. The explosion of Mt. Pinatubo in 1992 had lofted sulfate aerosols into the stratosphere, and a 2-year mini-hiatus followed. No spectacular Pinatubo-like volcano has occurred since then, but of course there have been many smaller ones. Were their residual aerosols cooling the climate? In addition, humans have been creating a slow-moving volcano of their own. One explanation for the 1945–1975 hiatus was cooling from the sulfate pollution created by the post-war growth of European and North American industry. When industry solved the acid rain problem by controlling sulfur dioxide emissions, the underlying greenhouse warming reasserted itself, and a period of steady temperature growth followed. Could the post-1998 hiatus be like the first one, this time due to the air pollution created by the rapidly industrializing economies of Asia? There are other greenhouse gases besides CO2; could the concentrations of one or more of the others have decreased enough to offset the rise in CO2 forcing? Could natural solar variability be part of the hiatus story? There had been an unusually long and deep minimum in the sunspot cycle during the hiatus and by inference a reduction in the intensity of sunlight reaching the earth. Finally, there are internal climatic cycles connected to the natural rhythms of ocean and atmospheric circulation and their interactions: what is the difference, if any, between the hiatus and the natural climate cycles that have gone on since time immemorial? The irregular variations in global temperature that we do see during the hiatus certainly seem like natural variability; couldn't the hiatus itself be a result of some larger cycle joining in? The most prominent candidate is the *La Niña/El Niño* cycle. The *El Niño*, a vast warming of the equatorial Pacific Ocean that reorganizes basin-wide weather patterns, occurs irregularly every 5 to 7 years. The return to normalcy is called the *La Niña*. The sea surface temperature cools by as much as two degrees centigrade (2 degC) as a *La Niña* progresses, enough when factored into computations of the global temperature to depress it. Perhaps a *La Niña*—a natural cycle—is doing the job.

If all of these effects were put together, would they account for the hiatus? Can better modeling and data explain the hiatus *ex post facto*? In the terms of the trade, climate scientists were asking whether a "convergence" of climate cycles together with the effects of volcanoes and air pollution explains the behavior of the global temperature during the hiatus. Undoubtedly, the list of mechanisms that make partial contributions to climate change will grow, but enough seems to

have been done that people are now beginning to understand how it all adds up.[2, 3] To work at the new levels of precision and completeness required to distinguish the effects of individual mechanisms is already an important improvement in technique.

There has been no hiatus of change in the Arctic and Antarctic. The extended warm period that is the hiatus has set in motion another warming mechanism whose impacts are unfolding dramatically near the poles. The polar climate is evolving so rapidly that the scientific community has had trouble documenting it. A recent analysis indicates that the local rate of Arctic warming significantly exceeds what had previously been expected from current climate models. This result suggests that the Arctic is playing a larger role in the contemporary climate than previously thought, and in particular motivates us to ask whether the profound changes at the poles are responsible for, or connected to, those at lower latitudes.

There is, therefore, a second paradox. Why were the poles warming more rapidly when the global temperature was growing more slowly? Which should the public take more seriously? Polar warming also attracted attention, this time shaded to the other side of the climate debate. Pictures and films of retreating Arctic Ice, stranded polar bears, and isolated Arctic villages in distress abounded. The tug at the public heartstrings seemed manipulative in the extreme to some. Practical people said that an ice-free Arctic Ocean might be bad for polar bears, but it would be a good thing for humans: it would open up the Arctic Ocean to shipping and resource exploration.

There has been no hiatus in weather disasters either. Because the impacts of extreme weather events are so visible, interpretation of their causes has always been an important component of both public and scientific debates. Prove to us, skeptics insist, that the increase in extreme climate events you now claim to be seeing is really due to greenhouse warming. Haven't we always had them? Aren't they just manifestations of natural climate cycles? Now, you will not find a single climate scientist saying that the time and place of an individual extreme event—a heat wave, drought, flood, or storm—can be predicted from global warming models.[e] But they have been saying for a long time that an increase in occurrence or intensity is the kind of thing their models would lead you to expect. Recently, climate researchers have begun to cite firmer evidence that this is happening. But honesty compels them at the same time to

e There is good reason for this. No giant set of master equations exists that describes how to go from a change in the drivers of climate change to a specific heat wave, for instance. Even if there were, the equations would be of the nonlinear type that produces chaotic results, so the best one could do when connecting one set of chaotic equations to another would be a statistical description.

admit that extreme events were part of natural climate cycles before humans started adding to greenhouse warming. No wonder ordinary citizens are tempted to ask: "Why tell us this? Come back when you have made up your minds. Besides, explain why there be should be more extreme events now when the global temperature is increasing more slowly than before." The public can be forgiven if it is confused. The fact of the matter is that climate science is faced with explaining a triple paradox. The paradoxes are related: the changes in the rates of temperature increase and Arctic sea ice retreat and the increase in extreme weather events all started at about the same time. One wonders whether any one of these paradoxes can be resolved without resolving them all. Until the triple paradox is explained there is little chance of untangling the public debate. This is the story traced out here.

Part 2. Aerosols and Sunspots

"Global warming" is a familiar term. People have gotten used to the idea that if we add carbon dioxide to the atmosphere the world will get warmer. The temperature will go up. Scientists use a vast modeling infrastructure to forecast how climate is expected to change in the future at every place on earth, yet of all this knowledge their public communication focuses on a number that only a physicist could love—the global average surface temperature. They then compare the same models, now applied to the past and current climate, with the number gotten from averaging millions of temperature measurements from land and sea over the entire earth—the measured global surface temperature. As everyone knows, the temperature varies from place to place, season to season, day to day, and from hour to hour, but if you average these millions of diverse measurements, you get a single magic number-one that conveys the misleading impression that the world will warm up uniformly. If these highly averaged modeling and measurement numbers agree, it is one sign of scientific success. However, the surface temperature is an imperfect index of a more fundamental quantity—the balance of incoming and outgoing radiation that determines whether energy is added to or subtracted from the climate system.

Radiative Forcing

Here the concept of radiative forcing is introduced so we can get an idea of the comparative sizes of the mechanisms that are causing climate change. *Radiative forcing* is the net radiant energy flux falling on a square meter at the earth's surface. Its units are Watts per square

meter, or W/m^2. According to IPCC AR5, the growth in atmospheric CO2 concentration accelerated after the year 2000 and is now the fastest since measurements began in 1957. CO2 forcing now increases at the rate of 0.27 W/m^2 per decade, which implies that it increased by 0.48 W/m^2 over the 18 years since 1998 when the hiatus began. This number scales the hiatus problem. One way to slow the growth of global temperature would be to find other mechanisms that reduce the energy flux by comparable amounts and ask whether acting separately or in concert they can account for the observed relatively constant temperature profile. This is the basic goal of the convergence program.

We should be careful. Carbon dioxide is responsible for only 60% of the forcing caused by humans. The next most important anthropogenic greenhouse gases are methane (0.54 W/m^2 in 2005), the chlorofluorocarbons responsible for the Antarctic Ozone Hole (0.39 W/m^2 in 2005), and nitrous oxide (0.18 W/m^2 in 2005). Perhaps their concentrations decreased during the hiatus. A study by James Hansen and his colleagues[4] eliminates this possibility: the net forcing from all the greenhouse gases added by humans grew at a steady pace during the hiatus.

Next, mechanisms are discussed that act to cool the surface of the earth in hopes of identifying what might be keeping the global temperature from growing as much as before. These mechanisms include volcanoes and air pollution, and solar variability.

Cooling from Volcanoes and Air Pollution

If the ocean possesses tremendous inertia, the atmosphere has very little. It can respond quickly to small changes in the balance of incoming solar radiation and outgoing infrared radiation that determines surface temperature. Scientists learned this in a graphic way in 1992 when Mt. Pinatubo exploded and set a plume of volcanic ash and gases high in the stratosphere. Among the plume components was sulfur dioxide (SO2)—the main culprit in creating acid rain. When SO2 arrives in the stratosphere, it sparks the creation of aerosol particles that, acting like little mirrors, reflect sunlight back into space. Pinatubo's aerosols remained in the stratosphere for about 2 years, and for that period of time the atmospheric warming rate slowed down, only to pick up again after the aerosols gradually disappeared.

Cutting off even a little sunlight makes a difference to the upper ocean. Sunlight penetrates to a depth of about 100m, so the surface layers of the ocean quickly respond by cooling when the solar radiation entering them is reduced. As we will see, the "Pinatubo effect" appears in the record of upper ocean energy content following the three major volcanic explosions that took place since 1958.[5] Now, there haven't

been any big volcanic explosions during the hiatus, but could all the little ones have affected the climate during the hiatus? Susan Solomon and her colleagues contrasted the "colossal" Pinatubo-like events with the many smaller ones that occur all the time. Her team found that they are creating a variable but persistent background layer of cooling stratospheric aerosols.[6] This layer contributes cooling of about –0.1 W/m^2, large enough to be included in climate models, but not large enough to account for the hiatus by itself.

Is there another source for a rise in sulfate cooling that could offset the continually increasing CO2 forcing? Industrial society is creating a slow-moving volcano called *air pollution*.[f] There is no explosion, so the pollution is not lofted to the stratosphere but stays in the lowest layer, the *troposphere*, where it is rained out in days or weeks rather than 2 years. A principal component of tropospheric pollution is, once again, SO2, which when converted to aerosols in combination with other pollutants, acts to reduce the intensity of sunlight at the earth's surface. As anyone can see, air pollution reduces the brightness of the atmosphere. It also seeds clouds, which do the same thing, so SO2's effects depend on local meteorology as well as the other pollutants in the atmosphere where it is emitted.

Sulfate pollution may explain the major hiatus in warming that occurred between 1945 and 1975. During that period, increasing SO2 emissions from the rapidly growing economies of North America and Europe almost completely counteracted the greenhouse warming from the CO2 from the same combustion sources. Since the aerosols reduce the intensity of visible sunlight near the earth's surface, atmospheric brightness should decrease when there is pollution. The measurements of visible light intensity during this period show dimming, consistent with the idea that pollution was reducing the warming rate. When North America and Europe brought their acid rain problem under control in the mid-1970s, sulfate cooling diminished, and the greenhouse warming that had always been there reasserted itself in the temperature record. The global surface temperature then increased continuously until the *El Niño* of 1997–1998 kicked off the hiatus.

This example made it natural to ask whether the present hiatus is like the previous one—all the more so because of the unprecedented rate at which China has been building coal-burning power plants in the past

f Air pollution is generated where human activity is intense, but winds carry it over intercontinental distances. Traces of pollution are everywhere. Layers of pollution are found in the atmosphere above the central Pacific, far from land, and in pristine Arctic and Antarctic snows. Satellite observations and observations of "earthshine" (i.e., the sunlight reflected from Earth onto the dark side of the moon) show that reflecting aerosols are distributed over large areas of the earth. Because pollution is now widespread, it affects the energy balance of the atmosphere and must be included in models of the climate.

two decades. Kauffman et al. 2011[7] pointed out that Chinese use of coal, a major source of sulfate pollution, rose dramatically after the year 2002. Between 2003 and 2007, Chinese coal consumption doubled and accounted for fully 77% of the 26% increase in world SO2 emissions that occurred during this period. That 4-year increase in SO2 supplied –0.06 W/m^2 cooling (without taking into account cloud amplification). However, it was temporary. The world has indeed learned from its acid rain experience. By 2006, China's efforts to reduce SO2 emissions began to bear fruit, and world SO2 emissions resumed their previous downward trend a few years later.[8] That is the good news. The bad news? Chinese coal consumption increased by another 50%, and now exceeds the rest of the world's put together[9]; and the CO2 warming is not being counteracted by the SO2 cooling that accompanied it the last time around when North America and Europe did it.

The Long Solar Minimum

Sunspots, or rather the lack of them, created a lot of attention during the hiatus. As is well known, the number of spots on the Sun's surface waxes and wanes with an 11- to 13-year cycle, a cycle that had been documented since the early 1600s when Galileo first observed them with his telescope. When the hiatus started in 1998, the sunspot count was increasing; the peak—"solar maximum"—was reached in 2001, and thereafter the sunspot count underwent an unusually deep decline. There was even a time, around 2008, when the sun had no spots. This situation looked ominous to experienced observers because the precursors that usually mark the beginning of the next cycle were not present. This unusual situation brought up associations to the period 1645–1715, when there were virtually no sunspots, the so-called Maunder Minimum, the coldest part of Europe's Little Ice Age. It was natural to ask whether the cooling needed to explain the hiatus was occurring because the Sun was putting out less sunlight. Eventually, the sunspot count started to increase, and by 2010, it appeared that the solar cycle was on its way to another maximum. In the meantime, an important recalibration of the measurements of the sun's light intensity had been completed.[10] A series of satellites has measured the intensity of the sunlight reaching the earth with exquisite precision for four decades. The total solar irradiance (TSI), the rate solar radiant energy falls on the earth's surface, has proven to be remarkably constant. However it does vary by about 0.1% peak to trough over the solar cycle. When the hiatus started in 1998, TSI was increasing; it peaked at the 2001 solar maximum, and then declined. The smooth decline observed from 2001 to 2010 amounted to a decrease in forcing of

–0.18 W/m^2, again large enough to be included in models, but its time profile cannot account for the global temperature observations.

An even more fundamental reason exists as to why the hiatus was not due to sunspots, or air pollution for that matter. The most rigorous measure of the rate of climate change is the small but persistent imbalance between the rates of absorption of visible sunlight and the escape of long-wave infrared radiation measured at the top of the atmosphere. James Hansen and his colleagues at the Goddard Institute of Space Studies argued that the earth was absorbing energy, about 0.56 W/m^2, during the solar minimum period[11]; both sunspots and air pollution would have reduced the energy flowing into the climate system. Similarly, Loeb et al.[12] found that the climate system had been steadily accumulating energy at a rate of about 0.5 W/m^2 between January 2001 and December 2010. They found that the difference in incoming and outgoing radiation at the top of the atmosphere and the increase in ocean heat content were mutually consistent within observational error, confirming that most of the radiant energy driving climate change ends up in the ocean.

Part 3. Burial at Sea

The oceans cover 70% of the earth's surface, so measurements of sea surface temperature dominate the computation of the global surface temperature. We can pretty much understand the hiatus if we can understand why the sea surface temperature increased more slowly during the hiatus than in the period preceding. A flurry of publications that started in 2013 and 2014 has brought us close to the answer: the oceans began to bury more heat in their deeper layers after the year 2000. There are only a few places where the combination of prevailing wind stress, evaporation, and the geographical particulars of ocean circulation allow warmed surface waters, normally lighter than the cold waters below, to sink deep beneath the surface. These include the Western Pacific, the mid-and high latitude North Atlantic, and the circumpolar Antarctic Ocean. All three regions have been sequestering heat. The new observations make it clear that we are observing a comprehensive regime change. The difference between pre- and post-1998 is particularly striking in the Atlantic Ocean heat content and in the tropical Pacific trade winds that drive the *La Niña/El Niño* cycle.

La Niña/El Niño

The global temperature record leading up to 1998 gave no clue a sudden slowdown in warming would occur. The hiatus started with a bang—the 1998 *El Niño*, one of the largest sea surface warming events

of its type on record, followed by a pronounced cooling that lasted for 2 years before warming resumed, but at a smaller rate than before.

The *La Niña/El Niño* cycle[g] is the most pronounced of the climate cycles that vary over the decadal time scales of interest here. Cane and Zebiak created the first model of it in 1985,[13] and networks of moorings were subsequently set up to monitor its development in the equatorial Pacific, Atlantic, and Indian oceans. The cycle is the largest and strongest in the Pacific, and this ocean is the subject of most studies of it. Figure 2 is a vertical cross-section at the Pacific Equator, looking northward, with the Peru to the right, and Indonesia/Australia on the left. We start our description with the *La Niña* phase, which is the more "normal" situation and, as we will see, the one that has been the most prevalent during the hiatus. Imagine that we can follow a parcel of cold water as it first wells up to the surface off the coast of Peru. The trade winds push our parcel westward, and as it moves, the tropical sun heats its top layer. Our parcel expands a tiny amount as it is heated and its exposure pushes up the sea level. Our parcel is following behind others that started their journeys earlier and warmed more; the net result is that the trade winds have to push our parcel up hill. Eventually the trades push it to the Indonesia/Australia coast where it has nowhere to go. It lingers in the Indonesian "Warm Pool," which satellites verify is the warmest and the highest spot in the Pacific.

Now one of two things can happen. In a *La Niña*, the surface waters are forced below because they have nowhere else to go, carrying to depth much of the thermal energy they acquired during their travel across the Pacific. Their heat is now temporarily sequestered, their energy unavailable to the atmosphere and sea surface for some time to come. But sequestration fails intermittently. From time to time, as the warm pool continues to heat up and rise, the trade winds diminish to the point where they can no longer push the water "uphill." Gravity then causes a spectacular "avalanche" of warmed surface water "downhill," eastward across the Pacific until a few months later, it encounters the west coasts of North and South America. Tropical surface waters that were heated once in their westward trip across the Pacific are heated more on their return trip back to South America. The sea surface temperature and the sea surface itself rise across almost the entire tropical Pacific. This is the warm *El Niño* phase. Because the warm water

g In the climate science world, what we have called the *La Niña/El Niño* cycle is called the *El Niño/Southern Oscillation* (ENSO) because the variations in ocean temperature are coupled to variations in atmospheric pressure; the warm *El Niño* phase goes together with high surface air pressure in the Western Pacific, whereas the cold *La Niña* goes with low air pressure. We have chosen our unconventional name because it emphasizes the cyclic nature of the ocean temperature variations.

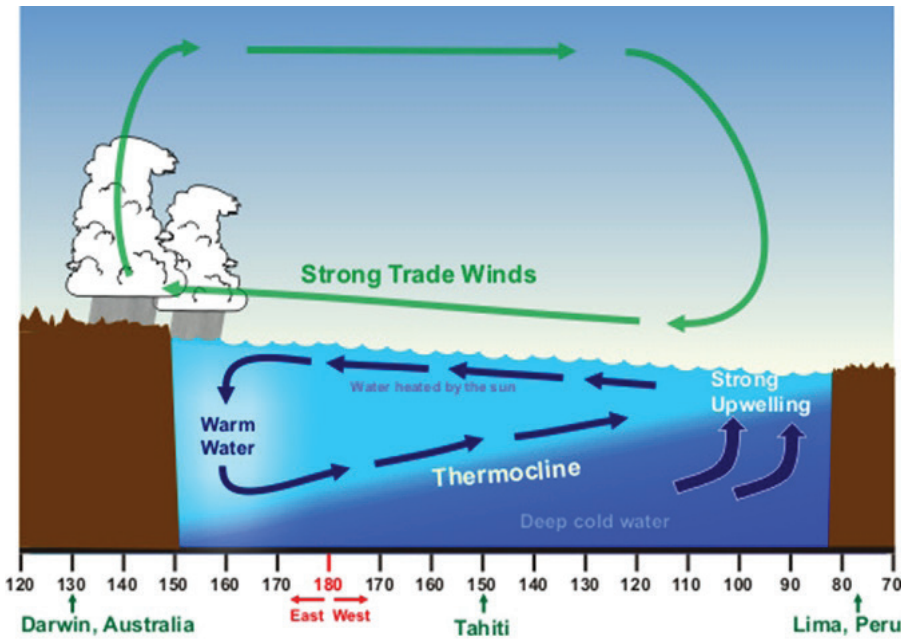

FIGURE 2. In the *La Niña* phase (above), trade winds in the tropical Pacific blow westward, causing warmed surface water to pile up in the Western Pacific off the coast of Asia. The warm water plunges to depth there and pushes cold water up in the Eastern Pacific. When the trade winds relax, gravity causes a rush of the piled-up warm water back across the Pacific until it encounters the west coasts of North and South America. This is the *El Niño* phase. Both the sea surface temperature and the sea surface itself rise across almost the entire tropical Pacific during an *El Niño*. Because the warm water often arrives at the Americas around Christmas-time, Peruvian fishers gave it the name *El Niño*, for the Christ child. The Walker circulation is the green circulation loop in the atmosphere; the trade winds are its surface component manifestation. Image: U.S. National Weather Service Jetstream.

often arrives off the coast of Peru around Christmas time, Peruvian fishers gave it the name *El Niño*, for the Christ Child. The orderly scientific mind gave the opposite phase the name *La Niña*.

The difference of the incoming solar radiation and outgoing long-wave infrared radiation fluxes at the top of the atmosphere provides an estimate of the basic rate at which radiant energy is being invested in the climate system. In general, the earth tends to gain more radiant energy during a *La Niña* and less during an *El Niño*.[14] The energy carried to *La Niña* sequestration cools the sea surface and consequently reduces the emission of outgoing long-wave radiation. However, solar heating remains the same so the climate system gains energy overall. By contrast, an *El Niño* event contains the seeds of its own dissolution, as

its warmer surface waters radiate more long-wave infrared to space as they spread across the Pacific. In fact, the super *El Niño* of 1998 was followed by a 2-year phase during which the sea surface temperature was supercool relative to before. The deeper waters had yet to show warming, which commenced around the year 2000.

What goes on at the equator does not stay at the equator. A switch from *La Niña* to *El Niño* is marked by a vast reorganization of the sea surface temperature across the entire Pacific Basin. The Pacific covers 46% of the earth's water surface, about one-third of its total area, and is larger than all the world's land area combined. The difference in SST between an extreme *La Niña* and an extreme *El Niño* can be as much as 8 degC in places; a good *El Niño* can temporarily increase the global temperature by 1 to 2 degC. A switch between phases also reorganizes the atmosphere's jet streams and their associated storm tracks. In an *El Niño*, the equatorward of the two—the so-called subtropical jet stream—blows west to east in a more or less straight line, pushing storms generated in the Central Pacific directly at the American coasts. Californians call the sequence of storms they get during an *El Niño* winter the "Pineapple Express" because they come directly from the ocean around Hawaii. By contrast, in a *La Niña*, the poleward of the two jet streams becomes lazy and folded and generates storms across middle America by bringing colder Arctic air into collision with warm moist air from the Gulf of Mexico to the south. It also tends to generate drought in western North America.

The tropical Pacific trade winds, whose behavior conditions the *La Niña/El Niño* cycle, changed character just before hiatus onset. According to a remarkable new analysis, between 1920 and 1998 the stresses exerted on equatorial ocean waters varied every 25 years or so between predominantly *El Niño* and predominantly *La Niña* biases, corresponding to the climate cycle known as the Pacific Decadal Oscillation that was first documented in SST measurements. The trade winds weakened during the 1998 *El Niño*, as one would expect. Here is the interesting point: the trade wind system developed a strengthening *La Niña* bias[15] that continued to develop without letup to at least 2015. By 2012, the size of this stress reached twice the maximum achieved in the previous 78 years. The inference is that warmed ocean waters were being forced to depth beneath the western Pacific warm pool.

If in tangled human affairs it is wise to follow the money, in complicated climate affairs it is fundamental to follow the energy. Until about 20 years ago, oceanographers had little idea how much heat was going into the depths of the ocean. Satellites measured the temperature at the sea surface, but what was going on beneath the surface was basically hidden. The biggest change came in the year 2000 with Project ARGO,

today an international system of some 3,900 robotic floats, small buoyant canisters that wander the oceans at depths down to 2,000 meters. Every 10 days or so, the floats are commanded to rise to the surface to broadcast their temperature, density, and salinity data to satellites overhead. It was ARGO that told us how much energy the oceans were taking up and it is ARGO that is beginning to tell us where that energy is going.

Meehl et al.'s[16] model analysis suggested that the oceans would take up heat during hiatus episodes. Balmaseda et al.'s[17] time history of ocean heat content (OHC) shown in Figure 3 reveals the different responses to volcanic cooling, the 1945–1975 hiatus, and the super-*El Niño* of 1998. The three major volcanoes that erupted since 1958, denoted by vertical yellow stripes, caused immediate decreases in the heat content of the shallow ocean, as one would expect since volcanic aerosols reduce the solar energy penetrating the top 100 meters of the ocean. The OHC time series also includes the second half of the 1945–1975 hiatus: here, the heat content contained in the ocean layers above 300m, 700m, and 2000m all tracked one another, just as they did following the volcanoes. In short, little change occurred in the apportionment of heat among the three layers following the volcanoes and during the 1945–1975 hiatus. The layering of heat changed dramatically once the present hiatus had started. The 1998 *El Niño*, denoted by the vertical green stripe, was followed first by a slight uptick in heat content and then a reduction, as would be expected because of the expected temporary increase in outgoing long-wave radiation loss after the *El Niño*. Then a striking change[17] occurred in both the rate of change of heat content and its apportionment among the layers beginning around the year 2000. The heat content in the upper 300 meters (black curve; Figure 3) increased slowly during the hiatus, as had to be the case since the global surface temperature did not increase much. What is different is the large, persistent increase of the heat content in the deeper layers. The heat content above 2000m (purple line; Figure 3) quadrupled between 2000 and 2010. The important point is that even though ocean surface warming slowed, energy was being added to the climate system during the hiatus.[h] Volcanoes, sunspots, and pollution cannot do that and, as the record shows, did not do that. The subsurface increase in energy content is what one would expect from the

h The warming rate corresponding to this removal of surface ocean heat, which can be calculated from the slope of the purple line (Figure 3) and the area of the oceans, was about 1.1 to 1.2 W/m^2 over the ocean. Given that the oceans comprise 70% of the surface area of the earth, this translates to 0.84 W/m^2 over the entire globe. The rate at which energy was being taken to depth (0.84 W/m^2) is more than enough to counteract the 0.43 W/m^2 increase in CO2 forcing that occurred during the hiatus. It even seems a little large.

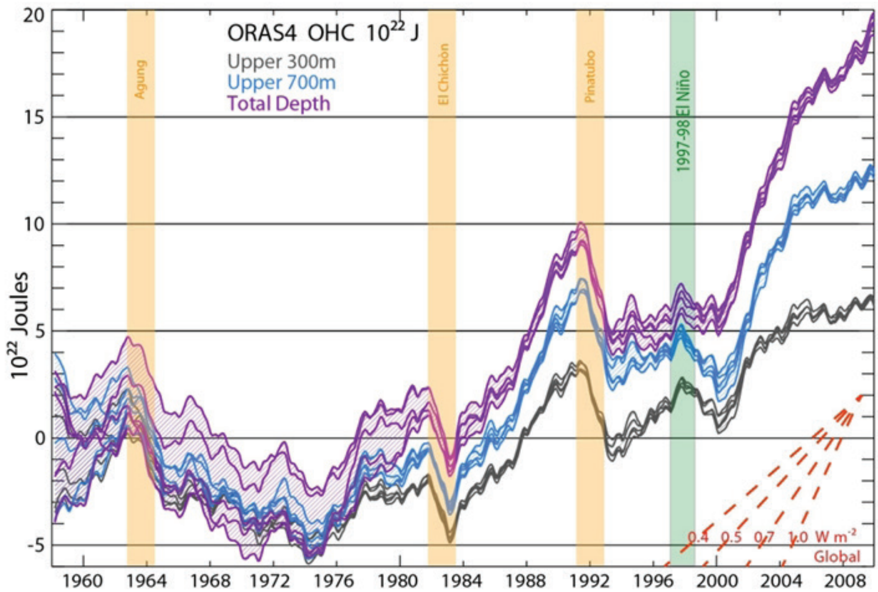

FIGURE 3. Balmaseda et al.'s time history of the heat content of the global ocean, (1958–2010) assembled and integrated by a numerical model from a variety of *in situ* measurements and, after 2000, the more complete data acquired by the ARGO system of robotic floats. The black line denotes the OHC contained in the 0m–300m layer; blue, 0m–700m; and purple, 0m–2000m, the depth limit of ARGO. When the lines track one another, as they do following the three large volcanic eruptions (denoted by yellow vertical bars), all the changes are taking place in the upper ocean. When the lines diverge, as they do after the year 2000, heat is being conveyed to the deeper layers. The surface warming period from 1975 to 1998 was a low sequestration state, although the heat content increased.

behavior of the tropical Pacific trade winds, which had been creating a persistent *La Niña* bias since 1998, and Balmaseda et al. argued that *La Niña* heat sequestration dominated the behavior of the global OHC.

So is the *La Niña* the whole story? Kosaka and Xie[18] produced a heuristic calculation that suggested it might be. They slaved a global climate model to the observed history of sea surface temperature over the tropical Pacific. Even though their surface temperature prescription was limited to 8.2% of the globe, their calculation reproduced the observed global temperature for the period 1970–2012, which included the end of the first hiatus, the period of warming before 1998, and the present hiatus. Moreover, their slaved model captured major seasonal and regional characteristics of the hiatus, including the winter cooling in northwestern North America and the prolonged drought in the

southern United States.[i] This should not be a surprise because the *La Niña/El Niño* cycle has been observed to have worldwide impacts, so forcing the model to have an *El Niño* or *La Niña* at the equator is likely to force the larger pattern as well. If this model result were to be the whole story, the western Pacific would be the primary place where warmed waters are sent to depth. It is not the whole story.

One of the twentieth century oceanography's great achievements is a conception: the "great ocean conveyor belt," the thousand-year worldwide circulation pattern wherein warmed surface waters plunge to depth to drive deep ocean currents that complete a global circuit when they resurface elsewhere. The conveyor belt is the primary way the oceans redistribute heat. There are specific places in each ocean where surface waters sink—the Western Pacific around Indonesia being only one. There, geography blocks the way and forces the waters downward. Surface waters can also sink if something makes them denser and heavier than those below, which happens when they are saltier. The classic case in point is the so-called Atlantic Meridional Overturning Circulation (AMOC), the North Atlantic's link in the great ocean conveyor belt. Picture the Gulf Stream carrying warm waters across the Atlantic from the Caribbean toward Northern Europe. As the Gulf Stream splits and part proceeds northward, the combination of wind, temperature, and atmospheric vapor pressure leads to significant evaporation, which leaves the remaining surface waters saltier, cooler, denser, and prone to sink. When it arrives further north at the Greenland and Labrador seas, it is blocked geographically; it collides with waters flowing southward from the polar sea; its motion stalls; winds from the Pole drive evaporation; and the water sinks to the bottom. The so-called North Atlantic Deep Water is formed in these two places.

Chen and Tung[19] contrasted the time histories of OHC depth distribution before and after the hiatus in all the oceans. Integrated over the globe, the total ocean sequestered much more heat after 1999 than before. The post-1999 heat found between 300m and 1500m depth would have continued the previous rate of surface temperature increase had it stayed between 0m and 300m depth. Chen and Tung also attacked the geographical issue in dispute by presenting separate OHC time histories for the Atlantic, Pacific, Indian, and Southern oceans; in particular, they contrasted the Atlantic and Pacific's OHC depth distribution

i Agreement between observations and a slaved model will not settle the public debate. This model treats the *La Niña/El Niño* cycle as an externality. It tacitly accepts that the cycles that have ruled seasonal and inter-annual climate for thousands of years have not been changed by the advent of anthropogenic greenhouse warming. Skeptics are likely to say, with some justification, something like: "Tell us why what you are observing isn't all natural cycles, just as your calculation assumes. Tell us why we should go to great expense to change what humans are doing."

averaged over the 13-year periods before and after the hiatus began. The Western Pacific did absorb more heat than average between 1999 and 2012 and less between 1985 and 1999, but so also did the North Atlantic and the circumpolar Southern Ocean. The Pacific warming was confined to shallow waters, whereas warming went much deeper in the Atlantic and Southern oceans. Chen and Tung then examined the role of the AMOC, focusing on salinity and OHC data in the sub-polar Atlantic between 45 and 65 degrees north latitude. A large increase in salinity developed between the years 2000 and 2004 and then held constant until the end of their data set in 2012. There can be no better indicator that surface waters were being prepared to sink. By contrast, no Atlantic salinity anomaly existed in the period preceding the hiatus. Although they did not emphasize the fact, Chen and Tung found that the circumpolar Southern Ocean began to take up heat around the same time as the sub-polar North Atlantic at about the same rate.

What can we make of all this? First and foremost, ocean heat content data and salinity data make it clear that hiatus onset marked a change between two distinct ocean states. During the hiatus two mechanisms—the Pacific *La Niña/El Niño* system and deep ocean sequestration by AMOC-like processes—were at work that were not as active in the period before.

Part 4. Arctic "New Normal"

Arctic Amplification

One of the earliest greenhouse warming models[20] predicted that the polar warming rate would significantly exceed the global average. This result is for a fundamental reason of climate dynamics. The most intense solar heating occurs in the tropics; there, more sunlight energy is absorbed during the day than is locally radiated back to space by long wavelength infrared radiation. The heat generated in the tropics has to be radiated back to space at higher latitudes, which lose more infrared energy than they gain from sunlight. Indeed, in the long polar night, the poles get no heat at all unless atmospheric currents bring it there from lower latitudes. As the popular song says, heat flows from the hotter to the colder. So, an equator-to-pole atmospheric circulation/ heat transport mechanism brings heat generated in the tropics to the colder poles. This mechanism has been known to be the most fundamental part of the climate system since the time of Edmond Halley in the late 1600s. This basic circulation pattern also redistributes the extra energy humans have been adding to the climate system since the beginning of the industrial era. The polar regions get two contributions from anthropogenic

greenhouse warming—one primarily because greenhouse gases in the polar atmosphere reduce nighttime cooling, and one from the heat arriving from the tropics that was added to by the greenhouse effect there. It is elusive to describe all this in words, but it is a basic feature of climate models and it was no surprise to the cognoscenti when the first Arctic Climate Impact Assessment, published early in the hiatus (ACIA, 2004[21]) but relying on pre-hiatus data, verified that the Arctic temperature had been increasing at more than twice the global rate, in general agreement with climate models. The 2011 follow-on to ACIA 2004—the Snow, Water, Ice, and Permafrost Assessment (SWIPA, 2011)—was a surprise.

The Arctic had shifted to a "new normal."[22] The contrast between the two assessments made only 7 years apart is so great that we may speak of a transition between two distinct states. First of all, overall warming was much faster than before[23]; the increase of average Arctic temperature between 2004 and 2011 was the fastest on record. Not only was the warming faster, but its spatial and seasonal pattern had also changed. Warming in 2011 was fastest in spring and autumn, whereas before 2004, it was in winter. In 2011, the warming was fastest over the ocean, whereas in 2004, it was fastest over land. These changes do not conform to earlier climate models. There is a reason why this is happening; Arctic sea ice and snow cover area systematically retreated during the hiatus, whereas they had ebbed and flowed in the period before. The newly exposed dark surfaces absorb more sunlight than the white snow and ice cover. In technical terms, the reflectivity, called *albedo*, was being lowered. Once started, the result can be even more warming and more snow and ice retreat in a kind of runaway.[j] The runaway stops only as the summer season advances into fall and there is less sunlight to be absorbed.

The balance of atmospheric heating due to sea ice and snow cover retreat, and that heat arriving from lower latitudes seems to have changed during the hiatus. The vertical structure of the Arctic atmosphere provides clues because different sources of heat warm different altitude layers. Changes in sea ice and sea surface temperature affect the atmosphere near the ocean surface, whereas heat coming from the equator will warm at higher altitudes. Graversen et al.[24] found greater warming aloft than at the surface over the period 1979–2001, which led them to conclude that atmospheric heat transport, not Arctic sea ice loss, was the main driver of Arctic amplification prior to 2001, consistent with the expectations from classical climate models. In contrast, by 2012, Screen et al.,[25] using data that extended into the hiatus, concluded

j The albedo effect works both ways: should ice and snow area start off by increasing, the rate of cooling would also be amplified.

that the vertical profile of Arctic warming was dominated by albedo warming from sea ice retreat. Given that the geographical pattern and timing of Arctic warming changed during the hiatus (SWIPA, 2011), it may not be a surprise that its vertical profile did, too.

When did this persistent albedo warming start? In other words, when did sea ice and snow area start to decrease in earnest? Satellites began to measure the area of Arctic sea ice in 1979, and we have reliable data since then. Arctic sea ice area waxes and wanes with the season but reaches its minimum at the end of northern hemisphere summer in September, when solar warming has had the longest time to act. The September data are the most sensitive to changes in temperature, and they show the clearest indication that the onset of the hiatus and the onset of persistent Arctic sea ice retreat took place at about the same time. Figure 4a shows the percent change in September ice area relative to the 1979–2012 average. Although the area fluctuated before 1998, a persistent decline began around 1998, the beginning of the hiatus. The June snow area measurements in Figure 4b tell a similar story. Snow area was less than the long-term average throughout the hiatus, and a persistent year-on-year decline started around 2001–2002.

How important is albedo warming on the global scale? The warming mechanisms triggered by Arctic sea ice and snow cover retreat have multiple contributing factors,[26] and it is hard to estimate an overall rate locally. Even if we could do that, it would be hard to get an accurate total from field measurements because of the patchy nature of the snow and ice cover. Satellite measurements average over all this complexity. Pistone et al. (2014)[27] correlated the changes in CERES satellite radiation budget measurements with the changes in sea ice area to estimate an Arctic-wide change in albedo, and thus to quantify its warming capacity. The implications are dramatic. They tracked the albedo change from 1979 to 2011. Over this period, the sea ice area decreased by 40%, and the Arctic averaged albedo dropped from 52% to 48%. This 4% change means that sunlight was depositing 6.4 Watts/m^2 more solar energy in the Arctic in 2011 than it had been in 1979. Of the 6.4 W/m^2 increase, two thirds (4.2 W/m^2) were added in the 10 hiatus years between 2001 and 2011. The local rate of albedo warming exceeds that from both local and remote greenhouse warming in the Arctic. It is even significant on the global scale. To put it into the larger context, if you spread the 6.4 W/m^2 over the surface of the earth, the global rate becomes 0.21 W/m^2, which is about one quarter of the increase due to the CO2 forcing added since 1979. The globally spread albedo warming during 2001–2011 of 0.14 W/m^2 was about half the increase in CO2 forcing, 0.27 W/m^2 during the same period. Finally, the peak rate of albedo warming in June is three times larger than previous estimates. This larger rate has yet to be

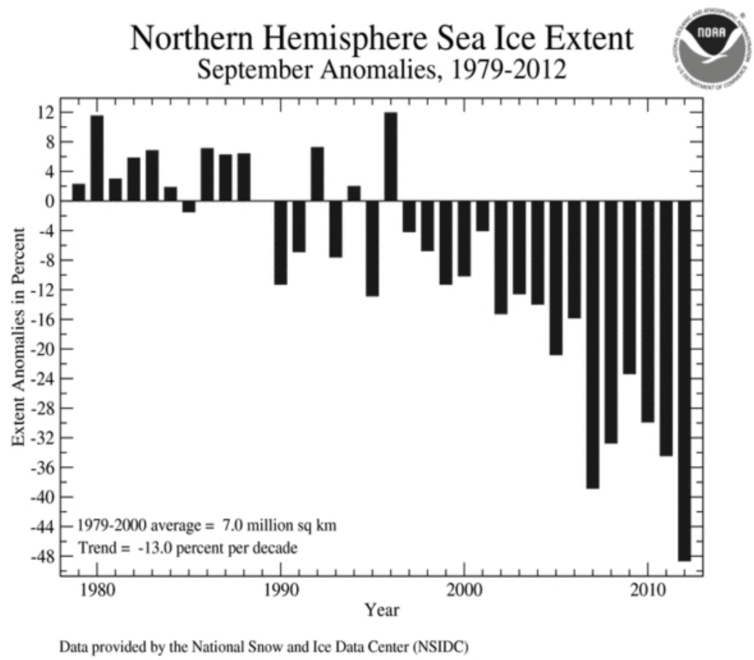

FIGURE 4a. Percent change in September Northern Hemisphere sea ice extent, relative to the 1979–2012 average. Note the change in character in the 1996–2000 period. These data imply that September albedo warming strengthened, with some ups and downs, as the hiatus progressed. Sea ice extent refers to the area in which there is a minimum of 15% ice cover. Figure courtesy of the National Snow and Ice Data Center, and the U.S. National Oceanographic and Atmospheric Administration.

incorporated into models, which may be a reason why current sea ice models do well in the period preceding hiatus onset but underestimate the rate of sea ice retreat during the hiatus.

Although most discussions of albedo warming focus on sea ice retreat, the changes in snow cover cannot be overlooked. About one third of Earth's land area is covered by snow some part of the year. The extent and duration of snow cover have been decreasing throughout the Arctic; the land area covered by snow in early summer (June) decreased by 18% since 1966. According to SWIPA 2011, the largest and most consistent change is earlier disappearance in spring, but snow onset in fall is also occurring later, so the snow season is shortening at both ends. The snow season shortened by as much as 20 days on the Northwest Pacific, Baffin Area, and Fenno-Scandian Coasts in the 36 years between the winters of 1972–1973 and 2008–2009. The shortening snow season and diminishing snow area both increase albedo warming. Over the

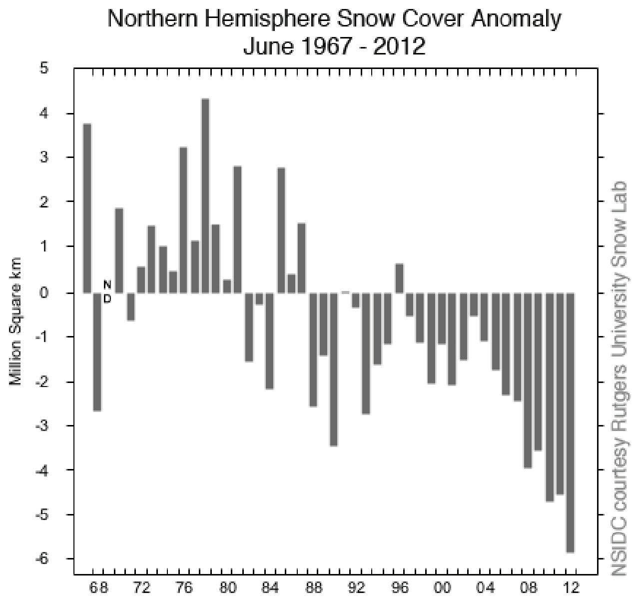

FIGURE 4b. Change in June snow cover area in millions of square kilometers, relative to the mean established between 1967 and 2012. Snow area was always less than the 1979–2012 average after 1998 and began a persistent decline around 2003. As this persistent decline was unfolding, freshwater was building up in the Arctic Ocean. The 2012 June snow cover area was the smallest on record up to that time.

period 2008–2012, June snow cover area decreased at twice the rate of September sea ice, a period when sea ice was retreating rapidly.

Snow-melt is an important contributor to the freshwater flow into the Arctic Ocean. About 10% of present global freshwater flows into only 1% of the ocean volume, where it can have a singularly large effect. All of the main sources of freshwater entering the Arctic Ocean are increasing—river discharge, rain/snow, melting glaciers, ice caps, and the Greenland Ice Sheet. An extra 7700km^3 of freshwater—equivalent to one meter of water over the entire land surface of Australia—has been added to the Arctic Ocean in recent years (SWIPA, 2011). Gravity data acquired by the GRACE satellites show that around 2003, a lens of freshwater began to build up in the Beaufort Gyre north of Canada and Alaska that grew persistently until it attained a volume of 6000km^3 in the 2009–2011 period.[28] It is well known that the addition of fresh water on top of salty water affects thermohaline ocean circulation since it suppresses sinking. The pattern of ocean circulation at lower latitudes can be affected by flows of freshened Arctic waters into the Greenland and Labrador seas. It is noteworthy

that the Beaufort Gyre freshwater lens began to grow at the same time as the salinity increase started in the North Atlantic.

A switch occurred in the behavior of Greenland and Antarctic Land Ice around the time the hiatus began. The scientists working on the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4) released in 2007 were caught in the midst of the hiatus. They couldn’t agree on the rates at which the Greenland and Antarctic Ice Sheets were disintegrating and flowing into the ocean. Now, disagreement among scientists about research in progress is common and essential to the scientific method. Their disagreement would not have had consequences beyond the world of science but for the fact that these ice mass loss rates are part of the estimation of the rate of sea level rise, in which all kinds of practical people are interested. IPCC, however, prides itself in releasing its pronouncements only when the scientists reach consensus. Because there was no consensus, IPCC chose to release a partial estimate of sea level rise, using only the part due to the much better founded partial rate that can be calculated from the measured ocean warming. IPCC was careful to call out the uncertainties in the ice melt rates, but practical people are not really very interested in the anxious handwringing of scientists. So, a substantial under-estimate of potential sea level rise got out there to affect the calculations of those charged with planning for sea level rise. A veritable explosion of research followed, so that by the time the IPCC’s fifth assessment was released in late 2013, it was apparent what had happened in 2007. The ice mass loss rates were undergoing a tremendous transformation. IPCC AR5 estimated that the rate from Antarctica probably increased by about a factor 5 between the two decades, 1992–2001 and 2002–2011; the Greenland rates increased by a factor 6 comparing the same two decades.

Part 5. Extreme Weather

Extreme events have been in the news recently. Australia had the worst heat wave in its recorded history in 2013–2014. America’s East Coast had an unusually large number of snowstorms in the same year. Tree ring records indicate that California is in the midst of its worst drought since 1580, and, for the first time, state officials announced that they would be unable to make deliveries to the State Water Project unless conditions changed. Britain had the most winter rainfall in 2013 and 2014 since record keeping began in 1766. The unusually serious flooding in England’s West Country attracted the attention of the media, but the media failed to put it into perspective. The trend had been building up throughout the decade. According to Coumou and Rahmstorf,[29] the year 2000 set a record for the wettest autumn in

England and Wales.[30] The period from May to July 2007 (a year of exceptional sea ice retreat) then became by far the wettest in England and Wales since records began in 1766,[31] with 406mm of rain (previous record: 349mm). This record was surpassed again in the winter of 2013 and 2014.

The year 2013–2014, although unusual by historical standards, fits a recent pattern that had begun to become clear by 2010.[32] In August 2010, the World Meteorological Organization issued a statement on the "unprecedented sequence of extreme weather events," saying that it "matches Intergovernmental Panel on Climate Change (IPCC) projections of more frequent and more intense extreme weather events due to global warming."[33] The simultaneous Moscow heat wave and Pakistani flooding that year illustrated how destructive extreme weather can be: the death toll in Moscow has been estimated at 11,000, and drought caused grain-harvest losses of 30%, leading the Russian government to ban wheat exports. At the same time, nearby Pakistan was hit by the worst flooding in its history, which affected approximately one fifth of its total land area and 20 million people.[34] These events were a motivation for the IPCC special assessment of extreme events issued in 2012.[35]

The climate science community has concentrated on asking to what extent increases in extreme events can be ascribed to greenhouse warming.[36] Because most of the evidence has been anecdotal, this case has been difficult to make quantitatively, but recent studies are beginning to document an increase. The community has not thought to associate the increase specifically with the hiatus. This is the question we ask here. Did the pattern of extreme events change when the Arctic sea ice began to retreat and the ocean state changed in the years 1998–2000?

It is easiest to pose this question in terms of heat waves because of the quantity and ubiquity of temperature data. There were seven "one-in-one-hundred-year" heat waves, during which temperatures reached 10 degrees Centigrade (10C) above average between 2003 and 2013 in Europe (2003), Greece (2007), Australia (2009), Russia (2010), Texas (2011), the United States (2012), and Australia again (2013) . It is unusual that one can go beyond this kind of anecdotal evidence to a quantitative analysis, but in the case of heat waves, this has been done. Two recent studies point to a major difference in heat wave occurrence before and after the onset of the hiatus. Barriopedro et al. (2011)[37] compiled a statistical distribution of the average summertime temperature in Europe for every year since 1500. This distribution provides the basis for a rigorous statistical comparison. The five warmest summers in this 510-year record occurred in the 8 years between 2002 and 2010, during the hiatus. These exceeded the 510-year mean by two to three standard deviations. James Hansen and his colleagues at the Goddard

Institute of Space Studies[38] found that summertime extremes of more than three standard deviations warmer than the mean of the local climate were practically absent in the 1960s, affecting less than 1% of th earth's surface. The area experiencing three standard deviation heat waves had increased to 4% to 5% by 2006–2008, and by 2009–2011, heat waves occurred on 6% to 13% of the land surface. It is important to note that the area doubled between the first and second halves of the hiatus.

The pattern of cold spells and winter storms seems also to have changed around hiatus onset. Climate scientists have long suspected that what goes on in the Arctic does not stay in the Arctic,[39] and there have been many studies searching for links between changes in the Arctic and climate events at lower latitudes. Francis et al.[40] related the time history of the west-to-east northern jet stream to that of Arctic sea ice extent. This jet stream circulates at 9km to 12km altitude around the pole, and it is sometimes called the "polar vortex" in the popular literature. Its behavior is related to the occurrence of extreme weather events at mid-latitudes. The vortex began to weaken when persistent sea ice retreat began in the 1996–1998 period, and it has continued to weaken. The extreme winter of 2009–2010 in the eastern United States and Western Europe has been traced to polar vortex intrusion.[41, 42] In simplified terms, Arctic warming reduces the temperature difference between equator and pole; the reduction in equato-to-pole[43] temperature gradient weakens the mid-latitude winds that confine the vortex, and the vortex becomes erratic. The result is that colder air that normally stays confined to the Arctic invades more southerly latitudes as deep meanders in the jet stream. The vortex was also invoked with much fanfare in the media to explain the extreme winter of 2013–2014 in the eastern United States.

There could be a common explanation of a whole class of extreme events that is caused by "blocking," in which a weather pattern persists for an unusually long time over one area of the earth, thereby concentrating its impact. The common feature of many extreme events is changes in the properties of planetary-scale waves. These so-called Rossby waves play the primary role in the communication of atmospheric heat, moisture, and momentum across the mid-latitudes between the tropics and the poles.[44] Rossby waves manifest themselves as typically four to six large-scale meanders of the jet stream. When these meanders have large amplitudes, they detach the masses of cold, or warm, air that become cyclones and anticyclones and are responsible for day-to-day weather patterns. The balance of cyclones and anticyclones determines how much tropical heat is transported through the temperate latitude zone toward the poles and establishes the meridional temperature gradient in the upper atmosphere.

The properties of the Rossby waves change themselves when the equator-to-pole temperature gradient they help determine changes.[45]

From time to time, these intertwined processes can lead to exceptional behavior. Francis and Vavrus'[46] observational analysis suggests that recent Arctic warming is leading to a slower speed and larger amplitude of the planetary waves and blocking. One result would be an increased probability of extreme weather events that stem from prolonged persistence of a weather pattern in one mode (e.g. drought, flooding, cold weather, heat waves). A theoretical analysis by Petoukhov et al.[47] argues in analogous fashion that slowly moving Rossby waves can be trapped in a band of mid-latitudes between the two jet streams, where the waves can be excited to large amplitudes, again leading to blocking and increased probability of extreme behavior.

Part 6. Patterns, Indices, Teleconnections

Indices

What is climate but the pattern in space and time of weather events? The challenge has been to document the events and perceive the patterns. It started with simple records of atmospheric temperature and pressure. The United Kingdom Meteorological Office maintains to this day a continuous record for central England that extends back to 1766. The connection between pressure and storminess was obvious to mariners, so documenting how pressure varies in space and time became the first avenue to a scientific description of climate. As weather instruments were gradually deployed around Europe, it became possible to compare time histories of pressure compiled at different weather stations. Soon it became clear that the European climate alternates between two basic patterns. When the prevailing Atlantic winds that bring moist air over Europe are strong, summers are cool and winters mild; when the winds are weak, central Europe is drier and has more heat waves in summer and cold snaps in winter. The winds originate in a prevalent low-pressure system located over the central North Atlantic—the Icelandic Low. Another persistent pressure system stands closer to the equator—the Azores High. The difference between the two pressures is an indicator of heat and moisture transport from south to north. The pressure difference varies in an irregular fashion over time—"oscillates." When the difference between the pressure at Lisbon and Reykjavik, Iceland, say, is large, Central European weather is mild and wet, and when that difference is small, weather is drier but with more extremes. The North Atlantic Oscillation Index (NAOI) is just this difference in pressure. A continuous record of the NAOI made from instrumental measurements extends back into the early nineteenth century, and has even been constructed from proxy records as far back as the Middle Ages.

An analogous Southern Oscillation Index (SOI) is computed from the surface air pressure difference between Tahiti and Darwin, Australia. The *La Niña* is associated with positive values of the SOI—above normal pressure over Tahiti and below normal pressure over Darwin—and the *El Niño* events with negative. The SOI is both an indicator of the trade winds that drive the *La Niña/El Niño* cycle and of the difference in sea surface temperature across the equatorial Pacific, since low atmospheric pressure tends to occur over warm water and high pressure over cold water. The coupling between pressure and sea surface temperature is so tight in the tropical Pacific that what we have called the *La Niña/El Niño* cycle is called the *El Niño-Southern Oscillation* (ENSO) in the trade. Today, with satellite observations, networks of observing stations, computer modeling, and fast communications, we can characterize weather pattern changes in space and time much more completely, yet we continue to use the North Atlantic and Southern Oscillation indices, and others like them, because they connect today's measurements with those made in the past.

Teleconnections

As has been related, scientists had known relationships existed between weather events in different parts of the world well before the physical mechanisms were understood. Modern climatologists, now equipped with huge data sets and computational capacity, can go beyond the events themselves to linkages among weather patterns in space and time-teleconnections. Although teleconnections provide only suggestive clues about causal relationships, climatologists would not go to the trouble of establishing the patterns and their associations unless they have faith that they will reveal how changes propagate within the climate system.

Tropical climatologists have known since the 1980s that the switch from a *La Niña* to an *El Niño* reorganizes weather and sea surface temperature patterns across the entire Pacific basin[48] and beyond. Although Arctic scientists find nothing quite so spectacular as an *El Niño* in their data, they have long suspected that sea ice and mid-latitude weather patterns are related. Although telecommunications have been established between the Arctic and mid-latitudes, and between the tropics and mid-latitudes, the connections between Arctic and tropical phenomena are less well studied. Are sea ice variability and the ENSO cycle related? Here, some of the work that has been done is reviewed with this hypothesis in mind.[49, 50]

The *La Niña/El Niño* system has been linked to a worldwide north-south pattern given the name *Arctic Oscillation*,[51] a mathematically

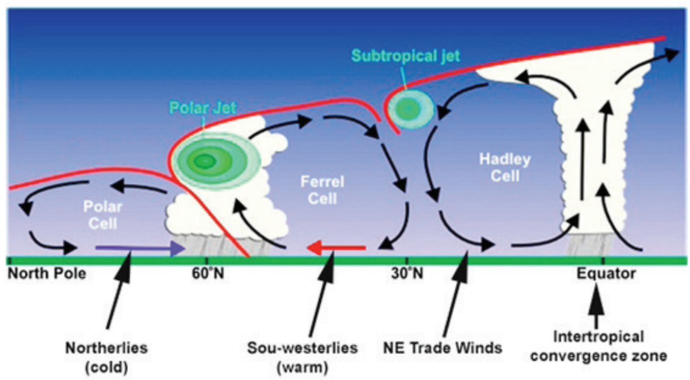

FIGURE 5a. Meridional atmospheric circulation. The north-south circulation of the atmosphere splits into three interacting cells. Jets streams flow in the upper troposphere at the boundaries where they interact. The subtropical jet is at about 30 degrees latitude, as shown, in the winter hemisphere and is displaced poleward in the summer hemisphere. The directions of the prevailing winds at the surface alternate between cells. The altitude of the boundary between the troposphere and the stratosphere diminishes as one moves toward the pole. Figure courtesy of NOAA COMET program.

sophisticated descendant of the *North Atlantic Oscillation*. The Arctic Oscillation (AO) compares sea level pressures averaged over the Arctic and in the annular band of latitudes between 37 and 45 degrees north around the world. Among other things, the AO is an indicator of worldwide extreme event occurrence, since Rossby waves propagate around the world in this mid-latitude band. When the AO index is positive (Arctic pressure lower than average), the poleward jet stream blows strongly and consistently from west to east and keeps cold Arctic air locked in the polar region. A negative AO index (higher Arctic pressure) is correlated with weaker west-east winds and more intrusion of polar air into middle latitudes. (Such an alternation of conditions is also associated with the *El Niño* and *La Niña*.) A detailed analysis of *El Niño* and *La Niña* composite profiles led Lee[52] to conclude that the Arctic winter (December–February) is anomalously warm (high pressure, AO negative) during a *La Niña* episode and anomalously cold during an *El Niño* (AO positive). A recent paper by Li, et al.[53] argues that the relationship between the AO and the *El Niño*-Southern Oscillation has strengthened since the mid-1990s, when September sea ice retreat started its persistent decline.

The computation of the AO is centered over the pole and averages over longitudinal variations in pressure. To next order, there are east-west variations. Superposed on the AO is a characteristic east-west "dipole" pressure pattern in which the behaviors of opposite sectors in

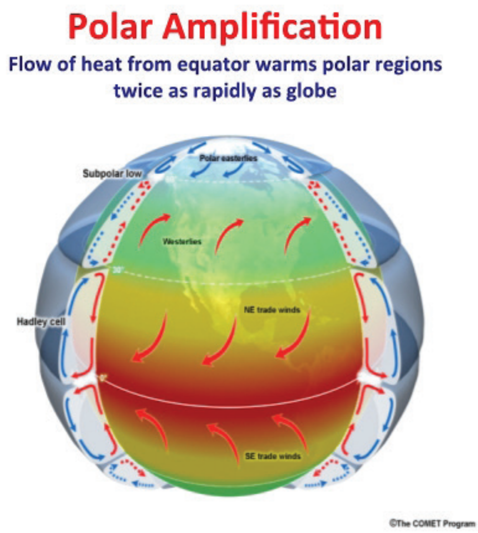

FIGURE 5b. The atmosphere's basic circulation in three dimensions. The generation of the trade winds at the Hadley-Ferrel Cell interface is made explicit; the jet stream there has been left off the diagram for simplicity. The interaction of the trade winds with the oceans creates the Walker circulation, which is sketched in Figure 2. The Northern and Southern Hemisphere circulation patterns are shown as symmetric, which is only approximately true because the Northern and Southern Hemisphere Ocean are so different in area. Figure courtesy of NOAA COMET program.

longitude are mirror images of one another. If one sector is warmer than usual, the other is cooler. More formally, the Arctic Dipole Anomaly (ADA) is the second leading mode of sea level pressure variability with the first mode being the AO.[54] The ADA has one pole over northeastern Canada and northern Greenland, and the other over the Kara and Laptev Seas north of Siberia. When the pressure is high over North America and low over the Siberian coast, the ADA is positive, and vice versa. The important point is that east-west pressure gradients drive north-south winds in a rotating atmosphere, so associated with the ADA are wind systems that drive polar waters and sea ice either toward the Greenland sector (ADA+) where they can escape the Arctic Ocean, or toward the Bering Straight (ADA–) where they are more confined geographically. In either sector, the winds from the south drive warm air and ocean water into the Arctic Ocean from the Bering Straight (ADA+) or from the Greenland sector (ADA–). This heat flow clearly contributes to sea ice disappearance. Given that the phenomena that define AO and ADA both affect sea ice extent, there are four possibilities: AO+, ADA+; AO–, ADA–; AO+, ADA–; and AO–, ADA+. In

2007 when sea ice extent was exceptionally low, ADA was positive and AO was negative.[55] It is important to note that the present ADA pattern first became pronounced about the time ocean sequestration began. Between 2001–2002 and 2005–2006, the pressure configuration that had prevailed before the hiatus was transformed into a totally different dipole structure between the Eurasian Arctic coast and North Pacific.

One of the poles of the Arctic Dipole is centered partially over the Pacific Sector, and a relationship between the ADA and the *La Niña/El Niño* cycle in the tropical Pacific would be expected. There are analogous cycles—the Antarctic Oscillation and Antarctic Dipole—in the Southern Hemisphere where, perhaps because of the absence of the geographical complexity in the Northern hemisphere, their relationships to the ENSO cycle may emerge more cleanly from the data. A 2004 study of earlier data by Yuan[56] documented the expected relation between *El Niño* events and the *Antarctic Dipole*—the east-west pattern of contrasting changes on the Pacific and Atlantic sides of Antarctica. The effects are precisely opposite during a *La Niña*, down to a reversal of the sense of the Antarctic Dipole mode.

These and other studies all emphasize the central role of the meridional (equator-to-pole) atmospheric temperature and pressure gradients. In general, a *La Niña*-AO negative (*El Niño*-AO positive) pattern is associated with a smaller (larger) equator to pole gradient. Several authors have suggested that the climate system (Figures 5a and 5b) can be thought of as a kind of network or circuit[57] whose linkages are revealed by teleconnections. If we adopt this simplified analogy, our basic premise is that equator and poles are connected in an atmospheric heat flow "circuit" in which solar heating in the tropics is the power source, the *La Niña/El Niño* cycle is a dissipative element,[k] albedo warming is a variable amplifier, and planetary (i.e., Rossby) waves are agents of transport at mid-latitudes.

The energy from sunlight is largely deposited in the tropical oceans to be redistributed within the climate system, eventually to be reradiated back to space in the form of long-wave infrared radiation. The Hadley Cell, the equator-to-equator circulation loop shown in Figure 5b, initiates the flow of heat away from the equator. The warmed atmosphere there rises, carrying energy-rich moisture with it. When this air reaches higher altitudes above the equator,[l] it splits into streams that move northward

k Like all analogies, this one is inexact, but a *La Niña*, by sequestering heat in the oceans, takes energy out of the atmosphere, whereas the *El Niño*, because it warms the ocean surface, temporarily causes the climate system to lose more energy by escaping long-wave infrared radiation.

l The term *equator* is used loosely; maximum ocean heating occurs when the sun is directly overhead. Thus, equator is used to mean the *instantaneous subsolar latitude*, which varies between 23.5 degN and 23.5 degS with season.

and southward. These streams cool at altitude, becoming heavier in the process, and sink back to the surface. The Northern and Southern subtropical jet streams are located above about 15km altitude where the Hadley cell circulation returns to the surface. The flow there divides; a part goes back to the equator and a part goes poleward. The equatorward return flows are the trade winds, shown in projection on the earth's surface. They both have a westward component because of the earth's rotation. Some of the Hadley Cell heat is sent poleward in the so-called Ferrel cell, where the method of heat transport differs. In the Hadley cell, it is accomplished by straightforward convection, whereas in the Ferrel Cell, where centrifugal forces are important, poleward transport requires the outbreak of cyclones and anticyclones, the balance of which adjusts the overall thermal energy flow. The poleward boundary of the Ferrel cell is set by where the centrifugal force due to the earth's rotation no longer sustains cyclonic flows. It is at this boundary that the polar jet stream flows in the upper troposphere, separating cold polar air from warmer midlatitude air.

Part 7. Summary

The great *El Niño* of 1998 marked a transition in atmospheric and oceanic state. This transition involved much more than the change in the growth rate of global surface temperature for which the term of art "hiatus" was devised. The change has been demonstrated clearly in Chen and Tung's[58] contrast of ocean states in the 12-year periods before and after 1999. The transition between the two states took about 4 years to accomplish. The September Arctic sea ice area and the tropical central Pacific trade wind stress anomaly peaked and began to decline around 1996, and the great *El Niño* broke out in the winter of 1997–1998. The ocean warming of that winter was followed by 2 years of cooling, apparently by radiative loss to space. There is no evidence for anomalous heat subduction to deeper ocean layers during these 2 years. Persistent heat sequestration commenced in the year 2000 and has continued to this day. It seems to have started with *La Niña* subduction to relatively shallow layers in the Western Pacific and to have been followed several years later by an increase in the salinity of the North Atlantic and the related sinking of warmer surface waters to intermediate depths. Overall, persistent ocean sequestration is carrying to depth the energy added to the system from both the yearly increase in greenhouse warming and its induced albedo warming.

Arctic sea ice extent and snow cover area have been persistently diminishing with some ups and downs since the hiatus started. September sea ice extent was especially small in the years 2007 and 2012, only to

increase somewhat in subsequent seasons, but overall, it decreased by about 40% relative to the 1979–2012 average during the hiatus. Northern Hemisphere June snow cover began its persistent decline around the year 2002. Seasonal albedo warming increased almost every successive year since 2000. Satellite measurements suggest that the local warming rate increased by about 4 W/m^2 overall since the hiatus began and added about 0.18 W/m^2 to the global rate, over and above the expected increase in the rate of greenhouse warming of 0.43 W/m^2 during the same period. The geographical, seasonal, and altitude patterns of Arctic warming changed after the hiatus began and now reflect the local dominance of albedo warming. There are numerous other manifestations of the acceleration of Arctic warming. The rate of increase of August ocean surface temperature accelerated from 0.35 degC/decade between 1982 and 1999 and 0.58DegC/decade between 2000 and 2012.[59] A new teleconnection, the Arctic Dipole Anomaly, emerged during the hiatus. More fresh water began flowing into the Arctic Ocean from the river systems on land. A lens of freshwater began to build up in the Beaufort Gyre poleward of Alaska and Canada around the year 2002. Most portentous of all, from the point of view of sea level rise, IPCC AR5 found that the rate of ice mass lost from the Greenland and Antarctica ice shelves increased by a factor 5 to 6 between the decade of the 1990s and the decade of the 2000s, that is to say, from before to after the hiatus began.

Part 8. In Search of a Unifying Theory

We have now reached the frontier where more research is needed. We have arrayed circumstantial evidence in a way that suggests that the changes in Arctic albedo warming, the *La Niña/El Niño* cycle, North Atlantic Ocean heat transport and sequestration, mid-latitude extreme events, and the diminished surface temperature growth rate are related to one another. However, circumstantial evidence is not proof, and our scenario is subject to criticism on both observational[m] and theoretical[n] grounds.

m Do we know whether the trends on which this hypothesis is based are real trends? Hiatuses appear in present global climate models, and there may be nothing special about the present one; the spread of temperature outcomes in the present model ensemble could accommodate today's hiatus; we have observed at most two cycles of the Pacific Decadal oscillation, so we do not know whether the present *La Niña* bias is anomalously long; the persistent growth in trade wind stress could likewise be an extra-large, extra-long fluctuation; observations of Arctic temperature have been under-sampled in the computations of the global temperature; and the ocean heat content reanalysis is unreliable in pre-ARGO times and might not reliably document a switch between pre- and post-hiatus behavior. These (valid) worries all indicate that our hypothesis stands on statistical foundations that will not be strengthened in the near future.

n Viewed intuitively, forcing of the gigantic *La Niña/El Niño* system by albedo warming

We do not have answers, but we do have a question: Was it a change in the nature of Arctic albedo warming that caused the hiatus?

At first sight, forcing of the gigantic *La Niña/El Niño* and AMOC systems by albedo warming in the tiny Arctic seems like the tail wagging the dog. But changing a key boundary condition can force major changes to propagate throughout dynamical systems. The best way to find out in our case is by using numerical climate models, but that is yet to be done. In the meantime, we can only venture the kind of intuitive word pictures that climate scientists use to describe to each other what is happening in their part of complex climate system.

Let us start by examining how albedo warming of the Arctic Ocean affects the atmosphere. The seasonal minimum sea ice area in September is now about 40% below its 1979–2012 average. On the other hand, the seasonal maximum sea ice area in March declined hardly at all over these 33 years, about 3%. This immediately tells us two important things. First, the dark ocean area that is exposed during the solar warming season from March to September increased more or less regularly every year since the hiatus began. Second, progressively more of the ice cover in March was first-year ice that disappears during the following summer and rebuilds during the winter. In the 1980s, multiyear ice comprised about 80% of the winter ice extent, while that fraction had dropped to about 20% in 2012.[60] The increase in first-year sea ice proportion adds to albedo warming in at least two ways: (1) first-year sea ice is more transparent, so more solar radiant energy penetrates to the water below, warming it, which in turn prompts more ice retreat; and (2) first-year ice tends to be patchy with ice pans alternating with pools of open ocean water, so the warming rate per unit area increases even when there is some ice cover. When Arctic sea ice retreats from March to September, the newly exposed ocean first stores the heat it acquires in its upper layers. As the autumn season progresses, the atmosphere becomes cooler than the ocean surface and the stored ocean heat (and moisture) enters the Arctic lower troposphere above the ocean surface.[61] Albedo warming should have its greatest impact on the atmospheric temperature gradient at this season.

Did these sea ice changes influence the ENSO cycle? We don't know for sure, but we can hypothesize that they did, and then ask how it might have happened. As noted above, albedo warming influences the atmospheric temperature difference between the equator and pole. The

in the tiny Arctic seems like the tail wagging the dog. However, changing boundary conditions propagate changes throughout dynamical systems. This issue can be settled only by modeling. Some modeling studies (S. P. Xie, private communication, 2014) suggest that warming confined to a narrow band of polar latitudes does produce worldwide effects. The key issue is how the trade winds would be affected.

temperature gradient in autumn defines the requirement for heat to flow from the tropics to the pole during the winter and spring. This heat flow in turn affects the regrowth of sea ice and snow cover. The seasonal patterns of solar heating in both the Arctic and the tropics change little from year to year, but albedo warming fluctuates, since snow and ice cover are highly variable. Let us picture how the atmospheric heat transport system might respond to its changeable Arctic boundary condition. Refer to Figures 5a and 5b, which are a schematic of the atmosphere's basic circulation patterns. The energy circulating in the Hadley Cell generated by tropical solar heating has to be partitioned at the poleward boundary of the cell—the location of the subtropical jet stream. Some of this energy is sent to the poles and some back towards the equator. If less goes poleward, more goes into the trade winds, and vice versa. If the changes in the polar warming are small enough or slow enough, the system can oscillate back and forth to balance things out. But when they are large enough, winter regrowth may not match summer retreat, and a persistent trend may emerge. If in successive years the seasonal albedo warming increases, a *La Niña* bias is reinforced. In a year of sea ice advance (relative to the previous year), the Arctic ocean is cooler at the end of summer, the autumnal pressure increase is smaller, and more Hadley Cell heat is sent toward the poles and less goes into trade winds, which eventually become slower and more erratic during the northern autumn season. But factors other than temperature, such as wind-driven transport, also affect ice cover and its associated albedo warming. Occasionally, a combination of circumstances produces a reduction in trade wind stress big enough to lead to a failure—an *El Niño*—at which point a new ocean state is temporarily established. Pacific Ocean heat sequestration is interrupted, and the ocean surface warms across the Pacific basin over the next three months. A pulse of heat is sent poleward across the Pacific longitude sector, and energy once sequestered is now radiated back to space until the ocean surface cools down. The subtropical jet stream intensifies, and "Pineapple Express" storms propagate west to east across the eastern Pacific.[o]

Could the change in Arctic warming also have prompted the sequestration of heat in the North Atlantic? Here we invoke a word picture that has been deployed to explain a spectacular paleo-climate event, the slowing of the AMOC by an outburst of fresh water from a gigantic lake created by glacier melt 8,200 years ago: Lake Aggassiz.[62] There could have been a small modern analog of this event. As

o My colleague Jeff Dozier has reminded me that not every *El Niño* configuration leads to heavy rain in California, as the *El Niño* interacts with other weather cycles, which, for simplicity of exposition, have not been considered here.

mentioned earlier, a lens of fresh water began to build up in the Beaufort Gyre north of Alaska and Canada beginning about 2002. In those seasons when the Arctic Dipole atmospheric pressure anomaly pushes winds away from the North American coast (ADA+), such fresh water can be pushed through the Fram Straight into the Greenland Sea, along with sea ice. Intrusions of ice or fresh water can temporarily shut off the formation of North Atlantic Deep Water, thereby pushing back on the AMOC flow and forcing Gulf Stream waters to sink in the Sub-Arctic North Atlantic rather than further north.

Next, we propose a scenario that pulls together the above arguments. Years of prior greenhouse warming thinned the Arctic sea ice and gradually increased the proportion of one-year ice. As the Arctic got warmer, the effective albedo of the one-year ice was also getting smaller; the warming rate increased before the ice went away altogether. Sea ice was getting thinner and more fragile. The additional blast of heat sent northward by the 1997–1998 super-*El Niño* may have triggered the present period of self-sustaining ice retreat, when seasonal regrowth is not making up for the previous year's loss. It is interesting to note that the equally large *El Niño* of 1982 did not create a hiatus, but then, the Arctic sea ice was probably not thin enough for 1982's warming to push the system beyond the tipping point. This comparison does suggest that the tipping point was eventually crossed because of the greenhouse warming that took place after 1982.

The 1998 *El Niño* seems to have pushed the climate system into a new quasi-steady state, called "metastable" by experts. If so, the present dynamical quasi-equilibrium could be maintained until ice and snow retreat stops. About 40% of the 1979 September sea ice area has been lost during the 16 years of the hiatus, 60% remains, so this situation might persist for another 20 to 30 years. It would probably take longer for the albedo warming from snow retreat to disappear. Chen and Tung noted that ocean states like that in the hiatus have a historical recurrence time of 40 to 60 years, but those took place in a different climate era. Among the experts, there seems to be agreement on a variety of grounds that the Arctic sea ice cannot last more than a few tens of years. However, the ultimate arbiter of truth is Nature herself.

Part 9. Perceptions and Implications

It had been clear since the early days of modern climate research in the 1950s and 1960s that "climate change" was a better descriptor of what was about to happen than "global warming," but "global warming" seemed like something that everyone could understand. This naïve attempt to communicate has come back to haunt us all. The concerted

effort on the part of the climate science community to replace the use of "global warming" with "climate change" has been derided as a deceitful attempt to obscure the fact that the world hasn't warmed for the last 16 years. No wonder the public debate is stalemated.[63]

Global temperature produces scientific clarity but public misunderstanding. Although using it as a benchmark may force intellectual discipline on scientists because it provides one number that all their models must compute, it is an elusive concept outside of science. Scientists use their vast modeling and observational infrastructure to compute a number that conveys the misleading impression that the world warms up uniformly, which is clearly contrary to human experience. People understand today's temperature and with a little thought they can recall a hot summer, but no one has experienced global temperature. They have no idea what a rise of a couple of degrees means for their lives, their families, and their communities.

It is a deceptively simple idea, to summarize expectations for the climate in terms of global temperature, and policy-makers have used it to set goals for climate management. The basic goal of the UN Framework Convention on Climate Change (UNFCCC, 1992) is to prevent "dangerous anthropogenic interference in the climate system." No one knew in 1992 how much warming is dangerous to human welfare, and no one knows today. At the 2009 UNFCCC Conference of Parties meeting in Cancun, the delegates declared that the goal of international action should be to limit warming to 2degC above the preindustrial level. The goal had a shaky basis in natural or social science, and some climate scientists fear it cannot be achieved. It was a policy-makers construction; it did focus the negotiations, but it made the media focus on global temperature as a measure of success or failure. Because global temperature has come to define a tripwire for political action, any mention of it triggers a conflicted public debate.

The hiatus has tripped us up. It makes today's climate models look unreliable. It undermines public confidence in policy and economic analyses whose goals have been to prescribe what to do and what we will have to pay to meet the 2degC target. The hiatus is showing how problematic the number we call global temperature is as a measure of climate risk. An unambiguous index of climate change risk would be wonderful, but one probably does not exist.[64] Economists and investors, when trying to extract useful knowledge about nonlinear complex economic systems do not rely solely on gross domestic product; they consult a basket of indices. Doctors call their basket of health indices vital signs. Climate change is too important not to do the same. The most fundamental indices of all have been there all along but unused for policy purposes—the top of atmosphere radiation imbalance and ocean heat content. The

radiation imbalance can tell us how much energy the climate system is taking up and measures the greenhouse effect directly. The oceans take up 90% of the energy added by greenhouse warming to the climate system, and since this energy will be released slowly, ocean heat content measures the committed long-term risk to future generations and planetary-scale ecology. We also need measures of short-term risk to society and infrastructure. A "volatility index" that measures the evolving risk from extreme events was described here—the area containing three standard deviation events in a given year. If we had paid attention to these indices[p] instead of global temperature, the hiatus might not have lulled the world into inaction as long as it did.

Author's Note (added 11 March 2016)

Significant publications bearing on the hiatus and its manifestations have been printed since the final submission of this paper on 23 November 2014. Fyfe et al.[q] document the slowdown in the growth of global temperature using a number of data sets. They show that today's climate models do not account for the hiatus. Karl et al.'s[r] reanalysis of global surface temperature suggests there has been little or no slowdown in global surface temperature growth since the year 2000. Karl et al.'s result is at variance with Fyfe et al.'s. Because of the other manifestations of change documented in this paper, I believe Fyfe et al.

A number of important ARGO results were published. Riser et al.[s] reviewed the first 15 years of ARGO observations. Roemmich et al.[t] and Wijffels et al.[u] show that planetary warming did not slow down during the hiatus. Roemmich et al. emphasize the importance of heat sequestration in the Southern Ocean. Indeed, Gleckler et al.[v] show that

p If we do pay attention to them for policy purposes, the first thing to do would be to assemble an international conference, perhaps under the auspices of the United Nation's Global Earth Observation organization, which assesses the requirements and technical readiness for these research measures to be used as reliable policy indicators. It would also be necessary to convene natural and social scientists to assess their precise meaning as indicators of climate risk.

q Fyfe, J. C., et al. "Making Sense of the Early-2000s Warming Slowdown." *Nature Climate Change* 6 (2016): 224–8. doi:10.1038/nclimate2938

r Karl, T. R., et al. "Possible Artifacts of Data Biases in the Recent Global Surface Warming Hiatus." *Science* 348, no. 6242 (2015): 1469–72.

s Riser, S. C., et al. "Fifteen Years of Ocean Observations with the Global Argo Array." *Nature Climate Change* 6, no. 2 (2016): 145–53; Project ARGO deployment cycle.

t Roemmich, D., et al. "Unabated Planetary Warming and Its Ocean Structure Since 2006." *Nature Climate Change* 5 (2015): 240–5.

u Wijffels, S., et al. "Ocean Temperatures Chronicle the Ongoing Warming of Earth." *Nature Climate Change* 6, no. 2 (2016): 116–8.

v Gleckler, P. J., et al. "Industrial-era Global Ocean Heat Uptake Doubles in Recent Decades."*Nature Climate Change* (2016). doi:10.1038/nclimate2915

one half of all the energy that humans have sequestered in the ocean since 1865 was put in after 1997—basically during the hiatus.

Briggs et al.[w] suggest that a set of "Planetary Vital Signs" supplement the use of global temperature as diagnostics of climate change.

It appears that the surface temperature hiatus definitively came to an end as 2016 began. The Pacific Ocean saw record surface temperatures, and the global surface temperature rose to its highest level on record. Based on their experience with previous events and the record Pacific Ocean temperature, many climate scientists proclaimed 2016 an *El Niño* year. However, it is a very different *El Niño* than the one in 1997–8. Ocean heat sequestration appears to be continuing, the jet stream remains extraordinarily deeply folded, and there have not been the expected "Pineapple Express" storms scooting across the Pacific. Hopes that this *El Niño* would make a major dent in California's record drought were not fulfilled. We seem again to be in a different unfamiliar climate state.

The worldwide consensus expressed in the Paris Agreement on Climate of December 2015 also has diminished the force of the arguments skeptics used to throw doubt on the reality of human-caused climate change. We will never know much the contrary publicity about the hiatus held up agreement, particularly in the United States. Thankfully, the hiatus in international decisionmaking has also come to an end.

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Endnotes

1. *Climate Change Evidence & Causes—An Overview from the Royal Society and the US National Academy of Sciences* (February 2014).

2. Schmidt, G. A., D. T. Shindell, and K. Tsigaridis. "Reconciling Warming Trends." *Nature Geoscience* 7 (March 2014): 158–60.

w Briggs, S., C. F. Kennel, and D. G. Victor. "Planetary Vital Signs." *Nature Climate Change* 5, no. 11 (2015): 969–970.

3. Kauffman, R. K., H. Kauppi, M. L. Mann, and J. H. Stock. "Reconciling Anthropogenic Climate Change with Observed Temperature 1998–2008." *PNAS* 108, no. 29 (2011): 11790–3. doi:10.1073/pnas.1102467108

4. Hansen, J., P. Kharecha, and M. Sato. "Climate Forcing Growth Rates: Doubling Down on Our Faustian Bargain." *Environ. Res. Letts.* 8 (2013). Open access. doi:10.1088/1748-9326/8/1/011006

5. Balmaseda, M. A., K. E. Trenberth, and E. Källén. "Distinctive Climate Signals in Reanalysis of Ocean Heat Content." *Geophysical Research Letters* 40, no. 9: 1754–9. doi:10.1002/grl.50382

6. Solomon, S., et al. "The Persistently Variable 'Background' Stratospheric Aerosol Layer and Global Climate Change." *Science* 333, no. 6044 (2011): 866.

7. Kauffman, R. K., et al., "Reconciling Anthropogenic Climate Change with Observed Temperature 1998–2008," 11790–3.

8. Klimont, Z., S. J. Smith, and J. Cofala. "The Last Decade of Global Anthropogenic Sulfur Dioxide: 2000–2011 Emissions." *Environ. Res. Lett.* 8, no. 1 (2013). Open access. doi:10.1088/1748-9326/8/1/014003

9. Shahbaz, M., S., Farhani, and I. Ozturk. "Coal Consumption, Industrial Production, and CO2 Emissions in China and India." Munich Personal RePEc Archive (paper 50618). Retrieved from http://mpra.ub.uni-muenchen.de/50618/

10. Kopp, G., and J. Lean. "A New Lower Value of Solar Irradiance: Evidence and Climate Significance." *Geophysical Research Letters* 38 (2011): L01706. Open access. doi:10.1029/2010GL045777

11. Hansen, J., M. Sato, P. Kharecha, and K. von Schuchmann. "Earth's Energy Balance and Implications." *Atmospheric Chemistry and Physics* 11 (2011): 13421–49.

12. Loeb, N., et al. "Observed Changes in Top-of-the-Atmosphere Radiation and Upper-Ocean Heating Consistent within Uncertainty," *Nature Geoscience Letters* 5 (2012). doi:10.1038/NGEO1375

13. Cane, M. A., and S. E. Zebiak. "A Theory for El Niño and the Southern Oscillation." *Science* 228 (1985): 1085–6.

14. Loeb, N., et al, "Observed Changes in Top-of-the-Atmosphere Radiation and Upper-Ocean Heating Consistent within Uncertainty." doi:10.1038 NGEO1375

15. England, M. H., et al. "Recent Intensification of Wind-Driven Circulation in the Pacific and the Ongoing Warming Hiatus." *Nature Climate Change* 4 (2014): 222–7. doi:10.1038/nclimate2106

16. Meehl, G. A., et al. "Model-based Evidence of Deep Ocean Heat Uptake during Surface Temperature Hiatus Periods," *Nat. Clim. Change* 1 (2011): 360–4. doi:10.1038/NCLIMATE1229

17. Balmaseda, M. A., et al., "Distinctive Climate Signals in Reanalysis of Ocean Heat Content," 1754–9.

18. Kosaka, Y., and S.-P. Xie. "Recent Global Warming Hiatus Tied to Equatorial Pacific Surface Cooling." *Nature* 501 (2013): 403–7. doi:10.1038/nature12534

19. Chen, X., and K.-K. Tung. "Varying Planetary Heat Sink Led to Global-Warming Slowdown and Acceleration." *Science* 345 (2014): 897–903. doi:10.1126/science.1254937

20. Manabe, S., and R. J. Stouffer. "Sensitivity of a Global Climate Model to an Increase of CO2 Concentration in the Atmosphere." *J. Geophys. Res.* 85 (1980): 5529.

21. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment (ACIA) Overview Report* (2004).

22. Jeffries, M. O., J. E. Overland, and D. K. Perovich. "The Arctic Shifts to a New Normal." *Physics Today* (October 2013): 35–40.

23. Wadhams, P. "The Polar Regions." Paper prepared for a joint symposium of the Pontifical Academy of Sciences and the Pontifical Academy of Social Sciences on Sustainable Humanity. Sustainable Nature: Our Responsibility, Vatican City (2014).

24. Graversen, R., et al. "Vertical Structure of Recent Arctic Warming." *Nature* 451 (2008): 53–6.

25. Screen, A., C. Deser, and I. Simmonds. "Local and Remote Controls on Observed Arctic Warming." *Geophysical Research Letters* 39 (2012): L10709. doi:10.1029/2012GL051598

26. Serreze, M., and R. G. Barry. "Processes and Impacts of Arctic Amplification: A Research Synthesis." *Global and Planetary Change* 77 (2011): 85–96.

27. Pistone, K., I. Eisenman, and V. Ramanathan. "Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice." *Proceedings of the National Academy of Sciences* 111 (2014): 3322–6. doi:10.1073/pnas.1318201111

28. Giles, K. A., et al. "Western Arctic Freshwater Storage by Wind-Driven Spin-Up of the Beaufort Gyre." *Nature Geoscience* 5 (2012): 194–7. doi:10.1038/ngeo1379

29. Coumou, D., and S. Rahmstorf. "A Decade of Weather Extremes." *Nature Climate Change* 2 (2012): 491–6. doi:10.1038/nclimate1452

30. Pall, P., et al. "Anthropogenic Greenhouse Gas Contribution to Flood Risk in England and Wales in Autumn 2000." *Nature* 470 (2011): 382–6.

31. World Meteorological Organisation. *State of the Climate in 2007* (2009).

32. Coumou, D., and S. Rahmstorf, "A Decade of Weather Extremes," 491–6.

33. World Meteorological Organization. (2010). *Weather Extremes in a Changing Climate: Hindsight on Foresight, Current Extreme Weather Events* (World Meteorological Organization, Geneva).

34. Hong, C. et al. "Roles of European Blocking and Tropical–Extratropical Interaction in the 2010 Pakistan Flooding." *Geophys. Res. Lett.* 38 (2011): L13806.

35. Intergovernmental Panel on Climate Change. "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation," (eds., C. B. Field, et al.), pp. 1–19. New York: Cambridge University Press, 2012.

36. Coumou, D., and S. Rahmstorf, "A Decade of Weather Extremes," 491–6.

37. Barriopedro, D., et al. "The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe." *Science* 332, no. 6026 (2011): 220–4.

38. Hansen, J., M. Sato, and R. Ruedy. "Perception of Climate Change." *Proceedings of the National Academy of Sciences* 109, no. 3 (2012): E2415–23. doi:10.1073/pnas.1205276109

39. Hoskins, B. J., and D. J. Karoly. "The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing." *J. Atmos. Sci.* 38 (1981): 1179–96. doi:10.1175/1520-0469(1981)038<1179:TSLROA>2.0.CO;2

40. Francis, J., et al. "Winter Northern Hemisphere Weather Patterns Remember Summer Arctic Sea-Ice Extent." *Geophysical Research Letters* 36 (2009): L07503. doi:10.1029/2009GL037274

41. Semenov, A. "Arctic Warming Favours Extremes." *Nature Climate Change* 2 (2012): 315–6. doi:10.1038/nclimate1502

42. Tang, Q., X. Zhang, X. Yang, and J. A. Francis. "Cold Winter Extremes in Northern Continents Linked to Arctic Sea Ices Loss." *Environ. Res. Lett.* 8 (2013). Open access. doi:10.1088/1748-9326/8/1/014036

43. Cohen, J., et al. "Winter 2009–2010: A case Study of an Extreme Arctic Oscillation Event." *Geophysical Research Letters* 37, no. 17 (2010). doi:10.1029/2010GL044256

44. Hoskins, B. J., and D. J. Karoly, "The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing," 1179.

45. Kaiser, J., K. Dethloff, and D. Handorf. "Stratospheric Response to Arctic Sea Ice Retreat and Associated Planetary Wave Propagation Changes." *Tellus A* (2013). Retrieved from http://www.tellusa.net/index.php/tellusa/article/view/19375

46. Francis, J. A., and S. J. Vavrus. "Evidence Linking Arctic Amplification to Extreme Weather at Mid-Latitudes." *Geophysical Research Letters* 39 (2012): L06801. doi:10.1029/2012GL051000, 2012

47. Petoukhov, V., et al. "Quasiresonant Amplification of Planetary Waves and Recent Northern Hemisphere Weather Extremes." *Proceedings of the National Academy of Sciences* 110 (2013): 5336–41. doi:10.1073/pnas.1222000110

48. Slonosky, V. C., L. A. Mysak, and J. Derome. "Linking Arctic Sea-Ice and Atmospheric Circulation Anomalies on Interannual and Decadal Timescales." *Atmos. Ocean* 35 (1997): 333–66. doi:10.1080/07055900.1997.9649596

49. Slonosky, V. C., L. A. Mysak, and J. Derome, "Linking Arctic Sea-Ice and Atmospheric Circulation Anomalies on Interannual and Decadal Timescales," 333–66.

50. Overland, J. "Atmospheric Science: Long-Range Linkage." *Nature Climate Change* 4 (2014): 11–12. doi:10.1038/nclimate2079

51. Chen W., X. Lan, L. Wang, and Y. Ma. "The Combined Effects of the ENSO and the Arctic Oscillation on the Winter Climate Anomalies in East Asia." *Chinese Science Bulletin* 58 (2013): 1355–62. doi:10.1007/s11434-012-5654-5

52. Lee, S. “Testing of the Tropically Excited Arctic Warming Mechanism (TEAM) with Traditional El Niño and La Niña.” *Journal of Climate* 25 (2012): 4015–22.

53. Li, F., H. Wang, and J. Liu. “The Strengthening Relationship between Arctic Oscillation and ENSO after the Mid-1990s.” *Intl. J. Climatology* 34 (2014): 2515–21. doi:10.1002/joc.3828

54. Wu, B., J. Wang, and J. E. Walsh. “Dipole Anomaly in the Winter Arctic Atmosphere and Its Association with Sea Ice Motion.” *J. Clim.* 19 (2006): 210–25. doi:10.1175/JCLI3619.1

55. Wang, J., et al. “Is the Dipole Anomaly a Major Driver to Record Lows in Arctic Summer Sea Ice Extent?” *Geophys. Res. Lett.* 36 (2009): L05706. doi:10.1029/2008GL036706

56. Yuan, X. “ENSO-Related Impacts on Antarctic Sea Ice: A Synthesis of Phenomenon and Mechanisms.” *Antarctic Science* 16, no. 4 (2004): 415–25.

57. Yamasaki, K., A. Gozolchiani, and S. Havlin, *Phys. Rev. Lett.* 100 (2008), 228501; Tsonis, A. A. and K. L. Swanson, *Phys. Rev. Lett.* 100 (2008), 228502; Donges, J. F., Y. Zou, N. Marwan, and J. Kurths, *Europhys. Lett.* 87 (2009), 48007; Berezin, Y., et al., *Nature Scientific Reports* 2 (2012), 666; Gozolchiani, A., S. Havlin, and K. Yamasaki, *Phys. Rev. Lett.* 107 (2011), 148501; Donges, J. F., Y. Zou, N. Marwan, and J. Kurths, *Eur. Phys. J. Special Topics* 174 (2009), 157; Guez, O., et al., *Europhys. Lett.* 98 (2012), 38006.

58. Chen, X., and K.-K. Tung. “Varying Planetary Heat Sink Led to Global-Warming Slowdown and Acceleration.” *Science* 345 (2014): 897–903. doi:10.1126/science.1254937

59. Stroeve, J. C., et al. “Changes in Arctic Melt Season and Implications for Sea Ice Loss.” *Geophys. Res. Lett.* 41 (2014). doi:10.1002/2013GL058951

60. Stroeve, J. C., et al. “Changes in Arctic Melt Season and Implications for Sea Ice Loss.” *Geophys. Res. Lett.* 41 (2014). Open access. doi:10.1002/2013GL058951

61. Serreze, M. C., et al. “The Emergence of Surface-Based Arctic Amplification.” *Cryosphere* 3 (2009): 11–19. doi:10.5194/tc-3-11-2009

62. Masson-Delmotte, V., et al. 2013. Information from Paleoclimate Archives. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Stocker, T. F., et al). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

63. Boykoff, M. T. “Media Discourse on the Climate Slowdown.” *Nature Climate Change* 4 (2014): 156–8. doi:10.1038/nclimate2156

64. Victor, D. G., and C. F. Kennel. “Ditch the 2 Degrees C Warming Goal.” *Nature* 514, no. 7520 (2014): 30–1.