Review of the consensus and asymmetric quality of research on human-induced climate change

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Abstract
Climate science is a massively interdisciplinary field with different areas understood to varying degrees. One area that has been well understood for decades is the fundamental fact that humans are causing global warming. The greenhouse effect has been understood since the 1800s, and subsequent research has refined our understanding of the impact of increased concentrations of greenhouse gases on the planet. Also increasing has been the consensus among the world's climate scientists that the basic principles of anthropogenic global warming (AGW) are correct. This has been demonstrated by multiple reinforcing studies that the consensus of scientists on the basic tenets of AGW is nearly unanimous. Nevertheless, the general public in many countries remains unconvinced not only of the existence of AGW, but also of the degree of scientific consensus. Additionally, there remain a few high-profile scientists who have continued to put forth alternative explanations for observed climatic changes across the globe. Here, we summarize research on the degree of agreement amongst scientists and we assess the quality of scholarship from the contrarian scientists. Many major contrarian arguments against mainstream thinking have been strongly challenged and criticized in the scientific literature; significant flaws have often been found. The same fate has not befallen the prominent consensus studies.

Measurements of scientific consensus on AGW

The evolution of scientific understanding is often characterized by novel studies that propose new and alternative explanations to the existing behaviors of the natural world. These explanations may or may not be initially accepted by their colleagues; however, further investigations are pursued to test the concepts.

This evolution has occurred in climate science in general and on the human impact on climate in particular. The first significant studies of the impact of increasing greenhouse gases on the Earth's climate were published more than 100 years ago (Fourier, 1824; Tyndall 1861; Arrhenius, 1896). In the following decades, the details of AGW were refined but the basic principles were already established.

Despite this solidification of the scientific community around the basic tenets of AGW, the general public has remained unconvinced with sizable populations either dismissive of AGW in general or dismissive of scientific consensus (Zimmerman, 2008; Doran and Zimmerman, 2009; Leiserowitz et al., 2011; Leiserowitz et al., 2012; Pew, 2012).

In order to establish the extent of the current scientific consensus, a number of different approaches have been pursued. Naomi Oreskes performed a seminal study on the scientific consensus (Oreskes, 2004) that involved the evaluation of 928 peer-reviewed journal articles published between 1993 and 2003 that were found using a literature search of "global climate change". The study used six different classifications for the abstracts: 1) endorsement of AGW, 2) evaluation of impacts, 3) mitigation proposals, 4) methods, 5) paleoclimate reconstructions, and 6) rejection of AGW. The author found 75% of the reviewed papers were in the first three categories as either explicit or implicit endorsements, while the remaining papers dealt were in categories 4 and 5. No papers fell into category 6.

A second study used a different methodology assessing the consensus of the basic tenets of climate change (Zimmerman, 2008; Doran and Zimmerman, 2009). There, the authors accessed a large dataset of Earth scientists (10,257 total) and requested the completion of an electronic survey. The survey was carried out through a professional survey site that limited answers to one for each invitation. Of the 3,146 respondents, more than 90% had a PhD and approximately 97% had advanced degrees. 267 respondents were actively publishing climate scientists with more than 50% of their publications in this area.

The respondents were asked a series of questions associated with their expertise, their perception of the causes of climate change, and their perception of the view of their colleagues. Perhaps the most critical question was number two in the survey, "Do you think human activity is a significant contributing factor in changing mean global temperatures?"

Based on the responses, the authors categorized the level of agreement with basic AGW tenets and expertise. They found that in general, as expertise level increased, so too did the consensus. For the most active climate scientists, approximately 97% agreed by answering "yes" to question number two. Despite this overwhelming agreement, the authors noted that only 47% of the general US population believes there is a scientific consensus.

The third significant work on scientific consensus was completed in 2010 (Anderegg et al., 2010). The approach taken in this study was to collect a listing of prominent climate researchers by utilizing authorship of significant climate-related documents. The list encompassed 1,372 researchers who were segregated into two groups (unconvinced by the evidence [UE], and convinced by the evidence [CE]). The authors were ranked by their expertise and prominence. Expertise was based on the number of climate-relevant publications authored by the scientist whereas prominence was measured by the impact of the published papers (number of citations of a researcher's four most cited papers). Among the conclusions of Anderegg et al., (2010) was that only 2% of the top 50 scientists fell into the UE category. They also found that on average, the UE authors as a group possessed a lower expertise and a lower prominence than the CE researchers. For instance, the average number of publications of the UE group was only half that of the CE population.

A subsequent survey of scientists affiliated with the American Meteorological Society (AMS) and the American Geophysical Union (AGU), with 489 participants, found that 97% agreed that global temperatures had increased in the past 100 years (Farnsworth and Lichter, 2012). 84% agreed that human-induced warming was occurring while 5% disagreed. Multivariate analysis found that whether scientists worked for government or industry had no influence on their climate opinions. However, scientists in academia were more pessimistic about future climate change. This analysis suggests that scientists' climate opinions are not based on workplace pressures or desires to further their own careers.

Recently, a study was published (Cook et al., 2013) which, similar to Oreskes (2004), surveyed the climate science literature. The authors examined over 12,000 abstracts from 1991-2011 dealing with "global climate change" or "global warming". They found that 66% of the abstracts expressed no position on AGW, 33% endorsed AGW, and 1% were either dismissive or uncertain. Among those abstracts that expressed a position on AGW, 97% supported the basic tenets. Cook et al. further invited the authors to self-rate their own manuscripts and similarly, among the 774 respondents whose research expressed a position on the basic tenets of AGW, 97% were affirmative.

Taken together, these studies are mutually reinforcing in their findings about the view amongst climate scientists about the human impacts on climate change. Those findings are: 1) there is near unanimity of consensus on the basic tenets of AGW, 2) the expertise of the scientists who agree with AGW is greater than of those that dissent, 3) the results are robust to various means of measure, and 4) the general public is not aware of the strong consensus.

It must be mentioned that these above statements should not be interpreted to mean there is no active research in climate change or areas of disagreement. In fact, after consensus on basic tenets is reached, science typically moves to new questions which help solidify the community's basic understanding (Shwed and Bearman, 2010). For instance, there are real questions about the role of natural variability in temporarily masking human-induced warming, the impact of human and volcanic aerosols and changes to extreme weather, among others (Francis and Vavrus, 2012; Greene et al., 2013; Tang et al., 2013; Fyfe et al., 2013; Schmidt et al., 2014; Visbeck, 2014; Santer et al., 2014; Trenberth and Fasullo, 2014; Wallace et al., 2014). These active areas of research are not focused on the basic and well-understood principles that human-emitted greenhouse gases are increasing, the Earth is being observed to warm, the Earth will continue to warm in the future, and that equilibrium warming for a doubling of carbon dioxide will be in the 1.5-4.5°C range (IPCC, 2001; IPCC 2007; Knutti and Hegerl, 2008; IPCC, 2013).

The strength of this conclusion on consensus is made stronger when official statements of authoritative bodies are considered. The leading expert body on assessing climate change is the Intergovernmental Panel on Climate Change (IPCC). As such, the IPCC has issued a series of increasingly definitive statements on the attribution of recent global warming that represent the evolving consensus position. The IPCC Second Assessment Report stated, "The balance of evidence suggests that there is a discernible human influence on the global climate" (IPCC, 1995). This position was strengthened in the Third Assessment Report in 2001, which concluded, "most of the warming observed over the last 50 years is attributable to human activities" (IPCC, 2001). A stronger IPCC statement on attribution came in the subsequent Fourth Assessment Report, concluding that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" with "very likely" defined as greater than 90% probability (IPCC, 2007). Most recently, the 2013 IPCC Fifth Assessment Report stated that evidence has strengthened further so that it is "extremely likely" (greater than 95% probability) that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC, 2013).

In addition to the IPCC, the national academies of at least 80 countries have implicitly or explicitly endorsed the consensus position (e.g. G8 + 5 Academies, 2009; NASAC, 2007; Joint Academies' statement, 2005; US National Academy and Royal Society joint statement, 2014). Concurring statements have also been issued by relevant professional organizations including the American Association for the Advancement of Science, American Geophysical Union, American Meteorological Society, European Geosciences Union, Geological Society of America, Geological Society of London, and Royal Meteorological Society. An open letter to the United States Senate urging steps to avoid severe impacts from climate change and affirming the consensus has been signed by an additional 15 professional societies. Governmental agencies tasked with studying the climate system, such as the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, United States Geological Survey, Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation have taken similar positions in endorsing the consensus.

The aforementioned consensus studies and community statements reflect nearly complete unanimity of the scientific community on the basic tenets of AGW.

The psychological significance of the "consensus gap"

Public perception of scientific consensus is important on several fronts. When forming views on complex scientific topics, the public relies on convenient heuristics such as the opinion of trusted sources of information. Public perception of scientific consensus also correlates with a number of important beliefs and attitudes, such as concern about the seriousness of climate change and support for mitigation policies (Ding et al., 2011; McCright et al., 2013). Malka et al. (2009) found perception of consensus mediates the relationship between climate knowledge and climate concern. That is, learning more about climate change yields perceptions of higher consensus, which causes increased concern. These findings reinforce others that communicating the scientific consensus increases people's understanding that climate change is happening (Lewandowsky et al., 2012; Bolsen et al., 2013).

However, arguably the most crucial element of consensus is the fact that public perception of scientific consensus is associated with support for mitigation policies (Ding et al., 2011; McCright et al., 2013). When the public think scientists disagree about AGW, they are less likely to support climate action. Consequently, the "consensus gap" representing the discrepancy between public perception and the overwhelming consensus among scientists has significant societal consequences.

Difficulties in conveying consensus to broad public

Over the past few decades, there have been active efforts to minimize public awareness of the expert climate consensus. Efforts by opponents of tobacco regulations, which first were employed to manufacture doubt about the scientific consensus linking smoking to cancer, have transitioned to climate science (Oreskes and Conway, 2010).

One technique has been through circulation and publication of petitions of persons who dismiss the science or by amplifying the voices of vanishingly few scientists who downplay the potential impacts of climate change. Often, these contrarian "experts" are presented as representing a sizable fraction of the climate science population, when in fact they are a very small minority.

One argument often presented is that consensus does not guarantee truth, and we agree. A scientific consensus is only robust when multiple lines of study confirm it. With respect to the basic tenets of AGW, it is reinforced by a wide diversity of observations, theoretical studies, and numerical simulation. Among these are temperature measurements in the oceans, land surface areas, and atmosphere clearly showing increases of thermal energy; satellite measurements showing changes to the net flow of heat at the top of the Earth's atmosphere; measurements of sea level rise; land and polar ice loss; paleoclimate variations driven partly by past greenhouse gas levels; and fingerprint signatures in the spatial patterns of climate change that point to human emissions as the principle force, just to list a few.

Despite the mutually reinforcing lines of observational evidence, there exists a persistent, small minority of contrarian climate scientists. It is possible that a small minority of talented individuals is more able to assess science than a larger body of experts. One way to investigate this potential is to retrospectively view the success or failure of major contrarian arguments in the past few decades to see how they were responded to in the scientific literature. Have the prominent contrarian views been widely accepted and adopted or has their importance been minimized by critiques and rebuttals that have been leveled in the literature?

To explore this potential, we have identified two of the most prominent arguments made against the AGW consensus: 1) the climate is not warming and 2) the Earth is not very sensitive to climate change and there are strong natural processes which will moderate climate change as emissions continue to rise (negative feedbacks). These two contrary views have been presented numerous times over the past two decades, and in hindsight it is possible to evaluate their intellectual merit.

Past scientific arguments contradictory to the AGW consensus

The Earth is not warming

Perhaps the most common argument to appear which counters the consensus AGW viewpoint is that the Earth is not warming. While recently this viewpoint has been associated with incorrect notion that the Earth surface has not, for example, warmed in the past 15 years

(Bloomberg, 2013; New York Times, 2013), it often is conflated with the concept that global warming has stopped. This, too, is false, as evident by measurements reported in numerous articles, such as Nuccitelli et al. (2012), Abraham et al. (2013), and Trenberth and Fasullo (2014). The foundation for many of the claims that the Earth has ceased or even slowed its warming is based on a selective assessment of small portions of the Earth system rather than the Earth as a whole.

However, the notion that parts of the Earth system which should warm with AGW are not warming perhaps had a genesis in the early 1990s when satellite temperature measurements became commonplace. Traditionally, Earth temperatures are measured by land-based temperature sensors; balloon sensors (radiosondes); temperature sensors on ships, buoys, or other ocean-going craft; and other instruments. Each of the different temperature-measuring methodologies suffers from limitations of geographical coverage and measurement accuracy. With the advancement of satellite measuring methodologies, it became possible to achieve near global coverage using microwave radiometers. The radiometers relate emission of atmospheric oxygen to temperatures throughout the atmosphere. With continuous and long-term records, it was possible to make longitudinal studies of the rate of temperature change in the troposphere and the stratosphere. A number of papers appeared in the early 1990s describing the methodology, accuracy, and findings (e.g. Spencer and Christy, 1990; Spencer and Christy 1993; Christy and Goodridge, 1995; Christy, et al., 1995; Christy and Spencer, 1995; Spencer, et al., 1996). Among the early findings was the surprising conclusion that the lower atmosphere of the Earth was cooling, in direct contradiction to the consensus AGW view.

Despite claims of accuracy from the authors, other researchers began to question the results (Hansen and Wilson, 1993; Schneider 1994; Hurrell and Trenberth, 1997; Hurrell and Trenberth, 1998; Wentz and Schabel, 1998) with many questions raised regarding the purported accuracy of the satellite measurements. Among the issues of concern were errors associated with merging satellite records, orbital decay of satellites as their altitude decreased over time, errors of on-board temperature calibration measurement systems, and drift in the time of observation and thus aliasing of the diurnal cycle.

The original authors defended the work in the scientific literature (Christy et al., 1997) and often pointed to comparisons of their measurements with weather balloon data (radiosondes) (e.g., Spencer and Christy, 1993; Christy and Spencer, 1995; Christy et al., 1998; Christy et al., 2000) as validation of the satellites. Meanwhile, as corrections were made to the methodology and new data were obtained, the original conclusions of a cooling troposphere were modified to show warming.

In the ensuing years, the critiques of the satellite records continued (Mears, et al., 2003; Mears and Wentz, 2005), which most notably identified an error in the diurnal correction of satellite drift (changes to the satellite orbit), an error acknowledged by the originators (Christy and Spencer, 2005).

The argument that comparisons with radiosonde data validated the satellite measurements was questioned when it was found that solar heating of the instruments or changes to instrumentation introduced errors in the measured temperatures (Sherwood et al., 2005; Randel and Wu, 2006). The accuracy of radiosonde temperature measurements and their utility in calibrating satellite data is still being dealt with in the literature (e.g., Thorne et al., 2005; Lanzante and Free, 2008; Allen and Sherwood, 2008; Santer et al., 2008; Titchner et al., 2009; Thorne et al., 2011;).

One other source of error has long been identified but still not fully quantified. It is the bias associated with the measurement instruments themselves on board the satellites. In particular, a warm calibration target is needed to relate the microwave emissions to atmospheric temperatures. When corrected, the trend in the middle part of the troposphere is found to be significantly greater than previously disclosed (Po-Chedley and Fu, 2012). This latest correction represents the still unsettled yet strongly rebutted satellite temperature trends and early claims of atmospheric cooling.

The result of this two-decade investigation is that the previously reported cooling of the atmosphere was based on faulty technique and equipment. In the ensuing years, various improvements have been made, and currently there is better agreement between different research teams measuring temperature trends in the lower and upper layers of the atmosphere. All data now shows that the lower atmosphere is heating (as expected) while the upper atmosphere is undergoing a long-term cooling trend (also as expected) because of increased emissions of greenhouse gases. This spatial behavior is a strong indicator that the temperature increases of the Earth's surface over the past 40 years is caused by greenhouse gas emissions (rather than by other causes such as increased solar activity). The evolution in estimated lower tropospheric temperature trends are shown in Figure 1.

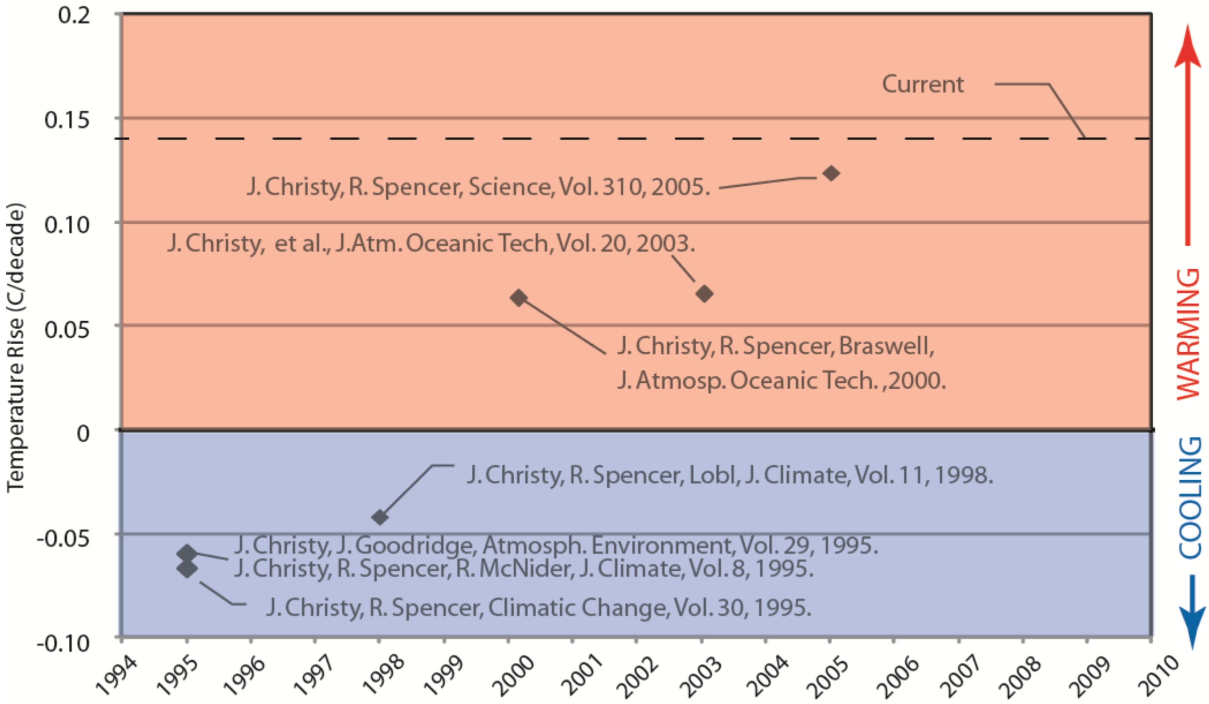

Figure 1. Evolution of lower tropospheric temperature trends from satellite observations.

The Earth has a natural climatic response that will offset greenhouse gas warming

There have been many arguments that suggest some natural phenomenon(a) will offset greenhouse gas warming (aside from the Planck response). The most commonly employed mechanism is some change to clouds that will cause a negative feedback (reduced warming) as greenhouse gases increase.

Among this group are studies reporting a specific cooling mechanism and studies that merely try to show by correlation that some undetermined mechanism exists. One attempt to suggest an actual mechanism was published in 2001 (Lindzen et al., 2001). The premise behind this work was that as the climate warms, the area covered by high cirrus clouds will contract to allow more heat to escape into outer space (similar to the iris in a human eye contracting to allow less light to pass through the pupil in a brightly lit environment). The so-called 'iris effect' would hypothetically increase the amount of outgoing infrared energy from the Earth, which would offset the added thermal energy to the Earth system and thereby counteract global warming.

While this concept gained much media attention, it was quickly and thoroughly rebutted within the scientific literature. Within approximately one year of publication of Lindzen et al., (2001), four refuting papers appeared (Fu et al., 2001; Hartmann and Michelsen, 2002; Lin et al., 2002; Del Genio and Kovari, 2002). These papers included numerous criticisms of the Lindzen et al., (2001) approach including the large geographical separation between deep convective clouds and those which experience variations in cloud-weighted sea surface temperatures (Hartmann and Michelsen, 2002). Another criticism was that clouds have a much higher reflectivity and larger infrared heat flows than the original study assumed (Lin et al., 2002). Also, the water vapor feedback from Lindzen et al., (2001) was overestimated by approximately 60% (Fu et al., 2001). Cloud observations from the Tropical Rainfall Measuring Mission did not support the hypothesis that tropical cirrus clouds contract with rising temperatures (Del Genio and Kovari, 2002). Finally, Lindzen et al., (2001) incorrectly estimated the impact of low tropical clouds (Lin et al., 2002).

The critiques of Lindzen continued throughout the years (Chambers et al., 2002; Lin et al., 2004; Rapp et al., 2005; Wong et al., 2006; and Trenberth and Fasullo, 2009), as did responses from proponents of the iris effect (Chou and Lindzen, 2005). The large volume of responses show that the scientific community took seriously the initial hypothesis but, despite years of investigation, found little evidence to support the conclusions of the proponents, and much evidence contradicting these conclusions.

Papers with the theme of low sensitivity/negative feedbacks have continued to appear in the literature. Among the most prominent was that of Spencer and Braswell (2008). It purported to examine how certain heat flows can contaminate the calculations of climate sensitivity from satellite observations. Shortly after its appearance in the literature, this manuscript was heavily criticized in a study that identified three significant errors (Murphy and Forster, 2010). Those errors were: 1) an unrealistic ocean mixed layer depth, 2) incorrect standard deviations of outgoing radiation, and 3) incorrect duration of calculations of model temperature variability. When these errors were corrected, the effect that was originally reported in Spencer and Braswell (2008) nearly disappeared.

A near contemporary to this study was published in 2009 (Lindzen and Choi, 2009). As with the lead author's earlier study on the so-called iris effect, this paper concluded that climate models overestimate the Earth's sensitivity to increases in greenhouse gases. They also claimed that the climate feedbacks observed from satellite sensors differed in character from the feedbacks predicted by computer models.

This paper was quickly responded to in the literature. Within approximately one year, four refutations appeared. For instance, Murphy (2010) showed that the Lindzen and Choi (2009) paper only focused on the tropics, yet applied their findings to the entire globe. Thereby, they neglected heat transport between different regions of the planet. They also made poor choices in their statistical methodology, which contributed to their low sensitivity estimate. Trenberth et al., (2010). Identified an even more substantial set of errors in the study. Those authors noted that Lindzen and Choi's choice for start and endpoints of their study were entirely subjective and that small modifications of the start and endpoints led to significant changes in conclusions. They also showed that Lindzen and Choi did not properly account for forcing in their statistical processing. Finally, Lindzen and Choi made a mathematical error in their computation of climate sensitivity. Other rebuttals (Chung et al., 2010; Dessler, 2010; Dessler, 2013) concurred with the prior analyses that the Lindzen and Choi low sensitivity results were unsupported by the evidence. A follow-on paper (Lindzen and Choi, 2011) was similarly rebutted by Dessler (2011) on methodological grounds.

One final example along this theme was published in 2011 (Spencer and Braswell, 2011), which purported to show that energy flows internal to the Earth system can corrupt analyses of the climate sensitivity. The authors suggested that when these internal effects are accounted for, the actual sensitivity of the Earth to greenhouse gases is lower than previously thought. This paper was quickly criticized by scientists in the media for its unsupported claims. The Editor-in-Chief of the publishing journal acknowledged and agreed with those criticisms; he resigned shortly after the paper was published (BBC, 2011). A rebuttal in the literature appeared promptly (Trenberth, et al., 2011), demonstrating a number of errors in the original paper. The identified errors included, 1) incorrect durations of model simulations, 2) unnecessary de-trending of results, 3) incorrect interpretation of modeling results, and 4) incorrectly implying causation of correlating phenomena (Dessler, 2011). As a result, the major conclusions of Spencer and Braswell (2011) were shown to be arbitrary and depend on subjective assumptions.

The examples highlighted in the preceding paragraphs show samples of high-profile publications on the topics of climate sensitivity and processes within the Earth's climate that purported to minimize future temperature variations. In these cases, there was quick reaction in the peer-reviewed literature, which cast strong doubt on the validity of the studies.

Commentary on scientific credibility

The case supporting the basic tenets of AGW is broad-based. It comes from observational evidence using many variables. It comes from understanding and theory that relates variables to one another in a consistent manner, based on established physical laws of nature and strong empirical relationships that have stood up to close scrutiny. It also comes from improved climate models and simulations of past climate for decades to millennia. Basic scientific methods encourage formulation of new hypotheses perhaps based on ideas, empirical relationships, or new observations, but they must be tested with independent data and analyses. In this way, a gradual coalescence has formed amongst the world's top climate scientists that humans are causing significant climate change. Of course, there are still areas of active debate, particularly associated with the role of climate change on extreme weather, on methodologies to improve climate measurements, and on the rate of evolution of the Earth's climate as the atmosphere changes (to name just a few). However, none of these areas of debate are significant challenges to the central tenets of AGW.

The above discussion has highlighted a few of the main scientific arguments proposed in contradiction with the consensus AGW viewpoint – ones that have not stood the test of time. The selected arguments were based on their impact in the public discussion of climate change and the rich literature available to assess their quality. These proponents are scientists and they have developed credentials in other parts of climate science, and hence they were taken seriously.

Consequently, the main contrarian arguments have invoked a series of investigations by expert research teams to verify their conclusions. In every case, it has been found that after a thorough review, the contrarian arguments did not survive scientific scrutiny unmarred. In fact, a surprisingly large number of the contrarian studies were directly refuted in the literature. This process reflects the normal scientific method in which claims made by a group of researchers are tested by independent groups.

In fact, there have been critical responses in the literature to many other contrarian articles which minimize the human impact on the climate or find fault with the mainstream AGW consensus or methodology: (Akasofu, 2013 ; Nuccitelli et al., 2013), (Mclean et al., 2009; Foster et al., 2010), (Douglass et al., 2008; Santer et al., 2008; Thorne et al., 2011), (Soon and Baliunas, 2003; Mann et al., 2003), and (Armstrong et al., 2008; Amstrup, et al., 2009) as separate examples on different topics. Another main contrarian argument has to do with the potential impact of solar variations and cosmic rays on climate. These too have been shown to be minor and, in many cases, the original works proposing such an impact were based on faulty data and/or analysis (Ammann et al., 2007; Bard and Frank, 2006; Benestad and Schmidt, 2009; Calogovic et al., 2010; Cubasch et al., 1997; Damon and Laut, 2004; Duffy, et al., 2009; Erlykin, Sloan and Wolfendale, 2009a; Erlykin, Sloan and Wolfendale, 2009b; Foukal, et al., 2004; Foukal et al., 2006; Kulmala et al., 2010; Laut, 2003; Legras et al., 2010; Lockwood and Frohlich, 2007; Sloan and Wolfendale, 2008; Solanki and Krivov, 2003; Trenberth and Fasullo, 2009). These topics have also been extensively reviewed in IPCC reports.

We do not intend this list to be exhaustive; there are many other examples that could be listed. Rather, these are representative of a seemingly frequent critical response following publication of contrarian AGW papers.

A few noteworthy comments are essential. First, in many of these examples, and in other examples not listed here, there were significant deficiencies in the analyses, which in many cases were conceded by the authors. It must be seen that these back and forth exchanges are the hallmark of the evolution of scientific development. In fact, the process of publishing rebuttals or critiques of contrarian views makes the field of science stronger.

With these comments as background, we conclude then that the quality of work of contrarian-view scientists, as showcased here by representative case studies, is notably lower than that of scientists who hold the consensus view. To our best knowledge, there are no comparable examples of major consensus viewpoints on the basic tenets of human-induced climate change that have been criticized to these extents in the literature or have been found to be fundamentally incorrect.

The observations showcased here were taken from the familiarity of the authors with the literature. These form the basis of a future systematic comparison of the rebuttal rate of contrarian view publications with those upholding the mainstream consensus. Such a systematic review would allow verification of the observations shown here.

Concluding remarks

It has been clearly shown by independent and complementary studies that the vast majority of climate scientists know that humans are causing significant changes to the Earth's climate. Regardless of the methodology, as a scientist's expertise and prominence increase, she or he is more likely to hold the consensus view. At the same time, there remain some issues in climate change science that have yet to be resolved. While these are important details, they do not undermine the view that there are basic observational and theoretical facts that are at the core of AGW.

In order to assess the quality of science representing the contrarian view, we have identified some of the most prominent themes of contrarian view (the Earth is not warming and the climate is not very sensitive to greenhouse gases because of an internal temperature-regulation mechanism). The selection of these two themes was a judgment by the present authors based on their significant roles in shaping public opinion, the frequency these themes are invoked in public discourse, and the rich history associated with their development.

We find that the scientific literature includes a series of strong responses from the mainstream scientific community including criticisms, corrections, and in some cases, resignation of editors. The contrarian views were often found to be unsubstantiated by the data and are no longer seriously considered by many climate scientists.

Insofar as these contrarian themes are representative of other contrarian viewpoints, our findings reinforce those of Anderegg et al., (2010) who found lower expertise and prominence among the contrarian scientists and those of Doran and Zimmermann (2009) who found that as scientific expertise increased, so did certainty in the main premises of AGW. Here we find case study evidence that the science representing major contrarian views is less robust than the counterparts that reflect the AGW consensus.

References

John P. Abraham et al., "A review of global temperature observations: Implications for ocean heat content estimates and climate change", Reviews of Geophysics, 2013, vol. 51, pp. 450-483.

Syun-Ichi Akasofu, « On the present halting of global warming », Climate, 2013, 1, pp. 4-11.

Robert J. Allen and Steven C. Sherwood, "Warming maximum in the tropical upper troposphere deduced from thermal winds", Nature Geoscience, 2008, vol. 1, pp. 399-403.

Caspar M. Ammann et al., "Solar influence on climate during the past millennium: Results from transient simulations with the NCAR climate system model", Proceedings from the National Academy of Sciences of the United States of America, 2007, vol. 104, pp. 3713-3718.

Steven C. Amstrup, et al., "Rebuttal of 'polar bear population forecasts: A public-policy forecasting audit'", Interfaces, 2009, vol. 39, pp. 363-369.

William R.L. Anderegg et al., "Expert credibility in climate change", Proceedings of the National Academy of Sciences of the United States of America, 2010, vol. 107, pp. 12107-12109.

J. Scott Armstrong, Kersten C. Green, and Willie Soon, "Polar bear population forecasts: A public policy forecasting audit", Interfaces, 2008, vol. 38, pp. 382-405.

Svante Arrhenius, "On the Influence of carbonic acid in the air upon temperature of the ground", The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science Series 5, 1896, vol. 41, pp. 237-276.

Edouard Bard and Martin Frank, "Climate change and solar variability: What's new under the sun?", Earth and Planetary Science Letters, 2006, vol. 248, pp. 1-14.

Rasmus E. Benestad and Gavin A. Schmidt, "Solar trends and global warming", Journal of Geophysical Research, 2009, vol. 114, paper D14101.

Bloomberg News, "Mystery of the 'missing' global warming," October 23, 2013 (http://www.bloomberg.com/news/2013-10-23/mystery-of-the-missing-global-warming.html)

British Broadcasting Corporation (BBC), "Journal editor resigns over 'problematic' climate paper", September 2, 2011 (http://www.bbc.co.uk/news/science-environment-14768574).

Toby Bolsen, Thomas J. Leeper, Matthew A. Shapiro, "Doing what others do: Norms, science, and collective action on global warming", American Politics Research, 2013, Vol. 42.

Jasa Calogovic et al., "Sudden cosmic ray decreases: No change in global cloud cover", Geophysical Research Letters, 2010, vol. 37, paper L03802.

Lin H. Chambers, Bing Lin, and David F. Young, "Examination of new CERES data for evidence of tropical iris feedback", Journal of Climate, 2002, vol. 15, pp. 3719-3726.

Ming-Dah Chou and Richard S. Lindzen, "Comments on 'Examination of the decadal tropical mean ERBS nonscanner radiation data for the iris hypothesis'", Journal of Climate, 2005, vol. 18, pp. 2123-2127.

John R. Christy and Roy W. Spencer, "Assessment of precision in temperatures from the microwave sounding units", Climatic Change, 1995, vol. 30, pp. 97-102.

John R. Christy and James D. Goodridge, "Precision global temperatures from satellites and urban warming effects of non-satellite data", Atmospheric Environment, 1995, vol. 29, pp. 1957-1961.

John R. Christy, Roy W. Spencer, and Richard, T. McNider, "Reducing noise in the MSU daily lower-tropospheric global temperature dataset", Journal of Climate, 1995, vol. 8, pp. 888-896.

John R. Christy, Roy W. Spencer, and William D. Braswell, "How accurate are satellite thermometers?", Nature, 1997, vol. 389, p. 342.

John R. Christy, Roy W. Spencer, and Elena S. Lobl, "Analysis of the merging procedure for the MSU daily temperature time series", Journal of Climate, 1998, vol. 11, pp. 2016-2041.

John R. Christy, Roy W. Spencer, and William D. Braswell, "MSU tropospheric temperatures: Dataset construction and radiosonde comparisons", Journal of Atmospheric and Oceanic Technology, 2000, vol. 17, pp. 1153-1170.

John R. Christy, et al., "Error estimates of the version 5.0 of MSU-AMSU bulk atmospheric temperatures", Journal of Atmospheric Oceanic Technology, 2003, vol. 20, pp. 613-629.

John R. Christy and Roy W. Spencer, "Correcting temperature data sets", Science, 2005, vol. 310, p. 972.

Eui-Seok Chung, Brian J. Soden, and Byung-Ju Sohn, "Revisiting the determination of climate sensitivity from relationships between surface temperature and radiative fluxes", Geophysical Research Letters, 2010, vol. 37, paper L10703.

John Cook, et al., (2013). "Quantifying the consensus on anthropogenic global warming in the scientific literature", Environmental Research Letters, 2013, vol. 8, paper no. 024024.

Ulrich Cubasch, et al., "Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model", Climate Dynamics, 1997, vol. 13, pp. 757-767.

Paul E. Damon and Peter Laut, "Pattern of strange errors plagues solar activity and terrestrial climate data", EOS, 2004, vol. 85, pp. 370, 374.

Anthony D. Del Genio and William Kovari, "Properties of tropical precipitating convection under varying environmental conditions", Journal of Climate, 2002, vol. 15, pp. 2597-2615.

Andrew E. Dessler, "A determination of the cloud feedback from climate variations over the last decade", Science, 2010, vol. 330, pp. 1523-1527.

Andrew E. Dessler, “Cloud variations and the Earth’s energy budget”, Geophysical Research Letters, 2011, vol. 38, paper L19701.

Andrew E. Dessler, “Observations of climate feedbacks over 2000-10 and comparisons with climate models”, Journal of Climate, 2013, pp. 333-342.

Ding Ding, Edward W. Maibach, Xiaoquan Zhao, Conni Roser-Renouf, and Anthony Leiserowitz, “Support for climate policy and societal action are linked to perceptions about scientific agreement”, Nature Climate Change, 2011, vol. 1, pp. 462–466.

Peter Doran and Margaret R.K. Zimmerman, “Examining the scientific consensus on climate change”, Eos, 2009, vol. 90, 22-23.

David H. Douglass, et al., “A comparison of tropical temperature trends with model predictions”, International Journal of Climatology, 2008, vol. 28, pp. 1693-1701.

Philip B. Duffy, Benjamin Santer, and Tom M.L. Wigley, “Solar variability does not explain late-20th-century warming”, Physics Today, January 2009, pp. 48-49.

Anatoly D. Erlykin, Terry Sloan, and Arnold W. Wolfendale, “The search for cosmic ray effects on clouds”, Journal of Atmospheric and Solar-Terrestrial Physics, 2009a, vol. 71, pp. 955-958.

Anatoly D. Erlykin, Terry Sloan, and Arnold W. Wolfendale, “Solar activity and the mean global temperature”, Environmental Research Letters”, 2009b, vol. 4, paper 014006.

Steven J. Farnsworth and Robert Lichter, “The structure of scientific opinion on climate change”, International Journal of Public Opinion Research, 2012, vol. 24, 93-103.

Grant Foster et al., “Comment on: ‘Influence of the Southern Oscillation on tropospheric temperature’ by J.D. McLean, C.R. de Freitas, and R. M. Carter”, Journal of Geophysical Research, 2010, vol. 115, paper D09110.

Peter Foukal, Gerland North, and Tom Wigley, “A stellar view on solar variations and climate”, Science, 2004, vol. 306, pp. 68-69.

Peter Foukal, et al., “Variations in the solar luminosity and their effect on the Earth’s climate”, Nature, 2006, vol. 443, pp. 161-166.

Jean-Baptiste Joseph Fourier, “On the temperature of the terrestrial sphere and interplanetary space”, Memoires de l’Academie Royale des Sciences, 1824, vol. 7, pp. 569-604.

Jennifer A. Francis and S. J. Vavrus, “Evidence linking Arctic amplification to extreme weather in mid-latitudes”, Geophysical Research Letters, 2012, vol. 39, paper L06801.

Qiang Fu, M. Baker, and Dennis L. Hartmann, “Tropical cirrus and water vapor: an effective Earth infrared iris feedback?” Atmosphere Chemistry and Physics Discussions, 2001, vol. 1, pp. 221-238.

John C. Fyfe et al., “Surface response to stratospheric aerosol changes in a coupled atmosphere-ocean model”, Geophysical Research Letters, 2013, vol. 40, pp. 584-588.

G8 + 5 Academies, G8+5 Academies’ joint statement: Climate change and the transformation of energy technologies for a low carbon future, 2009. http://www.nationalacademies.org/includes/G8+5energy-climate09.pdf

Charles H. Greene, Jennifer A. Francis, and Bruce C. Monger, “Superstorm Sandy: A series of unfortunate events?”, Oceanography, 2013, vol. 26, pp. 8-9.

James E. Hansen and Helene Wilson, “Commentary on the significance of global temperature records”, Climatic Change, 1993, vol. 25, pp. 896-910.

Dennis L. Hartmann and Marc L. Michelsen, “No evidence for iris”, Bulletin of the American Meteorological Society, 2002, vol. 83, pp. 249-253.

James W. Hurrell and Kevin E. Trenberth, “Spurious trends in satellite MSU temperatures from merging different satellite records”, Nature, 1997, vol. 386, pp. 164-167.

James W. Hurrell and Kevin E. Trenberth, “Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite microwave sounding unit records”, Journal of Climate, 1998, vol. 11, pp. 945-967.

IPCC Second Assessment Report (SAR), “Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, 1995”, Cambridge University Press, New York, NY, USA.

IPCC Third Assessment Report (TAR), "Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, 2001", Cambridge University Press, New York, NY, USA.

IPCC Fourth Assessment Report (AR4), "Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007", Cambridge University Press, New York, NY, USA

IPCC Fifth Assessment Report (AR5), "Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013", Cambridge University Press, New York, NY, USA

Joint Science Academies' Statement, "Global Response to Climate Change", 2005, available at http://www.academie-sciences.fr/actualites/textes/G8_gb.pdf#search=%22Joint%20Science%20Academies%E2%80%99%20Statement%3A%20Global%20Response%20to%20Climate%20Change%22

Reto Knutti and Gabriele C. Hegerl, "The equilibrium sensitivity of the Earth's temperature to radiation changes", Nature Geoscience, 2008, vol. 1, pp. 735-743.

Markku Kulmala, et al., "Atmospheric data over a solar cycle: No connection between galactic cosmic rays and new particle formation", Atmospheric Chemistry and Physics, 2010, vol. 10, pp. 1885-1898.

John R. Lanzante and Melissa Free, "Comparison of radiosonde and GCM vertical temperature trend profiles: Effects of dataset choice and data homogenization", Journal of Climate, 2008, vol. 21, pp. 5417-5435.

Peter Laut, "Solar activity and terrestrial climate: An analysis of some purported correlations", Journal of Atmospheric and Solar-Terrestrial Physics, 2003, vol. 65, pp. 801-812.

Bernard Legras, et al., "A critical look at solar-climate relationships from long temperature series", Climate of the Past, 2010, vol. 6, pp. 745-758.

Anthony Leiserowitz, et al., "Climate Change in the American Mind: Americans' Global Warming Beliefs and Attitudes in May 2011", Yale University and George Mason University, New Haven, CT, Yale Project on Climate Change Communication, 2011.

Anthony Leiserowitz, et al., "Climate change in the American mind: Americans' global warming beliefs and attitudes in September, 2012", Yale University and George Mason University, New Haven, CT: Yale Project on Climate Change Communication, 2012.

Stephan Lewandowsky, Gilles E. Gignac, and Samuel Vaughan, "The pivotal role of perceived scientific consensus in acceptance of science", Nature Climate Change, 2012, vol. 3, pp. 399-403.

Bing Lin, Bruce A. Wielicki, Lin H. Chambers, Yongxiang Hu, and Kuan-Man Xu, "The iris hypothesis: A negative or positive cloud feedback?" Journal of Climate, 2002, vol. 15, pp. 3-7.

Bing Lin, Takmeng Wong, Bruce A. Wielicki, and Yongxiang Hu, "Examination of the decadal tropical mean ERBS nonstanner radiation data for the iris hypothesis", Journal of Climate, 2004, vol. 17, pp. 1239-1246.

Richard S. Lindzen, Ming-Dah Chou, and Arthur Y. Hou, "Does the Earth have an adaptive infrared iris?", Bulletin of the American Meteorological Society, 2001, vol. 82, pp. 417-432.

Richard S. Lindzen and Yong-Sang Choi, "On the determination of climate feedbacks from ERBE data", Geophysical Research Letters, 2009, vol. 36, paper L16705.

Richard S. Lindzen and Yong-Sang Choi, "On the observational determination of climate sensitivity and its implications", Asia Pacific Journal of Atmospheric Science, 2011, vol. 47, pp. 377-390.

Mike Lockwood and Claud Frohlich, "Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature", Proceedings of the Royal Society, A, 2007, vol. 463, pp. 2447-2460.

Michael E. Mann, et al., "On past temperatures and anomalous last-20th century warmth", EOS, 2003, vol. 27, pp. 256-258.

Ariel Malka, Jon A. Krosnick, and Gary Langer, "The association of knowledge with concern about global warming: Trusted information sources shape public thinking", Risk Analysis, 2009, vol. 29, pp. 633–647.

Aaron M. McCright, Riley E. Dunlap, and Chenyang Xiao, "Perceived scientific agreement and support for government action on climate change in the USA", Climatic Change, 2013, vol. 119, pp. 1-8.

John D. McLean, Chris R. de Freitas, and Robert M. Carter, "Influence of the Southern Oscillation on tropospheric temperature", Journal Geophysical Research, 2009, vol. 114, paper D14104.

Carl A. Mears, Matthias C. Schabel, and Frank J. Wentz, "A reanalysis of the MSU channel 2 tropospheric temperature record", Journal of Climate, 2003, vol. 16, pp. 3650-3664.

Carl A. Mears and Frank J. Wentz, "The effect of diurnal correction of satellite-derived lower tropospheric temperature", Science, 2005, vol. 309, pp. 1548-1551.

Daniel M. Murphy, "Constraining climate sensitivity with linear fits to outgoing radiation", Geophysical Research Letters, 2010, vol. 37, paper L09704.

Daniel M. Murphy and P. M. Forster, "On the accuracy of deriving climate feedback parameters from correlations between surface temperature and outgoing radiation", Journal of Climate, 2010, vol. 23, pp. 4983-4988.

NASAC, Joint statement by the Network of African Science Academies (NASAC) to the G8 on sustainability, energy efficiency, and climate change, 2007. http://www.interacademies.net/File.aspx?id=4825

New York Times, "What to make of a warming plateau", June 10, 2013 (http://www.nytimes.com/2013/06/11/science/earth/what-to-make-of-a-climate-change-plateau.html?_r=0).

Dana Nuccitelli et al., "Comment on "Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts", Physics Letters A, 2012, vol. 376, pp. 3466-3468.

Dana Nuccitelli et al., « Comment on: Akasofu, S.-I. On the present halting of global warming », Climate, vol. 1, pp.76-83.

Naomi Oreskes, "Beyond the ivory tower. The scientific consensus on climate change", Science, 2004, vol. 306, 1686.

Naomi Oreskes, Erik M. Conway, "Merchants of doubt: how a handful of scientists obscured the truth on issues from tobacco smoke to global warming", Bloomsbury Publishing, USA, 2010.

Pew, "More say there is solid evidence of global warming", Pew Research Center for the People & the Press, 2012.

Stephen Po-Chedley and Qiang Fu, "A bias in the mid-tropospheric channel warm target factor on the NOAA-9 microwave sounding unit", Journal of Atmospheric and Oceanic Technology, 2012, vol. 29, pp. 646-652.

William J. Randel and Fei Wu, "Biases in stratospheric and tropospheric temperature trends derived from historical radiosonde data", Journal of Climate, 2006, vol. 19, pp. 2094-2104.

Anita D. Rapp, Christian Kummerow, Wesley Berg, and Brian Griffith, "An evaluation of the proposed mechanism of the adaptive infrared iris hypothesis using TRMM VIRS and PR measurements", Journal of Climate, 2005, vol. 18, pp. 4185-4194.

Benjamin D. Santer, et al., "Consistency of modelled and observed temperature trends in the tropical troposphere", International Journal of Climatology, 2008, vol. 28, pp. 1703-1722.

Benjamin D. Santer et al., "Volcanic contribution to decadal changes in the tropospheric temperature", Nature Geoscience, 2014, vol. 7, pp. 185-189.

Gavin A. Schmidt, Drew T. Shindell, and Kostas Tsigaridis, "Reconciling warming trends", Nature Geoscience, 2014, vol. 7, pp. 158-160.

Stephen H. Schneider, "Detecting climatic change signals: Are there any 'fingerprints'?", Science, 1994, vol. 263, pp. 341-347.

Steven C. Sherwood, John R. Lanzante, and Cathryn L. Meyer, "Radiosonde daytime biases and late-20th century warming", Science, 2005, vol. 309, pp. 1556-1559.

Uri Shwed and Peter S. Bearman, "The temporal structure of scientific consensus formation", American Sociological Review, 2010, vol. 75, pp. 817-840.

Terry Sloan and Arnold W. Wolfendale, "Testing the proposed causal link between cosmic rays and cloud cover", Environmental Research Letters, 2008, vol. 3, paper 024001.

Sami K. Solanki and Natalie A. Krivov, "Can solar variability explain global warming since 1970?", Journal of Geophysical Research, 2003, vol. 108, pp. SSH 7-1 – SSH 7-8.

Willie Soon and Sallie Baliunas, "Proxy climatic and environmental changes of the past 1000 years", Climate Research, 2003, vol. 23, pp. 89-110.

Roy W. Spencer and John R, Christy, "Precise monitoring of global temperature trends from satellites", Science, 1990, vol. 247, pp. 1558-1562.

Roy W. Spencer and John R, Christy, "Precision lower stratospheric temperature monitoring with the MSU: technique, validation, and results 1979-1991", Journal of Climate, 1993, vol. 6, pp. 1194-1204.

Roy W. Spencer, John R. Christy, and Norman C. Grody, "An analysis of "examination of 'global atmospheric temperature monitoring with satellite microwave measurements", Climatic Change, 1996, vol. 33, pp. 477-489.

Roy W. Spencer and William D. Braswell, "Potential biases in feedback diagnosis from observational data: A simple model demonstration", Journal of Climate, 2008, vol. 21, pp. 5624-5628.

Roy W. Spencer and William D. Braswell, "On the misdiagnosis of surface temperature feedbacks from variations in Earth's radiant energy balance", Remote Sensing, 2011, vol. 3, 1604-1613.

Qiuhong Tang, et al., "Cold weather extremes in northern continents linked to Arctic sea ice loss", Environmental Research Letters, 2013, vol. 8, paper 014036.

Peter Thorne, et al., "Revisiting radiosonde upper air temperatures from 1958 to 2002", Journal of Geophysical Research, 2005, vol. 110, paper D18105.

Peter Thorne, et al., "Tropospheric temperature trends: history of an ongoing controversy", Climate Change, 2011, vol. 2, pp. 66-88.

Holly Titchner, et al., "Critically assessing tropospheric temperature trends from radiosondes using realistic validation experiments", Journal of Climate, 2009, vol. 22, pp. 465-485.

Kevin E. Trenberth and John T. Fasullo, "Global warming due to increasing absorbed solar radiation", Geophysical Research Letters, 2009, vol. 36, paper L00706.

Keven E. Trenberth, et al., "Relationships between tropical sea surface temperature and top-of-atmosphere radiation", Geophysical Research Letters, 2010, vol. 37, paper L03702.

Kevin E. Trenbert, John T. Fasullo, and John P. Abraham, "Issues in establishing climate sensitivity in recent studies", Remote Sensing, 2011, vol. 3, pp. 2051-2055.

Kevin E. Trenberth and John T. Fasullo, "Earth's energy balance", Journal of Climate, 2014, (in press, http://dx.doi.org/10.1175/JCLI-D-13-00294.1)

John Tyndall, "On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction", Philosophical Magazine Series 4, 1861, vol. 22, pp. 169-194.

US National Academy and Royal Society, Joint Statement on climate change, 2014, http://royalsociety.org/policy/projects/climate-evidence-causes/.

Martin Visbeck, "Bumpy path to a warmer world", Nature Geoscience, 2014, vol. 7, pp. 160-161.

John M. Wallace, et al., "Global warming and winter weather", Science, 2014, vol. 343, pp. 729-730.

Frank J. Wentz and Matthias C. Schabel, "Effects of orbital decay on satellite-derived lower tropospheric temperature trends", Nature, 1998, vol. 394, pp. 661-664.

Takmeng Wong, Bruce A. Wielicki, and Robert B. Lee III, "Reexamination of the observed decadal variability of the Earth radiation budget using altitude-corrected ERBE/ERBS nonscanner WFOV data", Journal of Climate, 2006, vol. 19, pp. 4028-4040.

Margaret R.K. Zimmerman, "The Consensus on the consensus: An opinion survey of Earth scientists on global climate change", M.S. Thesis, University of Illinois at Chicago, 2008.