KEY SCIENTIFIC DEVELOPMENTS SINCE THE IPCC FOURTH ASSESSMENT REPORT

SCIENCE BRIEF 2 **JUNE 2009**

The Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report (AR4) in 2007. Since the IPCC considers only published, peer-reviewed science in its assessments, the AR4 did not examine any research published after July 2006. In the years since then, a significant body of new peer-reviewed science has been published, much of which is relevant to policy decisions that will be made before the next IPCC assessment, due in 2014. A brief overview of some key new findings is provided here.

The link between fossil fuel emissions and many aspects of climate change is increasingly clear. The AR4 concluded that greenhouse gas emissions from human activity are responsible for most of the increase in global average temperature with greater than 90 percent certainty (IPCC 2007a). Numerous recent findings explicitly link other aspects of climate change to human activities:

- Human-induced climate change is already affecting multiple systems, both physical (e.g., timing of seasonal lake freeze and thaw) and biological (e.g., seasonal timing of plant flowering and animal migration) (Rosenzweig et al. 2008).
- Changes in polar temperatures, both in the Arctic and Antarctic, have been attributed conclusively to human activity, with impacts on ecosystems, indigenous communities, ice sheet and ice shelf stability, and sea level rise (Gillett et al. 2008). A detectable human influence on Arctic sea ice melt extends back into the early 1990s, even before (and including) the recent rapid increase in melting (Min et al. 2008).
- Global precipitation trends have been linked to human-induced global warming; specific observations, including increased precipitation in Northern Hemisphere mid-latitudes, drier Northern Hemisphere tropics and subtropics, and wetter Southern Hemisphere tropics, are larger than model predictions and may already be impacting ecosystems, agriculture, and human health in certain regions (Zhang et al. 2007).
- Changes in the hydrological cycle of the western United States have been observed for the latter half of the 20th century, and a new study has shown that some 60 percent of the observed change in river flows, winter air temperature, and snow pack result from human-induced climate change (Barnett et al. 2008).
- Satellites show an increase in total atmospheric moisture content over the oceans since 1998, and this has been attributed to anthropogenic emissions of greenhouse gases, as opposed to natural causes or internal variability (Santer et al. 2007).
- For the regions of hurricane formation in the Atlantic and Pacific Oceans, new research finds a significant chance (84 percent) that human activities are responsible for most of the observed increase in the sea surface temperature, which contributes to more intense hurricanes (Santer et al. 2006).

Ocean acidification severely threatens marine ecosystems and fisheries. Oceans absorb much of the carbon dioxide (CO_2) that humans emit, and as the gas dissolves in the oceans, it forms carbonic acid and increases the acidity (lowers the pH) of the ocean water. In October 2008, a panel of 155 scientists declared that ocean acidification threatens the world's coral reefs, shellfish, and marine ecosystems generally.[1] The panel concluded that "ocean acidification may render most regions chemically inhospitable to coral reefs" by 2050. Increased acidity reduces the amount of carbonate in the oceans and makes it harder for shell-forming organisms to grow. This negatively impacts sea creatures such as corals and certain types of plankton that depend on the availability of carbonate to make their shells. Since many fisheries depend on corals and other shell-forming organisms to support their food chains, ocean acidification is a direct threat to food security, in addition to threatening biodiversity, tourism, and coastal protection (Hoegh-Guldberg et al. 2007). A decline in

---

[1] Declaration can be found at: http://ioc3.unesco.org/oanet/Symposium 2008/MonacoDeclaration.pdf

calcification rates (i.e., shell weights) has already been observed for several species (Moy et al. 2009; De'ath, Lough, and Fabricius 2009). Conditions detrimental to high-latitude marine ecosystems could develop within the next few decades (Orr et al. 2005). A recent modeling study concluded that by the time atmospheric concentrations of CO_2 reach 560 ppm “all coral reefs will cease to grow and start to dissolve” (Silverman et al. 2009).

Figure 2. *Image of the Wilkins Ice Shelf, along the western edge of the Antarctic Peninsula, after the recent collapse of an ice bridge. Chunks of ice of varying sizes are visible. Cracks in the ice are marked by dark areas, which are open ocean water; several large cracks can be seen in the right of the image. The fuzzy areas, particularly in the upper left, are due to clouds partially obscuring the view. This image was captured on April 12, 2009 using NASA's Terra spacecraft. Image courtesy of NASA's Earth Observatory (http://earthobservatory.nasa.gov/ NaturalHazards/ view.php?id=38235).*

A better understanding of the behavior of large ice sheets combined with observations of rapid melting have raised projections of 21st-century global sea level rise. New estimates of average global sea level rise by 2100 are significantly larger than in the AR4, as shown in Figure 1. The AR4 projected an average sea level rise of 0.18 to 0.59 meters (0.59 to 1.94 feet) by the end of the 21st century, but that estimate was driven mostly by the thermal expansion of the oceans as the water warms. However, due to an inability to model how ice moves in large, land-based ice sheets (i.e., the Greenland and Antarctic ice sheets), the IPCC did “not assess the likelihood, nor provide a best estimate or an upper bound for sea level rise” (IPCC 2007b). The upper end of the AR4 projection should not, therefore, be interpreted as an upper limit; in fact, it likely underestimates future sea level rise (Rahmstorf 2007; Jevrejeva et al. 2008). Two recent studies attempted to capture the ice contribution to future sea level rise more completely than the IPCC approach, each using different methods. Projections in these two studies ranged from 0.5 to 2.0 meters (1.64 to 6.56 feet) for the end of the 21st century (Rahmstorf 2007; Pfeffer, Harper, and O'Neel 2008). Two other studies found that sea level does not rise uniformly around the world and that the Pacific and Atlantic coasts of the United States will experience significantly more sea level rise than the global average (Bamber et al. 2009; Yin, Schlesinger, and Stouffer 2009). Moreover, the chances of abrupt, large-scale sea level rise may be greater than previously understood. Collapse of the West Antarctic Ice Sheet could cause global sea level to rise rapidly by more than 3 meters, or more than 10 feet (Bamber et al. 2009). One recent study found that global average sea level rose at an average rate of 1.5 meters (4.9 feet) per century during the last warm interglacial period about 120,000 years ago (Rohling et al. 2008). During that time, sea level along the coast of Mexico's Yucatan Peninsula jumped by 2 to 3 meters (6.6 to 9.8 feet) in less than a century, due to a period of ice sheet instability (Blanchon et al. 2009). The Earth's average temperature at that time was only about 1 °C (0.6 °F) warmer than at present.

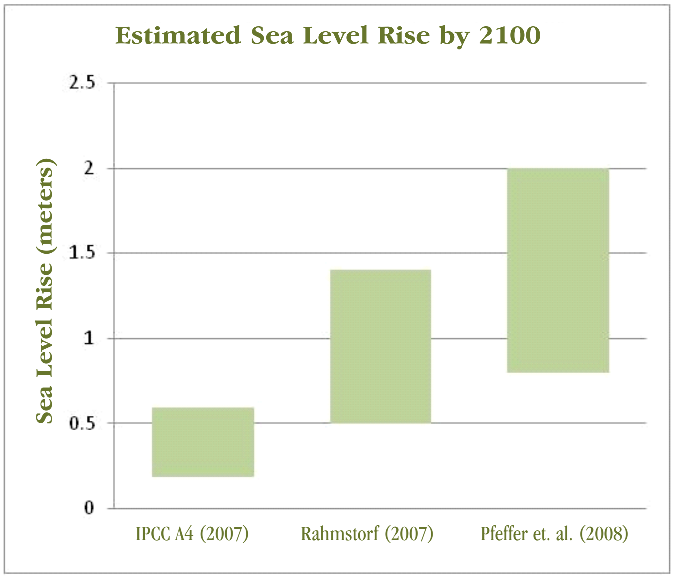

Figure 1. *Comparison of recent estimates of sea level rise in 2100, relative to 1990 levels.*

Surface melting of the Greenland Ice Sheet is accelerating. Satellite observations indicate that 2007 was a record year for Greenland surface melt—60 percent more melt than the previous record in 1998 (Mote 2007; Tedesco 2007). Increased melting along the edges of the ice sheet have exceeded annual snowfall in the interior regions (Mernild et al. 2009), meaning that the Greenland Ice Sheet is losing mass and contributing to sea level rise. Independent measurements from different satellites suggest that the Greenland Ice Sheet entered a period of accelerated melting starting in the summer of 2004 (Chen, Wilson, and Tapley 2006). The rate of ice melt in Greenland since 1990 and the significant increase in summer temperatures in Greenland have been linked directly to global warming (Hanna et al. 2008).

Antarctic ice shelves are collapsing more rapidly than expected. Ice shelves are created by the flow of glaciers and land-based ice sheets from the land into the ocean, and they form an extension of the ice sheet on the ocean surface. Ice shelves prevent rapid flow of land-based ice into the ocean by serving as a support structure. When ice shelves collapse, the glaciers behind them begin to flow into the ocean more rapidly, accelerating sea level rise (Rignot et al. 2004). The West Antarctic Ice Sheet continues to exhibit accelerated melting, with 10 major ice shelf collapses in the last decade. Most recently, the Wilkins Ice Shelf, along the West Antarctic Peninsula, suffered two large breaks: one[2] in early 2008 and another[3] in April 2009, when an ice bridge connecting the ice sheet to a small island collapsed, as pictured in Figure 2.

Improved analysis suggests that Antarctica is warming. A recent analysis indicates that West Antarctica has warmed at about the same rate as the rest of the globe over the past 50 years and that East Antarctica (and the continent as a whole) has also warmed slightly (Steig et al. 2009), as shown in Figure 3. Until recently, sparse data suggested that Antarctica—except for the Antarctic Peninsula—had cooled slightly over the past four decades (Chapman and Walsh 2007), but as noted in the AR4, models predict that Antarctica should be warming. The few long-term monitoring stations are mostly near the coasts, however, making it difficult to estimate the temperature trend for the entire continent. This new analysis provides better spatial understanding of temperature trends in Antarctica by combining the long-term records from a small number of older weather stations with the higher quality, short-term records from many more locations. Antarctica, on average, has warmed more slowly than the Arctic because (1) Antarctica is almost entirely covered by ice, which reflects sunlight back to space; (2) it is surrounded entirely by oceans, which warm more slowly than land; and (3) it lies under the stratospheric ozone hole, which has a regional cooling effect during the spring.

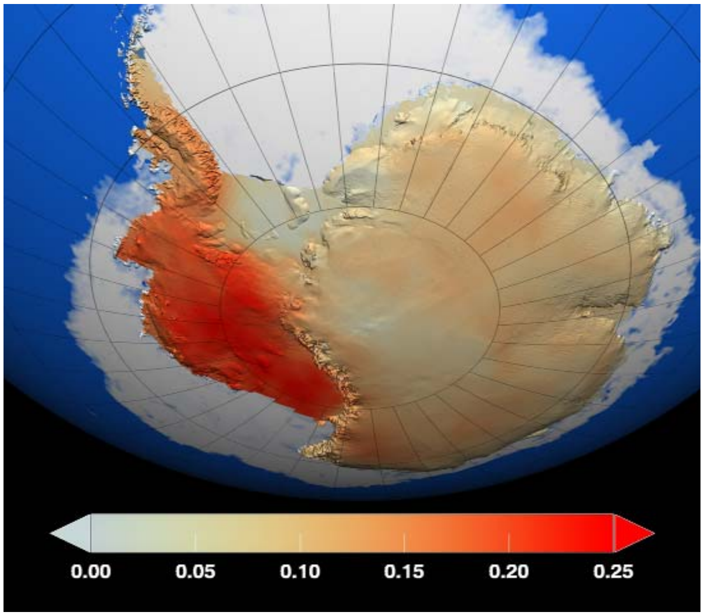

Figure 3. *Map of Antarctica showing the estimated average temperature change per decade (°C) from 1957 to 2006. The average increase per decade is 0.12 °C (0.22 °F), for a total change of 0.5 °C (1 °F) since 1957 (Steig et al. 2009). Image courtesy of NASA's Earth Observatory (http://earthobservatory.nasa.gov/ IOTD/ view.php?id=36736).*

Arctic sea ice is melting more quickly than projected. Recent studies indicate that the Arctic will probably be free of sea ice during the summer sometime between 2030 and 2080, much earlier than previously anticipated (Boé et al. 2009; Wang and Overland 2009). The extent of Arctic sea ice at its summertime minimum has declined by 34 percent since 1979, reaching a new record low[4] in 2007, as shown in Figure 4. The 2008 summertime sea ice extent was the second lowest on record, and 2008 may have set a new record for the lowest total volume of sea ice.[5,6] Models differ in their projections, but on average they underestimate by threefold the rate of sea ice loss that has been observed over the past three decades (Stroeve et al. 2007). Because ice is highly reflective while open water absorbs most of the incoming sunlight, an ice-free Arctic would accelerate global warming.[7]

---

[2] http://nsidc.org/news/press/20080325_Wilkins.html
[3] http://nsidc.org/news/press/20090408_Wilkins.html
[4] For more details on the decline of Arctic sea ice, see http://www.pewclimate.org/impacts/icecap (and references therein)
[5] http://nsidc.org/news/press/20081002_seaice_pressrelease.html
[6] http://www.arctic.noaa.gov/reportcard/seaice.html
[7] For a more complete explanation, see Pew's Climate Change 101 Series: http://www.pewclimate.org/global-warming-

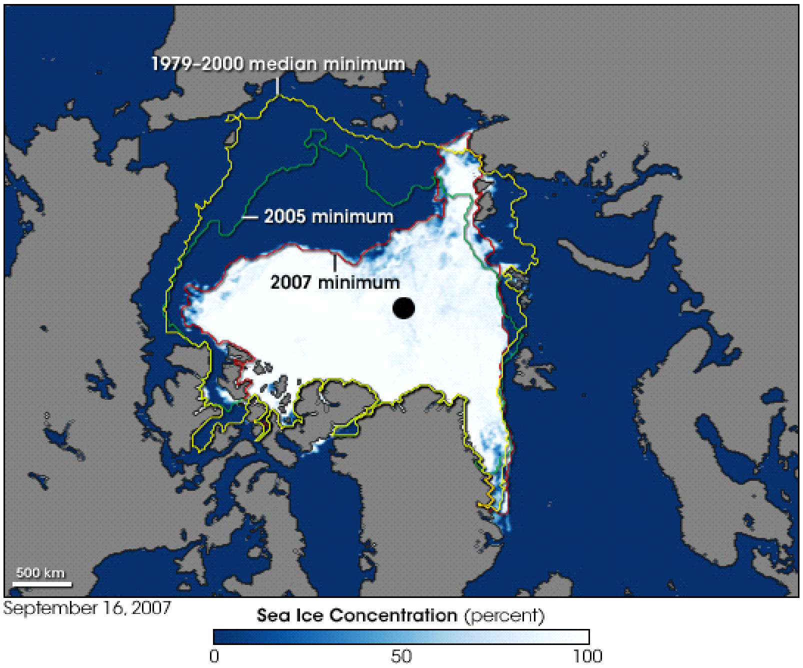

Figure 4. *Map of the Arctic showing the record low summer sea ice extent on September 16, 2007, compared to the median minimum extent from 1979—2000 and the 2005 minimum. Image courtesy of NASA's Earth Observatory (http://earthobservatory.nasa.gov/IOTD/ view.php?id=8126).*

Permafrost is thawing more quickly than previously thought. Most of the Arctic land mass sits on permanently frozen soils (permafrost) that contain large amounts of carbon—significantly more than currently exists in the Earth's atmosphere (Zimov, Schuur, and Chapin III 2006; Ping et al. 2008; Shuur et al. 2008). If these soils thaw, they will release large amounts of carbon into the atmosphere in the form of CO_2 and CH_4 (methane), the two most important greenhouse gases. The AR4 noted that permafrost temperatures have increased in many locations, but new research suggests that the permafrost may be thawing at a faster rate. Methane emissions from Siberian thaw lakes originate from thawing ancient organic matter below the surface. Methane emissions from these lakes may be more than five times higher than previous estimates, and expansion of thaw lakes in response to Arctic warming has led to an estimated 58 percent increase in methane emissions, largely from thawing permafrost (Walter et al. 2006). With further warming, methane emissions would increase further and perhaps nonlinearly, and since methane is a strong greenhouse gas, this process would amplify global warming. Many permafrost soils have warmed rapidly in recent decades, and the large amount of carbon in these soils "would release approximately 10 times the current atmospheric CH_4 burden" (Walter, Smith, and Chapin III 2007). At present, however, scientists lack sufficient knowledge to predict how rapidly this process will accelerate.

The impacts of climate change may persist for more than 1000 years, even after human-induced emissions of CO_2 stop completely. New studies find that warmer temperatures and changes in precipitation caused by CO_2 emissions from human activity are largely irreversible. Atmospheric temperatures are not expected to decrease for many centuries to millennia, even after human-induced greenhouse gas emissions stop completely (Matthews and Caldeira 2008; Solomon et al. 2009; Eby et al. 2009). In addition to long-term increases in temperature, climate models also suggest that a peak in CO_2 levels between 450 and 600 ppm produces irreversible rainfall reductions in many parts of the world. For example, a 15-20 percent reduction in rainfall in the southwestern United States is predicted—a larger decrease than the "Dust Bowl" of the 1930s (Solomon et al. 2009). In the models, these changes persist for more than 1000 years for two reasons: (1) the long lifetime of CO_2 in the atmosphere—some 25 percent of it may remain in the atmosphere for more than 5000 years (Montenegro et al. 2007; Eby et al. 2009)—and (2) the long period of time required for the transfer of heat between the oceans and the atmosphere. The uptake of heat by the oceans is expected to slow, causing atmospheric temperatures to remain elevated for thousands of years (Eby et al. 2009; Solomon et al. 2009).

Unmitigated CO_2 emissions will likely generate greater warming than previously estimated. Recent observations reveal that CO_2 emissions from human activities grew faster over the past decade than the IPCC previously expected. In 2000, the IPCC published a set of emissions scenarios intended to span a range of possible future development pathways (Nakiæenoviæ and Swart 2000). Although these scenarios assumed that no policies would be implemented to reduce global warming, some scenarios were relatively progressive with regard to energy efficiency and conservation, whereas others were not. Since 2000, the growth rate of actual CO_2 emissions has tracked the most pessimistic (i.e., the fastest growth rate for CO_2 emissions) of the IPCC scenarios (Canadell et al. 2007).[8] The same study estimated that the fraction of CO_2 emitted by human activities that stays in the atmosphere (the

---

[8] See also http://www.globalcarbonproject.org/

airborne fraction) is growing over time. Because of the accelerating emissions and the increasing airborne fraction, atmospheric CO_2 concentration increased at a rate of 2 ppm per year from 2000 to 2007, 33 percent faster than in the 1990s. Another recent study by analysts at MIT found that when a climate model was updated to include the most recent understanding of socioeconomic development, the carbon cycle, and natural climate drivers, the output of the model showed twice as much global warming at the end of the current century than before the model was updated, 9.4 °F (5.2 °C) in the updated model run compared to 4.3 °F (2.4 °C) before the update (Sokolov et al. 2009).

Summary. The majority of the new scientific insights described above are based entirely or partially on direct observations of climate change. Sea level is rising, global ice cover is diminishing, and biological systems are responding to climate change. In general, observed climate change is proceeding at a more rapid pace than anticipated by previous estimates or model projections. Recent revisions of projected changes are higher than earlier estimates and the IPCC projections published in 2007 now appear rather conservative in light of more recent observations and improved modeling techniques. Fortunately, strong policies to reduce greenhouse gas emissions can still avert the worst consequences of climate change.

References

Bamber, J. L., R. E. M. Riva, B. L. A. Vermeersen, A. M. LeBrocq. 2009. Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet. Science 324:901-903.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, and A. A. Mirin. 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080.

Blanchon, P., A. Eisenhauer, J. Fietzke, and V. Liebetrau. 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 458:881-884.

Boé, J., A. Hall, and X. Qu. 2009. September sea-ice cover in the Arctic Ocean projected to vanish by 2100. Nature Geoscience 2:341-343.

Canadell, J. G., C. Le Quéré, M. R. Raupach, C. B. Field, E. T. Buitehuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton, and G. Marland. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences 104:18866-18870.

Chapman, W. L., and J. E. Walsh. 2007. A Synthesis of Antarctic Temperatures. Journal of Climate 20:4096-4117.

Chen, J. L., C. R. Wilson, and B. D. Tapley. 2006. Satellite gravity measurements confirm accelerated melting of Greenland ice sheet. Science 313:1958-1960.

De'ath, G., J. M. Lough, and K. E. Fabricius. 2009. Declining Coral Calcification on the Great Barrier Reef. Science 323:116.

Eby, M., K. Zickfeld, A. Montenegro, D. Archer, K. J. Meissner, and A. J. Weaver. 2009. Lifetime of anthropogenic climate change: millennial time scales of potential CO2 and surface temperature perturbations. Journal of Climate 22:2501-2511.

Gillett, N. P., D. A. Stone, P. A. Stott, T. Nozawa, A. Y. Karpechko, G. C. Hegerl, M. F. Wehner, and P. D. Jones. 2008. Attribution of polar warming to human influence. Nature Geoscience 1:750-754.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffiths. 2008. Increased runoff from melt from the Greenland Ice Sheet: a response to global warming. Journal of Climate 21:331-341.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, and K. Caldeira. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318:1737.

IPCC. 2007a. Summary for Policymakers (WGI). In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 10.

IPCC. 2007b. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Core Writing Team, R. K. Pachauri, and A. Reisinger. Geneva, Switzerland: IPCC, 7.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth. 2008. Recent global sea level acceleration started over 200 years ago? Geophysical Research Letters 35:8715.

Matthews, H. D., and K. Caldeira. 2008. Stabilizing climate requires near-zero emissions. Geophysical Research Letters 35:L04705.

Mernild, S. H., G. E. Liston, C. A. Hiemstra, and K. Steffen. 2009. Record 2007 Greenland Ice Sheet Surface Melt Extent and Runoff. Eos, Transactions American Geophysical Union 90:13-14.

Min, S., X. Zhang, F. W. Zwiers, T. Agnew, J. St Jacques, D. J. Sauchyn, S. Pfirman, K. Hoff, B. Temblay, and C. Fowler. 2008. Human influence on Arctic sea ice detectable from early 1990s onwards. Geophysical Research Letters 35:L21701.

Montenegro, A., V. Brovkin, M. Eby, D. Archer, and A. J. Weaver. 2007. Long term fate of anthropogenic carbon. Geophysical Research Letters 34:L19707.

Mote, T. L. 2007. Greenland surface melt trends 1973–2007: Evidence of a large increase in 2007. Geophysical Research Letters 34:L22507.

Moy, A. D., W. R. Howard, S. G. Bray, and T. W. Trull. 2009. Reduced calcification in modern Southern Ocean planktonic foraminifera. Nature Geoscience 2:276-280.

Nakiæenoviæ, N. and R. Swart. 2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, N.Y., USA.

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, and F. Joos. 2005.

Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437:681-686.

Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. Science 321:1340.

Ping, C.-L., G. J. Michaelson, M. T. Jorgenson, J. M. Kimble, H. Epstein, V. E. Romanovsky, and D. A. Walker. 2008. High stocks of soil organic carbon in the North American Arctic region. Nature Geoscience 1:615-619.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. Science 315:368-370.

Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas. 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. Geophysical Research Letters 31:L18401.

Rohling, E. J., K. Grant, C. Hemleben, M. Siddall, B. A. A. Hoogakker, M. Bolshaw, and M. Kucera. 2008. High rates of sea-level rise during the last interglacial period. Nature Geoscience 1:38-42.

Rosenzweig, C., D. Karoly, M. Vicarelli, P. Neofotis, Q. Wu, G. Casassa, A. Menzel, T. L. Root, N. Estrella, and B. Seguin. 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453:353-357.

Santer, B. D., C. Mears, F. J. Wentz, K. E. Taylor, P. J. Gleckler, T. M. L. Wigley, T. P. Barnett, J. S. Boyle, W. Brüggemann, and N. P. Gillett. 2007. Identification of human-induced changes in atmospheric moisture content. Proceedings of the National Academy of Sciences 104:15248.

Santer, B. D., T. M. L. Wigley, P. J. Gleckler, C. Bonfils, M. F. Wehner, K. AchutaRao, T. P. Barnett, J. S. Boyle, W. Bruggemann, M. Fiorino, N. Gillett, J. E. Hansen, P. D. Jones, S. A. Klein, G. A. Meehl, S. C. B. Raper, R. W. Reynolds, K. E. Taylor, and W. M. Washington. 2006. Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. Proceedings of the National Academy of Sciences 103:13905-13910.

Schuur, E. A. G., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, and S. A. Zimov. 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. BioScience 58:701-714.

Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez. 2009. Coral reefs may start dissolving when atmospheric CO_2 doubles. Geophysical Research Letters 36:L05606.

Sokolov, A. P., P. H. Stone, C. E. Forest, R. Prinn, M. C. Sarofim, M. Webster, S. Paltsev, C. A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B Felzer, and H. D. Jacoby. 2009. Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. Journal of Climate DOI: 10.1175/2009JCLI2863.1.

Solomon, S., G. K. Plattner, R. Knutti, and P. Friedlingstein. 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106:1704-1709.

Steig, E. J., D. P. Schneider, S. D. Rutherford, M. E. Mann, J. C. Comiso, and D. T. Shindell. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature 457:459-462.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze. 2007. Arctic sea ice decline: Faster than forecast. Geophysical Research Letters 34:9501.

Tedesco, M. 2007. A new record in 2007 for melting in Greenland. Eos, Transactions American Geophysical Union 88:39.

Walter, K. M., L. C. Smith, and F. S. Chapin III. 2007. Methane bubbling from northern lakes: Present and future contributions to the global methane budget. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365:1657-1676.

Walter, K. M., S. A. Zimov, J. P. Chanton, D. Verbyla, and F. S. Chapin III. 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443:71-75.

Wang, M., and J.E. Overland. 2009. A sea ice free summer Arctic within 30 years? Geophysical Research Letters 36:L07502.

Yin, J., M. E. Schlesinger, and R. J. Stouffer. 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geoscience 2:262-266.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa. 2007. Detection of human influence on twentieth-century precipitation trends. Nature 448:461.

Zimov, S. A., E. A. G. Schuur, and F. S. Chapin III. 2006. Climate change: Permafrost and the global carbon budget. Science 312:1612-1613.

Pew Center on Global Climate Change
2101 Wilson Boulevard
Suite 550
Arlington, VA 22201
Phone (703) 516-4146

www.pewclimate.org