WORLD RESOURCES INSTITUTE

Climate Science 2009–2010 Major New Discoveries

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INTRODUCTION

This WRI Issue Brief highlights the latest major research in climate change science and technology. It presents a synthesis of current understanding of global warming at a critically important time, as the world continues to negotiate a comprehensive international climate agreement and countries begin to implement their national greenhouse gas emission reduction targets and actions. Our summary of select peer-reviewed science and technology publications from 2009 and 2010, including those from key general scientific and technical journals, aims to inform policymakers, the non-governmental organization (NGO) community, and the media, by:

- documenting the impacts of a changing climate that are already occurring as a result of increased global temperatures, altered precipitation patterns, sea level rise, and other changes in the climate system;
- synthesizing the current state of knowledge on how the climate is likely to change in the future; and
- identifying important advances related to technologies that could help to mitigate climate change.

The latest science summarized below suggests that the impacts of climate change in many areas of the world are not advancing linearly: profound changes are already occurring and models project even greater changes for the remainder of the 21st Century. The findings support the need for rapid and deep cuts in greenhouse gas emissions, and at the same time confirm that climate adaptation measures are increasingly required today—and will be ever more important in the future—to enhance the resilience of both human communities and ecosystems. There is new and abundant literature on four topics: *climate feedbacks* where the literature generally suggests positive feedbacks from many different processes; *sea level rise* where the evidence indicates that previous estimates of sea level rise are likely to be revised upward; *ocean acidification* where new science is confirming the potential global implications of an ocean that is already 30 percent more acidic than about 100 years ago; and on *climate impacts to ecological systems,* where the literature base on climate impacts is broadened to provide more evidence of changes to a variety of species, including lizards, tigers and butterflies.

Similar to previous years, this review is divided into four sections:

- Physical Climate
- Hydrological Cycle
- Ecosystems and Ecosystem Services
- Climate Change Mitigation Technologies and Geoengineering

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Printed on recycled paper
OCTOBER 2011
This version of the issue brief was updated on 15 October 2011 to reflect a correction in units.

SAMPLE FINDINGS

Physical Climate:

- 2000–2009 was the warmest decade on record since 1880 (NASA, p. 4).
- Models indicate that cumulative total anthropogenic carbon emissions need to be limited to 1 trillion tons if global average temperature increase is to remain below 2° C (roughly one half of the 1 trillion tons have already been emitted) (Allen et al., p. 4).
- The climate system has a number of different feedback mechanisms built into it, some of which are better known than others. New evidence suggests that as temperature rises, there may be positive feedbacks (processes that reinforce processes) through less cloud cover and in changes in aerosols, soils, peatlands, and Arctic ice cover (pages 6–11), which can lead to accelerated climate change impacts.
- Recent estimated projections of future global sea level rise (Horton et al., Vermeer and Rahmstorf, Grinsted et al., and Jevrejeva et al., p. 11) have generally been significantly higher than estimates from the 2007 IPCC Report. Additionally, new estimates also suggest that global sea level could rise approximately 3.26 meters from the melting of the West Antarctic Ice Sheet. If perturbations in Earth's rotation and shoreline migration are taken into account, the Pacific and Atlantic coasts of the United States, could be impacted by sea levels 25 percent higher than the global mean at the end of the century (Mitrovica et al., p. 12).

Hydrological Cycle:

- Observations show that multi-year (MY) winter sea ice area decreased by 42 percent between 2005 and 2008 and that there was a thinning of ~0.6 m in MY ice thickness over the same 4 years (average thickness of the seasonal ice in midwinter is ~2 m) (Kwok et al., p. 19).
- As much as 12 percent of the volume of Swiss alpine glaciers was lost over the period from 1999 to 2008 (Farinotti et al., p. 17).
- As glaciers melt, persistent organic pollutants are finding their way into "pristine" alpine lakes, representing a toxic "blast from the past" (Bogdal et al., p. 18).
- The rate of mass loss in the East Antarctic Ice Sheet may be greater than previously estimated (Chen et al., p. 15).
- Changing ice dynamics in the Arctic may be leading to an increase in observed "winter weather" including more snow and colder temperatures in temperate regions of the Northern Hemisphere (Francis et al. and Petoukhov et al., p. 21).

In preparing this review, WRI drew from a wide array of influential journals as well as information from organizations and from climate and energy websites (listed on page 46). Articles were drawn only from 2009 and 2010 publications. There were hundreds of publications we chose not to include because in our judgment they did not add significantly to what we already know. Where the literature suggests that the finding is preliminary or contradictory, we have indicated the need for more research. While we generally looked for papers with global implications, we have included a number of papers on topics that have heretofore not gotten a lot of attention such as human physiological limits to elevated temperatures. Each section contains short summaries of key scientific findings and their policy and research implications. This Issue Brief, in addition to WRI's Climate Science 2007 and 2008 Reviews, outlines new developments since the release of the Intergovernmental Panel on Climate Change's Fourth Assessment Report in 2007.

SAMPLE FINDINGS *(continued)*

Ecosystems and Ecosystem Services:

- New research suggests that while wildfire frequency increases in response to climate change globally, regional changes demonstrate both increases and decreases in wildfire distribution, largely mediated by regionally-specific vegetation, precipitation changes and CO_2 fertilization (Krawchuk et al., p. 30).
- Ocean acidification, which only recently was recognized a threat to coral in areas such as the Great Barrier Reef (and is happening much more quickly than anticipated (De'ath et al., p. 32), is now recognized as having implications for the entire ocean food web which is critical to whales, fish, and mollusks (snails and scallops) (Munday et al., Gooding et al. and Comeau et al., pages 33–34).
- Based on human physiological estimates, a global average temperature increase of 7° C, which is toward the extreme upper part of the range of current projections, would make large portions of the world uninhabitable (Sherwood et al., p. 28).
- The impacts of projected climate change on emperor penguin populations are likely to be significant; with a 36 percent probability of "quasi extinction" (greater than 95 percent decline) by 2100 (Jenouvrier et al., p. 25).
- A 28 cm future sea level rise is projected to reduce the current Bengal tiger habitat in the Sundarban region of Bangladesh by 96 percent and would likely reduce tiger numbers to 20 breeding pairs (Loucks et al., p. 26).

Climate Change Mitigation Technologies and Geoengineering:

- Land-use change associated with planting biofuel crops can have implications on the regional average temperatures through an albedo effect (Georgescu et al., p. 39).
- Advances in more flexible, cheaper small-scale solar photovoltaics could make it easier and less expensive to integrate solar-powered electricity generation into building materials (Lee et al., p. 36).
- If all urban surfaces worldwide were made reflective, the heat trapping effects of urban surfaces would be eliminated, an impact greater than eliminating the annual anthropogenic emissions of the entire globe (Akbari et al., p. 41).
- Geoengineering—"the deliberate large-scale manipulation of the planet's environment to counteract climate change" (Royal Society 2009)—is being more widely studied in terms of its potential to limit global warming if efforts to reduce emissions fail, as well as its implications. Various proposals (and preliminary findings), grouped into two categories—carbon dioxide removal (CDR) and solar radiation management (SRM—are summarized here (pages 40–44).

PHYSICAL CLIMATE

Temperature

According to NASA scientists (http://www.giss.nasa.gov/research/news/), 2010 was tied with 2005 as the warmest year on record—roughly 1.13°F warmer than the average over 1951–1980 (with global temperatures increasing roughly 0.36°F per decade since the late 1970s). Notably, 2010 was warm despite half of the year being affected by cool La Niña conditions. 2009 tied for the second warmest on record (and the warmest in the Southern Hemisphere). The National Aeronautics and Space Administration (NASA) has now established that 2000-2009 was the warmest decade on record since 1880 (http://www.giss.nasa.gov/research/news/20100121/). This section explores recent climate change science related to past and future changes in local and global temperatures.

Temperature Rise: Past and Future

- **G. A. Meehl, C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel**

  "Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S."

  Geophysical Research Letters

  2009, vol. 36

  The 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) forecasts that the United States will experience more extreme daily maximum temperatures and warmer minimum temperatures as a result of human-induced warming. Building on this finding, Meehl and colleagues use a collection of tens of thousands of temperature records from across the United States, representing more than half a century of data (1950–2006), in order to document changes in both record high and low temperatures and estimate how these trends are likely to change in the future. They find that the ratio of new record highs to new record lows is currently about 2:1; however, they reveal that this ratio has been increasing over time and could become as high as 50:1 by 2100, under a midrange (the IPCC A1B) warming scenario.

  Implications: This study demonstrates that we are already experiencing more record highs than record lows and that the gap is steadily widening between them. Notably, this gap has been widening at an increasing rate since the 1980s.

- **M. Allen, D. Frame, C. Huntingford, C. Jones, J. Lowe, M. Meinshausen, and N. Meinshausen**

  "Warming caused by cumulative carbon emissions to the trillionth tonne"

  Nature

  2009, vol. 458

  The authors of this paper find that cumulative greenhouse gas emissions over a given time period are a better indicator of the ability to limit the increase in temperature than greenhouse gas concentration stabilization targets (e.g. stabilizing carbon dioxide (CO_2) to 350 parts per million (ppm)). Using an ensemble of carbon cycle climate models, Allen and colleagues show that estimates of future warming are more dependent on total anthropogenic carbon emissions than on the realization of a specific stabilization scenario. The authors project that cumulative total anthropogenic carbon emissions need to be limited to 1 trillion tonnes if global average temperatures are to remain below the 2° C (range of 1.3–3.9° C) limit in temperature increase agreed to in the Copenhagen Accord.

  Implications: Because peak warming is sensitive not to the pathway of emissions, but simply to the total cumulative emissions, the authors suggest that to avoid a "dangerous total warming commitment," a climate policy framework should focus on the *emission rates* of shorter-lived non-CO_2 agents, such as methane and black carbon, and focus on total global *emissions budget,* or a "Cumulative Warming Commitment," for carbon emissions. Approximately one half of the 1 trillion tonnes have already been emitted and we are currently emitting close to 10 billion tonnes C per year. At that rate, by 2060 we would have emitted another half trillion tonnes, and in this analysis limiting warming to less than 2° C would require having net zero global carbon emissions after that date.

It's Getting Hot in Here

- **N. S. Diffenbaugh and M. Ashfaq**

  "Intensification of hot extremes in the United States"

  Geophysical Research Letters

  2010, vol. 37

  Diffenbaugh and Ashfaq use a nested climate model with a 25km grid-scale to analyze the impacts of near-term temperature rise on the United States. They project that over the next three decades extreme warm temperatures will increase significantly in the United States. Their model projects that by 2030–2039, 38 days of the year will be in the top 5 percent of current temperature extremes, meaning about twice as many extreme heat days will occur as currently. They also project a significant reduction in soil moisture over much of the United States (around 10 percent, and higher in the Ohio and Mississippi River valleys).

Implications: This model-based study points out that significant climate impacts will occur in the United States even if the global community succeeds in limiting warming to 2° C. Extremes in temperatures can have significant impacts on human health, agriculture, and ecological systems. Additionally, reductions in soil moisture and precipitation will have implications for the viability of some crops and for ecosystem health.

Temperature Rise: In the Short Run

- **J. L. Lean and D. H. Rind**

  "How will Earth's surface temperature change in future decades?"

  Geophysical Research Letters

  2009, vol. 36

While many focus on the long-term warming commitment, in this paper, Lean and Rind focus on shorter-term decadal scale temperature rise. In an effort to make more reliable forecasts of near-term temperature rise, the authors built a model based on recent observations of various drivers of change. They project that from 2009 to 2014, global surface temperatures will increase by 0.15° C (+/- 0.03°C), a rate that is 50 percent higher than IPCC projections. However, because of declines in solar activity resulting from the Sun's natural cycle, the increase from 2014 to 2019 would be 0.03° C (+/- 0.01° C). According to model projections, the rise in temperatures will not be evenly distributed across the globe. Northern mid-latitudes experience the greatest amount of warming (as much as 1° C) in the course of a single decade. The authors note that extreme events such as a strong El Niño episode (which could add significant warming) and major volcanic eruptions (which could lead to significant cooling) would need to be overlaid on their forecasts; at the moment they are not taken into account.

Implications: Since so many modeling results focus on longer-term warming, Lean and Rind attempt to "fill the gap" between short-term seasonal weather forecasting and long-term (30-year to century) forecasts of a changing climate. In so doing, they reveal that anthropogenic drivers of climate change influence on global temperatures even in the short term. Climate change, they show, is a problem today, and not just tomorrow.

Not Just Warmer Soils: Warmer Lakes as Well

- **J. Tierney, M. T. Mayes, N. Meyer, C. Johnson, P. W. Swarzenski, A. S. Cohen, and J. M. Russell**

  "Late twentieth-century warming in Lake Tanganyika unprecedented since AD 500"

  Nature Geoscience

  2010, vol. 3

Recent evidence has shown that the surface temperature in Lake Tanganyika, one of the most economically and biologically important large lakes in Eastern Africa, has increased over the last century and caused an increase in thermally induced stratification. As a result, its waters have become less biologically productive. Thermally-induced stratification occurs where warmer air temperatures create a bigger temperature difference between warm surface water and cooler deep water, preventing the two water masses from mixing, which in turn keeps deep-water nutrients from reaching the surface and supporting biological growth. While these trends are alarming, previous research had not determined whether the increase in temperature was due to anthropogenic warming, or if the recent surface temperature is anomalous in the lake's history. Tierney and colleagues took sediment cores from the lake bottom in order to analyze the recent history of the lake and answer these questions. By using membrane lipid ratios in lake sediment cores as a proxy for historical temperature trends, they were able to develop a temperature record from the lake for the last 1,500 years. They find that while the lake's temperature has been variable, and was moderately high around 500 AD and again in 1350 AD, no temperature increase within the last 1,500 years matches that observed today. Today's average surface temperature in Lake Tanganyika is about 26° C, almost 2° C warmer than any previous peak high.

Implications: By investigating the millennial temperature record, the authors demonstrate that the observed temperature increases over recent decades are likely the result of anthropogenic climate change. The effects of these rising temperatures have significantly altered the state of this ecosystem. Perhaps most significant, the temperatures have impacted fish populations, with major implications for nearby communities that depend on fish for protein.

It's Also Getting Cold in Here

- **J. Cattiaux, R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, and F. Codron**

  "Winter 2010 in Europe: A cold extreme in a warming climate"

  Geophysical Research Letters

  2010, vol. 37

  The Copenhagen climate summit of late 2009 was held during a very cold winter in Europe, leading some people to question, despite the robustness of the science, the core veracity of climate change. So why was the winter so cold? In this paper, Cattiaux and colleagues, using daily temperature and meteorological data to calibrate their model, place the winter of 2009–2010 in its full context. They show that the cold temperatures of Europe were not particularly extreme over the last 60 years and, most importantly, were warmer than would have been expected given the strong negative phase of the North Atlantic Oscillation (NAO). The NAO is a natural climatic cycle, and its phase is measured by the difference in pressure between the low pressure system over Iceland and the high pressure system over the Azores in the mid-Atlantic. In positive phases, the difference in pressure between these systems is more pronounced. However, in strongly negative phases the pressure gradient is weakened, which slows the predominant westerlies, allowing less warm maritime air to make its way inland, thus leading to colder and drier winters in Europe. Cattiaux and colleagues show that the temperatures in Europe during the winter of 2009–2010 were actually surprisingly higher than what would have been expected given the NAO phase.

  Implications: This paper shows that anthropogenic warming occurs on top of a baseline of climatic variability. Thus, given natural climatic cycles and oscillations, there will still be "colder" periods in a warming climate. In this case, the overall cycle has shifted upward: the colder periods have turned warmer, tempering the cold years, and warmer periods are also getting warmer, exacerbating hot extremes.

Earth System Feedbacks with Significant Implications for Future Warming

Greenhouse gas (GHG) concentrations in the atmosphere have continued to rise. According to data collected from the Mauna Loa Observatory in Hawaii (http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html#mlo), concentrations of carbon dioxide (CO_2) in 2010 rose to 389.8 ppm, up from 387.4 in 2009. Anthropogenic emissions of carbon dioxide in 2009 were 30.8 billion tons, 1.3 percent lower than 2008, a fact widely attributed to the global economic recession (Friedlingstein et al. 2010). In 2010, emissions were again higher. Because the atmospheric concentration of carbon dioxide is a stock, however, any level of emissions that is greater than the amount of carbon dioxide absorbed by natural systems each year will continue to increase atmospheric concentrations.

The climate system has a number of different feedback mechanisms built into it, some of which are better known than others. Feedbacks can be positive (reinforcing a process) or negative (dampening a process). If feedbacks within the climate system are triggered, the rise in atmospheric concentrations of carbon dioxide may far exceed the average rise in concentrations of 1.9 ppm/year over the last decade (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf). We focus in this section on climate feedbacks. The climate science literature of 2009 and 2010 has advanced knowledge of climate feedbacks. We showcase some of these findings below, discussing feedbacks pertaining to the gas hydrates in the deep ocean, ozone, aerosols, clouds, and carbon dioxide.

Climate Change Feedbacks in the Deep Sea: Gas Hydrates

- **D. Archer, B. Buffett, and V. Brovkin**

  "Ocean methane hydrates as a slow tipping point in the global carbon cycle"

  Proceedings of the National Academy of Sciences

  2009, vol. 106(49)

  Deep-sea sediments contain methane hydrates, crystal-like formations that trap methane, a greenhouse gas that is 21 times more potent than carbon dioxide. Globally, methane hydrates are thought to hold between 1,600 and 2,000 gigatonnes of carbon. As ocean floor sediment temperatures are low enough to keep these hydrocarbons solid and oxygen concentrations are low enough to prevent oxidation, these hydrate forms are generally stable. As the Earth warms and sediment temperatures rise, methane hydrates could become unstable, releasing methane to the atmosphere. The magnitude of release depends in large part on how bubbles of methane hydrate form in the deep sediment and percolate upward, through overlying sediment. Any methane freed would have to pass through a zone of sediment that is cooler than the melting temperature. The higher the volume of bubbles, the more easily these gases can migrate upward through the sediment, and eventually to the atmosphere. Archer and colleagues model what will happen to stocks of methane hydrates trapped in sediments under a uniform 3° C warming extended over the next 1,000 years. Under this scenario, they project that a warming-induced feedback of methane release will cause a further 0.5° C of warming above the stabilized 3° C warming scenario.

Implications: While the authors make significant assumptions about gas behavior and the uniformity of warming through the water column and sediment, there are large shallow methane hydrate deposits in the Arctic (where warming is occurring most rapidly, compared to other regions) that, if they become unstable, could be significant sources of a climate change-induced methane feedback. If the Earth warms by 3°C, which is not beyond the scope of possibility during the next century, this feedback could add 17 percent to projected global average temperature increases.

Climate Change Impacts on Ozone

- **M. Heggelin and T. Shepherd**

  "Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux"

  Nature Geoscience

  2009

Heggelin and Shepherd explore the impacts of human-induced climate change on the stratospheric ozone layer of the atmosphere, the ozone that blocks much ultraviolet (UV) radiation from reaching the Earth's surface. As the climate warms, stratospheric circulation is projected to accelerate and this warming-induced acceleration may impede progress in restoring the ozone layer. The authors compare models of the behavior of ozone in the stratosphere from the 1960s (before chlorofluorocarbons (CFCs) led to ozone depletion) with that of the 2090s (after implementation of the Montreal Protocol is projected to have restored the ozone layer). In doing so, the authors isolate the effects of climate change on the behavior of ozone in the stratosphere. The models used in this study project that climate change-induced warming leads to an increase in the movement of ozone from the stratosphere (where it blocks harmful UV radiation) to the troposphere (where it is considered a pollutant) by 23 percent, because of an increase in atmospheric circulation under global warming. The climate change-induced extra removal of ozone from the stratosphere would modestly increase the UV radiation index across the globe. These projected increases include 9 percent in the Northern Hemisphere and 4 percent in the tropics, while larger increases are projected for areas such as the far southern region of the globe (e.g. Australia, New Zealand, Argentina and Chile), where UV radiation is projected to increase by up to 20 percent seasonally by the 2090s. This increase represents almost one half of the increased UV radiation resulting from anthropogenic ozone depletion from CFC emissions.

Implications: The stratospheric ozone layer blocks the majority of harmful ultraviolet radiation from hitting the Earth's surface, and its preservation is critical to limiting the harmful effects of UV radiation, such as skin cancer. This study suggests that reducing emission of ozone-depleting CFCs alone will not sufficiently address ozone depletion because of climate change; any effort to address the negative impacts of ozone depletion will also necessitate significant efforts to control greenhouse gas emissions.

Ozone Depletion Impacts on Climate Change

- **A. Lenton, F. Codron, L. Bopp, N. Metzl, P. Cadule, A. Tagliabue, and J. Le Sommer**

  "Stratospheric ozone depletion reduces ocean carbon uptake and enhances ocean acidification"

  Geophysical Research Letters

  2009, vol. 36

The Southern Ocean carbon sink, which draws CO_2 out of the atmosphere and into the deep ocean, is not keeping pace with increasing concentrations of CO_2 in the atmosphere, a fact that has been widely reported and is often cited as an example of a troubling trend: a larger percentage of anthropogenic emissions stays in the atmosphere today than just a few decades ago. Lenton and colleagues show that when stratospheric ozone depletion (caused by emissions of chlorofluorocarbons in the 1970s and 1980s) is taken into account, coupled climate-carbon models suggest that stronger winds are ventilating carbon-rich deep water. This causes CO_2 to return to the atmosphere, thereby decreasing the sink function of the Southern Ocean. Because of this reduction in the sink, the authors estimate that 2.33 gigatonnes of carbon stayed in the atmosphere because of ozone depletion between 1987 and 2004, an amount roughly equivalent to the cumulative anthropogenic emissions from the United Kingdom during this same time period. Their models also show that this ozone depletion-induced effect (ozone depletion leading to a poleward shift in westerly winds, albeit through an unresolved mechanism, and causing CO_2 to be removed from deep ocean waters) explains observations of the weakening of the Southern Ocean carbon sink. Furthermore, the authors found that because the stronger winds lead to an increase in surface CO_2 concentrations, as carbon from the deep water is brought to the surface and exchanges with the atmosphere, ocean acidification will be exacerbated, despite the overall reduction in carbon storage in the oceans.

Implications: This study links stratospheric ozone depletion with a feedback to the climate system (reduction of the carbon sink) and negative impacts of carbon dioxide (ocean acidification), although the mechanism of this connection is not fully understood. The authors point out that while the Montreal Protocol has largely addressed the direct causes of stratospheric ozone depletion, and the ozone hole is projected to recover, the impacts of stratospheric ozone depletion are still leading to significant consequences. They also note that ozone depletion must be included in coupled chemistry-climate models used to assess the future impacts of climate change.

Aerosols and Dust

- **G. Myhre**

"Consistency between satellite and modeled estimates of the direct aerosol effect"

Science

2009, vol. 325

Estimates of global cooling effect of aerosols, some of which reflect solar radiation away from the Earth's surface, have been highly variable. In the 2007 IPCC Fourth Assessment Report, the average net radiative forcing (measurement of the difference between incoming and outgoing radiation) of aerosols was -0.5 W/m^2, with a range of -0.1 to -0.9 W/m^2 (the negative value indicates a net cooling effect). The uncertainty in estimates is driven in part by differences between global aerosol models and satellite observations, as well as by the difficulty of measuring aerosol effects under cloudy skies. In this study, Myhre uses updated aerosol density observations from satellites that take into account aerosol effects when clouds are present, as well as a recent state-of-the-art aerosol model. In so doing, he brings model estimates and satellite-based estimates of aerosol's radiative forcing into agreement. All in all, the best estimate of aerosol's contribution is -0.3 W/m^2, lower than the previous estimates. Other models assumed that aerosols have a uniform and constant influence on solar radiation; however, this study takes into account not only differences in aerosol effects depending on the cloudiness of the sky, but also of recent increases in black carbon emissions, which have an absorptive rather than reflective effect. Myhre thus provides a better estimate of the overall effect of aerosols on radiative forcing.

Implications: The physical explanation for the earlier discrepancy is that the relative increase in anthropogenic black carbon (absorbing aerosols) is much larger than the overall increase in the anthropogenic abundance of aerosols. Consequently, the "negating" effect of aerosols on radiative forcing is not as powerful as previously assumed. The author points out that the cooling effects of anthropogenic aerosols are equal to only 10 percent of the warming effect of anthropogenic greenhouse gases, resulting in a clear and consistent warming trend in net anthropogenic radiative forcing.

- **A. T. Evan, D. J. Vimont, A. K. Heidinger, J. P. Kossin, and R. Bennartz**

"The role of aerosols in the evolution of tropical North Atlantic ocean temperature anomalies"

Science

2009, vol. 324

Over the last 30 years, sea surface temperatures in the tropical North Atlantic have been rising steadily at a faster pace than in other regions: about 0.25° C per decade. Evan and colleagues challenge the assumption that this temperature increase is attributable to trends in human-induced warming. They use a quarter century of satellite imaging that has been used to track atmospheric dust blown from the Sahara to model the regional impacts of aerosol-induced cooling from this Saharan dust (the dust particles bounce solar radiation away from the Earth's surface leading to a cooling effect). They find that 69 percent of the upward temperature trend in sea surface temperatures can be accounted for by a decline in aerosol loadings due to lower dust concentrations in this area in recent years, a phenomenon that they indicate may be linked to climate change induced changes in moisture and winds.

Implications: The accelerated warming of the tropical North Atlantic can be attributed to both anthropogenic warming and climate change-induced reduction in cooling effects (via dust particles). Atlantic dust loading is projected by some models (Mahowald and Luo 2003) to decrease by 20–60 percent by the end of the 21st Century because of climate change-induced changes in soil moisture and wind patterns. Although this mechanism is not well understood, a continued decline in dust loads could lead to further warming in the tropical North Atlantic.

Cloud Feedbacks

- **A. E. Dessler**

"A determination of the cloud feedback from climate variations over the past decade"

Science

2010, vol. 330

The sensitivity of the Earth's climate system to changes in cloud coverage is one of the key uncertainties regarding the impacts of a changing climate. With a warmer climate, will there be more clouds that reflect more sunlight and thus induce a negative feedback cycle, keeping the surface from warming as much as it otherwise might? Or will there be fewer reflective clouds, and thus a warmer world as more solar radiation hits the Earth's surface, creating a positive feedback cycle? Answering these questions is complicated because clouds not only reflect sunlight, but also insulate the surface of the Earth. Dessler analyzes data regarding surface reflectivity at the top of the atmosphere from 2000 to 2010. During this time frame, he finds that there appears to be a positive feedback equal to about 0.54 W/m^2—meaning that warming-induced decreases in cloud coverage have allowed more incoming solar radiation reaching the Earth's surface (i.e. because it is not reflected), which in turn increases warming. Although models project that the long-term cloud feedback could be negative, Dessler contends that it is unlikely to be negative enough to outweigh the positive feedback found in the short term, an effect that is unlikely to change. Dessler does caution that, while he attempted to control for many factors that might also influence cloud cover, he did not explicitly account for the effects of aerosol emissions on cloud formation.

Implications: This paper is a significant contribution to the science of human-induced climate change, as the sign of the cloud feedback has been referenced as one of the greatest uncertainties of a changing climate. While Dessler's work does not resolve the exact amount of the cloud feedback, and therefore the overall relative contribution that clouds may have to the Earth's energy balance, it does provide new evidence that suggesting that the sign of the cloud feedback is moderately positive.

Carbon Dioxide Feedbacks

- **W.-J. Cai, L. Chen, B. Chen, Z. Gao, S. H. Lee, J. Chen, D. Pierrot, K. Sullivan, Y. Wang, X. Hu, W.-J. Huang, Y. Zhang, S. Xu, A. Murata, J. M. Grabmeier, E. P. Jones, and H. Zhang**

"Decrease in the CO_2 uptake capacity in an ice-free Arctic Ocean basin"

Science

2010, vol. 329

As more climate models project a future ice-free Arctic Ocean, scientists have begun to investigate what implications open Arctic water might have for the global carbon cycle. Some studies have suggested that open Arctic water will allow the ocean to absorb more carbon dioxide because there will be more open ocean area for highly productive phytoplankton blooms to draw down atmospheric carbon dioxide. This would create a negative feedback to global warming. Cai and colleagues compare satellite-based data from 2008 to ship-survey data from 1994 and demonstrate that the concentration of sea surface carbon dioxide was significantly elevated in 2008 compared to 1994. They argue that this increase in concentration of surface water carbon dioxide is largely driven by gas exchange with the atmosphere, which has higher concentrations of carbon dioxide because of human activities, such as burning of fossil fuels and deforestation. They further argue that, after waters become ice-free, thermal stratification of the water column (caused by warmer surface waters being separated from cooler deep waters) will set in. This will favor the production of microphytoplankton over that of larger phytoplankton which require more deep-water nutrients, which will not be accessible. Accordingly, the authors conclude that an ice-free Arctic is not likely to serve as a significant carbon dioxide sink in the future because of the shift in biological production toward microphytoplankton, which lowers biological carbon dioxide drawdown.

Implications: This study suggests that there is unlikely to be a significant and sustained negative feedback to global warming from an open ocean Arctic. Therefore, the carbon sink, at least in the Arctic, is not expected to compensate significantly for increased levels of carbon dioxide.

- **L. Cao, G. Bala, K. Caldeira, R. Nemani, and G. Ban-Weiss**

"Importance of carbon dioxide physiological forcing to future climate change"

Proceedings of the National Academy of Sciences

2010, vol. 107

Using a coupled global atmosphere-land surface model, Cao and colleagues study the effects of elevated carbon dioxide on the physiology of terrestrial plants, and the impact of these effects on the climate system. In doing so, they separate impacts on temperature and runoff (the amount of water leaving the system) into "direct" (or greenhouse effect) and "physiological" (or plant-mediated) components. They project that for a doubling of atmospheric carbon dioxide concentrations over the next century, the well-documented greenhouse radiative forcing effect leads to just under 3° C of warming over today's levels. The physiological effect on the terrestrial biosphere, the magnitude of which is modeled in this study for the first time, leads to 0.4° C of warming. This occurs because higher carbon dioxide levels cause plants' stomata, the leaf cells responsible for exchanging carbon dioxide and water vapor, to open less widely, reducing transpiration. The reduced transpiration from this physiological effect of carbon dioxide also has a significant effect on the hydrological cycle, increasing surface water runoff by about 8 percent.

Implications: By modeling the significance of the physiological effect of increased carbon dioxide concentrations via the reduction of leaf transpiration, Cao and colleagues demonstrate that understanding climate change only through the direct, or "greenhouse," effect of radiative forcing misses a meaningful part of the overall picture. While the physiological effect is not as large in magnitude as the greenhouse effect, the impact of carbon dioxide on plants could prove to have a significant and previously unappreciated impact on climatic change. Other recent studies, however, have indicated that the expansion of leaf area under elevated CO_2 might increase transpiration and decrease runoff, which would have a cooling effect as plants evaporate more water to the atmosphere (Bounoua et al. (2010) estimate this cooling effect to be as great as 0.6° C globally). It should also be kept in mind that plant uptake of carbon dioxide is one of the most important pathways for removal of carbon dioxide from the atmosphere and is a major negative feedback on emissions and therefore warming. Clearly, these feedbacks deserve further study.

- **B. Bond-Lamberty and A. Thomson**

"Temperature-associated increases in the global soil respiration record"

Nature

2010, vol. 464

Models and small-scale experiments have all indicated that there is likely a positive feedback to climate change from warmer soils, at least in the short term. As soils warm, the rate of microbial respiration, or decay of carbon-containing organic material, appears to speed up, releasing more carbon dioxide into the atmosphere. Bond-Lamberty and Thomson set out to see if they could find evidence in data on soil respiration collected around the globe that confirms this feedback effect. To do so, they constructed a data base of long-term assessments of soil respiration and correlated it with temperature anomalies. By accounting for factors that might influence various sites differently (e.g. regional climate, nitrogen cycle, leaf area, and light), they empirically isolated the climate change signal in changes to soil respiration. They found a previously unobserved trend: an increase in warming-induced global soil respiration from 1989 to 2008 on the order of 0.1 gigatonnes of carbon dioxide emitted per year. This translates to a feedback effect equivalent to the annual carbon dioxide emissions of Spain.

Implications: This is the first time that observational records have been used to estimate the scale of this particular climate change-induced feedback mechanism. The regional contributions to this global feedback remain unknown. Further experimental studies are also investigating how long the feedback effect lasts, and some recent evidence (Allison, Wallenstein, and Bradford 2010) indicates that the feedback effect may be short-lived. While more research is needed for a definitive conclusion, this study shows that, at least in the short term, this feedback is apparently significant on a global scale.

- **E. Dorrepaal, S. Toet, R. S. P. van Logtestijn, E. Swart, M. J. van de Weg, T. V. Callaghan, and R. Aerts**
  "Carbon respiration from subsurface peat accelerated by climate warming in the subarctic"
  Nature
  2009, vol. 460

  One third of the world's soil organic carbon is stored in northern peatlands. Increasing temperatures can result in a release of such carbon via respiration of carbon dioxide and, in turn, heightened temperatures as a result of the atmospheric buildup of CO_2 emissions. Understanding this feedback is an essential component of modeling future warming projections. Dorrepaal and colleagues experimentally warmed Swedish *Sphagnum* peatlands using open-top chambers over a period of eight years. They measured the change in CO_2 emissions in response to 1° C of artificial warming. They found that respiration rates of CO_2 emissions significantly accelerated under warming and remained elevated even after 8 years of treatment. Furthermore, 70 percent of the extra CO_2 emissions respired came from deeper subsurface carbon pools, which had been thought to be more stable.

  Implications: This study demonstrates that the potential for positive feedback in peatlands is larger than previously thought. If these results were extrapolated to the global total peatland cover, 1° C of additional warming above current levels—an amount of warming that we may well experience over the next several decades—could lead to 38-100 Mt C additional "feedback" emissions per year. The upper end of this range is approximately equivalent to the annual emissions of France.

Arctic Sea Ice Feedback

- **J. A. Screen and I. Simmonds**
  "The central role of diminishing sea ice in recent Arctic temperature amplification"
  Nature
  2010, vol. 464

  In global maps of average temperature increases, the Arctic region jumps out as the region that has experienced the fastest rise in temperatures in recent decades. This is called the "Arctic amplification," a phenomenon that is not fully understood. Several explanations have been put forward related to ocean circulation, sea ice dynamics, and changes in cloud cover. Screen and Simmonds present data, based on updated models, satellite imagery, and temperature records, demonstrating that the Arctic amplification is primarily due to reductions in sea ice cover, and not to changes in cloud cover. The reductions in sea ice lead to a positive feedback: as sea ice melts, more darker-colored ocean water is exposed that absorbs more incoming solar radiation, which leads to further warming. Their data show a clear link between sea ice reduction and increases in temperature at regional and pan-Arctic scales.

  Implications: The authors caution that because we can expect further reductions in ice cover, we can certainly expect further increases in Arctic near-surface air temperatures. However, the authors are not only describing a distant phenomenon. This study shows that a sea ice-temperature feedback is happening already, with all of the associated implications for Arctic communities and ecosystems, including both loss of sources of livelihood and loss of habitat for already endangered species.

Ocean Behavior

While many other areas of this report confirm trends of which the scientific community was already aware of, this section presents some very new findings with regard to how climate change will impact oceans—for example, that sea level rise will not be uniform across the globe.

Global Sea Level Rise

The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated that, under business-as-usual, we are likely to experience 0.18-0.59 meters of global average sea level rise by 2100. Many in the scientific community have argued that the IPCC estimate is too conservative because it does not adequately address the dynamics and feedbacks of ice sheet decline. Several studies on the topic have recently been published but came too late for inclusion in the Fourth Assessment Report; for example, in 2007, Stephen Rahmstorf published an estimate of 0.5–1.4 meters of global average sea level rise by 2100. Since that time, several more scientists have published estimates of global sea level rise likely to be experienced by 2100. More recent estimated projections of future global sea level rise (Horton et al. 2008, Vermeer and Rahmstorf 2009, Grinsted et al. 2009, and Jevrejeva et al. 2009, to name a few) have generally been significantly higher than estimates from the 2007 IPCC Report. Two of the more prominent such studies were published in early 2010 and are described below.

- **S. Jevrejeva, J. C. Moore, and A. Grinsted**
  "How will sea level respond to changes in natural and anthropogenic forcings by 2100?"
  Geophysical Research Letters
  2010, vol. 37

For this study, the authors use an inverse statistical model that is constrained by the observed sea level rises at tide gauges around the world. As input to the model, they use six different IPCC radiative forcing scenarios (different amounts of warming based on different projected future rates of anthropogenic emissions). They also include likely contributions from changes in natural solar radiation and potential volcanic eruptions, which have a cooling effect. By combining all of these factors, they are able to produce a range of projected sea level rise within a confidence limit of 95 percent. Their result: 0.59 to 1.8 meters of global sea level rise by 2100. Less than 5 percent of this result is related to natural forcings; it is thus dominated by anthropogenic warming. In short, the upper bound of the 2007 IPCC estimate is the lower bound of the 2010 Jevrejeva et al. estimate.

- **A. Grinsted, J. C. Moore, and S. Jevrejeva**
  "Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD"
  Climate Dynamics
  2010, vol. 34

In this paper, the same authors seek to estimate future sea level rise using nearly 2000 years of global temperature and sea level data estimated from multiple proxy sources. From these data they construct a model that projects recent sea level trends on the basis of the past temperature-sea level relationship. They find that over the past two millennia the lowest average sea levels occurred around 1730, when they were about 20 centimeters lower than today's levels, and the highest average sea levels occurred around the year 1150, which were about 15 centimeters higher than today. For a mid-range warming scenario (IPCC scenario A1B), the authors' model projects 0.9 to 1.3 meters of sea level rise by the end of the century.

Implications: Regardless of the precise method used, it appears that the IPCC 2007 sea level rise estimates may in fact be too low. While the rise by the year 2100 is almost certain to be below 2 meters, uncertainty is large and the debate on the magnitude of sea level rise is continuing (Lowe and Gregory, 2010). Sea level rise of close to 1 meter would have very destructive implications for coastal communities in many countries, with some that are already vulnerable becoming more so and others presumed to be relatively safe becoming vulnerable.

Cruically, adaptation efforts will need to be coupled with mitigation activities. For example, Moore et al. (2010) find that even if we were to go to zero anthropogenic emissions today, 30 centimeters of sea level rise is still likely by the end of the century. This is due to thermal inertia in the atmosphere and ocean systems; the anthropogenic greenhouse gases that have already accumulated in the atmosphere will continue to warm the oceans, as water slowly heats up and expands over the next century. Therefore, in addition to steep emissions reductions, coastal planning to prepare for these impacts will also be necessary.

Sea Level Rise and the West Antarctic Ice Sheet

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

- **J. X. Mitrovica, N. Gomez, and P. Clark**
  "The sea-level fingerprint of West Antarctic collapse"
  Science
  2009, 323

The 2007 IPCC Fourth Assessment Report estimates that a full collapse of the West Antarctic Ice Sheet would lead to a uniform sea level rise of approximately 5 meters across the globe. These calculations were primarily done on the basis of estimating the volume of total ice, and thus water, contained in the ice sheet. Bamber and colleagues have derived a much better estimate of what water from the ice sheet would enter the sea as it melts and what might stay on land. They estimate a global sea level rise of approximately 3.26 meters resulting from the instantaneous melting of the West Antarctic Ice Sheet. Notably, the authors find that the impacts of the sea level rise would not be uniform around the globe. Because of perturbations in Earth's rotation and shoreline migration, the impacts are projected to be most pronounced on the Pacific and Atlantic coasts of the United States, where sea level rise could be 25 percent higher than the global mean.

Mitrovica and colleagues present a model that echoes Bamber et al.'s conclusion that the impacts of sea level rise will not be regionally uniform. As the West Antarctic Ice Sheet melts, it loses mass. The resulting loss of the gravitational pull of the West Antarctic Ice Sheet will reduce the attraction of surrounding waters to Antarctica, and these waters will actually migrate away from the continent. This has the effect of increasing the magnitude of sea level rise elsewhere on the globe, specifically the Western North Atlantic and Indian Oceans.

Implications: While Bamber and colleagues' reassessment of the contribution of the West Antarctic Ice Sheet collapse to sea level rise is lower than previous estimates, it still represents a catastrophic scenario. Most significant, the authors calculate regional differences due to gravitational effects that were almost never taken into account in previous projections. Unlike water being added to a bathtub, with the surface of the water rising at the same rate at all points no matter where water enters, sea level rise will not affect all coastlines in the same way. Mitrovica and colleagues suggests that if the West Antarctic Ice Sheet were to collapse, sea level rise around Washington, D.C. would be 26 percent greater than the global mean. The melting of the Greenland Ice Sheet and mountain glaciers would complicate this regional picture.

Sea Level Rise and the United States

- **J. Yin, M. E. Schlesinger, and R. J. Stouffer**

"Model projections of rapid sea-level rise on the northeast coast of the United States"

Nature Geoscience

2009

Currently, the elevation of the sea levels near the eastern U.S. coast is not uniform, with sea levels that are actually physically lower near the coast than further off shore. This "slope" of sea level is a result of the robust Gulf Stream and North Atlantic currents that are part of the Atlantic Meridional Overturning Circulation (AMOC) system, which transfers heat from the tropics to the poles. According to an ensemble of climate models used in this study, ocean surface warming and the freshening of the Labrador Sea, an area of deep-water formation (where salty waters mix with fresh waters and are chilled and accordingly sink), due to ice melt and precipitation, are projected to slow down the AMOC. If this slowing occurs, it will "flatten" the local sea level slope by eliminating the current difference in near-shore/off-shore sea level height. Range estimates for the 21st Century indicate that this increase may be on the same order of magnitude as global sea level rise from thermal expansion, ranging around 0.2–0.3m of additional sea level rise for Boston, New York and Washington, D.C. by the end of the century. This model does not include the impacts of the melting of the Greenland Ice Sheet on global sea level, nor does it include the extent to which that additional freshwater could help slow down or even shut down the AMOC, which would also contribute to dynamic regional sea level rise.

Implications: The slowing down of the AMOC has been a subject of inquiry, because, it would reduce the heat transfer to Europe, leading to regional cooling trends. Yet rather than study the implications of a slower AMOC on Europe, Yin et al. present new evidence of impacts to North Atlantic coastlines, with significant implications for major U.S. metropolitan centers. This would have the effect of increasing coastal sea levels from Newfoundland to Cape Hatteras. Notably, however, Yin et al. did not assess the likelihood of an AMOC slow down, and some recent studies have given less support for the idea that the AMOC may be slowing down based on recent observations that the AMOC itself is highly variable (see Cunningham et al. 2007).

- **M. D. Blum and H. Roberts**

"Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise"

Nature Geoscience

2009

The Mississippi Delta is geologically young, built by sediment deposits that have accreted after sea level rise decelerated since the last ice age. Now that humans have built dams and levees on the river, however, the rate of sediment loading to the Mississippi River has been reduced from its natural level, and, thus, the delta is no longer building up at the same rate. According to this study, given new estimates of accelerating anthropogenic sea level rise associated with global warming, sediment deposition cannot keep up, and the authors project that we will witness further significant losses of the delta to the sea as a result of subsidence. Based on tide-gauge readings, the authors project that an additional 10,000–13,500 square kilometers of land will be lost by 2100 under current sedimentation rates and a midrange warming scenario (IPCC

A1B). If current sea level rise were only 1 millimeter per year, the authors suggest that removing dams and levees would restore sedimentation loads to prehuman levels, and would be sufficient to avoid this loss. However, even if sediment deposition were restored—in other words dams and levees were removed—under the current projections of 3 millimeters per year of sea level rise, the delta would still continue to lose large amounts of area.

Implications: The combined effects of human engineering of a large water system and human-induced global sea level rise are reversing the natural process of delta formation at the mouth of the Mississippi River. Coastal developments and critical wildlife habitat are projected to be lost to the sea as a result of the combined influence of these two factors. This region may continue to suffer as it faces the ongoing threat of loss of land over the course of the next century.

- **D. B. Bahr, M. Dyurgerov, and M. F. Meier**
  "Sea-level rise from glaciers and ice caps: A lower bound"
  Geophysical Research Letters
  2009, vol. 36

Bahr and colleagues have embraced a straightforward method of estimating the sea level rise that will occur due to the melting of mountain glaciers and polar ice caps: the estimate of a glacier's accumulation area ratio (AAR), or the ratio of area in which the glacier accumulates new mass from snowfall to the area of the entire glacier. A glacier in equilibrium will maintain its total ice mass. The authors measured AARs from 86 mountain and ice cap glaciers around the world from 1997 to 2006 and found that on average glaciers are 23 percent below equilibrium. This means that the area that accumulates new snow is far less than that sufficient to maintain the current glacier size, even without any further warming of the climate. Thus, it is possible to estimate the sea level rise from *already committed glacial melt*. The authors estimate that *without* further warming of the Earth system, we are already committed to 1.8 meters of sea level rise resulting from ice loss, and that 3.7 meters is possible over the next century if we continue to warm without climate mitigation activities. While the authors note that the 1.8 meters of sea level rise to which we are already committed has no time bound (it may not necessarily all occur in the next century), they suggest that much if not all of it is likely to occur within the next 100 years.

Implications: This study documents a notable rise in the contribution to sea level rise from melting mountain and marine-terminating glaciers, which models of sea level rise have struggled to estimate. The numbers provided in this study are a lower-bound following the methods used by the authors. However, 1.8 meters of global sea level rise in the next century even with significant action to mitigate greenhouse gas emissions is a much higher estimate than reported in the most recent IPCC report (estimates all under 1 meter), and certainly merits attention and careful further study. Global sea level rise of 1.8 meters would have significant negative impacts in low-lying countries around the world.

HYDROLOGICAL CYCLE

Climate change is expected to bring about significant changes to the hydrological cycle: including to glacial and snow melt, water supply, plus the frequency and intensity of storms. Recent science suggests that we are already witnessing a rapidly changing world—with ice melt at record highs in many areas, some areas getting much drier, and others getting much wetter.

Glacial/Snow Melt

If current trends continue unabated, ice and snow loss will have significant ramifications for sea level rise and freshwater sources, with attendant, imminent impacts on both human and natural systems. The research described below is only a sample of recent findings on glacial and snow melt across Antarctica, Greenland, mountainous areas, and the Arctic. Taken collectively, they illustrate a world in which maps may need to be redrawn as the landmarks we have long been accustomed to change before our eyes.

Antarctic Ice Sheet Loss

- **J. L. Chen, C. R. Wilson, D. Blankenship, and B. D. Tapley**
  "Accelerated Antarctic ice loss from satellite gravity measurements"
  Nature Geoscience
  2009

  In this study, Chen and colleagues report estimates in ice volume changes on the West and East Antarctic Ice Sheets based on 7 years of data collected from the Gravity Recovery and Climate Experiment (GRACE). In doing so, they rely on several space-based techniques to measure changes, including radar-based methods and measurements of mass changes related to gravity. The researchers estimate that the Antarctic continent has been losing ice volume at a rate of 190 gigatonnes per year (+/-77 gigatonnes) over the period 2002–2009. A gigatonne of melted ice is equal to a cubic kilometer of water, meaning that this loss is roughly equivalent to adding the water held by seven Lake Champlains to the ocean every year. This new estimate is significantly greater than previous estimates using GRACE, which the authors attribute to better estimates using a longer data series and more sophistication in built-in error correction algorithms. Notably, this study also reports estimates that the East Antarctic Ice Sheet is declining in mass at a rate of 57 +/- 52 gigatonnes per year, which is much greater than previous studies, many of which estimated ice mass *growth* in the East Antarctic. Declines in the ice mass of the East Antarctic Ice Sheet have been most pronounced since 2006.

  Implications: Long-term global projections of sea level rise rest heavily on what happens to the Antarctic ice sheets. This study provides troubling new estimates that the rate of mass loss may be greater than previously thought, especially in the East Antarctic Ice Sheet, which had until now had been thought to be declining more slowly or even growing.

Greenland

- **T. Phillips, H. Rajaram, and K. Steffen**
  "Cryo-hydrologic warming: A potential mechanism for rapid thermal response of ice sheets"
  Geophysical Research Letters
  2010, vol. 37

  The authors analyzes the effects of cryo-hydrologic warming on the melting of the Sermeq Avannarleq glacier, a portion of the Greenland Ice Sheet. Cryo-hydrologic warming occurs when melt-water flowing through and over the ice is re-exposed to sub-freezing, winter temperatures and thus refreezes, a physical process that releases heat. The authors have hypothesized that, as more water melts during the melting season, the re-freezing of this water leads to warmer temperatures in the glacier in the freezing season, which in turn has a feedback effect leading to more melt in the spring. They argue, based on their models and observed temperature data from the ice sheet, that this likely is not to be a localized phenomenon, but rather one that occurs throughout a melting ice sheet, rapidly accelerating overall warming on the time scale of years to decades. They suggest that further field research is needed in order to quantify the significance of this effect.

  Implications: While further research is needed to assess the magnitude of the effect and develop empirical evidence, hydrologic-thermal feedback may be a potential mechanism that explains the relatively rapid response of ice sheet loss due to a warmer climate.

Ice Sheets: Hints of a Negative Feedback

- **C. Schoof**

"Ice-sheet acceleration driven by melt supply variability"
Nature
2010, vol. 468

Melting of ocean-terminating ice sheets is contributing to global average sea level rise. Scientists have documented a positive feedback in which more surface meltwater leads to faster acceleration of ocean-terminating glaciers (i.e. physical velocity increases) as well as to rapid thinning of the glacier. Schoof, however, provides evidence of a different feedback—this time negative. He argues that ice-sheet acceleration and dynamic thinning is driven not only by more surface meltwater, but also by the variability of such flow. Using a dynamic model of heat transfer within ice sheets, Schoof shows that, above a certain rate of flow of meltwater, the glacier may actually decelerate the glaciers slide toward the ocean, rather than accelerate, which reduces glacial thinning along the ocean-terminating edge. In this situation, a steady supply of meltwater slows down the thinning of the ice sheets because the larger volume of meltwater forms a narrow channel, which reduces the overall amount of ice exposed to the warmer liquid water. Less or intermittent melting spreads the meltwater out over the ice, incurring a more pronounced positive feedback because the warmer meltwater helps melt more ice. Schoof argues that the daily freeze-thaw cycles and rain events on glacier surfaces lead to a highly variable flow of surface meltwater, and as long as the pressure and flow rate of this water is sporadic and variable, the melting water will continue to accelerate the glacier's slide toward the ocean and the overall rate of melting on the ice edge. While there is some observational evidence for this feedback, more research is needed to confirm the phenomenon.

Implications: Schoof has shown that the simple positive feedback generally assumed to be leading to more meltwater and faster melting is actually more complex than previously thought. The feedback mechanism may vary from region to region depending on the unique structure of the ice, nature of the weather conditions, and the dynamics of temperature variability. The good news is that some models of rapid melting of the ocean-terminating Greenlandic glaciers may overestimate the speed of ice sheet melt in areas where there is a steady supply of meltwater. However, the dynamism of freeze-thaw cycles and rain events suggests that steady supplies of meltwater will not be a common occurrence.

The Consequences of Subtropical Waters and Glaciers Mixing

- **F. Straneo, G. S. Hamilton, D. A. Sutherland, L. A. Stearns, F. Davidson, M. O. Hammill, G.B. Stenson, and A. Rosing-Asvid**

"Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland"
Nature Geoscience
2010, vol. 3

In summer 2008, Straneo and colleagues collected water samples and measured water temperature, density, and salinity in an East Greenlandic fjord by ship. Warm subtropical waters were found throughout the fjord. Waters had been replenished through wind-driven mixing from off of the continental shelf, where subtropical waters occur throughout the year because of the Gulf Stream. The authors found that these warm waters were causing "significant" rapid melting of the glaciers that terminate in this fjord.

Implications: As Rignot and colleagues found (see next paper), the ends of ocean-terminating glaciers in Greenland have been rapidly disappearing, and this has led the flow of these glaciers to accelerate, leading to a feedback of ice-mass loss that has the potential for warming the global climate and increasing sea levels. This paper provides observational evidence that warmer sea surface temperatures in the North Atlantic, linked to global temperature increases caused by anthropogenic warming, might have a positive feedback and accelerate melting of the Greenland Ice Sheet. This is significant because it is one more factor that may be further accelerating loss of the ice sheet, which is critical to estimates of future global sea level rise.

Ice Sheets: Observing the Edge and, Perhaps, the Precipice

- **E. Rignot, M. Koppes, and I. Velicogna**
  "Rapid submarine melting of the calving faces of West Greenland glaciers"
  Nature Geoscience
  2010, vol. 3

  Rignot and colleagues provide measurements of the rate at which the submarine portions of glaciers are melting at the edge of the West Greenlandic Ice Sheet. They find rates of submarine melt rates ranging from 0.7 + or - 0.2 to 3.9 + or - 0.8 meters per day that are two orders of magnitude faster than surface melting rates. Submarine melting has a greater potential to dislodge glaciers, and as glaciers retreat, melting is further increased as the submerged area increases, creating a positive feedback. They argue that the oceans thus strongly influence glacier dynamics and are accelerating overall rates of thinning and melting. They suggest further that analysis is needed of the precise mechanistic drivers that underlie their observations.

  Implications: As more research is done, ice and glacier dynamics are revealed to be more complex than initially expected, as Schoof has shown (see above). Still the most recent data show that we are losing the edges of glaciers at an alarming rate, accelerating sea level rise.

Mountain Glaciers

- **B. Xu, J. Cao, J. Hansen, T. Yao, D. Joswia, N. Wang, G. Wu, M. Wang, H. Zhao, W. Yang, X. Liu, and J. He**
  "Black soot and the survival of Tibetan glaciers"
  Proceedings of the National Academy of Sciences
  2009, vol. 106(52)

  Black carbon, or soot produced from biomass and fossil fuel burning, can lead to surface warming, given its particulate makeup which can trap solar radiation. Furthermore, once deposited, it can alter surface reflectivity, making surfaces darker, more readily absorbing incoming solar radiation (much like a dark shirt on a summer day), and in turn making surfaces warmer. Xu et al. present ice core data from glaciers on the Tibetan Plateau over the last 50 years in an effort to study snow accumulation. They measured the concentrations and geographic distribution of black carbon deposited from soot on the snow. They find that levels of black carbon are high enough to decrease the surface reflectivity of glaciers by 10 to 100 percent, depending on the size and shape of the snow crystals in the glacier and on whether or not the black carbon is incorporated within the crystals or on top of it. Furthermore, deposition of black carbon has been accelerating since 1990, concurrent with the rapid industrialization of South and East Asia. Increases have been greatest along the southern edge of the Tibetan Plateau as a result of black carbon carried by summer monsoon winds from the South. In addition to summer deposition, the winter-time South Asian Haze, also called the brown cloud, has directly contributed to black soot deposition on the plateau. The seasonality of the brown cloud likely maximizes the impact of black carbon's effect on snow melt, because concentrations of black soot in the ice have been highest in the winter, thereby accelerating the onset of the spring melt.

  Implications: Meltwater from Tibetan Plateau glaciers is a major supply of freshwater for the Ganges, Indus, and Brahamaputra Rivers. Millions of people in East and South Asia rely on these water supplies for irrigation, drinking water, and hydropower. As these glaciers melt rapidly and meltwater seasonality is altered, heavier spring floods and longer dry periods with low freshwater volumes are anticipated. While quantifying the exact contribution of black carbon to increased warming requires further research, the results of this study show that concentrations of soot deposited on glaciers are high enough to have impacts on future water supply.

- **D. Farinotti, M. Huss, A. Bauder, and M. Funk**
  "An estimate of the glacier volume in the Swiss Alps"
  Global and Planetary Change
  2009, vol. 68

  Understanding the science behind the rapid decline of mountain glaciers requires good estimates of the total ice volume of mountain glaciers, something particularly difficult to measure directly and fraught with uncertainty when estimated by extrapolation. Farinotti and colleagues have developed a mass balance model using topographical maps of 25 square meters resolution and satellite observations of ice in order to more accurately estimate total ice volume in Swiss mountain glaciers. By applying this model over time, they estimate that up to 12 percent of the volume of Swiss alpine glaciers has been lost over the period from 1999 to 2008, including 3.5 percent during the record warm temperatures of 2003.

Implications: Perhaps the most important finding of this study is that in less than a decade, a very significant volume of ice could be lost. The pronounced influence of the extreme heat wave of 2003 on glacial melt is an important testament to the significant long-term impact that even one extreme year can have on the mass balance of mountain glaciers and the associated hydrological cycle.

- **C. Bogdal, P. Schmid, M. Zennegg, F. Anselmetti, M. Scheringer, and K. Hungerbuhler**

"Blast from the past: Melting glaciers as a relevant source for persistent organic pollutants"
Environmental Science and Technology
2009, vol. 43

As mountain glaciers rapidly decline, the increased flux of meltwater will have hydrological, biological, and chemical consequences for the surrounding ecosystems. Bogdal and colleagues have measured the concentrations of persistent organic pollutants in lake sediment cores over a 60-year period. Many of these chemicals were in peak human production in the 1950s–1960s, which is well documented in sediment records from both low altitude and high altitude lakes, which show a spike in organochlorine compounds (PCBs, dioxins, and DDT) concentrations from this period. During the 1970s and 1980s, however, as knowledge of the toxicity of these chemicals increased and in turn policies banning their use were introduced, the concentrations in lake sediments declined. However, Bogdal and co-authors have observed an alarming recent phenomenon in sediment cores from Swiss high-alpine lakes fed by glacial meltwater: a steady increase in the amount of toxic organochlorine compounds from 1990 to 2005, representing a "second peak" of these chemicals. There has been no significant recent atmospheric deposition of these chemicals, leading the authors to conclude that the source of the second wave of toxic chemicals is glacial meltwater. During the 1950s and 1960s, organochlorine compounds were deposited directly onto glaciers. As the glaciers melt today, these persistent organic pollutants are now finding their way into "pristine" alpine lakes, representing a toxic "blast from the past."

Implications: The authors point out that glacial meltwater from rapidly melting alpine glaciers may represent a significant, temporary new source of contaminating pollution to high alpine lake ecosystems, which are often used for human consumption of drinking water. Beyond the implications for these specific ecosystems, their results show that changes to the hydrological cycle under global warming may have unanticipated knock-on effects that range far beyond changes in temperature, precipitation, and sea level, including potential increases in pollution.

- **W. W. Immerzeel, L. P. H. van Beek, and M. F. P. Bierkens**

"Climate change will affect the Asian water towers"
Science
2010, vol. 328

- **G. Kaser, M. Grosshauser, and B. Mareizon**

"Contribution potential of glaciers to water availability in different climate regimes"
Proceedings of the National Academy of Sciences
2010, vol. 107(47)

One of the greatest concerns about the pace and magnitude of human-induced climate change is how it might compromise the water security of the more than 1 billion people in Asia, mostly in India and China, who live in river basins that are fed by Himalayan glaciers and snow. The flows from these water resources are essential to agricultural production and maintaining drinking water supplies. As temperature rises, there are concerns about the long-term stability of these flows. Immerzeel and colleagues have sought to characterize the risk that climate change poses to the river basins fed by the Himalayan glaciers: the Indus, the Brahmaputra, the Yellow, the Yangtze, and the Ganges. Rather than model the effects that might likely to occur under various warming scenarios, the authors use a metric that calculates how much of the annual flow depends on snow-melt for its volume. They determine that the Indus and the Brahmaputra are most susceptible to climate change-induced changes in snow-melt water flow. The authors find that increases in precipitation in the Yellow River basin, combined with its low dependence on snow-melt water, may actually increase overall water availability for agriculture in the near term in this region.

Whereas Immerzeel et al. analyzed the long-term stability of the Himalayan glaciers as a water source, Kaser and colleagues use temperature and precipitation records to assess the immediate vulnerability of different river basins around the globe to climate change. They do so by assessing the relative contribution of glacial meltwater to the current water supply. The authors postulate that the impact of water losses from climate change will not be as pronounced in wetter areas with a defined rainy season as it will in drier areas because the former are not as dependent on glacial meltwater for their water supply. Using a simple model which argues that glacial melting should occur when temperatures are above freezing, and tracking precipitation, the authors compare glacier-fed rivers in Alaska, Europe, Central, South and East Asia, and northern Russia. They find that impacts on the seasonal availability of glacial meltwater are most significant in river basins that flow through seasonally arid regions. The contribution of glacial meltwater is much less for rivers that flow through already wet lowland regions fed with a seasonal rain cycle. This leads the authors to conclude that, despite some uncertainties in seasonal fluctuations of glacial discharge, the Aral Sea basin may suffer the most from the losses of glacial inputs as the climate warms. Yet the authors conclude that, with the exception of the Indus River, most South Asian and East Asian rivers face a relatively more moderate threat from climate change's impact on glacial meltwater supply than those in arid areas. This paper also shows that the specific climate, topography and flow regimes of different rivers strongly affect the ways in which climate change is likely to affect people who depend on rivers for agricultural production.

Implications: Kaser et al. show that drier river basins are *more* dependent on glacial meltwater supplies than wetter river basins, and that this basin-specific effect is important enough to make a meaningful difference for climate change adaptation purposes. The impacts in wetter river basins will nonetheless be significant, as Immerzeel et al. show in assessing the risks of climate change-induced water scarcity in India and China. Immerzeel and colleagues show that broad, regional-scale projections of water scarcity are likely to obscure important local and basin-specific differences. They argue that climate change adaptation efforts should initially be focused in the Indus and Brahmaputra River valleys that will experience the most immediate effects of climate change.

Arctic

Sea Ice Loss: The (Very Recent) Past

- **R. Kwok, G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi**
  "Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008"
  Journal of Geophysical Research
  2009, vol. 114

It may have gone mostly unnoticed, but over the course of the last few years, the planet has crossed a line: the total volume of multi-year Arctic sea ice is now less than the total volume of single-year Arctic sea ice. According to Kwok and colleagues, the pack of sea ice that survives through each summer is now smaller in size than the pack of sea ice that has melted completely each summer and refrozen each winter, a noteworthy milestone in the process of Arctic sea ice decline due to climate change. This finding is according to Kwok and colleagues, who used satellite imagery from the Ice Cloud and Land Elevation Satellite (ICESat) campaign to estimate both sea ice extent and thickness and monitor changes between 2003 and 2008. These estimates were further with observations from moorings in the Beaufort and Chukchi Seas. Their observations show that multi-year winter sea ice area decreased by 42 percent between 2005 and 2008, and there was a remarkable thinning of ~0.6 m in MY ice thickness over the same 4 years (average thickness of the seasonal ice in midwinter is ~2 m). The dramatic changes in multiyear sea ice are driven mostly by the thinning of this ice, rather than by the loss of area.

Implications: Recently observed losses of multi-year sea ice are happening very quickly, with implications including positive climate feedback effects (less ice in the summer increases absorption of solar radiation), environmental stresses to Arctic fauna, and the opening of the northwest and northeast passages for commercial shipping and navigation. While the loss of sea ice extent, especially in summer, has been widely reported and is well documented, the thinning of multiyear winter sea ice has not been studied to the same degree and may offer clues to the ultimate fate of the ice over the next few decades.

Sea Ice Loss: The Future

- **M. Wang and J. E. Overland**

  "A sea ice free summer Arctic within 30 years?"

  Geophysical Research Letters

  2009, vol. 36

  September 2008 followed 2007 as the second sequential year with an extreme summer Arctic sea ice extent minimum. Using the observed 2007 and 2008 September sea ice extents as a starting point, the authors predict an expected value for a nearly sea ice-free Arctic in September by the year 2037. The first quartile of the distribution for the timing of September sea ice loss will be reached by 2028. The analysis is based on projections from six IPCC models, selected subject to observational constraints. Uncertainty in the timing of a sea ice free Arctic in September is based on both within-model contributions from natural variability and between-model differences.

  Implications: Although such sea ice loss was not indicated until much later in the century in the IPCC Fourth Assessment Report, the results from many models suggest an accelerating decline in the summer minimum sea ice extent during the 21st Century.

- **I. Eisenman and J. S. Wettlaufer**

  "Nonlinear threshold behavior during the loss of Arctic sea ice"

  Proceedings of the National Academy of Sciences

  2009, vol. 106(1)

  The loss of Arctic sea ice is projected to have a positive ice albedo feedback: as sea ice melts, newly uncovered darker colored ocean water absorbs more solar radiation, which, in turn, leads to additional melting of sea ice. This has led some researchers to suggest that there may be a tipping point, beyond which the feedback mechanism takes over and the melting of sea ice will become an irreversible process. Eisenman and Wettlaufer use a model of sea ice thermodynamics in response to different theoretical temperature scenarios to understand the likely behavior of Arctic sea ice as global warming continues.

  They find that the behavior and growth of thin sea ice may actually stabilize the ice albedo feedback, allowing for the existence of a stable seasonally sea ice-free Arctic. That is, even if all of the summer sea ice melts, sea ice thermodynamic modeling projects that thin winter sea ice would still return, despite the feedback effect. However, their modeling suggests that if further warming continues after a period of seasonally sea ice free conditions, there is an abrupt and irreversible threshold (located at a change in heat flux of about -23 W/m^2) beyond which the Arctic Ocean will become perennially ice free.

  Implications: About half of the 2007 IPCC atmosphere ocean global climate models project a summer sea ice-free Arctic by 2100, but only a few of these models project a perennially sea ice free Arctic, and this only after a quadrupling of preindustrial CO_2 (~1000ppm, a figure that is not likely to be reached within this century). This paper, by contrast, provides a model-based thermodynamic mechanism to explain why we might expect a gradual loss of summer sea ice initially, but may risk an abrupt and profound shift to a completely ice-free Arctic, even before reaching such high concentrations.

- **S. C. Amstrup, E. T. DeWeaver, D. C. Douglas, B. G. Marcot, G. M. Durner, C. M. Bitz, and D.A. Bailey**

  "Greenhouse gas mitigation can reduce sea ice loss and increase polar bear persistence"

  Nature

  2010

  Amstrup and colleagues have modeled what reducing anthropogenic greenhouse gas emissions may mean for the future of Arctic sea ice, and thus for the future of the polar bear which relies on the sea ice. Specifically, they use climate models, satellite imagery, and a model of polar bear habitat based on distance from sea ice edge to shore to project whether a "tipping point" temperature (such as that postulated by Kwok et al.) might be reached after which sea ice would rapidly decline. They find that under all climate models, sea ice extent (and polar bear habitat) responds linearly to greenhouse gas concentrations in the atmosphere; that is, they observe no tipping point.

  Implications: The implication of this linear response of sea ice cover to greenhouse gas concentrations is that a reduction in anthropogenic emission of greenhouse gases to the atmosphere may be able to slow the observed trend in declining Arctic sea ice. In other words, despite the results from many other papers which find that we are already committed to significant climate change impacts, this paper argues that it is not too late to take action.

Can Melting Ice Be Cooling Europe?

- **J. A. Francis, W. Chan, D. J. Leathers, J. R. Miller, and D. E. Veron**
  "Winter Northern Hemisphere weather patterns remember summer sea ice extent"
  Geophysical Research Letters
  2009, vol. 36

- **V. Petoukhov and V. A. Semenov**
  "A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents"
  Journal of Geophysical Research
  2010, vol. 115

The decline in Arctic Ocean sea ice extent may have impacts that stretch beyond its immediate surroundings. In these two papers, the effects of the loss of sea ice on weather patterns in the Northern Hemisphere *outside* of the Arctic region are investigated. Francis et al. use satellite measurements of summer sea ice cover and detailed annual weather data to understand how reductions in summer sea ice may influence winter weather patterns. Petoukhov and Semenov focus on how reductions in wintertime sea ice cover north of Russia may influence winter weather in Europe.

Francis et al. find that after September (the month of the year when sea ice cover is lowest), the exchange of heat and moisture from the open ocean surface is greater. This has several effects, including weakening of the stratification of the lower atmosphere leading to a larger layer of the atmosphere close to the surface that holds heat, as well as substantial increases in cloud cover. These changes to the heat and moisture of the lower atmosphere over the Arctic in the late summer and early autumn appear to influence pressure and temperature patterns over much of the Northern Hemisphere, leading, among other things, to increased wintertime precipitation outside the Arctic.

While Cattiaux and colleagues (see above) have attributed the recent colder-than-average winters in Europe to the negative phase of the North Atlantic Oscillation (NAO), Petoukhov and Semenov investigate a different possible dynamic that may be at least partly responsible for the recent winter temperature trends across northern Europe: melting sea ice in the Barents and Kara Seas, portions of the Arctic Ocean north of Russia. Winter sea ice cover has been greatly decreasing in these seas, which causes the lower troposphere (the portion of the atmosphere closest to the Earth's surface) to warm slightly because of the heat-trapping properties of the open ocean (compared to an ice-covered ocean). Petoukhov and Semenov's general circulation model projects that this heating of the lower troposphere, despite its relatively small magnitude, may trigger an anticyclonic, high pressure anomaly over the Arctic Ocean. In other words, according to their model, the warmer air essentially creates a pressure and temperature gradient that sucks heat out of Europe, resulting in an anomalous continental cooling of -1.5° C (averaged across the continent) in the winter.

Implications: These investigations reveal that one of the feedbacks of changing ice dynamics in the Arctic may be an alteration of dominant seasonal climate patterns. In both studies, the melting of sea ice may lead to an increase in observed "winter weather" including more snow and, according to Petoukhov and Semenov's analysis, colder temperatures. During the snowy winter of 2010–2011 in North America, the popular press began covering stories about the breakdown of the polar vortex due to sea ice cover decline, leading to snowier winters, and Francis et al.'s work provides further scientific information about the links between sea ice and weather (albeit focusing on Europe). While Petoukhov and Semenov's analysis remains preliminary, their data suggest that the recent spate of anomalously cold winters in Europe may actually be due in part to Arctic sea ice decline. The authors write, "Our results imply that several recent severe winters do not conflict the global warming picture but rather supplement it…"

Water Supply

The supply of freshwater is fragile. It is already being altered by non-climate drivers, such as agricultural diversion and increased consumption. Climate change can further affect supply as a result of changes to precipitation, runoff, and groundwater. The research highlighted below paints a bleak picture of future freshwater supplies, with implications for crop productivity, ecosystem function and reliable drinking water supplies, among other challenges.

- **M. Biasutti and A. H. Sobel**
  "Delayed Sahel rainfall and global seasonal cycle in a warmer climate"
  Geophysical Research Letters
  2009, vol. 36

  In the Sahel region, climate change-induced alterations of the hydrological cycle will have profound impacts on agriculture and the resilience and adaptability of human communities. Biasutti and Sobel employ a wide array of climate models in an effort to project how greenhouse gas emissions increases will affect the hydrological cycles of the Sahel. No matter the model, the projections are similar: by the end of this century, under a midrange warming scenario (the IPCC's A1B emissions scenario), the rainy season will start later (by 3–4 days) and have a shorter duration (5 days less) in the Sahel. These delays and shortenings, while seemingly small, are likely to reduce crop yields with consequences for agricultural production in the region.

  Implications: For decades, many inhabitants of the Sahel region have struggled to maintain a viable existence on this agriculturally marginal land, which stretches along the southern edge of the Sahara desert. Meanwhile, this paper projects a shift in the hydrological cycle is coupled with projected increases in temperature, which would likely lead to both warmer and drier conditions during the critical beginning of the growing season in this already vulnerable region.

Changes in River Discharge

- **A. Dai, T. Qian, K. Trenberth, and J. D. Milliman**
  "Changes in continental freshwater discharge from 1948 to 2004"
  Journal of Climate
  2009

  Dai and colleagues have compiled a data set of runoff from 921 rivers across the globe spanning a record of more than five and a half decades from 1948 to 2004. Previous studies have reported that river runoff is increasing because warming evaporates more water, leading to increases in extreme precipitation events and an "acceleration" of the hydrological cycle. Based on the river flow records, Dai et al. find that in most places, contrary to previously reported results, river runoff is actually decreasing. This trend is primarily linked to reduction in precipitation over some river basins that are experiencing droughts, as well as to decadal atmospheric oscillation patterns. The notable exception is for rivers flowing into the Arctic Ocean basin, which are increasing in runoff, a result consistent with previous studies. The authors argue that this increase in the Arctic flow may be due to climate-induced increases in snow melt.

  Implications: If these trends continue unabated, many regions will face challenges as total water availability decreases while seasonality of runoff changes. This can lead to climate change-induced floods in spring in some regions, as glaciers and snowpack melt, while rivers are likely to then run dry later in the season. In particular, lower total discharge in river basins in temperate and tropical areas will put stresses on communities already experiencing freshwater shortages.

- **T. Barnett and D. W. Pierce**
  "Sustainable water deliveries from the Colorado River in a changing climate"
  Proceedings of the National Academy of Sciences
  2009, vol. 106(18)

  The combined effects of warming temperatures on snowmelt, evaporation, and precipitation will likely have profound influences on seasonality of streamflow patterns in many global regions. For decades, energy production, agriculture and other critical human infrastructure has been built with the assumption that the seasonality and volume of past stream-flow patterns will continue indefinitely into the future. Barnett and Pierce use a model specifically designed for the Colorado River, incorporating its use by humans, in order to estimate the impacts that climate-induced reductions in Colorado River runoff will have for future water deliveries to human users. This model projects a 10–30 percent reduction in Colorado River runoff by 2050 because of anthropogenic climate change. Barnett and Pierce find that even at the low end of this range, 60 percent of scheduled water deliveries for human use will not likely be able to be met by mid-century.

Implications: The already overstretched Colorado River will be even further stressed by the impacts of climate change. The authors conclude that current human use of the Colorado River is not sustainable under scenarios of climate change and will result in significant and frequent failure to meet scheduled water deliveries in the U.S. Southwest. The authors argue that adjustments of human demands on water resources, even at modest levels, could be sufficient to avoid catastrophic delivery failures. Thus, adapting human infrastructure and behavior will be critical in the basin.

Storms

The impacts of extreme weather events such as cyclones are fresh in the minds of many, as 2009 and 2010 witnessed a significant number of such storms. While no one event can be attributed to climate change, we are witnessing "new normals" around the world, and decision makers have increasingly been challenged to react quickly to deploy resources and rebuild damaged communities and infrastructure. In the section below, we highlight a few of the scientific articles published over the past 2 years on the impact of climate change on storms.

- **M. A. Bender, T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. M. Held**
  "Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes"
  Science
  2010, vol. 327

- **K. E. Kunkel, D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith**
  "Recent increases in U.S. heavy precipitation associated with tropical cyclones"
  Geophysical Research Letters
  2010, vol. 37

One of the most consistently uncertain, but potentially significant, effects of climate change is its impact on the frequency and intensity of tropical cyclones. Because of the extreme destructive potential of hurricanes and the recent experiences of Hurricanes Katrina and Rita in the United States, understanding this dynamic as well as possible is a top priority for both climate researchers and decision makers. Over the last 3 years, several studies have found that there appears to be an increase in the *intensity* of hurricanes, but not necessarily in their frequency (Emanuel et al. 2008; Wu and Wang, 2008; Elsner et al. 2008). For this paper, a team of National Oceanographic and Atmospheric Administration scientists use a hurricane-prediction model with ensemble forecasts of 18 global climate models to project hurricane activity over the rest of the 21st Century. They find that the frequency of intense hurricanes (category 4 or 5) is likely to increase significantly. Their model projects an increase in the number of intense storms by 80 percent by the end of the 21st Century. They attribute this change to warmer sea surface temperatures. While the overall frequency of hurricanes is likely to decrease, the model suggests that there will be a significant increase in the frequency of powerful storms after 2070.

Kunkel and colleagues have investigated a long-term data set of U.S. precipitation records from 1895 to 2008. They found that since 1994 the number of extreme precipitation events associated with tropical cyclones (where extreme is defined as daily amounts exceeding a threshold for a 1 once-in-5-year occurrence) has been 30 percent greater than the long-term average. In other words, in the last 15 years, tropical storms have produced significantly more heavy rain events in the United States than during the previous century. The authors note that this is not a result of the increase in the number of hurricanes and tropical storms; rather, there has been a significant increase in extreme rainfall associated with each storm event.

Implications: Bender et al. build on other recent research that suggests that a consensus is emerging with regard to climate change's impacts on hurricanes, leading to more intense, but not necessarily more frequent, events. This finding has significant implications in the southeastern United States, where coastal populations, ecosystems, and infrastructure will be at heightened risk to these extreme events. Kunkel and colleagues show that one of the projected effects of climate change—an increase in extreme precipitation—appears to already be observable. While this study stops short of trying to demonstrate causality between extreme rainfall and climate change, the data provide evidence for a trend of increasing extreme rainfall associated with tropical storms.

- **A. Seth, S. A. Rauscher, M. Rojas, A. Giannini, and S. J. Camargo**
  "Enhanced spring convective barrier for monsoons in a warmer world"
  Climatic Change
  2010

A great deal of attention has recently been paid to the likelihood that climate change will lead wet areas to become wetter and dry areas to become drier, or, in other words, that current climatic patterns will intensify. This shift is expected to occur because of both feedback effects and changes in seasonality of precipitation patterns. Seth and colleagues analyze the projected 21st Century behavior of one such critical pattern: the monsoon system in South Asia. Using a suite of coupled-climate model projections (based on the 2007 Coupled Model Intercomparison Project CMIP3), the authors find that the annual cycle changes to the monsoon system have global implications: there is a redistribution of precipitation from spring to summer in North America, West Africa, Southern Africa, South America, and Southeast Asia for the years 2070–2099. Therefore, more rain is expected in the later part of the rainy season, while the early "rainy" season will likely remain dry. The authors find that, in South Asia, wet areas may get wetter by 20 percent (measured as difference in precipitation amount), and dry areas drier by 20 percent, when precipitation is averaged over the whole season. The authors find that the mechanism responsible for this seasonal shift can be explained by warmer winter temperatures leading to a more stable spring convective system, in which reduced surface moisture and stable atmospheres prevent spring rains from occurring. This happens because warm convective regions that are already moist draw moisture horizontally from less convective regions. The increased moisture in these regions leads to more precipitation, while in the already dry regions, warming and moisture loss lead to a more stable, less moist regime.

Implications: The authors caution that more observation-based data are required to confirm the universality of this climatic trend. However, if true, it could be one of the most important predictive insights to inform the design of climate adaptation interventions, given the likely profound consequences for agriculture, water resources, and ecosystems across the globe.

ECOSYSTEMS AND ECOSYSTEM SERVICES

The diversity of species on Earth, ecosystems, and the services they provide are being transformed at a rate unprecedented in modern times. Climate change compounds other drivers such as land conversion and pollution. The recent science described below—covering issues from food security, to wild fires, habitat destruction, and marine and terrestrial species, among others—provides evidence that many of the world's natural assets are in peril. These stories underscore an urgent need for both substantial and rapid mitigation efforts, as well as adaptation efforts to strengthen the resilience of ecosystems in a changing climate.

- **D. Battisti and R. Naylor**

  "Historical warnings of future food insecurity with unprecedented seasonal heat"

  Science

  2009, vol. 323

  Using a combination of 23 climate models, Battisti and Naylor assess the impacts of increasing temperature on global food supply. Their model ensemble indicates that in the tropics and sub-tropics, it is highly likely (greater than 90 percent probability) that, in the absence of efforts to reduce greenhouse gas emissions, the average growing season temperature during the last decades of the 21st Century will exceed the most extreme temperatures experienced at any point during the 20th Century. Their model projects this result for much of China, Indonesia, India, large portions of South America, all of Turkey and about half of Africa, In temperate regions, the models suggest that 20th Century and early 21st Century temperature extremes (like those experienced during the 2003 heat wave in Europe) will become the norm.

  Implications: The authors point out that higher temperatures alone will have significant negative effects on crop yields, even without the projected impacts of associated drought. Experimental models of most major grains suggest that the temperature increases that are projected will reduce yields by 2.5–16 percent, simultaneously stressing already vulnerable populations (Peng et al. 2004; Lobell and Field 2008). They suggest that food shortages like those experienced in the Sahel in the 1960s and in the former Soviet Union in the 1970s are highly likely to become the norm in the absence of meaningful mitigation and adaptation actions.

- **S. Jenouvrier, H. Caswell, C. Barbaud, M. Holland, J. Stroeve, and H. Weimerskirch**

  "Demographic models and IPCC climate projections project the decline of an emperor penguin population"

  Proceedings of the National Academy of Sciences

  2009, vol. 106(6)

  Using observations of emperor penguin populations collected over 43 years, Jenouvrier et al. developed a population model that projects the response of emperor penguin populations to climate change. By combining this population model with a global circulation model that projects future sea ice extent among other impacts, the authors assessed future climate change impacts on Emperor penguin populations. Populations are projected to decline, with the probability of "quasi extinction" (greater than 95 percent decline) by 2100 at 36 percent. The ecological mechanisms underlying this projected decline are thought to be both direct and indirect. Direct effects on population growth could result from the impacts of early sea ice breakup on breeding success. Indirect food web effects are posited to the result of a reduction in krill abundance associated with reduced sea ice extent (sea ice is a critical habitat for krill, as they feed on algae that live beneath the ice). While emperor penguins do not prey on krill, they prey on fish which in turn prey on krill.

  Implications: Projected physical disruptions to ecosystems dependent on sea ice are likely to be profound during the current century. Species dependent on this habitat structure, which is likely to rapidly decline, are especially vulnerable to climate change-induced declines in population, as the opportunities and time scale for adaptation are severely constrained. This study provides one example of the negative impacts of the loss of sea ice and krill, a key species, on a particularly charismatic bird species and associated Antarctic food webs.

The Tiger and the Sea

- **C. Loucks, S. Barber-Meyer, M. A. Abraham Hossain, A. Barlow, and R. M. Chowdhury**

"Sea level rise and tigers: Predicted impacts to Bangladesh's Sundarbans mangroves"
Climatic Change
2010, vol. 98

There are many ways that climate change is expected to affect both organisms and ecosystems: disrupted timing of breeding, thermally induced physiological stress, induced mismatch between the life cycles of predator and prey, and habitat change. In the case of the already threatened tigers of the Sundarban mangrove swamps of Bangladesh, climate change-induced loss of habitat appears likely to be very detrimental to the species survival. Loucks and colleagues constructed a detailed digital elevation model based on over 80,000 GPS points to develop an accurate map of the mangroves. They find that 28 centimeters of future sea level rise will reduce the current tiger habitat by 96 percent, and likely reduce tiger numbers to 20 breeding pairs. This is predicted to occur under current projections of sea level rise during the next half-century. While previous studies have discussed the likely negative impact of sea level rise on tigers, this is the first to provide detailed subcentimeter assessments of the impact of sea level rise on habitat in the Sundarban mangroves.

Implications: While sea level rise of less than a half meter is sometimes classified as "non-catastrophic" this paper highlights that the sea level rise expected over the next few decades, which may be considered to be unavoidable even in the face of strong mitigation action, will have catastrophic effects for notable threatened species. The authors suggest that, if focused policies are not undertaken to mitigate the effects of rising seas, the Sundarban tigers will likely "join the polar bear as early victims of climate change-induced habitat loss." The Sundarban tigers already occupy only 7 percent of their historical range.

Tipping Points for Populations

- **D. F. Doak and W. F. Morris**

"Demographic compensation and tipping points in climate-induced range shifts"
Nature
2010

As the climate warms, many plant species, especially those in the sub-arctic regions, experience a push-pull between range shifts and demographic population changes. For example, some species of plant have exhibited marked northward range shifts in North America. As temperatures become warmer on average, the biogeographic "envelope" in which plants are able to grow has shifted, and thus the distribution of the species moves. However, some species do not exhibit such range shifts, perhaps due to what the authors refer to as a "buffering" effect owing to demographic compensation for warming: in other words, adaptation to changing climate. Using observations from multiple sites spanning decades, Doak and Morris investigate two species of tundra plants whose southern ranges have not shifted northward. These plants exhibit an enhanced growth response to warmer temperatures, despite lower survival and recruitment; some plants appear able to adapt to the warmer temperatures and are maintaining their presence in the original range. However, Doak and Morris caution that there is evidence that the most extreme warm temperatures have pronounced negative impacts on overall population growth rates and survival of the two species. These extreme temperatures thus represent a tipping point for these species, and the results suggest that this persistence of some plant species in the face of warming may be short-lived as warming trends continue.

Implications: This paper provides evidence for some minimal "adaptation" in the form of demographic compensation to climate change in the northern temperate and sub-Arctic regions of North America. The authors' research also suggests that threshold temperatures, beyond which both growth and, ultimately, survival is no longer possible for some species, may begin to occur in the next few decades.

- **M. Daufresne, K. Lengfellner, and U. Sommer**
  "Global warming benefits the small in aquatic ecosystems"
  Proceedings of the National Academy of Sciences
  2009, vol. 106(31)

While it is well documented that as global average temperature rises, species shift their ranges to higher altitudes and higher latitudes and alter their seasonal timing, Daufresne et al. propose an additional "universal" rule: species' body size will decrease in response to higher temperatures. Building on established ecological theories that warmer regions are inhabited by smaller species (Bergmann's rule), that, within a species, smaller sized populations are found in warmer climates (James' rule), and that for cold-blooded organisms, individuals will have decreasing body size with increasing temperature (Temperature-Size rule), the authors tested various hypotheses relating the body size of many commercial fish species to water temperature using observational and experimental data in conjunction with a thorough metaanalysis. They found that global warming led to increased numbers of smaller fish species and a decrease in mean body size across species, due to smaller size at age of maturity and an increase in the proportion of juveniles. This, in turn, led to a decrease in the body size of the overall community.

Implications: This proposed "universal" response to heightened temperatures offers a useful theory for the ongoing work of understanding and predicting how ecosystems, communities, populations and individuals will respond to a changing climate. The authors point to widely documented observations of increasing proportions of juveniles within commercial fishery populations. This has widely been attributed to the impact of fishing and overfishing on these populations. As this study suggests, understanding the future of fisheries will require understanding of the impacts of *both* fishing and climate change on commercial fish stocks as we move to a warmer—and smaller—world.

What Is Happening to the Cold-Blooded Animals?

- **R. B. Huey, C. A. Deutsch, J. J.Tewksbury, L. J. Vitt, P. E. Hertz, H. J. Álvarez Pérez, and T. Garland Jr.**
  "Why tropical forest lizards are vulnerable to climate warming"
  Proceedings of the Royal Society B
  2009

Using a combination of literature review, field sampling investigations and laboratory studies of tropical forest lizards species in Puerto Rico, Huey et al. performed research in an effort to to determine whether warmer temperatures negatively impact tropical forest lizards. To answer this question, the authors conducted field surveys of lizard species' thermoregulatory behavior (basking) and thermal sensitivity. In particular, they focused on the behavior of four species of Puerto Rican *Anolis* and *Sphaerodactyus* lizards. They compared lizard body temperatures and thermally-dependent sprinting behavior from experiments in the 1970s and 1980s to 2008 temperatures. They find that a warming climate negatively impacts lizard thermal tolerance. The authors conclude that "some tropical forest lizards 'can't take the heat.'"

Implications: The authors demonstrate that tropical forest cold-blooded species are likely to be, and in fact, may already be impacted by thermal stresses associated with climate change. They suggest that as tropical forests warm, climate change may offer opportunities for invasion by open-habitat species as a result of their efforts to adapt to warmer climates, fundamentally altering the structure and function of tropical forest ecosystems.

- **M. E. Dillon, G. Wang, and R. B. Huey**
  "Global metabolic impacts of recent climate warming"
  Nature
  2010

- **B. Sinervo, F. Mendez de la Cruz, D. B. Miles, et al.**
  "Erosion of lizard diversity by climate change and altered thermal niches"
  Science
  2010, vol. 328

Climate change is already impacting organisms around the globe. Significant changes in species distribution, the timing of critical events in the life cycle of organisms, and even extinctions, have been observed and are projected to be more likely in a changing climate. Many of these impacts are driven by the impact of higher temperatures on the physiology of organisms. Because the Arctic has warmed more substantially than the tropics (due, in part, to localized warming feedbacks associated with ice melt), it is generally assumed that impacts on polar species are currently, and will likely continue to be, more pronounced than in the tropics, where temperatures are already quite warm. However, Dillon and colleagues show that, because the relationship between temperature and the metabolic rate (of enzyme activity) in organisms is not linear but exponential in ectotherms (cold-blooded animals), even small increases in temperatures observed in the tropics are already having significant physiological impacts in tropical ectotherms, such as lizards. The authors suggest that the small absolute value of temperature increases in the tropics has masked the physiological impacts that are occurring. The scientists find that the modeled metabolic impacts (measured in watts of energy per gram of organism) of climate change over the last three decades have been most significant in tropical regions.

While many papers and reports on the impact of climate change focus on projected future impacts in, for example, 2050 or 2100, Sinervo and colleagues set out to assess the impacts of warming temperatures that have already affected populations of lizards around the globe. Analyzing field observational studies of 30 species of Mexican lizards from 1975 to 2009, they find that 12 percent of local populations of lizards have gone extinct. Using a physiological model of lizard response to warming based on the Mexican observations, they estimate that globally, 4 percent of lizard populations have gone extinct since 1975 as a result of climate change. Based on these observed trends, the authors ultimately project future lizard species losses caused by climate change and find that by 2080, 39 percent of local lizard populations and 20 percent of global lizard species will be extinct.

Implications: Taken together, these studies demonstrate that warming experienced over the last three decades has had a significant impact on many local lizard populations, as well as populations of invertebrates and amphibians around the globe. And these trends are expected to get much worse, with one in five lizard species becoming extinct in the next 70 years as a result of climate change. The authors highlight an area of concern for future studies of climate change impacts on physiology: most models project monthly or yearly temperature averages, but what is of most importance, at least to lizard species loss, may actually be estimates of daily temperature maxima, rather than averages, because extreme temperatures can have some of the greatest impacts on populations of ectotherms.

Just Too Darn Hot . . .

- **S. C. Sherwood and M. Huber**
  "An adaptability limit to climate change due to heat stress"
  Proceedings of the National Academy of Sciences
  2010, vol. 107(21)

It has often been assumed that human adaptation to climate change is largely a function of the distribution of economic resources, and that there is no fundamental physiological limit on the human capacity to adapt to increased temperatures. The authors find, however, that extremely high temperatures can prevent humans from regulating their own body temperatures because they cannot dissipate enough excess heat, leading to the shut down of core metabolic functions. Based on physiological estimates, the authors conclude that a global average temperature increase of 7° C, which is toward the upper part of the range of current projections, would make large portions of the world uninhabitable. A global temperature increase of 12° C, which could occur solely from the combustion of all estimated fossil fuel reserves, would render much of the globe uninhabitable by humans.

Implications: Temperature increases of this magnitude are not likely to be experienced in this century, but the authors suggest the need for a modification in the ways human adaptation to climate change is conceptualized by decision makers. For example, the authors point out that one major implication of their work is that the "costs" assigned to future warming scenarios are currently too low, because they do not account well for the possibility of such catastrophic events and major changes to the habitability of the planet. As they point out, current economic models treat a 10° C rise in temperature as having an equivalent economic effect to a major recession, when it might actually render half the planet uninhabitable.

- **S. Feng, A. B. Krueger, and M. Oppenheimer**
  "Linkages among climate change, crop yields, and Mexico-US cross-border migration"
  Proceedings of the National Academy of Sciences
  2010

Humans are also likely to change their distribution in response to climatic shifts. Climate change-induced reductions in agricultural yields are projected to lead to human migration, including migration across international borders. The authors of this study assessed the role of climate change-induced crop yield reductions on emigration on a state-by-state basis in Mexico. They find that there has been a positive relationship between climate impacts on crop yield loss (as opposed to land use or policy-related losses) and the number of people leaving a given Mexican state to emigrate to the United States during the decade from 1995–2005; for about every 10 percent decrease in crop yield there is an associated 2 percent of the population that emigrates. Extrapolating, based on these observed, state-level migration patterns, the authors project that under the (relatively conservative) B1 future warming scenario, by the year 2080, climate change will likely induce an additional 1.5 to 6.5 million Mexicans to emigrate across the U.S. border; however, social and economic factors in both countries are likely to be a major determinant of immigration trends.

Implications: Increasingly climate change is being viewed in the United States as a potential threat to national security. Changes in land-use patterns and agricultural policies in Mexico and other Central American countries have already caused waves of emigration to the United States. Climate change is likely to augment this trend as it impacts crop yields in some of the most vulnerable and poorest areas of southern Mexico. Currently, the number of net immigrants crossing into the United States every year from Mexico is estimated at around 200,000, although it has been declining because of U.S. policies and economic conditions. This research projects an average of an additional potential 20,000–100,000 "climate immigrants" per year over the coming decades. And as the climate warms, the impacts are likely to become greater. Thus climate change could play a significant role in domestic and international policy debates in the United States related to immigration in the future.

- **G. Beaugrand, C. Luczak, and M. Edwards**
  "Rapid biogeographical plankton shifts in the North Atlantic Ocean"
  Global Change Biology
  2009, vol. 15

Climate change, and specifically increased global average temperature, is projected to have significant effects on species distributions, which will shape the future composition of ecosystems. Copepods are microscopic animals that are critical components to the functioning of North Atlantic food webs. Beaugrand and colleagues correlated recent zooplankton copepod species data from the Continuous Plankton Recorder (CPR) project in the North Atlantic with sea surface temperature (SST) records from 1958 to 2005. In doing so, they separate out the effects of natural decadal cycles, like the North Atlantic Oscillation index, which is reflected in regional weather patterns in the North Atlantic, and changes in Northern Hemisphere sea surface temperature associated with anthropogenic global warming. They found significant and rapid poleward shifts in assemblages of copepod zooplankton species, with northward movement at rates of over 20 kilometers per year over the last five decades. The authors caution that these shifts may not be entirely attributable to changes in temperature, because in some cases species migrated at faster rates than temperatures changed.

Implications: The robustness of the long-term CPR and SST data set demonstrates that zooplankton species, which occupy an important position in the marine food web as a conduit for energy transfer from primary producers to commercial fisheries, are rapidly changing in the North Atlantic. However, there is strong evidence that species that once dominated the temperate marine zones are now rapidly advancing into subarctic marine spaces, and once-tropical species are now rapidly advancing into temperate marine spaces, with major implications for the composition of marine ecosystems that comprise important fisheries.

Forests and Wildfires

- **M. A. Krawchuk, M. A. Moritz, M.-A. Parisien, J. Van Dorn, and K. Hayhoe**
  "Global Pyrogeography: The Current and Future Distribution of Wildfire"
  PLoS ONE
  2009, vol. 4(4)

- **M. S. Balshi, A. D. McGuire, P. Duffy, M. Flannigan, D. W. Kicklighter, and J. Melillo**
  "Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st Century"
  Global Change Biology
  2009, vol. 15

- **M. Flannigan, B. Stocks, M. Turetsky, and M. Wotton**
  "Impacts of climate change on fire activity and fire management in the circumboreal forest"
  Global Change Biology
  2009, vol. 15

Increases in both the frequency and extent of wildfire are often cited as salient examples of the effects of climate change that can have immediate and significant impacts on human communities. Yet our understanding of both climate change impacts on the extent of wildfire regimes and the potential climate feedbacks of wildfire has until recently been limited.

Krawchuk et al. set out to understand how and, crucially, where, wildfire regimes are likely to respond to climate change. To do so, they establish a global baseline of wildfire distribution and frequency, using detailed correlative analyses of the environmental controls of wildfire, which they found to be primary production (the production of plant matter from carbon dioxide, mainly through photosynthesis), temperature, and precipitation regimes. They then used general circulation models under IPCC climate change scenarios to project future changes. They found that while wildfire frequency increases in response to climate change globally, regional changes demonstrate both increases and decreases in wildfire distribution, largely mediated by regionally specific vegetation and precipitation changes. Notably, the increases in wildfire extent are projected to be in the United States and Canada, Europe, and western China. Decreases in wildfire extent are projected for parts of East Asia, Africa, and Australia.

Implications: As wildfire extent increases, there may be feedbacks to the climate system. For example, Balshi et al. apply their Terrestrial Ecosystem Model to examine the impact of increases in wildfire on CO_2 emissions. Their model projects substantial (two- to fourfold) increases in carbon dioxide emissions from increased wildfire by the end of the century. It is important to note, however, that Northern forests are currently a large sink of carbon (meaning they uptake more carbon than they emit). Whether they become a net source because of wildfire ultimately strongly depends on the extent to which carbon dioxide fertilization increases in carbon uptake. Also, as noted by Flannigan and colleagues, the ability of fire management systems to respond to fires in a changing climate will increasingly be stretched.

Using Past Fires to Predict Future Fires

- **O. Pechony and D. T. Shindell**
  "Driving forces of global wildfires over the past millennium and the forthcoming century"
  Proceedings of the National Academy of Sciences
  2010, vol. 107(45)

One of the main fears of near-term global warming, augmented by the devastating fires in Russia in summer 2010, is the increasing prevalence of destructive wildfire with increasing temperatures. Wildfires, however, are caused not just by temperature but also are associated with drought conditions, winds, human activity, and land cover. Pechony and Shindell construct a model of the driving factors behind global wildfire regimes over the last 1,200 years and use this model to understand how fire is likely to behave over the next century. They conclude that, until the Industrial Revolution, wildfire occurrence was largely a function of precipitation, with fires occurring most commonly in drought-stricken areas. After the Industrial Revolution, they argue, fire was largely driven by direct human activity. Having parameterized their model so it successfully predicts past fire regimes, the authors then projected future fire regimes until 2100. They find that over the next century, higher temperatures as a result of global warming will be the most significant driver of wildfire.

Implications: As temperatures continue to rise and more extreme heat waves are predicted, the results of this study suggest that future warmer temperatures will play the salient role in determining future fire regimes in which wildfire extent and intensity will increase. According to the authors, this increase will not be uniform across geographic space but likely will be concentrated in areas where drier conditions are most prevalent.

- **C. Jones, J. Lowe, S. Liddicoat, and R. Betts**
  "Committed terrestrial ecosystem changes due to climate change"
  Nature Geoscience
  2009

  Jones and colleagues at the Met Office Hadley Centre in England make the case for ecosystem scientists and climate change policymakers to consider the concept of "committed" ecosystem change. Rather than treating climate change impacts as transient impacts that begin when a certain rise in temperature is reached, Jones et al. present a coupled global circulation climate-vegetation model for the Amazon which indicates that even before impacts of climate change—induced forest die-back in the Amazon are observed, significant amounts of dieback may already have been committed to. For example, while observed die-back under a scenario where warming is limited to 2° C is approximately zero in 2050, committed die-back over the next centuries may be as high as 30 percent. This is due to climate change impacts continuing even after global temperatures are stabilized.

  Implications: The authors note that above a "threshold temperature" of average warming, tropical forest ecosystems become "committed" to significant climate change impacts. They argue that this temperature rise is below the 2° C limit much discussed by policy makers. Although there is uncertainty inherent in their models, this paper makes a critical point: decision makers will need to change the standard conceptions of climate change impacts given the potential for early commitment to long-term responses. This will put a premium on proactive decision-making processes that advance both mitigation and adaptation interventions today even if impacts have not become manifest.

If a Butterfly Flaps Its Wings Too Early… ?

- **M. R. Kearney, N. J. Briscoe, D. J. Karoly, W. P. Porter, M. Norgate, and P. Sunnucks**
  "Early emergence in a butterfly causally linked to anthropogenic warming"
  Biology Letters
  2010, vol. 6

  Using 65 years of volunteer collected data cataloging the emergence date of the Australian butterfly *Heteronympha merope* in grasslands around Melbourne, Kearney and colleagues show that the mean emergence date has advanced 1.5 days per decade over the last six and a half decades. In order to understand how changing temperatures are influencing this species, they constructed a model of the temperatures likely to be experienced by the butterfly pupae living in grasslands just a few inches above the ground. They then conducted incubation experiments, rearing butterflies in glass vials from egg to emergence under controlled temperature conditions, and measured the thermal response to development. Based on results from the experiment and model, as well as historical records, they conclude that the warming experienced over the last 65 years should have resulted exactly in the actually observed shift in emergence dates. The authors thus conclude that their results "very strongly" indicate that the changes in emergence date of this Australian butterfly result from the impacts of anthropogenic climate change on its developmental biology.

  Implications: The authors conclude that studies directly linking climate change to physiological development rates and to observed phenological shifts provide a good framework for conservation management under global climate change.

Tipping points for forests

- **L. F. Salazar and C. A. Nobre**
  "Climate change and thresholds of biome shifts in Amazonia"
  Geophysical Research Letters
  2010, vol. 37

  Recently there has been considerable attention to the idea that beyond critical climate tipping points, ecosystems may fundamentally change character. In this study, Salazar and Nobre set out to understand thresholds in the Amazon forest. They use a vegetation model forced with model-projected climate anomalies (from the IPCC

A2 scenario) for temperature, precipitation, and carbon dioxide fertilization (the effect of additional CO_2 in the atmosphere "fertilizing" trees, causing them to uptake more carbon dioxide and grow at a faster rate). They find that, in the absence of any carbon dioxide fertilization effects, anticipated temperature increases of 2–3° C above present levels could lead to a transition in much of southeastern Amazonia from tropical rainforest to savanna scrubland, as the Amazon becomes warmer and drier. The authors find that temperature increases and precipitation decreases drive this trend. If a carbon dioxide fertilization effect is included, then a temperature increase of 4–5° C is required to realize the same ecosystem impacts.

Implications: This paper shows the likelihood of significant biome changes in parts of the Amazon tropical forest, with profound implications for biodiversity and feedbacks to the global climate system. Salazar and Nobre also highlight the critical role that carbon dioxide fertilization effects can have in mitigating these changes and the need for further and careful study of this effect. The carbon sink of terrestrial plants is large and is even increasing (Raupach 2011). However, recent studies using experimentally elevated free-air carbon dioxide chambers have indicated that the effects of carbon dioxide fertilization, while significant, may be shorter-lived and lower than originally thought (Lobell and Field 2008; Ainsworth et al. 2008).

Ocean Acidification

Rising atmospheric carbon dioxide (CO_2) concentrations have resulted in increased concentrations of dissolved CO_2 in the oceans, in turn lowering of ocean pH as CO_2 molecules react with water to form an acid. Thus far, the pH of the global oceans has been lowered by approximately 0.1 units since the start of the industrial era. Because pH is a logarithmic scale, this 0.1 unit drop is equivalent to a 30 percent increase in the acidity of ocean water. It is important to keep in mind that even with this increase in acidity, ocean water is not actually an acid, it is still basic: the oceans are, however, steadily becoming more acidic as the pH drops because of anthropogenic carbon dioxide emissions. The rate at which this increase in acidity is occurring is unprecedented in the last 65 million years of the oceans' history, putting profound pressures on species to adapt quickly (Ridgwell and Schmidt 2009).

The impacts of both elevated ocean temperatures and increasing carbon dioxide concentrations are projected to have profound, though species-specific, effects on marine organisms. For many calcifying organisms including corals, ocean acidification has negative impacts on growth and fitness. Calcifying organisms require the presence of calcium ions and carbonate ions in water in the right ratio in order to make their calcium carbonate skeletons. As the oceans become more acidic, the carbonate ions react with the extra acid and fewer of them are available for calcifying organisms to use to make their shells. In addition to effects on coral, several other papers' findings indicate that ocean acidification is also becoming a threat to other ocean fauna, from fish to mollusks, with potentially significant impacts for the ecology of many regions of the world's oceans, as well as the sustainability of some fisheries.

- **G. De'ath, J. M. Lough, and K. E. Fabricius**
  "Declining coral calcification on the Great Barrier Reef"
  Science
  2009, vol. 323

Increasing the relative acidity of the oceans can cause great harm to calcifying organisms, as their calcium carbonate shells grow more slowly and, in some cases, dissolve. While previous laboratory studies have confirmed that decreasing pH reduces the growth rate of reef-building corals, De'ath and colleagues measured the calcification rates of Great Barrier Reef reef-forming *Porites* corals in the wild in order to understand how corals have been responding to acidification thus far.

Using x- and gamma-ray densitometry, the authors compared calcification rates of coral samples with sea surface temperature records over the last 400 years. Their results show that calcification has rapidly declined since 1960, with the most dramatic decline from 1990 to 2005. They attribute the decline to lowered global ocean pH. The authors suggest that a tipping point may have been reached in the late 20th Century, when declining pH, combined with increasing frequency of temperature-related stresses, led to rapid decline of calcification in this genus of coral.

Implications: De'ath et al. show that the projected impacts of ocean acidification are already occurring on the Great Barrier Reef. While further laboratory and experimental studies are required to better understand ecosystem thresholds, the possibility that a tipping point may have already been crossed is quite significant, with concomitant impacts for predator-prey relationships, ecosystem health, and livelihoods of communities that depend on such ecosystems.

- **P. Munday, D. Dixson, J. Donelson, G. Jones, M. Pratchett, G. Devitsina, and K. B. Døving**

  "Ocean acidification impairs olfactory discrimination and homing ability of a marine fish"

  Proceedings of the National Academy of Sciences

  2009, vol. 106(6)

  Much of the attention and concern over ocean acidification has been focused on the impacts of decreasing pH on calcifying organisms that precipitate calcium carbonate skeletons. Munday et al. turn their attention to the impact of increasing CO_2 concentrations and lowered pH on reef fish larvae, and in particular on their ability to sense chemical cues from vegetation, which reef fish use in order to find suitable habitats on which to settle.

  In an experimental design using orange clownfish, the authors tested the impact of ocean pH associated with elevated atmospheric concentrations of CO_2. They reared fish larvae in standard ocean pH (8.15), and pHs of 7.8 and 7.6, lowered by elevating CO_2 concentrations to 1,000 and 2,000 parts per million respectively (current concentrations are 387 parts per million CO_2). Larvae in each of the three groups were then presented with three plant vegetation olfactory stimuli: a tropical rainforest tree species which is known to indicate a suitable habitat; a swamp tree species, known to be avoided by larvae; and a savannah grass as a neutral control. While the larvae that developed in standard conditions exhibited a strong and projected preference for the positive cue, avoidance of the negative cue, and indifference to the neutral cue, larvae grown in pH 7.8 water exhibited a strong preference for the avoidance cue, and larvae grown in pH 7.6 water showed no preferences whatsoever and appeared to lack the ability to respond to olfactory cues. The authors were not able to determine the mechanistic causation behind the strong impacts of lowered pH on fish olfaction; they found no physical alteration of the olfactory system. They suggest that lower pH exposure may disrupt the transfer of chemosensory signals within the neurosensory system.

  Impacts: Regardless of the specific physiological mechanism underlying these observations, the implications for fish populations that rely on olfactory cues are profound. If nothing is done to mitigate carbon dioxide emissions, eventually carbon dioxide concentrations could climb high enough to lower pH sufficiently to disrupt fish larval olfaction. This reduced ability to respond to cues would alter population connectivity patterns and possibly strongly negatively affect fish survival.

- **R. Gooding, C. Harley, and E. Tang**

  "Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm"

  Proceedings of the National Academy of Science

  2009, vol. 106(23)

  Gooding and colleagues investigated the combined effects of increased temperature and carbon dioxide on a keystone predator of the Pacific Northwest: the ochre sea star. In controlled laboratory experiments, they measured feeding and growth rate responses to increases in both temperature and CO_2. Higher temperatures, they found, increase both growth and feeding rates. They also found that higher CO_2 concentrations had a positive effect on overall growth rate, despite the increased acidity's lowering the calcified mass content in the sea star's exoskeleton. The calcified portion of a sea star exoskeleton is a relatively minor fraction of its overall mass, unlike shell-forming organisms. The authors note that the physiological mechanism underlying the observed increase in growth rate under elevated CO_2 will require further study.

  Implications: While the results of this study indicate that some organisms may benefit (in terms of growth and feeding rate) from elevated temperature and carbon dioxide, the fact that the sea star's principle prey, the mussel, is predicted to suffer the full consequences of ocean acidification suggests that the impacts of climate change on ecosystems will be mediated by combinations of species-specific responses throughout the food web.

- **S. Comeau, G. Gorsky, R. Jeffree, J. L. Teyssié, and J. P. Gattuso**

  "Impact of ocean acidification on a key Arctic pelagic mollusk (*Limacina helicina*)"

  Biogeosciences

  2009, vol. 6

  While much of the attention about the increasing acidity of the oceans as a result of CO_2 emissions is focused on the threat to coral reef ecosystems, changing ocean pH, and its consequences for shell-forming organisms, may pose a serious threat to other food webs. Pteropods (literally, "winged-foot") are sometimes known as "sea-butterflies" because their gastropod foot (like the foot on a snail or scallop) has evolved into a feather-like structure that allows them to swim and move up and down in the open ocean. Pteropods are a critical food source for whales, fish, and zooplankton in both the Arctic and Southern Oceans. In a field experiment conducted off of Svalbard, north of Norway, Comeau and colleagues measured the impact of 760 parts per million CO_2 (pH 7.8) ocean water on the pteropod *Limacina helicina* calcification rates. They found that under elevated CO_2 and thus lower pH, pteropod calcification rates declined by 28 percent when compared with calcification at 350 parts per million (which roughly represents 1990 levels).

Implications: The authors suggest that the reduction in ocean pH from 8.1 to 7.8, which they say is likely to occur in the early 2100s if CO_2 continues to be emitted at its current pace, will threaten pteropod populations which the authors suggest would "likely cause dramatic changes to the structure, function and services of polar ecosystems."

- **S. Cooley and S. Doney**
  "Anticipating ocean acidification's economic consequences for commercial fisheries"
  Environmental Research Letters
  2009, vol. 4

What will ocean acidification, and its associated effects on marine calcifying organisms, mean for commercial fisheries of mollusks like clams and mussels? In order to answer this question, Cooley and Doney assessed the economic effects of ocean acidification on mollusks using a simple model that links projected declines in marine calcifying organisms from ocean acidification to projected declines in US commercial mollusk harvest. Using the 2007 harvest values as a baseline, the authors calculate potential future losses under different emissions scenarios and discount these economic losses into present value. The net present value of losses resulting from a modest estimate of 10–25 percent aggregate decrease in U.S. mollusk harvests could total US$1.7–10 billion by 2060.

Implications: While the authors note that their model excludes complexities of ecosystem responses to acidification, their results provide a baseline economic analysis of the considerable losses that ocean acidification could mean for US fisheries by mid-century.

No Bleaching? No Acidification? Global Warming Still a Problem for Corals

- **N. E. Cantin, A. L. Cohen, K. B. Karnauskas, A. M. Tarrant, and D. McCorkle**
  "Ocean warming slows coral growth in the central Red Sea"
  Science
  2010, vol. 329

Coral reefs are facing multiple anthropogenic threats: warming waters, ocean acidification, and coastal eutrophication. Cantin and colleagues document the impact of rising tropical sea surface temperatures on *Diploastrea heliopora*, an important reef-building coral in the Red Sea. Using three-dimensional CT scans to assess annual coral growth, they find that growth has declined by 30 percent just since 1998 in otherwise apparently healthy colonies of corals. Furthermore, they show that the reduction in growth rate shows a clear causal link to warmer summer temperatures, which have for the last decade been 1.5° C above the mid-20th Century mean in the region. This reduction in growth has not been due to thermally-induced bleaching (loss of symbiotic photosynthetic zooxanthellae), which has not been widely observed, but rather has been due to thermally induced stresses limiting the corals' ability to calcify. The authors also suggest that temperature, rather than ocean acidification, is the culprit, as the high temperatures in the Red Sea have kept the saturation state of calcium carbonate (aragonite) higher than it otherwise would have been under elevated CO_2 (ocean acidification is caused by elevated CO_2 concentrations, which reduces the saturation state of calcium carbonate, preventing calcifying organisms from making their shells: but, in the Red Sea, the calcium carbonate saturation state is still high because of the warmer temperatures, and thermal stress is the cause of the decline in calcification). Using a mid-range (the IPCC's A1B) emissions scenario to extrapolate their observations into a future, warmer climate, the authors conclude that growth of this coral species may halt entirely by 2070.

Implications: As the authors point out, their results suggest that, unless global emissions reductions are achieved in the near-term, the coral reefs in the Red Sea are unlikely to survive. Particularly noteworthy is the finding that thermal stress induced by contemporary global warming, even in the absence of bleaching, ocean acidification, or coastal pollution, has been sufficient to significantly impact tropical reef-forming corals.

- **W. Cheung, V. Lam, J. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly**

  "Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change"

  Global Change Biology

  2009, vol. 16

  In this study, Cheung and colleagues modeled the projected impacts of climate change on global marine fisheries. The authors combined species-specific bioclimate envelope models for more than 1,000 commercially exploited species with models projecting future changes in primary production of phytoplankton and temperature. Under a mid-range warming scenario (the IPCC's A1B scenario), northern latitude fisheries near Greenland, Alaska, eastern Russia and Norway are projected to increase by 30–70 percent in maximum potential catch, whereas low-latitude maximum potential fish catch is projected to significantly decrease—by up to 40 percent. The most significant declines are projected to occur in the tropical seas around Indonesia, southern China and Chile.

  Implications: Understanding how fisheries will be affected by a changing climate is essential to understanding the implications of climate change for the global food supply. While the authors caution that there is uncertainty inherent in their model projections, as a result of uncertainties in estimating phytoplankton production and modeling bioclimate envelopes, this study presents a coarse-level indication of future global fishery trends. Most notably the authors identify a trend where maximum fish catch declines in the exclusive economic zones of the most socioeconomically vulnerable regions.

CLIMATE CHANGE MITIGATION TECHNOLOGIES AND GEOENGINEERING

While the previous sections have painted a picture of a world forever changed by global warming, the advancement of mitigation technologies, if supported by policy signals and research and development, can make a significant difference in changing our greenhouse gas emissions-intensive trajectory. The following section highlights technological advances and development in key mitigation technologies. Breakthroughs highlighted include new designs, materials, efficiency gains, and energy storage solutions.

Batteries, Energy Storage, and Electricity

Batteries are an essential component of the low-carbon future: because electricity generation from renewable energy sources is intermittent, the ability to store that power and use it later is critical to a successful global transition.

Wires Made of Paper, Batteries Made by Viruses, Fuel Cells Made from Bacteria

- **L. Hu, J. W. Choi, Y. Yang, S. Jeong, F. La Mantia, L.-F. Cui, and Y. Cui**

  "Highly conductive paper for energy-storage devices"

  Proceedings of the National Academy of Sciences

  2009, vol. 106(51)

  Hu and colleagues coated commercially available paper (like the paper in your printer) with carbon nanotubes (nano-scale structures made of carbon), creating a highly conductive substrate with very low resistance (as low as 1 ohm). This highly conductive paper was able to achieve a specific capacitance of 200 farad (coulomb/volt) per gram of material, or four times the capacitance of plastics, which are another potential substrate. The amount of energy that the paper was able to hold was also higher than other previously reported values for flat conductive substrates. The authors suggest that their conductive paper has several advantages over plastic substrates: it is cheap, highly adhesive, and takes nanotube coating well. It is thus highly scalable as a technology that is not only demonstrably useful but also potentially marketable.

  Implications: The authors see applications of nanocoated conductive paper in new energy-storage devices (batteries), enabling this technology and its enhanced efficiency to be used in conjunction with solar and wind energy technologies in future renewable energy systems.

- **Y. J. Lee, H. Yi, W.-J. Kim, K. Kang, D. S. Yun, M. S. Strano, G. Ceder, and A. Belcher**

  "Fabricating genetically engineered high-power lithium ion batteries using multiple virus genes"

  Science

  2009, vol. 324

  The authors endeavor to enhance the energy storage of lithium-ion batteries at both high charge and high discharge rates by boosting lithium ion transport in composite electrodes. To do this they engineered clones of the M13 bacteriophage virus (a virus that only infects bacteria and is commonly used for its applications in biotechnology) by manipulating two viral genes: one to have a protein chain with high affinity for carbon nanotubes and the other with a peptide chain capable of binding iron-phosphate to create a biological structure for the cathode. This biologically derived system was capable of retaining capacity at high charge and discharge rates.

  Implications: The advantage of the genetically engineered virus system is that it may allow electrodes in batteries to be made from new materials that could not be used before because they had such low conductivity, thus greatly expanding the range of possible energy storage system design materials. The use of biologically derived materials is also more environmentally benign when compared with traditional battery manufacturing processes.

- **Z. He, J. Kan, F. Mansfield, L. Angenent, and K. Nealson**

  "Self-sustained phototrophic microbial fuel cells based on the synergistic cooperation between photosynthetic microorganisms and heterotrophic bacteria"

  Environmental Science and Technology

  2009, vol. 43

  The authors have developed a microbial fuel cell, consisting of a water column and sediment, which continuously generates current when illuminated in a cycle of light followed by darkness. The source of energy is light, which is used by photosynthetic microorganisms in the cell to create biomass. While the precise mechanism is not fully elucidated, it is thought that the photosynthesizers then produce organic matter, which is oxidized by heterotrophic bacteria living in the sediment. These bacteria generate an electron flow from this reaction, depositing the electrons onto an anode. The light/dark variation was required for the fuel cell to function, in part because both photosynthetic and heterotrophic bacteria are required and a fully illuminated environment did not create the proper balance of microbial activity.

Implications: The authors demonstrate that microbial fuel cells can serve as stand-alone electricity generators that are easy to maintain, with potential for use in off-grid installations or remote (e.g. rural) sites for small-scale electricity generation. While the concept clearly works, more work is needed to understand the underlying mechanics of microbial fuel cells in order to understand how to optimize them.

Nanotechnology and Electricity Generation

- **R. Yang, Y. Qin, C. Li, G. Zhu, and Z. L. Wang**
  "Converting biomechanical energy into electricity by a muscle-movement-driven nanogenerator"
  Nano Letters
  2009, vol. 9(3)

  By using a nanogenerator consisting of a zinc oxide nanowire on a flexible substrate, Yang and colleagues were able to capture electric potential and initiate electron flow into a circuit. They did so by converting the energy from small biomechanical motions such as the tapping of a human finger or the running of a hamster on a wheel.

  Implications: While there is not a large amount of energy generated from such small-scale muscle movements, this research shows that systems can be developed to scavenge low-frequency biomechanical energy, which would otherwise be lost. While every little bit counts, the costs associated with such a scheme are currently prohibitively high.

- **A. Magasinski, P. Dixon, B. Hertzberg, A. Kvit, J. Ayala, and G. Yushin**
  "High-performance lithium-ion anodes using a hierarchical bottom-up approach"
  Nature Materials
  2010, vol. 9

  There is a lot of potential for more efficient, higher capacity lithium-ion batteries that use silicon instead of graphite. However, the application of this technology has been hampered by difficulties in both production and operation of the anode (negatively charged pole) of the Li+ batteries. Magasinski et al. have designed a production system for silicon anodes on the nanoscale (1-100 nanometers) that are designed to provide optimized access of lithium ions, which enhances the efficiency of the electrical storage system of the battery. These newly designed anodes have been shown to be efficient, safe and perform stably at higher capacity than the anodes used in currently commercially available lithium-ion batteries.

  Implications: The authors argue that making anodes in this manner is low cost and easily scalable and that this breakthrough should lead to a broader application of silicon-based lithium-ion batteries, with a potential to make energy storage more efficient globally.

Solar Energy

Research on solar power in 2009 and 2010 focused on new designs and materials, and efficiency gains. Notably engineers are starting to combine design types for greater efficiency gains. We describe some highlights below.

Organic Photovoltaics

- **M. Lee, R. Eckert, K. Forberich, G. Dennler, C. Brabec, and R. A. Gaudiana**
  "Solar power wires based on organic photovoltaic materials"
  Science
  2009, vol. 324

  By wrapping a wire photovoltaic made of a conducting polymer and a chemical derivative of fullerene, a carbon-based compound, with a silver-film counter-electrode wire, and encasing these wires in a transparent polymer, Lee and colleagues were able to develop an organic-based photovoltaic cell in flexible wire shape. The transparent polymer focuses light onto the photovoltaics, and can compensate for shadowing effects as the wire twists, enhancing the efficiency of energy capture to approximately 3 percent, whereas previous attempts had not achieved greater than 1 percent efficiency in flexible-wire designs.

  Implications: More flexible, cheaper small-scale solar photovoltaics could make it easier and cheaper to integrate solar-powered electricity generation into building materials by avoiding the space requirements of large cells.

- **J. W. Schwede, I. Brgatin, D. C. Riley, B. E. Hardin, et al.**
  "Photon-enhanced thermionic emission for solar concentrator systems"
  Nature Materials
  2010, vol. 9

  Solar power can be generated by two methods: a photon-based "quantum" method (electron flow generated as a result of photon excitation due to the Sun's light energy striking a modified silicon wafer system, commonly known as photovoltaics) and the use of the Sun's heat energy for thermal energy systems. The latter is currently done both passively, through building design, window placement and controlling shade, and purposefully, through concentrating solar thermal systems. Schwede and colleagues have developed a new method of capturing the Sun's energy that uses a method called "PETE" (photon-enhanced thermionic emission) which they describe as a "combination" of the quantum and thermal methods. In this method, semiconductor cathodes will emit photon-excited electrons at high temperatures. If solar energy is used to thermally heat the system, a thermal "boost" allows the energy that is normally lost because it is in excess of the bandgap to be captured within a vacuum.

  Implications: The PETE method is still in the design stages but an idealized solar cell using this technology would be more efficient than standard photovoltaic cells. The system also generates waste heat that can be captured and used for thermal energy services rather than electrical energy services, which in turn has the potential to reduce non-renewable energy requirements.

- **A. Nattestad, A. J. Mozer, M. K. R. Fischer, Y.-B. Cheng, A. Mishra, P. Bauerle, and U. Bach**
  "Highly efficient photocathodes for dye-sensitized tandem solar cells"
  Nature Materials
  2010, vol. 9

  One of the main challenges in scaling up traditional solar cells is their use of silicon for the photovoltaic material. Dye-sensitized solar cells are a potential alternative and behave more like a leaf's chlorophyll. They typically operate as photoanodes, where an incident photon (light) causes a dye to inject an electron into a (n-type) semi conductor. However, they can also be designed to operate as photocathodes where the dye absorbs a photon and then a (p-type) semiconductor injects an electron into the dye. Combining the two types of dye-sensitized solar cells can create a solar-powered, electricity generation system that does not rely on a traditional silicon cell. One of the major issues with these tandem dye-sensitized solar cells has been the inefficient performance of the photocathode portion of the cell. Nattestad et al. have sought to remedy this by designing a new material to be used for the photocathode: they inject a p-type semiconductor, which is the electron donor, with a dye that allows for rapid transfer of the electron. They then make a variable-length oligothiophene "bridge" to control the spatial gap between charge carriers, increasing efficiency of the cell. They report a sevenfold increase in efficiency over previously reported efficiencies.

  Implications: This new system may be sufficient to make dye-sensitized solar cells on a commercial scale and more efficient replacements for "conventional" solar cells using silicon. In addition to being more efficient, dye-sensitized solar cells can be cheaper and more easily manufactured.

Biofuels

Biofuel energy is derived from biological materials, such as crops, grasses, and wood. Studies this year show new types of biological materials—including, of all things, shrimp shells—can be used to generate energy. New research also explores the impacts of the use of biofuels on regional climates and on greenhouse gas emissions.

Biofuels: Using Shrimp to Make Biodiesel

- **L. Yang, A. Zhang, and X. Zheng**
  "Shrimp shell catalyst for biodiesel production"
  Energy and Fuels
  2009, 23

  The authors used shrimp shells as a catalyst for the production of biodiesel from rapeseed (Canola) oil through transesterification with methanol, a process that converts the oil to a useable, burnable biodiesel. Currently, this process is inefficient because the catalysts that are used have to be separated from the reaction and end up producing large amounts of chemical waste water. The porous structure of shrimp shell, however, allowed for the reaction of the vegetable oil and methanol to form biodiesel (which is a fatty acid methyl-ester) at efficiencies approaching 90 percent and without the requirement of large amounts of waste water.

Implications: Shrimp shells are biodegradable and are a waste by-product of the shrimping industry, and are thus considered ideal catalysts, being both cheap and more environmentally friendly than traditional strong bases like sodium hydroxide.

Biofuel Feedbacks to Climate

- **M. Georgescu, D. B. Lobell, and C. B. Field**

"Potential impact of U.S. biofuels on regional climate"

Geophysical Research Letters

2009, vol. 36

Significant research in recent years has investigated the negative impacts of biofuel production on water use and land use and on the overall life-cycle emissions from biofuels currently under production, including indirect emissions from land-use change and nitrogen fertilizer application (e.g. Melillo et al. 2009). Georgescu and colleagues investigate an additional effect of large-scale biofuel production: the direct impact of land-use conversion on the climate (rather than the effect mediated by the storage of and emissions of carbon dioxide). They use a Weather Regional Forecasting (WRF) model to conduct a sensitivity experiment to quantify the impact of corn biofuel production in the United States on regional climate. They find that at the local to regional scale, changes in temperature of 1° C above current levels are possible as a result of changes to albedo, or surface reflectivity, and soil moisture. They also find that conversion of maize to switchgrass (*Miscanthus*) could lead to localized cooling on the order of 1–2° C because of the higher leaf area index and deeper rooting depth of the perennial switchgrass.

Implications: The authors show that biofuels, and specifically the choice of biofuel crop, can have an impact on local climate. The perennial switchgrass showed an advantage over maize for biofuel use: in addition to switchgrass's not being part of the current food system, conversion to it from maize could help regionally cool the climate, offsetting part of the warming trend rather than exacerbating it.

- **R. J. Plevin, M. O'Hare, A. D. Jones, M. S. Torn, and H. K. Gibbs**

"Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated"

Environmental Science and Technology

2010, vol. 44

- **D. M. Lapola, R. Schaldach, J. Alcamo, A. Bondreau, J. Koch, C. Koelking, and J. A. Priess**

"Indirect land-use changes can overcome carbon savings from biofuels in Brazil"

Proceedings of the National Academy of Sciences

2010, vol. 107(8)

The biofuels revolution has transformed many countries' economies, such as Brazil's, and energy and agricultural policies, such as those of the United States. Initially biofuels were cast as zero-carbon-dioxide-emitting sources of energy because the carbon in the fuel was derived from plant materials that absorbed carbon dioxide from the atmosphere. However, increased attention has recently been paid to analyzing the greenhouse gas emissions associated with the combustion of biofuels through "indirect land use change" (ILUC) (e.g. the land use change resulting from biofuels being grown on previously uncultivated lands and resulting in the loss of stored carbon of the converted land). Until now, there have not been good estimates of the aggregate ILUC emissions associated with biofuel production. Plevin et al. and Lapola et al. measure and assess the ILUC emissions associated with biofuel production using a simple model based on fuel yields, agricultural demand and normalized carbon dioxide emissions from land conversion. Plevin et al. show that the global ILUC emissions associated with biofuel production outweigh any carbon gain from the replacement of fossil fuels, while Lapola et al. document this same phenomenon in detail in the Brazilian case.

Implications: These studies offer a warning on the further use of biofuels, even potentially those that were previously considered to be of low-carbon intensity because they involved less direct land-use conversion, if these biofuel crops displace other food crops. These articles demonstrate that ILUC emissions cannot be ignored and omitted from the carbon accounting exercises used in decision making in the energy sector.

Carbon Capture

Carbon capture has increasingly gained attention as we continue to struggle to embrace alternatives to carbon-intensive energy supplies and technologies. Recent research from 2009 and 2010 shows how carbon can be captured more efficiently with less energy loss throughout the process.

- **R. Vaidhyanathan, S. S. Iremonger, G. K. H. Shimizu, P. G. Body, S. Alavi, and T. K. Woo**
  "Direct observation and quantification of CO_2 binding within an amine-functionalized nanoporous solid"
  Science
  2010, vol. 330

  The challenges involved in capturing carbon dioxide emitted from industrial sources are significant, and both cost reduction of capturing the carbon and the permanence of geologic storage are major foci of policy debates and academic discussions. Carbon dioxide is typically a small fraction of the air molecules in industrial emissions, posing a challenge of how to separate the CO_2. Current methods, as Vaidhyanathan et al. describe, rely on a chemisorptive "scrubber" which uses a nitrogen-containing alkanoamine solvent to form N-C bonds. In order to remove the CO_2 and "regenerate" the scrubber so it can keep capturing CO_2, this bond has to be broken, which requires heating and a lot of energy, thus increasing the cost of the operation and reducing its efficiency. More recent ideas have been to use nanoporous materials that increase surface area infused with amines that will bind with CO_2 forming metal-organic frameworks. While results indicate that this system may enhance CO_2 uptake, designing CO_2 scrubbers requires understanding the molecule-to-molecule interactions that take place within the substrate. In this study, the authors used crystallography and powerful computers to model how CO_2 was binding to the nanoporous substance and what forces were involved in increasing the energy required to operate the system. They found that "smarter" designed substrates could be built to space CO_2 binding sites to reduce dispersion force interactions (electrostatic interactions between molecules), allowing for a lower-energy and more efficient carbon capture system to be developed.

  Implications: This type of detailed nanoscale engineering study will likely lead to the ability to design more efficient, less costly systems for capturing CO_2 emissions in the future, with significant implications for advancing carbon capture.

Geoengineering

In a 2009 report, the Royal Society defines geoengineering as "the deliberate large-scale manipulation of the planet's environment to counteract climate change." Broadly, the various proposals for geoengineering to address climate change are grouped into two categories: carbon dioxide removal (CDR) and solar radiation management (SRM). CDR techniques seek to alter the global carbon cycle by manipulating natural biological, geophysical, and chemical processes on land or in the oceans to remove CO_2 from the atmosphere and thus reduce warming. In contrast, by increasing the reflectivity of the Earth's atmosphere or the Earth's surface, and thus increasing its albedo—or by reducing solar radiation that is absorbed by the surface by enhancing absorption of radiation in the atmosphere—SRM techniques seek to reduce planetary warming *despite* increasing concentrations of anthropogenic greenhouse gases in the atmosphere. For example, recently a particular SRM proposal has gained attention: injection of sulfur dioxide into the stratosphere, where it would oxidize creating sulfate aerosol particles that scatter solar radiation, reflecting some of it back into space and thereby cooling the Earth's surface. The idea is based on observations that volcanic eruptions emit large quantities of sulfate aerosol into the upper atmosphere and that these aerosolized particles have led to global cooling events, such as that which followed 1991 eruption of Mount Pinatubo in the Philippines.

Because of the global scale of many of these proposals, there have been concerns about potential side-effects or serious consequences for agriculture, water availability, ecosystems and human communities. In October 2010, the United Nations Convention on Biological Diversity's 10th Conference of the Parties, meeting in Nagoya, Japan, issued a decision that calls for a moratorium on any large-scale implementation of geoengineering that would affect biodiversity, until adequate scientific basis exists to justify such activities. An exception is made for small-scale research studies. Below are some of the last 2 years' highlights in geoengineering research, a topic that remains controversial politically but continues to gain attention given the slow pace of mitigation.

Carbon Dioxide Reduction

- **F. Lu, X. Wang, B. Han, Z. Ouyan, X. Duan, H. Zheng, and H. Miao**
  "Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland"
  Global Change Biology
  2009, vol. 15(2)

- **W. Schlesinger**
  "On fertilizer-induced soil carbon sequestration in China's croplands"
  Global Change Biology
  2009, vol. 16(2)

The definition of what constitutes geoengineering is under debate. Large-scale alterations of the carbon cycle can happen intentionally, for example through the deliberate reforestation of landscapes or the widespread application of iron on the oceans to induce a phytoplankton bloom to draw carbon dioxide out of the atmosphere. Lu and colleagues reported that the application of nitrogen fertilizers to lands enhances carbon fixation by plants and thus the fraction of carbon stored in the soil. The authors found, based on observational and experimental evidence, that application of nitrogen fertilizers in China could lead to 12 Mt C sequestered per year—a relatively modest but not insignificant total, about equal to the annual emissions of Norway. Schlesinger, however, pointed out that all methods or proposals for enhanced sequestration in soils must take account of the full life-cycle emissions of that process.

Implications: The creation of nitrogen fertilizers is an energy and fossil-fuel intensive process. Schlesinger calculates that the carbon dioxide emissions associated with the production of the fertilizers would fully negate the enhanced sequestration in the soils.

- **P. Köhler, J. Hartmann, and D. A. Wolf-Gladrow**
  "Geoengineering potential of artificially enhanced silicate weathering of olivine"
  Proceedings of the National Academy of Sciences
  2010, vol. 107(47)

While much of the recent attention to geoengineering has focused on reflecting more of the Sun's incoming energy through solar radiation management, Kohler and colleagues describe another potential manipulation of the global climate cycle that could mitigate rising carbon dioxide emissions: enhanced silicate weathering, which chemically removes carbon dioxide from the atmosphere by forcing it to react with other mineral compounds. Olivine (magnesium silicate) reacts with carbon dioxide and water to form magnesium ions, carbonate, and hydrogen silicate. If olivine were sprinkled as a fine dust over terrestrial systems, it would react with atmospheric carbon dioxide and flush its byproducts—magnesium ions, carbonate, and hydrogen silicate—through the Earth's rivers. The authors calculate, based simply on the ratios in the chemical equations, that up to 1 gigatonne of carbon dioxide emissions per year could be sequestered through this method.

Implications: The carbon captured would end up being sequestered in the global ocean. The authors do highlight that localized impacts of changing acidity and alkalinity of rivers and coastal areas might occur if this method were implemented on a global scale. This could have significant implications for marine ecosystems and the food supply. The authors provide a "back of the envelope" conceptual calculation indicating that, based on general chemical principles, enhanced weathering could remove carbon dioxide physically from the atmosphere in a meaningful way. However, these results, as the authors admit, do not address the ecological or economic burden of implementing such a plan.

Solar Radiation Management: Cooling the Planet

- **H. Akbari, S. Menon, and A. Rosenfeld**
  "Global cooling: Increasing world-wide urban albedos to offset CO_2"
  Climatic Change
  2009, vol. 94

Many urban areas have higher temperatures (heat islands) than the surrounding countryside because their surfaces (infrastructure) absorbs more incoming radiation and because of poorer circulation patterns. By making urban surfaces (buildings, pavement, etc.) more reflective and thereby increasing the albedo of cities, part of this heating effect can be mitigated. Akbari and colleagues model the use of reflective materials on urban surfaces, showing that an increase in urban area albedo (surface reflectivity) by 0.1 (albedo is unitless) could be achieved. This would be the equivalent, if implemented on a global scale in the cities of the world, of eliminating the heat trapping effects of 44 gigatonnes of carbon dioxide, which is more than the current annual emissions of the entire globe.

Implications: Relatively cheap and simple solutions can have significant impacts, which is why U.S. Secretary of Energy Steven Chu recommended painting roofs of buildings white. Coordinated global implementation, however, requires meaningful international policy coordination.

- **V. Brovkin, V. Petoukhov, M. Claussen, E. Bauer, D. Archer, and C. Jaeger**
  "Geoengineering climate by stratospheric aerosol injections: Earth system vulnerability to technological failure"
  Climatic Change
  2009, vol. 92

- **P. Heckendorn, D. Weisenstein, S. Fueglistaler, B. P. Luo, E. Rozanov, M. Schraner, L. W. Thomason, and T. Peter**
  "The impact of geoengineering aerosols on stratospheric temperature and ozone"
  Environmental Research Letters
  2009, vol. 4

- **H. D. Matthews, L. Cao, and K. Caldeira**
  "Sensitivity of ocean acidification to geoengineered climate stabilization"
  Geophysical Research Letters
  2009, vol. 36

- **P. J. Irvine, D. J. Lunt, E. J. Stone, and A. Ridgwell**
  "The fate of the Greenland Ice Sheet in a geoengineered, high CO_2 world"
  Environmental Research Letters
  2009, vol. 4

No one has experimentally tested a large-scale release of sulfate aerosol particles to cool the planet, although "natural" experiments such as volcanic eruptions have led to periods of cooling because the particles reflect sunlight. Brovkin and colleagues estimate that 9 megatonnes of sulfur as sulfate would be required to keep global warming below 2° C. They argue that this release would lead to a global reduction in precipitation (because clouds condense around sulfur aerosol particles in such a way as to hold more moisture in the atmosphere and allow less to precipitate), and would not address concerns about ocean acidification because solar radiation management does not remove carbon dioxide from the atmosphere. Moreover, the sulfur dioxide could even cause additional ocean acidification as it forms an acid when dissolved in the water.

Heckendorn and colleagues use a 3D chemistry climate model and find that because aerosols are likely to increase in size because of coagulation, this will reduce their cooling effect. They also suggest that aerosol injection will have significant negative impacts on stratospheric ozone and will lead to ongoing depletion of the ozone layer due to hydroxyl catalyzed ozone destruction.

Matthews and colleagues suggest that because sulfate-aerosol-induced cooling will alter the energy balance of the planet, it might redistribute CO_2 emissions in the land, air, and ocean reservoirs. In particular, their model suggests that some additional CO_2 might be absorbed by a cooler-than-business-as-usual biosphere. While this might slightly temper the acidification of the oceans by lowering the CO_2 concentration from what it otherwise would be, the authors' model shows that aragonite saturation (a measure of available calcium carbonate for organisms that form shells) will continue to decline due to lower ocean pH from continually rising CO_2 emissions.

There are many risks associated with the injection of sulfate aerosols into the atmosphere; however if these obstacles could be overcome, it may be possible to use such a measure to delay the effects of warming on sensitive regions. Irvine et al. show through the use of a model that solar radiation management could prevent the melting of the Greenland ice cap even with a "modest" application of sulfate aerosols. This is because of a regionally specific effect: only 20 percent of the sulfate required to limit *global* temperature rise by 2° C would be required to prevent Greenland Ice Sheet melt.

Implications: While it does appear that sulfate aerosol injection would cool at least some portions of the planet, significant side effects, including disruptions to the hydrological cycle and ozone layer, are also possible and apparent in model-based experiments. Implementing geoengineering may come with serious consequences, and, ultimately, the decision to geoengineer would be a political and not a scientific one.

- **A. Jones, J. Haywood, O. Boucher, B. Kravitz, and A. Robock**

"Geoengineering by stratospheric SO_2 injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE"

Atmospheric Chemistry and Physics

2010, vol. 10

Because almost no scientist wants to conduct a preliminary natural experiment on the scale of full implementation, geoengineering researchers have turned to global climate models to assess the potential impacts of injecting aerosols into the stratosphere to cool the planet. Specifically, they model a world in which aerosols are injected into the stratosphere over the equator in the Indian Ocean for 20 years. Stratospheric aerosols reflect sunlight and thus reduce the amount of the Sun's energy that will reach the surface of the Earth and warm the planet. Jones and colleagues compare the UK Met Office and NASA GISS model simulations of regional near surface air temperature changes and summer precipitation changes in this geoengineered world. The two models agree that the Arctic would cool more relative to business-as-usual warming, but net warming is still observed in the Arctic (as the cooling is unable to offset all warming), while the tropical regions cool relative to current temperatures but only slightly. This effect is more pronounced in the Met Office model than the NASA model. Both models also suggest decreases in precipitation in the equatorial regions, Southeast Asia and the United States.

Implications: The authors present their results as a consensus of model predictions of the likely impacts of equatorial sulfate aerosol injection, if it were ever to be implemented. Precipitation reductions are observed, and the Arctic will still warm slightly, even if global temperature rise is held in check by the aerosol injection. The authors hope that these results, if they are repeated frequently across many models, can demonstrate a robust assessment of the response of the Earth's system to geoengineering.

- **D. W. Keith**

"Photophoretic levitation of engineered aerosols for geoengineering"

Proceedings of the National Academy of Sciences

2010, vol. 107(38)

David Keith explores the possibility of injecting aerosolized particles that have been engineered to overcome the size constraints of sulfate aerosols which may not have an optimal cooling effect. Such small aerosolized particles could reduce the potential negative impact on the environment. He suggests, based on model results, that engineered nanoparticles, which are smaller than sulfate aerosols, could naturally levitate (through photophoretic forces produced by the temperature difference between the particle and the surrounding air) above the stratosphere, which would reduce the likelihood of ozone disruption in that layer. His research also suggests that longer-lived particles might reduce the reliance on continual injection, which could be costly.

Implications: Keith is suggesting that further research be directed in a "next generation" of aerosols to overcome some of the efficiency and environmental drawbacks that have been identified inadvertently during atmospheric research experiments. This paper helps move the discussion forward, but more research and experimental testing is necessary to demonstrate the effects that his models show.

- **P. J. Irvine, A. Ridgwell, and D. J. Lunt**

"Assessing the regional disparities in geoengineering impacts"

Geophysical Research Letters

2010, vol. 37

Irvine and colleagues use a coupled climate model to determine the regionally specific impacts of a scenario in which carbon dioxide concentrations are four times what they are today, but warming is mitigated through a generic solar radiation management. The scenario would reduce incoming solar radiation, although the authors do not specify by what mechanism. Their results suggest that it is not possible to equally cool the entire Earth through the generic SRM. For example, in a $4xCO_2$ (quadrupled levels of CO_2 concentrations compared to preindustrial levels) world, fully implemented geoengineering would result in 0.5° C cooling around the equator, but 1° C warming at the poles, as a result of regional feedbacks. The authors also see significant impacts of this SRM technique on precipitation. For example, in the United States, without geoengineering, there would be an average increase in precipitation across the country of nearly 8 percent, while under the geoengineering scenario, precipitation declines by nearly 12 percent. However, the authors also find that it is possible to balance the impacts by allowing "modest" global warming to happen by injecting a smaller amount of aerosols. If this were achieved, the models predict no disruption to the hydrological cycle. This "partial" case, they argue, should be considered in the suite of geoengineering strategies, rather than simply "none" or "full."

Implications: The authors admit that this is an illustrative rather than fully predictive result, because it is based on one model simulation and many assumptions. However, their results are salient because they demonstrate that there may be significant trade-offs between temperature and precipitation management *if* a decision were ever to be made to engage in solar radiation management, and that some sort of balance might be possible. The regional disparity of impacts, especially to crop yields, poses a politically difficult hurdle.

Making the Oceans (and Clouds) Brighter

- **J. R. G. Evans, E. P. J. Stride, M. J. Edirisinghe, D. J. Andrews, and R. R. Simons**

  "Can oceanic foams limit global warming?"

  Climate Research

  2010, vol. 42

Aerosolized particles are not the only thing that humans are capable of manipulating in order to reflect more sunlight back into space. Evans and colleagues at University College in London propose the concept of seeding rafts of bubbles in the surface of the ocean elecrohydrodynamically (using microfluidics to control water tension on a very small scale). This method would require substantial engineering work to anchor the machinery in the ocean on a large scale, a point highlighted by the authors. The authors suggest they can increase the albedo of the global ocean in a way to meaningfully affect the climate, simply because foam is white and reflects solar radiation away from the surface. There is also a further feedback effect to the climate, because the more bubbles in foam, the more salt spray is ejected into the atmosphere, and thus the more cloud condensation nuclei which further increase the albedo of the Earth's surface. They also argue that this method might be more environmentally friendly than other proposals because it is unlikely to significantly disrupt biogeochemical or hydrological cycles. They do, however, speculate that changing the small-scale energy balance (creating bubbles adds energy) of the surface of the ocean might influence global physical oceanographic currents and patterns in unknown ways (microturbidity of the ocean surface is increasingly found to be important in controlling larger scale geographic phenomena that are ecologically significant).

Implications: As noted above, in 2009, Secretary of Energy Steven Chu suggested that homeowners in the United States fight global warming by painting their roofs white to reflect sunlight, among embracing other activities. Increasing the bubble concentration would effectively do the same thing in the ocean, although the feasibility and practicability of a manipulation on a scale large enough to affect climate is still a matter of academic discussion.

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ACKNOWLEDGMENTS

The authors greatly acknowledge Alistair Hunt, David Lea, Philippe Marbaix, Walt Meir, Carol Turley, Rachel Warren, and Jean-Pascal van Ypersele for review of earlier drafts of this manuscript. We also thank our colleagues at WRI for serving as internal reviewers: David Tomberlin, Jennifer Morgan, Micah Ziegler, James Bradbury, Stephanie Hanson, Tom Damassa, Letha Tawney, James Anderson, Alison Carey, Loretta Cheung, Erin Kempster, and Jon Strahl. For editing, design and other support, particular thanks are due to Ashleigh Rich, Greg Fuhs, Maggie Powell, Hyacinth Billings, Kevin Lustig, Maggie Barron, Janet Ranganathan, Michael Oko, Lydia Weiss, Christina Deconcini, and Raquel Gonzalez.

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ISBN: 978-1-56973-781-1