WRI ISSUE BRIEF

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Climate Science 2007 Major New Discoveries

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INTRODUCTION

Continuing with its annual series, WRI has reviewed some of the major climate change science research and innovations of 2007. The review describes potential future ramifications of human-induced climate change and also documents the impacts borne already by human and natural systems as a result of increased global temperatures and altered precipitation patterns. Clearly emerging from this review is that climate change is transforming the hydrological cycle and physical climate, and has begun to significantly alter ecosystems as well as the services humans derive from them.

Perhaps most significantly, several of the studies reviewed here suggest that climate impacts are continuing to escalate. Some impacts, such as those related to ice melt and ocean acidification, are accelerating exponentially. This new literature raises critical questions:

- Where do natural tipping points lie?
- How close are we to overshooting such tipping points in various systems, or have we already done so?
- What will the world look like when we overshoot them?

Overall, the findings in this review support the notion that rapid and substantial mitigation efforts are needed, and that adaptation measures are increasingly required today – and will be ever more important in the future – to bolster the resiliency of both human and non-human populations in a changing climate.

In preparing this review, WRI drew from a wide array of journals and information from organizations and climate/energy web sites, including:

- *Applied Physics Letters*
- Associated Press
- British Columbia Ministry of Forests and Range
- *Conservation Biology*
- *Geophysical Research Letters*
- *Global Change Biology*
- *JOM* (a publication of the Minerals, Metals & Materials Society)
- *Journal of Experimental Biology*
- *Journal of Geophysical Research*
- *Journal of Photochemistry and Photobiology B: Biology*
- *Journal of Wildlife Management*
- National Aeronautics and Space Administration
- *Nature*
- *Philosophical Transactions of the Royal Society A*
- *Proceedings of the National Academy of Sciences*
- *Proceedings of the Royal Society B: Biological Sciences*
- *Quaternary International*
- *Renewable Energy Access*
- *Science*

In each case, articles were only drawn from 2007 publications.

Similar to previous years' *Climate Science*, this review is divided into four sections:

1. Physical Climate (temperature increases, ocean behavior, abrupt change, and greenhouse gas and aerosol concentrations)
2. Hydrological Cycle (hurricanes, glacial/snow melt, oceans, and water supply)
3. Ecosystems and Ecosystem Services
4. Climate Change Mitigation Technologies

Every story contains a short summary, as well as a section on implications.

One of the major science events in 2007 was the release of the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC AR4). A brief review of some of the new science in that report is provided, with a particular emphasis on comparing this most recent report to previous assessments (see table). However, we do not seek to undertake here a thorough review of that major work. The executive summaries of each of the working group reports (on climate science, impacts, and response strategies) can be found on the IPCC web site, along with a synthesis report linking the conclusions from the full documents (see http://www.ipcc.ch).

The material included in this review broadly supports that presented in the Fourth Assessment Report. However, this material is more recent: rules governing the IPCC assessments require that all material be reviewed by the working groups prior to incorporation into the report. Thus, there are no 2007 articles in the AR4 – and few 2006 articles either. This note, while having nowhere near the comprehensiveness of an IPCC assessment report, still serves a useful purpose in outlining new developments since the IPCC AR4.

PHYSICAL CLIMATE
(GREENHOUSE GAS AND AEROSOL CONCENTRATIONS, TEMPERATURE INCREASES, OCEAN BEHAVIOR, AND ABRUPT CHANGE)

The studies in the following section highlight some of the recent scientific findings with regard to how the physical climate has been transformed as a result of human activities. This literature, which looks at heightened greenhouse gas concentrations, increased temperatures, ocean behavior, and abrupt climate change, adds to the compelling evidence that trends of significant changes outlined in the 2005 and 2006 WRI *Climate Science* reviews are continuing unabated.

Greenhouse Gas and Aerosol Concentrations

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/**), concentrations of carbon dioxide (CO_2) in 2007 rose to an annual mean of 383.7 ppm, from the 2006 mean of 381.9 ppm. The research below documents advances in our scientific knowledge on GHG concentrations.

- **Michael R. Raupach, Gregg Marland, Philippe Ciais, Corinne Le Quéré, and Christopher B. Field "Global and regional drivers of accelerating CO_2 emissions"**
  Proceedings of the National Academy of Sciences
  12 June 2007, vol. 104 no. 24, pp. 10288-10293

  Raupach et al. note that the growth rate of carbon dioxide emissions from fossil fuel consumption and industrial processes has grown from 1.1% per year over the 1990s to more than 3% per year from 2000 to 2004, consistent with data from the U.S. Energy Information Administration (EIA) and the U.S. Carbon Dioxide Information and Analysis Center (CDIAC). Developed countries, while contributing the greatest percentage to total emissions, had a lower rate of emissions growth than developing nations. In 2004, 73% of emissions growth was attributed to developing nations, although their emissions contribution was only 41% of the global total. The dominant causal factor of emissions growth is fossil fuel consumption. The authors find that declining trends in energy intensity of GDP and carbon intensity of energy are now being slowed and even reversed, and thus decarbonization trends are not as strong as previously.

Implications: If carbon intensity of GDP continues to rise, global concentrations and consequent climate change are also likely to be more significant. Scenarios of future climate-related damages (such as those of the IPCC), which to date have been based on more optimistic assumptions, may prove to be conservative descriptions of possible future damages. The distribution of emissions is partly due to fossil fuel dependence of rapidly developing nations, and partly due to the transfer of industrial activities to developing countries. However, while developing country emissions are rising rapidly, only 23% of total emissions since the Industrial Revolution can be attributed to these nations. This disparity has implications for future mitigation policies with regard to how targets and timetables are determined in an equitable manner.

- **Michael I. Mishchenko, Igor V. Geogdzhayev, William B. Rossow, Brian Cairns, Barbara E. Carlson, Andrew A. Lacis, Li Liu, and Larry D. Travis**

  "Long-Term Satellite Record Reveals Likely Recent Aerosol Trend"

  Science

  16 March 2007, vol. 315 no. 5818, p. 1543

  Mishchenko et al. study global satellite data of aerosol optical thickness (the degree to which aerosols inhibit transmission of sunlight to the Earth's surface due to their optical scattering properties) collected from the Global Aerosol Climatology Project record. Taking into account spiking stratospheric aerosol levels created by El Chichon and Mount Pinatubo volcanic eruptions, they find a decrease in tropospheric aerosol optical thickness over the period from 1981 to 2005. Hazy days typically have aerosol optical thickness readings of 2 or more, while clear days have readings closer to 0. From 1991 to 2005, for example, the authors find that aerosol optical thickness decreased by at least 0.02.

  Implications: While the authors note methodological uncertainties, this study, if confirmed, suggests that decline of aerosol optical thickness would lead to increased absorption of solar radiation by the Earth's surface, rather than solar radiation being scattered back into space by aerosols. These results could partially explain the reemergence of a warming trend after the cooling trend from the 1940s to the 1970s. Further, if the trend continues as air pollution is abated, warming could be amplified in the future.

- **Joseph R. McConnell, Ross Edwards, Gregory L. Kok, Mark G. Flanner, Charles S. Zender, Eric S. Saltzman, J. Ryan Banta, Daniel R. Pasteris, Megan M. Carter, and Jonathan D. W. Kahl**

  "20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing"

  Science

  7 September 2007, vol. 317 no. 5843, pp. 1381-1384

  Black carbon emissions, which result from industrial processes that burn fossil fuels and biomass burning from deforestation and forest fires, are critical components of the Earth's energy balance. McConnell et al. collected ice cores from Greenland to trace black carbon deposition throughout the last century and a half. The ice cores revealed that after 1850, not only did black carbon deposition increase to seven times that of preindustrial times, but the black carbon record suggests that industrial emissions overwhelmed those from forest fires, consistent with the onset of the Industrial Revolution. Today black carbon emissions are lower than maximum levels at the turn of the 20th century. However, cleaner combustion in North America is apparently being offset by increased fossil fuel burning in Asia.

  Implications: While most aerosols lead to climate cooling, black carbon particles absorb sunlight and exacerbate warming. In addition, in high latitudes, such as the boreal forests, black carbon can accumulate on snow, lowering surface reflectivity, absorbing solar radiation, and providing a positive feedback to warming. The McConnell study is a critical additional step in understanding how black carbon might have contributed to climate change over time, and suggests it might have played a critical role in the enhanced warming observed, particularly in the Arctic.

Temperature Increases

According to NASA, 2007 was tied with 1998 as Earth's second warmest year in the last century. According to the Goddard Institute for Space Studies, the 14 warmest years on record have all occurred since 1990 and, according to NOAA's National Climate Data Center (NCDC), the rate of temperature increase since 1976 has been three times that of the trend during the century. In the United States, much of the Southeast and West and some large regions of the Upper Midwest and Northeast experienced severe drought, with impacts on wildfire and water resources (**http://www.ncdc.noaa.gov/oa/climate/research/2007/ann/ann07.html**). The stories below highlight some of the recent scientific advances with regard to changes in the Earth's surface and atmospheric temperatures.

- **Noah S. Diffenbaugh, Jeremy S. Pal, Filippo Giorgi, and Xuejie Gao**

  "Heat stress intensification in the Mediterranean climate change hotspot"

  Geophysical Research Letters

  15 June 2007, vol. 34, L11706

  Diffenbaugh et al. evaluate how climate change will impact heat stress – measured by daily maximum temperature, daily minimum temperature, and Heat Index – in the Mediterranean region. They use climate model-derived data to depict climate changes based on two IPCC emission scenarios in which atmospheric CO_2 concentrations rise to 800 and 600 ppm by 2100. They find potential daily maximum temperature increases of as much as 8.5°C and daily minimum temperature increases of as much as 7°C. The authors also find that "dangerous or extremely dangerous" levels of the Heat Index (temperatures in excess of 40.6°C) are more likely in the southern and eastern Mediterranean, raising heat stress risk 200% to 500% in the region.

  Implications: The authors' analyses suggest that earlier estimates of regional global temperature increases may have been conservative. They also expand the available information on the effects of higher concentrations of CO_2 and temperature. Their analysis suggests that efforts to limit GHG emissions (and hence concentrations) would have substantial value: in the lower concentration scenario, while it is still substantial, heat stress risk is only half that of the higher scenario.

- **Michael Previdi and Beate G. Liepert**

  "Annular modes and Hadley cell expansion under global warming"

  Geophysical Research Letters

  17 November 2007, vol. 34, L22701

  Rainfall and evaporation in the intertropics are controlled in part by atmospheric circulation along the mid-latitude oceanic storm tracks. Areas of rising air determine wet regions as precipitation outweighs evaporation, whereas regions characterized by sinking air are dry due to higher evaporation levels. This band of atmospheric circulation around the intertropics is known as the Hadley cell. Some models project that warming will result in a poleward migration of the Hadley cell, expanding subtropical dry zones. Using coupled climate models employed in the IPCC's Fourth Assessment Report, Previdi and Liepert assess whether seemingly unrelated systems, the Northern Hemisphere and Southern Hemisphere annular modes (NAM and SAM, which are dominant modes of atmospheric variation), play a role in the Hadley cell and subtropical dry zone expansion. In an effort to determine causality of the influence of NAM and SAM on the intertropics movement, the authors apply linear regression methods. The multi-model ensemble indicates that in the Northern Hemisphere the subtropical dry zones expand poleward 0.40° for every standard deviation increase of the NAM; and in the Southern Hemisphere 0.26° for every standard deviation increase in the SAM.

  Implications: The Previdi and Liepert study demonstrates that changes in mid/high- latitude atmospheric dynamics can result in altered tropical circulation patterns, with implications for hydrological cycles and poleward expansion of dry regions. These changes could have concomitant impacts on human livelihoods, as some populated areas located poleward of the Hadley cell could become drier if the subtropical dry zones expand. And, according to Seidel et al. (*Nature Geoscience*, January 2008, vol. 1, pp. 21-24), if the tropics are widened, trace greenhouse gases could be redistributed in the stratosphere, which could exacerbate the greenhouse effect.

Ocean Behavior

According to new research in 2007, a variety of ocean trends, attributed at least in part to human-induced climate change, warrant significant concern. Collectively, this research suggests that changes to ocean behavior are proceeding at a rapid rate – and potentially that tipping points in this physical system may be nearly or even already surpassed.

- **Ken O. Buesseler, Carl H. Lamborg, Philip W. Boyd, Phoebe J. Lam, Thomas W. Trull, Robert R. Bidigare, James K. B. Bishop, Karen L. Casciotti, Frank Dehairs, Marc Elskens, Makio Honda, David M. Karl, David A. Siegel, Mary W. Silver, Deborah K. Steinberg, Jim Valdes, Benjamin Van Mooy, and Stephanie Wilson**
  "Revisiting Carbon Flux Through the Ocean's Twilight Zone"
  Science
  27 April 2007, vol. 316 no. 5824, pp. 567-570

  Buesseler et al. have shed light upon the dark ocean depths, which they call the "twilight zone" – between 1000 meters and the sunlit zone – with their analysis of how efficiently carbon is transferred from these levels to the deep ocean. Their work makes use of the Vertical Transport in the Global Ocean (VERTIGO) project, which employed sediment traps in both the Hawaiian and Northwest Pacific Ocean. They find that, perhaps as a result of the relatively highly productive diatoms in the Northwest Pacific, particulate organic carbon is more efficiently transferred from the "twilight zones" to the deep ocean in the Northwest Pacific than in the Hawaiian Ocean. Only 20% of carbon was transferred to the deep ocean in Hawaii, whereas 50% was transferred in the Northwest Pacific.

  Implications: Variability of particulate organic carbon transport to the deep ocean from the "twilight zone" is currently not represented in ocean models. However, the ability to store carbon at great depths, and for long periods, reflects the sink capacity of the ocean. The authors discover that transfer of particulate organic carbon and other matter, and therefore carbon sequestration capacity, can vary substantially: depending on specific physical and biogeochemical properties, carbon storage capacity may vary by at least a factor of two in different regions of the world ocean. This would substantially change the estimates of CO_2 residence time, as well as of long-term reductions in emissions required for stabilization of the climate system. However, the scientists themselves conclude that more research is needed to determine why some oceans enable particulate transfer more than others, and how widespread this phenomenon may be.

- **Corinne Le Quéré, Christian Rödenbeck, Erik T. Buitenhuis, Thomas J. Conway, Ray Langenfelds, Antony Gomez, Casper Labuschagne, Michel Ramonet, Takakiyo Nakazawa, Nicolas Metzl, Nathan Gillett, and Martin Heimann**
  "Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change"
  Science
  22 June 2007, vol. 316 no. 5832, pp. 1735-1738
  (Originally published in *Science Express* online on 17 May 2007)

- **Ute Schuster and Andrew J. Watson**
  "A variable and decreasing sink for atmospheric CO_2 in the North Atlantic"
  Journal of Geophysical Research
  8 November 2007, vol. 112, C11006

  Approximately 25-30% of the annual global emissions of CO_2 are sequestered in the oceans. Le Quéré et al. estimate the CO_2 sink in the Southern Ocean over the period of 1981 to 2004, using a new combined dataset incorporating both a series of stations in the Southern Ocean as well as a wider set of worldwide data points. Adopting an inverse calculation that computes CO_2 flux distributions building on an atmospheric transport model and atmospheric CO_2 concentrations, the authors find that over the period studied, the sink in the Southern Ocean was weakened by 0.08 PgC/year per decade (from an estimated total of 0.1 to 0.6 PgC/y). They suggest this weakening is a result of anthropogenic changes in wind and air temperatures, with wind the dominant factor.

  Schuster and Watson, working in the North Atlantic, use merchant ship sea surface temperature observations and observe partial pressure of CO_2 collected from the United Kingdom to the Caribbean to assess the change in the North Atlantic sink. Their results suggest a decline in North Atlantic CO_2 uptake of approximately 50% between the mid-1990s and 2002-2005. With the exception of the western subtropics, they estimate that CO_2 uptake capacity between 20°N and 65°N has diminished by roughly 0.24 PgC annually during this period. They attribute these changes to changes in surface temperatures and ventila-

tion of the North Atlantic, buffer capacity, and to the North Atlantic Oscillation, which the authors suggest are due to both natural variation and human activities.

Implications: While simple carbon chemistry would suggest that the ocean CO_2 sink should continue to increase, Le Quere et al. demonstrate that that physical responses to other climatic factors, such as wind patterns, are significant determinants of sink capacity. Given that winds over the Southern Ocean are modeled to become more intense if climate change is left unabated, the Southern Ocean sink could decrease substantially in as little as a quarter of a century. The southern hemisphere conclusions are mirrored in Schuster and Watson's results, which suggest that this phenomenon is also found in the North Atlantic (although not necessarily for the same reasons). If the loss of ocean carbon sink capacity becomes a global phenomenon, it could lead to significant and rapid increases in global atmospheric CO_2 concentrations. The sink decline rates suggested by these studies indicate that important regional tipping points could come within the next several decades.

- **Oleg A. Saenko, Andrew J. Weaver, Daniel Y. Robitaille, and Gregory M. Flato**
  "Warming of the subpolar Atlantic triggered by freshwater discharge at the continental boundary"
  Geophysical Research Letters
  4 August 2007, vol. 34, L15604

  Many have speculated that freshwater flow into the North Atlantic could result in reductions of heat transported to the northern hemisphere, leading to cooling in the North. The changes would be caused by a decline in the Atlantic Meridional Overturning Circulation (AMOC), which can essentially be thought of as a density-driven deep water pump. The widely held view is that as lower-density freshwater is added to the North Atlantic, the strength of this deep water pump is weakened, compromising the ocean's ability to bring heat to the northern hemisphere. However, Saenko et al. demonstrate that if the freshwater is added along continental boundaries rather than over the entire subpolar Atlantic, the result is quite different: while the AMOC will be weakened, a warming over much of the subpolar Atlantic results, as well as changes to wind and ocean circulations. Using the Canadian Centre for Climate Modeling and Analysis' coupled atmospheric-ocean general circulation mode, as well as NCAR's Climate System Model Ocean Model, Saenko et al. run three scenarios: one in which freshwater is discharged uniformly across the Atlantic between 50 and 70°N; a second in which the same amount of freshwater is discharged along the boundary of Greenland; and lastly, a scenario modeling discharge only along the northeast coast of North America. The two cases in which freshwater injection is located near the ocean boundaries result in enhanced heat transport north; this effect is greatest in the earlier decades.

  Implications: As glacial meltwater increases and freshwater flows from continents, this study suggests that widespread warming, as well as wind and ocean convection changes, could transform the subpolar Atlantic. Attendant physical changes include a further and more rapid retreat of subpolar Atlantic sea ice, along with a more rapid decline in the ecosystem that such sea ice supports. Furthermore, the change in polar albedo may create an additional positive feedback for more rapid regional/global temperature increases.

- **J. C. Duplessy, D. M. Roche, and M. Kageyama**
  "The Deep Ocean During the Last Interglacial Period"
  Science
  6 April 2007, vol. 316 no. 5821, pp. 89-91

  During the last interglacial period (129,000 to 118,000 years ago), the seas were 4 to 6 meters higher than today's levels. This sea level rise resulted from melting in both Greenland and West Antarctica. Duplessy et al. set out to determine whether the North Atlantic Deep Water, which brings warmth to the Antarctic waters via the Southern Ocean, was the driver for the partial melting of the West Antarctic Ice Sheet during that period. Based on an examination of the oxygen isotopic composition in benthic foraminifera, Duplessy et al. found that melting, and resultant sea level rise, could be attributed to a warming deep ocean.

  Implications: Southern Ocean temperatures have recently risen 0.2°C. This is comparable with increases in the last interglacial period, when ocean temperatures rose between 0.1°C and 0.5°C. Even very moderate additional ocean warming could trigger ice sheet melting, as warm temperatures meet ice shelves of both the Greenland and West Antarctic Ice Sheets. The science is not yet adequate to determine if ocean (and air) temperatures have already passed the tipping point where rapid ice sheet melting would occur, but recently observed increases in both

Greenland and West Antarctic Ice Sheet melting suggest a possible causal connection that if borne out is likely to result in an accelerating pace of sea level rise.

Abrupt Change

Abrupt, nonlinear change poses significant problems for decision makers, as impacts do not accumulate steadily and gradually over decades and centuries. Rather, impacts can be triggered suddenly and proceed exponentially, producing systems with no analog in historic planning records. Abrupt, nonlinear change can be a manifestation that tipping points in physical and biological systems have been passed. The research discussed below adds to a growing literature on abrupt change.

- **James Hansen, Makiko Sato, Pushker Kharecha, Gary Russell, David W. Lea, and Mark Siddall**
  "Climate change and trace gases"
  Philosophical Transactions of the Royal Society A
  15 July 2007, vol. 365 no. 1856, pp. 1925-1954
  (Originally published online 18 May 2007)

  Global climate forcings, mechanisms that alter the balance between incoming solar energy and outgoing heat from Earth, can trigger substantial feedbacks that can lead to Earth being "whipsawed between climate states." Hansen et al. find that the time scale of ice sheet response is tied to the time scale of climate forcings. The common assumption was that ice sheet response was on multi-millennia time scales, because forcings present during glacial–interglacial periods were tied to long-period orbital cycles. Hansen et al., however, assert that because human-induced climate forcings are not only larger in scale but occur far more rapidly, ice sheet response may not correspond to the long time scale inferred from the palaeoclimate data. Therefore, ice sheet disintegration triggered by warming would likely happen more quickly. They suggest that this might be on a centennial time scale – and explicitly do not rule out changes even on a decadal time scale. Their analysis also revisits the issue of "climate sensitivity" (i.e., how much temperature would change in response to a specific forcing). The long-held assumed "climate sensitivity" to forcings has been 0.75°C per W/m^2 : that is, for every W/m^2 absorbed by the Earth's surface, the temperature would rise 0.75°C. Under the revised Hansen et al. analysis, if other "slower" forcings such as vegetation and ice sheet cover, which are currently fixed in models, are taken into account, the climate sensitivity is doubled – to 1.5°C per W/m^2.

  Implications: Hansen et al.'s findings regarding the rapid ice sheet response time frame, as well as an enhanced global climate sensitivity to forcings, has significant implications for climate impacts, particularly if emissions, and thus forcings, continue unabated. They write, "The climate sensitivities we have inferred from palaeoclimate data ensure that a BAU [business as usual] GHG emission scenario would produce global warming of several degrees Celsius this century, with amplification at high latitudes." Such warming would almost certainly lead to much more rapid than anticipated ice sheet disintegration, and sea level rise.

- **John W. Williams, Stephen T. Jackson, and John E. Kutzbach**
  "Projected distributions of novel and disappearing climates by 2100 AD"
  Proceedings of the National Academy of Sciences
  3 April 2007, vol. 104 no. 14, pp. 5738-5742

  Williams, Jackson, and Kutzbach analyze the prospects for creation of novel climates and/or disappearance of existing climates given projections of warming. They use a nine-model ensemble for evaluating the IPCC A2 emissions scenario (where temperatures increase by 2°C to 4°C by 2100) and an eight-model ensemble to evaluate the B1 scenario (with increases of 1°C to 2.5°C by 2100). Their results indicate that under the A2 scenario, 12-39% of the globe's terrestrial surfaces will witness novel climates (those that have never been historically observed in a given locale) by the end of the century, and 10-48% will see disappearing climates (where an entire climatic regime is no longer to be found in a given locale) by 2100; under the B2 scenario, 4-20% of the terrestrial surface will see both novel and disappearing climates. These values roughly double when conservative dispersal limitations are considered. Novel climates are most pronounced in tropical and subtropical regions, especially in the Amazonian and Indonesian rainforests. Disappearing climates are primarily located in tropical mountains and poleward regions of continents.

  Implications: Regions that will see novel/disappearing climates overlap closely with hotspots of biological diversity, and tropical ecosystems could be the most adversely impacted due to their endemism (in which species are

found that live nowhere else in the world) and relatively stable temperatures. Species in poleward areas will also suffer large impacts. Furthermore, existing conservation approaches may be "insufficient" to conserve endemic species, which could become extinct as these climates are modified or disappear altogether. While the climates may be altered linearly, the authors state that biotic responses to such novel/disappearing climates will likely be nonlinear with tipping points that could lead to rapid and irreversible changes.

- **Matthew T. Reagan and George J. Moridis**
  "Oceanic gas hydrate instability and dissociation under climate change scenarios"
  Geophysical Research Letters
  27 November 2007, vol. 34, L22709

  Ocean gas hydrates are composed of crystalline compounds which can dissociate into a gaseous form, as gas particles are trapped within the crystal form and are released when the form changes shape. Stability depends on two factors: pressure and temperature. Reagan and Moridis modeled the behavior of oceanic gas hydrates under three scenarios: first, cold, deep hydrates located at 1000 m in ocean depth with a seafloor temperature of 4°C; second, warm, intermediate-depth hydrates located at 570 m in depth with a seafloor temperature of 6°C; and, lastly, cold, shallow hydrates at 320 m, with a temperature of 0.4°C. They then assessed the reactions of the hydrates to temperature increases of 1°C, 3°C and 5°C over the next century, while holding upper boundary pressure constant. They find that the cold, deep hydrates' stability is retained at all three temperatures, and gas begins to escape only under a 10°C increase over 100 years scenario. The warm, low-depth hydrates begin to dissociate within 44 years under the 1°C scenario, within 22 years under the 3°C scenario, and within two decades under the 5°C scenario. Lastly, the cold, shallow hydrates exhibit a stronger reaction, releasing substantial amounts of methane into the sediment column over a century: 71.8 kg of methane/m^2 under a 1°C scenario; 119 kg of methane/m^2 under a 3°C scenario; and 145 kg of methane/m^2 under a 5°C scenario. Under the 3°C scenario, after 100 years, 36 m of the hydrate depth would be lost. It is important to note that this study examines methane release only from the top of the sediment column, not into the atmosphere.

  Implications: It is clear from this and other studies that higher temperatures can augment rates of methane dissociation. However, we now also have confirmation that the depth and location of the hydrates matters. The substantial volumes of cold, shallow hydrates, such as those found in the Arctic, could dissociate rapidly under warming ocean temperatures. Ocean hydrates contain methane, which when dissociated releases methane gas – with a global warming potential of at least 22 times that of CO_2 on a century time frame (and much higher on a decadal time frame, which has significance for surpassing short-term thresholds in biological and physical systems). Indeed, methane dissociation in the oceans has been hypothesized to have sparked massive palaeoclimatic swings, such as in the late Quaternary period. Moreover, methane release can act as a positive feedback: as methane is released from the ocean into the atmosphere, the climate warms, in turn releasing more methane as ocean hydrate dissociation is further triggered. Given the relatively modest temperature changes at which methane release occurs, this model suggests we may be in for a major abrupt climate change at global average temperatures only slightly higher than those of today, although further study is needed to determine how much of the methane released from marine hydrates would actually enter the atmosphere.

HYDROLOGICAL CYCLE
(GLACIAL/SNOW MELT AND WATER SUPPLY)

In addition to the literature on the physical climate, scientists in 2007 produced a flurry of research articles related to alterations of the hydrological cycle as a result of human-induced climate change. Warming of the climate has concomitant impacts on the hydrological cycle, making some areas drier and others wetter. This in turn will lead to snow and glacial melt in some regions, with impacts to run-off volume and timing, and accelerating snow build up in other regions as precipitation increases due to the water carrying capacity of clouds in a warming world. The section below provides an overview of some of the latest science regarding changes in the hydrological cycle. Overall, the research supports the bleak trends reported in WRI's 2005 and 2006 *Climate Science* briefs.

Perhaps one series of stories from previous years warrants a special note: that of hurricanes. Since the 2005 reports that the frequency of strong hurricanes had increased over the past 30 years, there has been considerable new work in this field – some corroborating that climate change has been the driver of the observed trends, and others suggesting it is still within the range of natural variability. No compelling conclusion has yet been reached in this area and while a number of new articles have been produced, they are not reported on here.

Glacial/Snow Melt

While global warming is an accurate term for the average temperature change associated with an increase in concentrations of greenhouse gases, the increase in temperature is not evenly distributed. Rather, it is greatest at the poles – which hold the largest share of the Earth's snow and ice. As the bright surface of the ice/snow melts, it reveals darker terrestrial or marine surfaces below, leading to a feedback effect, where the melting is accelerated due to a lowering of surface reflectivity. The research described below is only a small sample of new work highlighting some of the changes to glaciers and snow in Antarctica, the Arctic, South America, Greenland, and Asia. A single statistic highlights the already observed – and staggeringly large – extent of change. Record melting was observed using NASA satellite data over the Greenland ice sheet's higher altitude regions in 2007 – with a 150% increase over the mean melting rate previously observed, equal to more than two times the surface area of the United States. 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.

Antarctica

- **Helen Amanda Fricker, Ted Scambos, Robert Bindschadler, and Laurie Padman**
  "An Active Subglacial Water System in West Antarctica Mapped from Space"
  Science
  16 March 2007, vol. 315 no. 5818, pp. 1544-1548

  Fricker et al. used NASA's Ice, Cloud and Land Elevation Satellite (ICESat) to map the Whillans and Mercer ice streams in West Antarctica. Using multiple satellite images from February 2003 to June 2006, they detail surface elevation changes, which, when combined with ice-thickness and subglacial pressure data, signal a possible subglacial water source. Fricker et al. suggest that a previously undetected subglacial lake exists below the ice. The lake is being drained by two large ice streams, which in combination have transported up to 2 km^3 of water from 2003 to 2006 from the ice sheet.

  Implications: The authors note that subglacial water movement is very rapid compared with other mechanisms of ice flow. Water transport could result in large volumes of expelled freshwater and ice into the ocean within months or years, with grave implications for sea level rise as well as for local changes in salinity and water chemistry.

- **M. Tedesco, W. Abdalati, and H. J. Zwally**
  "Persistent surface snowmelt over Antarctica (1987–2006) from 19.35 GHz brightness temperatures"
  Geophysical Research Letters
  22 September 2007, vol. 34, L18504

  Tedesco, Abdalati, and Zwally use NOAA/NASA Pathfinder SSM/1 Level 3 EASE-Grid brightness temperature data and a wet-snow algorithm to assess snowmelt over Antarctica. They develop maps of melting from 1987 to 2006 and find that melting has been increasingly migrating inland since 1987, to areas as far as 875 km inland and 2000 m above sea level. For the continent as a whole, they find a decrease in both the duration and extent of melting; however, they note several important sub-continental features. Their analysis shows melting of the Transantarctic

Mountains in 2005 for the first time since record-keeping began, increases in the duration of melting in the Amery and Wilkes zones, and increases in both the duration and extent of melting on the Ross Ice Shelf.

Implications: Snowmelt on an ice sheet can lead to meltwater collecting on the ice surface and forming large surface and subsurface lakes. It can also burrow into the ice sheet to form vertical shafts connecting the sheet surface to the base, thereby lubricating the base and tremendously expediting heat transfer from the surface to the base. In turn, the process substantially increases the rate of ice flow in the ocean and, therefore, the rate of global sea level rise. Such melting-related phenomena have been observed in Greenland's ice sheet, but had not been documented prior to this study on Antarctica. Even a relatively minor loss of Antarctic ice sheet cover could have major sea level rise repercussions; loss of ice cover in the West Antarctic Ice Sheet alone would lead to a sea level rise of several meters.

Greenland

- **Thomas L. Mote**

  "Greenland surface melt trends 1973 – 2007: Evidence of a large increase in 2007"

  Geophysical Research Letters

  30 November 2007, vol. 34, L22507

  Mote uses data from the Electrically Scanning Microwave Radiometer (ESMR), the Scanning Multichannel Microwave Radiometer (SMMR), and the Special Sensor Microwave/Imager (SSM/I) to piece together data on Greenland surface melt extent from 1973 to 2007. For those areas of missing data Mote uses a measure of "seasonal melt departure," which applies deviations from average ice melt. He finds that the amount of melting in 2007 over some parts of Greenland was as much as 50 more days of melting than average, and melt onset occurred 20-30 days earlier in southern Greenland. Melt area in 2007 was 60% greater than 1998's previous record. Melting has increased since the 1970s.

  Implications: Mote hypothesizes that the dramatic increase in melting in 2007 could be the result of effects from the 2002-2006 melting episodes. He suggests that these effects might include a decline in surface albedo, warmer snow resulting from the recent warmer winters, or changes in winter snow accumulation. Whatever the causal mechanism of melting, it is known that Greenland ice melting will lead to considerable sea level rise. In addition, meltwater reaching the base of the ice sheet can hasten glacier export to the ocean. Total ice volumes in Greenland would, if melted, raise sea level by about 7 m. The increased rate of observed melting suggests that IPCC AR4 projections in which Greenland would not see substantial ice losses this century may be significant underestimates.

Arctic

- **NASA**

  "Record Arctic Sea Ice Loss in 2007"

  http://earthobservatory.nasa.gov/Newsroom/NewImages/Images/arctic_ams_2007259.jpg

  According to the National Snow and Ice Data Center (NSIDC), levels of Arctic sea ice from June through September 2007 were at a record low of 4.13 million km^2. The Center collected images of arctic sea ice extent using the Advanced Microwave Scanning Radiometer, and found that sea ice had fallen 38% below average levels, and 24% below the previous record low in 2005. The ice melt accelerated during the latter half of June, which was characterized by warmer temperatures and clear skies, allowing for more solar radiation to hit the Earth's surface.

  Implications: As sea ice melts, it exposes dark ocean waters, which absorb solar radiation. This change in surface reflectivity, or albedo, can produce a positive warming feedback, contributing to further melt and impeding wintertime ice recovery. Other satellite data (from the QuikSCAT/Seawinds scatterometer as well as long-term data from the Drift-Age Model) note perennial sea ice has also declined: data record a perennial ice loss of 23%, or 1.08 x 10^6 km^2 – comparable to the size of California and Texas together – between 2005 and 2007. From 1970 to 2000, 0.5 x 10^6 km^2 perennial ice was lost per decade (Ngheim et al. "Rapid Reduction of Arctic Perennial Sea Ice." *Geophysical Research Letters.* Vol. 34, October 2007). Loss of both summer and winter ice can inhibit regrowth of ice the following year. The nonlinear ice loss is significant, suggesting that an ice-free Arctic may arrive within the next several decades rather than next century. In fact, Daniel Cressey reported in *Nature* (Vol. 449, September 2007) that the Northwest Passage, recognized as the shortest shipping route between the Atlantic and Pacific, was free of snow and fully navigable in 2007 for the first time in recorded human history. This in turn has implications for transport, as well as potential exploitation of the area's resources.

South America

- **J. L. Chen, C. R. Wilson, B. D. Tapley, D. D. Blankenship, and E. R. Ivins**
  "Patagonia Icefield melting observed by Gravity Recovery and Climate
  Experiment (GRACE)"
  Geophysical Research Letters
  17 November 2007, vol. 34, L22501

  Chen et al. relied on the Gravity Recovery and Climate Experiment (GRACE), which calculates monthly mass redistribution on a 1° by 1° area, to identify the change in the mass of the Patagonia Icefield of South America from 2002-2006. The scientists found that in that period, the Icefield melted at a rate of 27.9 ± 11 km^3/year, adding 0.078 ± 0. 031 mm/year to global sea level rise. These results are consistent with other data collected by Rignot et al. in 2003. This ice melt constitutes an average 1.6 m/year loss of ice thickness.

  Implications: The Patagonia Icefield is roughly 17,200 km^2 in area and, according to the authors, the second largest ice body in the Southern Hemisphere. The melting of this large ice mass has implications for sea level rise, although the implications are more significant for communities and ecosystems that depend on the glacier's freshwater.

Ice melt and sea level rise

- **Andrew Shepherd and Duncan Wingham**
  "Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets"
  Science
  16 March 2007, vol. 315 no. 5818, pp. 1529-1532

  Shepherd and Wingham compare results from three methods – mass budget methods that balance gain from snowfall with loss from melting; altimetry measurement of ice-sheet volume change; and changing gravitational attraction of ice sheets, through Gravity Recovery and Climate Experiment (GRACE) satellites – to assess the contribution of the Antarctic and Greenland Ice Sheets to global ocean volumes. Their study suggests that the East Antarctic Ice Sheet is growing by 25 Gt per year, the West Antarctic Ice Sheet is shrinking by 50 Gt per year, and the Greenland Ice Sheet is shrinking by 100 Gt per year. Resultant sea level rise from ice sheet contributions is on the order of roughly 0.35 mm per year, or 125 Gt of ice annually.

  Implications: While scientists are able to reduce the uncertainty of melting ice sheet contribution to sea level rise, they also note continuing inadequacy in the projections, which are still unable to accurately account for several factors, including the acceleration of flow from ice discharge, regional behavior, and details of ice streams. However, it is becoming increasingly clear that there are "triggers" for rapid increases in the rates of ice flow – with concomitant consequences for sea level rise globally. Meier et al. (in *Science*, 24 August 2007, vol. 317 no. 5841, pp. 1064-1067) corroborate the essential message that ice melt is more rapid than suggested in earlier analyses. Their work indicates that mountain glaciers and ice caps are likely to contribute more than 60% of the total sea level rise in the next century, and that the combined total sea level rise from ice sheets as well as glaciers and ice caps, under current trends, would be 560 mm ± 230 mm. This rate is substantially higher than the much more conservative estimate of the IPCC AR4.

Water Supply

According to the United Nations Development Programme's 2007/2008 Human Development Report, *Fighting Climate Change: Human Solidarity in a Divided World* (**http://hdr.undp.org/en/media/hdr_20072008_en_chapter2.pdf**), many regions, especially in the developing world, face heightened water stress and scarcity as a result of warming, and associated alterations in glacial and snow cover, precipitation levels, runoff, and evaporation patterns. Scarce water supplies could become commonplace for an additional 1.8 billion people by 2080. Exacerbated by non-climate factors as well, drought-prone countries may increasingly engage in political conflict with other nations over transnational water sources, face agricultural shortages and health risks, and witness a loss of ecosystem services. Recent scientific work has corroborated and expanded our understanding of the expected changes in the hydrological cycle that are anticipated to lead to additional stress on water supplies.

- **Frank J. Wentz, Lucrezia Ricciardulli, Kyle Hilburn, and Carl Mears**
  "How Much More Rain Will Global Warming Bring?"
  Science
  13 July 2007, vol. 317 no. 5835, pp. 233-235

- **Xuebin Zhang, Francis W. Zwiers, Gabriele C. Heger, F. Hugo Lambert, Nathan P. Gillett, Susan Solomon, Peter A. Stott, and Toru Nozawa**
  "Detection of human influence on twentieth-century precipitation trends"
  Nature
  26 July 2007, vol. 448, pp. 461-465

  Warmer air can hold more water vapor, but some general circulation models (GCMs) suggest that the future rate of increase in precipitation will be lower than that of total water vapor accumulation. Wentz et al. use Special Sensor Microwave Imager (SSM/I) data from 1987 to 2006, a period that witnessed a rise in temperatures of 0.19 ± 0.04 K per decade, augmented with precipitation data over land from the Global Precipitation Climatology Project, to evaluate this phenomenon. Extrapolating into the future, the authors conclude that the GCMs may have underestimated the precipitation rate, and that water vapor and precipitation will rise at roughly the same rate. They attribute the discrepancy to the time period studied, errors in satellite retrievals or a compensating error in the GCMs to account for radiative balance, as well as built-in assumptions in GCMs about the transport of water vapor slowing.

  In another study, Zhang et al. rely on precipitation data from the Global Historical Climatology Network and compare observations to climate model data in an effort to determine whether land precipitation patterns have been dominated by natural variability or human-induced changes in the periods of 1925 to 1999 and 1950 to 1999. They find that anthropogenic causes contributed to 50-85% of the 1925 to 1999 trend of increased precipitation from 40°N to 70°N; 20-40% of the 98 mm per century drying in the northern subtropics and tropics; and 75-120% of the 82 mm per century moistening in the southern tropics and subtropics.

  Implications: If the projections of Wentz et al. prove correct, greater rainfall in some areas will have sustained and significant impacts on the hydrological cycle, ecosystems, and human populations as intensity and distribution of rainfall changes. They also may require recalibrating the GCMs to adjust for precipitation effects that may currently be incorrectly modeled. Zhang et al.'s study demonstrates that natural variability alone cannot explain precipitation changes, and thus it is possible to speculate that future human activities will have substantial implications on precipitation patterns.

- **Richard Seager, Mingfang Ting, Isaac Held, Yochanan Kushnir, Jian Lu, Gabriel Vecchi, Huei-Ping Huang, Nili Harnik, Ants Leetmaa, Ngar-Cheung Lau, Cuihua Li, Jennifer Velez, and Naomi Naik**
  "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America"
  Science
  25 May 2007, vol. 316 no, 5828, pp. 1181-1184

- **Gregory J. McCabe and David M. Wolock**
  "Warming may create substantial water supply shortages in the Colorado River basin"
  Geophysical Research Letters
  27 November 2007, vol. 34, L22708

  Seager et al. used 19 climate models and assumptions from the Intergovernmental Panel on Climate Change's A1B scenario, in which atmospheric CO_2 levels reach 720 ppm by 2100, to examine future climatic impacts to North America's Southwest. The models show that we are in the midst of the onset of drying climatic conditions, which was triggered at the end of the 20th century and early 21st century. Most significantly, the median reduction in moisture, calculated by the difference between precipitation and evaporation, is projected to reach a level comparable to Dust Bowl drought conditions of the 1930s by the middle of the 21st century. The authors conclude that drying is imminent or already underway and conditions will be "unlike any climate state we have seen in the instrumental data."

  In another study in the same region, McCabe and Wolock collected data on the Upper Colorado River basin's flow to assess the relationship between flow and temperature and how climate change could affect the basin in the future. They obtained the flow data, covering the years 1906 to 2004, from the U.S. Bureau of Reclamation; temperature data were collected on a monthly basis from 1895 to 2004 by the Precipitation-elevation Regression on Independent Slopes Model (PRISM). A water-balance model was used

to estimate streamflow. The scientists examined stream flow under a 0.86°C warming scenario, equal to the temperature increase in the region over the last century, as well as a 2°C future warming scenario. They found that in the absence of concomitant precipitation increases, the 2°C warming resulted in a 17% reduction in the basin water supply. When they compared their results with tree-ring reconstruction data, they discovered that the basin is likely more sensitive to temperature than previously thought, suggesting potentially dire consequences for similar arid/semi-arid ecosystems if future warming is not accompanied by increased precipitation.

Implications: A significant proportion of the U.S. population lives in the Southwest. The drying of the region has socio-economic and cultural implications for human populations, as well as consequences for natural ecosystems and, in turn, ecosystem services. Furthermore, the models do not take into account evaporation, and water withdrawals due to other human activities. Given compounding factors such as increased consumption demand due to population growth, as well as water requirements for agriculture and other activities, it is likely that water shortages could be even graver than these results suggest. Human and ecosystem consequences may be exacerbated by legal history: the Colorado River supply is allocated on the basis of the Colorado River Compact, an agreement made in 1922, not only an extraordinarily wet year but also during a period with significantly lower population size. Given the projected drying, it seems increasingly likely the Compact will not be realized, given the lower flow rates.

ECOSYSTEMS AND ECOSYSTEM SERVICES

As physical and hydrological cycles are altered as a result of the build up of greenhouse gases, ecosystems become affected. The literature described offers a clear indication that several ecosystems have already been altered due to climate change, with some species struggling to contend with altered predator-prey relationships, migration patterns, population sizes, and other impacts. The Intergovernmental Panel on Climate Change's Fourth Assessment Report (**http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf**) states that with another 1.5°C to 2.5°C of warming, almost a third of species would face a likely increased risk of extinction; while 40-70% of species may disappear with a 3.5°C increase. In addition to being inherently undesirable, the loss of species and ecosystems results in a loss of the services humans derive from species, such as medicine, clean water, carbon dioxide sequestration capabilities, clean air, fiber, and tourism.

- **John P. Smol and Marianne S. V. Douglas**
  "Crossing the final ecological threshold in high Arctic ponds"
  Proceedings of the National Academy of Sciences
  24 July 2007, vol. 104 no. 30, pp. 12395-12397

  Small ponds in the high Arctic are important hotspots of biological diversity. However, as many of these ponds are quite shallow, warming temperatures and modified precipitation patterns are speculated to impact water levels, and, in turn, habitat for species. Smol and Douglas examine data from ponds on Cape Herschel, Nunavut, Canada over a 24-year period beginning in the early 1980s. They found that since July 2006, the geography of the landscape had been changed, with ponds drying up altogether and several others at very low water levels. Pond desiccation is attributed to higher rates of evaporation due to warming, as well as lack of ice.

  Implications: Smol and Douglas state that the studied Arctic ponds have persisted through millennia, and, the rapid and large change observed represents a "tipping point" in the ecosystem. In addition to the impacts on pond ecosystems, including to waterfowl, invertebrates, and drinking water/food for many other animals, the authors state that adjacent wetland ecosystems will be impacted. They postulate that vegetation will be more susceptible to fires, given dry conditions, and that wetlands could shift from a carbon sink to a carbon source.

- **O. Hoegh-Guldberg, P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, and M. E. Hatziolos**

  "Coral Reefs Under Rapid Climate Change and Ocean Acidification"

  Science

  14 December 2007, vol. 318 no. 5857, pp. 1737-1742

  Hoegh-Guldberg et al. study atmospheric concentrations and temperatures derived from the Vostok ice core in an effort to assess conditions that have supported coral reefs. Then, using an ecological model with a 50-year time series, they study coral recovery, degradation, and resilience to a variety of possible future acidification and bleaching conditions. They developed three scenarios: (1) stabilizing carbon dioxide concentrations at 380 ppm; (2) carbon dioxide concentrations of 450 to 500 ppm; and (3) increases to more than 500 ppm. At 380 ppm, impacts of climate change, while present, do not fundamentally alter coral reefs in most of their present range. At this CO_2 concentration level, non-climate impacts, such as chemical run off, invasive species, sediment loading, and others are more central to management priorities. Under the second scenario, coral diversity is lost and coral is more vulnerable to other factors such as coralline algae decline, correlated with pH. However, if carbon dioxide concentrations rise to about 500 ppm, the authors state that "these changes will reduce coral reef ecosystems to crumbling frameworks with few calcareous corals." Hoegh-Guldberg et al. suggest that at least half of reef-dependent organisms will likely become extinct under this scenario. They suggest the adaptive ability of coral species is low.

  Implications: Given current rates of emissions growth, the majority of future emissions scenarios suggest that atmospheric carbon dioxide concentrations are likely to rise to well above 500 ppm (stabilization at 450 or 500 ppm would require peaking emissions in the next few decades, which is not likely given current policy globally, yet not necessarily out of the question). The loss of reefs will impact regional economies as tourism and fisheries are damaged. The authors note that, for example, tourism constitutes as much as half of the GDP of some Caribbean nations. As the diversity of reef species is lost, developing countries will be disproportionately adversely impacted, given their low adaptive capacity and high dependence on reef services.

- **Eric V. Regehr, Nicholas J. Lunn, Steven C. Amstrup, and Ian Stirling**

  "Effects of Earlier Sea Ice Breakup on Survival and Population Size of Polar Bears in Western Hudson Bay"

  Journal of Wildlife Management

  November 2007, vol. 71 no. 8, pp. 2673–2683

  Polar bears require ice to rest upon while they are foraging, as well as for reproduction. In the Arctic, however, ice coverage has changed as a result of warming temperatures and modified atmospheric circulation patterns. Regehr et al. set out to determine the implications of ice changes on polar bear populations. They base their study in the western Hudson Bay, which is ice free in the summer and fall. Ice has been breaking apart three weeks earlier than three decades ago, with implications for the length of foraging and, in turn, the bears' ability to give birth and nurse cubs while being confined to their dens. While sightings of polar bears in the region have increased, the authors posit that this is due not to higher population levels, but rather a stressed and hungry population of bears entering human-habited regions in an effort to find food. The authors captured polar bears from 1984 to 2004 and determined their age, population size, and distribution. They found that the region's polar bear population fell from 1,194 in 1987 to 935 in 2004. While adult populations were stable, younger polar bear survival was found to be dependent upon the spring ice breakup date. They employed the Cormack-Jolly-Seber (CJS) model and attribute the compromised polar bear survival to early spring ice breakup and resultant lack of reserves for winter and later rearing of cubs.

  Implications: The study provides an additional indicator of the impacts of warming on species – particularly those in the rapidly changing Arctic. It highlights the interactions between ice, species impacts, and human interactions. The conclusions provide additional support for legal decisions such as that made by the U.S. Department of Interior that polar bears face endangerment as a species due to climate change. The longer-term implications are further highlighted in the authors' own conclusions, with their acknowledgement that the studied polar bears are at the southern edge of the species' survival range, and thus the patterns depicted in this study may "foreshadow the demographic responses and management challenges that more northerly polar bear populations will experience."

- **Inger Greve Alsos, Pernille Bronken Eidesen, Dorothee Ehrich, Inger Skrede, KristineWestergaard, Gro Hilde Jacobsen, Jon Y. Landvik, Pierre Taberlet, and Christian Brochmann**

  "Frequent Long-Distance Plant Colonization in the Changing Arctic"

  Science

  15 June 2007, vol. 316 no. 5831, pp. 1606-1609

  As a result of changes in temperature and precipitation, some species will experience range changes in a poleward direction. One question that has concerned climate modelers, conservation biologists, and species managers has been whether species migration will be possible, especially if long-distance transport – for example, from island to island – is necessary. This study by Alsos et al. traces the colonization of nine species of Arctic plants in the Svalbard Archipelago in an effort to determine the geographic origins of current plant distribution. The scientists analyze 4,439 samples; methods include genetic analysis through amplified fragment-length polymorphism, Bayesian clustering analyses, ordination, and a tree-building algorithm. They find that the plant species had colonized from nearby regions, such as northwestern Russia, using dispersal vectors including driftwood, wind, animals, and winter sea ice. In the large majority of the studied species – eight out of nine species – numerous successful colonization attempts were needed to establish a population in Svalbard. Thus, one lucky colonization event would not guarantee species establishment; rather, the authors suggest that between 6-38 plants of each species had to migrate and survive in Svalbard's conditions prior to population establishment.

  Implications: The authors suggest that arctic flora are highly mobile as a result of genetic selection over thousands of years in response to cyclical glacial periods. While the species studied within this analysis were successful in their colonization attempts, it remains unknown whether species in other regions of the world have been selected for such traits and, moreover, whether genetic evolution could be quick enough to respond to anthropogenic climate change, given the unprecedented rate of warming. Also, some dispersal vectors listed in this study, such as ice presence in winter, may not exist in other ecosystems, potentially compromising species' colonization abilities.

- **James Battin, Matthew W. Wiley, Mary H. Ruckelshaus, Richard N. Palmer, Elizabeth Korb, Krista K. Bartz, and Hiroo Imaki**

  "Projected impacts of climate change on salmon habitat restoration"

  Proceedings of the National Academy of Sciences

  17 April 2007, vol. 104 no. 16, pp. 6720-6725

  Battin et al. employ downscaled climate model data, as well as a physically-based hydrologic model linked with a salmon life-cycle model, to estimate climate change impacts on Chinook salmon habitat and species number in the U.S. Snohomish River Basin. Holding land use constant, their models forecast a decline in spawning population by 2050, ranging from 20% (HadCM3 model) to 40% (GFDL model). They find that climate impacts were most pronounced at high elevations; therefore, restoration activities at lower elevations may be more promising for mitigating climate impacts to the species.

  Implications: Billions of dollars have been devoted to aquatic restoration in the United States, but few efforts model climate change impacts into their long-term planning. Not only do higher water temperatures affect early stages of the salmon life cycle, but altered precipitation patterns can reduce viable aquatic habitat and alter peak flow timing, providing dangerous waters for spawning salmon. This study suggests that fish habitat in other river basins may be affected similarly. Thus, not only should climate impacts be incorporated into management and restoration plans, but restoration efforts will need to be adaptive in nature so they can respond to impacts and new scientific information on species' vulnerability and adaptability.

- **Hans O. Pörtner and Rainer Knust**

  "Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance"

  Science

  5 January 2007, vol. 315 no. 5808, pp. 95-97

  While each species will respond uniquely to climatic change, one common effect among many aquatic species is a compromised ability to engage in aerobic activity. When an aquatic species is stressed thermally, its circulation levels decrease and, as a result, oxygen cannot adequately feed vital organs. Pörtner and Knust tested this concept in an eelpout species, *Zoarces vivparus*, in the German Wadden Sea. They note that the water temperatures

had risen in the region by 1.13°C, making the site an appropriate one for assessing the eelpout's response. They collected data on eelpout abundance from 1954 to 1989 in 5-year running means, sampling in July, and found that abundance had decreased during the period. Pörtner and Knust derive aerobic performance via calculations of critical oxygen tensions or concentrations, and discover that species abundance is indeed associated with oxygen limitation and thermal sensitivity. They find that their data collected in the field is consistent with laboratory-derived data collected in previous studies on thermal tolerance.

Implications: According to the authors, species' thresholds in oxygen circulation may be reached long before other climate impacts come into play, such as food limits, predation, and diseases. The authors also suggest that if species were able to adapt, other functions may be compromised, such as development, performance, and fecundity, as energy budgets for the species will be redistributed. And if certain species have higher survivability than others, it may result in alterations to the food web and, in turn, to aquatic ecosystem composition.

- **A.C. Gange, E. G. Gange, T. H. Sparks, and L. Boddy "Rapid and Recent Changes in Fungal Fruiting Patterns"**

  Science

  6 April 2007, vol. 316 no. 5821, p. 71

  While significant headway has been made in understanding how climate impacts biota, the majority of studies focus on the springtime behavior of higher organisms, during which many species blossom and breed. Gange et al. set out to determine whether climate change has had similar impacts on fungi, and they turn to a previously understudied time of year: autumn. The researchers examine 52,000 fruiting records of fungi across roughly 1,400 regions in England from 1950 to 2005. They find that the fruiting season has doubled in length: in the 1950s it was 33.2 ± 1.6 days, whereas today it is 74.8 ± 7.6 days. On average, species that are fruiting earlier are doing so 8.6 ± 0.6 days per decade, and those with delayed fruiting events are fruiting 7.5 ± 0.5 days per decade later, with resultant lengthening of fungal seasons. The authors find that these trends parallel changes in temperature and precipitation in the region.

  Implications: In addition to the elongated fruiting season of fungi in autumn, the authors note that spring fruiting, previously uncommon, can be attributed to warming. The altered fruiting patterns will manifest themselves in higher decay rates throughout the forests, with implications for ecosystem structure and function. The interaction of fungi and the ecosystem cycle is quite delicately balanced; changing fundamental parameters such as these are likely to have still unanticipated knock-on consequences for other macro and micro fauna and flora.

- **K. B. Suttle, Meredith A. Thomsen, and Mary E. Power "Species Interactions Reverse Grassland Responses to Changing Climate"**

  Science

  2 February 2007, vol. 315 no. 5812, pp. 640-642

  While many studies on climate impacts to biota and ecosystems employ modeling, Suttle, Thomsen, and Power rely on a field experiment to explore the response of northern California grasslands to climate change. They created 18 circular 70 m^2 experimental plots and applied three different timings of augmented precipitation levels (44 cm per year, constituting a 20% increase over the average) in winter and spring, along with a control trial with natural rainfall timing. The scientists ran the experiment for five years and discovered that the timing of additional rainfall determined ecosystem structure changes. While the winter and ambient plots responded similarly, the spring excess rainfall augmented primary production during the first two years, especially within nitrogen-fixing forbs – a change which supported more complex predator-prey relationships as a result of the heightened food availability. However, in marked contrast, in subsequent years species richness decreased substantially as forbs were supplanted by grasses. In fact, by the last year of the study, plant species as well as herbivore and predator diversity had each declined by 50%, and invertebrate richness by 20%.

  Implications: This study effectively demonstrates that ecosystem structure is sensitive to precipitation timing, which has already been altered in many regions as a result of human-induced warming. The study also suggests that it is only over the longer term that changes become apparent: near-term shifts may appear positive when long-term outcomes are more serious. The results apply not only to the ecosystems themselves, but also to the need to run longitudinal studies: long-term data and analysis must be the basis for both good scientific assessment and for management planning.

- **Ruth Bibby, Polly Cleall-Harding, Simon Rundle, Steve Widdicombe, and John Spicer**

  "Ocean acidification disrupts induced defenses in the intertidal gastropod Littorina littorea"

  Global Change Biology

  22 December 2007, vol. 3 no. 6, pp. 699-701

  Bibby et al. find that ocean acidification due to build-up of carbon dioxide in the oceans not only has direct effects on marine species' mortality but also indirect effects, such as on defense mechanisms. Studying the gastropod *Littorina littorea*, the authors find that the snail species could no longer respond to predator crabs in the same manner when carbon dioxide levels are heightened. The scientists exposed the periwinkles in South Devon to acidified seawater and predator crabs. Under higher pH, these periwinkle snails not only failed to develop thick protective shells, their typical response to predation, but also had slower metabolism. In addition, they engaged in "avoidance behavior" and attempted to stay away from their predators.

  Implications: The pH of seawater has already dropped 0.1 pH units and is projected to drop as much as 0.4 units by 2100, which is significant given pH's logarithmic scale, Previously, scientists had omitted indirect impacts of ocean acidification in their studies. This research demonstrates that indirect effects, such as those related to defense mechanisms against predators, are not only real but can also have significant implications on marine communities, as species behavior will have ramifications on predator–prey interactions and community structure. Weaker shells can result in higher mortality due to predator crushing; avoidance behavior can limit the time available for feeding, impacting tropic dynamics as grazing is reduced.

- **Keiron P. P. Fraser, Andrew Clarke, and Lloyd S. Peck**

  "Growth in the slow lane: protein metabolism in the Antarctic limpet ***Nacella concinna*** **(Strebel 1908)"**

  The Journal of Experimental Biology

  1 August 2007, vol. 210 no. 15, pp. 2691-2699

  Fraser, Clarke, and Peck find that climate change is impacting the *Nacella concinna,* a limpet species in Antarctica. Increased water temperatures were found to limit protein synthesis retention efficiency (PSRE), which measures protein growth and, in turn, soft tissue somatic growth within the organisms. The scientists maintained various water temperatures in the laboratory at Rothera Research Station in Antarctica in an effort to assess impacts on protein synthesis. The scientists discovered that when temperatures were increased above 1°C, PSRE decreased. Prior to this study, climate impacts to Antarctic ectotherms' protein metabolism had yet to be studied.

  Implications: The authors suggest that higher water temperatures along Antarctica will result in reduced protein synthesis and decline of polar limpets. According to a press release on the story (**http://www.antarctica.ac.uk/press/press_releases/press_release.php?id=294**), limpets could be replaced by other species, which could affect ecosystem dynamics. Seabirds, fish, and starfish all depend upon this common limpet species as a dietary staple; thus limpet decline could have significant implications for other species. The Antarctic has warmed approximately 2-3°C over the past 50 years – a rate nearly three times the global average. It is anticipated additional warming of at least this magnitude will occur over the next century. This study suggests we can expect to see fundamental changes in basic ecosystems in the Antarctic as warming proceeds.

- **Cagan H. Sekercioglu, Stephen H. Schneider, John P. Fay, and Scott R. Loarie**

  "Climate Change, Elevational Range Shifts, and Bird Extinctions"

  Conservation Biology

  February 2008, vol. 22 no. 1, pp. 140-150

  (Manuscript accepted 20 August 2007)

  Sekercioglu et al. assess the impacts of climate change on landbirds, which represent 87% of all birds, at various elevations. They use six emissions scenarios based on the IPCC's Fourth Assessment Report's "likely" (or with at least a 66% probability) estimates of temperature increases. They also employ four habitat scenarios in an effort to evaluate how bird species' habitat types will change with warming. They find that, assuming half of lowland species' lower elevational limit is raised, warming of 2.8°C will result in the extinction of 400-550 bird species by 2100. With 6.4°C, and all lowland species' elevational limit moved higher, 30% of all landbirds, or roughly 2,500 species, will become extinct by 2100.

  Implications: Most notably, only 21% of the species that face extinction under the authors' scenarios are currently considered threatened, demonstrating that climate change poses novel threats in addition to other impacts such as

land use conversion and invasive species. Moreover, the authors find that the extinction risk is non-linear and more warming has significantly larger impacts on landbirds. Absent major policy efforts, the IPCC projects global average temperatures to increase 0.2°C/decade, suggesting increasing threats to landbirds coming well before the end of the century.

- **Angus R. Westgarth-Smith, Suzanne A.G. Leroy, Philip E.F. Collin, and Richard Harrington**
  "Temporal variations in English populations of a forest insect pest, the green spruce aphid (Elatobium abietinum), associated with the North Atlantic Oscillation and global warming"
  Quaternary International
  October–November 2007, vol. 173–174, pp. 153–160

- **B.C. Ministry of Forests and Range, Forest Analysis and Inventory Branch**
  "Timber Supply and the Mountain Pine Beetle Infestation in British Columbia: 2007 Update"
  http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/Pine_Beetle_Update20070917.pdf

  Westgarth-Smith et al. find that the green spruce aphid *Elatobium abietinum* has responded to climate change by initiating spring migration earlier in the season. They use aphid data from a trap placed in southern England over 41 years, as well as data on the North Atlantic Oscillation (NAO) as a climate proxy. They find that over the period from 1966-2006, the warmer weather and positive NAO index resulted in earlier aphid migration, and that aphid population size increased.

  The British Columbia Ministry of Forests and Range, in their 2007 report on the mountain pine beetle outbreak, show that in 2007, the impacted area had increased to 13 million hectares (from 4.2 million hectares in 2003). Mountain pine beetles prefer mature lodgepole pines and while they typically die off with cold snaps, warmer temperatures in the region have allowed them to persist. They cut off the nutrient and water supply of the trees by burrowing in trees' bark. The Ministry finds that 40% of merchantable pine volume – 12% of total merchantable volume on the timber harvesting land base in British Columbia – has been impacted from 1999 to 2006. They project that if the pine beetle outbreak continues at the same pace, it will kill off 78% of the pine volume – 23% of total merchantable volume on the province's timber harvesting land base – by 2015.

  Implications: The green spruce aphid is a pest of the Picea, or spruce, species. The authors state that the winter NAO index is projected to become increasingly positive with implications of greater aphid populations with earlier migration and, in turn, damage to spruce species. This kind of increased pest population has been documented elsewhere as well; not only are the pine beetle infestations induced by climate, but changes in soy and wheat devouring insects are as well (see the USDA Agricultural Research Service programs at **http://www.ars.usda.gov/research/programs/programs.htm**). In addition to ecological impacts (e.g., as mature stands that are critical habitat for species are affected), the loss of forests has implications for the strength of the regional economy, especially for those who depend on the use of insect-impacted timber and rely upon the forest sector for their livelihoods.

- **Daniel W. McKenney, John H. Pedlar, Kevin Lawrence, Kathy Campbell, and Michael F. Hutchinson**
  "Potential Impacts of Climate Change on the Distribution of North American Trees"
  Bioscience
  December 2007, vol. 57 no. 11, pp. 939-948

  McKenney et al. establish that climate change will have profound impacts on North American tree species. They study 130 species and employ a climate envelope approach (which is based on a combination of climate factors including temperature, precipitation, and soil moisture) to evaluate the impacts to species' range and niche, using the IPCC's A2 and B2 emissions scenarios. They find that under optimal conditions, tree species ranges should move approximately 700 km north, and their habitable zones would decrease on average by more than 10%. However, if tree dispersal to future viable habitat is not successful, and instead species are restricted to their current ranges, climate envelopes decrease by 58% on average during the 21st century, moving approximately 330 km north, with 17 species decreasing their climate envelope by 80%.

  Implications: Depending on species' adaptive capacity, climate change impacts will vary. If species ranges can shift to suitable new habitats, there will be a greater chance of range maintenance. However, if species are restricted to their current ranges, which is likely in many

regions due to development pressures on the periphery of protected areas, viable habitat will decrease dramatically. Range shifts will have impacts on ecosystem composition as species' ranges shift individualistically, with potential concomitant impacts to ecosystem health.

- **Rosamond L. Naylor, David S. Battisti, Daniel J. Vimont, Walter P. Falcon, and Marshall B. Burke**

  "**Assessing risks of climate variability and climate change for Indonesian rice agriculture**"

  Proceedings of the National Academy of Sciences

  8 May 2007, vol. 104 no. 19, pp. 7752-7757

  Annual and interannual cyclical events are key determinants of agricultural species viability, and anthropogenic climate change is projected to alter the course of such events. Naylor et al. study this phenomenon in Indonesian rice production, which is heavily dependent on the El Niño – Southern Oscillation (ENSO) timing. As the ENSO is altered, a default adaptation strategy has been employed in the region: delayed planting, which the authors suggest prolongs the "hungry season," as the season is cut short. The researchers relied on projections of climate impacts on ENSO over Java and Bali, 55% of Indonesia's rice production region. They used global climate models from the IPCC's Fourth Assessment Report, and created empirical downscaling models to depict changes to monsoons and ENSO to the region over the next half century. They found that the monsoon is likely to be delayed as a result of ENSO variability. Spring rains will not make up for the lack of rain during other parts of the year, and drought conditions could prevent rice planting.

  Implications: Depressed levels of rice production have significant implications for food security, as in three decades more than 50% of the world will rely upon rice as their main dietary staple (http://www.worldbank.org/html/cgiar/press/pres0599.html). Naylor et al. suggest that adaptation policies that incorporate water storage and irrigation, as well as crop diversification, will be of high value to the region. In addition, they call for research devoted to drought-resistant rice species. The past year's rapid escalation in food prices, along with civil unrest consequential to limits, is a harbinger for what might occur as climate continues to change – particularly if aggressive global food policies are not implemented.

CLIMATE CHANGE MITIGATION TECHNOLOGIES

The last year has seen significant advances in climate change mitigation technologies, which are essential to curbing greenhouse gases – as well as coping with their consequences. From solar cells to biofuels; to efficient cars; to hydrogen, geothermal and ocean/tidal power; the technologies highlighted in the stories below suggest that, if coupled with financial incentives and resources for commercialization, climate-friendly technologies will become increasingly available. If developed and applied properly (i.e., in a carbon-negative or carbon-neutral way), not only will these climate change mitigation technologies lower the GHG emissions and resultant impacts associated with energy use, but they will also reduce the cost of clean energy sources. To date, however, few are adequately scaled up: a key challenge over the coming years will be to promote rapid penetration of these and other technologies in both developed and developing countries. In addition, a very important consideration that remains unclear is the life-cycle carbon balance of many of these technologies – i.e., when scaled to the appropriate level, it is not certain whether some of these technologies will indeed benefit the climate, or whether they will end up being carbon-positive and, therefore, do more harm than good.

By their nature, many of the advances reported below are yet to be (or will never be) found reported in peer reviewed journals – but rather are in press releases or corporate and academic bulletins. It is therefore impossible to state with certainty that these results presage new commercial technology development, or if instead they mark only interesting new developments in the long process between the laboratory bench and industrial-scale application. In either case, they represent advances that give considerable hope that society can effectively combat climate change and mitigate its worst effects.

- **Bing Tan, Elizabeth Toman, Yanguang Li, and Yiying Wu**

  "Zinc Stannate (Zn_2SnO_4) Dye-Sensitized Solar Cells"

  Journal of the American Chemical Society

  11 April 2007, vol. 129 no. 14, pp. 4162-4163

  Tan et al. discover a way to enhance the efficiency of dye-sensitized solar cells (DSSCs), which are fashionable alternatives for future expansion of solar power due to their low cost. They are made of red dye and white

metal oxide powder, and thus,retain a pink color rather than the blue associated with most solar cells due to their anti-reflective coating. The engineers incorporate Zn_2SnO_4 nanoparticles in the DSSCs and compare their performance with DSSCs that include only simple binary oxides. The engineers achieve an efficiency of 3.8%, which is a significant advancement over the 1.2% efficiency of a simple binary oxide, like SnO_2, in a DSSC.

Implications: While more research is needed before the DSSC efficiency increases to match the efficiency of conventional solar cells, the cost of DSSC production is a quarter of the cost of commercially available silicon-based solar cells. Therefore, once efficiency is boosted, the DSSC design could make solar energy more competitive with traditional fossil fuel-derived energy.

- **Matthew C. Beard, Kelly P. Knutsen, Joseph M. Luther, Qing Song, Wyatt Metzger, Randy J. Ellingson, and Arthur J. Nozik**

  "Unique Quantum Effect Found in Silicon Nanocrystals: Quantum Dot Materials May Improve Efficiency of Silicon Solar Cells"

  National Renewable Energy Laboratory News Release

  24 July 2007, NR-2007,

  Available online at http://www.nrel.gov/news/press/2007/525.html

  Silicon, the most comment semiconductor in solar cells, typically loses half of its energy gathered from sunlight in the form of heat. Scientists at the U.S. Department of Energy's National Renewable Energy Laboratory have developed a way to use quantum dots, or nanocrystals – typically only used in non-silicon materials that can be environmentally harmful – in silicon. Unlike traditional silicon, silicon nanocrystals release more than one electron per photon of sunlight, a phenomenon known as "multiple exciton generation." This electron multiplication can boost the efficiency of solar cell production of energy.

  Implications: Solar cells with nanocrystal silicon can maintain efficiencies of 44%, far above the efficiencies reached by conventional solar cells. If silicon nanocrystals become commercially available, this boost in efficiency can make solar power more economical.

- **Jin Young Kim, Kwanghee Lee, Nelson E. Coates, Daniel Moses, Thuc-Quyen Nguyen, Mark Dante, and Alan J. Heeger**

  "Efficient Tandem Polymer Solar Cells Fabricated by All-Solution Processing"

  Science

  13 July 2007, vol. 317 no. 5835, pp. 222-225

  Kim et al. developed a tandem solar cell, connecting two solar cells with a titanium oxide layer which transports electrons. The stacked photovoltaic cells can increase the voltage (as the voltage of the cells is additive), and absorb a wider range of photo energies. The engineers use polymer-based materials for the cells and remarkably reach a record efficiency of 6.5%, which improves upon the previous 5% power-conversion efficiency of organic solar cells.

  Implications: Efficiency improvements for polymer solar cells have significant implications because photovoltaic cells made from organic materials are of lower cost than others, and can be used for coating and printing. The authors suggest that the low efficiency has previously been a barrier to commercial-scale deployment. In a summary of the article in ScienceDaily (**http://www.sciencedaily.com/releases/2007/07/070712143246.htm**), one of the researchers stated that the technology could be commercially viable in three years.

- **Syed Shams Yazdani and Ramon Gonzalez**

  "Anaerobic fermentation of glycerol: a path to economic viability for the biofuels industry"

  Current Opinion in Biotechnology

  June 2007, vol. 18 no. 3, pp.213–219

  While biodiesel production has ramped up over the past few years, a consequence of the production process is the waste byproduct glycerin. Engineers from Rice University have recently developed a way to get rid of the glycerin and produce more fuel at the same time. They found that an *E. coli* strain can convert glycerin to ethanol via anaerobic fermentation, which not only diminishes the cost of glycerin waste disposal, but also produces another transportation fuel – ethanol.

  Implications: The engineers suggest that for every 100 units of biodiesel produced, ten units of glycerin can be created via the *E. coli* conversion. This byproduct can, in turn, be fermented into the higher-value ethanol product. However, proper choice of biodiesel feedstock is critical;

otherwise, increasing demand for biodiesel (as well as other biofuels) might lead to disastrous unintended effects such as large-scale destruction of tropical ecosystems, which would ultimately undermine carbon sequestration benefits of biofuels.

- **Yuriy Román-Leshkov, Christopher J. Barrett, Zhen Y. Liu, and James A. Dumesic**

  "Production of dimethylfuran for liquid fuels from biomass-derived carbohydrates"

  Nature

  21 June 2007, vol. 447, pp. 982-985

  Román-Leshkov et al. have recently developed a way to produce a liquid transportation fuel deprived from fructose, which can be gathered from biomass or glucose processing. The process creates 2,5-dimethylfuran, which can be more effective than ethanol for transport needs because it has a higher boiling point and energy density and is not water-soluble.

  Implications: The authors suggest that this biomass-derived liquid fuel for the transportation sector could have significant advantages over ethanol. This advancement could not only foster energy independence for transportation fuels but also address some of ethanol's weaknesses, including its volatility, water solubility which contaminates the fuel source, and low energy density. However, fructose production may still conflict with food crop production – a problem that has increasingly plagued the ethanol industry over the past year.

- **R.E. Camacho, A.R. Morgan, M.C. Flores, T.A. McLeod, V.S. Kumsomboone, B.J. Mordecai, R. Bhattacharjea, W. Tong, B.K. Wagner, J.D. Flicker, S.P. Turano, and W.J. Ready**

  "Carbon Nanotube Arrays for Photovoltaic Applications"

  JOM **(Journal of The Minerals, Metals & Materials Society)**

  March 2007, vol. 59 no. 3, pp. 39-42

  Camacho et al. have stacked arrays of carbon nanotubes vertically with cadmium telluride and cadmium sulfide to enhance the light-trapping properties of solar cells. The towers of nanotubes are able to trap incoming solar radiation with increased efficiency: the scientists find that the efficiency (photocurrent per cm^2 of footprint) of the stacked arrays is 63 times more than a planar single crystal silicon device, which typically reflects a substantial amount of energy due to its flat shape.

  Implications: While not commercially available yet, the 3D solar cell design is a significant advancement in solar cell technology. In addition, its 63-fold photocurrent per area increase can be achieved in a compact design because thick coating of photovoltaic materials, often used to boost efficiency, is no longer necessary.

- **Shaoan Cheng and Bruce E. Logan**

  "Sustainable and efficient biohydrogen production via electrohydrogenesis"

  Proceedings of the National Academy of Sciences

  20 November 2007, vol. 104 no. 47, pp. 18871–18873

  Energy derived from hydrogen is typically created through hydrolysis, a process which splits water to produce hydrogen, and which requires an alternative fuel source, typically natural gas. Researchers at Penn State, Cheng and Logan have recently developed a novel way to create the same hydrogen – through conversion of cellulose. They develop microbial fuel cells made of graphite anodes treated with ammonia gas, which boosts adhesion of bacteria; cathodes made of carbon with platinum catalyst; and anion exchange membranes, which reduce the amount of hydrogen lost in the process and enhance proton conduction. This novel arrangement not only creates bioelectricity when the organic matter is exposed to oxygen, but hydrogen gas can be produced when a small voltage (> 0.2 volts) is added. This process is known as electrohydrogenesis. The scientists found that the energy efficiency was 288% (i.e., 288 times more energy was produced than the energy input into the process), compared with water electrolysis to produce hydrogen with average efficiency of 50-70%.

  Implications: Hydrogen production typically requires a fossil fuel-derived energy source to split water apart. However, Cheng and Logan demonstrate that hydrogen can be produced with organic matter. Moreover, the authors suggest that use of cellulose for hydrogen, and in turn hydrogen-powered vehicles, could be more readily applied than cellulose for ethanol generation, which requires cellulose conversion first to sugar and then ethanol. Even if a hydrogen economy doesn't emerge for some time due to infrastructure delays that lag behind research advances, the authors suggest that fertilizer production could take advantage of electrohydrogenesis, because manufactur-

ing could be powered by wood chips' cellulose, which is converted to hydrogen, reducing transportation fuel use and costs as fertilizer can be produced on site.

- **Nancy Stauffer**
  "MIT researchers work toward spark-free, fuel-efficient engines"
  MIT News: MIT Energy Initiative
  23 July 2007, available online at http://web.mit.edu/newsoffice/2007/engine-0723.html

  Spark ignition automobiles lose considerable energy through the spark operating mode. MIT engineers have recently developed a way to eliminate the spark in the engine, greatly improving fuel efficiency. They developed a "homogenous charge compression ignition" (HCCI), which enables combustion to happen in multiple places in the combustion chamber, lowering the need for fuel input and incoming air, which wastes a substantial amount of energy.

  Implications: According to the press release, switch ignition elimination could save a million barrels of oil a day (for reference, the United States uses 20 million of barrels every day). Moreover, fuel efficiency will be improved, saving a few miles per gallons in new models of cars. Unfortunately, there are fewer conditions in which HCCI can operate, but engines could be designed as hybrid, electing to run in HCCI mode whenever possible. Tests demonstrate that HCCI mode could be chosen 40% of driving time in urban environments.

- **"Harvesting the Power of Ocean & Tidal Energy"**
  RenewableEnergyWorld.com
  1 August 2007, available online at http://www.renewableenergyworld.com/rea/news/story?id=49500

  British engineers in Cornwall, England, have recently developed a novel ocean turbine, dubbed the Osprey turbine. The device is designed on a vertical axis with the gearbox and generator located above the water level, which can work at various depths to account for tidal cycles and water body heights. The engineers suggest that the technology can be placed on pontoons or on the seabed. Perhaps most significantly, it is modular so it can be used for small-scale applications, as well as stacked for increased generation.

  Implications: According to the article, 20% of the United Kingdom's electricity needs can be met by wave and tidal power. The engineers state that the Osprey turbine will not negatively impact the marine ecosystems in which it is placed. They suggest that the Osprey turbine could lead to commercial availability of tidal power, and that the turbines could be placed in common sites such as old mill locations.

- **Jiwen Liu, Manoj A. G. Namboothiry, and David L. Carroll**
  "Optical geometries for fiber-based organic photovoltaics"
  Applied Physics Letters
  26 March 2007, vol. 90 no. 13, pp. 133515-1 – 133515-3

  Liu et al. note that conventional thin solar cells made from organic materials do not absorb sunlight effectively. In this research, Liu et al. created thin-film devices with a tin oxide conductor and solid core fibers, which augment the efficiency of this class of photovoltaics. A story on the development ("Plastic Solar Cell Efficiency Hits 6% in U.S. Lab", 4 May 2007, available online at **http://www.renewableenergyworld.com/rea/news/story?id=48378&src=rss**) suggests that the efficiency gain – at 6% efficiency, double the 3% level of two years ago – has brought plastic solar cells closer to commercialization. Efficiencies of at least 8% are needed for commercial sale.

  Implications: These thin plastic solar cells could be made inexpensively and used in building materials, such as roof tiling. The costs of such technologies have remained prohibitive – at two to five times the costs of conventional power. Continually boosting levels of efficiency are increasingly making solar PV more competitive.

- **Zong-Bo Qiu, Xiao Liu, Xiang-Jun Tian, and Ming Yue**
  "Effects of CO_2 laser pretreatment on drought stress resistance in wheat"
  Journal of Photochemistry and Photobiology B: Biology
  30 January 2008, vol. 90 no. 1, pp. 17–25

  Drought causes species to be toxically stressed, and generation of reactive oxygen species (ROS) is a signal of biotic and abiotic stress. Drought also inhibits species response to ROS. Qiu et al. applied CO_2 pretreatment lasers to wheat species *Triticum aestivum L.* seeds, to assess whether laser exposure to CO_2 had an impact on ROS generation and, in turn, drought resistance. The CO_2 laser was directed toward 40 seed embryos in four series of tests: a control run, as well as 1-minute, 3-min-

ute, and 5-minute bouts, with each test replicated five times. Smaller amounts of laser pretreatment – for 1 and 3 minutes – did, in fact, mitigate the toxic effect, while the 5-minute pretreatment was not as successful. The authors propose that modest amounts of CO_2 laser may "scavenge ROS."

Implications: Qiu et al. suggest that CO_2 laser pretreatment could bolster the resiliency of wheat species to drought, which is projected to increase in many regions as a result of anthropogenic climate change. Thus, CO_2 laser pretreatment could be explored as a potential adaptation strategy to enhance food security for communities that depend on wheat.

IPCC Assessment Reports

The findings and language of the following tables are taken directly from the first, second, third and fourth IPCC Assessment Reports (FAR, SAR, TAR, AR4). The executive summaries of each of the working group reports (on climate science, impacts, and response strategies) can be found on the IPCC web site, along with a synthesis report linking the conclusions from the full documents (see http://www.ipcc.ch).

HUMAN ATTRIBUTION OF MOST OF THE OBSERVED INCREASE IN GLOBAL AVERAGE TEMPERATURES SINCE THE MID-20TH CENTURY

FAR (1990)	We are certain emissions resulting from human activities are substantially increasing the atmospheric concentrations of greenhouse gases. These increases will enhance the greenhouse effect, resulting on average in additional warming of the Earth's surface.
SAR (1995)	The balance of evidence suggests a discernible human influence on global climate.
TAR (2001)	Most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.
AR4 (2007)	Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.
Rationale for Revisions	Since the late 1980s, there has been an increasingly close scrutiny of the temperature record, as well as new model estimates of variability and of the climate response to natural and anthropogenic forcing. Furthermore, our understanding of climate processes and their incorporation in climate models have improved, including with respect to water vapor, sea-ice dynamics, and ocean heat transport. These studies have allowed a broader and more confident assessment of the relationship between observed warming and impacts than was made in the TAR.

CHANGES TO THE HYDROLOGICAL SYSTEM

FAR (1990)	Precipitation is expected to increase on average in middle and high latitude continents in winter (by some 5-10% over 35-55°N). Confidence in regional estimates is low, especially for the changes in precipitation and soil moisture. Not possible to give reliable predictions at smaller scales demanded for impacts assessments. Do not know if, or in what way, large-scale weather regimes (including tropical storms, such as hurricanes and typhoons) might change.
SAR (1995)	Confidence is higher in the hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in the regional projections, where confidence remains low. There is more confidence in temperature projections than hydrological changes. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms (e.g., tropical cyclones).
TAR (2001)	Based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to increase during the 21st century. By the second half of the 21st century, it is likely that precipitation will have increased over northern mid- to high latitudes and Antarctica in winter. At low latitudes there are both regional increases and decreases over land areas. Larger year to year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected. Increase in globally averaged precipitation and more intense precipitation events very likely over many areas.
AR4 (2007)	Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100), continuing observed patterns in recent trends. Heavy precipitation events and frequency increases over most areas is very likely.
Rationale for Revisions	There is a continually improving understanding of the drivers for precipitation at both regional and global scales, leading to increasing confidence in projections due to global warming.

IPCC Assessment Reports

RISK TO UNIQUE AND THREATENED SYSTEMS

FAR (1990)	Ecosystems will change in structure. Over time, some species may be displaced to higher latitudes or altitudes. Rare species with small ranges may be prone to local or even global extinction. Climate change likely to affect ocean circulation and mixing patterns, and hence phytoplankton distribution and net primary production.
SAR (1995)	There will likely be reductions in biological diversity and in the goods and services that ecosystems provide society. No mention of acidification.
TAR (2001)	Ecological productivity and biodiversity will be altered by climate change and sea-level rise, with an increased risk of extinction of some vulnerable species (high to medium confidence). Recently it has been suggested that a doubling of CO_2 levels could reduce reef calcification, but this effect is very difficult to predict. Such effects could be noticed by 2100 because of the decreased availability of CaCO3 to corals. In combination with potentially more frequent bleaching episodes, reduced calcification could impede a reef's ability to grow vertically in pace with sea-level rise.
AR4 (2007)	There is medium confidence that approximately 20 to 30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5 to 2.5°C over 1980-1999 levels. While the effects of observed ocean acidification on the marine biosphere are as yet un-documented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g., corals) and their dependent species.
Rationale for Revisions	More specific information is now available across a wide range of systems and sectors concerning the nature of future impacts, including some fields not covered in previous assessments. More recent studies have enabled enhanced systematic understanding of the timing and magnitude of impacts related to differing amounts and rates of climate change.

RISK OF EXTREME WEATHER EVENTS

FAR (1990)	No clear evidence that weather variability will increase in the future. However, with a modest increase in mean temperature, the number of days with temperatures above a given high value could increase substantially.
SAR (1995)	Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms (e.g., tropical cyclones).
TAR (2001)	Models project that increasing atmospheric concentrations of greenhouse gases result in changes in frequency, intensity, and duration of extreme events, such as more hot days, heat waves, heavy precipitation events, and fewer cold days. Many of these projected changes would lead to increased risks of floods and droughts in many regions, and predominantly adverse impacts on ecological systems, socio-economic sectors, and human health. High resolution modeling studies suggest that peak wind and precipitation intensity of tropical cyclones are likely to increase over some areas. There is insufficient information on how very small-scale extreme weather phenomena (e.g., thunderstorms, tornadoes, hail, hailstorms, and lightning) may change.
AR4 (2007)	Increases in drought, heat waves and floods are projected in many regions and would have mostly adverse impacts, including increased water stress and wild fire frequency, adverse effects on food production, adverse health effects, increased flood risk and extreme high sea level, and damage to infrastructure.
Rationale for Revisions	Responses to some recent extreme climate events reveal higher levels of vulnerability in both developing and developed countries than was assessed in earlier assessments. There is now higher confidence in the projected increases in droughts, heat waves and floods, as well as their adverse impacts.

IPCC Assessment Reports

SEA LEVEL RISE PROJECTIONS

FAR (1990)	0.2 m by 2030 and 0.65 m by 2100.
SAR (1995)	0.15 to 0.95 m from the present to 2100.
TAR (2001)	0.09 to 0.88 m between 1990 and 2100.
AR4 (2007)	0.18 to 0.59 m for 2090-2099 relative to 1980-1999.
Rationale for Revisions	Sea level rise projections have fluctuated over the course of the IPCC Assessments, largely due to different views on sea ice cover, the rate of glacial melt, and the rate of melting in Greenland and Antarctica. Even the most recent (AR4) sea level projections do not include uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993-2003, but these flow rates could increase in the future (and more recent scientific studies — including several in this compendium — suggest they are doing so). In addition, a narrower confidence range is used in the AR4: 90% vs. the Third Assessment Report's 95%. Therefore, the upper values of the ranges given should not be considered upper bounds for sea level rise.

TEMPERATURE CHANGE PROJECTIONS FOR THE NEXT TWO DECADES

FAR (1990)	Under the IPCC BaU scenario, increase of global temperature of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C). This will result in a warming of about 1°C by 2025.
SAR (1995)	Projected rate of mean warming over the next decade is 0.3°C/decade, reduced to 0.2°C/decade in assimilations allowing for the effects of sulfate aerosols.
TAR (2001)	Warming is likely to lie in the range of 0.1 to 0.2°C per decade over the next few decades under the IS92a scenario.
AR4 (2007)	For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios.
Rationale for Revisions	Since the IPCC's first report in 1990, assessed projections have suggested global averaged temperature increases between 0.15 and 0.3°C per decade from 1990 to 2005. This can now be compared with observed values of 0.2°C per decade, strengthening confidence in near-term projections.

RANGE OF FUTURE WARMING

FAR (1990)	Likely increase in global mean temperature of about 3°C above 1990 levels before the end of the 21st century (4°C above pre-industrial levels).
SAR (1995)	1-3.5 °C over the period 1990 to 2100.
TAR (2001)	1.4 to 5.8°C over the period 1990 to 2100.
AR4 (2007)	1.1-6.4°C over the period 1990 to 2100.
Rationale for Revisions	The newer assessments of the likely ranges rely on a larger number of climate models of increasing complexity and realism, as well as new information regarding the nature of feedbacks from the carbon cycle and constraints on climate response from observations. Assessed upper ranges for temperature projections are larger than in previous reports mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks.

IPCC Assessment Reports

IMPACTS TO THE CRYOSPHERE

FAR (1990)	Glacier shrinkage will continue and accelerate in a warming climate. The role of polar ice sheets is expected to be minor; Antarctica is expected to contribute negatively to sea level (due to increasing snow accumulation); a rapid disintegration of the West Antarctic Ice Sheet is unlikely within the next century. There is considerable uncertainty as to how precipitation patterns in Greenland will change in a warmer climate.
SAR (1995)	Models project that between one third and one half of existing mountain glacier mass could disappear over the next 100 years. Little change in the extent of the Greenland and Antarctic ice sheets is expected over the next 50-100 years.
TAR (2001)	Northern Hemisphere snow cover and sea-ice extent are projected to decrease further. Glaciers and ice caps are projected to continue their widespread retreat during the 21st century. The Antarctic ice sheet is likely to gain mass because of greater precipitation, while the Greenland ice sheet is likely to lose mass because the increase in runoff will exceed the precipitation increase. Concerns have been expressed about the stability of the West Antarctic ice sheet because it is grounded below sea level. However, loss of grounded ice leading to substantial sea level rise from this source is now widely agreed to be very unlikely during the 21st century, although its dynamics are still inadequately understood, especially for projections on longer time-scales. The Antarctic ice sheet is likely to increase in mass during the 21st century, but after sustained warming the ice sheet could lose significant mass and contribute several meters to the projected sea-level rise over the next 1,000 years. In contrast to the Antarctic ice sheet, the Greenland ice sheet is likely to lose mass during the 21st century and contribute a few cm to sea-level rise.
AR4 (2007)	There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales.
Rationale for Revisions	There is better understanding than in previous reports that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales. Dynamical processes seen in recent observations but not fully included in ice sheet models assessed in the AR4 could increase the rate of ice loss. Thus, AR4 projections may understate both ice cover and consequent sea level rise during the next century.

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