WRI ISSUE BRIEF

WORLD RESOURCES INSTITUTE

Climate Science 2008 Major New Discoveries

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INTRODUCTION

This annual WRI review highlights the latest major research and innovations in climate change science and technology. It presents a timely synthesis of current understanding of global warming at a critically important time for the United States and the world. The international community is negotiating a new global agreement to reduce emissions of greenhouse gases for the period post-2012, while the U.S. Congress is drafting landmark climate and energy legislation to reduce domestic emissions. Our review of select peer reviewed 2008 science and technology publications, including those from key general scientific journals and technical journals, aims to inform policymakers and legislators, the NGO community, and the media, by:

- describing the wide-ranging potential ramifications of human-induced climate change;
- documenting the impacts that are already occurring as a result of increased global temperatures, altered precipitation patterns, sea level rise, and other changes in physical and hydrological systems; and
- identifying important advances relating to technologies that could help to reduce greenhouse gas emissions in the future.

The latest science summarized below supplies further evidence confirming that anthropogenic activities are the primary cause of rising temperatures over the last century, and supports the need for rapid and substantial greenhouse gas mitigation efforts worldwide. It also confirms that adaptation measures are increasingly required today – and will be ever more important in the future – to enhance the resilience of both human and non-human populations in a changing climate.

Similar to previous WRI Climate Science reports, this review is divided into four topic sections:

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

In preparing this review, WRI drew from a wide array of influential journals as well as information from organizations and climate/energy websites (listed on page 27). Articles were drawn only from 2008 publications. Each section contains short summaries of key scientific findings and their policy and research implications. This Issue Brief, in addition to WRI's Climate Science 2007 Review, serves to outline new developments since the release of the Intergovernmental Panel on Climate Change's Fourth Assessment Report in 2007.

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SAMPLE FINDINGS

Physical Climate:

- Sea ice loss in the Arctic could have the potential to warm ground up to 1500 km inland, threatening to trigger "rapid degradation" of permafrost (Lawrence et al., p 3).
- The rate of growth of global carbon dioxide emissions between 2000 and 2007 was four times that of the previous decade (Global Carbon Project, p. 4).
- A large majority of warming over the last century can be attributed to human activities rather than natural factors, such as solar variability (Lean and Rind, p. 7).
- If atmospheric carbon dioxide concentrations reach 700 ppm by 2100 (concentrations in 2008 were 385.57 ppm), daily maximum temperatures are projected to rise to 40°C in the U.S. Midwest and Southern Europe and exceed 50°C in Australia, India, the Middle East, and parts of Africa (Sterl et al., p. 6).

Hydrological Cycle:

- From 1996 to 2006, the rate of ice mass loss on the Antarctic continent increased by 75% (Rignot et al., p. 10).
- The rate of melting and thinning of thirty glaciers across nine mountain ranges around the world doubled between 2004–2005 and 2005–2006 (World Glacier Monitoring Service, p. 13).
- Up to 60% of the hydrological changes in the Western United States are due to human activities, a trend which, if sustained, "portends…a coming crisis in water supply" (Barnett et al., p. 14).

Ecosystems and Ecosystem Services:

- Changes in 28,800 plant and animal systems and 829 physical climate systems have led scientists to conclude that human-induced warming is already "having a significant impact" on natural and physical systems (Rosenzweig et al., p. 16).
- Due to climate change-induced beetle infestations, the forests of British Columbia will turn from a small net sink of carbon dioxide to a large net source by 2020, with emissions trumping those related to forest fires (Kurz et al., p. 19).
- If carbon dioxide emissions continue unabated, tropical ocean "dead zones" are likely to increase by 50% by 2100 (Oschlies et al., p. 20).

Climate Change Mitigation Technologies:

- A promising method of capturing carbon dioxide directly from the air is under research and development (Keith et al., p. 26).
- A new non-toxic, inexpensive technology for storing solar energy, with potential applications for generating hydrogen power, has been discovered (Kanan and Nocera, p. 23).

PHYSICAL CLIMATE

Overview

The studies in this section describe some of the 2008 findings on abrupt change, temperature change, greenhouse gas and aerosol concentrations, and ocean behavior. Taken together, these articles provide additional data confirming the trends that have been emerging in WRI's 2005 – 2007 Climate Science Reviews. More light is shed on topics such as: the possible impacts of abrupt change associated with human-induced climate change; the effects of greenhouse gas and aerosol emissions on local and global temperatures; humanity's footprint on warming in Antarctica; rising daily minimum and maximum temperatures around the world; and climate-driven trends in ocean behavior.

Abrupt Change

Abrupt, non-linear change is perhaps the most challenging problem associated with human-induced climate change. There is no common definition of abrupt change. From a geological perspective, any change occurring from a few decades to a few centuries may be viewed as abrupt; from an ecological perspective, changes in climate that result in the widespread displacement or loss of a significant number of species may be considered abrupt; and from a societal perspective, changes in climate occurring within one to two human generations which result in drastic disruption to the way current civilization is organized and functions might be considered abrupt. Should abrupt climate change occur, human and ecological systems might not be able to adapt. Some possible abrupt physical and ecological events that have been proposed include: a dramatic reorganization of the thermohaline circulation (the ocean's conveyer belt effect that moves equatorial heat to the north, warming Europe), rapid deglaciation, and melting of permafrost or increases in soil respiration leading to fast changes in the carbon cycle.

- **D. Lawrence, A. Slater, R. Tomas, M. Holland, et al.**
  "Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss"
  Geophysical Research Letters
  13 June 2008, vol. 35

  In this study, Lawrence et al. suggest that rapid sea ice loss events could lead to warming inland – up to 1500 km inshore – which in turn can trigger or further permafrost thawing. During such events, warming is accelerated due to rapid ice loss events, which reveal a darker water surface, absorbing more incoming solar radiation. During early autumn, the thinner ice pack is also less efficient in insulating the atmosphere from the warmer ocean waters below, leading to the transport of heat to the terrestrial Arctic. The scientists used a Community Land Model as a predictive tool and found that ground heat accumulation in permafrost is 3.5 times greater when sea ice is lost than when sea ice is present.

  Implications: The authors discovered a new feedback loop between sea ice loss, land warming, and permafrost degradation. They found that sea ice loss can "trigger rapid degradation" of those areas of permafrost that are already warming. Given that Arctic sea ice retreat has accelerated, their study could have significant implications for the future stability of permafrost. A new inventory of high-latitude permafrost carbon storage (E. Schuur, J. Bockheim, J. Canadell, E. Euskirchen, et al., "Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle." *BioScience*, September 2008, vol. 58) provides new insights about the potential release of permafrost carbon to the atmosphere. The inventory doubles previous estimates and suggests that permafrost carbon storage is, therefore, comparable to double the amount of carbon stored in the atmosphere.

- **Martin Kennedy, David Mrofka, and Chris von der Borch**
  "Snowball Earth termination by destabilization of equatorial permafrost methane clathrate"
  Nature
  29 May 2008, vol. 453

  Roughly 635 million years ago, the Earth – which previously had been encased in ice, according to the "snowball Earth" hypothesis – deglaciated and witnessed one of the most significant climatic shifts in its history. Relying on measurements from marine sediments in methane seeps, Kennedy et al.'s study attributes the dramatic shift in climate to the methane release from low-latitude permafrost methane clathrates, or crystal-like formations that trap methane gas. The destabilization of clathrates acted "as a trigger to catastrophic climate and biogeochemical reorganization of the Earth system."

  Implications: Kennedy et al. conclude by stating that the process of methane release that they identified depicts the consequences of a strong climate forcing "not unlike projected future effects of atmospheric CO_2." The scientists

note that permafrost clathrates (bonded molecules in a cage-like formation that trap gases within) are now becoming less stable in part due to human-induced warming. Furthermore, they suggest that this destabilization could generate a positive feedback that could lead to destabilization of marine clathrates, i.e. methane clathrates beneath the ocean floor. Methane gas is already leaking from the bottom of the ocean: scientists have recently found 250 plumes of methane gas being released from the ocean floor northwest of Svalbard in the Arctic (Quirin Schiermeier, "Fears surface over methane leaks." Nature News, *Nature,* published online 26 September 2008. vol. 455). Although current concentrations of dissolved methane in the area are higher than those found even a few years ago, the authors indicate that these methane plumes may have existed for thousands of years and caution against attributing their activity to human-induced warming.

Greenhouse Gas and Aerosol Concentrations

Research in 2008 on greenhouse gases and aerosols enhances understanding of how these substances affect global and local temperatures. The atmospheric concentration of carbon dioxide is at a record high of 385.57 ppm (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt). According to the Global Carbon Project, the rate of emissions growth of carbon dioxide between 2000 and 2007 was four times that of the previous decade ("Growth in the global carbon budget: Updated global carbon budget released," *EurekAlert!*, 25 September 2008). China is now the biggest contributor of carbon dioxide emissions – 21% of global carbon dioxide emissions, up from 14% in 2002 – with the United States following closely behind, contributing 19% of global carbon dioxide emissions ("Carbon dioxide emissions rise to record levels." Nature News in Brief, *Nature*, 1 October 2008, vol. 455). Also, after a decade of almost no growth, global concentration of atmospheric methane is now on the rise (M. Rigby, R. Prinn, P. Fraser, P. Simmonds, et al., "Renewed growth of atmospheric methane." *Geophysical Research Letters*, 20 November 2008, vol. 35). The research below highlights recent findings related to greenhouse gas and aerosol concentrations.

- **D. Lüthi, M. Le Floch, B. Bereiter, T. Blunier, et al.**
  "High-resolution carbon dioxide concentration record 650,000–800,000 years before present"
  Nature
  15 May 2008, vol. 453

- **L. Loulergue, A. Schilt, R. Spahni, V. Masson-Delmotte, et al.**
  "Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years"
  Nature
  15 May 2008, vol. 453

  Air bubbles trapped in Antarctic ice cores, which provide a record of the atmospheric concentrations of the past, have recently been used to extend the record of atmospheric concentrations of carbon dioxide (Lüthi et al.) and methane (Loulergue et al.) to 800,000 years before the present. This is the most comprehensive record available to date, and reconfirms the relationship between the gases and Antarctic temperature (Ed Brook, "Palaeoclimate: Windows on the greenhouse." Nature News and Views, *Nature,* published online 15 May 2008, vol. 453).

  Implications: This record provides evidence that today's levels of carbon dioxide and methane, two key greenhouse gases, are unmatched for at least 800,000 years, extending the previous record of 650,000 years.

- **R. Weiss, J. Mühle, P. Salameh, and C. Harth**
  "Nitrogen trifluoride in the global atmosphere"
  Geophysical Research Letters
  31 October 2008, vol. 35

  In this study, Weiss et al. measured nitrogen trifluoride (NF_3) in air collected from several stations in the Northern Hemisphere over the past few decades. They found that from 1978 to 2008 the concentration of NF_3 had increased roughly 11% per year. NF_3 has a global warming potential of 17,000 times that of carbon dioxide (that is, a unit of NF_3 emitted has 17,000 times the warming impact of carbon dioxide on the Earth's climate).

  Implications: NF_3 is not included in the greenhouse gases covered by the first phase of the Kyoto Protocol or in national reporting requirements. Production of consumer products that result in NF_3 – e.g. manufacturing of liquid crystal flat panel displays, thin-film photovoltaic cells, and the cleaning of electronic equipment and microcircuit

etching – are on the rise, in part because the U.S. Environmental Protection Agency has encouraged the use of NF_3 to substitute for another greenhouse gas which cannot break down as easily (Richard Conniff, "The greenhouse gas that nobody knew," *Environment360*, 12 November 2008). However, Weiss et al. found that 16% of the gas is released into the atmosphere, in contrast with industry estimates that suggest a significantly lower percentage of 2% or 3%. Given the rate of growth of this potent greenhouse gas, Prather and Hsu (Michael J. Prather and Juno Hsu, "NF_3, the greenhouse gas missing from Kyoto." *Geophysical Research Letters*, 26 June 2008, vol. 35) have called for its inclusion in the second commitment period of the Kyoto Protocol (or a successor to the Protocol).

- **V. Ramanathan and Y. Feng**
  "On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead"
  Proceedings of the National Academy of Sciences
  23 September 2008, vol. 105

  Ramanathan and Feng suggest that even if atmospheric concentrations of greenhouse gases were frozen at 2005 levels, we may have already committed to 2.4°C (with a 1.3°C to 4.3°C range) of warming above preindustrial levels. To obtain this figure, the scientists considered the effect of the abatement of aerosols, which, as a result of their reflectivity of solar radiation, have a cooling effect on the climate collectively. As air pollution policies become more stringent and more common, reflective aerosol levels will decrease, allowing for more solar radiation to be absorbed by the Earth's surface.

  Two recent studies indicate that aerosol reduction efforts have contributed to local warming. Ruckstuhl et al. (C. Ruckstuhl, R. Philipona, K. Behrens, M. Coen, et al., "Aerosol and cloud effects on solar brightening and the recent rapid warming," *Geophysical Research Letters*, 24 June 2008, vol. 35) show that a decline in aerosol concentration over mainland Europe since 1980 has led to solar brightening and likely contributed to the rapid warming experienced on the continent. Another study describes the same phenomenon, this time in California. Novakov et al. (T. Novakov, T. Kirchstetter, S. Menon, and J. Aguiar, "Response of California temperature to regional anthropogenic aerosol changes," *Geophysical Research Letters*, 4 October 2008, vol. 35) suggest that the state's reduction of anthropogenic aerosol concentrations after 1990 contributed to surface temperature increases.

  Implications: Ramanathan and Feng point out that the Intergovernmental Panel on Climate Change's forecasts assume that aerosol levels will stay at their current levels, failing to anticipate the clean-up of aerosol pollution in urban centers. When the abatement of such aerosols is included in models, attainment of climate targets might be even more difficult than previously anticipated, as this study demonstrates. It should be noted that some challenges to Ramanathan and Feng's work have surfaced (Hans Joachim Schellnhuber, "Global warming: Stop worrying, start panicking?" *Proceedings of the National Academy of Sciences*, 23 September 2008, vol. 105) calling into question the authors' model assumptions – most importantly, the assumption that atmospheric concentrations of greenhouse gases will remain at least at 2005 levels (i.e. not be reduced), but also the lack of consideration of changes in land cover or volcanic emissions and assumed rate of aerosol reduction that may be overly optimistic. Despite such criticisms, Ramanathan and Feng's study demonstrates that if urban centers continue to reduce aerosol levels – critical for attaining clean air goals – these activities will increase the climate mitigation burden. Ramanathan and Feng conclude by urging decision makers to consider the tradeoffs between climate mitigation and air pollution abatement, and recommend that special emphasis be placed on reducing absorbing aerosols (such as soot) in addition to reflective aerosols (such as sulphate aerosols).

Temperature

According to NASA's Goddard Institute for Space Studies (GISS) (http://data.giss.nasa.gov/gistemp/2008/), the year 2008 was the ninth warmest in the instrumental record but the coolest since 2000. The GISS researchers attribute the relatively cool temperature to a strong La Niña in the tropical Pacific which occurred during the first half of 2008. They note that while the Pacific Ocean was marked by lower temperatures – which reduced the average global temperature – the Arctic, Antarctic Peninsula, and Eurasia were "exceptionally warm." Also, they note that solar output was at the lowest level since satellite measurements began, a factor which also contributed to this year's global temperature.

- **N. Gillett, D. Stone, P. Stott, T. Nozawa, et al.**
  "Attribution of polar warming to human influence"
  Nature Geoscience
  November 2008, vol. 1

  The Intergovernmental Panel on Climate Change's recent Fourth Assessment Report states that Antarctica is the only continent in which warming had yet to be attributed to human activities. In this study, Gillett et al. relied on the CRUTEM3 land surface temperature data set from 1900-2008, as well as coupled model simulations, and found that natural factors cannot explain the temperature patterns in the Arctic and Antarctic regions. Thus, they conclude that a human footprint on Antarctica's warming can be detected.

  Implications: Their findings are the first to document the human influence on warming in both Arctic and Antarctic land surface temperatures, demonstrating the signature of anthropogenic activities on all continents. Warming at high latitudes has severe implications for increasing glacial and snow melting and attendant risks for sea level rise.

- **D. Van Vuuren, M. Meinshausen, G. Plattner, F. Joos, et al.**
  "Temperature increase of 21st Century mitigation scenarios"
  Proceedings of the National Academy of Sciences
  7 October 2008, vol. 105

  In this study, Van Vuuren et al. modeled the radiative forcing and climate implications of various greenhouse gas emissions scenarios. They modeled baseline scenarios in which no climate change mitigation policy was adopted, and found that by 2100 greenhouse gas emissions were 250% larger than 2000 levels, and projected temperature increases were 2.6°C to 4.6°C relative to 1990 temperature levels. A group of 15 policy scenarios (including baseline scenarios with emissions rising 70% to 250% above 2000 levels by 2100, and mitigation scenarios with emissions peaking between 2020 and 2040, with the most stringent mitigation scenario reducing emissions 20% to 60% below 2000 levels by mid-century) input into two simple climate change models resulted in a range of carbon dioxide concentrations from 380 to 620 ppm by 2100, and temperature increases of 1.1°C to 2.4°C by 2100 relative to 1990 levels. The authors find that the average minimum warming for the most stringent mitigation scenario is 1.4°C over 1990 levels by 2100, of which 0.6°C is due to the climate system inertia alone.

  Implications: Van Vuuren et al. conclude that even under the most stringent greenhouse gas mitigation scenario, which has a full range of temperature increases of 0.5°C to 2.8°C by 2100, meeting a 2°C temperature target over preindustrial levels "is possible, but is not at all guaranteed." The authors conclude that adaptation efforts will be essential for contending with the impacts of climate change.

- **S. Brown, J. Caesar, and C. Ferro**
  "Global changes in extreme daily temperature since 1950"
  Journal of Geophysical Research
  13 March 2008, vol. 113

- **A. Sterl, C. Severijns, H. Dijkstra, W. Hazeleger, et al.**
  "When can we expect extremely high surface temperatures?"
  Geophysical Research Letters
  19 July 2008, vol. 35

  Analyzing a daily gridded temperature data set covering the period from 1950 to 2004, Brown et al. detected a significant positive trend in extreme daily temperature (those temperatures that lie in the greater than 98.5 or less than 1.5 percentiles) for both the daily maximum and minimum distributions since the mid-20th Century. They found warming to be greatest in regions within Russia and Canada where the daily minimum temperatures have warmed by over 4°C since 1950. Maximum temperature extremes were found to be highest in Canada and Eurasia, where peak temperatures were 1°C to 3°C higher than 1950 levels. Brown et al. also found that the daily minimum temperatures have increased at a faster rate than maximum temperatures, with implications for freezing points and growing seasons.

  In another study, motivated by the European heat waves in 2003 and 2006, Sterl et al. performed 17 runs with a coupled climate model and found that temperature extremes in Australia, India, the Middle East, North Africa, the Sahel, and equatorial and subtropical South Africa are projected to exceed 50°C by the end of the century if carbon dioxide concentrations reach 700 ppm. Their simulations also forecast temperatures rising to 40°C in Southern Europe and the U.S. Midwest by 2100.

Implications: Temperature extremes can lead to extreme events such as heat waves, with adverse effects on human health and ecosystems. The regions that are projected to experience temperature extremes in the Sterl et al. study are heavily populated and the authors state that if such extreme temperatures persist for just several days they could threaten human lives.

- **M. Mann, Z. Zhang, M. Hughes, R. Bradley, et al.**

  "Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia"

  Proceedings of the National Academy of Sciences

  9 September 2008, vol. 105

  Scientists use proxies, such as pollen, ice cores, tree rings, among others, to reconstruct past temperatures before the instrumental record began. In this study, Mann et al. used an expanded database composed of 1,209 proxy series to determine hemispheric and global surface temperature variations over the last two thousand years. When not including tree-ring proxies – which are subject to caveats – they found that recent Northern Hemisphere warmth likely exceeds any warmth realized in at least the last 1300 years, even when taking into account uncertainty ranges. If tree-ring data are included, the warming over the past decade is anomalous for at least the last 1700 years.

  Implications: This study provides yet another confirmation of the validity of Mann et al.'s famous 1998 'hockey stick' results (proxy-based data on Northern Hemisphere mean temperature that resembles a hockey stick pattern, due to a swift climb in temperature after centuries of slow change). Reliance on tree-ring proxies has been somewhat controversial. If short-term records from multiple trees are pieced together, scientists need to account for the differences between older and newer trees, as tree rings narrow as they grow older. However, when the decline of ring width due to aging is removed statistically, the climate signal can also be partially removed ("Global warming greatest in past decade," *ScienceDaily,* 2 September 2008). Thus, Mann et al.'s study is significant because it is the first to combine multiple proxies to develop such a long temperature record and demonstrate that – even in the absence of tree-ring proxy data – this past decade's warmth is unmatched during the past 1300 years.

- **Judith Lean and David Rind**

  "How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006"

  Geophysical Research Letters

  16 September 2008, vol. 35

  Global and regional surface temperatures rise as a result of both natural factors and human activities. Until this study, some analyses had suggested that up to 69% of the warming in the past century globally was driven by natural factors, namely solar variability. In this study, Lean and Rind performed linear regression analyses on observational data to evaluate the relative contribution of natural versus human influences on global and regional surface temperatures from 1889 to 2006. They accounted for solar radiation, volcanic activity, human activities, and other determinants of temperature. They found that solar-induced warming contributed 10% of surface warming in the last century – and an even smaller percentage in the last quarter century – rather than the 20% to 30% figure that had been estimated in earlier assessments.

  Implications: Lean and Rind's study shows that the bulk of warming over the last century can be attributed to human activities rather than to natural factors, such as solar variability, further confirming the anthropogenic, or human-induced, role in recent climate change.

Ocean Behavior

The research below describes climate-driven trends in ocean behavior, including those related to ocean circulation, ocean acidification, sea level rise, ocean warming, and ocean's effects on the carbon cycle.

- **Geun-Ha Park, Kitack Lee, and Pavel Tishchenko**

  "Sudden, considerable reduction in recent uptake of anthropogenic CO_2 by the East/Japan Sea"

  Geophysical Research Letters

  12 December 2008, vol. 35

  Park et al. report that the East/Japan Sea, located in the North Pacific, is not sequestering the same amount of anthropogenic carbon dioxide as it used to. Analyzing data from three surveys conducted in 1992, 1999, and 2007, and performing linear regression, the scientists found that the average uptake was 0.3 ± 0.2 mol C/m^2 per year during the period from 1999 to 2007 versus 0.6 ± 0.4 mol C/m^2 per year for the 1992 to 1999 period. They

attribute the decline to a weakening of the overturning circulation of this sea; accordingly, the carbon dioxide is not transported from the surface waters to greater depths as efficiently as in the past. Interestingly, they also found that the majority of recent anthropogenic carbon sequestration activities transpired in shallow waters less than 300 meters in depth.

Implications: While the authors caution against extrapolating the findings globally, they conclude by stating that their findings might be a harbinger of future changes in the vital carbon sequestration capabilities of the global ocean.

- **C. Böning, A. Dispert, M. Visbeck, S. Rintoul, et al.**
  "The response of the Antarctic Circumpolar Current to recent climate change"
  Nature Geoscience
  23 November 2008, vol. 1

- **Anne Barnett**
  "Ozone hole weakens oceanic carbon sink"
  Nature News
  9 December 2008 (published online)

- **S. Son, L. Polvani, D. Waugh, H. Akiyoshi, et al.**
  "The impact of stratospheric ozone recovery on the Southern Hemisphere westerly jet"
  Science
  13 June 2008, vol. 320

  At least three studies performed this year explore the future of the Southern Ocean's ability to sequester carbon. In one study, Böning et al. show that despite the intensification of Southern Hemisphere westerly winds, the dominant wind pattern between 30°S and 60°S which is projected to grow stronger with human-induced warming, the Antarctic Circumpolar Current (ACC) has been left unaffected by the increased wind stress. It had been thought that the future of the Southern Ocean sink would depend on the intensified westerly winds' effects on the ACC. However, this study, performed with floats collecting temperature and salinity data in the Southern Ocean, suggests that coarse-resolution models may have led to erroneous conclusions about the Southern Ocean carbon sink. The Southern Ocean accounts for roughly 40% of the global ocean uptake of anthropogenic carbon dioxide emissions over the past two centuries.

  Another study, performed by Lenton and colleagues (in press), as summarized by Barnett, does not provide such a promising conclusion, however. The scientists found that as a result of the ozone hole presence, the Southern Ocean's ability to sequester carbon dioxide has been compromised. Lenton et al. presented their findings at a 2008 meeting of the CARBOOCEAN project in France. They suggested that stratospheric ozone damage strengthens southern winds that can in turn alter ocean currents, leading to the migration of sequestered carbon to the ocean's surface. When ozone depletion was incorporated into the models, the scientists found a strong effect on the strength of the carbon sink. And what if the ozone hole were successfully healed? A study by Son et al. showed that the recovery of the ozone hole, predicted to occur before mid-century as a result of the Montreal Protocol implementation, accordingly weakens westerly winds. They used the Chemistry-Climate Model Validation models, which incorporate an interactive stratospheric chemistry.

  Implications: The results of Lenton et al.'s and Böning et al.'s studies are somewhat contradictory. However, Lenton states that Böning and his colleagues did not include the exchange of carbon dioxide; rather they just examined ocean currents. It is also important to take note of Son et al.'s results which suggest that Lenton et al.'s conclusions may not hold the same significance if the ozone hole were to fully recover, as it probably will by mid-century, assuming the global ban on ozone-destroying chemicals remains in effect. In fact, if the ozone hole closes, it could assist in counteracting the intensification of westerlies (mid-latitude winds that blow in a westward direction) due to the build up of greenhouse gases. However, the weakening of the westerly jet could have implications for surface temperatures, sea ice, and storm tracks. Thus, the future of the crucial Southern Ocean carbon sink remains highly uncertain.

- **K. Hester, E. Peltzer, W. Kirkwood, and P. Brewer**
  "Unanticipated consequences of ocean acidification: A noisier ocean at lower pH"
  Geophysical Research Letters
  1 October 2008, vol. 35

  Hester et al.'s study highlights an unforeseen consequence of the acidification of the world's oceans: noise. Their data indicate that sound absorption in the range between 0.01 – 10 kHz has decreased more than 12%, and the authors

attribute the amplification of the noise to acidified waters. Sound absorption is in part determined by ocean pH, and while scientists have studied the relationship in the past, the authors state that previous efforts had not explored the implications of human-induced acidification on the noise levels of the ocean. Hester and colleagues collected data on pH from the GLODAP Atlas and calculated the sound absorption from a well-established equation, as well as the percentage of pH change that could be attributed to fossil fuel combustion. The authors suggest that future carbon dioxide emissions from fossil fuel combustion, and resultant acidification, will lead to further lowering of sound absorption – and, in turn, sound traveling farther – by almost 40% by 2050.

Implications: Hester et al. note that, in conjunction with increased noisiness due to other human activities such as shipping, these amplified noise levels will be within the range that has been deemed critical for military activities. They also highlight environmental consequences, such as those related to compromised marine mammal communication.

- **S. Minobe, A. Kuwano-Yoshida, N. Komori, S. Xie, et al. "Influence of the Gulf Stream on the troposphere"**

  Nature

  13 March 2008, vol. 452

  The Gulf Stream is an ocean current that originates in the Gulf of Mexico and extends at its northern edge toward Europe. The Gulf Stream influences the climate of the east coast of North America and the west coast of Europe. In this study, Minobe et al. demonstrate how the Gulf Stream affects the troposphere, the lowest layer of the atmosphere which extends on average 11 km above the Earth's surface. With the use of weather analyses, satellite observations, and an atmospheric general circulation model, they discovered that the Gulf Stream influences the entire troposphere. The Gulf Stream releases heat due to evaporation, leading to the development of a band of rain alongside the ocean current. Their data suggest that the Gulf Stream controls much more of the global climate than previously thought, and has the ability to influence weather and climate patterns over the Northern Hemisphere, if not globally ("Gulf stream leaves its signature seven miles high," *ScienceDaily,* 24 March 2008*).*

  Implications: The authors note that the Gulf Stream is projected to slow with higher levels of greenhouse gas concentrations, and suggest that such changes could result in precipitation anomalies and wider atmospheric circulation ramifications, influencing the climates of remote locations.

HYDROLOGICAL CYCLE

Overview

The studies in this section describe some of the findings published in 2008 from around the world on glacial and snow melt, water supply, and storms. Warming, which is exacerbated at the poles, has significant implications for glacial and snow melt. 2008 research confirms the trends established in previous years, that melting is accelerating in most regions. This year's research on water supply provides new evidence of the local manifestations of climate change impacts, with some areas becoming much wetter, others much drier. It highlights the risks inherent in extreme rainfall, early snowmelt, and periods of drought, among other phenomena, and describes trends already underway in many parts of the world. Uncertainty remains over the role of human-induced climate change in hurricane activity.

Glacial/Snow Melt

A few startling news stories highlight the effects already being borne on snow and ice: the Wilkins Ice Shelf in Antarctica has been collapsing (Michon Scott, "Disintegration: Antarctic warming claims another ice shelf," NASA Earth Observatory, 26 March 2008); the Markham Ice Shelf (50 km^2) and portions of the nearby Serson Ice Shelf (122 km^2) have broken away in the Canadian Arctic ("Major ice-shelf loss for Canada," *BBC News*, 3 September 2008); the Ward Hunt Ice Shelf, the largest in the Arctic, has cracked into three pieces ("Ward Hunt Ice Shelf, largest in Northern Hemisphere, has fractured into three main pieces," *ScienceDaily,* 16 April 2008); the Northeast passage, along the Russian Arctic coast, was free of ice in September of 2008 – the first time both it and the Northwest Passage have been recorded as open at the same time ("The Northern Sea Route (Northeast Passage) appears 'open,'" *National Ice Center,* 11 September 2008); during the melt season of 2008, the Arctic sea ice was at its second lowest level, after 2007's record low, since satellite measurements began in 1979 ("2008 among the ten warmest years; marked by weather extremes and second-lowest level of Arctic ice cover" Press Release No. 835, *World Meteorological Organization*); and a 29 km^2 portion of the Petermann glacier in Greenland broke off (Rich Monastersky, "Arctic warming spurs record warming." *Nature*, published online 17 December 2008). The research presented below describes some of the advances in climate science published in 2008 regarding glacial melt and snow melt, organized by region.

Antarctica

- **E. Rignot, J. Bamber, M. Van Den Broeke, C. Davis, et al.**

  "Recent Antarctic ice mass loss from radar interferometry and regional climate modeling"

  Nature Geoscience

  February 2008, vol. 1

  Rignot et al. focus on measuring recent Antarctic ice loss. They rely on surface velocity data, collected with the use of interferometric synthetic-aperture radar (InSAR), to detect the movement of glaciers and ice streams covering 85% of the continent's coastline. They also use data on glacier baselines and surface elevation, as well as snow accumulation data. Their data indicate that the continent experienced a net loss of mass from 1996 to 2006, during which the mass loss had increased by 75%. They find that ice loss in East Antarctica is probably not contributing to the overall loss of ice on the continent, as some areas are thinning while others are gaining volume. Instead, ice loss is concentrated in the Pine Island Bay area of West Antarctica and the northern edge of the peninsula.

  Implications: The authors suggest that changes in glacial flow – rather than in snow accumulation – may be the dominant factor in the ice mass balance changes on the continent. A 75% increase in total ice mass loss in one decade is significant, and greater than forecasts predicted. Rignot et al.'s results warrant serious attention, particularly given the implications for sea level rise.

Arctic

- **J. Comiso, C. Parkinson, R. Gersten, and L. Stock**

  "Accelerated decline in the Arctic sea ice cover"

  Geophysical Research Letters

  3 January 2008, vol. 35

  A number of 2008 studies are dedicated to the unusually low levels of Arctic sea ice cover during the previous summer. While most focus their attention on attributing the causes of the decline, Comiso et al. studied the event as part of a larger trend in the region's sea ice cover. They performed time series analyses using data from satellite passive-microwave imagery data and find that ice cover reached a new low, with the extent of the summer 2007 ice being 24% lower, and area being 27% below the previous record set in 2005. Their data indicate that the loss of sea ice cover is accelerating: while the rate of loss of total

sea ice extent and area was 2.2% and 3.0% per decade respectively from 1979 to 1996, it was 10.1% and 10.7% per decade respectively for the past decade.

Implications: Comiso et al. state that "the situation may be changing" given the low levels of sea ice cover in 2005, 2006, and 2007. Indeed, the National Snow and Ice Data Center (NSIDC) found that summer Arctic ice cover in 2008 was at its second lowest minimum since records began in 1979 – only 9% over the 2007 record and 34% below average levels (NSIDC 2008 Year-in-Review, 7 January 2009, http://nsidc.org/arcticseaicenews/2009/010709.html). Also, sea ice cover in 2008 was below average throughout the year, having been influenced by the 2007 melting. The authors state that a sea ice-free Arctic summer could become a reality within the coming decades, and they conclude that loss of ice in the peripheral seas could have "major consequences" on Arctic and sub-Arctic ecosystems, given these regions' high primary productivity.

Alps

- **M. Huss, A. Bauder, and M. Funk**

  "Mass balance changes of 30 Swiss glaciers during the 20th Century"

  Eos Transaction AGU 89 (53) Fall Meeting Supplement, Abstract C52A-08

  A recent study by Huss et al. presented at the December 2008 American Geophysical Union meeting focused its attention on the loss of glaciers in the Swiss Alps. The scientists calculated surface mass balances of 30 representative glaciers in the Swiss Alps from 1900 to 2007. They employed a mass balance model with air temperature and precipitation inputs and found that over the period from 1907 to 2007, as well as the period of 1957 to 2007, there was a net loss of glacial mass. Perhaps most significantly, they found that the rate of loss was "substantially steeper" in the last half century than the overall century's rate.

  Implications: The authors attribute the changes in glacial mass to the prolongation of the melting season. The non-linear nature of glacial retreat is significant; if the trend continues unabated, it will have significant implications for human-built and natural systems that depend on glacial run-off. According to Huss (Jonathan Amos, "Swiss glaciers 'in full retreat,'" *BBC News,* 19 December 2008), southwestern Switzerland relies on the run-off for hydroelectric power production, and more than half of the consumed electricity in the country is produced from hydroelectric sources.

Himalayas

- **N. M. Kehrwald, L. G. Thompson, Y. Tandong, E. Mosley-Thompson, et al.**

  "Mass loss on Himalayan glacier endangers water resources"

  Geophysical Research Letters

  22 November 2008, vol. 35

  Kehrwald et al. devote this study to assessing glacial loss in the Himalayas by analyzing four ice cores collected in 2006 from the Naimona'nyi Glacier in Tibet. They discovered that there have been no net gains of ice mass since at least 1950, as radioactivity would have been recorded after that year given the thermonuclear bomb testing in the following two decades. The authors state that the loss of ice on the Naimona'nyi Glacier is the highest documented ice field thinning of all glaciers. They argue that factors such as wind did not increase since 1950 and, thus, cannot attribute for the ice loss. They state that their data suggest melting is the primary determinant of ice loss, consistent with the trend of increasing air temperatures in Tibet since 1950.

  Implications: The authors note that more than 80% of glaciers in western China have retreated over the last half century, with retreat accelerating at a rate greater than that of other regions. They describe several negative consequences of glacial mass loss, including seasonal shifts in peak water supply, flood risks, and precipitation variability. Most significantly, the Naimona'nyi Glacier feeds the Indus, Ganges, and Brahmaputra Rivers, and loss of glacial mass – which previously hadn't been accounted for at such high elevations – could be detrimental to those populations that depend on these water sources. Kehrwald et al. conclude by stating that if other glaciers in the area are similarly impacted by warming, there could be "substantial consequences" for half a billion people.

Iceland

- **Carolina Pagli and Freysteinn Sigmundsson**

"Will present day glacier retreat increase volcanic activity? Stress induced by recent glacier retreat and its effect on magmatism at the Vatnajökull ice cap, Iceland"

Geophysical Research Letters

7 May 2008, vol. 35

Pagli and Sigmundsson devote this study to the effects of melting glaciers on volcanic activity. In some locations, such as Vatnajökull, Iceland's largest ice cap, when glaciers retreat, the solid Earth beneath changes its form as a result of fluxes in crustal stress. The scientists calculated the rate of pressure changes in the mantle, and stress changes in the elastic crust, due to ice cap thinning. They found that the present-day rate of ice thinning leads to mantle melting of 1.4 km^3 per century, constituting a roughly 10% increase in magma production – comparable to an eruption every 30 years if melted lava were to break the surface.

Implications: The authors' data provide reason to expect increased seismic activity in the future. The authors state that other areas that might witness similar phenomena include Mount Erebus in Antarctica, the Aleutian Islands volcanoes in Alaska, and the volcanoes of southern Patagonia.

Greenland

- **S. Das, I. Joughin, M. Behn, I. Howat, et al.**

"Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage"

Science

9 May 2008, vol. 320

- **I. Joughin, S. Das, M. King, B. Smith, et al.**

"Seasonal speedup along the western flank of the Greenland Ice Sheet"

Science

9 May 2008, vol. 320

Two recent studies, when taken together, suggest that while surface melting can drain to the base of the Greenland Ice Sheet much more quickly than previously thought, such drainage and resultant lubrication of the bottom of the Ice Sheet has not been found to be the main determinant of the rate of ice discharge from outlet glaciers. However, it can cause large increases in aggregate ice sheet flow. In the first study, Das and colleagues conducted research in July of 2006 on two supraglacial lakes on the Greenland Ice Sheet. Such lakes sit atop glaciers and are formed by surface melting. Global Positioning System (GPS) data captured an event in which one of the lakes, with a surface area of 5.6 km^2, drained completely in 1.4 hours. The meltwater had led to fractures in the ice surface, which in turn caused the formation of moulins, or large cleavages down to the base of the glacier – 1 km in depth – which drained the lake water quickly. In the second study, Joughin et al. compiled data collected from interferometric synthetic aperture radar (InSAR) and GPS observations of two supraglacial lakes. Their data indicate a significant speedup of summer flow from the ice sheet as a whole – of up to 50 to 100%. Yet, they find that less than 15% of outlet glacier flow speedup was melt-induced, suggesting that while the larger ice sheet is affected, some of its outlet glaciers are relatively insensitive to surface meltwater. Joughin et al. state that although lubrication of the glacial base due to surface meltwater might affect large regions of the Greenland Ice Sheet, it is unlikely to have a catastrophic effect.

Implications: Das et al.'s discovery of rapid and direct transport of meltwater to the bed of the ice sheet suggests that the phenomenon can occur much faster than previously thought. However, Joughin et al.'s results indicate that while meltwater-induced basal lubrication can greatly increase whole-ice sheet flow, major speedups in glacier flow were less driven by this mechanism than other factors. Consistent with this latter finding, a study performed by Holland et al. suggests that the rapid acceleration of the Jakobshavn Isbræ in Greenland was catalyzed by the arrival of warm subsurface ocean waters (D. Holland, R. Thomas, B. Young, M. Ribergaard, et al., "Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters," *Nature Geoscience*, October 2008, Vol. 1). These studies demonstrate the need to explore a wide variety of determinants of ice sheet dynamics to gain a better understanding of risks to the Greenland Ice Sheet and future sea level rise. It should be mentioned that the transport of water to the glacier's base also results in a rapid transport of heat to the bottom of the ice sheet. The traditional assumption in models – that the heat would have to be conducted through the ice itself – is thus incorrect, and it may well be that this overall heat transport is what will prove most important.

- **I. Howat, B. Smith, I. Joughin, and T. Scambos**
  "Rates of southeast Greenland ice volume loss from combined ICESat and ASTER observations"
  Geophysical Research Letters
  9 September 2008, vol. 35

  Howat et al. combined two different ice volume observational techniques – the Ice, Cloud and Land Elevation Satellite (ICESat)-derived surface elevation changes and Advanced Spaceborne Thermal Emission and Reflection (ASTER) digital elevation models – to estimate ice volume loss on the Greenland Ice Sheet. They found that between 2002 and 2005, the Ice Sheet had lost 108 km^3 of volume per year. Interestingly, the majority of ice loss could be traced to smaller glaciers, rather than the two largest glaciers, which had contributed less than 30% of the volume loss. They also found more volume loss from dispersed inland thinning than glacial outlet thinning.

  Implications: The combination of observational methodologies allowed for the scientists to gain a more comprehensive picture of ice volume flux. Their findings demonstrate that thinning is not localized but is rather distributed throughout the ice sheet. This study underscores the important role that small glaciers play in ice sheet volume loss, as well as the notion that continuing changes in outlet glacier flow could have a large effect on ice sheet dynamics and mass loss.

Ice Melt and Sea Level Rise

- **"Meltdown in the mountains: Record glacier thinning means no time to waste on agreeing new international climate regime"**
  United Nations Environment Programme (UNEP) Press Release
  16 March 2008

- **http://www.geo.unizh.ch/wgms/mbb/mbb9/sum06.html**
  The World Glacier Monitoring Service (WGMS) has recently found that the rate of melting and thinning of thirty glaciers across nine mountain ranges around the globe doubled between the periods 2004–2005 and 2005–2006. The WGMS calculated mass balance values from 1980 to 2006. Since 1980, ice thickness on these glaciers was reduced 11.5 meters on average.

  Implications: The WGMS data depict the acceleration of mountain glacier melting across most of the world. A substantial portion of the world's population relies upon mountain glaciers for drinking water, power generation, and agriculture.

Water Supply

The research presented below highlights the risks inherent in climate-related phenomena. The authors not only present results from climate modeling forecasts, but also describe actual trends – such as prolonged dry episodes, and changes in river flow and snow pack – that are already underway in many parts of the world.

- **Pavel Groisman and Richard Knight**
  "Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years"
  Journal of Climate
  May 2008, vol. 21

  Groisman and Knight devote this study to assessing whether prolonged dry episodes – which they define as series of days without more than 1 mm of precipitation – have become more frequent in the contiguous United States over the past four decades. They relied on daily precipitation data from weather stations throughout the country and focused their attention on the dry episodes during the warm season. While no changes were evident in the Northwest, they found that the number of dry episodes lasting at least one month in the eastern United States, and at least two months in southwestern United States, have increased substantially. The eastern United States is now experiencing month-long – or longer – dry episodes at a rate of five or six times in the span of four decades instead of two to three times in that same period. Dry episodes of 30 or more days in California now occur every few years.

  Implications: The authors state that prolonged dry episodes during the warm season will be a much more significant hazard than a decrease in the number of rainy days. They highlight consequences for terrestrial ecosystems and agriculture, as water resources could dwindle between rain events.

- **T. Barnett, D. Pierce, H. Hidalgo, C. Bonfils, et al.**
  "Human-induced changes in the hydrology of the western United States"
  Science
  22 February 2008, vol. 319

  Barnett and colleagues devote this study to identifying the causes of changes in the hydrological cycle in the American West from 1950 to 1999. Using a multivariable detection and attribution methodology, and comparing models that are partially driven by human activities contributing to warming, such as fossil fuel burning, vs. those driven by natural variability, they found that up to 60% of the hydrological changes are due to human activities. In other words, human activities have contributed to as much as 60% of the changes in trends in river flow, winter air temperature, and snow pack in the western United States.

  Implications: If climate-intensive activities continue unabated, water resources in the West could be significantly impacted. Accordingly, the authors conclude that their data "portend…a coming crisis in water supply" for the region.

- **Richard Allan and Brian Soden**
  "Atmospheric Warming and the Amplification of Precipitation Extremes"
  Science
  12 September 2008, vol. 321

  Models forecast that a warmer atmosphere will hold more moisture and rainfall events will become more common in the tropics. In this study, Allan and Soden suggest that such precipitation events will be more extreme than previously thought. The researchers compared model predictions (using multiple Coupled Model Intercomparison Project 3 (CMIP3) models) of daily precipitation over tropical oceans with data collected from satellite observations. They found that the observations and model simulations do not match perfectly, with the simulated rate of extreme rainfall events being lower than the observations.

  Implications: The authors conclude that model-simulated projections underestimate the increased rate of heavy rainfall events in the tropics and suggest that they could underestimate future projections. They note that it is crucial to establish whether the discrepancy can be explained by inadequacies in the observing system, by the representation of decadal changes in aerosol-driven radiative forcing and associated surface flux changes, or by deficiencies in model parametrizations and simulation of current rainfall distributions. Their study has implications for flood control, agriculture, and infrastructure.

- **N. Abram, M. Gagan, J. Cole, W. Hantoro, et al.**
  "Recent intensification of tropical climate variability in the Indian Ocean"
  Nature Geoscience
  December 2008, vol. 1

  The Indian Ocean Dipole (IOD) is an important driver of tropical weather patterns in the Indian Ocean. Abram et al. use data from corals in western Indonesia to construct sea surface temperature and rainfall data that were driven by IOD events. By extending the record back to 1846, they were able to detect "an exceptional increase" in the frequency and strength of IOD events over the past century. Also, they found an intensified positive feedback between Asian monsoons and the IOD.

  Implications: The authors suggest that human-induced climate change will lead to a strong interdependency between the IOD and Asian monsoon precipitation variability. IOD events can result in drought in western Indonesia and southern Australia and heavy rainfall events in eastern Africa and India, especially as a result of the strengthened Asian monsoon rainfall, with implications for human-built and natural systems alike.

Storms

Uncertainty regarding the role of human-induced climate change in hurricane activity remains. This year's research continues to present data on the relationship between hurricane activity and climate change. Some research corroborates, while some contests, previous findings on this complex relationship. For example, see:

- **James Esner, James Kossin, and Thomas Jagger**
  "The increasing intensity of the strongest tropical cyclones"
  Nature
  4 September 2008, vol. 455

- **Kerry Emanuel, Ragoth Sundararajan, and John Williams**

  "Hurricanes and global warming: Results from downscaling IPCC AR4 simulations"

  Bulletin of the American Meteorological Society

  March 2008, vol. 89

- **Mark Saunders and Adam Lea**

  "Large contribution of sea surface warming to recent increase in Atlantic hurricane activity"

  Nature

  31 January 2008, vol. 451

This year's research also sheds light on several new aspects of climate impacts on storms; we focus our attention on these findings.

- **Sirpa Hakkinen, Andrey Proshutinsky, and Igor Ashik**

  "Sea ice drift in the Arctic since the 1950s"

  Geophysical Research Letters

  3 October 2008, vol. 35

  Warming temperatures have led to a northward shift of Arctic storm tracks, resulting in heightened storm activity and sea ice drift in the region. In this study, Hakkinen and colleagues used data on ice drift from the National Snow and Ice Data Center (NSIDC), as well as from several ice camps and buoys, to assess sea ice motion. They also studied data on wind stress, an indicator of storm activity. The scientists found that sea ice drift in the Arctic gradually accelerated from 1950 to 2006, a pattern which the authors attribute to increased Arctic storm frequency and/or intensity.

  Implications: Most significantly, Hakkinen et al. suggest that changes in storm activity could lead to changes in vertical ocean stratification. If the Arctic Ocean stratification were to weaken, the authors suggest that such resultant deep convection could create the conditions for a new sink for atmospheric carbon dioxide, which they said would "affect the whole climate system and its evolution."

- **P. Zhang, H. Cheng, R. Edwards, F. Chen, et al.**

  "A test of climate, sun, and culture relationships from an 1810-year Chinese cave record"

  Science

  7 November 2008, vol. 322

  Zhang et al. constructed data on the Asian Monsoon variability with the analysis of a unique 118-mm-long stalagmite from Wanxiang Cave, located in a region in China that is affected by the summer Asian Monsoon. The stalagmite had grown from 190 to 2003 A.D. and the record exhibits climate fluctuations. It shows a correlation between the demise of many dynasties – such as the Tang, Yuan, and Ming Dynasties – and climatic variability, namely via the decline in the Asian Monsoon. The scientists found that the Asian Monsoon has weakened over the past 50 years, much of which occurred over the last two decades. They suggest that the dominant forcing of Asian Monsoon variability is human-induced after 1960.

  Implications: Zhang et al. state that the late 20th Century trends in the Asian Monsoon "are clearly anomalous" when compared to the rest of the 1810-year record, given their human footprint. They note that periods of stronger Asian Monsoon coincided with the first few decades of the Northern Song Dynasty, which was marked by a booming population and increased rice cultivation; yet, weak Asian Monsoon periods coincided with periods of unrest, at the end of several major dynasties.

ECOSYSTEMS AND ECOSYSTEM SERVICES

Overview

As more data are collected on the interplay between ecosystems, the services derived from ecosystems, and global climate change, trends are not only emerging but being confirmed. The stories below highlight some of the impacts that are already unfolding in various locations around the world, or will soon do so: changes in seasonality and attendant implications for predator-prey relationships; impacts of ocean acidification and ice loss on marine life; the spread of invasive species; and the expansion of so-called "dead zones" in the oceans which harbor little life, among others. While by no means comprehensive, the research presented below provides a snapshot of how climate change affects ecosystems and the services they provide to humans.

- **C. Rosenzweig, D. Karoly, M. Vicarelli, P. Neofotis, et al.**

  "Attributing physical and biological impacts to anthropogenic climate change"

  Nature

  15 May 2008, vol. 453

  Rosenzweig et al. have found that observed impacts in numerous physical and biological systems from 1970 to 2004 have been caused by human-induced climate change. They used a joint attribution study, which first demonstrates that the changes are due to warming and then that warming is due to human activities rather than natural variability. The researchers performed a meta-analysis of published findings referencing documented changes in 28,800 plant and animal systems and 829 physical systems, 90% and 95% of which changed in the expected direction due to warming respectively. They conclude that human-induced warming is "having a significant impact" on global natural and physical systems, as well as some continental systems.

  Implications: This study relied upon an expanded data set from the one these authors had used in the 2007 IPCC Working Group II report on impacts, and further confirms the attribution of physical and biological impacts to human-induced warming rather than natural variability. However, data from most tropical and sub-tropical regions is still sparse.

- **K. Carpenter, M. Abrar, G. Aeby, R. Aronson, et al.**

  "One-third of reef-building corals face elevated extinction risk from climate change and local impacts"

  Science

  July 2008, vol. 321

  Carpenter et al. devoted this study to assessing the extinction risk of zooxanthellate coral, a reef-building species, to climate change. The scientists relied upon the International Union for Conservation of Nature (IUCN) Red List Categories and Criteria, a commonly used metric of species endangerment/extinction risk calculated by incorporating species' habitat and population sizes, as well as estimates of reef area lost. Carpenter and colleagues studied 704 of the 845 reef-building coral species (141 species lacked data) and found that 231 species, or roughly 33%, were threatened (from all stressors, with risks heightened by climate change and local-level anthropogenic impacts), and 407 species were either threatened or near threatened. Those species that were not threatened occupy deep, low reef slopes and can thrive in habitats other than reefs. The scientists found that the extinction risk of reef-building corals is higher today than in the past: prior to 1998, only 20 species would have been considered as near threatened, and 13 as threatened. Their data also indicate that the percentage of coral species that are threatened exceeds most other animal groups, with the exception of amphibians. Species that were found to be at greatest risk are located in the Indo-Malay-Philippine archipelago, as a result of human disturbances compounded by climate change.

  Implications: The study states that the resilience of corals will be dependent upon ability to adapt, future atmospheric concentrations of carbon dioxide, and the reduction of non-climate stressors, such as eutrophication, sewage discharge, and coastal development. Bleaching events may become so common that the species will be unable to recover and will be pushed to extinction. The loss of coral species will have concomitant impacts on reef-dependent species and, thus, on marine ecosystems and global biodiversity at large. The authors point out that the loss of reef-building corals will have cascading impacts on food security, given that human populations on the order of hundreds of millions depend on reef fish for food sources.

- **S. Cherry, A. Derocher, I. Stirling, and E. Richardson**

  "Fasting physiology of polar bears in relation to environmental change and breeding behavior in the Beaufort Sea"

  Polar Biology

  22 October 2008, vol. 32

  Cherry et al. dedicate this study to the rate of fasting among polar bears in the eastern Beaufort Sea, near the Arctic Ocean. The scientists located 436 polar bears by helicopter, anesthetized them, and then took measurements of and drew blood from the bears during April and May of 1985, 1986, 2005, and 2006. The blood samples were analyzed for the serum urea creatinine ratios, which indicate whether the bear is in a fasting state. Cherry et al. found that fasting increased from 9.6% in 1985, 10.5% in 1986, 21.4% in 2005, to 29.3% in 2006. All bears, representing various ages, sexes, and reproductive classes, exhibited an increase in fasting over time, but adult males were most prone to fasting.

  Implications: The authors state that their findings are consistent with other research on food stress and polar bears. They suggest that fasting may be attributable to a decline in prey – ringed seals – availability, perhaps due to the loss of sea ice and changes in ice composition.

- **N. Dulvy, S. Rogers, S. Jennings, V. Stelzenmüller, et al.**

  "Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas"

  Journal of Applied Ecology

  August 2008, vol. 45

  Paralleling the elevational migration trends of terrestrial species in a warming climate, Dulvy et al. have found that climate change can drive marine species to cooler ocean depths as a result of temperature changes. They examined the response of 28 bottom-dwelling fish species in the North Sea from 1980 to 2004, a region which had warmed 1.6°C over the period, by calculating the distance that the fish species traveled north, south, deep, and shallow. They found that in addition to a northward shift in mean latitude and southward shift in minimum latitude, most fish species had also deepened their ranges, with the assemblage of the 28 species deepening on average 3.6 meters per decade, with some species up to 10 meters per decade.

  Implications: The authors state that deeper habitats are often smaller in volume, potentially posing limits to the habitat available to those species inclined to deepen in warming waters. The deepening of fish species will have implications for marine ecosystem composition, as new species enter new territories.

- **R. Feely, C. Sabine, J. Hernandez-Ayon, D. Ianson, et al.**

  "Evidence for upwelling of corrosive 'acidified' water onto the continental shelf"

  Science

  3 June 2008, vol. 320

- **J. Hall-Spencer, R. Rodolfo-Metalpa, S. Martin, E. Ransom, et al.**

  "Volcanic carbon dioxide vents show ecosystem effects of ocean acidification"

  Nature

  3 July 2008, vol. 454

  While studies of ocean acidification are often limited to computer models and controlled experiments, two recent studies document acidification events already transpiring. In one study, scientists Feely et al. examined coastal waters in California that have become acidified. Conducting hydrographic surveys in May and June of 2007, collecting water from 13 cross-shelf transects from central Canada to northern Mexico, Feely et al. found that significant portions of the upwelled seawater were undersaturated in calcium carbonate, a sign that the oceans had absorbed anthropogenic carbon dioxide, had become acidified, and as a result had fewer carbonate ions in the water. Carbonate ions are used in calcium carbonate skeleton and shell formation, and thus are critical building blocks for many marine organisms. Feely et al. note that this ocean condition was projected for 2050 rather than today.

  In another study, Hall-Spencer and colleagues studied the effects of carbon dioxide flux from volcanic vents in Italy, which can contain 90-95% carbon dioxide. The scientists compared vents that were of normal pH with those of reduced pH. At sites with a mean pH of 7.8-7.9 (acidified waters) – versus a normal pH of 8.1-8.2 – species numbers had decreased by 30%. Also, in these acidified sites, the ecosystem composition had shifted from species that typically occupy coastal communities to one lacking scleractinian, or stony, corals and with reduced abundance

of sea urchin and coralline algae, species critical to reef ecology.

Implications: Feely et al.'s study demonstrates that coastal areas, which are economically important regions, are already being impacted by the upwelling of corrosive, acidified water. Hall-Spencer et al.'s study is unique in providing a natural experiment of how acidification affects marine ecosystems. They found that some marine organisms disappeared due to skeletal dissolution in the acidic waters, with implications for rocky shore communities. They cite literature suggesting that the loss of species such as sea urchins can trigger a decline in ecosystem complexity and stability.

- **H. Geisz, R. Dickhut, M. Cochran, W. Fraser, et al.**
  "Melting glaciers: A probable source of DDT to the Antarctic marine ecosystem"
  Environmental Science and Technology
  30 April 2008, vol. 42

  The use of the synthetic pesticide Dichloro-Diphenyl-Trichloroethane (DDT) has been banned in the Northern Hemisphere and regulated in the rest of the world due to its negative impacts on wildlife and human health. As a result, traces of DDT have declined in most bird populations in recent decades. However, Geisz et al. have found that levels of DDT in Adélie penguins from the Western Antarctic Peninsula have not fallen. The scientists collected Adélie penguin carcasses and eggs at the Palmer Archipelago in 2004 and Cape Crozier on Ross Island in 2006. Tissues and eggs were analyzed for DDT and its derivatives. The scientists hypothesize that DDT levels did not decline because there was a current source of exposure to DDT: ice. They concluded that DDT was being released via ice melting into coastal waters – and measurements confirm that surrounding glacial water does contain DDT – deposited on Antarctic ice sheets in the past when it was still in widespread use.

  Implications: According to the authors, average temperatures in the winter have risen 6°C over the last three decades on the Antarctic Peninsula, hastening glacial melting. The Antarctic food web could be affected as DDT accumulates in higher trophic levels and population dynamics are altered. The adverse effects of long-term exposure to DDT have been documented in the Arctic, where exposed wildlife demonstrated immunosuppression, lower metabolic rates, and other physiological impacts.

- **K. Kausrud, A. Mysterud, H. Steen, J. Vik, et al.**
  "Linking climate change to lemming cycles"
  Nature
  6 November 2008, vol. 456

  The tales of lemming (a type of small rodent) population explosions in Norway are famous, having given rise to the myths of mass lemming suicides, as large numbers of lemmings migrate together – at times jumping into water to cross to other land masses, and drowning in the process – to find new sources of food. Yet, since 1994, there has been a notable absence of population booms of the Norwegian lemming *Lemmus lemmus*. In an effort to determine the factors of this decline in population peaking, Kausrud et al. relied on a 38-year record from 1970 to 2007 of rodent population sizes, based on data obtained from traps. They also assessed the subnivean (or layer under the snow cover) environment, as the lemming species will reproduce only in favorable subnivean conditions. Additionally, the scientists collected data on predator ground-nesting bird populations to assess species interaction dynamics. They found that subnivean conditions fluctuated with temperature changes. Moreover, changes in lemming population size, and the absence of peak population years, were attributable to the winter weather and snow conditions.

  Implications: The scientists found a high correlation between the density of rodent species and ground-nesting birds, and note the effects of climate change on this predator-prey relationship and, in turn, implications for food web dynamics. Accordingly, they speculate that it is probable that the decline of snowy owls and arctic fox on the Scandinavia peninsula is due to the absence of peak years of lemmings. In conclusion, the authors suggest that, given projections of more precipitation and warmer temperatures in Norway, the lemming cycle will "cease."

- **J. Lenoir, J. Gégout, P. Marquet, P. de Ruffray, et al.**
  "A significant upward shift in plant species optimum elevation during the 20th Century"
  Science
  27 June 2008, vol. 320

  Lenoir et al. assess the impacts of climate change on forest plant communities in lowland to upper subalpine ecosystems (0 to 2600 m) throughout six western European mountain ranges. They rely upon two large-scale floristic inventories, and identified 171 species for use in the study.

Studying the periods of 1905-1985 and 1986-2005, they found that species at higher elevations shifted their distributions most quickly. The authors rule out attribution to changes in precipitation, atmospheric nitrogen deposition, land use, invasive species, and carbon dioxide fertilization, and instead argue that warming is the determinant of range shifts. Overall, the average rate of change across the entire gradient was 29.4 ± 10.9 m per decade.

Implications: This study demonstrates that the plant species composition of ecosystems can (and in this case has already started to) change rapidly with changing climate. As plant species ranges shift, there will be attendant predator-prey relationship changes, presenting management and conservation challenges.

- **W. Kurz, C. Dymond, G. Stinson, G. Rampley, et al.**

"Mountain pine beetle and forest carbon feedback to climate change"

Nature

24 April 2008, vol. 452

The mountain pine beetle attacks trees by burrowing under the bark of the tree and cutting off the tree's nutrients. While the beetle typically dies off in cold snaps, warming temperatures have led to significantly augmented population numbers, as the beetle is able to withstand winter temperatures and successfully breed. Kurz et al. dedicate this study to assessing the net impacts of the mountain pine beetle, forest fires, and timber harvesting in south-central British Columbia from 2000-2020. Using Monte Carlo simulations for a forest ecosystem model in an effort to simulate future net biome production, the scientists were able to develop forecasts of future beetle dynamics. They found that from 2003-2020, as a result of the beetle infestation, the forest turns from a small net sink of carbon dioxide to a large net source, emitting 17.6 MtC annually, and this loss of net biome production fails to recover by 2020.

Implications: While forest fires are already a significant source of carbon dioxide emissions in the region, from 2005-2014 the emissions related to the pine beetle epidemic are modeled to trump those related to forest fires. The authors state that 13% of the total forest product sector harvest in the region would be impacted by the pine beetle during the period. Thus, in addition to adverse ecosystem and climate effects, the loss of forests will have significant economic and livelihood impacts, as the forestry sector is a cornerstone of the province's economic well-being. It is important to note that the pine beetles' impacts are not constrained to British Columbia. The beetle infestation is projected to lead to the death of more than two million acres of forests in Wyoming and Colorado this year (Jim Robbins, "Bark beetles kill millions of acres of trees in west," *The New York Times*, 18 November 2008).

- **D. Lobell, M. Burke, C. Tebaldi, M. Mastrandrea, et al.**

"Prioritizing climate change adaptation needs for food security in 2030"

Science

1 February 2008, vol. 319

Given scant resources and limited time for advancing adaptation, Lobell et al. devote this study to the prioritization of adaptation investments for food security by identifying those areas and crops that are at greatest risk from climate change. They evaluated the risks of climate change to a variety of crop species in 12 vulnerable regions that lack food security but have similar diets and agricultural production systems. Using climate projections from 20 general circulation models, as well as statistical crop models, the researchers assessed the food security impacts in 2030 – a year chosen for its relevance to decisions related to large agriculture investments, which usually require 15 to 30 years for full returns – by developing probabilistic projections of production impacts. They found that several crops in both South Asia and Southern Africa will be most impacted in the absence of adaptation measures.

Implications: The researchers found that wheat in South Asia, rice in Southeast Asia, and maize in Southern Africa have an estimated 95% or higher probability that climate change will harm production if adaptation measures are not undertaken. If adaptation investment decisions are instead based on those crops that might be most vulnerable to high impact, low probability events, sorghum from the Sahel, maize from Southern Africa, and several other South Asian crops would be prioritized.

- **Abraham Miller-Rushing and Richard Primack**

  "Global warming and flowering times in Thoreau's Concord: A community perspective"

  Ecology

  February 2008, vol. 89

  This study demonstrates that warming can bring about an earlier onset of vegetation and flowering. Miller-Rushing and Primack rely on flowering data, some of which Henry David Thoreau collected, over three periods: 1852-1858, 1878-1902, and 2004-2006. They analyzed the first flowering dates for 43 species in the area, a region which had warmed 2.4°C from 1852 to 2006, and found that, on average, the species flowering dates had advanced seven days, with flowering timing positively correlated with mean temperatures of the months before flowering, as well as January temperatures.

  Implications: Early onset of vegetation and flowering can have rippling effects through the food chain as the timing of peak food availability is altered.

- **C. Moritz, J. Patton, C. Conroy, J. Parra, et al.**

  "Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA"

  Science

  10 October 2008, vol. 322

  Moritz et al. dedicate this study to exploring the impacts of climate change on small mammals in Yosemite National Park in California. The authors state that while most studies of climate impacts to biota are based on models of future range shifts or data that have been collected over a short time frame, they are fortunate to have data that span almost a century, as they repeated John Grinnell et al.'s survey performed from 1914-1920. They relied on trapping and occupancy modeling to assess species richness in an area that spans 3000 meters in elevation. Between the times Grinnell and colleagues collected their observations and Moritz et al. performed their research, minimum temperatures had increased by 3°C in the area and over half of the studied 28 species had moved upwards in elevation by roughly 500 meters on average. While those species occupying low elevations were able to increase their range, those at higher elevations experienced range contraction.

  Implications: Range expansion and contraction not only have implications for the species themselves – especially for those whose ranges are contracting at a rapid pace – but also for ecosystem composition, as new species move into previously unoccupied ecosystems, and other species can no longer withstand portions of their ranges. The authors underscore the importance of protected areas, suggesting that the species diversity in Yosemite has yet to be affected significantly because species could move along an elevational gradient and connected landscape.

- **A. Oschlies, K. Schulz, U. Riebesell, and A. Schmittner**

  "Simulated 21st Century's increase in oceanic suboxia by CO_2-enhanced biotic carbon export"

  Global Biogeochemical Cycles

  11 November 2008, vol. 22

- **Jeffrey Polovina, Evan Howell, and Melanie Abecassis**

  "Ocean's least productive waters are expanding"

  Geophysical Research Letters

  14 February 2008, vol. 35

- **L. Stramma, G. Johnson, J. Sprintall, and V. Mohrholz**

  "Expanding oxygen-minimum zones in the tropical oceans"

  Science

  2 May 2008, vol. 320

  Three recent studies show that portions of the oceans are becoming – or will become – less productive with warming. In the first study, Oschlies et al. demonstrate that heightened levels of carbon dioxide can also lead to an increase in "dead zone" occurrence in tropical oceans. Dead zones are areas of the oceans that are hypoxic, or low in oxygen, and thus, fail to harbor life – hence their name. Dead zones have been caused by nitrogen inputs (such as fertilizer run-off and sewage) and compromised water flow. The scientists used a UVic Earth System Climate Model, and extrapolated from data collected from experimental mesocosm enclosures of plankton communities exposed to varying levels of carbon dioxide concentrations. If emissions continue unabated, their data indicate that tropical dead zones will increase by 50% by 2100.

  In a second study, Polovina et al. found that gyres (circular patterns of ocean currents) in the oceans that are

"oligotrophic" (or low in nutrients) are expanding faster than predicted by climate models, consistent with global warming. Relying upon Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite data on ocean chlorophyll levels from 1998-2007, the researchers found that ocean gyres low in chlorophyll levels, a good indicator of oligotrophic oceans, have been growing at a rate of 0.8% in the South Atlantic to 4.3% in the North Atlantic annually. These oligotrophic areas are taking over a combined 0.8 million km² of productive, high chlorophyll regions in the Pacific and Atlantic annually – equivalent to 6.6 million km² over the nine-year period, constituting an increase of 15% over 1998 levels. The authors state that the expansion of oligotrophic gyres is consistent with the warming of mean monthly sea surface temperatures over subtropical gyres. They suggest that as these gyres become warmer, they become more strictly layered (i.e. less well-mixed), leading to the expansion of oligotrophic zones. A study by Stramma and colleagues is consistent with Polovina et al.'s findings. Stramma et al. conclude that regions of low oxygen have been expanding in the eastern tropical Atlantic and equatorial Pacific over the past half century. Constructing and analyzing an oxygen time series in tropical oceans, they found that between 300 and 700 meters in ocean depth, oxygen levels had decreased 0.09 to 0.34 micromoles per kg per year.

Implications: Oschlies et al. state that their findings have "severe implications" for higher trophic levels that are dependent upon specific nutrient levels, as nutrient recycling processes will vary according to oxygen concentrations. As Stramma et al. note, low oxygen levels have important implications for fisheries management, carbon and nitrogen cycles, and marine ecosystems.

- **C. Raxworthy, R. Pearson, N. Rabibisoa, A. Rakotondrazafy, et al.**

"Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar"

Global Change Biology

6 May 2008, vol. 14

Due to its geographic isolation and tropical climate, Madagascar harbors some of the highest levels of biodiversity globally, much of which is endemic, or found nowhere else on Earth. At the same time, the country's species are among the most vulnerable, primarily due to land conversion. Raxworthy and colleagues show that another human-induced factor – climate change – can lead to species degradation. They studied Madagascar's highest massif, a group of mountains created by the movement of the Earth's crust, called the Tsaratanana Massif, which is rich in endemism. Sampling transects from 1400 to 2876 meters in 1993 and 2003, and relying on weather station and reanalysis data, as well as historical climate model data, the scientists estimated range shifts of 30 species of reptiles and amphibians. Overall, the species shifted the elevational midpoint of their ranges from 19 to 51 meters upslope, during a period in which the temperature increased between 0.1 and 0.37°C. Performing an elevational range displacement analysis, the scientists predict that three species on the massif – two of which were not found again in the 2003 resampling and one which had only been observed once in 1949 – will lose their habitat completely – and at warming of only 1.7°C. The authors state that under mid-range warming scenarios two of these three species could be extinct within 50 to 100 years.

Implications: The authors state that their findings highlight the importance of incorporating future climate impacts in reserve planning, such as placing a premium on protecting upslope habitat. They also call for additional data on possible climate impacts on tropical montane ecosystems, given the deficit of studies conducted in these areas and the significance of climate risks to species due to the high levels of biodiversity and endemism in these regions.

CLIMATE CHANGE MITIGATION TECHNOLOGIES

Overview

The following section highlights significant technological advances and developments in key climate change mitigation technologies, including solar, thermoelectric power, biofuels, wave energy, batteries and ultracapacitors, and carbon capture and storage. Breakthroughs highlighted include new designs, materials, efficiency gains, and energy storage solutions.

Solar

The adoption of policies and financial incentives by several countries is promoting widespread diffusion of photovoltaic cells. In 2008, approximately 5.2 GW were installed while revenues reached over $ 30.5 billion. The competitive industry that has emerged (along with government programs) is promoting innovative basic and applied research which aims to increase the efficiency of solar cells and reduce the costs of the production and installation chain. Research on solar power in 2008 focused on new designs and materials, cost-cutting features, and efficiency gains. Among the technology breakthroughs in efficiency this year:

- The efficiency of the multi-junction solar cell increased from 37.6% (achieved in July 2008) to 39.7% due to the incorporation of III-V semiconductors ("Fraunhofer ISE researchers achieve 39.7% solar cell efficiency," *RenewableEnergyWorld.com,* 30 September 2008);
- The efficiency of the silicon solar cell was boosted to 25%, achieved with a design that captures a broader spectrum of light ("Highest silicon solar cell efficiency ever reached," *ScienceDaily*, 24 October 2008);
- The efficiency of solvent-free dye-sensitized solar cells reached a record 8.2% with the use of an electrolyte salt-based solution in lieu of organic solvents ("New efficiency benchmark for dye-sensitized solar cells," *ScienceDaily,* 2 July 2008);
- The efficiency of polymer solar cells increased to 5.6% as a result of a new polymer substitute ("Polymer solar cells with higher efficiency levels created," *ScienceDaily*, 1 December 2008);
- Scientists at Northwestern University boosted the efficiency of power conversion from 2-4% to 5.2-5.6% of the bulk-heterojunction solar cell by applying a new anode coating of nickel oxide ("Special coating greatly improves solar cell performance," *ScienceDaily*, 26 February 2008);
- Scientists at the Rensselaer Polytechnic Institute developed a new antireflective coating for solar panels which enables the solar cell to absorb the entire spectrum of light – including UV, infrared, and visible light – and absorb light at almost every angle, irrespective of the sun's position, increasing the efficiency from 67.4% to 96.21% (Michael Mullaney, "Solar power game-changer: 'Near perfect' absorption of sunlight, from all angles," *Rensselaer Polytechnic Institute Press Release*, 3 November 2008);
- The U.S. Department of Energy's Idaho National Laboratory created a new design – with flexible nanoantennas on plastic sheets, which are directed to catch infrared rays – for solar energy collectors, capturing as much as 92% of infrared light ("Flexible nanoantenna arrays capture abundant solar energy," *ScienceDaily*, 12 August 2008);
- With the use of alkanedithiols as processing additives, scientists achieved a 5.1% efficiency for plastic solar cells, among the highest efficiencies for the technology type ("Toward the next generation of high-efficiency plastic solar cells," *ScienceDaily,* 19 March 2008); and
- MIT scientists developed a novel design for solar concentrators in which solar cells are only found at the edges, rather than covering the entire material (e.g. a window or roof), increasing the system's efficiency by 50% with little additional costs (Elizabeth Thomson, "MIT research may bring down cost of solar energy," *MIT News Office,* July 16, 2008).

Several other research innovations are highlighted below.

- **National Renewable Energy Laboratory Newsroom "NREL solar research gains two R&D 100 awards" 17 July 2008**
- **National Renewable Energy Laboratory Newsroom "Record makes thin-film solar cell competitive with silicon efficiency" 24 March 2008**
- **National Renewable Energy Laboratory Newsroom "NREL, HelioVolt receive technology transfer award for PV manufacturing technology" 7 October 2008**

  The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) made some notable advances in solar cell technology in 2008. The Laboratory's creation of the "Inverted Metamorphic Multi-Junction solar cell" set three world records related to efficiency. The technol-

ogy grows the solar cell upside down, which eliminates the need for a thick germanium bottom layer, reducing 94% of the cell's weight and related costs. The new cell is also highly flexible. In another technological advance, NREL created a copper indium gallium diselenide (CIGS) thin-film photovoltaic. The deposit of inks is central to the design, simplifying the manufacturing process and resulting in a highly flexible film.

Implications: The Inverted Metamorphic Multi-Junction solar cell is not only more efficient than other solar technologies, but has lower associated costs of operation and manufacturing, increasing its appeal on the commercial market. Because the inks in the thin-film technology can be applied directly to building materials, commercialization could possibly "turn entire buildings and other structures into small, self-sustaining power plants" in the future.

- **Matthew Kanan and Daniel Nocera**
  "In situ formation of an oxygen-evolving catalyst in neutral water containing phosphate and CO_2+"
  Science
  22 August 2008, vol. 321
- **"MIT researchers discover new energy storage solution"**
  Renewable Energy World
  4 August 2008
- **"Researchers generate hydrogen without the carbon footprint"**
  ScienceDaily
  18 July 2008

Research has also advanced the potential for solar power in hydrogen production. For example, MIT scientists have recently developed a new non-toxic, inexpensive technology for storing solar energy, with potential applications for generating hydrogen power. Matthew Kanan and Daniel Nocera based their discovery around plant photosynthesis. They built a solar cell that can split water, producing hydrogen for use in a fuel cell. To achieve this, they incorporated a novel catalyst of an inert indium tin oxide electrode in phosphate-buffered water containing cobalt ions. Penn State scientists, led by Craig Grimes, have also developed a procedure for splitting water to produce hydrogen via solar energy. They used a nanotube design with a photoelectrochemical diode made of titanium dioxide and copper titanium.

Implications: Current technologies that split water are typically costly and require toxic environments to operate. While far removed from commercial availability, Kanan and Nocera's catalyst technology relies on materials that occur naturally and, according to the authors, are abundant. Grimes et al.'s design, while yet to achieve advanced efficiencies, signifies an advancement given its low costs and durability.

- **J. Yoon, A. J. Baca, S. Park, P. Elvikis, et al.**
  "Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs"
  Nature Materials
  November 2008, vol. 7
- **Andrew Mitchinson**
  "Materials science: Solar cells go round the bend"
  Nature
  9 October 2008, vol. 744

Yoon et al. have developed a new silicon solar cell that is "ultrathin," highly flexible, lightweight, and transparent. Their design incorporates large-scale arrays of silicon solar microcells, carved from a block of silicon, which are applied to a substrate via a printing process. Electrodes are used to connect the microcells to one another on top of the substrate. The cells can be as thin as 100 nanometers and take up as little space as a few micrometers. They are also transportable; they not only bend easily but maintain their efficiency when bent.

Implications: The authors state that the materials involved in the design are long-lasting and durable. The new design also requires less silicon, lowering costs and material input. The ultrathin solar cell's transparency could facilitate its application in windows.

Thermoelectric Power

Heat can be converted into electricity with the use of thermoelectric materials. Among other applications, thermoelectric materials could be used in vehicles, converting engine exhaust – typically wasted heat – into energy. Research conducted in 2008 introduced new thermoelectric materials, such as tallium-doped lead telluride, described below.

- **Pam Frost Gorder**

  "Material may help autos turn heat into electricity"

  RenewableEnergyWorld.com

  25 July 2008

  In a research advancement regarding thermoelectric materials, researchers from Ohio State University, led by Joseph Heremans, have developed a new type of material comprised of tallium-doped lead telluride. This material has doubled the efficiency of commercially available materials.

  Implications: Tallium-doped lead telluride can not only withstand heat but is most effective at between 450°C and 950°C – the same high temperatures at which vehicle engines and many other technologies operate. Almost 60% of energy produced by a conventional gasoline engine can be lost via waste heat; this material could help utilize such energy.

Biofuels

Biofuel energy is derived from biological materials, such as crops, grasses, and wood. New research advances the state of knowledge on the biofuel production process, how biofuels can be used in hydrogen fuel cells, and new biofuel sources – critical breakthroughs for reducing our dependence on fossil fuels. However, new findings warn that the life cycle emissions associated with some biofuels are higher than previously thought.

- **T. Searchinger, R. Heimlich, R. Houghton, F. Dong, et al.**

  "Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change"

  Science

  29 February 2008, vol. 319

- **J. Fargione, J. Hill, D. Tilman, S. Polasky, et al.**

  "Land clearing and the biofuel carbon debt"

  Science

  29 February 2008, vol. 319

  Searchinger et al. demonstrate that corn-based ethanol – as a result of land competition and consequent conversion of forest and grasslands into agricultural areas – can be far more carbon intensive than gasoline. They found that over three decades, if life cycle emissions – including those related to land use changes – are accounted for, corn-based ethanol will result in double the amount of greenhouse gas emissions associated with gasoline. And if U.S. corn fields were converted to switchgrass, a 50% increase in emissions over three decades would ensue, as a result of emissions from land use changes. Their analysis considers several related factors that determine cropland changes and associated emissions: as demand for biofuels increases, prices of crops increase; agricultural exports are in turn lowered; and farmers have to increase yields and convert land previously uncultivated. Land conversion leads to greenhouse gas emissions, and agricultural lands typically sequester less carbon than the converted forests or grasslands.

  In a related study, Fargione et al. suggest that unless biofuel crops are grown only on abandoned agricultural lands, or fuel is derived from waste biomass, biofuel production will result in higher emissions than fossil fuels as a result of emissions associated with land conversion. They suggest this situation could last for decades, or even centuries, until the "carbon debt" due to land conversion is "repaid" through lower emissions associated with the use of biofuels. Fargione et al. reached their conclusions by calculating the carbon debt associated with the life cycle emissions of various biofuels. For example, conversion of Indonesia and Malaysian rainforest for palm biodiesel would result in an 86-year carbon-debt. That is, biofuels would have to be produced on the land for 86 years in order for the displaced carbon emissions to compensate for the carbon losses incurred when the land was converted.

  Implications: Both articles demonstrate the need to consider life cycle emissions, especially indirect effects such as land conversion. Fargione et al. suggest that – with the exception of sugarcane ethanol and soybean biodiesel in Cerrado – all biofuel scenarios would result in higher greenhouse gas emissions than those related to the displaced fossil fuels for at least 50 years. However, they do highlight the potential of growing native biofuel crops on degraded agricultural lands, and Searchinger et al. note the promise of cellulosic ethanol in avoiding land use conversion.

- **"New method turns wood into sugar for biofuels"**

  RenewableEnergyWorld.com

  28 October 2008

  Researchers at the Max Planck Institute for Coal Research in Germany have developed a novel approach to making sugar-based ethanol. Bathing plants in an ionic liquid,

the scientists were able to break down the cellulose into glucose chains. They then used a solid acid resin to break the chains apart into sugar molecules for use as ethanol.

Implications: The researchers highlight the versatility of the process: even wood can be used as inputs, reducing competition with agricultural land (although it should be noted that there could be negative ecosystem implications of harvesting woody debris from forest ecosystems). Previous attempts to break down cellulose into sugar have required large energy inputs to raise the pressure and temperature of the process, as well as acid baths. However, the technology is far from commercialization, as the ionic solvent remains costly.

- **"Sugar-powered cars: World's most efficient method to produce hydrogen developed"**
  ScienceDaily
  10 April 2008

- **"A better way to make hydrogen from biofuels"**
  ScienceDaily
  21 August 2008

  Research has advanced the application of biofuels in hydrogen production processes. Percival Zhang and colleagues announced at the 235th meeting of the American Chemical Society that they had succeeded in creating the most efficient means of producing hydrogen for electricity, using plant cellulose rather than a carbon-intensive fuel. Zhang et al.'s process involves the mixing of starch and 13 enzymes with water, ingredients which are then placed into a reactor. In related research, Ozkan and colleagues from Ohio State University have developed a novel way to convert ethanol to produce hydrogen. They discovered a new catalyst – cerium oxide – which has a 90% yield of hydrogen. Cerium oxide is inexpensive, as it is not a precious metal, and can be used directly inside reactors to produce hydrogen for immediate consumption.

  Implications: By relying upon a process based on plants rather than fossil fuels, the life cycle emissions associated with the hydrogen production can be considerably lower. Also, Ozkan et al.'s catalyst costs a fraction of rhodium, a precious metal that is commonly used as a catalyst in hydrogen production systems. While Zhang et al.'s system remains inefficient, according to the researchers, the technology could be used in small hand-held devices – perhaps within the next three to five years.

Wave Energy

Mechanical energy from moving water can be converted into electrical energy. Research has introduced new wave power designs and has expanded the application of wave technologies into slower moving water.

- **"'Anaconda' could provide up to 20 MW of wave energy"**
  RenewableEnergyWorld.com
  15 July 2008

  Engineers have recently created a novel design for harnessing wave energy, entitled the Anaconda for its snake-like features. One side of the long, thin rubber device floats under the surface of the water, with the other side facing into the waves. Inside the Anaconda is water. Although both ends are sealed shut, when a wave hits, a mini wave of pressure is created inside the Anaconda, which in turn spins a turbine and creates power.

  Implications: The advantages of the design are its rubber composition, avoiding metal, which has higher maintenance costs. However, the technology remains in a research and development stage. While cost competitive with other wave energy devices, generation of electricity through the Anaconda is twice as costly as electricity generated from coal.

- **Nicole Casal Moore**
  "New 'Vivace' system draws renewable energy from slow water currents"
  RenewableEnergyWorld.com
  2 December 2008

  Most technologies that generate power from water depend on waves, tides, or fast moving water. Yet the majority of water moves at a pace of less than 3 knots. At the University of Michigan, Michael Bernitsas has developed the VIVACE (Vortex Induced Vibrations for Aquatic Clean Energy) system, which enables the harnessing of energy from slow moving water. When placed in water, the VIVACE, which is shaped like a cylinder, disrupts the current and creates small vortices, which in turn push the device around. This movement creates mechanical energy which is then converted into electricity.

  Implications: Energy produced from a VIVACE device could cost $0.05 per kilowatt-hour, less than U.S. wind energy costs and similar to nuclear energy costs. A pilot

project is planned in the Detroit River. An advantage of the VIVACE over dams and turbines is that the system will not result in large-scale disruption of currents, safeguarding marine ecosystems.

Batteries and Ultracapacitors

A significant hurdle in advancing renewable power is storage, given the intermittency of some renewable energy sources. Research conducted in 2008 introduced numerous advances with regard to battery and ultracapacitor storage, highlighted below.

- **Argonne National Laboratory**
  "New battery outperforms current batteries in HEV applications"
  http://www.anl.gov/techtransfer/pdf/Profile_LI_Battery_08RD_winner.pdf

  Winning the 2008 R&D Award for its design, the U.S. Department of Energy's Argonne National Laboratory and EnerDel have created a lithium ion battery that is not only smaller and lighter than technologies based on nickel-metal hydride batteries but also more efficient and longer-living. The researchers were able to achieve higher efficiency and durability with the use of hard crystalline materials: $LiMn_2O_4$ in the cathode and $Li_4Ti_3O_{12}$ in the anode.

  Implications: As the press release from Argonne National Laboratory states, this battery design – as a result of its safety features, performance, durability, and low costs – "will remove the remaining barriers now inhibiting consumer acceptance of HEVs [hybrid electric vehicles]." In addition to vehicles, the researchers note possible applications in the military and aerospace sectors, given the performance of the battery at high temperatures.

- **"Breakthrough in energy storage: New carbon material shows promise of storing large quantities of renewable electrical energy"**
  ScienceDaily
  17 September 2008

  Ultracapacitors are alternatives to batteries for storing electrical energy. A team of researchers at the University of Texas at Austin has recently advanced ultracapacitor technology by incorporating a carbon-based sheet, composed of graphene, into its design. Graphene has a large surface area, even when it is one-atom thick, as in the University of Texas at Austin's design. A larger surface area places more of the material in contact with the electrolyte and, in turn, more ions can be stored. The use of graphene in an ultracapacitor has the potential for doubling its storage capacity.

  Implications: Ultracapacitors can be used with batteries or on their own, and have several advantages over batteries, including durability, light weight, lower maintenance, and a wide temperature operating range, among other merits.

Carbon Capture

As climate change impacts are felt throughout the world and carbon policies advance, carbon capture has gained increasing attention. While technologies for capturing carbon dioxide emissions are probably decades from commercialization, research is advancing the possibility of artificially sequestering carbon in the future.

- **"Global warming fix? Carbon dioxide captured directly from air with simple machine"**
  ScienceDaily
  30 September 2008

  Research scientists David Keith and colleagues have engineered a method for capturing carbon dioxide directly from the air. They developed a tower-shaped machine described as a "near-commercial technology" which can capture as much as 20 tonnes of carbon dioxide annually with a meter's worth of scrubbers. The machine requires 100 kilowatt hours of electricity to scrub each tonne of carbon dioxide.

  Implications: The technology remains in research and development phases, and Keith et al. have recently filed for patents. However, if the process could be scaled up and costs could be lowered, the technology could constitute a significant breakthrough. While energy inputs – and related emissions – remain a major concern, Keith states that if the machine were used to sequester the carbon dioxide from a coal-powered plant, it could capture 10 times the amount of carbon dioxide associated with the energy inputs required for operating the machine.

- **Peter Kelemen and Jürg Matter**

"In situ carbonation of peridotite for CO_2 storage"

Proceedings of the National Academy of Sciences

11 November 2008, vol. 105

Kelemen and Matter recently discovered in Oman that an exposed piece of peridotite, a type of igneous rock composed primarily of olivine and pyroxene, can rapidly sequester significant amounts of atmospheric carbon dioxide under certain conditions. The captured gas is converted into solid carbonate minerals. The rock's natural carbonation process can be sped up under higher temperatures and via the input of carbon dioxide at high pressures, among other processes such as drilling and hydraulic fracturing.

Implications: The authors state that in theory more than one billion tons of carbon dioxide could be sequestered in Oman annually by this enhanced process of peridotite carbonation. They also note that the sequestration technique could be inexpensive, safe, and permanent and would not require transportation. More research needs to be performed before the process is applied on a larger scale.

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