WRI ISSUE BRIEF

WORLD RESOURCES INSTITUTE

# CLIMATE SCIENCE 2006 MAJOR NEW DISCOVERIES

KELLY LEVIN AND JONATHAN PERSHING

## INTRODUCTION

This note reviews some of the major climate change science research and innovations of 2006. The 2006 research confirms a trend that has become increasingly clear: climate change not only has significant ramifications for the physical climate, hydrological cycle, and ecosystems, but many significant impacts are already being witnessed today. Climate change has begun—much more rapidly and more fundamentally than heretofore anticipated—to transform the world. The rate and magnitude of these changes have implications not only for global efforts to reduce global greenhouse gas emissions, but also for efforts to adapt to both the already observed impacts and to the anticipated additional consequences that will emerge as global warming trends continue.

This review is an update to a similar report prepared in 2006 that reviewed new findings from 2005. As with that note, in preparing this review, WRI consulted a number of journals (*Nature, Science, Geophysical Research Letters, Proceedings of the National Academy of Sciences, Climatic Change, Global Biogeochemical Cycles, Heredity, Conservation Biology, Annual Review of Ecology, Evolution, and Systematics, Biodiversity and Conservation*) and information from organizations and climate/energy websites (Department of Energy, World Meteorological Organization, Renewable Energy Access, United Nations Development Programme, and U.S. Geological Survey).

Similar to last year's Climate Science Stories, the review is presented in four sections, which categorize the stories into:

1. Physical Climate (temperature increases, ocean behavior, abrupt change, and greenhouse gas concentrations)
2. Hydrological Cycle (hurricanes, glacial/snow melt, and water supply)
3. Ecosystems and Ecosystem Services
4. Climate Change Mitigation Technologies and Economics (excluding those that are proprietary to private companies or not open to peer review)

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

While this report has been prepared looking *only* at new scientific findings from 2006, a wider and considerably more comprehensive review and assessment has been released in the first half of 2007 by the Intergovernmental Panel on Climate Change (IPCC). Prepared by scientists from more than 130 countries, that report will offer not only a more thorough examination of the scientific and technology literature, but provide a much more in-depth analysis of how the literature's results should be interpreted. Broadly, however, this short review corroborates the IPCC findings.

While the IPCC's report is more authoritative, it has one significant difference: the IPCC rules set a deadline for the inclusion of material in order to assure that all literature cited has been fully reviewed and responses have been incorporated. The IPCC thus does not include all of the results from analyses completed during 2006. In contrast, *Climate Science 2006,* while significantly less comprehensive, includes new scientific material from as recently as December 2006. Some of this material, particularly that related to ice cover (including in Greenland, Antarctica, and mountain glaciers), suggests the IPCC's findings are generally cautious. However, as with any new literature, it will take some time to assess the validity and robustness of the new results cited here.

Perhaps the strongest message to emerge from this report is that the scientific community is ever more emphatic about the scale of change, the human cause of change, and the rapidity with which

change is becoming manifest. Altogether, the individual results described below suggest that the window of opportunity to act to avoid the worst of the prospective impacts and damage is rapidly closing. Furthermore, these results suggest that we may already be seeing signs that abrupt, nonlinear climate change is materializing, and that tipping points in natural systems may be in close reach, if not already exceeded.

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

As in 2005, a number of new studies in 2006 provided continued and increasingly robust evidence that the physical climate system is changing. These studies suggest, however, that the changes are being observed in ways that, while predicted, had been anticipated to be slower and more modest than observed. This section reviews some of these recent results, including changes in global and regional temperatures, ocean behavior, abrupt climate change, and the increase in greenhouse gas concentrations.

### Greenhouse Gas Concentrations

Greenhouse gas (GHG) concentrations continue to rise at a steady and increasing rate. For the month of December 2006, the atmospheric concentration of $CO_2$, measured at Mauna Loa in Hawaii by NOAA (see: http://www.cmdl.noaa.gov/projects/web/trends/co2_mm_mlo.dat), was 382.43 ppm. Over the past few years, $CO_2$ concentration has increased by as much as 2.5 ppm/year—much faster than in earlier years, when the concentration seldom increased by more than 1.0 to 1.5 ppm a year. According to Australia's CSIRO (http://www.csiro.au/csiro/content/standard/ps2im.html), global emissions of $CO_2$ in 2005 were approximately 7.9 billion metric tons (of carbon)—an increase of more than 2.5 percent over 2004. This represents a very significant increase. In the 1990s, annual $CO_2$ emissions growth was less than 1 percent per year.

### Temperature Increases

One of the most significant indicators of global climate change is an increase in the global average surface temperature. Not only is 2006 the warmest on record for the contiguous United States (http://www.ncdc.noaa.gov/oa/climate/research/2006/ann/us-summary.html), as well as tied for 5th warmest year on record globally (http://www.ncdc.noaa.gov/oa/climate/research/2006/dec/global.html#Temp), but other studies indicate a continued (at least century-long) warming trend, and a projected continued increase in global average surface temperature going forward.

- **Lawrimore, Jay and David Easterling. "Climate of 2006 – December in Historical Perspective." National Climatic Data Center (Asheville, North Carolina). 12 January 2007 at http://www.ncdc.noaa.gov/oa/climate/research/2006/dec/dec06.html**
- **World Meteorological Organization."WMO Statement on the Status of the Global Climate in 2006." 14 December 2006 at http://wcrp.wmo.int/pdf/press_release_768.pdf.**

  According to estimates from the National Climatic Data Center, the largest global archive center of weather data, the global average of land and sea surface temperatures for January-December 2006 was tied for the fifth warmest on record. The World Meteorological Organization, a Specialized Agency of the United Nations system, reported that the temperature increase in the past 30 years greatly exceeds increases in previous decades. The study, based on climatic datasets maintained by the UK and U.S., finds that the temperature increase (measured as an increase over the mean between 1961 and 1990) was twice as large in the Northern Hemisphere as in the Southern Hemisphere (0.53°C vs. 0.27°C).

  ***Implications:*** The events depicted above are in accordance with trends over the past century. Moreover, the United Kingdom's Meteorological Office predicts that 2007 will be the warmest year ever as temperatures will be bolstered by the El Niño that emerged in the eastern Pacific Ocean in 2006, which is anticipated to exacerbate the warming trends experienced in 2006 (http://www.metoffice.gov.uk/corporate/pressoffice/2007/pr20070104.html).
- **Hansen, James; Sato, Makiko; Ruedy, Reto; Lo, Ken; Lea, David W; and Martin Medina-Elizade. "Global Temperature Change." *Proceedings of the National Academy of Sciences* 103(39): 14288-14293 (26 September 2006) at http://www.pnas.org/cgi/content/abstract/103/39/14288.**

  The Earth has warmed 0.8°C in the last century, having increased 0.2°C per decade within the last 30 years. Using paleoclimatic data gathered from climate proxies as well as global temperature records, Hansen et al. suggest that temperatures in the western Pacific Ocean are now within roughly 1°C of the maximum temperature ever experienced during the last one million years. Moreover, the scientists suggest

that the warming differential between the western and eastern Pacific regions may be making an increasing contribution to the strength of El Niño, especially those that occurred in 1983 and 1998. They note that species extinctions are already occurring today and will become even more likely as a result of future warming. A warming of 3°C, the scientists wrote, could result in the extinction of roughly 60% of all species. In addition, drawing information from the Middle Pliocene, an era about three million years ago when temperatures were 2 to 3°C warmer and sea level was 25-35 meters higher than today's level, Hansen et al. suggest that warming greater than $1^0$C will constitute a "dangerous" level of warming.

***Implications:*** Avoiding dangerous human interference with the climate is the objective of the United Nations Framework Convention on Climate Change. The Hansen et al. study suggests that virtually any additional increase in global temperature represents a "dangerous" level. Because global temperature is currently increasing approximately 0.2°C per decade, and there is considerable infrastructural inertia (i.e., it will take decades to develop viable alternatives to fossil energy, replace car fleets, build new buildings and industry, etc.), this study implies that we must act soon and with considerable stringency to avoid major damages.

- **Scheffer, Marten; Brovkin, Victor; and Peter M. Cox. "Positive Feedback between Global Warming and Atmospheric $CO_2$ Concentration Inferred from Past Climate Change." *Geophysical Research Letters* 33(L10702). 26 May 2006 at http://www.agu.org/pubs/crossref/2006/2005GL025044.shtml.**

- **Torn, Margaret S. and John Harte. "Missing Feedbacks, Asymmetric Uncertainties, and the Underestimation of Future Warming" *Geophysical Research Letters* 33(L10703). 26 May 2006 at http://www.agu.org/pubs/crossref/2006/2005GL025540.shtml.**

Despite modelers' best efforts to project future warming, model results could be altered for several reasons, such as because of the feedback from changes in the terrestrial sinks of carbon dioxide and methane (for example, increased emissions resulting from the melting of permafrost); the decline in the ocean sink (as algal growth precludes $CO_2$ absorption or ions from calcium carbonate-based shells are released and the ocean becomes more saturated with $CO_2$); and/or changes in albedo (from loss of snow and ice cover).

Scheffer et al. analyze past feedbacks and employ a model to come up with a potential range of positive feedbacks. They find that an extra 15% to almost 80% warming should be added to future projections as a result of taking potential feedbacks into account. Torn and Harte's analysis corroborates this, finding that current models underestimate critical positive feedbacks of $CO_2$ and methane. They suggest that the equilibrium temperature change associated with a doubled $CO_2$ concentration should be revised upward from 1.5 to 4.5°C to 1.6 to 6°C warming. Torn and Harte's analysis relies on ice core data and known climatic relationships which demonstrate a sizeable, long-term feedback that is not usually included in standard models. They are particularly concerned about permafrost thawing, which emits methane and carbon dioxide and changes soil carbon storage.

***Implications:*** If proven correct, these studies' results suggest the potential for a significant amplification in warming, as well as an exacerbation of deleterious regional climate impacts (e.g. permafrost thawing has already caused ecological and infrastructural damage). This, in turn, suggests both a more limited time to forestall climate change, and a need to rapidly improve global climate adaptation programs.

## Ocean Behavior

None of the 2006 reports are of the scale of those in 2005 (e.g., with the startling information about the decline in the volume of water circulating in the eastern North Atlantic Ocean as reported by Bryden et al. in *Nature* in December 2005 or the radical change in ocean acidity as indicated in the 2005 report of the UK Royal Society). Nonetheless, they indicate an ongoing and significant set of observed and projected changes.

- **Church, John A. and Neil J. White. "A 20th Century Acceleration in Global Sea-level Rise." *Geophysical Research Letters* 33(L01602). 6 January 2006 at http://www.agu.org/pubs/crossref/2006/2005GL024826.shtml.**

Church and White document sea level rise over the 20th century based on data from tide-gauge records from 1950-2000. The authors find that sea level rise rapidly accelerated after 1993 when compared with other periods during the century. Earlier analyses of sea level rise had failed to detect such an acceleration.

***Implications:*** This research suggests that if the new, higher rates of sea level rise continue, ocean levels would be 28 to 34 centimeters higher than 1990 levels by 2100, which is consistent with moderate warming scenarios.

However, the results also suggest a non-linear behavior—which, if carried forward into the future, could imply higher than anticipated increases, with concomitant impacts to coastal ecosystems and low-lying populations. The dynamic behavior of ice sheets, as well as the processes that might lead to it, are currently not incorporated into IPCC estimates of sea level rise. If such dynamic effects are included, the full range of possible sea level rise, including all uncertainties, is likely to be even greater than anticipated by the IPCC.

- **Rennermalm, Asa K.; Wood, Eric F.; Dery, Stephen J.; Weaver, Andrew J.; and Michael Eby. "Sensitivity of the Thermohaline Circulation to Arctic Ocean Runoff."** ***Geophysical Research Letters*** **33(2006). 20 June 2006 at http://www.agu.org/pubs/crossref/2006/2006GL026124.shtml.**

  The thermohaline circulation is a critical component of ocean circulation, acting as a conveyer belt bringing colder, polar deepwater to the equator and warmer surface waters to the North Atlantic. Rennermalm et al. demonstrate that river runoff from the Arctic plays a critical role in determining the circulation's strength. The authors used a model developed by the University of Victoria and examined the sensitivity of the circulation to varying levels of river discharge. An inverse relationship between the strength of the thermohaline circulation and Arctic river runoff was found (the higher the runoff, the weaker the circulation).

  ***Implications:*** Warming temperatures in the Arctic are leading to ice melt and increased river runoff. Between 1936 and 1999, river discharge increased by 7% and between 1957 and 2004, the thermohaline circulation, measured in the North Atlantic, had apparently slowed by 30% (although more recently, there has been some suggestion that such shifts mark fluctuations rather than an overall slowing). While other factors contribute to the circulation mechanism, the authors suggest that river runoff is a major factor affecting the strength of this ocean conveyer belt. The weakening of the thermohaline circulation, the authors suggest, could eventually lead to its collapse, which would impact the transfer of warm waters to the North Atlantic and have larger consequences for regional temperature and precipitation (particularly in northern Europe, which has been warm despite its latitude).

- **Peterson, Bruce J.; McClelland, James; Curry, Ruth; Holmes, Robert M.; Walsh, John E.; and Knut Aagaard. "Trajectory Shifts in the Arctic and Subarctic Freshwater Cycle."** ***Science*** **313(5790): 1061-1066. 25 August 2006 at http://www.sciencemag.org/cgi/content/full/313/5790/1061.**

  Peterson et al. quantify all freshwater inputs to the Arctic and North Atlantic to assess whether the freshening—or reduction in salinity—of the North Atlantic can be attributed to these sources instead of ocean mixing and circulation processes. They find that over the last 50 years 2000 $km^3$ of freshwater was discharged from glacial melt; 15,000 $km^3$ from sea ice loss; and 20,000 $km^3$ from excess river flow and precipitation—a total that matches the measured ocean freshening. They hypothesize that as freshwater accumulates in the Arctic Ocean, it is likely to spread southward.

  ***Implications:*** Freshwater inputs and their spread to other latitudes are likely to impact ocean and atmospheric cycles, which could have large implications for regional temperature and moisture. The inputs analyzed by Peterson et al. have been demonstrated by other research to largely result from human-induced warming. If freshwater contributions continue unabated, the impacts to ocean behavior will likely be amplified. Some models have projected that a freshening of the oceans will slow or even stop the ocean's conveyer belt, or thermohaline circulation. Changes in ocean salinity could also shift entire coastal ecosystems as nutrient fluxes and phytoplankton and zooplankton production is altered.

- **Fedorov, A. V.; Dekens, P. S.; McCarthy, M. ; Ravelo, A. C., deMenocal, P. B.; Barreiro, M.; Pacanowski, R. C.; and S. G. Philander. "The Pliocene Paradox (Mechanisms for a Permanent El Niño)."** ***Science*** **312(5779): 1485-1489. 9 June 2006 at http://www.sciencemag.org/cgi/content/full/312/5779/1485.**

  The Pliocene epoch (which ended ~2 million years ago) had a climate similar to our own (although somewhat warmer). However, although the carbon dioxide concentration was similar to today's, sea levels were roughly 25 meters above current levels, and polar temperatures were substantially higher. Federov and colleagues explain the "Pliocene paradox" in a recent publication in *Science* magazine, finding that a permanent El Niño changed cloud distribution and extent, causing a change in the local albedo. The authors suggest that the Pliocene climate could return if the increases in the carbon dioxide concentration

continue and that this would lead to greater precipitation and temperatures at high latitudes and a deepening of the layer between surface and deep ocean waters.

***Implications:*** The IPCC's Third Assessment Report suggests sea level rise would be a modest 9–88 cm with projected climate changes over the next 100 years. However, if Fedorov et al.'s analysis is correct, a more radical shift could occur—with the potential for constant El Niño conditions, massive ice melt causing 25 meters of sea level rise above today's levels, and with drastic implications for low-lying ecosystems and peoples.

- **Vecchi, Gabriel A. ; Soden, Brian J.; Wittenberg, Andrew T.; Held, Isaac M.; Leetmaa, Ants; and Matthew J. Harrison. "Weakening of Tropical Pacific Atmospheric Circulation Due to Anthropogenic Forcing."** ***Nature*** **441(7089): 73-76. 4 May 2006 at http://www.nature.com/nature/journal/v441/n7089/full/nature04744.html.**

  Vecchi et al. find that since the mid-19th century, the Walker Circulation (a component of tropical atmospheric circulation which cycles across the equatorial region of the Pacific Ocean) has weakened. The scientists attribute the weakening to human-induced climate forcing and suggest that the weakening may increase to roughly 10% by 2100. As ocean surface water warms, water vapor increases at a faster rate than precipitation, which impacts atmospheric circulation.

  *Implications:* When the Walker Circulation is weakened, upwelling of nutrient-rich waters around the equator is dampened. Without these biologically rich waters, marine ecosystems could face a major transformation and a substantial loss of productivity. These changes would come on top of the already observed reductions in productivity measured in the Millennium Ecosystem Assessment of 2005, largely due to human activity in the oceans and along coastal areas.

## Abrupt Change

Much of the analysis of future global climate has assumed that changes will be incremental and relatively slow. Thus, while major effects could emerge, they will only arise over decades or even centuries. However, an emerging literature has been developing that suggests an alternative: the climate system may reach a threshold and tip quickly into a new state—with massive changes arising in a few years rather than over a period of decades to centuries. Such abrupt shifts have been observed extensively in the geologic record—indeed, they seem to be the norm rather than the exception.

- **Tebaldi, Claudia; Hayhoe, Katharinec; Arblaster, Julie M. and Gerald A. Meehl. "Going to Extremes: An Intercomparison of Model-Simulated Historical and Future Changes in Extreme Events."** ***Climatic Change*** **79(3-4). December 2006 at http://springerlink.com/content/08l058mt1k828814/.**

  While climate models often agree on mid-range estimates of a climatological response, it is more difficult to find agreement with regard to extreme scenarios. However, a new study by Tebaldi and colleagues illustrates the emerging consensus among nine of the world's leading climate models on future extreme climate events. Simulating conditions between 1980-1999 and 2080-2099 and adopting scenarios for various warming regimes, the models examined ten indicators of climate extremes and all agreed on several key conclusions. While the average growing season could lengthen in Europe, Asia, and North America and frost days could decrease in number, much of the news is negative. Dry events, which can lead to or exacerbate droughts, may be more characteristic of southern Europe, eastern Brazil, and the western U.S. Meanwhile, regions that lie in higher northern latitudes will experience heavy precipitation, and increased risk of heat waves along with considerably warmer nights, will affect all regions.

  ***Implications:*** Extreme events are difficult to plan for and, the authors note, contribute to the majority of climatic damages. The events described in this study would have devastating economic, ecological, and social impacts and should be taken seriously in management plans, adaptation initiatives, and mitigation targets. The authors do suggest that the risk of such extreme changes is reduced under lower emissions scenarios.

- **Holland, Marika M.; Bitz, Cecilia M.; and Bruno Tremblay. "Future Abrupt Reductions in the Summer Arctic Sea Ice."** ***Geophysical Research Letters*** **33(L23503). 12 December 12, 2006 at http://www.agu.org/pubs/crossref/2006/2006GL028024.shtml.**

  Warming is accentuated at the poles in part because of changes in albedo, or surface reflectivity. This is due in part to melting ice exposing open water, which more readily absorbs incoming solar radiation (open water, with a dark surface, absorbs more energy than does the reflective ice). This positive feedback partly explains the dramatic changes in the Arctic over the last several decades. A new study

by Marika Holland et al. attempts to determine whether such positive feedbacks, exacerbated by Atlantic Ocean warming, can lead to rapidly accelerating changes in Arctic sea ice cover. Employing the Community Climate System Model, Holland et al. studied trends of recent ice retreat and constructed future ice scenarios for the coming century. The results indicate that ice retreat will not be constant but, rather, that accelerating changes in ice cover will characterize future decades. Notably, the models suggest that by 2040, there may no longer be any summer sea ice coverage in the Arctic, an estimate that is decades earlier than previous estimates.

***Implications:*** The authors suggest that the risk of complete Arctic summer sea ice loss after one year of accelerated ice retreat is higher under augmented greenhouse gas emissions, and it will be increasingly difficult to regain ice coverage during winters. Feedback loops such as these may be found in other parts of the climate system; virtually all point to greater change than might be expected under the more common incremental modest global warming scenarios usually presented in the literature.

- **Leifer, I.; Luyendyk, B. P.; Boles, J.; and J. F. Clark "Natural Marine Seepage Blowout: Contribution to Atmospheric Methane." Global Biogeochemical Cycles 20(GB3008). 20 July 2006 at http://www.agu.org/pubs/crossref/2006/2005GB002668.shtml.**

  Leifer et al. show that methane, a greenhouse gas that, on a mass basis, has 23 times the global warming potential of $CO_2$, is being released from geologic sources on the sea floor. Studying the ocean bottom off the coast of Santa Barbara, California, Leifer et al. measured the seepage of methane with the use of video cameras, test dye, and flight photography of the bubbling methane once it had reached the surface. The results provide unprecedented documentation of a methane eruption from a marine seepage today.

  ***Implications:*** Some climate scientists have hypothesized that if methane were to be released from natural geologic sources on the sea floor, it could rise and leak into the atmosphere, augmenting greenhouse gas levels. Blowout events, such as one documented in this study, can lead to rapid transfer of methane. This research enhances our understanding of potential methane budget increases and the possibility of abrupt climate change. If, as some scientists have asserted, warming ocean temperatures lead to a collapse of methane hydrates (crystalline structures that lock up methane), the gas could be rapidly transferred to the atmosphere from depths of hundreds of meters. This could be a significant problem, since some scientists (e.g. see Archer, David. "Fate of Fossil-fuel $CO_2$ in Geologic Time." *Journal of Geophysical Research* 110(**C09S05**), 21 September 2005 at http://www.agu.org/pubs/crossref/2005.../2004JC002625.shtml) believe that hydrate deposits are as abundant as all fossil fuel resources combined (equating to several thousand gigatons of carbon).

- **Zimov, Sergey A.; Schuur, Edward A. G.; and F. Stuart Chapin III. "Permafrost and the Global Carbon Budget." *Science* 312(5780): 1612-1613. 16 June 2006 at http://www.sciencemag.org/cgi/content/full/312/5780/1612.**

  In addition to the world's oceans, soils and vegetation, permafrost—or permanent frozen land—is a substantial reservoir of carbon. Zimov, Schuur and Chapin quantify the carbon content of permafrost and find that 950-970 gigatons of carbon are stored in various permafrost types – a total that more than doubles estimates from previous (incomplete) studies. (For comparison, there is ~650 gigatons of carbon stored in vegetation globally.) Their study also shows that this stored carbon is quickly released when permafrost is thawed.

  ***Implications:*** Thawing of permafrost occurs when there are prolonged periods of temperatures above freezing. We are already witnessing such a phenomenon today—and expect more as global warming continues. In addition to the landscape degradation that occurs when permafrost thaws, the massive volumes of carbon stored in the permafrost could have devastating consequences for the future climate should it be released into the atmosphere.

- **Zhang, Minghua and Hua Song. "Evidence of Deceleration of Atmospheric Vertical Overturning Circulation over the Tropical Pacific." *Geophysical Research Letters* 33(L12701), 16 June 2006 at http://www.agu.org/pubs/crossref/2006/2006GL025942.shtml.**

  Sea level pressure is the atmospheric pressure caused by the weight of the total column of air on the sea. Zhang and Song have found that sea level pressure has been reduced between 2–13% over the past five decades. Using data collected by ships and marine stations, as well as two general circulation models, they attribute the change in sea level pressure to recent warming. They conclude that the over-

turning circulation of the atmosphere, which results from varying pressure gradients and is key in weather and climate regulation, is weakening. Zhang and Song expect such weakening to lead to a decline in the strength of the trade winds — and over time, sustained El Niño conditions.

***Implications:*** While the trade winds are no longer pivotal for intercontinental commerce, they are critical for migrating species as well as a significant influence on global weather patterns. Changes to these—and perhaps, more seriously, expected sustained El Niño systems—can have considerable negative social and ecological consequences.

## HYDROLOGICAL CYCLE (HURRICANES, GLACIAL/SNOW MELT, AND WATER SUPPLY)

The hydrologic cycle, with its attendant rainfall, droughts, storms, and runoff, is an essential element of modern human and natural ecosystems. Climate change is clearly changing the norms. Recent literature highlights the extent of the changes. The overall projections remain bleak, in spite of some new studies that suggest that some elements of change, such as hurricane intensity, may not be worsening as quickly as thought in 2005.

### Hurricanes

Following the flurry of new analyses reported in 2005 (e.g. see Emmanuel and Webster et al. reporting in *Nature* and *Science* in 2005) on the increasing severity of hurricanes and typhoons in the world's ocean basins, the scientific community has undertaken new, albeit yet inconclusive, analysis. On balance, the studies in 2006 suggest increased storm intensities are real and likely to increase with a continued rise in average global temperatures (see the exemplary studies reported below). However, others suggest that the outcome may not be so dire: that monitoring techniques may be flawed (misconstruing hurricane intensities); that new technology is merely counting more storms and, therefore, skewing the statistics; or that the storm frequency is merely part of a larger multi-decadal cycle and not a function of climate change. The general consensus seems to be that there is a real trend, even if it is, to a certain extent, overlain by other phenomena.

- **Trenberth, Kevin E. and Dennis J. Shea. "Atlantic Hurricanes and Natural Variability in 2005."** ***Geophysical Research Letters*** **33(L12704). 27 June 2006 at http://www.agu.org/pubs/crossref/2006/2006GL026894.shtml.**
- **Santer, B.D.; Wigley, T.M.; Gleckler, P.J.; Bonfils, C.; Wehner, M.F.; Achutarao, K; Barnett, T.P.; Boyle, J.S.; Bruggemann, W.; Fiorino, M.; Gillett, N.; Hansen, J.E.; Jones, P.D.; Klein, S.A.; Meehl, G.A.; Raper, S.C.; Reynolds, R.W.; Taylor, K.E.; and W.M. Washington. "Forced and Unforced Ocean Temperatures in Atlantic and Pacific Tropical Cyclogenesis Regions."** ***Proceedings of the National Academy of Sciences*** **103(38): 13905-13910. 12 September 2006 at http://www.pnas.org/cgi/content/abstract/103/38/13905.**

  Trenberth and Shea set out to determine causal factors in 2005's unusual hurricane activity (a record 28 named storms in the North Atlantic alone, including the greatest number of category 4 and 5 storms). While rising sea surface temperatures have long been linked to increased hurricane activity, analyses often fail to determine the proportion of sea surface temperature increase that is due to natural variability versus human-induced climate change. The authors find that of the 0.9°C increase in sea surface temperatures in the tropical North Atlantic from 1901–1970, 0.45°C—or half—can be attributed to climate change driven by human activity, while only 0.2°C can be attributed to lingering impacts of the El Niño and the remainder is due to natural variation. Thus, the largest share of warming of tropical Atlantic sea surface temperature is due to human-induced climate change.

  Santer et al. use 22 climate models to determine what percentage of sea surface temperature increases, and resultant hurricane intensity, is due to natural variables rather than external forcings. They find that between 1906-2005 there was an 84% likelihood that two-thirds of the sea surface temperature rise resulted from external variations that are "forced" on the system. Specifically, they note that of these external factors, human-induced variation is the primary cause of rising sea surface temperature.

  ***Implications:*** These studies corroborate the idea that anthropogenic climate change can and has increased hurricane intensity. If correct, they bear out earlier economic and social implications: the 2005 hurricane season not only caused infrastructure damage and monetary losses on the order of US$200 billion, but also considerable loss of lives. If global greenhouse gas emissions remain unchecked, we will continue to raise sea surface temperatures substantially with attendant increases in storm intensity.

## Glacial/Snow Melt

Warming temperatures and the resultant changes in surface reflectivity have implications for glacial and snow melt. The stories below suggest that melting trends are significant and in some regions accelerating. One of the most telling tales of ice sheet melt is the recent calving off of the 66 $km^2$ (equivalent to11,000 football fields) Ayles ice shelf, one of six remaining ice shelves in Arctic Canada. While the event transpired in 2005, scientists only recognized the loss in 2006 by looking at satellite images of the area. The ice shelf was at least 3,000 years old (http://www.cbc.ca/cp/science/061228/g122802A.html).

- **Rignot, Eric and Pannir Kanagaratnam. "Changes in the Velocity Structure of the Greenland Ice Sheet." *Science* 311(5763): 986-990. 17 February 2006 at http://www.sciencemag.org/cgi/content/full/311/5763/986.**
- **Chen, J. L.; Wilson, C.R. ; and B. D. Tapley. "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet." Science 313(5795): 1958-1960. 29 September 29, 2006 at http://www.sciencemag.org/cgi/content/full/313/5795/1958.**

  While most surveys and projections of the Greenland ice sheet report a net loss of glacial coverage, these studies argue that many previous assessments underestimate the loss, as they both ignore some of the dynamic nature of ice loss as well as ice loss in a number of major glaciers that were not included in surveys. Employing satellite radar and remote sensing, Rignot and Kanagaratnam find that Greenland's ice mass loss doubled in the last ten years—from ~90 $km^3$/yr to 220 $km^3$/yr, which indicates that Greenland's contribution to global eustatic sea level rise increased from 0.23 ± 0.08 mm/year in 1996 to 0.57 ± 0.1 mm/year in 2005. Most significantly, the large majority of this loss was caused by ice discharge from glaciers, resulting from velocity increases and changes in outlet glaciers which draw from interior basins, rather than runoff. This loss is confirmed by Chen, Wilson, and Tapley using other satellite gravity measurements. According to their analysis, previous estimates were off by a factor of three (earlier numbers suggest a net loss of 82 ±28 $km^3$/ year, while the new assessment shows a loss of 239 ±23 $km^3$ /year). Chen et al. attribute the discrepancy to substantial increase in melting within the last year and a half, as well as better resolution in their models.

  ***Implications:*** The methods employed in these studies produce results that far exceed previous estimates of glacial loss. They suggest that earlier global models both significantly underestimated glacial loss, and represent an artificially low estimate of total ice sheet melting. This, in turn, has implications for the timing of large scale Greenland ice melt, for general ocean circulation, and for consequent sea level rise. It might be noted that if it were entirely melted, the Greenland ice sheet would contribute roughly 7 meters of global sea level rise.
- **Velicogna, Isabella and John Wahr. "Measurements of Time-Variable Gravity Show Mass Loss in Antarctica." *Science* 311(5768): 1754-1756. 24 March 2006 at http://www.sciencemag.org/cgi/content/full/311/5768/1754.**
- **Monaghan, A.J.; Bromwich, D.H.; Fogt, R.L.; Wang, S.; Mayewski, P.A.; Dixon, D.A.; Ekaykin, A.; Frezzotti, M.; Goodwin, I.; Isaksson, E.; Kaspari, S.D.; Morgan, V.I.; Oerter, H.; Van Ommen, T.D.; Van der Veen, C.J.; and J. Wen. "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year." *Science* 313(5788): 827-831. 11 August 2006 at http://www.sciencemag.org/cgi/content/full/313/5788/827.**

  The UN's Intergovernmental Panel on Climate Change projects in its 2001 report that the next century will see some net ice gain—rather than net loss—from Antarctica as precipitation (and hence snow thickness) increases with global warming. However, Velicogna and Wahr argue that this projection fails to take into account coastal regions, where the ice has low thresholds for resistance to temperature rise. Using data from the Gravity Recovery and Climate Experiments (GRACE) survey satellite, the scientists were able to measure the ice loss. They found that Antarctica contributed 0.4 ± 0.2 mm of sea level rise per year during the period 2002 to 2005, the majority of which was coming from the Western Antarctic ice sheet. In a separate study, Monaghan et al. demonstrate that snowfall over the Antarctic continent has not increased since the 1950s, and, therefore, sea level rise will likely continue unmitigated, as Antarctica is characterized by a net mass loss.

  ***Implications:*** Antarctic melt is usually not included in medium- and short-term models of global warming impacts and sea level rise. If the findings in these studies turn out to be true, such melting must be included in climate models—and the results will raise overall anticipated sea levels.

- **Overpeck, J.T.; Otto-Bliesner, B.L.; Miller, G.H.; Muhs, D.R.; Alley, R.B.; and J.T. Kiehl. "Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise." *Science* 311(5768): 1747-1750. 24 March 2006 at http://www.sciencemag.org/cgi/content/full/311/5768/1747.**

  Overpeck et al. assert that sea level rise may very well be substantially faster and more significant than initially thought. Examining the last interglacial period 127,000 to 130,000 years ago (the Eemian interglacial), during which warming was approximately equivalent to that projected for the year 2100, they find sea levels 4 to 6 meters above those of the present day. Moreover, they found that sea level rise (specifically related to melting of the Greenland ice sheet and the West Antarctic ice sheet) was extremely rapid. They conclude that the potential for massive ice sheet loss is real, and that it may be triggered even with modest warming.

  ***Implications:*** If this result is correct, it suggests the linear projections of ice sheet melt—assumed to be quite modest in most global warming scenarios—are vastly understated. The expectation that global warming could exceed levels of the last interglacial further increases the significance of these results, implying a clear potential for sea level rise of several meters by 2100 rather than only the tens of centimeters suggested.

- **Josefino C. Comiso. "Abrupt Decline in the Arctic Winter Sea Ice Cover." *Geophysical Research Letters* 33(L18504) 30 September 2006 at http://www.agu.org/pubs/crossref/2006/2006GL027341.shtml.**

- **National Snow and Ice Data Center. "Arctic Sea Ice Shrinks as Temperatures Rise." 3 October 2006. http://nsidc.org/news/press/2006_seaiceminimum/20061003_pressrelease.html.**

  While scientists have predicted a future decline in winter sea ice coverage in the Arctic, so far, those losses had been thought to still be minimal. However, Comiso analyzed trends in winter ice coverage loss in the Arctic and found that winter ice loss was at record levels in both 2005 and 2006. Using satellite data, surface temperature data, and data on natural variability and wind, Comiso shows that ice has retreated in the region roughly 66% more than in previous years. He suggests that warm temperatures prevent the refreezing of the ice, which leads to a downward spiral in ice loss. Comiso asserts that many forces are at play: ice-albedo feedbacks, which occur when ice retreats and, in turn, solar radiation reflectivity is altered, increasing absorption rates; higher greenhouse gas levels, which lead to more warming; and the power of longwave radiation during darker months in winter.

  In addition, research led by Walt Meier has detected a large polynya (an area of open water that persists despite being surrounded by sea ice) north of Alaska. While the scientists have yet to determine whether the polynya appearance can be attributed to warming, Meier did note that climate change would likely result in polynya features. At its greatest extent, the polynya was as big as the state of Indiana.

  ***Implications:*** These results show that the projections of winter ice retreat have already arrived in the Arctic—well ahead of expectations. However, it is too early to determine whether this is a true trend, unlike that of summer sea ice, which is known to have thinned and retreated significantly over the last several decades. The disappearance of winter ice is likely to lead to a more rapid retreat of ice in the summer and, in turn, an increase in the rate of annual loss of Arctic ice cover, bringing closer the date at which the Arctic is ice-free.

- **Zemp, Michael; Haeberli, Wilfried; Hoelzle, Martin; and Frank Paul. "Alpine Glaciers to Disappear within Decades?" *Geophysical Research Letters* 33(L13504). 15 July 2006 at http://www.agu.org/pubs/crossref/2006/2006GL026319.shtml.**

  According to Zemp et al., alpine glaciers in the European Alps had already lost almost 50% of their 1850 mass by 2000, with the majority of ice disappearing since 1985. Employing measurements, remote sensing, and modeling, Zemp et al. quantified past glacial loss as well as projected area change. They find that the large majority (approximately 90%) of alpine glaciers are less than 1 $km^2$ in size, which will further increase their vulnerability to future warming. Modeling future ice loss, the authors suggest that under a scenario of 3°C warming, only 10% of the area covered by glaciers in 1850 would be left. A 5°C warming scenario would leave the European Alps essentially completely ice free.

  ***Implications:*** The loss of the European Alps' glaciers will transform ecosystems as glacial runoff disappears: sediment loads will be altered, affecting river composition; stability of montane slopes will weaken; and water resources will be at risk. The same consequences would exist for other regions of the world with mountain glaciers.

## Water Supply

One of the most devastating potential climate related impacts is likely to be water related. According to a 2006 United Nations Development Report (http://www.unesco.org/water/wwap/wwdr2/table_contents.shtml), as of 2000, 20% of the global population had no natural water supply, and 65% had only low-to-moderate supplies. In a world in which shortages of potable water already afflict millions of people, further losses from climate related changes will pose enormous difficulties. While human communities may adapt, natural ecosystems may be permanently destroyed.

- **Bradley, Raymond S.; Vuille, Mathias; Diaz, Henry F.; and Walter Vergara. Threats to Water Supplies in the Tropical Andes. *Science* 312(5781): 1755-1756. 23 June 2006 at http://www.sciencemag.org/cgi/content/full/312/5781/1755.**

  Warming at higher altitudes has severe implications for glacial melt. Bradley et al. report that warming in the tropical Andes will be more pronounced at higher rather than lower altitudes. Until recently, few measurements had been made above 4,000 meters, and, thus, warming at higher latitudes had not been adequately documented. The scientists obtained measurements from 268 mountain stations, which indicate that tropical Andes' temperatures increased roughly 0.11°C per decade between 1939 and 1998. Extrapolating these trends, as well as predicted $CO_2$ levels and changes in surface reflectivity as glaciers melt, the scientists entered the data into eight general circulation models and found that glaciers in the American Cordillera—a mountain range extending from Alaska to Chile—may disappear within the next few decades

  ***Implications:*** Many cities are almost entirely dependent on water from high altitude sources. For example, La Paz and Quito, rely partly on glacial water sources. In addition, agriculture relies on a steady glacial source, as does hydroelectric power, which many Andean countries depend on for energy sources. Depletion of such resources could lead countries in search of new forms of energy, and they may turn to fossil fuels which will further exacerbate climate change and, in turn, glacial melt. Ecosystems are also dependent on high altitude water stocks, and the loss of this water supply could lead to ecosystem transformation and biodiversity loss, with grave implications for the services generated by ecosystems.

- **Maarten de Wit and Jacek Stankiewicz. "Changes in Surface Water Supply Across Africa with Predicted Climate Change." *Science* 311(5769): 1917-1921. 31 March 2006 at http://www.sciencemag.org/cgi/content/full/311/5769/1917.**

  De Wit and Stankiewicz calculate future water supply in Africa by examining the reduction in drainage capability. Even using (as the authors state) a somewhat optimistic model, they find that there is a nonlinear relationship between rainfall and drainage density, which is a ratio of the length of streams divided by the area of the drainage basin. Areas with low levels of rainfall have very little drainage capabilities. The authors discover that future precipitation regimes will lead to a decrease in drainage, and a quarter of Africa's surface water will be left increasingly vulnerable by the end of the 21st century. In some cases, losses will be extremely severe: for example, de Wit and Stankiewicz predict that regions around Cape Town will lose at least half of their perennial supply.

  ***Implications:*** Not only do water shortages have drastic implications at local and regional scales, but water bodies (both lakes and rives) are also often areas of intense conflict: almost 40% of all international border areas are water-based. The flows (or lack thereof) are already exacerbating regional and international tensions, and will likely become worse as other climate impacts limit food production and increase disease.

- **Goswami, B. N.; Venugopal, V.; Sengupta, D.; Madhusoodanan, M. S.; and Prince K. Xavier. "Increasing Trend of Extreme Rain Events Over India in a Warming Environment." *Science* 314 (5804): 1442-1445. 1 December 2006 at http://www.sciencemag.org/cgi/content/full/314/5804/1442.**

  Because the average rainfall over the past five decades in India has remained relatively constant despite rising global temperatures, few clues about climate change's impact on India's monsoon season had previously been revealed. However, a new study by Goswami and colleagues was able to differentiate between moderate (5 mm/day to <100 mm/day) and extreme (> or = 100 mm/day) rain events during the monsoon season and discovered that although the mean rainfall remained unchanged, extreme events increased while moderate events declined. The scientists relied upon rain level data from over 1,800 stations throughout the country for the last 50 years of the 20th century, as well as regional climatic data. From 1951 to 2000, extreme monsoon events increased in both frequency and intensity, and

smaller monsoon storms decreased in trend during the same period.

***Implications:*** According to the reinsurance company Munich Re, weather-related damages in India have cost more than US$20 billion (http://www.nature.com/news/2006/061127/full/061127-12.html). Extreme monsoon events can have social, economic, and environmental ramifications. Increased rainfall can result in infrastructural damage, as well as potential natural and agricultural species decline, as flooding and landslides become more frequent. And decreased numbers of moderate storms can exacerbate drought throughout the country, as groundwater reservoirs are unfilled while surface runoff and soil erosion increases.

## ECOSYSTEMS AND ECOSYSTEM SERVICES

Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. Climate change science suggests ongoing shifts are being observed—and can be expected to continue—with evolving changes in temperature, precipitation and atmospheric composition. These will in turn lead to further changes in both ecosystems and the services they provide.

### Ecosystems

- **Parmesan, Camille. "Ecological and Evolutionary Response to Recent Climate Change."** ***Annual Review of Ecology, Evolution, and Systematics*** **37: 637-669. December 2006 at http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.ecolsys.37.091305.110100.**

In one of the most comprehensive syntheses of the impacts of climate change on species, Parmesan synthesizes 866 peer-reviewed papers, written from 1899-2003, that depict climate change impacts on global biota. Her conclusion: human-induced climate change has already affected biodiversity. The review covers phenologic changes, interactions across trophic levels as species' timing mismatches, range shifts, and changes in evolutionary processes. Parmesan notes that springtime has arrived earlier on every continent but one; that many predator-prey relationships have changed as a result of mistiming; that numerous species are migrating poleward; that disease vectors are altering ranges and populations with negative consequences; and that ranges of many species are contracting, leading to extinction of individual species.

***Implications:*** This extraordinarily thorough review indicates that we are already seeing major climate-related consequences to global biodiversity. It implies a similar reduction in the services that people derive from biodiversity, such as medicines, water filtration, air purification, carbon dioxide sequestration, and others.

- **Regehr, Eric V.; Amstrup, Steven C.; and Ian Stirling. "Polar Bear Population Status in the Southern Beaufort Sea." U.S. Geological Survey Open-File Report 2006-1337 at http://pubs.usgs.gov/of/2006/1337/.**

Regehr, Amstrup, and Stirling document the decline in polar bears in the Arctic as a result of sea ice retreat in our warming climate. Polar bears depend on ice floes to feed from (the ice gives them a resting place as they swim to find their prey), as well as to breed. The scientists found that the rate of cub survival in the southern Beaufort Sea had significantly decreased from the periods between 1967-1989 and 1990-2006. In addition, in performing skull measurements and weight analyses, they found that the adult male polar bears in the last two and a half decades were far lighter than those captured before 1990.

***Implications:*** The decline in polar bear cub survival, as well as adult size and weight, has paralleled a loss of sea ice, which the species depends on. The results from this study are consistent with other assessments of climate impacts on the Arctic. The status of the polar bear is currently being considered by the U.S. Government, as it may warrant listing as a threatened species. The World Conservation Union (IUCN), the world's leading body on cataloging threatened species, has already added the polar bear as a threatened species in its 2006 "Red List" (http://www.iucn.org/en/news/archive/2006/05/02_pr_red_list_en.htm).

- **Westerling, A. L.; Hidalgo, H. G.; Cayan, D. R.; and T. W. Swetnam. "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity."** ***Science*** **313(5789): 940-943. 18 August 2006 at http://www.sciencemag.org/cgi/content/full/313/5789/940.**
- **Kasischke, Eric S. and Merritt R. Turetsky. "Recent Changes in the Fire Regime across the North American Boreal Region—Spatial and Temporal Patterns of Burning across Canada and Alaska."** ***Geophysical Research*** **Letters 33(L09703). 3 May 2006 at http://www.agu.org/pubs/crossref/2006/2006GL025677.shtml (errata at http://www.agu.org/pubs/crossref/2006/2006GL026946.shtml).**

Many of those living in the western U.S. have noted an increase in forest fire activity. However, it has previously been challenging to determine causality—is it a change in management or climatic factors that lead to the change? A new study by Westerling et al. suggests spring and summer warming, compounded by an earlier snow melt in the spring months, which leaves trees more combustible for longer periods of time, is to blame. Using a comprehensive database of wildfire activity in the western U.S. since 1970, as well as management and climatic data, the authors rely on statistical associations to explain the cause of this phenomenon. The authors demonstrate that recent years of earlier snow melt increased fire burn area more than 6.5 times that of previous years. Human-induced climate change, which they assert is a causal mechanism in current burning patterns, has brought drier conditions to the North American boreal regions. These impacts have fostered the growth of the size and length of burns.

Kasischke and Turetsky reach similar conclusions. Tracking the fire regime in the North American boreal region over the period from 1959 to 1999, the authors obtained data on fire size, fire events, and seasonal patterns and found that while the area burned by human-ignited fires has decreased over the four decades studied, the burned area in the region has doubled between the 1960s/70s and 1980s/90s. Moreover, the frequency of fire events on a large scale has increased. The authors attribute the recent fire regime to warming trends.

***Implications:*** Increased forest fire activity has sociological, cultural, and ecological repercussions. Fire regime changes will not only challenge managers in the North American boreal regions but may also impact the ecosystem processes in the region. Perhaps most significantly, drying conditions coupled with larger fire events could lead to the burning of organic soil layers. This will further impact biodiversity composition, growth rates, and nutrient cycles. The studies suggest an additional financial impact: U.S. federal agencies spend over US$1 billion per year on fire fighting, and U.S. forest land plays a significant role in the livelihood of many communities.

- **Malcolm, Jay R.; Liu, Canran; Neilson, Ronald P.; Hansen, Lara; and Lee Hannah. "Global Warming and Extinctions of Endemic Species from Biodiversity Hotspots."** ***Conservation Biology*** **20(2): 538-548. April 2006 at http://www.blackwell-synergy.com/doi/full/10.1111/j.1523-1739.2006.00364.x.**

  Conservation biologists Malcolm et al. explore the impacts of a doubling of $CO_2$ levels on endemic species (species that are confined within the given area) in areas of rich biodiversity, or "hotpots." They identified 25 hotspots, which house 44% of the world's plant species and 25% of vertebrates, and ran 14 runs with general circulation models and global vegetation models. While some species in hotspots were able to migrate and survive, others were left more vulnerable to climate change, including those located in the hotspots of the Caribbean, Southwest Australia, Tropical Andes, Cape Floristic Region, Indo-Burma, and the Mediterranean Basin. Malcolm et al. found that under doubled $CO_2$ levels, some hotspots lost 39-43% of species. This loss translates into a potential extinction of over 55,000 endemic plant species and 3,700 endemic vertebrate species. The authors found that the extinction predictions were not unique to hotspots; other ecosystems could face similar extinction events.

  ***Implications:*** Absent strong climate policy, it is anticipated that atmospheric $CO_2$ concentrations would double well before the end of the century, with concomitant global warming. This research confirms that climate change will be one of the leading factors of species degradation in decades to come, with the loss of thousands to tens of thousands of endemic species.

- **Scholze, Marko; Knorr, Wolfgang; Arnell , Nigel W.; and I. Colin Prentice. "A Climate-Change Risk Analysis for World Ecosystems."** ***Proceedings of the National Academy of Sciences*** **103(35): 13116-13120. 29 August 2006 at http://www.pnas.org/cgi/content/full/103/35/13116.**

  Collecting data from 16 atmosphere-ocean general circulation models and 52 model runs, scientists Scholze et al. examined the ecosystem response to temperature rise between 1961-1990 and that projected for 2071-2100. They used three different temperature scenarios: less than 2°C increase, 2-3°C increase, and more than 3°C. Under each warming scenario, risk of ecosystem change increased. For example, fire events are exacerbated, and the risk of forest transformation to non-forest ecosystems are greater (e.g. while historically less than 5% of the land was transformed, this rises to 43% with a rise of 2°C; 75% with a rise of 2-3°C; and 85% with an increase of more than 3°C). Moreover, the authors demonstrate that one of their modeled terrestrial land sinks, which ordinarily sequesters carbon, turns into a source of carbon under the greater-than 3°C warming scenario, creating an additional warming feedback.

***Implications:*** Higher temperatures result in higher risks to ecosystem resiliency, and such responses are non-linear. Even small temperature shifts (less than 2°C) are still significant.

- **Jonzen, Niclas; Linden, Andreas; Ergon, Torbjørn; Knudsen, Endre; Vik, Jon Olav; Rubolini, Diego; Piacentini, Dario; Brinch, Christian; Spina, Fernando; Karlsson, Lennart; Stervander, Martin; Andersson, Arne; Waldenstrom, Jonas Lehikoinen, Aleksi; Edvardsen, Erik; Solvang, Rune; and Nils Chr. Stenseth. "Rapid Advance of Spring Arrival Dates in Long-Distance Migratory Birds."** ***Science*** **312(5782): 1959-1961. 30 June 2006 at http://www.sciencemag.org/cgi/content/full/312/5782/1959.**

- **Both, Christian; Bouwhuis, Sandra; Lessells C. M.; and Marcel E. Visser. Climate Change and Population Declines in a Long-distance Migratory Bird.** ***Nature*** **441: 81-83. 4 May 2006 at http://www.nature.com/nature/journal/v441/n7089/full/nature04539.html.**

  As climate change takes its toll on the world's ecosystems, species will vary in their adaptive response to change, sometimes adversely impacting one another as food chain dynamics shift. One example is the shift in migratory birds, which can be expected to time their movement around breeding and food availability. While it is expected that migratory birds traveling only short distances would be able to understand environmental cues better than long-distance migratory birds who cannot detect changes in their faraway destination, Jonzen et al. find that European long-distance migratory birds are changing their spring arrival dates in Scandinavia more than short-term migratory birds. The scientists also demonstrate that bird arrival dates in the Mediterranean have moved forward, suggesting the advance in arrival is triggered earlier in their journey. The authors propose that altered migration timing will lead to evolutionary changes—as individuals able to adapt to climatic changes are favored.

  Both et al. provide additional documentation for this phenomenon, studying the interaction between climate change and the habits of the pied flycatcher, a long distance migratory species which depends on caterpillars for food. They examined the timing of peak caterpillar populations and arrival dates of the flycatchers in nine populations in the Netherlands. They found that due to warming, the peak availability of prey-caterpillar populations was occurring earlier in the season, and that by the time the birds arrived, they often did not have enough food for their nestlings. According to Both and colleagues, this led to a 40% population decline of the flycatcher over the past 20 years.

  ***Implications:*** Temporal peak food availability is common in many food chains, and the mistiming between predator and prey species is not a novel phenomenon. While these climate-change driven trends are already being manifest in migratory species, it can be anticipated that additional species will be affected as the food chain is further modified due to climatic shifts.

- **Balanyá, Joan; Oller, Josep M.; Huey, Raymond B.; Gilchrist, George W.; and Luis Serra. "Global Genetic Change Tracks Global Climate Warming in** ***Drosophila subobscura*****."** ***Science*** **313(5794): 1773-1775. 22 September 2006 at http://www.sciencemag.org/cgi/content/full/313/5794/1773.**

- **Sarup, P.; Srensen, JG; Dimitrov, K; Barker, JSF; and V. Loeschcke. "Climatic Adaptation of** ***Drosophila buzzatii*** **Populations in Southeast Australia."** ***Heredity*** **96(6): 479–486. June 2006 at http://www.nature.com/hdy/journal/v96/n6/abs/6800828a.html.**

  Not only are species' ranges shifting and population dynamics and breeding seasons being altered in our warming climate, but micro-changes to species, as genetic composition shifts, are transpiring as well. Balanyá and colleagues document genetic changes in populations of a fly species *Drosophila subobscura* in three continents over the course of roughly two and a half decades. They find that of 22 population groups, 21 altered their genotypes to those of low latitude populations which live in warmer climates. They attribute this genetic shift to the species' adaptation to climate change. Sarup and colleagues document a similar change to a different *Drosophila* species. They show that in 11 populations of *Drosophila buzzatii* located in southeastern Australia selection for adaptive traits to warming was occurring. Thirteen of the nineteen traits that are relevant to adaptive capacity to climatic geographical constraints were altered, as more resilient genotypes were selected for.

  ***Implications:*** The studies suggest both that warming is occurring, and also that species are beginning to adapt. However, while the genetic shifts in the studied *Drosophila* species were relatively rapid due to short generation lives, other species may not have the capacity to adapt as easily. Genetic change of this type is symptomatic of disruption of natural ecosystems and will no doubt have consequences for population dynamics and species resiliency to changing climate conditions.

- **Grebmeier, J.M.; Overland, J.E.; Moore, S.E.; Farley, E.V. Carmack, E.C.; Cooper, L.W.; Frey, K.E.; Helle, J.H.; McLaughlin, F.A.; and S.L McNutt. "A Major Ecosystem Shift in the Northern Bering Sea."** ***Science*** **311(5766): 1461-1464. 10 March 2006 at http://www.sciencemag.org/cgi/content/full/311/5766/1461.**

  Grebmeier and colleagues document a dramatic ecosystem change in the northern Bering Sea that has been contemporaneous with higher atmospheric and ocean temperatures, as well as increased sea ice loss. Where previous conditions favored species that relied on ice cover, such as marine mammals like walruses and whales, the ecosystem is now being overtaken by pelagic fish species.

  ***Implications:*** This study has far-reaching consequences for marine ecosystems and productivity. Ecosystem composition can be expected to be altered under warming temperatures as marine mammals and seabirds suffer from ice loss, and pelagic fish species increase in the absence of predators. Simultaneously, some commercial fish stocks may be negatively impacted as species migrate out of fishing zones or die off.

- **Doney, Scott C. "Plankton in a Warmer World."** ***Nature*** **444:695-696, 7 December 2006 at http://www.nature.com/nature/journal/v444/n7120/full/444695a.html.**

  With the advent of satellite technology, the ocean can be scanned within a few days and comparative measurements of ocean productivity in multiple marine regions easily obtained. Doney uses such satellite measurements to determine the health of phytoplankton, small marine organisms that live in the top layer of the ocean. He finds that phytoplankton productivity trends parallel climatic changes: as sea level temperatures increase, phytoplankton productivity decreases. He attributes this decline to warming-induced inhibition of ocean layer mixing, which limits the upwelling of nutrients (e.g. iron and nitrogen) from lower ocean layers.

  ***Implications:*** Phytoplankton is a key underpinning of the marine food web, and loss of productivity could have significant ramifications for other marine species and fisheries. It is likely that marine ecosystem productivity will decline if warming increases at its current rate. In addition, phytoplankton are a natural sink for atmospheric $CO_2$, which is absorbed during photosynthesis. Therefore, their loss may also have a feedback effect on global $CO_2$ concentrations.

## Ecosystem Services

- **Long, S.P.; Ainsworth, E.A.; Leakey, A.D. B.; Nosberger, J.; and D.R. Ort. "Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising $CO_2$ Concentrations."** ***Science*** **312(5782): 1918-1921. 30 June 2006 at http://www.sciencemag.org/cgi/content/full/312/5782/1918.**

  Some climate models project that rising carbon dioxide levels will facilitate plant growth through increased fertilization and offset any negative ramifications of climate change to crop yield. However, a new study by Long et al. produces findings of significantly dampened crop yield under scenarios of higher carbon dioxide levels. The scientists rely on an experiment employing the free-air concentration enrichment technology (FACE), which releases carbon dioxide at different points along a 20-meter diameter plot in the field. Exposing major grain crop types to enhanced carbon dioxide levels, they find that by 2050 the crop yield is 50% less than earlier studies exploring crop growth in warming conditions.

  ***Implications:*** The authors state that given the results from the FACE experiments, grain crops will not flourish as much as previously thought. Moreover, increased carbon dioxide fertilization may not be able to outweigh the negative ramifications for global food supply, as crop yield will likely suffer under future climate regimes.

- **United Nations Development Programme. 2006.** ***Human Development Report 2006. Beyond Scarcity: Power, Poverty and the Global Water Crisis.*** **http://hdr.undp.org/hdr2006/.**

  The 2006 UN Human Development Report is dedicated to the global water crisis—one that the Millennium Development Goals attempts to address. While there are multiple factors in water source degradation, climate change is among the most critical. The report notes that water-stressed areas will be further challenged by climate change as precipitation patterns vary with rising global temperatures. Extreme events, such as flooding, will increasingly become the norm, as will unpredictable water sources. The report draws particular attention to a projected rapid decline in water availability in East Africa, with concomitant loss of up to 33% maize supply, 20% sorghum, and 18% millet, resulting in 75-125 million additional people suffering from hunger. In addition, it notes the projected continued glacial melting throughout South America, southern Asia, and East Asia; the alteration of monsoon patterns in southern Asia; and the saltwater intrusion into

freshwater delta systems as sea level rises. The Report states that current climate adaptation support is "piecemeal" and "woefully inadequate" and includes some recommendations for addressing the global water crisis, including a call for an increase in adaptation funds and a bolstering of water management strategies.

***Implications:*** According to the Report, over 1 billion people lack access to clean water, and 2.6 billion do not have sufficient sanitation. In addition, the report notes that the water crisis is the second largest factor in childhood mortality, and 1.8 million children die every year because of water-borne diseases and inadequate sanitation.

## CLIMATE CHANGE MITIGATION TECHNOLOGIES

This year has seen the development—albeit not yet the commercialization—of a number of new technologies that could substantially reduce the cost of and expand the potential for global GHG emissions reductions. These technologies range from new electric generation (solar electricity) to alternatives to gasoline for the transport sector (e.g. through new nano-technologies for biodiesel) to technologies that may help minimize some of the impacts from climate-related increases in disease. Other technologies with mitigation potential are being developed that are not discussed here because they are either proprietary or not open to peer review. Collectively, these and other technological developments, coupled with adequate additional resources for commercialization, could allow significant reductions in global GHG emissions, and given the likely rise in climate impacts from existing (and already locked in) climate effects, help reduce likely climate- related damages.

- **Kleiner, Gregg. "Tiny Microreactor for Biodiesel Production Could Aid Farmers, Nation." Oregon State University Press Release. Oregon State University News and Communication Services. 20 February 2006 at http://oregonstate.edu/dept/ncs/newsarch/2006/Feb06/microreactors.htm.**

  Researchers at the Oregon Nanoscience and Microtechnologies Institute and Oregon State University are in the process of creating a small chemical reactor that could decrease the time required for and substantially lower the cost of biodiesel production. The reactor is comprised of nanotechnologies (most of the component parts are substantially smaller than the width of a human hair) which rapidly convert vegetable oils and alcohol into biodiesel. This new device is faster—up to ten to a hundred times—than current processes. The microreactor system would replace conventional biodiesel production methods, which involve dissolving a catalyst and a waiting period of up to 24 hours while a slow chemical reaction occurs.

  ***Implications:*** The new microreactor is highly portable, and if commercialized, might be easily distributed to the farm, eliminating the step of transport and lengthy production processes for biomass inputs. This in turn will reduce energy input, as well as costs. The technology, however, is still in the experimental stage and does not yet have commercial scale investments.

- **Alper, Hal; Moxley, Joel; Nevoigt, Elke; Fink, Gerald R.; and Gregory Stephanopoulos. "Engineering Yeast Transcription Machinery for Improved Ethanol Tolerance and Production." *Science* 314(5805)1565–1568. 8 December 2006 at http://www.sciencemag.org/cgi/content/full/314/5805/1565.**

  Ethanol is produced in a fermentation process that adds yeast to plant material. Currently, there is a limit to how much ethanol can be produced with available yeast strains. However, taking advantage of a mutant strain with higher glucose/ethanol tolerances, researchers from the Massachusetts Institute of Technology (MIT) created a new form of yeast that can accelerate ethanol production. In a novel technique called transcription machinery engineering (gTME), the scientists were able to alter the transcription factors—which control the expression of multiple genes—and enhance the ability of yeast to persist in higher ethanol environments. Alper et al.'s yeast strain was approximately 150% as efficient as conventional strains. This boost in ethanol production efficiency could speed production processes.

  ***Implications:*** While grain-based ethanol production yields only minor climate benefits in a full root-to-tank analysis, such new technologies could alter the equation, making ethanol a significantly less $CO_2$ intensive fuel source, and an attractive alternative to gasoline.

- **Tilman, David; Hill, Jason; and Clarence Lehman. "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass." *Science* 314(5805): 1598-1600. 8 December 2006 at http://www.sciencemag.org/cgi/content/full/314/5805/1598.**

  As nations look toward biofuels to replace $CO_2$ intensive fossil fuels, questions have been raised as to the most efficient source crop. Researchers from the University of Minnesota contend that not one species—but a mix of species—is more energy efficient

and has more ancillary benefits for the environment, such as biodiversity conservation. Tilman et al. collected a decade's worth of data from 16 prairie species and demonstrate that when planted in degraded agricultural areas, an assortment of prairie grasses can produce 238% more energy than any one of the studied 16 species alone. For example, when grown in poor soil, switchgrass produced less than a third of the energy than the mixed species yielded, and did not outperform any of the other species planted by itself. Large gains are also found on nutrient-rich land, where the prairie grass mix produced 51% more energy than corn.

***Implications:*** The researchers claim that if mixed species of prairie grasses were planted on all of the world's degraded agricultural lands, 13% of petroleum consumption could be displaced and 19% of electricity needs could be met by this source alone. Moreover, a diversity of native crops can yield additional benefits, including species protection and reduced water contamination.

- **Renewable Energy Access. "New Technology Uses Cellulosic Biomass to Produce Ethanol." 19 September 2006 at http://www.renewableenergyaccess.com/rea/news/story?id=46004.**

  Ethanol produced from biomass, or plant-derived material, is limited in part by fermentation inhibitors, which are byproducts of production and impair the sugar-to-alcohol process. A new organism, developed by Honda R & D Co., Ltd. and the Research Institute of Innovative Technology for the Earth (RITE), reduces the level of fermentation inhibitors and, as a result, boosts the yield of alcohol during the fermentation process. This supplemental alcohol can be used for energy production. The new "RITE strain" microorganism not only increases efficiency of ethanol production from biomass but it also makes some previously impractical species, such as rice straw, viable for ethanol production.

  ***Implications:*** The partners developing RITE strain organisms are in the process of developing a pilot project to deploy the technology on a larger scale. If successful, the enhanced cellulosic ethanol production could not only increase supplies of ethanol but could also employ previously unused species for production.

- **Bray, Hiawatha. "MIT Research May Spell End for the Battery." *The Boston Globe*. 26 June 2006. http://www.boston.com/business/technology/articles/2006/06/26/mit_research_may_spell_end_for_the_battery/.**

  Researchers from Massachusetts Institute of Technology (MIT) are now in the process of experimenting with carbon nanotubes in capacitors, which are commonly used to store electricity in electric circuits, to make a "supercapacitor". Capacitors can recharge in a small fraction of the time needed by traditional batteries—within a few seconds—and can be recharged a hundred times more often than a battery can be recharged in its lifetime.

  *Implications:* While the researchers point out that the supercapacitor has a few more years before commercial availability, if successful, this new use of capacitors could make the electric car more cost effective and long-lasting, as battery lifetime and recharging time becomes greatly enhanced.

- **"Brown Engineers Build a Better Battery—With Plastic." Brown University Media Relations, Public Affairs and University Relations. 13 September 2006 at** http://www.brown.edu/Administration/News_Bureau/2006-07/06-022.html.

  While batteries are excellent vehicles for storing energy, they cannot deliver electric charge rapidly. Instead, capacitors are commonly used, such as in electronic technologies. Capacitors produce power rapidly, but fail to store charge well. Researchers Palmore and Song of Brown University recently set out to combine the best of both worlds: a capacitor-battery hybrid. The hybrid was created by dipping two plastic strips with gold covering into chemical compounds that have different conductive properties. One side could act like a battery, while the other could serve as the capacitor.

  ***Implications:*** While the technology is not yet fully worked out (for example, it displays considerable storage losses after recharging), the new hybrid capacitor/battery can deliver more than 100 times more charge, or power, than a conventional battery made of alkaline materials. In addition, it is as thin as a few pieces of paper and smaller than a credit card, which could lead to many commercial applications.

- **Associated Press. "Professor Devises New Form of Solar Cell." 28 November 2006. Available online from Environmental News Network at http://www.enn.com/today.html?id=11739.**

  Solar energy holds tremendous potential for mitigating climate change, but solar cell technologies struggle to commercially compete with conventional fossil fuels. However, a recent breakthrough by chemist Pam Shapiro

of the University of Idaho has developed a new way of reorganizing solar cells, which could lead to high boosts in energy efficiency, paving the way for solar technologies to enter the market with greater ease. Shapiro and her colleagues developed a solar cell arrangement that layers quantum dots—composites of copper, selenium, and indium—between solar cells. Typically, solar cells overheat and lose energy during the electricity-generating process; with Shapiro's new arrangement, however, the quantum dots absorb the energy that might have been lost and store it within the unit for future use.

***Implications:*** The new quantum dot technology has more than doubled the energy efficiency of standard solar cells. Energy savings could reduce the price per kilowatt hour of a solar cell, and, as a result, solar energy may become more cost effective and commercially viable in the future.

- **Kielich, Chris. "New Record Achieved in Solar Cell Technology." Department of Energy Press Release. 5 December 2006 at http://www.energy.gov/news/4503.htm.**

  Solar cells collect and convert the Sun's energy into electricity. However, until now, solar cell engineers could not surpass a conversion efficiency of 40%. A new research project funded by the U.S. Department of Energy was able to exceed this goal and attain an efficiency of 40.7%. The new solar cell uses an optical concentrator and is a multi-junction cell, which is designed with several layers. As the sunlight passes through each layer, energy is repeatedly captured, storing more energy than a non-layered cell.

  *Implications:* According to the Department of Energy, this boost in energy efficiency will drop solar electricity prices to 8 to 10 cents per kilowatt hour and make solar energy more competitive. The Department predicts that by 2015, 1-2 million houses in the nation could be powered by solar energy if prices decline to this level.

- **American Chemical Society. "Ultrathin, Dye-Sensitized Solar Cells Called Most Efficient to Date." *Science Daily*. 20 September 2006 at http://www.sciencedaily.com/releases/2006/09/060918201621.htm.**

  Another solar energy efficiency barrier has been broken with the enhancement of the class of ultrathin solar cells. Solar cells that are ultrathin, such as those used in paints and window coatings, cannot gain the same efficiency as more conventional technologies—usually reaching only a 4 to 5 % efficiency. However, Swiss chemists have developed a new efficient ultrathin solar cell that uses titanium dioxide arranged in nano-crystal formations which act as semiconductors and which has an efficiency of 11%. The ultrathin solar cells (known as Graetzel's cells) are expected to be commercially available in two to three years. The researchers suggest that the films of solar cells will be low cost and flexible and can be applied to many surfaces.

  ***Implications:*** The energy efficiency gains could reduce the price of solar power and potentially allow this thin film technology to be applied more widely in building.

- **Thomson, M. C.; Doblas-Reyes, F. J.; Mason, S. J.; Hagedorn, R.; Connor, S. J.; Phindela, T.; Morse, A. P. and T. N. Palmer. "Malaria Early Warnings Based on Seasonal Climate Forecasts from Multi-model Ensembles." Nature 439: 576-579. 2 February 2006 at http://www.nature.com/nature/journal/v439/n7076/full/nature04503.html.**

  Malaria results in more than a million deaths each year, the large majority of which occur in sub-Saharan Africa. Management of the malaria epidemic in part depends on lead time to prepare for the height of the mosquito vector populations, as well as the length of gestation time. A new technique proposed by Thomson et al. incorporates the use of a climate forecast model to predict when malaria risk will be at its peak, by examining climatic variables which influence the proliferation of mosquitoes. They deployed their system in Botswana and were able to give policy-makers and health program officers up to four months of additional notice.

  ***Implications:*** One of the effects of climate change deemed extremely likely is an increase in the range of malaria-carrying mosquitoes. Techniques that can provide advance warning of malarial risk will be critical in combating this particular climate-generated impact. While developed using traditional climate variability analytic tools, the technique clearly has enormous value in a world of changing climate.

## CLIMATE CHANGE ECONOMICS

While many authors have specifically examined the science of climate change, there is also a wealth of literature examining the economic costs of action—or inaction. While this is only a very brief review, the politics of climate mitigation and adaptation suggest the economic issues are likely to become increasingly significant. Thus, this section provides a short list of some of the more recent and important work.

Collectively, the reports and articles cited here significantly raise earlier estimates of the costs of climate impacts, while reaffirming the results of many earlier studies suggesting that mitigation measures are both feasible and relatively inexpensive in comparison (see, for example, the IPCC's 2001 Working Group 3 Report on Mitigating Climate Change).

- **Stern, Nicholas. 2006. *Stern Review on the Economics of Climate Change*. (Cambridge University Press: Cambridge, United Kingdom), October 30 at http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.**

  A comprehensive report by former World Bank chief economist Nicholas Stern undertaken on behalf of the UK government documents both the costs of climate change and of options for mitigation and adaptation. The Stern report estimates the cost of a changed climate could be from 5% to 20% of global GDP. Costs include those related to losses from declining agricultural production, heat-waves, droughts, flooding events, extreme precipitation, biodiversity loss, disease spread, and soil erosion. Conversely, the study estimates that a stabilization at 500-550 ppm $CO_2$equivalent ($CO_2$e, a measure of the contribution of six key greenhouse gases) will cost the global community roughly 1% of GDP by 2050. Necessary changes would include decarbonizing 60% the power sector. Policies called for in the Stern report include a strong carbon signal through taxes, trading, or regulation, and research and development into low carbon-intensive technologies. In addition, Stern suggests that activities to curtail greenhouse gas emissions will be substantially more expensive if action is delayed rather than initiated in the near future: if we fail to act within the next decade or two, stabilization at 550 ppm $CO_2$e may be too challenging to achieve at all.

  ***Implications:*** While critics have suggested the Stern report uses too low a discount rate (magnifying the impacts on future generations and raising the cost of inaction), the report is likely to generate considerable international debate—and may presage new and equally strong results from the more extensive IPCC report (to be released in mid-2007). However, it remains to be seen if any of the solutions recommended in the report meet the acid test of political acceptability and become enacted into national or international legislation. Furthermore, even the stabilization level suggested by Stern (at 550 ppm $CO_2$e) is likely to generate considerable climate-rated impacts and global costs.

- **Nordhaus, William D. "Geography and Macroeconomics: New Data and New Findings." Proceedings of the National Academy of Sciences 103(10): 3510-3517. 10 February 2006 at http://www.pnas.org/cgi/content/full/103/10/3510.**

  The Nordhaus paper evaluates the linkages between geographic variables and GDP using new data and simplified climate scenarios. While he concludes that cold regions (e.g. ice-covered Greenland and Siberia) tend to have lower area GDP values than do warmer regions, he also projects that a doubling of the $CO_2$ concentration along with concomitant temperature increases, would lead to major loss in global GDP. In one scenario, Nordhaus models a 3°C temperature increase, and in a second scenario, both temperature and precipitation change. Population-weighted GDP loss ranges from 1.7% (in the temperature only case) to 3% (in the temperature and precipitation case).

  ***Implications:*** As with the Stern report described above, this study substantially raises earlier estimates of the cost of inaction on climate change—including significantly lower earlier estimates by the author. Furthermore, the study highlights some of the regional disparities of climate consequences, suggesting that the poorest regions (e.g. Africa) would continue to see some of the worst damages.

- **Edenhofer, Ottmar, Carlo Carraro, Jonathan Kohler and Michael Grubb, editors. The Energy Journal: 207-222 (Special Issue # 1: Endogenous Technological Change and the Economics of Atmospheric Stabilisation). Available online through the Innovation Modelling Comparison Project at http://www.econ.cam.ac.uk/research/imcp/.**

- **Giles, Jim. "Economists claim carbon cuts won't break the world's bank." Nature 441: 264-265. 18 May 2006 at http://www.nature.com/nature/journal/v441/n7091/full/441264b.html.**

  A recent study evaluating multiple computer generated economic models of climate mitigation costs suggests that stabilization of carbon dioxide concentrations at 450 ppm $CO_2$ would not nearly be as expensive as previous estimates, which suggested stabilization costs would equate to 3-15% of global GDP in 2100. According to the results of this project (the Innovation Modeling Comparison Project), nine of the eleven models in the study result in costs of less than 0.5% of GDP loss by 2100 for stabilization at 450 ppm.

Moreover, climate mitigation may result in net benefits, as new technologies may spur growth.

***Implications:*** As the price of climate-related damages continues to rise, the development and penetration of new technologies offers the potential for ever lower costs to solve the problem. In fact, the net economic impact from new technology deployment may even be positive. However, it is an outstanding question as to which companies and sectors will benefit the most from technological innovation.

## Acknowledgments

The authors gratefully acknowledge Michael MacCracken and Pushker Kharecha for review and revisions of this manuscript.

## About the Authors

**KELLY LEVIN** is a Ph.D. candidate at the Yale School of Forestry and Environmental Studies dedicating her research to global governance of climate change and biodiversity. As a climate policy and technical analyst for the Northeast States for Coordinated Air Use Management's (NESCAUM) Climate and Energy Team, she facilitated the development of a regional greenhouse gas registry for the Northeast and Mid-Atlantic states. She holds a bachelor's degree in ecology and evolutionary biology from Yale College and a master of environmental management from Yale's School of Forestry and Environmental Studies.

**JONATHAN PERSHING** is the director of the Climate, Energy, and Pollution Program (CEP) at the World Resources Institute. He is active in work on domestic and international climate and energy policy, including emissions trading, energy technology, and the evolving architecture of international climate agreements. He has served as the head of the Energy and Environment Division at the International Energy Agency in Paris, deputy director and science advisor for the Office of Global Change at the U.S. Department of State, and a U.S. negotiator for the UN climate change convention and its Kyoto Protocol. Dr. Pershing is the author of several books and numerous articles on climate change, and energy and environmental policy, and holds a doctorate in geology and geophysics from the University of Minnesota.

## About WRI

World Resources Institute (WRI) is an environmental think tank that goes beyond research to find practical ways to protect the earth and improve people's lives.

Our mission is to move human society to live in ways that protect Earth's environment and its capacity to provide for the needs and aspirations of current and future generations.

Because people are inspired by ideas, empowered by knowledge, and moved to change by greater understanding, WRI provides —and helps other institutions provide — objective information and practical proposals for policy and institutional change that will foster environmentally sound, socially equitable development.

WRI organizes its work around four key goals:

- People and Ecosystems. Reverse rapid degradation of ecosystems and assure their capacity to provide humans with needed goods and services.
- Climate, Energy, and Transport. Protect the global climate system from further harm due to emissions of greenhouse gases and help humanity and the natural world adapt to unavoidable climate change.
- Markets and Enterprise. Harness markets and enterprise to expand economic opportunity and protect the environment.
- Governance and Access. Guarantee public access to information and decisions regarding natural resources and the environment.

For more information about World Resources Institute, please visit www.wri.org.

ISBN 978-1-56973-648-7