WRI ISSUE BRIEF

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Climate Science 2005
Major New Discoveries

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Introduction

2005 was a year in which the scientific discoveries and new research on climate change confirmed the fears and concerns of the science community. The findings reported in the peer-reviewed journals last year point to an unavoidable conclusion: The physical consequences of climate change are no longer theoretical; they are real, they are here, and they can be quantified.

In this short paper, WRI reviews some of the major discoveries from the past year. Taken collectively, they suggest that the world may well have moved past a key physical tipping point.

In addition, the science tells us the effects of climate change are at a scale that adds enormous urgency not only to the efforts to prevent additional change, but equally important, to efforts to adapt to the impacts already occurring.

Finally, the science makes it clear that additional climate impacts will result even if emissions of greenhouse gases are halted immediately.

A wide body of scientific and technical literature was reviewed in the preparation of this paper, including key general science journals (*Nature* and *Science*), several technical journals (*Geophysical Research Letters, Annals of the Missouri Botanical Gardens, Ecology Letters, Ecology, Environment International, and Journal of Climate*) and key material from web sites and international organizations (RealScience.org, the UN's Food and Agriculture Organization, the U.S. Department of Energy and others).

Each scientific paper is briefly described, along with the full citation to the original paper, and a short comment regarding the implications of each discovery is offered.

For ease of reading and organizational simplicity, the discussion below is separated into four sections:

- Physical climate (solar radiation, temperature increases, thermal inertia, and GHG concentrations)
- Hydrological cycle (hurricanes, glacial/ snow melt, oceans, and water supply)
- Ecosystems (ecosystem services, food supplies, carbon sequestration)
- Technologies for climate change mitigation

The next major international assessment of the science of climate change, by the Intergovernmental Panel on Climate Change (IPCC), is planned for release next year. That report will address these as well as other discoveries related to the science, impacts, and potential response strategies to climate change.

However if the new scientific findings reviewed here (coupled with the overall trend of rapid increases in greenhouse gas emissions) are any indicator, they suggest the world is in both for an ominous report, and more significantly, a major shift in Earth's climate.

Physical Climate (solar radiation, temperature increases, thermal inertia, ocean behavior and greenhouse gas concentrations)

Recent scientific studies confirm that human-induced climate change is leading to increases in atmospheric and ocean temperatures. Studies conducted in 2005 also note that there will be a delay in climate impacts as a result of thermal inertia. Therefore, even if our society were to halt greenhouse gas emissions today, we have already committed to substantial warming and sea level rise in future years.

Temperature, solar radiation, thermal inertia and ocean behavior

1. *2005 Temperature Records*

   NASA's Goddard Institute for Space Studies team collected data on 2005 temperatures and found that the annual mean global temperature data for January through December of this year was higher than the average for those months in 1998, which was the previous record-breaking warmest year.

- **http://data.giss.nasa.gov/gistemp/**

  The annual mean global surface temperature differs by 0.6°Celcius from the base period (1951–1980) mean, and 0.8°Celcius in the past century. After 2005 and 1998, the next warmest years are 2002 and 2003, respectively. The 2004 meteorological year follows as the subsequent warmest year.

  Record warmth in 2005 is notable, because global temperature has not received any boost from a tropical El Niño this year. The prior record year, 1998, on the contrary, was lifted 0.2°Celcius above the trend line by the strongest El Niño of the past century.

  Recent warming coincides with rapid growth of human-made greenhouse gases. Climate models show that the rate of warming is consistent with expectations.

  Implications: The observed rapid warming gives enormous urgency to discussions about how to slow greenhouse gas emissions; models project continued increases in both GHG concentrations and, thus, global temperature unless considerable reductions are taken.

2. *Energy Imbalance*

   Using a climate model that incorporates anthropogenic greenhouse gas emissions, scientists have recently concluded that the Earth is absorbing more energy than it emits. The energy imbalance, when compared to temperature measurements, indicates a lag in atmospheric warming.

- **Hansen, James et al. "Earth's Energy Imbalance: Confirmation and Implications." Science. Volume 308. 3 June 2005 at www.sciencemag.org**

  The study's results are substantiated by ocean heat content measurements and surface air temperature records over the past decade. The authors suggest that even if we were to halt changes to atmospheric composition today, we should expect to see an increase in warming of 0.6° Celsius in the future. The lag in climate forcing leads the authors to underscore the need for early action, given that ice melting and sea level rise will advance in years to come due to the climate system's inertia.

  Implications: The energy imbalance and the lag in climate response cited in Hansen's study suggests there are significant climate effects that will only reveal themselves with time. We are thus committed to considerable additional future warming from historic emissions — but also, unless we cut emissions sharply, we will see considerable additional future effects. As a result of thermal inertia, delaying action is likely to amplify change in the future.

3. *Risk of Exceeding Temperature Target of 2°C Above Pre-industrial Levels*

   Over two hundred scientists, government officials, and members of civil society gathered in Exeter, United Kingdom (UK) in February of 2005 to discuss what constitutes — and how we can avoid — dangerous climate change. Among the noteworthy papers presented at the conference, one explored the risks of exceeding a 2°C equilibrium temperature target. The author of this paper concluded that delay in action by as few as five to ten years will increase the probability of exceeding the threshold dramatically.

- **Meinshausen, Malte. "On the Risk of Overshooting 2°C." Proceedings from "International Symposium on Stabilisation of Greenhouse Gas Concentrations — Avoiding Dangerous Climate Change", Exeter 1–3 February 2005 at http://www.stabilisation2005.com/programme.html**

  Meinshausen assigns a probability of exceeding the 2°Celcius threshold a risk of between 68% and 99% at 550 ppm CO_2 equivalence levels. However, he suggests that the risks of exceeding the threshold are reduced at lower stabilization levels. For example, at levels of 400 ppm CO_2 equivalence, the risks are significantly reduced (to 20% or less).

  Implications: According to the IPCC 2001 report, impacts associated with climate increase markedly when global temperatures rise 2°C or more above today's levels. This suggests that aggressive action will be needed: current concentrations are more than 380 ppm and rising about 2ppm per year. Unfortunately, global policy is not now on course to limit concentrations to below 400 pm, the level judged "safe" in this analysis.

4. *Solar Radiation and Climate Change*

While a few regions are still experiencing global dimming due to aerosols and dust, according to two studies conducted this year, many areas are now witnessing some increased brightness as a result of pollution abatement. However, this brightness brings reason to worry: air pollution may have masked the effects of climate change, and additional solar brightening may hasten temperature rising.

- **Wild, M. et al. "From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth's Surface." *Science*. Volume 308. 6 May 2005 at www.sciencemag.org**
- **Pinker, R. et al. "Do Satellites Detect Trends in Surface Solar Radiation?" *Science*. Volume 308. 6 May 2005 at www.sciencemag.org**

The degree to which global dimming has shielded climate change effects is still unclear, and scientists are in the process of researching the linkage. Preliminary research conducted by Martin Wild suggests that air pollution prior to 1990 may have protected us from 50% or more of warming.

Implications: Air pollution, which blocks some amount of solar radiation, may have shielded us from climate change impacts. Because major urban areas have been successful in abating pollution (with consequent improvement in air quality), particles that block incoming solar radiation have been reduced, and, as a result, incoming solar radiation reaching the earth is stronger. Increases in incoming radiation increase the Earth's warming — and thus, climate change impacts may be augmented in the future as a result.

Ocean behavior

1. *Human-induced Climate Change and Oceans*

The world's oceans have been warming over the past few decades. While the warming signal is not straightforward, scientists have recently concluded that the observed warming is caused by human-induced climate change, and that natural forcing, such as by solar or volcanic factors, cannot explain the phenomenon.

- **Barnett, Tim et al. "Penetration of Human-Induced warming into the World's Oceans." *Science*. Volume 308. 8 July 2005 at www.sciencemag.org.**

The study demonstrates that modeling uncertainties are quite small — and preclude a simple "natural fluctuation" explanation for ocean warming. The authors thus conclude the warming is caused by human induced climate forcing. In addition, the authors offer new confidence in climate models and suggest that global models can make reliable predictions for the next two to three decades.

Implications: Over the past decade, policymakers have called for only limited climate action based on the assumption that the science of climate change may be wrong. Those holding this view have claimed that uncertainties in the underlying physics mean that human induced changes in atmospheric composition would only lead to insignificant changes in the climate system. This study, which concludes with confidence that ocean warming is due to human-induced climate change (which is in turn caused by the release of greenhouse gas emissions), solidly refutes those skeptical views. Furthermore, the study's conclusions that oceans are warming suggests that we can expect substantial additional impacts as the climate system moves into a new global temperature equilibrium.

2. *Emissions Stabilization and Consequences for Global Mean Temperature and Sea Level Rise*

Even if we were to stop climate forcing today, the inertia in the oceans would lead to a rise in sea level and global mean temperatures for decades to come.

- **Wigley, T. M. L. "The Climate Change Commitment." *Science*. Volume 308. 18 March 2005 at www.sciencemag.org**
- **Meehl, Gerald A. et al. "How Much More Global Warming and Sea Level Rise?" *Science*. Volume 307. 18 March 2005 at www.sciencemag.org**

According to the Wigley study, even if we froze atmospheric composition at today's levels, the inertia in the ocean system alone could raise global mean temperatures by 2° to 6° Celsius by the year 2400 and sea levels by 25 centimeters per century until at least the year 2400. This is confirmed by independent work by Meehl et al., who conclude that if greenhouse gas levels were stabilized at 2000 levels, atmospheric temperatures would still increase by 1.1–3.5° Celsius and sea levels would rise by an additional 13-30 cm by the end of this century.

Implications: Recent scientific studies confirm that human-induced climate change is leading to rising ocean and atmospheric temperatures. These studies confirm expectations that there will be a delay in climate impacts as a result of the ocean's thermal inertia. Therefore, even if our society were to halt greenhouse gas emissions today, we have already committed to substantial warming and sea level rise in future years. Furthermore, the longer our society waits to curtail emissions, the more significant the climate impacts we will commit to in the future. Given that emissions are not currently being capped, we are not on a track to limit either sea level rise or temperatures even at the levels these models indicate .

3. *Slowing of Atlantic Conveyer Belt*

A recent scientific study provides evidence that the Atlantic conveyer belt is slowing. The data suggests that the Atlantic overturning circulation is 30% slower than that of the period between 1957 and 2004, although the direct impacts of climate change to the overturning circulation have yet to be documented through observations.

- **Bryden, Harry L. et al. "Slowing of the Atlantic Meridional Overturning Circulation at 25°N." *Nature*. Volume 438. 1 December 2005 at www.nature.com**

The analysis is part of a periodic sampling of ocean flows at 25°N latitude. The most recent surveys, undertaken in 1998 and 2004 show notable decreases in deep circulation flow. The reduction in volume of the flow is huge: the equivalent of 60 times the flow of the Amazon River.

Implications: Global ocean circulation is one mechanism though which temperature throughout the world is regulated; warm waters around the equator flow northward and bring heat to Northern Europe, while cool waters from the polar region flow southward. Reductions in the volume of these flows are likely to yield a corresponding reduction in the northward heat flux. Should this be sustained, it would be extremely significant: modeling experiments suggest that this kind of decrease should be associated with a decrease in ocean temperatures in the North Atlantic of up to 2°Celcius or so, and maybe 0.5°Celcius over Europe. While such changes have not yet been observed (both the North Atlantic and Europe have warmed over this time period), if the trend continues we may expect considerable changes in the temperature and climate of Europe.

Greenhouse Gas Concentrations

1. *Greenhouse Gas Levels and Climate from Ice Core Sampling*

Two scientific reports released this year have used ice core samples from East Antarctica to detect greenhouse gas cycles of the past 650,000 years.

- **Spahni, Renato et al. "Atmospheric Methane and Nitrous Oxide of the Late Pleistocene from Antarctic Ice Cores." *Science*. Volume 310. 25 November 2005 at www.sciencemag.org**
- **Siegenthaler, U. et al. "Stable Carbon Cycle-Climate Relationship during the Late Pleistocene." *Science*. Volume 310. 25 November 2005 at www.sciencemag.org**

The ice cores, sampled and analyzed by the European Program for Ice Coring in Antarctica, reveal the long-term glacial-interglacial cycles of the climate and provide records of atmospheric carbon dioxide, methane, and nitrous oxide for the time period. The researchers note that methane and carbon dioxide levels after the Industrial Revolution remain unmatched to any record during the 650,000 years before the Revolution.

Implications: It has often been asserted that the geological record contains previous cases where CO_2 concentrations have risen to extraordinary heights — with little or no concomitant climate change. This data makes clear that we have surpassed any previous data in terms of GHG concentrations — and are, thus, in uncharted territory in terms of potential impacts and damages.

Hydrological cycle (hurricanes, glacial/snow melt and water supply)

One of the most significant impacts of climate change is predicted to be shifts in storm intensities, a rise in sea level, and increasingly rapid snow and ice melt (both from mountain glaciers, as well as in the Arctic).

Hurricanes

According to recent scientific studies, increased intensity of hurricanes can be attributed in part to climate change. In addition, scientists are now drawing a link between climate change and the first ever South Atlantic hurricane, which occurred in Spring 2004.

1. *Hurricane Intensity and Climate Change*

   Two recent scientific findings conclude that there has been an increase in hurricane intensity and attribute this trend in part to climate change.

- **Emanuel, Kerry. "Increasing Destructiveness of Tropical Cyclones over the past 30 years." *Nature*. Volume 436. 4 August 2005 at www.nature.com**
- **P. J. Webster et al. "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment." *Science*. Volume 309. 16 September 2005 at www.sciencemag.org**

While scientists have yet to conclude whether the number of hurricanes per year is correlated with climate change (Trenberth, Kevin. "Uncertainty in Hurricanes and Global Warming." *Science.* Volume 308. 17 June 2005 at www.science.mag.org) these two recent studies demonstrate that there has been an increase in hurricane intensity and attribute this trend to climate change, among other factors. Emanuel developed an index based on factors associated with hurricane destructive power. It includes sea surface temperature (which has been rising in part due to climate change and is correlated with hurricane intensity), as well as interannual and interdecadal swings in storm frequency, wind shear, sub-surface ocean temperatures, and tropospheric temperatures. Emanuel coupled the projected trends for hurricane intensity with the observed trends, and concludes that the observed increase in hurricane intensity far exceeds the pace of the predicted increase; he also concludes that climate change can be expected to further increase the intensity of hurricanes in the future.

Webster *et al.* shed additional light on the relationship between hurricane intensity and climate change, examining the upward trend in the number of category 4 and 5 hurricanes over a thirty year period. Their findings are consistent with climate models that attribute more intense storms to higher levels of greenhouse gases, which contribute to climate change.

Implications: There has been almost a doubling of hurricane power dissipation over the period on record, and future climate change, according to these analyses, can be expected to bring a greater number of intense storms. Given damages associated with intense storms over the recent past (for example, reports by Munich Re and others indicate weather-related damages over the past 25 years at about $1.5 trillion), we will need to increase our capacity to deal with damages to coastal communities and ecosystems.

2. *First South Atlantic Hurricane*

   First hurricane ever reported in the South Atlantic hit southern Brazil in Spring 2004:

- **Pezza, Alexandre and Simmonds, Ian "The First South Atlantic Hurricane: Unprecedented Blocking, Low Shear, and Climate Change." *Geophysical Research Letters*. Volume 32. 12 August 2005 at http://www.agu.org/journals/gl/**

The first hurricane ever reported in the South Atlantic hit southern Brazil in Spring 2004. Pezza *et al.* suggest that the persistence of the conditions that caused the hurricane can be attributed to climate change. Their analysis showed that the Caterina hurricane (named after Brazil's Saint Caterina State), accumulated its strength as a result of atmospheric anomalies — an unparalleled combination of wind shear and rare conditions at mid-to-high latitudes — which themselves are attributed to climate change. The authors conclude by drawing a direct link between South Atlantic hurricanes and climate change.

Implications: The expected persistence of such anomalies under a climate change future is likely to lead to increased intensity and frequency of Southern Atlantic storms. Few South American communities have experience dealing with hurricane intensity storms — suggesting that considerable effort will be required to minimize community and coastal ecosystem damages.

Glaciers and Snow Melt:

Glaciers are retreating; ice sheets are melting and collapsing; and early snowmelt is augmenting warming rates. Recent scientific studies document these climate change impacts in detail and discuss implications for the future.

1. *Arctic Sea Ice Levels and Climate Change*

   NASA scientists have long been tracking Arctic sea ice, which has been significantly retreating over recent years. June, which brings about the start of the melting season, established a record low in 2005 for sea ice cover — 6 percent below average.

- **NASA Earth Observatory, at http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=16978**

While historically, the ice has always regained coverage during the wintertime, recent years' warming has prevented such recovery. Arctic sea ice has been markedly decreased in the winter months as well as in the summer months. Following the trend set over the past few years, 2005 will likely be yet another year characterized by record low sea ice concentrations, according to NASA predictions.

Implications: The melting of sea ice is occurring more rapidly than heretofore predicted. Ice melting leads to changes in ocean salinity, freshening ocean waters and potentially contributing to changes in thermohaline circulation (the ocean's conveyer belt effect that moves equatorial heat to the north, warming Europe). Consistent with the trend in decreased sea ice concentrations, the study's results foreshadow a future of low sea ice cover with increasing concomitant effects.

2. *Antarctic Glacial Retreat*

A study published this year in the journal *Science* examined 244 marine glaciers in Antarctica and found that glaciers across the Antarctic Peninsula have been melting at unprecedented, accelerating rates.

- **Cook, A.J. et al. "Retreating Glacier Fronts on the Antarctic Peninsula over the Past Half-Century."** ***Science*****. Volume 308. 22 April 2005 at www.sciencemag.org**

The study measured glacial cover over several decades and found that 87% of the 244 Antarctic glaciers have retreated. Cook et al. combined several research methodologies, including aerial photographs and satellite imagery, to assess the state of Antarctic Peninsula glacial ice cover.

Implications: The study's results confirm modeling predictions that polar regions will warm at faster rates than lower latitudes. Moreover, the rate of change, as demonstrated by Cook and colleagues, is much faster than previously anticipated. As with other studies of Arctic melting, the results may, over time, lead to a fundamental change in thermohaline circulation – as well as to local faunal and floral changes as species seek to adapt to changing conditions.

3. *Ice Sheet Melting and Relation to Sea Level Rise*

A recent scientific study of Antarctic and Greenland ice sheets suggests that current modeling efforts have potentially significant shortcomings, as they do not fully assess the positive feedback loop between ice sheet melting and sea level rise.

- **Alley, Richard et al. "Ice-Sheet and Sea-Level Changes."** ***Science*****. Volume 310. October 2005 at www.sciencemag.org**

Ice sheet melting due to a warming climate may contribute further to climate change than earlier studies anticipated, as sea level rise from melting affects ocean circulation, which, in turn leads to additional climate changes. According to Alley et al., few projections fold in the potential interrelatedness of ice sheet melting, ocean circulation, and climate change. Lacking data on these relationships, scientists have not been able to assess the impacts of these feedbacks.

Implications: Theoretical assessments suggest that one critical consequence of adding fresh water to the oceans will be a slowing in ocean circulation. A second consequence of ice melt is sea level rise — which until recently had been thought to contribute less to ocean levels than thermal expansion but now is assumed to play a more significant role. While existing model projections already suggest potentially major effects from continued climate change, the results of this study suggest that previous studies understate the consequences, as they do not take into account the full suite of ocean/ice/temperature interactions.

4. *Antarctic Peninsula's Larsen Ice Shelf Stability and Climate Change*

Since a large portion of the Larsen B ice shelf collapsed in 2002, scientists have been studying the region for clues as to why the event occurred. New results suggest a combination of factors: not only has the ice been thinning throughout the present geological era (the Holocene epoch), but human induced climate change leading to regional Antarctic warming has also played a role in thinning and collapse.

- **Domack, Eugene et al. "Stability of the Larsen B Ice Shelf on the Antarctic Peninsula during the Holocene Epoch."** ***Nature*****. Volume 436. 4 August 2005 at www.nature.com**

The ice shelf collapse, some 12,500 km^2 in area, was unprecedented during the past 10,000 years. Domack et al. used a variety of paleontological and geological techniques to detect ice shelf thinning. They discovered that while there has been considerable long-term thinning in the ice over the past several thousands of years, it has been the recent warming over the Antarctic peninsula that triggered the collapse. They note that the event is unprecedented in the past 11,500 years — during which entire period the ice shelf has been quite stable.

Implications: With both models and theory predicting that the poles will warm faster than equatorial regions, we may expect increasing instability in the Antarctic ice shelf. Collapse of major ice shelves, such as the Larsen B ice shelf studied by Domack et al., can have adverse impacts to the Antarctic ecosystem, as coastal species are no longer able to survive in the changed environment. The collapse is another signal that climate is changing — and that the theory is more and more being borne out in direct observation.

5. *Land Surface Changes and Amplified Future Arctic Summer Warming*

While many scientists have long been following the pronounced summer warming in the Arctic, a recent scientific study takes Arctic research one step further by assessing the feedbacks between land surface changes due to summer warming and the implications for future summer warming. One new study shows that atmospheric warming has led to a lengthened snow-free season in arctic Alaska, which has in turn led to terrestrial changes, such as shrub and tree expansion.

- **Chapin III, F.S. et al. "Role of Land Surface Changes in Arctic Summer Warming."** ***Science*****. Volume 310. 28 October 2005 at www.sciencemag.org**

Chapin et al. show that land surface changes provide a positive feedback, and augments atmospheric warming by a factor of two to seven. They suggest that terrestrial transformations will increase local atmospheric warming by roughly three watts per square meter per decade (similar in magnitude to the regional heating expected over multiple decades from a doubling of atmospheric CO). In turn, the rate of summer warming will increase significantly, magnifying climate change impacts in Arctic communities and ecosystems. The study's authors posit that summer warming will be further amplified as a result of ongoing additional land surface changes.

Implications: Many species of arctic animals can only prosper under current conditions of ice and snow — including popular megafauna such as the polar bear and the arctic seal. Changes in vegetation as well as in temperature will reduce the aerial extent of their habitat. Increased warming will have other consequences as well: subsistence communities livelihoods may be threatened, and many human infrastructures that rely on winter ice cover (for example, ice roads for haulage to Alaska's North Slope oil wells) may have a reduced capacity due to such changes.

Hydrological Cycles, Water Supply:

Climate change is altering hydrological cycles, with long-term implications for global food availability and the viability of ecosystems. We are already seeing changes in the frequency and intensity of drought and flooding. In addition, mountain snowmelt is coming earlier due to warming temperatures, limiting water supply during peak demand season.

1. *Climate Change and Precipitation*

A study conducted this year has broad implications for future global precipitation variance, suggesting that several regional precipitation trends can already be detected and will likely increase in the future due to climate change. In particular, wet regions are increasingly experiencing higher levels of precipitation, and arid areas are witnessing reduced levels and becoming drier.

- **Dore, Mohammed H.I. "Climate Change and Changes in Global Precipitation Patterns: What do We Know?"** ***Environment International*****. Volume 31. October 2005 at www.sciencedirect.com/science/journal/01604120**

Dore compiles and reviews regional and continental levels of precipitation and is able to draw conclusions regarding rainfall patterns. He attributes the precipitation patterns and variance to climate change and ocean currents. In addition, he links precipitation variance with global food availability and states that food security will be hit hard by climate change.

Implications: Changes in precipitation are one of the expected impacts of climate change. This study suggests the changes are already observable — and are likely to intensify with additional warming. Further changes in precipitation patterns (both in intensity and variability) will require communities increasingly to control for drought and flooding. Implications for food availability, particularly in drought or flood prone areas, could be significant.

2. *Climate Change, Deforestation and Amazon Hydrological Cycle*

 Scientists have recently discovered that deforestation in the Amazon is leading to greater changes in the Amazon's climate and hydrological cycles than initially predicted.

- **Chagnon, F.J.F. and R.L. Bras. "Contemporary Climate Change in the Amazon." *Geophysical Research Letters*. Volume 32. 2005 at http://www.agu.org/journals/gl/**

 Chagnon and Bras conclude that rainfall is actually increasing over deforested areas as a result of shallow cloud levels over the area and at higher levels than first predicted. Deforestation thus becomes another determining factor of the region's hydrologic cycle.

 Implications: Scientists have already concluded that deforestation releases significant levels of greenhouse gases, which are stored in the forest's carbon sinks. According to many scientists, increased levels of greenhouse gases are altering global precipitation levels and variance. This study implies that deforestation by itself can also dramatically change hydrological cycles, compounding climate change effects. Given its size and role in distributing freshwater through the ecosystem, the Amazon hydrological cycle is key to global climate patterns. The study's findings suggest that the shifting patterns of rainfall and shallow clouds could have dramatic implications for the global climate.

3. *Amazon Basin and Drought*

 A study conducted this year by the Amazon Environmental Research Institute suggests that the extreme drought characterizing the Amazon Basin may have been driven by Atlantic Ocean surface warming and resultant air circulation changes. Researchers at a forest monitoring station run by the Woods Hole Research Center also state that rising sea surface temperatures in the North Atlantic could be responsible for the record drought.

- **Amazon Environmental Research Institute, http://forests.org/articles/reader.asp?linkid=47478**
- **Hopkin, Michael. "Amazon Hit by Worst Drought for 40 Years: Warming Atlantic Linked to Both US Hurricanes and Rainforest Drought." *Nature News*. 11 October 2005 at www.nature.com**

 Warming sea surface temperatures create both low pressure and high pressure storm systems over the Atlantic. The low pressure systems are characteristic of the North Atlantic and bring increased precipitation to nearby regions. The high pressure systems, however, hold less rainwater and concentrate over the South Atlantic, leading to lower precipitation levels in regions like the Amazon. The current drought is considered the most severe in the last half century and has brought devastation to many local communities and ecosystems in the Amazon.

 Implications: Increasing greenhouse gas concentrations and resulting global temperature increases may lead to even more pronounced and lengthy periods of drought in the Amazon. Not only will the Amazon's ecosystem services, population and biodiversity be negatively impacted, but the rainforest's capacity to sequester carbon may also be compromised.

4. *Climate change and western North American water supply*

 Scientists Iris Stewart and colleagues examined snowmelt in western North American streams and suggest that climate fluctuations are driving changes in the timing of snowmelt, which is increasingly becoming triggered earlier in the season.

- **Stewart, Iris T et al. "Changes toward Earlier Streamflow Timing Across Western North American." *Journal of Climate*. Volume 18. April 2005 at http://ams.allenpress.com/amsonline/?request=get-abstract&doi=10.1175%2FJCLI3321.1**

 The scientists examined streamflow from 1948 through 2002 for over three hundred stream systems and provide evidence that that the early onset of snowmelt is characteristic of a much larger portion of the region's streams than initially anticipated. Of the snowmelt-dominated gauges, which totaled 241 in number, two-thirds had an early spring onset date of more than three days.

 Implications: Snowmelt supplies water to western North American rivers and will impact many communities (e.g. drinking water availability, hydroelectric utilities, and agricultural lands will be affected) and ecosystems that rely on these water sources. Early melting may lead not only to increased intensity of spring-time flooding, but also of summer droughts when meltwater is not available at all.

5. *Climate Change Impacts on Water Availability in Snow-Dominated Regions*

   A recent scientific study published in the journal *Nature* predicts that climate change will bring devastating impacts to communities that obtain water from melting glaciers and snow packs.

- **Barnett, T. P. et al. "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions."** ***Nature*****. Volume 438. 17 November 2005 at www.nature.com**

  Climate change is affecting hydrological cycles. One consequence is that snow and ice levels have been reduced; another is that snowmelt is occurring earlier in the spring season. Many regions lack the capacity to store winter and spring run-off for later in the season, when it is needed to meet peak summer demand. The authors review regional impacts in the Western USA, the Rhine River valley in Europe, the Hindu-Kush region in Asia, and the South American Andes. As one example, they cite Peruvian glaciers, where there has already been a 25% reduction in ice volume over the last thirty years, and where water resources will be substantially constrained in the absence of the glaciers. The authors conclude that the problem is increasingly urgent, indicating their expectations that water availability will dramatically decrease over the coming years.

  Implications: More than one sixth of the global population lives in regions that depend on snow and glaciers for water supply. With snow, ice and glacial melting from climate change, future water availability will be compromised, which could lead to a loss of potable water, population displacement, significant agricultural losses, and massive ecosystem degradation.

Ecosystems and Ecosystem Services:

Climate change is taking its toll on ecosystems and the services that humans derive from them. Species are already migrating out of historic ranges to cooler climates. Habitats are becoming reduced as a result of temperature increases. Food chains have been dramatically altered, as species fail to adapt to climate change impacts. Further alterations in ecosystem provisioning services, including wood products, drinking water supply, and soil productivity can be expected as climate continues to change.

Ecosystem effects

Entire ecosystems (ecological systems including interlinked fauna, flora and the physical framework in which they live) are being affected by climate change. Plants and animals associated with certain geographic regions are moving — or dying. Observed changes are already significant; future changes are expected to be even more fundamental as species adapt to changing climatic conditions.

1. *African Plant Diversity and Climate Change*

   A recent scientific study exploring climate change impacts on sub-Saharan African plant species predicts that climate change will trigger species migration and lead to habitat reduction:

- **McClean, Colin et al. "African Plant Diversity and Climate Change."** ***Annals of the Missouri Botanical Garden*****. Volume 92. 2005 at http://www.jstor.org/journals/00266493.html**

  The authors examined over 5,000 African plant species in climate models and predict that 81%–97% of the plant species' suitable habitats will decrease in size or shift due to climate change. By 2085 between 25% and 42% of the species' habitats are expected to be lost altogether.

  Implications: While these models are only a preliminary step in assessing climate change impacts to sub-Saharan African plant diversity, they do provide a clear indication of the vulnerability of plant species in Africa to climate change. Ecosystems services that rely on sub-Saharan African plant diversity, including indigenous foods, as well as both locally used and potentially exotic plant-based medicines, are likely to be adversely impacted. It must be noted that their study also assumes that shifting species will be able to move — and not have migration pathways blocked by human development, or other geographic features. If such assumptions are not borne out; the overall decline could be even more severe.

2. *Species' Ranges and Climate Change*

   A recent study of 16 Spanish butterfly species documents a move upward in elevation as a result of temperature rise.

- **Wilson, Robert et al. "Changes to the elevational limits and extent of species ranges associated with climate change."** ***Ecology Letters*****. Volume 8. November 2005 at http://www.blackwell-synergy.com/doi/abs/10.1111/j.1461-0248.2005.00824.x**

While models have projected that species are likely to move upwards in elevation as a result of temperature rise in the future, scientists have recently documented that the shift is already occurring. The sixteen butterfly species studied in central Spain have shifted their ranges by 212 meters (about 700 feet) in elevation during the last thirty years, which has seen an increase in 1.3°C mean annual temperature. The scientists project that the species' habitat has already decreased by one-third and is likely to decrease by 50–80% during the next hundred years if climate change is left unabated.

Implications: The results suggest that climate change is already causing species range shifts and habitat loss with long-term implications for species' survivability. Moreover, recent scientific studies (Thomas, J.A. "Comparative Losses of British Butterflies, Birds, and Plants and the Global Extinction Crisis." Science. Volume 303. 19 March 2004 at www.sciencemag.org) have suggested that butterflies act as indicator species and signal early warning — much like a canary in a coal mine. This species characteristic supports one of the conclusions from Wilson's study that more widespread ecosystem loss is already underway, and will likely become more severe in the future.

3. *Climate Change and Antarctic Fur Seals*

Scientists engaged in a twenty-year study of Antarctic fur seal pups have found that the increased monthly average sea surface temperature, which they link to climate change, can explain the recent reductions in pup production.

- **Forcada, Jaume et al. "The Effects of Global Climate Variability in Pup Production of Antarctic Fur Seals. *Ecology*. Volume 9. 25 January 2005 at http://www.esajournals.org/esaonline/?request=search-simple**

The authors argue that anomalies in the sea surface temperature likely caused a reduction in available prey populations of krill (the base of the seal food chain). Resulting undernourishment has in turn significantly reduced the breeding potential of Antarctic fur seal females. Thus, a twenty year trend of increased monthly average sea surface temperature, driven by climate change, can explain the recent reductions in seal pup production.

Implications: This study demonstrates the potential for climate change to severely impact marine ecosystems throughout the entire food chain. While no specific studies have yet been undertaken, it may be anticipated that, by extension, reductions in fur seal populations will in turn negatively impact their own predators, including leopard seals and killer whales. Furthermore, it demonstrates that indirect effects quite far down in animals' food chains can have devastating effects at the top in large and often already threatened megafauna.

4. *Climate Change and Distribution of Marine Fish Populations*

Sea temperature rise is causing fish species in the North Sea to shift their ranges northward in latitude and/or deeper to find colder waters. The North Sea waters have warmed by 1.1°C over the past 30 years.

- **Perry, Allison et al. "Climate Change and Distribution Shifts in Marine Fishes." *Science*. Volume 308. 4 June 2005 at www.sciencemag.org**

Of the 36 species examined in the North Sea (including exploited and non-exploited species), two-thirds were found to be migrating to cooler waters. The 'center" of species populations moved from nearly 50 to more than 400 km north, while southern boundaries moved from over 100 to more than 800 km north. Species that shifted their distributions the most were smaller and had faster life cycles than those species that did not shift. Because species are shifting at different rates and amounts, the authors expect their results to have implications for commercial fisheries; some of the northern waters to which fish are migrating are already among the most over-fished in the world.

Implications: Changes in North Sea fisheries, already under stress from over-fishing, are likely to accelerate with climate change. Fisheries may need to shift to smaller and more adaptable species, as the effects of climate change continue to disrupt marine ecosystems, and as fish populations depart for cooler waters and interact with new marine species. On economic grounds alone, this could have huge implications: the North Sea fishery is valued billions of dollars a year. Of equal significance is the clear indication that climate change has already begun to interfere with large scale marine habitats.

5. *Implications of Warming on Plant and Animal Species*

Scientists have recently discovered that the shift in global temperatures of 5° to 10° C at the beginning of the Eocene Epoch (roughly 55.8 million years ago) caused "large and rapid" shifts in the range as well as the morphology of a variety of plants.

- **Wing, Scott et al. "Transient Floral Change and Rapid Global Warming at the Paleocene-Eocene Boundary." *Science*. Volume 310. 11 November 2005 at www.sciencemag.org**

The authors state that these ancient climate shifts mirror those projected over the next century as greenhouse gas emissions lead to rapid global warming. They conclude that a similar level of change in the range of plant species can be expected as human induced climate change proceeds.

Implications: Geologically, periods of rapid temperature change have been associated with mass extinctions, including of marine and terrestrial organisms. While temperature changes of 5° to 10° C are at the upper end of the range of global average increase projected over the next century, they are consistent with expected temperature changes in higher latitudes. The observation that ancient flora shifts were quite rapid, and that species migrated both across continents and within continents suggests a similar pattern may be observed today — although human activities — including urban features and agriculture — may block continent-scale migrations. It thus seems likely that ecosystems will be disrupted as species both seek to move, and as they decline in the face of climatic change.

6. *Ocean Acidification, Marine Organisms, and Climate Change*

Two scientific studies published this year signal that the oceans are getting more acidic and that marine organisms' ability to survive will be compromised.

- **"Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide." Royal Society. December 2005 at http://www.royalsoc.ac.uk/displaypagedoc.asp?id=13539**
- **Orr, James C. et al. "Anthropogenic Ocean Acidification Over the Twenty-First Century and Its Impact on Calcifying Organisms." *Nature*. Volume 437. 29 September 2005 at www.nature.com and http://sciencenow.sciencemag.org/cgi/content/full/2005/928/5**

The Royal Society paper establishes that oceans are absorbing carbon dioxide from the atmosphere, resulting in ocean acidification. The study states that in the last two centuries oceans have absorbed roughly half of the amount of CO_2 emitted by fossil fuel use and cement production. This assimilation of carbon dioxide has caused ocean pH to be reduced as hydrogen ion concentrations increase.

Orr et al. conclude that higher ocean acidity will be devastating to the marine environment within a short period of time — within tens of years instead of hundreds of years. Basing analyses on thirteen global carbon models under assumed a "business-as-usual" trend in greenhouse gas emissions, their conclusions are that the oceans will be undersaturated in calcium carbonate: leading to increasing difficulty for shelled organisms to create skeletons and shells. By 2050, with increasing CO_2 concentrations and increased acidity, the problem will be severe in the polar waters of the Southern Ocean, and by 2100, all of the Southern Ocean and the sub-Arctic Pacific Ocean levels will be undersaturated with calcium carbonate.

Implications: Acidification of the oceans will likely wreak havoc on marine species and entire ecosystems. Given that the oceans have already absorbed a substantial amount of carbon dioxide, we have already committed to an irreversible amount of ocean acidification. As a result, we will likely see additional stress on coral reefs (already under threat due to ocean warming); other fish and aquatic organisms may be stressed as well. It is likely that rebalancing the ocean pH will take thousands — or even hundreds of thousands of years.

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. With climate change, we can expect processes and services to change – often for the worse. Droughts, floods, changing disease and pest vectors will all contribute to the reduction, leading to loss of food as well as other economic benefits.

1. *Declining European Ecosystem Services*

"Ecosystem services" are the conversion of natural assets — such as trees, snow cover, soil fertility, etc. — into valuable benefits such as wood products, winter tourism, and arable land. A scientific study conducted in Europe this year states that climate change will alter — usually for the worse — the supply of European ecosystem services over the next century.

- **Schröter, Dagmar et al. "Ecosystem Service Supply and Vulnerability to Global Change in Europe."** ***Science*****. Volume. 27 October 2005 at www.sciencemag.org**

While climate change will result in enhancements of some ecosystem services, a large portion will be adversely impacted because of drought, reduced soil fertility, fire, and other climate change driven factors. Thus, Europe can expect a decline in arable land, a decline in Mediterranean forested areas (although there will be an overall increase in European forest), a decline in the terrestrial carbon sink and soil fertility, and an increase in the numbers of basins with water scarcity. This will all increase biological impoverishment, and lead to a significant decline in mountain tourism. While the study suggests all of Europe will be affected, its primary focus was on the southern portion around the Mediterranean.

Implications: While this study assessed ecosystem services only in Europe, the consequences are likely applicable to ecosystem services across the globe. Furthermore, other parts of the world with lower levels of economic development and poorer infrastructure (including in particular those countries that primarily rely on agriculture or fiber for their economic well-being) are less likely to be able to cope with declining services than Europe.

2. *Climate Change and World's Food Supply*

A study conducted this year by the United Nations Food and Agriculture Organization (FAO) and the International Institute of Applied Systems Analysis (IIASA) reveals that climate change will significantly impact the global food supply.

- **Food and Agriculture Organization of the United Nations (FAO), Report of the 31st Session of the Committee on World Food Security Rome, 23–26 May 2005 at http://www.fao.org/clim/docs/CFS/CFS.pdf**

The study quantified crop damages using spatial soil and climate data and then overlaid projections for productivity potential under a changed climate. The results project a loss of 11% of arable land in the developing world due to climate change, including a loss of cereal production in 65 developing countries (for these countries, the loss equates to roughly 16% of agricultural GDP in 1995 dollars). The study suggested that some of the losses would be offset: "new" land available at high latitudes could become available in Russia Northern Europe and North America. However, the distributional effects would, overall be quite negative.

Implications: Not only will food security be threatened by climate change impacts, but the agricultural GDP loss will also result in economic devastation for many developing countries. The developing world already has to contend with food shortages as a result of invasive species, inefficient food distribution, lack of arable land, and other factors, and climate change presents yet another factor that wreaks havoc on food supply. Climate change, in additional to exacerbating these effects, may also lead to food shortages and trigger social unrest, as well as accelerate malnutrition and disease. While overall food production may not be threatened, those least able to cope will have another cost: food imports from the North.

3. *Carbon Sequestration and Rising Atmospheric Carbon Dioxide Levels*

A 2005 study suggests that rising atmospheric CO_2 will ultimately lead to reduced carbon sequestration through trees' roots in forest soil. Therefore, as CO_2 levels increase in the atmosphere, forests will not be able to perform their role as carbon sinks as well as they do under lower concentrations — in turn, increasing the level of CO_2 that will stay in the atmosphere and exacerbate global warming.

- **Heath, James et al. "Rising Atmospheric CO_2 Reduces Sequestration of Root-Derived Soil Carbon."** ***Science*****. Volume 309. 9 September 2005 at www.sciencemag.org**

The authors conclude that while increased levels of atmospheric CO_2 leads to increased tree growth, associated increases in microbial respiration lead to a decreasing quantity of CO_2 being sequestered through the trees' roots into the forest soil. Observed reductions were approximately 40%. While the study examined only a small sample, the authors believe the process would hold at large scale, and suggests that annual carbon sequestration through sinks may be significantly reduced in the future as atmospheric carbon dioxide levels rise.

Implications: The study's findings imply that projections of carbon sequestration are likely optimistic. If forests are not able to sequester carbon at the rates anticipated, global warming is likely to proceed at a much more rapid rate than anticipated. Furthermore, the process seems to create a positive feedback loop: the higher the atmospheric levels of CO_2, the less soils absorb — and therefore, the more rapidly atmospheric levels rise. Thus, not only may efforts to control global GHG concentrations through forest carbon sequestration be limited, but we may need to revise upward our expectations of the rate of global climate change.

Climate Change Mitigation Technologies

Several technological breakthroughs have occurred in 2005, which could reduce costs and ease the transition to a reduced carbon economy. These technologies run the gamut from biofuel technology advancements to fuel cell improvements to hydrogen energy innovations. Several of new developments from 2005 are described here.

1. *Waste CO_2 from Ethanol Plant Used for Enhanced Oil Recovery*

A project funded by the U.S. Department of Energy made a technological breakthrough this year for CO_2 use in enhanced oil recovery.

- **http://www.netl.doe.gov/publications/press/2005/tl_kansas_co2.html**

The project recovered CO_2 byproducts from ethanol production and recycled them in an enhanced oil recovery project in central Kansas. The Department of Energy states a single plant could both provide injection fluid to assist in the production of five million oil barrels a year for 25 years, as well as sequester 1.5 million tons of CO_2.

Implications: Enhancing the efficiency of oil recovery directly increases supply. While a 5 million barrels a year is a tiny share of US demand, if this technology were applied on a larger scale, the additional supply could have implications for oil imports and prices. On the sequestration side, while questions remain about long term monitoring of geologically stored carbon, the benefits of avoiding its release into the atmosphere are significant. Finally, the process is a net economic winner: according to DOE, if all ethanol plants' waste CO_2 were sequestered by enhanced oil recovery projects, the benefits could equate to US $88 million over a decade. Such calculations do not even include the cost of avoided climate change — with extremely high values.

2. *Nanotechnology Increasing Efficiency of Solar Cells*

A recent study by scientists at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) demonstrates that solar cells can be made more efficient through the application of nanotechnology. DOE researchers state that "quantum dots" can convert more than 65 percent of solar energy into electricity, which could roughly double existing solar cell efficiency.

- **http://www.nrel.gov/news/press/2005/1805_quantum_dot.html and http://pubs3.acs.org/acs/journals/toc.page?incoden=nalefd**

Quantum dots," also called "nanocrystals," can produce more electricity than solar cells. While solar cells can convert one photon of solar energy to one electron (with the rest being lost as thermal byproduct), "quantum dots" can reduce heat waste and convert up to three electrons per sunlight photon.

Implications: The Laboratory's research team suggests that "quantum dots" could make solar energy more efficient and cost-effective, critical if solar technology is to replace coal or gas as a power source at competitive market rates. In addition, the researchers have suggested that the technology could be applied in the future to photoelectrochemical cells, creating a renewable method for generating hydrogen — which might be used in place of gasoline as a mobile fuel source as well as a stationary source of electricity.

3. *Solar Technology and Hydrogen Creation*

Scientists from Weizmann Institute of Science in Israel have recently discovered a method to extract zinc metal using solar power, which in turn can then be used to produce hydrogen.

- **http://www.nature.com/news/archive/051121.html**

The researchers focused an intense beam of sunlight, created with over sixty mirrors, onto zinc oxide and charcoal. Zinc powder is then created, which can in turn be used to produce hydrogen, released from water when poured over the powder. The process is not completely carbon free, as the charcoal releases carbon monoxide, which will convert to atmospheric CO_2.

However, the Institute claims that if the technology were applied to a larger industrial project, the carbon monoxide could be used to create more hydrogen. In an effort to reduce the carbon byproducts, the researchers aim to explore whether agricultural waste can be used in lieu of charcoal.

Implications: Hydrogen is a clean fuel source that can be used in fuel cells, power vehicles, and generate heat and electricity. However, hydrogen gas does not exist in a natural form that can be used and captured. Thus, its use is dependent on extracting it from compounds that contain hydrogen. The production process can be energy and carbon intensive. If researchers are successful, the hydrogen production process could become more climate friendly — and even cost-effective. In addition, ongoing research may succeed in developing a process that could use solar technology for hydrogen production in vehicles — eliminating the need to develop a new infrastructure to deliver hydrogen to vehicles.

4. *Fuel Cell Technology Advancement*

Scientists from Virginia Polytechnic Institute and State University have recently developed an innovative electronic technology that makes fuel cells more efficient and could reduce their size and costs.

- **http://www.netl.doe.gov/newsroom/index.html**

The technology converts direct current (DC) voltage into alternating current (AC) with appreciable gains in efficiency. According to the researchers, a one percent increase in efficiency can cut costs by $5-$10/kilowatt. Such efficiency gains would eliminate large, expensive additional converters and/or capacitors, thereby reducing fuel cell system size and costs.

Implications: The technology will make fuel cells more cost-effective, smaller, and more efficient, with implications for deployment on a larger scale. If successful, this project will promote the creation of fuel cells that are attractive to residential and commercial electricity markets, as well as transportation and utility sectors.

5) *Novel Catalytic Process for Biodiesel*

Researchers at the University of Wisconsin have recently developed a new catalytic process that can convert almost any type of plant matter into fuel.

- **Huber, G.W. "Production of Liquid Alkanes by Aqueous-phase Processing of Biomass-Derived Carbohydrates." *Science*. Volume 308. 3 June 2005 at www.sciencemag.org and www.cnn.com/2005/TECH/06/07/biofuel.vision/**

Traditional biofuels, such as ethanol, rely on the fatty acid portion of the plant, which only comprises approximately 10 percent of plant mass. With the new catalytic process, agricultural waste could be transformed into biofuels more readily. In addition, the advanced process produces 2.2 units of energy for every unit used, and is more efficient than existing biofuels (which produce half of that amount of energy per unit used).

Implications: The innovative catalytic reactor is not only more efficient, but could also cut down on agricultural waste and reduce the need to convert lands into biofuel stocks. Biofuels are a cleaner alternative to fossil fuels and create farming jobs and income. In addition, sustainably grown cops release no CO_2 over their lifetime.

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