Testimony for a Hearing of the Senate Environment and Public Works Committee

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The Warming Oceans: Present and Future Impacts

It seems as though the weather gods have gone berserk in recent years, as nearly every day the headlines report unusual droughts, floods, prolonged cold and snow, heat waves, or unusual weather events happening somewhere around the globe. Sea level is rising ever faster, and its contribution to damage from coastal storms is already being felt. Nearly three-quarters of the sea ice floating on the Arctic Ocean has disintegrated…in only 30 years. How and why are these changes happening, and what can we expect in decades to come?

Atmospheric changes drive ocean changes

In the past year, the human/Earth system reached three important milestones.

- In 2012 more carbon dioxide was emitted into the atmosphere than ever before.
- The amount of carbon dioxide in the atmosphere reached 400 parts per million, a 40% increase since the beginning of the industrial revolution. The last time the atmosphere contained this much carbon dioxide (about 2 million years ago), the Earth was several degrees warmer and the seas were tens of feet higher.
- Arctic sea ice melted to its lowest summer extent in at least 5000 years.

Greenhouse gases, of which carbon dioxide is one, trap heat emitted by the Earth's surface. This fact has been known for over a century. As human activities augment CO_2 concentrations in the atmosphere through fossil fuel burning, we are effectively putting a thicker blanket on the planet. The oceans absorb the vast majority of this excess energy, and because of water's huge heat capacity, the warming process takes a long time. This is why the Earth's temperature is not as warm as it was 2 million years ago: we've added the CO_2 so fast that the warming hasn't been able to catch

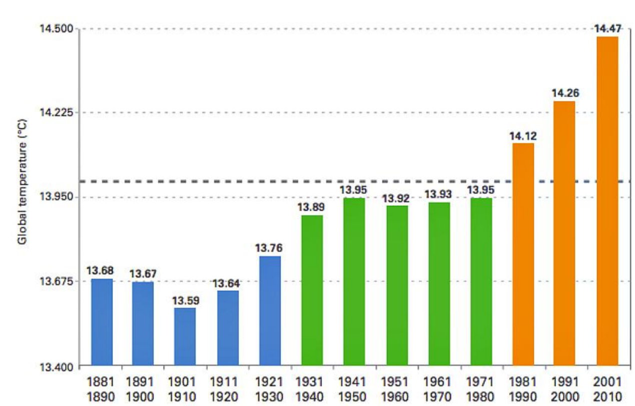

Figure 1: Global average temperature by decade. From http://library.wmo.int/pmb_ged/wmo_1119_en.pdf

up. But it's starting to.

This month the U.N. released a report stating that the past decade was the warmest in at least 160 years (**Figure 1**). Counter to claims by those who choose to ignore peer-reviewed scientific research, the heating of the Earth is not slowing down. Because of surface cooling over much of the Pacific Ocean in recent years owing to natural fluctuations in ocean circulation patterns, global-average *air* temperatures have not risen as fast as during the previous decade. Instead, the additional heat trapped by greenhouse gases has warmed deeper layers of the ocean, as evident in **Figure 2**.

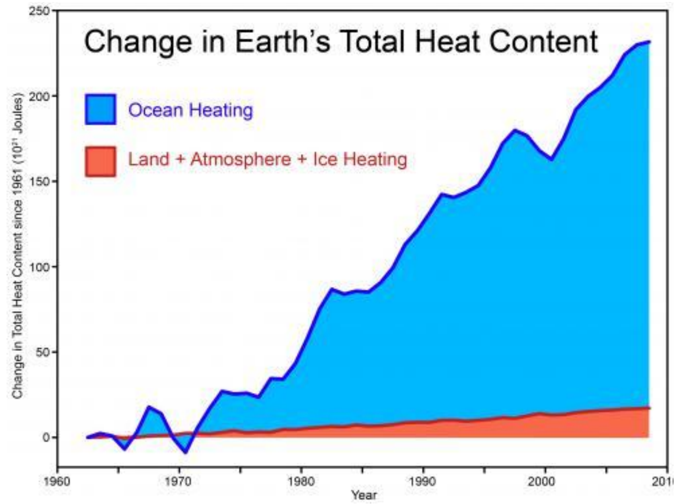

Figure 2: Changes in Earth's heat content, from Church et al (2011).

The Earth's Surface is Not Warming Uniformly

Owing to the effects of ocean currents, weather patterns, and variations in surface characteristics, temperature changes around the globe are far from uniform. This is abundantly clear in **Figure 3**, which illustrates the temperature differences from normal during the past decade. While nearly everywhere warmed, the changes were larger over land than over the oceans, and warming was especially pronounced over the Arctic. Differences in temperature are the drivers of weather patterns, so these spatial differences in warming must disrupt what we consider to be normal weather conditions.

Surface temperature changes are also affected by natural fluctuations in ocean conditions, such as El Niño/La Niña, the Pacific Decadal Oscillation, and the Atlantic Multi-decadal Oscillation, but as shown in **Figure 2**, the overall trend is for global ocean heating.

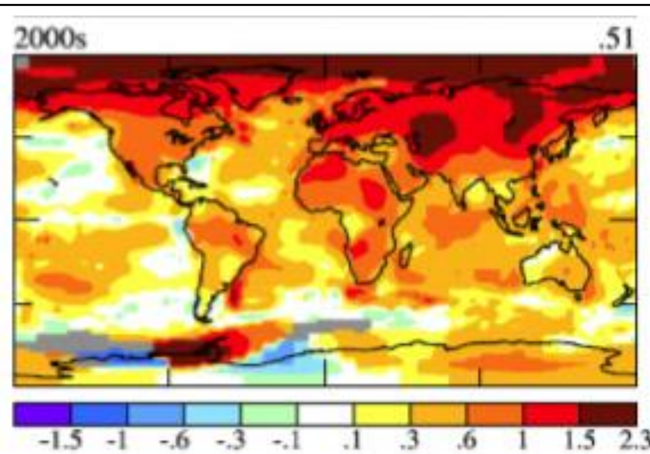

Figure 3: Annual surface temperature differences from normal during 2000-2010. From NASA/GISS.

Warming Oceans Contribute Directly to Sea Level Rise

A basic fact of physics is that when a gas or liquid warms, it expands. Warmer oceans have contributed about half of the observed global-average sea level rise (~1 foot since 1900). The pace of warming has increased, and so has the rate of sea level rise. By the end of the 21st century, sea levels are expected to be about 3 feet higher, which will have devastating impacts on low-lying coastal cities and communities around the world. Approximately 600 million people will be affected. Even if storms do not increase in frequency or intensity (which is *not* the expectation), they will ride on a higher ocean, increasing the destruction by storm surges and wind-driven waves.

Just as temperatures are not changing uniformly, neither will sea-level rise. Some land areas have been sinking and others rising since the last ice age, which either exacerbates or lessens the impact of rising seas. Changes in ocean currents also redistribute heat, and thus affect the amount of water expansion in a particular area. The loss of Greenland's ice sheet and other large masses of land ice also influence sea levels by imposing gravitational changes. The sum of these influences result in the low-lying and densely populated mid-Atlantic coast of the U.S. experiencing some of the largest increases in sea level (http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

Warming Oceans Cause Increased Evaporation of Moisture into the Atmosphere

As the oceans and atmosphere warm, evaporation from the ocean surface increases, which adds water vapor to the air. This extra water vapor plays several important roles in exacerbating climate change. First, water vapor is a potent greenhouse gas, and as its concentration increases, additional heat is trapped, amplifying the original surface warming – a classic example of a positive feedback in the system. The second effect is to provide additional fuel for storms, because when water vapor condenses into cloud droplets, heat is released into the atmosphere. This energy is the primary power source for hurricanes in particular, as well as for other types of storms. Third, the additional water vapor enables storms to produce more rain and snow, increasing

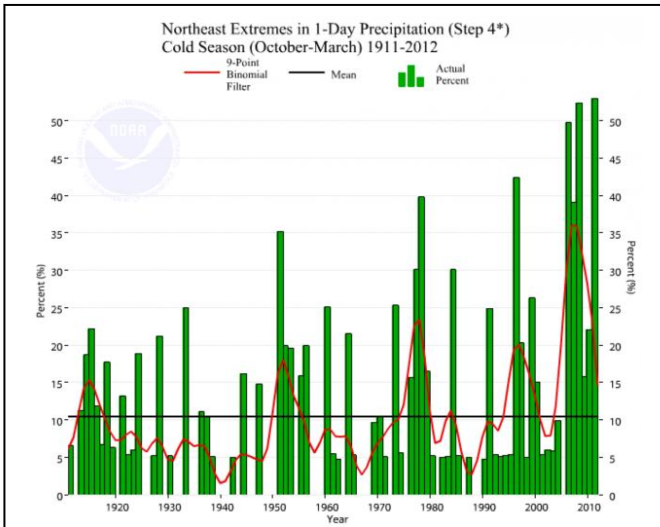

Figure 4: Heavy precipitation events are increasing in the northeastern U.S. From NOAA Climate Extreme Index.

the likelihood of severe rain events, flooding, and heavy snow falls. Heavier precipitation events have already been documented in the northeastern U.S. (**Figure 4**). Fourth, it is one of the main factors contributing to the disproportionate warming occurring in the Arctic, especially in winter and spring. The ramifications of this are discussed later.

Warmer Oceans May Affect Tropical Storms

Very warm ocean temperature is one of the essential ingredients for the development of tropical storms, primarily because it drives large evaporation rates, which supply copious amounts of water vapor that fuel the storms. As the oceans continue to warm, hurricane seasons are expected to lengthen, and the regions where tropical storms can develop and survive will expand. The situation that existed during Superstorm Sandy's lifespan may offer a glimpse of what we can expect to see occur more often in the future.

When Sandy moved out of the Caribbean in late October, it encountered ocean temperatures much above normal for late October all along the east coast of the U.S., which may have allowed the storm to survive intact longer and travel farther north than would be typical for that time of year (**Figure 5**). Meanwhile, the ingredients for an autumn nor'easter were gathering along the eastern seaboard. Because Sandy endured so far north, the two systems – that normally occur in distinct seasons – were able to coalesce into the powerful hybrid storm that wreaked havoc from Delaware to Nova Scotia, along with record blizzard conditions in West Virginia.

Figure 5: Superstorm Sandy survived farther north than usual for a late-October tropical storm, where it merged with a developing nor'easter. From ClimateCentral.org.

Warming Oceans Contribute to Sea Ice Loss in Both Hemispheres

A number of factors contribute to the recent and ongoing rapid decline of the Arctic sea ice cover (**Figure 6**). These include rising air temperatures, increasing water vapor and clouds, changing wind patterns, and warming oceans. As sea ice retreats, less of the sun's energy is reflected back to space by the diminished ice surface and more of it is absorbed into the ocean. In 2012 alone, the extra energy absorbed into the Arctic Ocean where there used to be ice is roughly the amount used to power the entire United States for 25 years! As this energy warms the ice-free areas, more melting ensues, establishing another powerful positive feedback in the system. Additional ocean heat is also entering the Arctic from lower latitudes via currents flowing in from the North Atlantic and North Pacific Oceans. This source of heat has been shown to be particularly important for reducing the ice extent in the Arctic north of Norway during winter and north of Alaska during summer. Rising ocean temperatures have also been implicated in thinning ice shelves along the Antarctic Peninsula and in warming the air in that region.

Figure 6: Summer Arctic sea ice has declined in extent by HALF and in volume by THREE-QUARTERS in only 30 years. Image from LiveScience.org.

A Rapidly Warming Arctic Disrupts Weather Patterns in the Northern Hemisphere

Recent research has revealed some less intuitive links between climate change and the escalation of extreme weather. The Arctic is warming two to three times faster than the rest of the northern hemisphere owing primarily to sea-ice loss, earlier snow melt on Arctic land in spring, and increasing water vapor. This so-called "Arctic amplification" means that the temperature difference between the Arctic and mid-latitudes is lessening. This is important because the west-to-east winds of the jet stream are driven by that temperature difference. The jet stream is a fast river of wind high in the atmosphere that takes on a wavy path as it encircles the northern hemisphere, forming the boundary between warm air to the south and cold air to the north. As its westerly flow weakens owing to the reduced Arctic/mid-latitude temperature difference, the waves in its trajectory tend to take larger north-south swings (**Figure 7**). These waves control weather systems on the surface: conditions tend to be clear and dry in the part of the wave where winds blow from the northwest, and it's generally stormy where winds come from the southwest. As the waves increase in size owing to Arctic amplification, they are expected to progress eastward more slowly, which means that the weather associated with those waves lasts longer in any particular location (Francis and Vavrus, 2012). Larger waves are also more likely to form "blocks," which are like back-eddies in a stream that tend to prevent the jet-stream waves on either side—and the weather associated with them—from moving at all.

Large excursions of the jet stream caused many of the recent extreme weather events, such as the unusually cold, snowy winters experienced recently in Alaska and Europe, the unprecedented flooding in Alberta and the Mississippi Valley, and the ongoing drought and heat waves in western North America. The rapidly warming Arctic appears to be increasing the likelihood of blocking over the North Atlantic, and may have contributed to the unusual wind conditions that steered Sandy on its unprecedented westward path toward New Jersey.

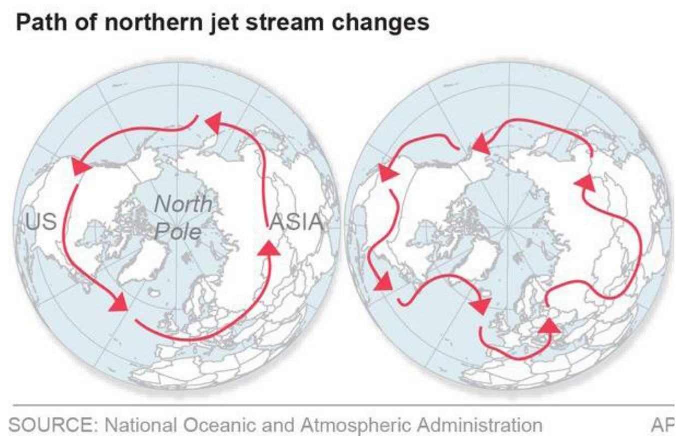

Figure 7: The jet stream, 3 miles above the surface, usually moves fast and relatively straight. Lately it has meandered north and south, causing unusual weather around the northern hemisphere. From NOAA/AP.

The Bottom Line

As the oceans continue to absorb additional heat trapped by ever-accumulating greenhouse gases, as sea ice continues to disappear, and as the Arctic continues to warm faster than the rest of the globe, we can only expect to see more weather-related adverse impacts. The details of those impacts are still emerging from ongoing research, but the overall picture of the future is clear.

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