A Factual Look at the Relationship between Weather and Climate

David W Titley, Rear Admiral USN (Ret.), Ph.D.

Professor of Practice and Director, Center for Solutions to Weather and Climate Risk

The Pennsylvania State University

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Thank you Chairman Stewart, Ranking Member Bonamici, distinguished members of the Committee on Science, Space and Technology for the opportunity to present today. This is a privilege to come before you today and discuss this very important topic.

I am David Titley and currently serve as the Founding Director of the Center for Solutions to Weather and Climate Risk at the Pennsylvania State University. I had the honor of serving in the United States Navy for 32 years and retired last year as a Rear Admiral and Assistant Deputy Chief of Naval Operations for Information Dominance. When I retired, I was also the Oceanographer and Navigator of the Navy, and Director of U.S. Navy Task Force Climate Change. Subsequent to my time in the Navy, I served as Deputy Undersecretary of Commerce for Operations, sometimes known as the Chief Operating Officer position of the National Oceanic and Atmospheric Administration (NOAA). My Center at Penn State currently receives no Federal Funding; my views today are my own. I am here today because I believe a factual discussion of climate change, its links to weather, what we do and do not know, and some possible ways to deal with this challenge of an uncertain future is a very important discussion for our nation's leadership to have. Thank you for holding this hearing.

In the Navy we have a saying, to just give me the 'Bottom Line Up Front' or BLUF. So here's my BLUF for today's hearing:

- **<u>The Change is Real:</u>** The change in the climate, and therefore the change in the weather, is real. Multiple independent sources of data show a rise in temperatures and rise in the ratio of record high temperatures to record low temperatures; an increase in the intensity of precipitation events – that is, the hardest rains are getting harder; the continued collapse in the area and amount of summer-time sea ice in the Arctic Ocean;

an acceleration of sea level rise; acidifying oceans; and ecosystems moving poleward and up in elevation where possible.

- **The Absence of Evidence is not the Evidence of Absence:** Although we know a lot, we don't know everything. Specifically, there is still much to discover about how the changing climate will impact rainfall in specific areas, the number, distribution and intensity of severe storms, and the impact on hurricane and typhoon frequency, size, and strength. How the changes in Arctic Sea Ice and the opening of the Arctic Ocean will impact the weather we experience here in the mid-latitudes is still being debated and explored within the weather and climate communities. But I cannot over-emphasize that not knowing is very different than knowing that there not an impact. As Dr. Jeffrey Marquess and I stated in a recent Op-Ed: "to ignore the possibility of change is the same as assuming we have high confidence there will be no change - and that is simply not true."[1]
- **We know how to succeed even when the future is unknown:** Traditional risk planning takes the chance or probability of an event and multiplies it by the impact. But even when it is difficult to assess the likelihood of a specific event, there are still available methods by which risk planning and mitigation can be accomplished. Our national security teams frequently have to account for these "deep uncertainties" and they have a variety of tools to assist them. Rich scenario planning, assumptions-based planning and similar methods can be used with the goal of identifying all plausible vulnerabilities and their subsequent impacts. National Security and strategic military planners have used these tools successfully for decades – we can apply these methods and adapt them to the climate change challenge.

The earth's climate has naturally varied for millions of years (Figure 1 – From John Englander "High Tide on Main Street"; it will continue to do so for millions more (e.g., . However, humans, through the release of greenhouse gases, also have the capability to modify the earth's climate in a way that previously could occur only by nature. If the climate has always changed in the past and will do so in the future, then why do we care? We care because we are forcing a change to a system that has been remarkably stable in the past 8-12 thousand years (Figure 2 -- From John Englander "High Tide on Main Street"); the time when humans developed agriculture, civilization and our modern way of life. It's not that the climate of the past few thousand years is optimal *per se*, but its stability allowed us to base a civilization on an overall predictability of where our coasts would be, when the rains would come, and the length of the growing seasons. Later on we would construct our buildings, towns, and cities all based on a historical understanding of the averages and extremes of our historical climate. And must

[1] http://hamptonroads.com/2013/11/marqusee-and-titley-did-we-learn-hurricane-sandy

importantly, we made a foundational assumption that past climate predicted our future. Those assumptions no longer hold.

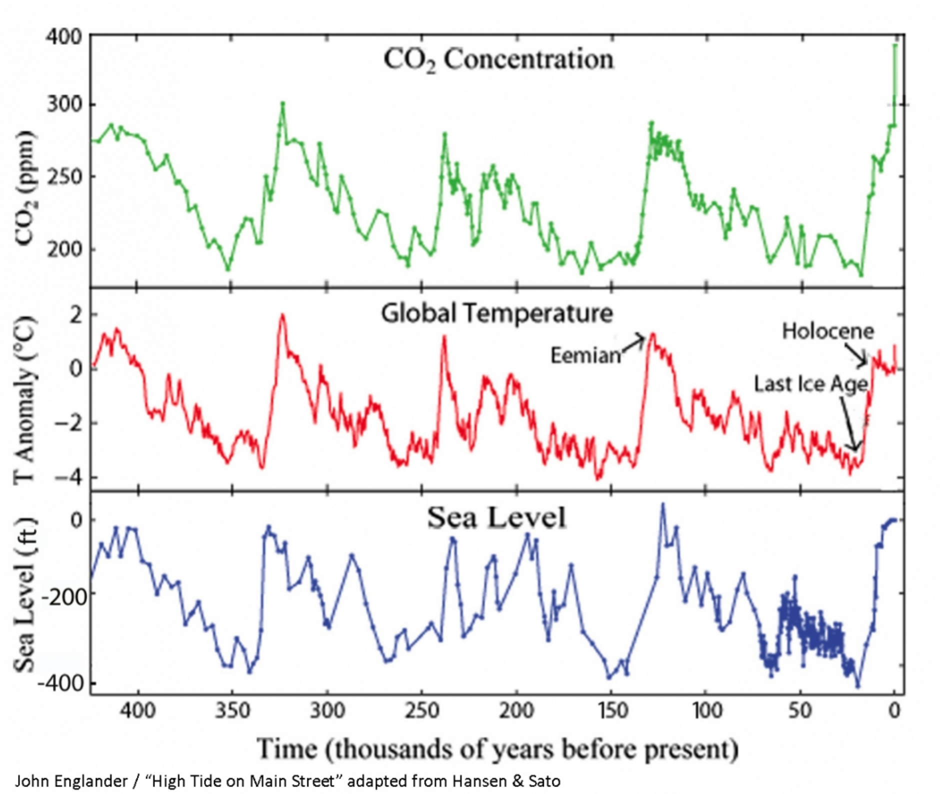

Figure 1 – From John Englander "High Tide on Main Street"

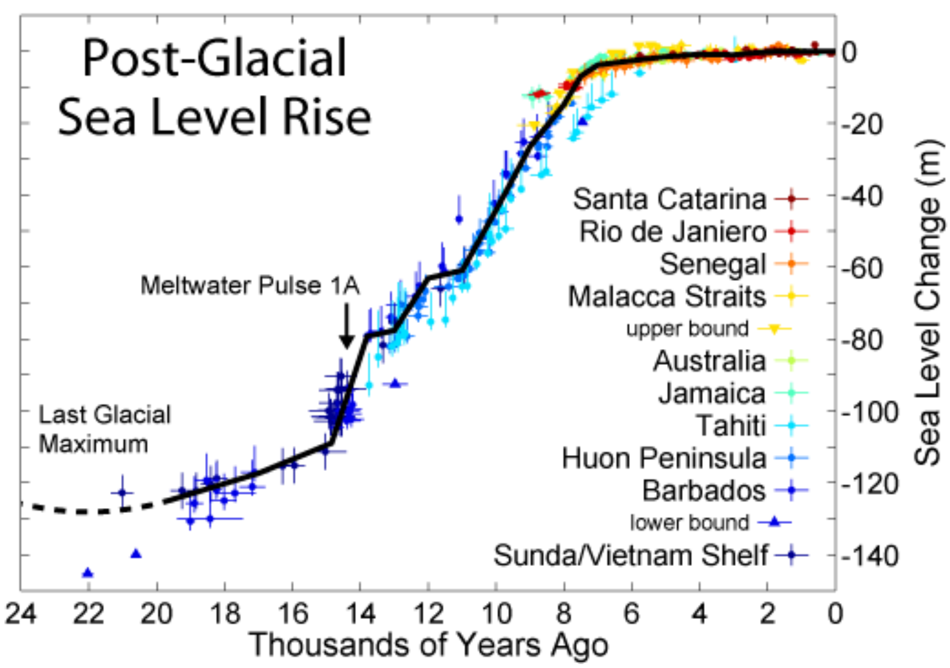

Figure 2 -- From John Englander "High Tide on Main Street"

While we certainly don't know everything about climate change and how it will impact the weather, we do know quite a lot. Doctors Heidi Cullen and Marshall Shepherd both testified earlier this year before the U.S. Senate Committee on the Environment and Public Works. Both witnesses eloquently and factually addressed what we know about rising temperatures and changing rain and snowfall patterns. To quote Dr. Cullen: "Across the globe, we are observing things we would not expect to observe in a climate controlled purely by natural variability. According to NOAA, 2012 was the 10th warmest year since climate records began in 1880." Dr. Cullen goes on to state that "this marks the 36th consecutive year (since 1976, when Gerald R. Ford was President) that the yearly global temperature was above average."[2] A record like that is equivalent to flipping a coin and getting 'heads' 36 consecutive times. The chances of that happening with an un-weighted coin: 1 in 68 billion. Put another way, you are almost 400 more times more likely to win the Powerball jackpot than you are to see this temperature record if the climate was not changing. Dr. Cullen goes on to state that the first 12 years of the 21st century rank in the top 14 warmest of all years recorded (again, since 1880), and that last year was warmer than every year in the 20th century except for 1998.

The United States is participating fully in this trend. As noted by Dr. Marshall in his testimony, "NOAA confirms that average temperature in the United States for 2012 was ... 3.2 degrees Fahrenheit above the 20th century average, and 1.0 degree above 1998, the previous warmest year in the United States"[3] (Figure 3).

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[2] http://www.epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=c88f09be-da24-4501-8a69-c53f6b730c81

[3] http://www.epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=1f670e51-ddc9-4ef0-a3a7-b8d4afb8effc

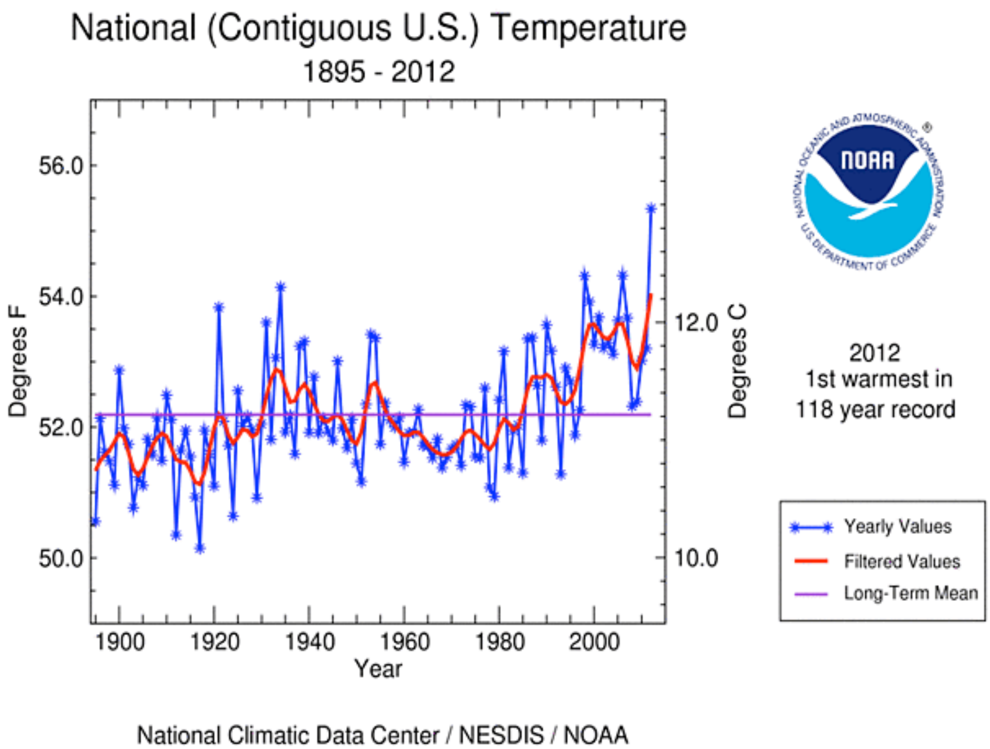


Figure 3

Another way to look at the change in temperature is to examine and compare the ratio between record high temperatures and record low temperatures (Figure 4 -- Meehl et. al. The Relative Increase of Record High Maximum Temperatures Compared to Record Low Minimum Temperatures in the U.S., Geophysical Research Letters, 2009). While there is much season-to-season and year-to-year variability, when we step back and examine the data some overall trends become clear. If the climate were not changing, we would expect to see fewer record highs and record lows, and a roughly equal ratio between highs and lows. Instead, the data show a distinct upward bias in the ratio. What is particularly interesting is a slight increase in the number of record highs, but a dramatic decrease in the number of record lows being set; on average, nights are warming faster than days. An example of this phenomenon can be seen in the temperature record for Washington DC (Figure 5 – Grieser http://www.washingtonpost.com/blogs/capital-weather-gang/wp/2013/06/26/warm-temperature-records-dramatically-outpacing-cold-records-in-washington-d-c/).

With respect to heavier amounts of rain, or increased downpours, I again quote Dr. Cullen: "Heavy downpours are increasing nationally, especially over the past three to five decades. According to the draft National Climate Assessment, those events in the top 1 percentile of intensity have increased in every region of the contiguous United States since 1958 – with the largest increases occurring in the Midwest and Northeast (Figure 6 -- Percent increase from 1958 - 2011 in the amount of precipitation falling in very heavy events. Draft National Climate Assessment, Chapter 2, 2013). The reason for these heavier rain events is relatively simple: in a world warmed by heat-trapping greenhouse gasses, there's more evaporation, the atmosphere can hold more water vapor, and when that water vapor condenses as rain or snow, there's more of it available to fall." However, just as noted with the temperature record, there is still much seasonal, annual, and inter-seasonal variability in the precipitation. Human-forced climate change has not replaced either natural climate variability nor the day-to-day changes in weather we are all familiar with. Rather, the human-induced changes in climate are in addition to those produced by nature.

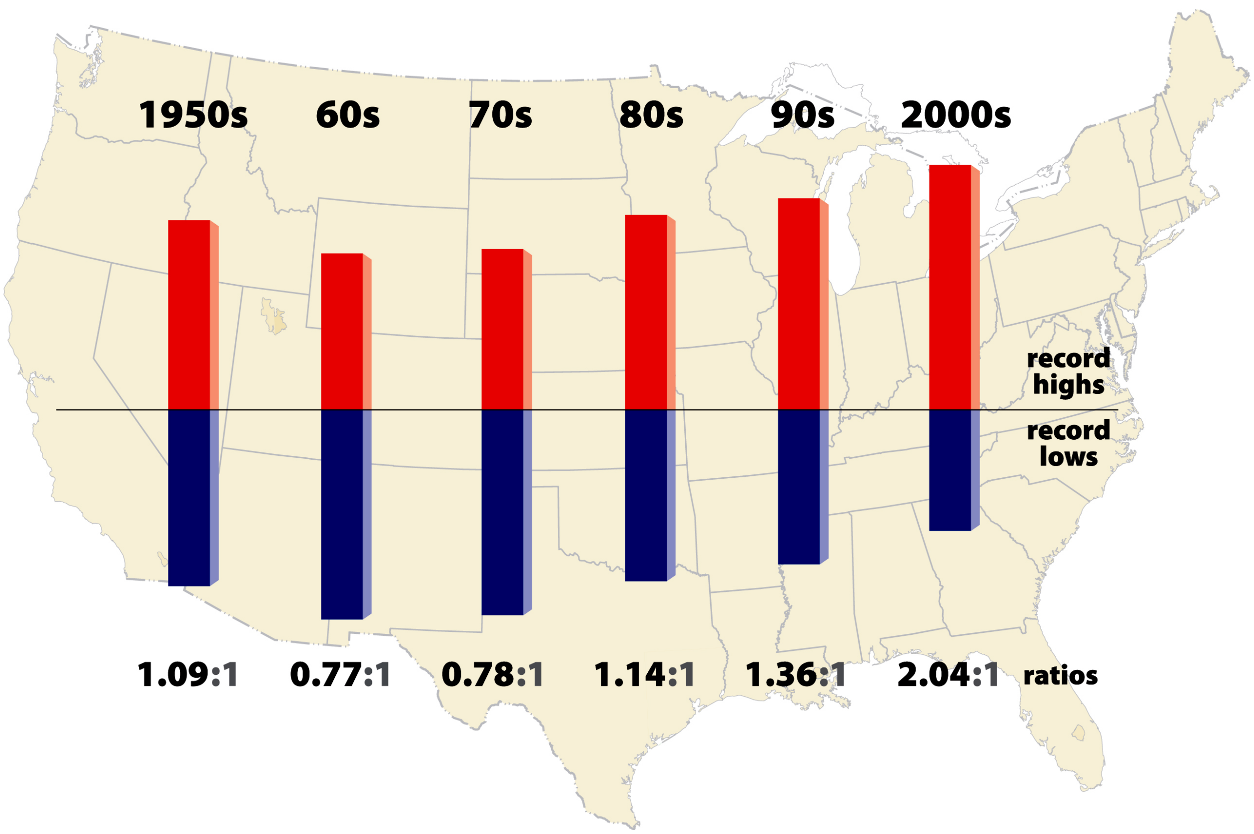


Figure 4 -- Meehl et. al. The Relative Increase of Record High Maximum Temperatures Compared to Record Low Minimum Temperatures in the U.S., Geophysical Research Letters, 2009

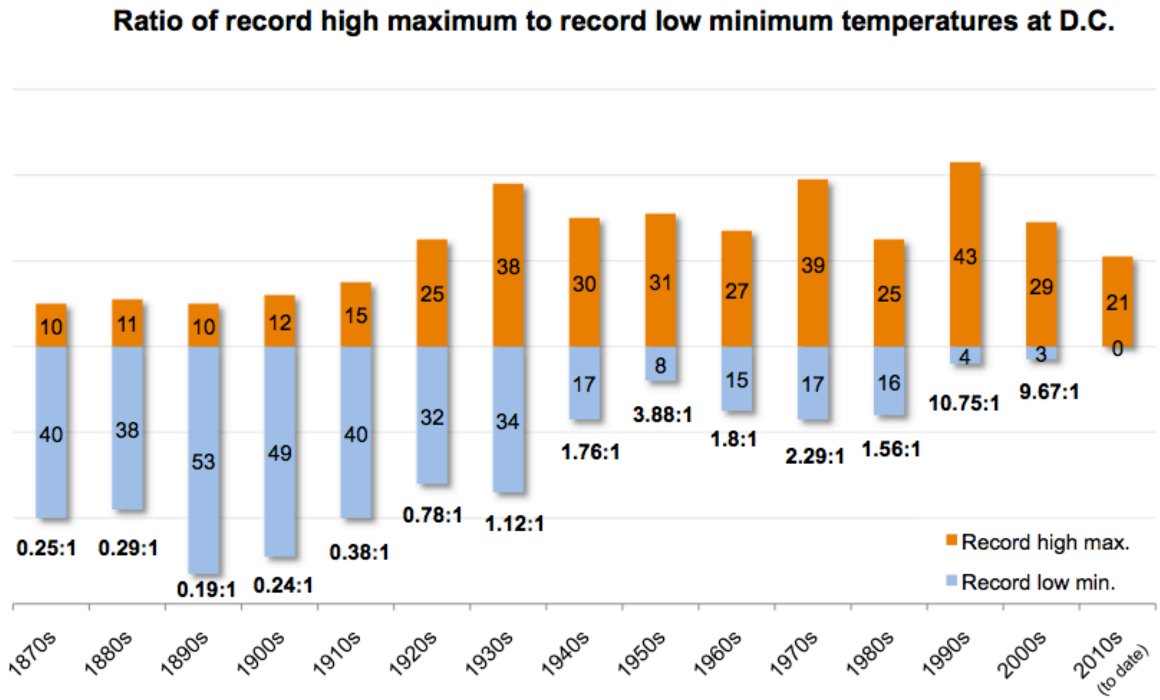


Figure 5 – Grieser http://www.washingtonpost.com/blogs/capital-weather-gang/wp/2013/06/26/warm-temperature-records-dramatically-outpacing-cold-records-in-washington-d-c/

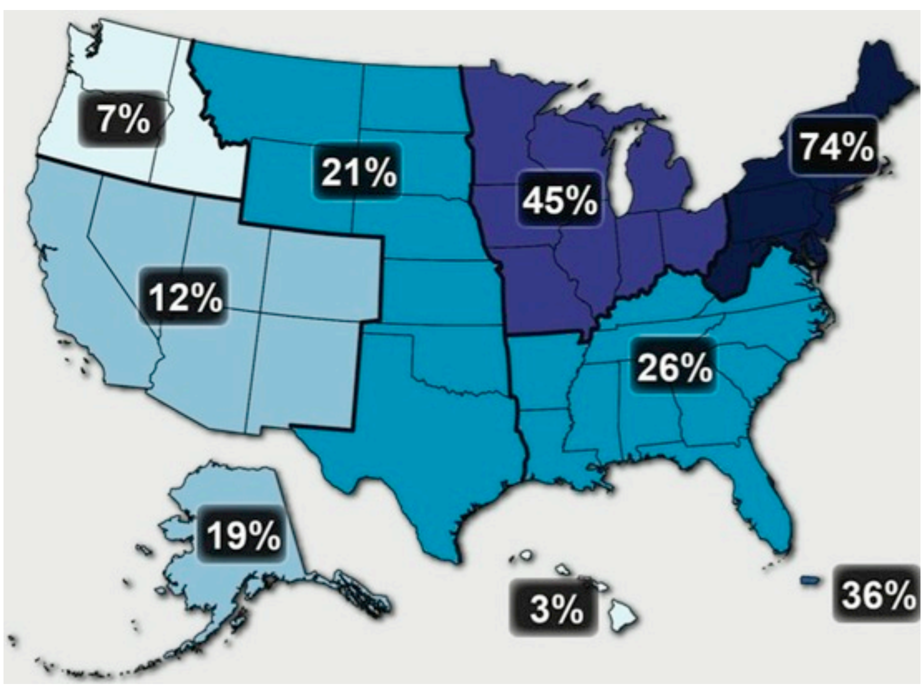
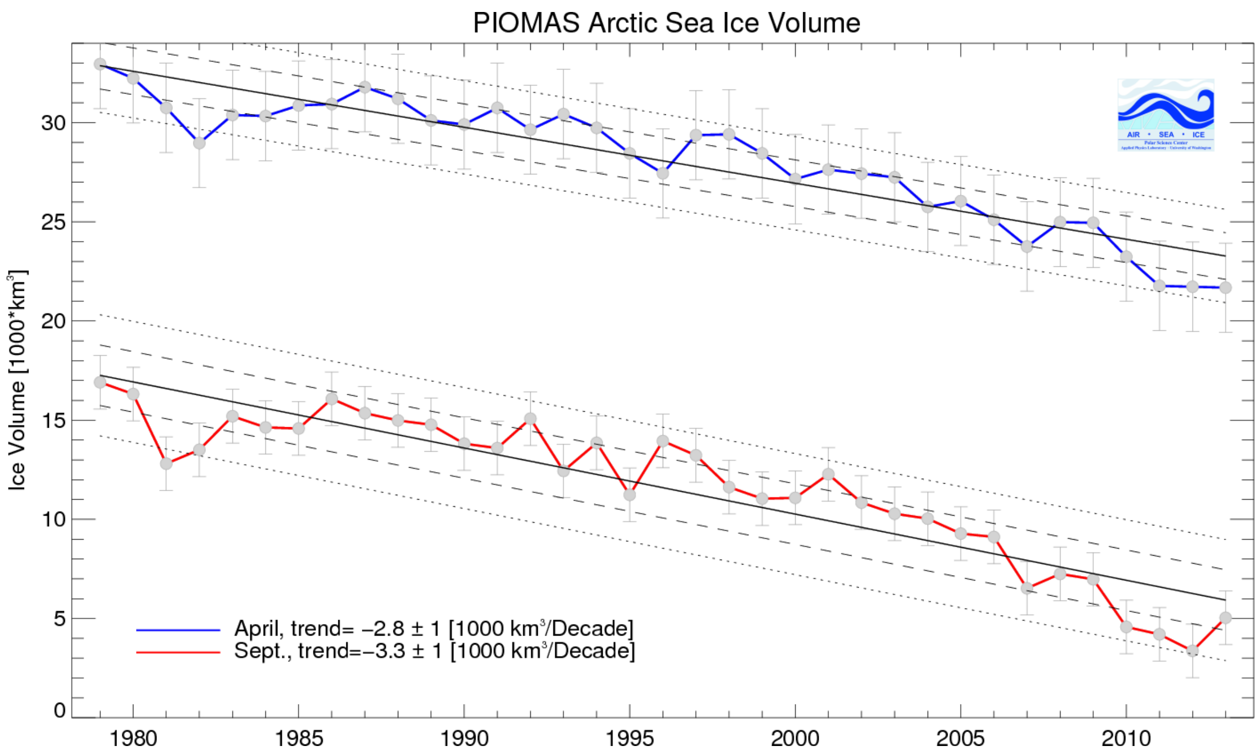


Figure 6 -- Percent increase from 1958 - 2011 in the amount of precipitation falling in very heavy events. Draft National Climate Assessment, Chapter 2, 2013

Nowhere in the world are the changes to today's climate more dramatic than in the Arctic. In less than a generation, the Arctic has transitioned from an Ocean that remained mostly frozen year round with extensive thick, multi-year ice to an environment with greatly reduced ice area and thickness. In 2009 I told Navy leadership that I expect to see several weeks of ice-free conditions in the arctic by the mid-to-late 2030's. When I made that forecast, many people thought I was way too aggressive in expecting the ice to disappear. Now, less than five years later, people believe I may have been too conservative on my forecast. Figure 7 -- PIOMAS Mean monthly Arctic Sea Ice Volume for April and September. Dashed lines parallel to linear fit represents one and two standard deviations from the trend. Error bars are estimated based on thickness observations and model sensitivity studies. Adapted from Schweiger et. al, Uncertainty in modeled Arctic sea-ice volume. Journal Geophysical Research, 2009from the University of Washington's Polar Science Center, shows the decline in both winter (April) and summer (September) ice volume (or the average extent multiplied by the average thickness). Note the lack of recovery in volume between 2012 and 2013.



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Another component of climate change that is increasing well known is Sea Level Rise. Caused by the warming of the ocean (e.g., thermal expansion), melting glaciers and increasingly the flow of both the Greenland and West Antarctic ice sheets into the ocean; sea level rise is one of the most serious implications of climate change. A rise in the global sea level provides a higher "launching point" for any storm surge. Figure 8 -- *Past and future sea-level rise. For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red, RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown. Source: IPCC AR5 Fig. 13.27.* shows the latest IPCC projections for average global sea level rise. The Panel now expects a rise between 60 cm and a meter (or about 2-3 feet) by 2100. This is a substantial increase over the 2007 IPCC report. The rise in average sea level is one of the reasons that coastal flooding is expected to worsen, even without assuming any change in the frequency or intensity of the storms themselves. Higher sea levels also increase the risk of salt-water intrusion on fresh water aquifers and impede the drainage of storm sewers. In fact today in Miami Beach at high tide storm sewers routinely back up and flood seawater onto the streets they are supposed to be draining.[4] Figure 9 -- "Recurrent Flooding Study for Tidewater Virginia (2013). Data courtesy of L. Atkinson, Old Dominion Universityshows the number of hours a neighborhood in Norfolk Virginia is now flooding each year. Like all weather and climate data, there is much short-term variability, but the accelerating trend is clear – and worrisome.

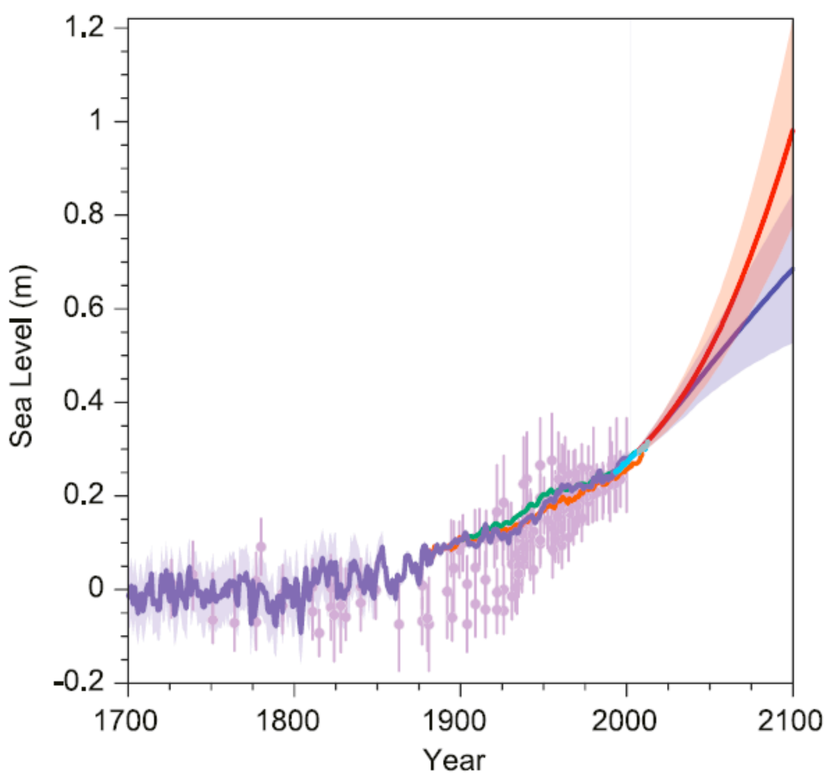

Figure 8 -- *Past and future sea-level rise. For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red,*

[4] http://miami.cbslocal.com/2013/10/17/blame-the-moon-for-south-floridas-tidal-flooding/

RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown. Source: IPCC AR5 Fig. 13.27.

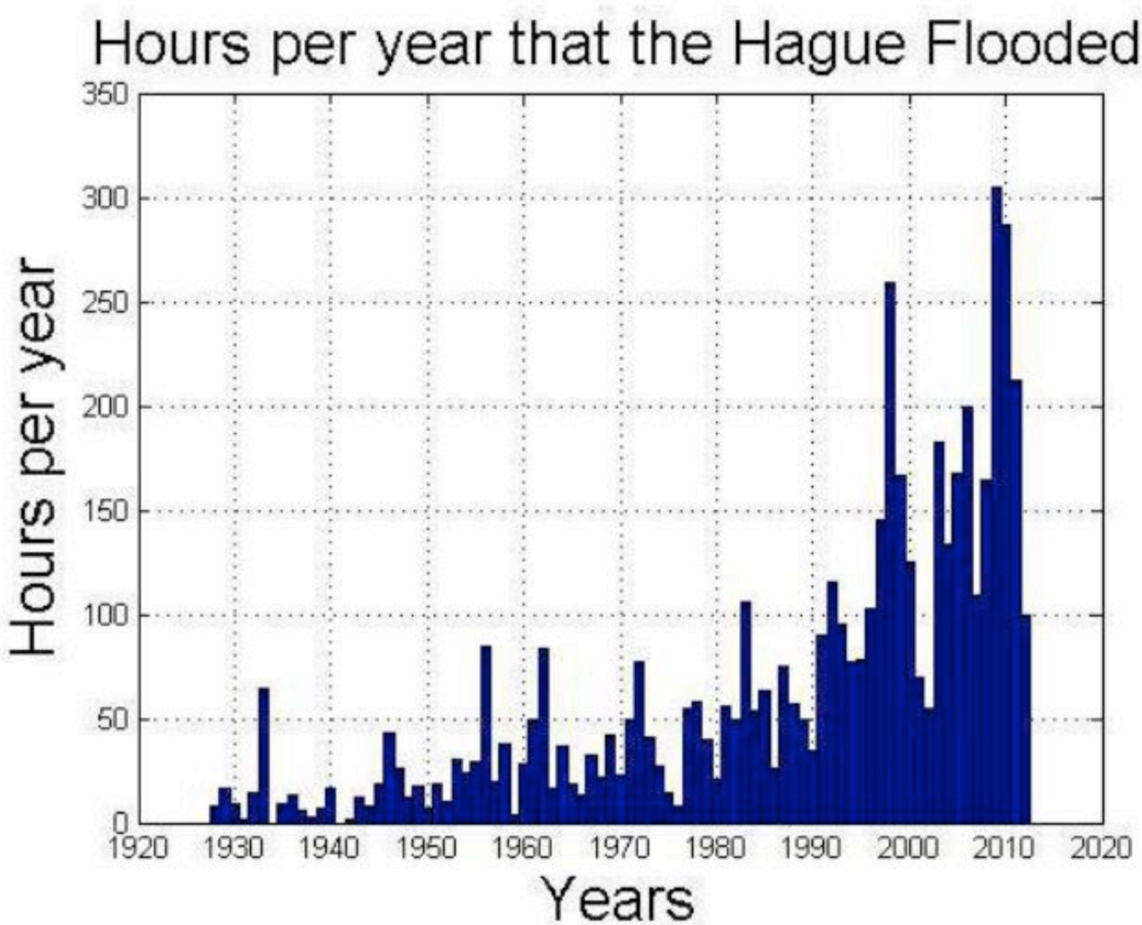

Figure 9 -- "Recurrent Flooding Study for Tidewater Virginia (2013). Data courtesy of L. Atkinson, Old Dominion University

In addition to these observed physical changes (temperature, rainfall intensity, Arctic sea ice, sea level rise) observed, there are equally dramatic changes in the ecosystems. Flora and fauna have been moving polewards and upwards at a rate of 10.5 miles and 36 ft respectively, per decade[5]. These changes are most apparent at the boundary of an ecosystem. Species are stressed when, for whatever reason, they can no longer migrate as quickly as the climate is changing. The climate change is exacerbating changes and existing stresses in the ecosystem, with the unfortunate consequence of increasing risk to pests and invasive species. As an example, the Greater Yellowstone Ecosystem now hosts a bark beetle population "outside the historic range of

5 National Climate Assessment, Chapter 8 (2013)

variability"[6]. Warmer winters have allowed more beetles to survive winter, complete two lifecycles in a year rather than the tradition one, and move further north and up in elevation.

In summary, a combination of multiple, independent sources of data provide the basis to the latest conclusion from the Intergovernmental Panel on Climate Change: "Warming of the climate system is unequivocal, and since the 1950's, many of the observed changes are unprecedented over decades to millennia… Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system[7]." We should not be surprise; these conclusions rest on science discovered in the 19th century by Fourier, Tyndall, Arrhenius and their colleagues.[8]

A graphical summary (Figure 10 -- Source: http://www.munichre.com/app_pages/www/@res/pdf/media_relations/press_dossiers/durban_2011/press_folder_durban_2011_en.pdf) from Munich Re shows the increasing number of storm, hydrologic and climatological events over the past 30 years. Note how the number of geophysical events (e.g., earthquakes, tsunamis, volcanic eruptions) remains relatively constant, while the trend for weather, water and climate events is on the rise.

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[6] *Ibid*

[7] Summary for Policy Makers of the Working Group I contribution to the IPCC Fifth Assessment Report (2013)

[8] http://www.aip.org/history/climate/co2.htm

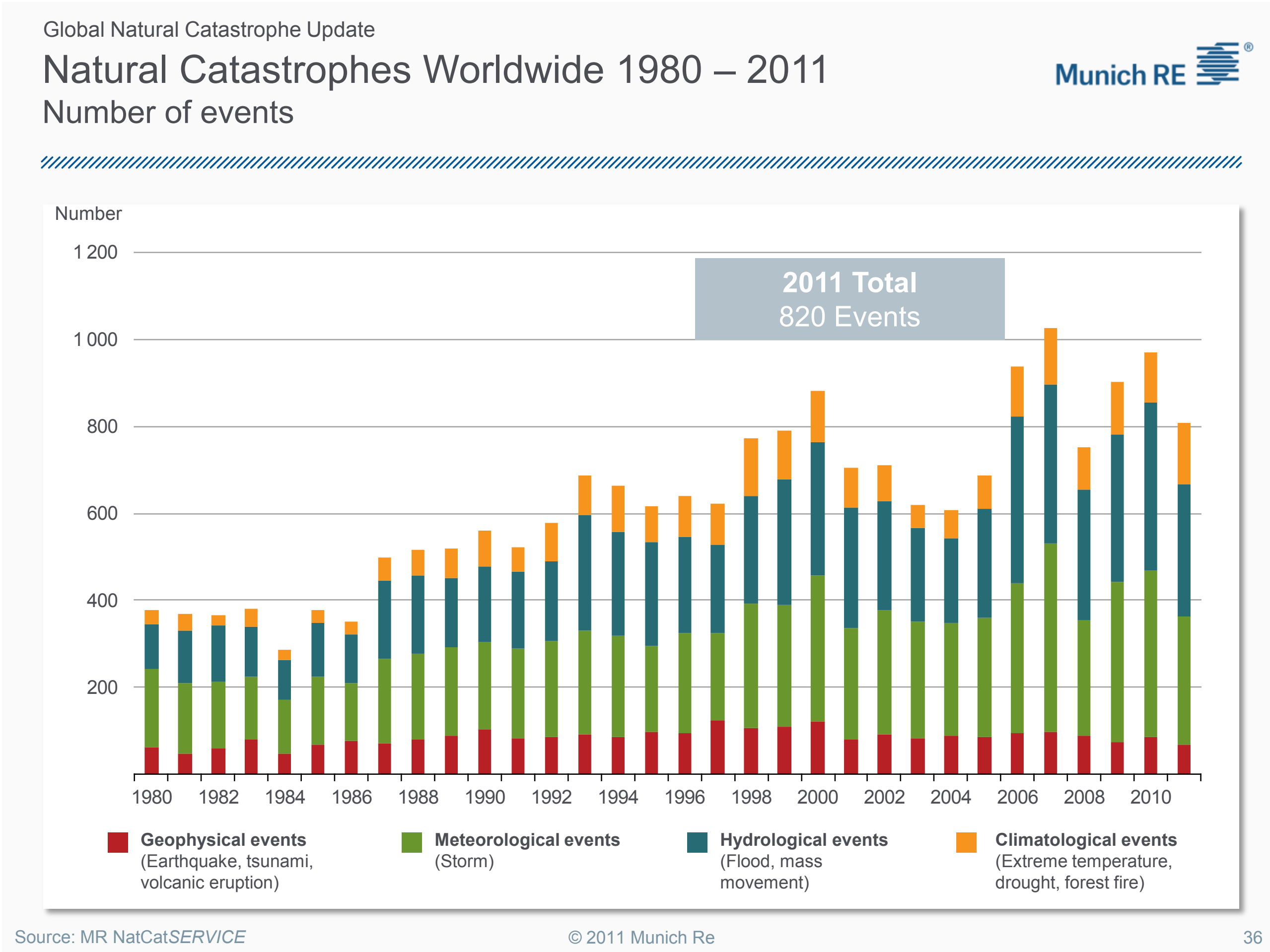

Figure 10 -- Source:
http://www.munichre.com/app_pages/www/@res/pdf/media_relations/press_dossiers/durban_2011/press_folder_durban_2011_en.pdf

But, while the 'big picture' is well understood, there are still important details yet to be discovered. Many of these details involve severe thunderstorms and tornados, as well as tropical cyclones, commonly known as hurricanes or typhoons. There are varied reasons for no clear links: the natural variability may overwhelm any climate signal, especially if the historical record contains changes in observational methods or instruments; a changed climate may simultaneously enhance and suppress a specific type of weather phenomena; or there simply may not be a link between the changed climate and the specific weather type in question.

Tornados are a good example of high-impact weather where we do not yet know if there is a climate link. A casual glance at the record of destructive tornados, shown in Figure 11, would at first glance seem to indicate either no link between climate change and the number of violent (F3+) tornados – or perhaps even a slight decrease with time. However, as described by Dr. Paul Markowski and colleagues' excellent recent article[9] the U.S. record of violent tornados is far

[9] http://www.livescience.com/41632-the-truth-about-tornadoes.html

from consistent in its assessment, with over-rating tornado strength common prior to the 1970's and frequently under-rating intensity in the 2000's.

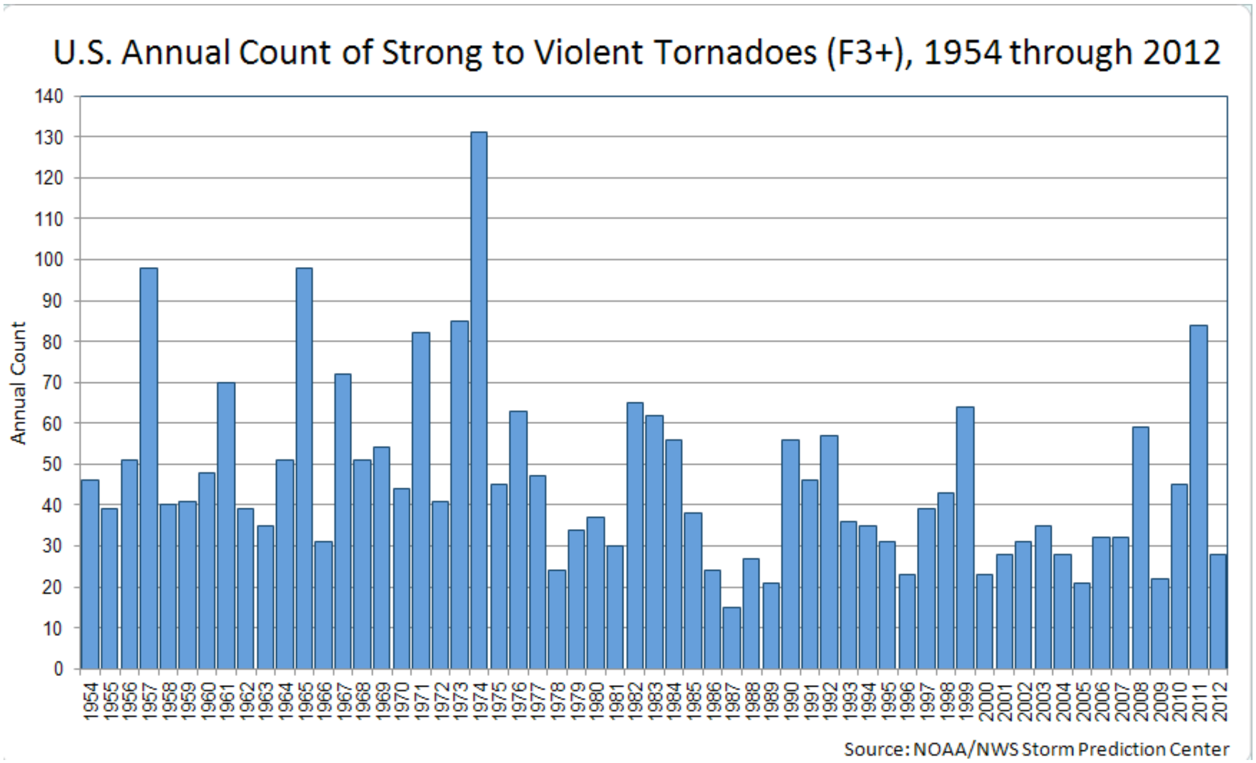

Figure 11

The link between hurricanes and typhoons and climate change is still not yet known. Large annual and regional variation and many competing, and conflicting, factors come together when trying to explain the past and predict the future of hurricane intensity. Hurricanes require a deep layer of warm water to reach their maximum intensity. The average water temperature of the top few hundred feet of ocean determines the storm's maximum potential strength. And we know the upper layers of the ocean have been warming. But hurricanes are not only creatures of the ocean – they cannot exist unless the atmosphere is also favorable. 'Favorable' for a hurricane means consistent winds with increasing height, high moisture content and a general rising of the atmosphere. If these conditions are not met, the hurricane either will not form, or it will be much weaker than its potential. The just-concluded 2013 northern hemisphere hurricane and typhoon season saw examples of a unfavorable and favorable atmospheres: In the North Atlantic, dry, sinking air and hostile winds produced one of the quietest hurricane seasons in recent memory. By contrast, favorable atmospheric conditions and very warm, deep waters spawned five 'super-typhoons' with sustained winds greater than 150 mph, including Super-Typhoon Haiyan that made landfall in the Philippines with maximum sustained winds estimated at 195 mph.

What does all this mean? The absence of evidence is not the evidence of absence. Or stated another way, saying we don't know today the impact of climate change on these phenomena is very different than stating that climate change has no impact on typhoons and hurricanes. What we do know is that these storms are forming in a warmer, moister environment and above a warmer ocean. We also know that current research indicates our future may include more intense, and possibly more frequent, storms[10]. That is a risk not to be summarily discounted.

I am frequently asked if a specific or extreme event (for example, typhoon, Sandy, drought, snowstorm) is or is not "caused" by climate change. Frankly, that is the wrong question. It's like asking someone if their childhood upbringing "caused" him or her to attend a specific college. It's more useful to think of climate as the deck of cards from which our daily, specific weather events are dealt. And as the climate changes, so does our deck of cards. For every degree of warming, we add an extra Ace into the deck. So, over time, the unusual hands, like a Full House with Aces high, become more plausible – and more common – with time.

A useful way to think about how to deal with this uncertain, but not completely unknown, future is through a risk management framework. Rather than wait for a series of extreme, or disruptive, events to occur and then react, an alternate way to approach our changing climate may be to adopt some proven tenets from the security community. Figure 12 Source: http://online.wsj.com/news/articles/SB10001424053111904106704576583203589408180# shows the number of war-related deaths on the battlefield over the past 70 years.

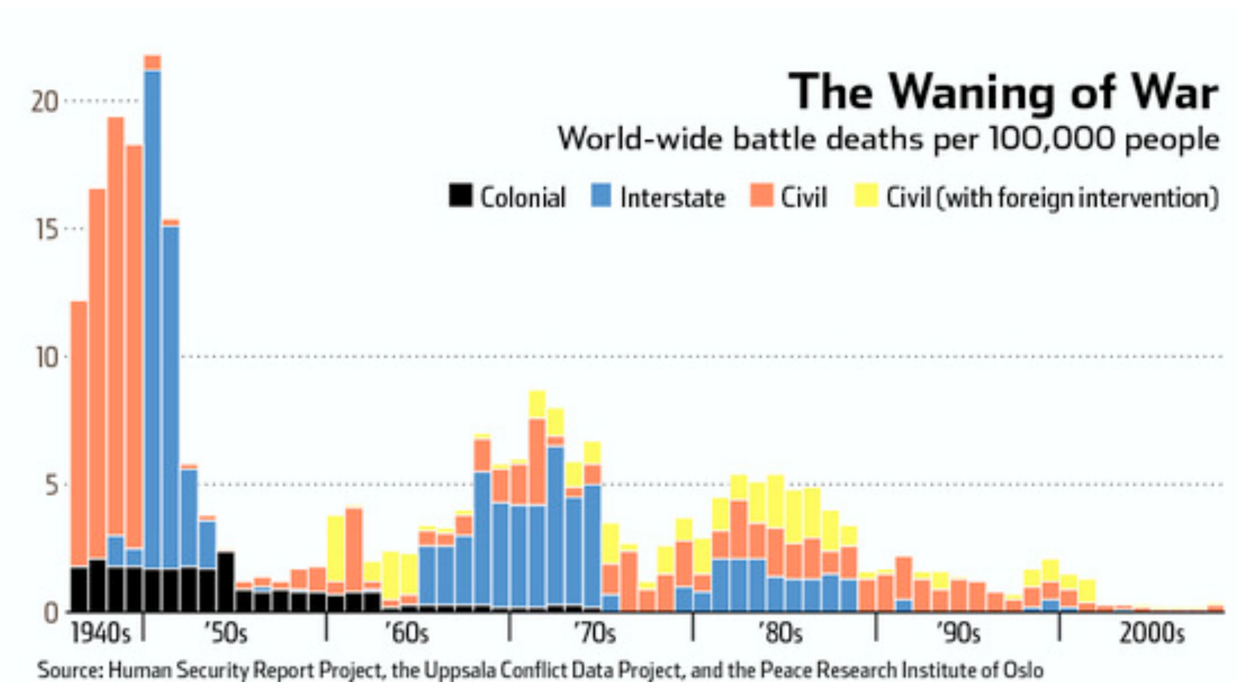

Figure 12 Source: http://online.wsj.com/news/articles/SB10001424053111904106704576583203589408180#

[10] Emanuel, K., Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity over the 21st Century. *Proceedings National Academy of Sciences*, 2013

If these statistics are the climate-equivalent of extreme events, one might be tempted to say we no longer have a need to invest in our military or domestic security programs. That would of course be ridiculous; we rightly invest in our security and defense as one component of hedging against unknown or unlikely security risks. Likewise with a changing climate: it matters less which specific event was or was not directly related to climate change or how many specific events occur in any given year. Climate risks and security risks share another trait in common: "The worst matters much more than the bad"[11]. In other words: What are the near-term and future risks to our way of life – and what policies and structures should we put in place to manage and mitigate those risks?

So how might we go about such a challenge? One way might be to start with this six-step process, consistent in broad goals with the President's Climate Action Plan[12]:

- Develop better understanding of the factors and primary drivers behind the loss numbers. The first step to solving a problem is making sure you are working on the right issues.
- Set up a monitoring system. Assign specific responsibilities. Many National Academy Society (NAS) reports have called for such a monitoring system. The NAS 'Abrupt Climate Changes' report released last week is the latest to call for such a monitoring system.
- Adjust policies today for what we know – and for what we might reasonably expect in the coming decades. Hope should not be the strategy.
- Invest in better understanding – and ultimately prediction – at the boundary between weather and climate. While scientifically this is very challenging, it is also very important for people and a myriad of decisions. From a security, economic, agricultural, infrastructure and policy perspective, greater climate knowledge of the next few seasons to the next decade or two would be extremely useful. While we should not use today's uncertainty as an excuse to defer action, better understanding of the climate over the next 2-20 years would be very useful in allocating scarce resources. The Department of the Navy is funding today the 'Earth System Prediction Capability' or ESPC – an interagency program designed to provide our country the next-generation of integrated air-ocean-ice-land prediction system[13]. Navy is working with other components of the DoD, as well as NOAA, NASA and the Department of Energy to ensure our nation has

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[11] Burroughs, William "Climate Change in Prehistory: The End of the Reign of Chaos", Cambridge University Press, 2005

[12] http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf

[13] http://espc.oar.noaa.gov/

the world's best operational weather and climate prediction tools at our disposal. This National Imperative must be a National Priority.

- As we work on adapting to our changing climate we should not lose sight of the big picture: how to move the world's energy system to a predominantly non-carbon based energy source to power the world. How can we unleash the innovation and energy that makes our country great to solve one of the grand challenges of the 21^{st} Century? We are the country that is developing a self-driving car and whose private companies can send satellites to geosynchronous orbit. With the right policies I am sure our private sector can develop – and profit from – energy solutions that will power the world in a sustainable fashion into the future.

In closing, our country is dealing with a significant change in the world's climate; it is a large challenge. But our country has met challenges of this magnitude before and succeeded – and we will do so again. We do not need the "4-D's": Doom, Denial, Despair and Delay. They are not helpful. We don't know everything but we know enough to act now. By focusing our efforts in a risk-based framework on meeting the climate challenge, we can prepare for the short-term while shaping our longer-term future. We can provide the policies, stability and guidance our country needs to unleash our country's energy, creativity and initiative. I am convinced we will be proud and amazed at what we can accomplish. Thank you very much for your time and attention; I look forward to taking your questions.