Senate Commerce Committee Field Hearing on Extreme Weather and Coastal Flooding

Ben Kirtman, Ph.D.
Professor, University of Miami – Rosenstiel School for Marine and Atmospheric Science
Director, Cooperative Institute for Marine and Atmospheric Studies
Program Director for Climate and Environmental Hazards, Center for Computational Science

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Mr. Chairman, Ranking Member Nelson, distinguished members of the U.S. Senate Committee on Commerce, Science, and Transportation and members of the House of Representatives, thank you for this opportunity to come before you today and share my thoughts regarding climate variability and climate change, and how this affects Florida.

I've been a climate scientist for about 25 years, having received my Ph.D. in 1992. Ten years ago, I joined the University of Miami Rosenstiel School of Marine and Atmospheric Science as a Professor of meteorology and physical oceanography and in 2016 was appointed as the Director of the Cooperative Institute of Marine and Atmospheric Studies. I use complex earth system models and the most sophisticated supercomputers throughout the United Stated to investigate the predictability of the climate system on time scales from days-to-decades.

I served as a coordinating lead author for the Intergovernmental Panel on Climate Change (IPCC) working group one – the Scientific Basis and have chaired several national and international scientific panels and working groups. I'm an Executive Editor of Climate Dynamics and an Associate Editor of the American Geophysical Union Journal of Geophysical Research (Atmospheres). I have received research grants from the National Science Foundation, Department of Energy, NOAA, NASA, and the Office of Naval Research, and I lead the North American Multi-Model Ensemble Prediction (NMME) Experiment. I'm the author and/or co-author of over 120 peer reviewed papers focused on understanding and predicting climate variability on time scales from days to decades.

And as a Floridian, I am grateful for the Committee's focus on a matter that hits very close to home for many of us in this room.

First and foremost, as a scientist my goal is to understand how the earth system works and how to predict its evolution into the future. As weather and climate scientists, it is our hope that policy makers will be able to utilize the best available science to help: (1) save lives, (2) protect property, (3) enable economic opportunity and (4) secure our national defense.

My testimony will summarize the current state-of-the-science in climate variability and change on a global scale, and how these global drivers affect the local Florida environment. The over-arching key points are summarized below, and the remaining text goes into further detail with data and figures. Much of the material included here is from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5, Stocker et al. 2013; Kirtman et al. 2013), which assesses our current scientific understanding of climate change. It is important to understand that any robust conclusions in the IPCC assessment report require: (i) multiple disparate lines of evidence and (ii) quantitative estimates of uncertainty. This assessment process summarizes the best available science.

The Science: Global Climate Drivers of Regional Change

(i) CO_2 levels in the atmosphere affect global temperatures.

(ii) During the last 800,000 years (excluding the modern era; 1900-present), CO_2 levels in the atmosphere have ranged from about 180 parts per million by volume (ppmv) to about 280 ppmv. The oscillations were between 180 and 280 ppmv; these changes took approximately 10,000 to 40,000 years to occur. Current CO_2 levels are about 405 ppmv and the increase from 280 to 405 ppmv took less than 150 years (see Fig. 1). This rapid increase in CO_2 is unprecedented in any observational estimate.

(iii) Since the 1950's the climate system has warmed and it is 100% unequivocal (see Fig. 2). There are robust multiple lines of evidence - multiple studies that involve different observational instruments that measure different components of the climate system - that support this conclusion.

(iv) The bulk of the warming since the 1950's is extremely likely (95-100% certainty) due to human activities (i.e., increases in CO_2 levels associated with the consumption of fossil fuels; see Fig. 3 and Fig. 4).

(v) Given its importance in Florida, sea level merits special attention. Paleo sea level data from the last 3000 years, until approximately 1900, has been remarkably stable; there has been little change in the global mean. However, since about 1900 global mean sea level has steadily risen consistent with the warming seen (Fig. 5).

(vi) Regional climate changes are more difficult to assess. This is because the natural variability tends to be larger on the local scale, and this makes it more challenging to isolate the anthropogenic signal. Nevertheless, regional changes in temperature through out much of the U. S. show a pronounced warming trend (see Fig. 6).

(vii) There is evidence that at regional scales along the eastern U.S., and in Florida in particular, the sea level rise is accelerating (see Fig. 7).

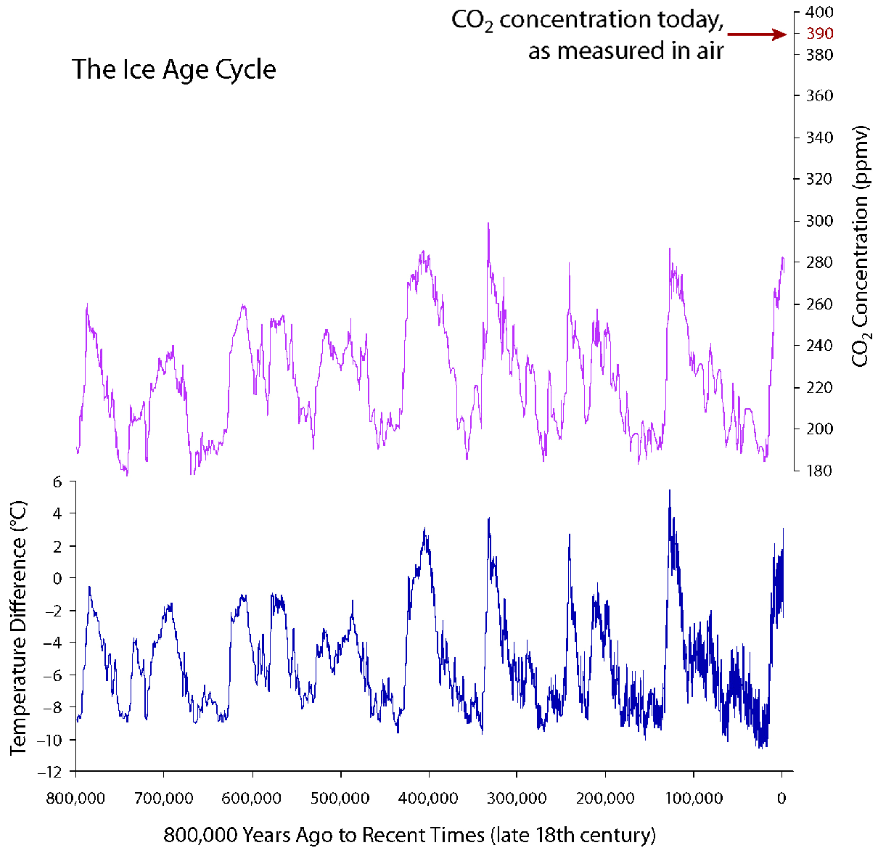
(viii) There is *no* compelling scientific evidence that any of the trends that we currently see are going to reverse themselves. There is, however, compelling evidence that the current trends will continue for at least the next 25 years, and there is even some evidence that particular trends may accelerate. Even if one is skeptical that human activities are the cause of these trends, there is a clear local need to protect lives and property, and ensure economic opportunity in response to changes we see today. Robust, well-calibrated, scientifically based predictions of the next 25-years and beyond (see Fig. 8) are the first step in developing effective adaptation strategies and to capitalize on the associated economic opportunities.

(ix) Florida is well positioned to respond to the challenges and opportunities associated with climate change. The academic community has established the Florida Climate Institute (FCI; https://floridaclimateinstitute.org). The Florida Climate Institute (FCI) fosters interdisciplinary research, education, and extension to: Improve our understanding and the impact of climate variability, climate change, and sea level rise on the economy, ecosystems, and human-built systems; Develop technologies and information for creating opportunities and policies that reduce economic and environmental risks; and Engage society in research, extension and education programs for enhancing adaptive capacity and responses to associated climatic risks. We collaborate with the local, state, and federal government to address our most pressing adaptation problems.

(x) The process of challenging the conventional wisdom is a critical component of how robust science progresses. We should always be respectful of differing perspectives, accounting for new information and ideas and then test them through the scientific method. This is how science works, this is how we find fact. When it comes to policy, I would just ask that policy makers take into account the best available science. When it comes to climate change, the scientific consensus is not cavalier, it is prudent and conservative, and is the best available science.

Basic Global Climate Change

Figure 1 shows 800,000 years of CO2 and temperature from ice core records from Vostok, Antarctica. The temperature near the South Pole has varied by as much as 20°F (11°C) during the past 800,000 years. The cyclical pattern of temperature variations constitutes the ice age/interglacial cycles. During these cycles, changes in carbon dioxide concentrations (in purple) track closely with changes in temperature (in blue), with CO2 lagging behind temperature changes. Because it takes a while for snow to compress into ice, ice core data are not yet available much beyond the 18th century at most locations. However, atmospheric carbon dioxide levels, as measured in air, are higher today than at any time during the past 800,000 years. Source: National Research Council (https://nas-sites.org/americasclimatechoices/more-resources-on-climate-change/climate-change-lines-of-evidence-booklet/evidence-impacts-and-choices-figure-gallery/figure-14/).



Source 1 for top image: Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T. F. Stocker. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature 453(7193):379-382, doi: 10.1038/nature06949.
Source 2 for bottom image: Jouzel, J., V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Minster, J. Nouet, J. M. Barnola, J. Chappellaz, H. Fischer, J. C. Gallet, S. Johnson, M. Leuenberger, L. Loulergue, D. Luethi, H. Oerter, F. Parrenin, G. Raisbeck, D. Raynaud, A. Schilt, J. Schwander, E. Selmo, R. Souchez, R. Spahni, B. Stauffer, J. P. Steffensen, B. Stenni, T. F. Stocker, J. L. Tison, M. Werner, and E. W. Wolff. 2007. Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317(5839):793-797.

One of the top level conclusions of the IPCC AR5 is that the since the 19^{th} century the climate system has warmed. This conclusion is based on multiple lines of evidence from many different data sets that have been collected using different instruments. All of these data sets, whether they are ocean, land, or sea-ice measurements point to one unequivocal conclusion – the world has warmed. Figure 2 summarizes the results from many several of these different data sets. For example, there are four different data sets used to estimate global land surface temperature changes, and they all indicate a warming of about 2.5^{o}F. There are six different data set used to estimate global sea level, and again they all agree in the upward trend. Summer arctic sea-ice extent is estimated using six different data sets, and they all indicate the same downward trend.

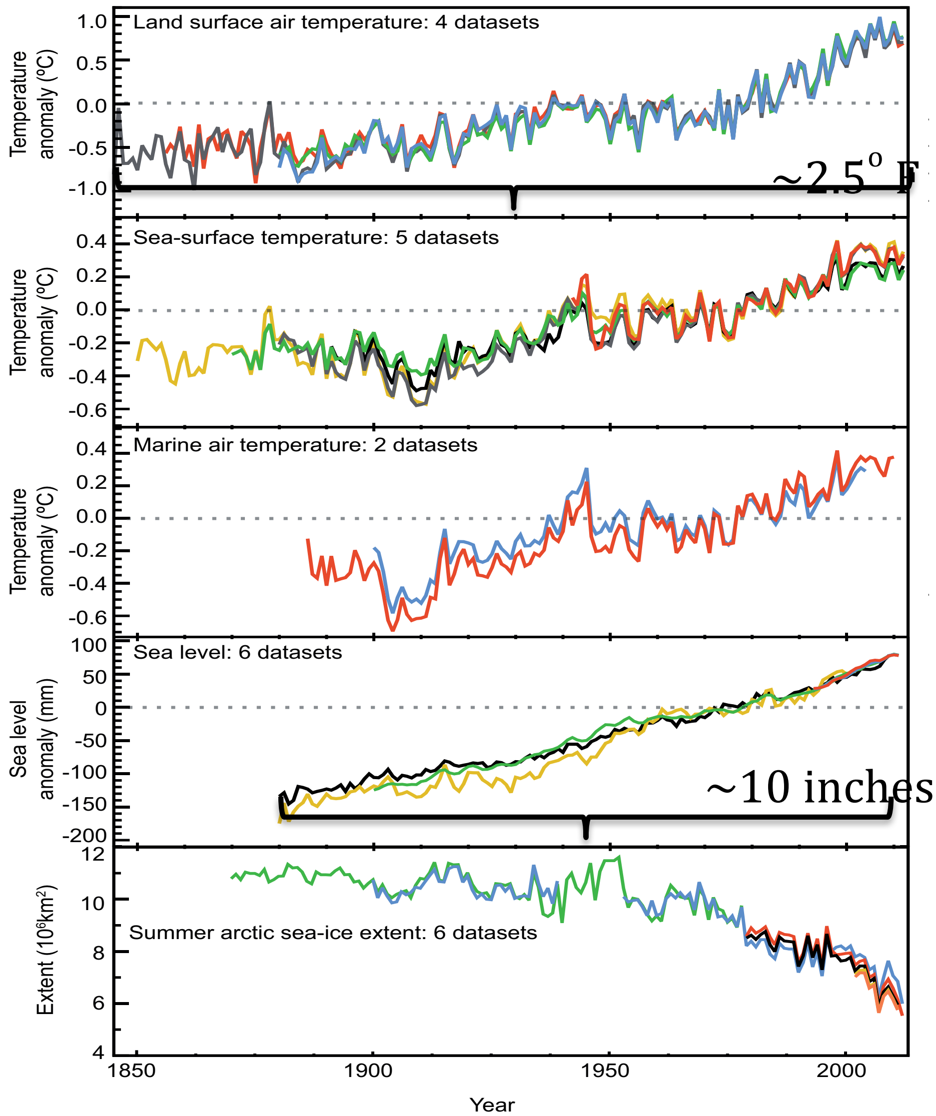


Figure 2: Multiple independent indicators of a changing global climate. Each line represents an independently derived estimate of change in the climate element. In each panel all data sets have been normalized to a common period of record. Figure take from IPCC AR5 and a full detailing of the data sources is given in Stocker et al. (2013, supplementary material).

Perhaps the most important question that needs to be addressed is how do we know the trends seen in Fig. 2 are due to human activities. There are two typical approaches. The first is referred to detection and attribution studies (Bindoff et al. 2013). Figure 3 summarize a classic detection and attribution study based on observational estimates of global mean surface temperatures. The time series analysis separates the global mean temperature changes due to: El Nino (panel b), volcanoes (panel c), solar output (panel d), and other modes of climate variability like the AMO (panel f). The global mean temperature changes associated with the changes in greenhouse gases such a CO2 are shown in panel e, and demonstrate that it is extremely likely (95-100%) that the bulk of the warming since the 1950s is due to human activities.

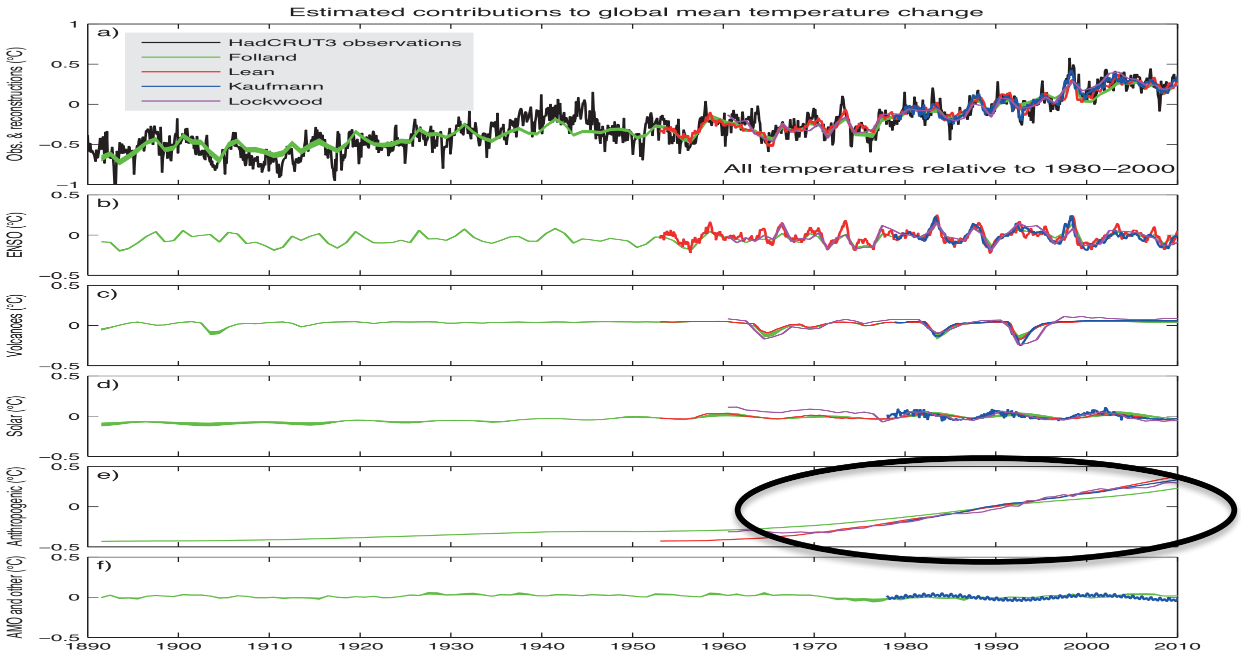


Figure 3: (Top) The variations of the observed global mean surface temperature (GMST) anomaly from Hadley Centre/Climatic Research Unit gridded surface temperature data set version 3 (HadCRUT3, black line) and the best multivariate fits using the method of Lean (red line), Lockwood (pink line), Folland (green line) and Kaufmann (blue line). (Below) The contributions to the fit from (a) El Niño-Southern Oscillation (ENSO), (b) volcanoes, (c) solar forcing, (d) anthropogenic forcing and (e) other factors (Atlantic Multi-decadal Oscillation (AMO) for Folland and a 17.5-year cycle, semi-annual oscillation (SAO), and Arctic Oscillation (AO) from Lean). (From Lockwood (2008), Lean and Rind (2009), Folland et al. (2013) and Kaufmann et al. (2011), as summarized in Imbers et al. (2013).) See Figure 10.6 in Bindoff et al. (2013) for references and details.

The second approach for attributing the observed warming to human activities is based on climate model simulations. Again, as with the data analysis shown in Fig. 3, the climate models used in the assessment of the climate of the 20th century have been developed and validated by different modeling centers in different countries around the world – multiple lines of evidence supporting the conclusion. The approach is to simulate the climate of the 20th century with and without the anthropogenic changes in CO2. The results and then be compared with the observed temperature record. An example of this for global mean temperature is shown in Fig. 4. Again, the results point to the same conclusion – the bulk of the warming since the 1950s is due to human activities.

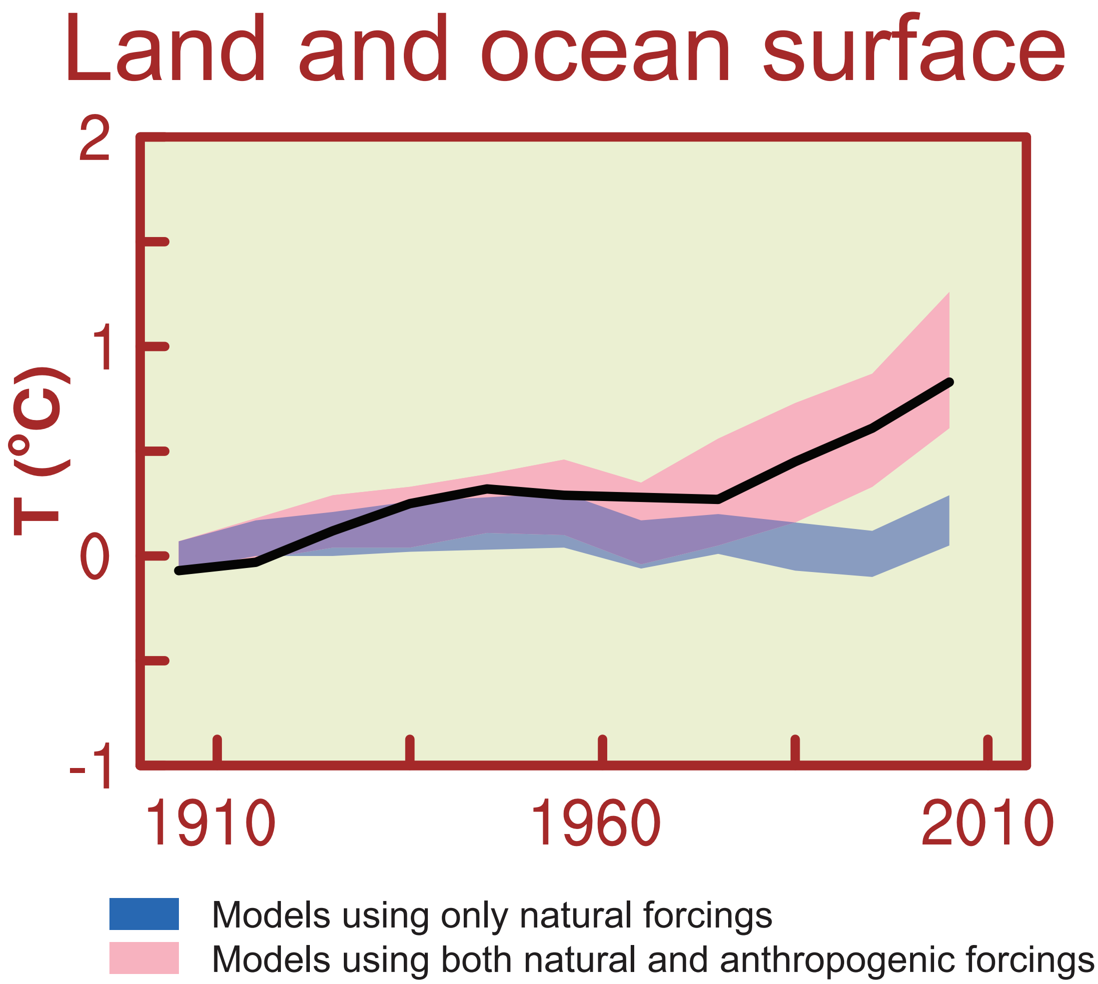


Figure 5: Comparison of observed (black curve) and multi-model simulated global mean temperature with natural and anthropogenic forcing (pink swath) and just natural forcing (blue swath). The width of the swaths correspond to the 5%-95% range from the multi-model ensemble simulations. Figure adapted from Stocker et al. 2013.

Sea level rise associated with climate change is of particular importance to Florida. Here we show results from Church et al. (2013) which includes a detailed analysis of paleo and historical estimates of global sea level and more recent modern instrument records. The results further underscore the unequivocal conclusion that human activities are leading to profound changes in the climate system.

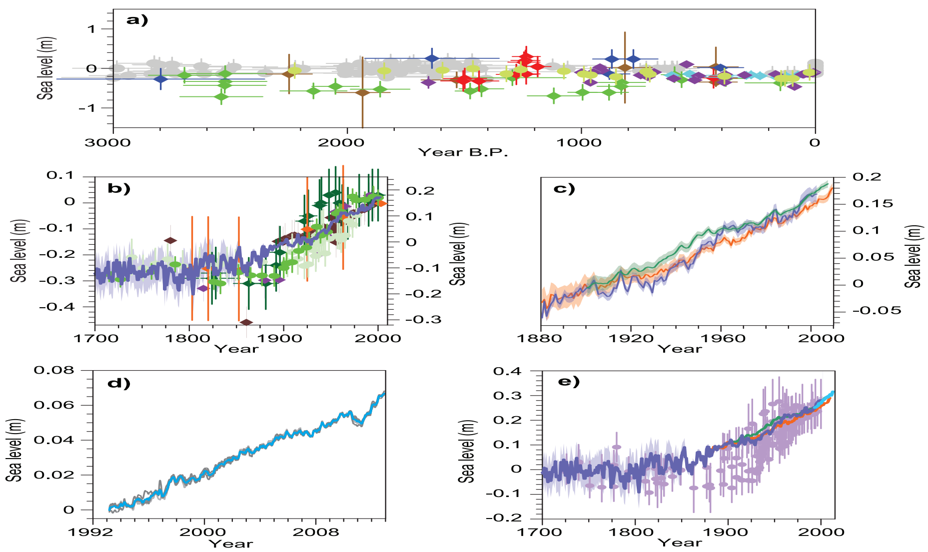


Figure 5: a) Paleo sea level data for the last 3000 years from Northern and Southern Hemisphere sites. The effects of glacial isostatic adjustment (GIA) have been removed from these records. Light green = Iceland (Gehrels et al., 2006), purple = Nova Scotia (Gehrels et al., 2005), bright blue = Connecticut (Donnelly et al., 2004), blue = Nova Scotia (Gehrels et al., 2005), red = United Kingdom (Gehrels et al., 2011), green = North Carolina (Kemp et al., 2011), brown = New Zealand (Gehrels et al., 2008), grey = mid-Paci c Ocean (Woodroffe et al., 2012). (b) Paleo sea level data from salt marshes since 1700 from Northern and Southern Hemisphere sites compared to sea level reconstruction from tide gauges (blue time series with uncertainty) (Jevrejeva et al., 2008). The effects of GIA have been removed from these records by subtracting the long-term trend (Gehrels and Woodworth, 2013). Ordinate axis on the left corresponds to the paleo sea level data. Ordinate axis on the right corresponds to tide gauge data. Green and light green = North Carolina (Kemp et al., 2011), orange = Iceland (Gehrels et al., 2006), purple = New Zealand (Gehrels et al., 2008), dark green = Tasmania (Gehrels et al., 2012), brown = Nova Scotia (Gehrels et al., 2005). (c) Yearly average global mean sea level (GMSL) reconstructed from tide gauges by three different approaches. Orange from Church and White (2011), blue from Jevrejeva et al. (2008), green from Ray and Douglas (2011) (see Section 3.7). (d) Altimetry data sets from ve groups (University of Colorado (CU), National Oceanic and Atmospheric Administration (NOAA), Goddard Space Flight Centre (GSFC), Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO), Commonwealth Scienti c and Industrial Research Organisation (CSIRO)) with mean of the ve shown as bright blue line (see Section 3.7). (e) Comparison of the paleo data from salt marshes (purple symbols, from (b)), with tide gauge and altimetry data sets (same line colours as in (c) and (d)). All paleo data were shifted by mean of 1700–1850 derived from the Sand Point, North Carolina data. The Jevrejeva et al. (2008) tide gauge data were shifted by their mean for 1700–1850; other two tide gauge data sets were shifted by the same amount. The altimeter time series has been shifted vertically upwards so that their mean value over the 1993–2007 period aligns with the mean value of the average of all three tide gauge time series over the same period. References and details in Church et al. 2013.

Regional Climate Change

Regional climate changes are more difficult to assess. This is because the natural variability tends to be larger on the local scale, and this makes it more challenging to isolate the anthropogenic signal. Nevertheless, regional changes in temperature thought much of the U. S. show a pronounced warming trend (see Fig. 6).

US Temperature Change 1991-2012 vs. 1901-1960

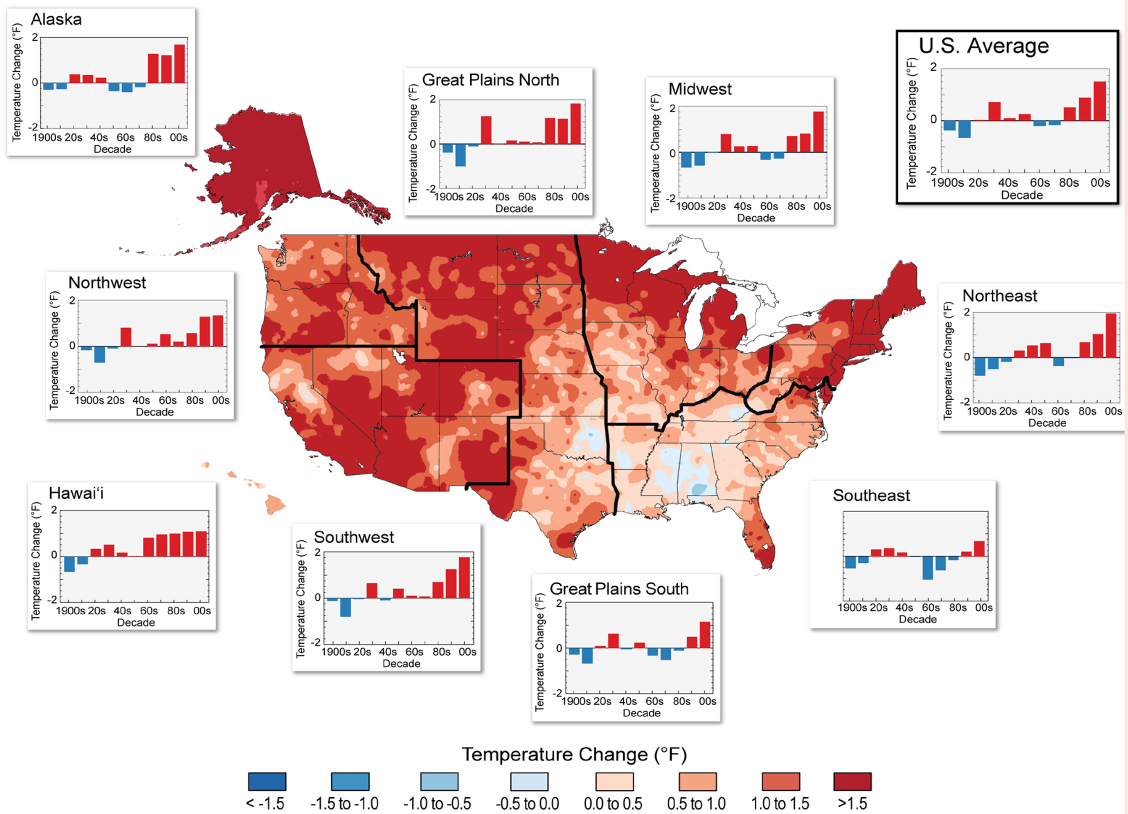


Figure 6: The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'i. The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC). Figure taken from Melillo et al. 2014.

There is evidence that sea level rise along the eastern seaboard of the US is accelerating (Fig. 7 below). The factors for the acceleration are not well understood but could be due to changes in ocean circulation associated with global warming, Greenland ice melt also associated with global warming or even land subsidence.

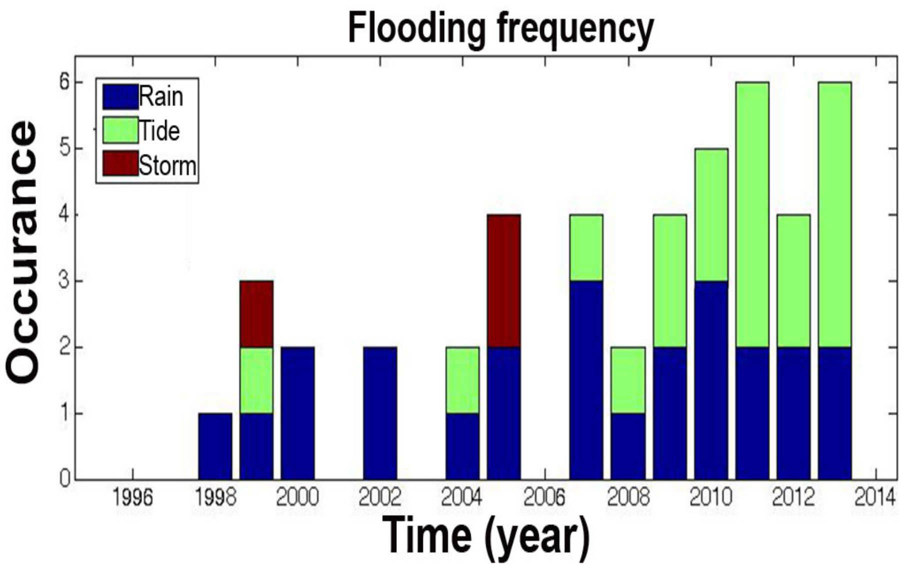


Figure 7: Flooding frequency in Miami Beach. Figure adapted from Wdowinski et al. (2016)

Finally, there is *no* compelling scientific evidence that any of the trends that we currently see are going to naturally? reverse themselves. There is, however, compelling evidence that the current trends will continue for at least the next 25 years, and there is even some evidence that particular trends (regional sea level) may accelerate (see discussion of Fig. 7).

Predicting the Future

Even if one is skeptical that human activities are the cause of these trends, there is a clear local need to protect lives and property, and ensure economic opportunity in response to changes we see today. Robust well-calibrated scientifically based predictions of the next 25-years (and beyond) are the first stop in developing effective adaptation strategies and to capitalize on the associated economic opportunities. Figure 8 show projected changes up to 2035.

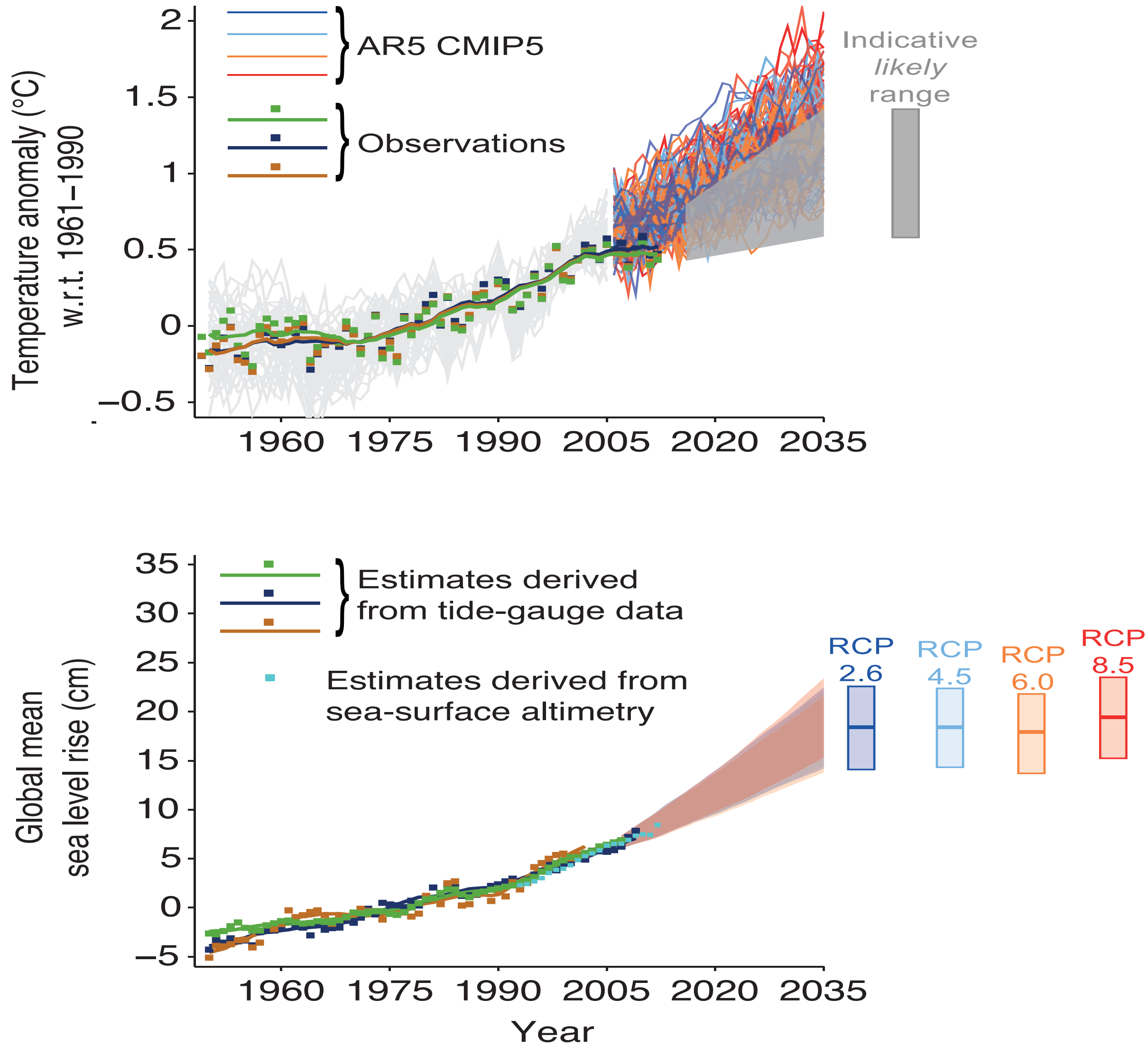


Figure 8: Projected changes in global temperature and sea level from IPCC AR5. See Stocker et al. 2013 for details.

References:

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merri eld, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S.

Unnikrishnan, 2013: Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Com- mitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang, 2013: Near-term Climate Change: Projections and Predictability. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assess- ment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wdowinski, S. R. Bray, B. P. Kirtman, Z. Wu, 2016: Increasing flooding hazard in coastal communities due to raising sea level: Case study of Miami Beach, Florida. *Ocean and Coastal Management*, **126**, 1-8.