Climate system change, from global to local:

Lake Winnipeg Watershed

Review on regulation of Lake Winnipeg

Prepared for the Manitoba Clean Environment Commission

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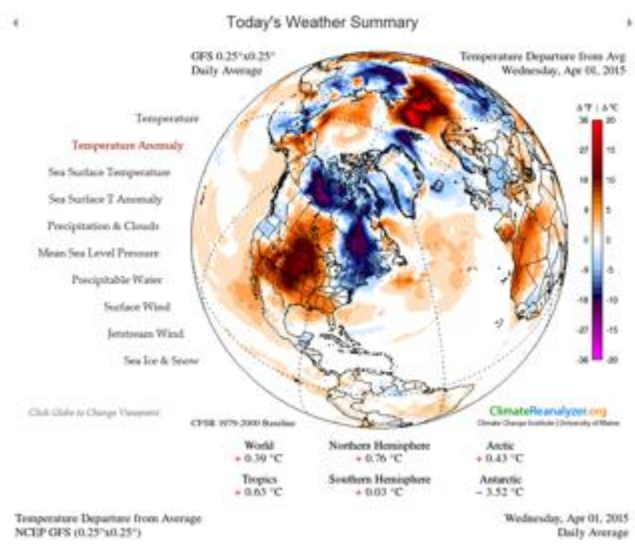

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Introduction

In 2008 Lenton et al. assessed potential tipping elements in the climate system, including Arctic sea-ice, Greenland and West Antarctic ice sheets, Amazon and boreal forests, monsoons, permafrost, and methane hydrates. This report will discuss some key aspects of the most vulnerable elements, including those that seem to be most rapidly changing, potentially causing cascading effects. Implications to the local scale, specifically to the Lake Winnipeg Watershed will also be examined.

Over the last few years it has become increasingly evident that the climate system on the Earth is changing in a nonlinear fashion. Rapidly rising anthropogenic greenhouse gas emissions from fossil fuel combustion and land use changes (Figure 1) are causing significant global warming (IPCC AR5 WG1 to 3, 2013 and 2014; also see Figures 2 and 3). Large positive feedbacks (see glossary explanation), for example in the Arctic from increased solar absorption due to greatly decreasing albedo from reduced sea ice (Figures 4 and 5), Greenland melt ponds (Figure 6), and terrestrial snow cover (Figure 7) are significantly amplifying atmosphere and ocean warming, resulting in large Arctic methane emissions from thawing terrestrial and marine permafrost, most noticeably over the Eastern Siberian Arctic Shelf and in other shallow marine regions (Figure 8, terrestrial permafrost map in Figure 9). In addition there is an increase in storm frequency, intensity, and duration leading to increased coastal erosion in the Arctic. Combined, these feedback effects are warming the Arctic at rates that are 4 to 5 times greater than the global average temperature rise. The greatly reduced equator-to-pole temperature gradient acts, in a climatological sense, to slow the jet stream winds and this should influence Rossby wave properties including increasing amplitude, changing spatial location, wavelength and symmetry (Francis and Vavrus, 2012); also see Figures 10 and 11. This in turn would increase the frequency, severity, duration, and spatial range of extreme weather events such as flooding, heat waves, and droughts (Hansen et. al., 2012). In addition, it causes "weather whiplashing", which are rapid jumps in temperature (hot to cold and vice versa) and/or precipitation (drought to flood and vice versa); for example see Figure 12. Examples of torrential rain events in Canada include Calgary flooding (Figures 13 and 14) and Toronto flooding. An extensive heat wave event killed more than 70,000 people in Europe in 2003 (Figure 15). More recently, extensive heat over Lake Erie caused and explosion of algae that shut down the Toledo water supply (Figure 16). These weather extremes will be greatly amplified if the late summer sea ice cover completely vanishes within the next few years. However, most climate models have under-projected the rates of change being observed (see Figure 5), for example they project summer sea ice vanishing between 2040-2070 (IPCC AR4, 2007; AR5, 2013) while extrapolating from measurements strongly suggest that this will happen before 2020 (see Figure 4). Model projections for methane release from Arctic sources suggest negligible emissions this century (IPCC AR4, 2007; IPCC AR5, 2013; NRC, 2013) while near real-time satellite data is showing large rises in methane levels in the Arctic are occurring even today (see Figure 8).

Overview: Abrupt climate change

There have been many times in the history of the Earth when regional (as well as global) temperatures have changed extremely quickly (nonlinearly, even abruptly) relative to the much more common incremental (linear) change periods (Alley et al. 2003, Chapman Conference 2009, Cronin 2009, IPPC AR5 2013, NRC report 2013). For example, during Dansgaard-Oeschger (DO) oscillations in the last ice age between 70 to 30 ka (1 ka = one thousand years ago) there were up to 29 abrupt warmings in which the temperature over Greenland as determined from proxy ice core records typically rose in the range of 5 to 10 ^{o}C (from glacial conditions at roughly -30 ^{o}C up to -20 ^{o}C) on a timescale of two decades or less (Singh et. al, 2013). The largest amplitude DO event had a temperature rise of 16 ^{o}C (Lang et al. 1999). There were also rapid rises of temperature with correspondingly rapid rises of global sea level during the Younger Dryas (YD), the last interglacial (Eemian), as well as during the Paleocene-Eocene Thermal Maximum (PETM) (Cronin, 2009). In Hansen et al., 2007 there is an extensive review on contemporary climate change and positive feedbacks and sensitivity of climate to forcings which can move the climate quickly between different states.

Contemporary global climate system change

As a Phd candidate at the university of Ottawa, and part time professor, my teaching and research focus is in abrupt climate change.

My working research hypothesis is outlined as follows: We are presently in the very early stages of an abrupt climate change transition, at least for some elements of the climate system, most notably those in the Arctic region. Greenhouse gas (GHG) levels have increased in magnitude and rate (IPCC AR5, 2013; also see Figure 1) enough to rapidly melt large areas of the Arctic sea ice (Figures 4 and 5), Greenland (Figure 6) and terrestrial snow cover (Figure 7) to greatly reduce the albedo resulting in larger solar absorption in the region. This in turn is causing significant Arctic amplification of temperature rates of change as compared to the global mean temperature rates of change (Figures 2 and 3). Therefore the equator-to-north-pole temperature gradient is greatly reduced. Thermodynamic heat flow considerations (heat moves from hot areas to cold areas) necessitate a reduction in the amount of heat transported northward from the equator to the Arctic via both the atmospheric circulation and ocean circulation patterns. Lower volume flow rates northward (in the atmosphere and oceans) leads to decreased wind speeds in high altitude jet streams and/or a spatial narrowing of the jet stream cross sectional area. It also leads to an increase in the meridional amplitude of the Rossby wave (jet streams) in the Northern Hemisphere (NH), and likely more fragmentation (filimentation) as well as changes in the number and location of the pressure ridges and troughs (Figures 10 and 11). Since the latitudinal pressure gradient force (PGF) has decreased with the temperature gradient reduction, the land/ocean temperature contrasts have larger relative influence on the atmospheric circulation pattern, and the jet streams have an increased tendency to larger amplitude blocking events with longer duration (persistence). Since heat flow from the equator northward is divided into roughly 2/3 atmospheric and 1/3 ocean (Srokosz et al., 2012), the atmospheric changes are the most significant. However there is also a reduction in ocean currents (including the Atlantic Ocean Gulf Stream and the Pacific Ocean Kuroshio Current). Combined with the elevated water vapor content of the atmosphere from increased evaporation with global average temperature rise (rising exponentialy with temperature according to the Clausius-Clapeyron equation; approximated to roughly 7% per ^{o}C for small temperature change) (Peixoto and Oort, 1992) these atmospheric circulation changes may be leading to more extreme weather events, most notably to torrential downpours (Coumou and Rahmstorf, 2012; IPCC SREX, 2012). Examples of this in Canada are Calgary in June, 2013 (Figures 13 and 14) and Toronto in July, 2013.

The Arctic amplification is also leading to increasing amounts of methane emissions in the northern region (from terrestrial permafrost (Marshall, 2013; see Figure 9 for Canadian permafrost map) and marine sources (ocean floor embedded permafrost and marine clathrates) (Shakova et al., 2010, 2013)), contributing to rising global methane levels and higher regional forcing in the Arctic further amplifying the warming (see Figure 8). As the Arctic albedo continues to decrease in the next few years with declining sea ice area, decreasing terrestrial snow cover area, and decreasing Greenland ice cap reflectance from melt ponds and old ice exposure, my view is that the frequency, intensity, duration, and spatial extent of these extreme weather events will continue to increase perhaps as high as an order of magnitude (based on the increased radiative forcing). Effects on human civilization and well-being would be very significant under this scenario as climate instability increased. More specifically, there would be immediate threats to global food supply, city and rural infrastructure, and loss of global biodiversity with species extinctions as well as increased ocean acidification. This would certainly cause great economic hardships and national conflicts and wars over ever scarcer resources. It is becoming increasingly obvious to ever larger numbers of the public and scientific communities that our global weather patterns are rapidly changing at rates that are unprecedented in human experience. System stability can no longer be taken for granted.

The mainstream scientific consensus view as summarized by the IPCC AR5 document that was released in late September, 2013 provides a comprehensive view of relatively recent scientific thinking on climate change (up to April, 2011; since the peer reviewed paper cutoff date for AR5 was April, 2013 and a paper has to have been published for two years to be included). Although this extensive body of work determines that the probability of human caused global warming occurring is now >95%, it still has the conclusion that the methane emissions from the Arctic and other regions is growing slowly, and will continue to grow slowly for the forseable future (over the next century) even in the worst case IPCC scenario RCP8.5 (Representative Concentration Pathway with 8.5 W/m^2 of ERF (Enhanced Radiative Forcing) by 2100) considered in the CMIP5 (Climate Model Intercomparison Project V study). As far as extreme weather events go, the document recognizes increases and provides an update on the interim SREX document on this topic (IPCC SREX, 2012). However, connections between the increasing levels of extreme weather and increased rates of Arctic albedo reduction are not considered, and thus a short-term ramping up of such events as albedo ramps down is not considered in any of the CMIP5 models in the report.

Examining the overall tipping elements of the climate system, Lenton et al., 2008 used expert panel judgement to categorize relative risks, timescales of change, and effects. An even more recent document titled “Abrupt Impacts of Climate Change, Anticipating Surprises” (NRC, 2013) expanded on a previous document titled “Abrupt climate change: Inevitable surprises” (NRC, 2002) and considers that methane emissions will not rise significantly enough over the next century to cause abrupt climate change, although the document does consider a higher risk of WAIS (Western Antarctic Ice Sheet) collapse leading to greatly elevated GMSL (Global Mean Sea Level) rates of rise. There is clearly disagreement in the literature regarding the importance of near-term methane changes in the climate system.

Global climate system context

Rapidly increasing anthropogenic fossil fuel combustion, as well as changing land use practices and industrial growth are rapidly accelerating growth in concentrations of atmospheric greenhouse gases (GHGs), most notably for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as shown in Figure 1. These greenhouse gases (having recently reached 400 ppm, 1850 ppb, and 325 ppb, respectively at Mauna Loa) are at concentrations much higher than upper limits of their previously narrow ranges (180 to 280 ppm, 350 to 750 ppb, and 200 to 280 ppb, respectively) for at least the last 800,000 years as measured from Antarctic ice sheet ice core records (and confirmed back to 120,000 years in Greenland ice core records) (IPCC AR5, 2013). Higher levels of GHGs are trapping more long-wave radiation (heat) in the climate system and are warming the atmosphere and oceans. According to Ramanathan and Feng, 2008 the measured increase in GHG since the preindustrial era has very likely committed the Earth to a warming of 2.4 ^{o}C (1.4 ^{o}C to 4.3 ^{o}C) above the preindustrial era. Since removal of anthropogenic CO_2 from the atmosphere by natural processes alone would take many hundreds-of-thousands of years, the warming is essentially irreversible on human timescales (IPCC AR5 WG1, 2013) unless emissions are halted and methods are used to remove CO_2 from the atmosphere (for example by accelerating the sink rates); collectively these methods are categorized under Carbon Dioxide Removal (CDR).

Accelerated increases in temperatures in the Arctic region appear to be causing large structural system element changes. Arctic sea ice cover and terrestrial snow cover have rapidly declined; from 1979 to 2012 the snow cover area (Figure 7) has lost an average -17.6% per decade (Derksen and Brown, 2012) while the sea ice cover area has decreased an average of -10% per decade (varying between -13% per decade in September and -2.6% per decade in March) (Perovich et al, 2012). Recently, a new record low in Arctic sea ice area was set in the summer melt season ending September 16th, 2012 representing a decline of 18% relative to the previous record low in 2007 (49% below the long term average from 1979 to 2000). Year-to-year variability appears to be increasing with the declining sea ice area trend (Figures 4 and 5). Positive feedbacks in the Arctic, mainly from the declining albedo due to collapse of highly reflective sea ice and snow cover (replaced by dark ocean water and permafrost, respectively) have caused an amplification of warming in the high Arctic by factors of 4x to 5x (Lesins, 2012, 2013); also see Figures 2 and 3.

Further acceleration in Arctic rates of warming are presently occuring as methane concentrations in the Arctic region are rapidly rising. Specific sources include terrestrial permafrost rapidly thawing due to increased shortwave radiation absorption and thus heating due to the absence of high albedo snow cover, most notably the Yedoma region in Siberia (Vonk et al., 2013). In the last year, methane caused craters have been discovered in northern Siberia (likely from thawing methane clathrates). High levels of methane have also been measured along Arctic coastal permafrost regions as increased wave action and larger storm surges due to stronger, more frequent and longer duration polar cylones in the newly opened Arctic ocean are inundating shallowly sloping coastlines and causing increased erosion rates (Gunther, 2013a,b). Also, the oceans over shallow continental shelves in the region are warming significantly causing perforations in the sea floor sediment layers releasing large area plumes of methane, most notably over the East Siberian Arctic Shelf (ESAS) (Shakova et al., 2010, 2013). Methane surges are also observed from deeper waters (Ruppel, 2011). Direct flask measurements at weather stations in Svalbaard and Barrow (ESRL data) and remote sensing satellite measurements (AIRS data, IASI data) have detected large methane concentrations throughout the Arctic.

On the global scale methane concentration levels have experienced an increase since 2007 (see Figure 1), reflecting a change from the prior leveling out trend (ESRL data). Outside of the Arctic, methane emissions have been measured on continental shelves off the southeastern U.S. seaboard (Brothers et al., 2012) that are warming due to the Gulf Stream shift closer to the coastline. Destruction of wetlands, increases in rice production (Archer, 2010) and increased global energy dependence on fracking for natural gas in shales and sediments are also contributing significantly rising global methane levels (Tollefson, 2013). Since the global warming potential of methane is about 150x that of carbon dioxide over timescales of a few years (IPPC AR5, 2013), the significance of methane is increasing rapidly.

The importance of the accelerated Arctic warming at rates up to 4x to 5x larger than global average temperature increase cannot be underestimated; what happens in the Arctic does not stay in the Arctic. Since the equator mean annual temperature has a very small variation (mean temperature changes < 3 ^{o}C seasonally), and the increase in temperature from climate change is relatively small there (most of the increase in energy there goes into latent heat from increased evaporation of the oceans), the equator-to-Arctic temperature gradient rapidly decreases. This reduces the equator-to-pole pressure gradient (from basic meteorology); and results in a smaller thermodynamic driving force (which moves heat from warm regions like the equator to cold regions like the poles, proportionately to the temperature gradient) (Barry and Chorley, 2010; Peixoto and Oort, 1992). The net result from the Arctic warming via decreased albedo (increased absorption of shortwave radiation) is that less heat moves from the equator to the Arctic region; via both the atmosphere and oceanic circulation patterns.

In the atmosphere, when a stationary air parcel is acted on by a PGF (Pressure Gradient Force; arising from a temperature gradient) it accelerates until it reaches geostrophic flow (PGF = Coriolis force). As this flow moves to higher latitudes there is geographic constriction in cross-section, and increases in speed enhanced by conservation of total vorticity (angular momentum in a fluid) and the increasing Coriolis force (which is zero at the equator, and increases with latitude to a maximum at the pole) deflecting it to the right (in the northern hemisphere) (Peixoto and Oort, 1992). The net result is the formation of jet streams. When the temperature gradient is reduced (either from seasonal change or Arctic amplification) there is a smaller northward heat transport so the northern hemisphere jet streams have smaller volume flow rates Q (m^3/s); to preserve angular momentum they generally move southward. Smaller Q means a smaller (velocity) x (cross-sectional area) product, so the jets can narrow and/or decrease speed and/or become broken up and/or change latitude. As Q decreases, the land/ocean temperature contrast and land topography become more important (even dominant) factors in jet stream behaviour, and as these Rossby waves respond they tend to distort and have higher amplitudes (become more meridional) and thus more easily locked to the fixed continental-ocean geography in the northern hemisphere. Thus, blocking becomes more persistent (Woolings et al., 2012; Francis et al., 2013; Overland et al., 2013).

The spatial and temporal characteristics of the high altitude jet streams play a crucial role in controlling and guiding weather patterns (Barry and Chorley, 2010). In the boreal summer with a warmer northern hemisphere from higher solar zenith angles (thus higher solar intensities) the cold air does not extend as far south and therefore the jet streams are located closer to the pole. At the present time, albedo feedbacks are rapidly reducing this volume of cold air in the Arctic. In the boreal winter, as the volume of cold air in the Arctic increases the equator-to-pole temperature gradient increases and the jet streams move roughly twice as fast, on average. However, with Arctic temperature amplification primarily from summer albedo reduction (less sea-ice means a larger area of dark ocean water which can absorb more solar radiation, thus much more heat is stored during the summer melt season). With the seasonal change from summer to fall and then winter, large amounts of heat escape from the warmer oceans leading to disruption of the polar vortex (jetstreams become more meridional (wavy), average eastward velocity decreases and more flow fragmentation (namely there are large width and velocity variations). Thus, the weather patterns which are guided along the jetstreams are changed (extreme weather events like torrential rains increase in frequency, severity, duration, and vary in spatial extent from the norm). In addition, there is now 4% more water vapor in the atmosphere now than there was 3 decades ago (7% per ^{o}C x 0.6 ^{o}C of warming); this is due to the increased evaporation levels from a rising global average temperature and the increased ability of warmer air to hold more water (from Clausius-Clapeyron equation) (Peixoto and Oort, 1992). The extra water vapor in the atmosphere is providing large amounts of latent heat energy to fuel more massive and intense storms. The slower jet streams are indicative of slower storm advection. Coumou and Rahmstorf, 2012 have suggested that these two factors, combined, are causing increasing frequencies, amplitudes, durations, and changing spatial extents of many severe weather events, leading for example to torrential rains and subsequent floods, long duration droughts leading to crop failures, and also more derechos and haboobs; however attribution research is in early stages. An increase in heat wave extremes has been statistically confirmed for summer (June, July, August) by Hansen et al., 2012a. For example, this extremely wavy Rossby wave pattern of jets resulted in patterns like the low pressure trough for a month causing Pakistan flooding in the summer of 2010 (70% of country flooded) simultaneously with the blocking high pressure ridge over Moscow causing a record heat wave with record forest fires causing a loss of 40% of the Russian grain crop and up to 50,000 fatalities (Coumou and Rahmstorf, 2012). Similar persistent jet stream activity is associated with the recent southwestern U.S. drought, and was directly responsible for the redirection of Hurricane Sandy to make an unprecedented left turn and impact the New Jersey and New York coastal regions (Beckwith, 2012b; Livescience, 2013).

For the duration of Earth's history the climate system has undergone both linear and nonlinear changes. Linear changes, in which incrementally larger forcings (internal or external to the system) cause a given system element to respond by reconfiguring with incrementally larger proportionate responses is the most frequent system behavior. Non-linear changes, in which a given forcing results in the system element responding disproportionately larger are usually much less frequent, and very difficult to anticipate in advance. Each specific system element responds to the forcing with its own characteristic response time, which is typically hours to days with the atmosphere and months to years to centuries or even millennia with the oceans and cryosphere, and even longer (geological timescales) with the lithosphere. However there are thresholds (tipping points; birfurcation points) in most systems. When a threshold or "tipping point" is crossed by either a large forcing or by the cumulative buildup of many small incremental forcings then the system can respond with a surprisingly large and unexpected change (relative to linear changes) that is disproportionate to the forcing. This nonlinear or abrupt change (regime shift) usually eventually leads to a new stable state (in which linear changes again become the norm). Contemporary changes in various elements of the climate system (such as Arctic albedo decline, methane emission increase) are occuring at rates faster than linear due to positive feedback effects.

In the records of past climates, in which temperature and rainfall and other climate parameters are obtained from various proxies such as pollen records, tree rings, ice cores on Greenland and Antarctica, and marine sediments, among others, it is very clear that there have been many rapid or abrupt transitions in temperature and precipitation. Some causes of extremely rapid changes (D-O oscillations, YD) have been attributed to a switch on (or off) in the global ocean current pattern known as the Atlantic Meridional Overturning Circulation (AMOC) (Broecker, 2010). Others (PETM) have been attributed to large sudden emissions of methane from the ocean floor hydrates (Kennett et al., 2003).

It is essential that we understand how quickly the changes in the Earth climate system can occur and learn about the type of climate regimes that we can end up reaching within a decade or two if we experience an abrupt climate change transition. For example, is the climate of the Earth heading to a much warmer overall state in which snow and ice in the Arctic regions becomes a distant memory? If so, then can societal adaptation adjust to the rapid rates of change, and can mitigation be utilized to slow the changes?

Arctic albedo decline (terrestrial snow cover, sea ice, and Greenland); temperature amplification

The most sensitive elements of the climate system seem to be located in the Arctic region and consist of a) sea ice volume and b) thickness (PIOMAS, and CryoSat-2 data (Laxon et al., 2013)), c) sea ice extent (NSIDC data) and d) area (Cryosphere Today), e) sea ice motion, specifically at export regions (U.S. Navy data), and f) terrestrial snow cover area, mostly in the boreal spring (Rutgers University Global Snow Lab data (Derksen and Brown, 2012). Other physical measurements that affect ice melt, such as ocean temperature and salinity with depth, ocean currents, and regional meteorology will also be examined in relation to other variables. The overall decline in Arctic albedo, mainly from sea ice and snow cover area reductions, but also from Greenland albedo decrease (Box et al., 2012, 2013) will be studied in relation to the associated known feedbacks (mostly positive).

While some research suggests that the albedo effect of the Arctic terrestrial snow cover decline is roughly equivalent to that of the Arctic summer sea ice decline (Flanner et al., 2011), more recent work (Tang et. al., 2013) finds that the sea ice effect on atmospheric jet streams is larger. The present consensus on Arctic sea ice decline based on CMIP5 modeling projections and ERF forcing scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) from the IPCC AR5 (2013) report are consistent with the results of CMIP3 model projections from IPCC AR4, 2007. The basic conclusion is that the Arctic sea ice will not vanish completely (at least to an area < 1 million km^2) for the first time (i.e., near the end of the melt season in September) for at least 30 years or longer (2040 to 2070). However, observations from the summer 2012 melt season indicated that the ice extent reached record lows, and the pattern of decline recorded from data-model hybrids (PIOMAS) conflicts strongly with this view, suggesting that the ice extent may become < 1 million km^2 before the end of this decade. This view is gaining traction via continued monitoring of Arctic sea ice volume data and by results from a higher-resolution Regional Climate Model (RCM) applied in the Arctic (Maslowski et al., 2012) in contrast to the lower-resolution IPCC AR5 Global Climate Models (GCMs). The RCM suggests that the sea ice will first vanish within a very short time (2016 $\pm$ 3 years). Recent Cryosat-2 satellite measurements of sea ice thickness (Laxon et al., 2013) adds credibility to this rapid sea ice loss scenario. Of course negative feedbacks which are not currently identified may affect this prediction, flattening out the current downward trend. Possibilities may include a) open water and thin ice freezes faster than thick ice, and b) thinner ice spreads more increasing albedo, and c) marine cloud cover increases with more open water, leading to cooling.

A main objective of ongoing Arctic research is to put more accurate bounds on the potential date of loss of essentially all sea ice in the Arctic Ocean (ranging from about 2016 per Maslowski et al., 2006, 2012) to the decades 2040 - 2070 per IPCC AR5. In conjunction with Arctic terrestrial snow cover reduction (mostly in the spring), this is decreasing the albedo of the Arctic region (which has already decreased from 52% to 48% between 1979 and 2011 according to a Scripps Institute study of CERES satellite data http://www.nasa.gov/content/goddard/nasa-satellites-see-arctic-surface-darkening-faster/index.html#.U_TmbPldV8E.

Overall Arctic changes can also be examined in a top-down Arctic climate system approach. Climate changes in the Arctic are larger and faster than anywhere else on the planet.

There are many interacting processes and elements that are changing, and clearly these need to be researched in detail. However, to understand the system, and the importance of sea ice and snow cover decline, it is important to understand the fundamentals of these changes. For example, during the record breaking 2012 summer melt season an extremely rare and very large cyclone churned over the Arctic ocean region in early August (from Aug. 2nd to 10th) and the ice was shredded into smaller (larger surface area) chunks, and transported out into the open Atlantic ocean via the Fram Strait. Within the Arctic basin near the North Pole, the ice was fractured and melted very quickly due to ocean mixing whereby warmer, saltier water from cyclone churning was brought up from 500m depths (as measured by tethered ocean buoys) to displace the fresher and colder surface melt water surrounding the ice near the surface. In addition, the extremely deep central pressures of the cyclone caused a storm surge by pulling up the surface level of the water by about 30 cm across a large portion of the region resulting in larger inward flows of warmer Pacific water (through the Bering Strait) and warmer Atlantic water (from the Norwegian Sea and between Iceland and Svalbard). Also, the duration of the cyclone was 10 days which is unusually long for such a storm, however research suggests the potential for Arctic cylones to last up to 30 days duration with increased warming of the region (Zhang et. a., 2004). The storm maintained power via injection of sensible heat energy from Siberia which had 20 ^{o}C high temperatures and large concentrations of soot and ash from large area forest fires burning at that time in the high north. Also, the storm was constrained to the Arctic Ocean basin. As it started to head southward out of the basin the large rightward deflection from the strong Coriolis force (maximized right at the North Pole) caused it to curve continuously to the right and head back to the central part of the basin again, in a meandering circular loop. To further compound the melting, incoming fresh water flows from the major Siberian rivers into the Arctic Ocean basin contributed greatly to melting due to their elevated temperatures and large flow rates sourced from amplified land warming resulting in large terrestrial snow melt. Atmospheric data for the region to analyze these effects can be obtained from NCEP reanalysis. The frequency, amplitude, duration, and spatial extent of cyclones has been increasing in the Arctic and northern hemisphere mid-latitude regions over the last several decades. The nonlinear loss of sea ice volume is occurring for every month of the year, not just in the boreal summer months. If the ice indeed leaves the Arctic ocean in a summer before 2020 (for a month or less) then the next two warmest months (August and October) may trend to zero within a year or two later, followed by another two months (November and July) within about 3 or 4 years. Calculations by Wadham's (personal communication) and others suggest that radiative forcing by sea ice is about 0.1 W/m^2 now, will triple when the ice is gone for a few months, and will be 7x when the ice is gone for half the year. Arctic ice behavior in 2013 was unprecedented in March (from Satellite images) with significant and widespread cracking at the time of usual maximum strength, but the summer minimum had more ice than in 2012, as did 2014. In March 2015 the winter sea ice maximum extent set a record low; it is clear that there is great variability and many records are being broken.

As the ice rapidly vanished during the boreal summer in 2012 (reducing area and thickness) the ocean water heating rates increased at all depths. For example, water over the relatively shallow (maximum depth 50 m) ESAS (Eastern Siberia Arctic Shelf) warmed with temperature anomalies typically in the range of 3 to 5 ^{o}C (maximum measured 7 ^{o}C) resulting in perforations of the frozen marine sediments and increases in methane emission ebullition through the water column (Shakova et al., 2013). Methane emission changes in the Arctic are discussed in the next section and can be a strong feedback.

Albedo reduction is the strongest feedback thus far. As fast as the sea ice decline trends are (namely a 49 % area loss over 3 decades or so) (from PIOMAS data, and CryoSat-2 data published in Laxon et al., 2013), with a mean loss of 12 % per decade it was still superceded by terrestrial snow coverage loss (18.7 % per decade in the time period from 1979 to 2010) (Derksen and Brown, 2012). These large rates of decline of highly reflective terrestrial snow cover and sea ice area (albedos above 80 % or so (snow and ice), being replaced with albedos less than 30 % (exposed ground) or less than 10 % (dark sea water)) are collapsing the regional albedo. Greenland melt is also lowering albedo, although the area is lower (compared to sea ice loss and snow cover loss) so the effect is smaller. Thus, the increased absorption of shortwave solar radiation in the region causes large warming anomalies over extended periods of time. For example, Greenland underwent an exceptional and unprecedented reduction in albedo over the space of 4 days in July, 2012. The area percentage of the ice cap undergoing surface melt increased from 40% of the Greenland ice cap to 97% within these 4 days, which was an incredibly abrupt change in its own right given the high altitude of the peak (3275 m). Albedo of the Greenland cap dropped significantly due to increased meltwater pooling on the surface, exposure of entrained dirt and soot in the ice, and possible increased levels of soot and ash deposition from Siberian fires being sucked into the cylonic type storm systems. In fact Greenland ice melt rates are estimated in a recent paper to have increased about 5x between the mid-1990s and the present (Shepherd et al., 2012); this represents a doubling rate of <7 years. Finally, the rapid tropospheric warming of the Arctic atmosphere is allowing less stratospheric heating such that in 2010 there was an unprecedented 40% drop in Arctic ozone concentrations (Manney et al., 2011). For the first time in the ozone record, the Arctic ozone hole size and magnitude rivaled that of the yearly ozone hole that forms in the much colder Antarctic stratosphere. This part of the study aims to put the overall Arctic changes into a more global context.

In summary, the Arctic sea ice and spring snow cover are both trending strongly downward. While the global temperature increase has slowed over the last 15 years or so, the warming of the Arctic in recent years is much faster than anticipated (AMAP, 2009, 2012). Other Arctic feedback effects (based on ice motion, fracturing behavior, cyclone frequency and severity, ocean temperatures and salinity) need to be researched. What is clear is that the Arctic amplification (warming in Arctic versus global warming average) was as large as 4x over the last 3 decades (Screen et al., 2012) and is primarily due to the decline in albedo of terrestrial snow cover area and sea ice area (Screen et al., 2010). This resulted in an albedo feedback radiative forcing of 0.3 to 1.1 W/m^2 based on observations (Flanner et al., 2011). With further decline we can calculate the additional radiative forcing in the region (for both albedo, as well as for methane emissions) to determine the overall additional Arctic amplification effects. It is expected that this Arctic amplification will change many aspects of the climate outside of the region, including atmospheric circulation patterns, vegetation, and the carbon cycle and have large impacts in and beyond the Arctic (Serreze and Barry, 2011). What is not known is how quickly these changes will occur, the magnitude of the changes, and the effects on the overall climate system.

Arctic methane emission increases (from marine sediments and terrestrial permafrost), global warming potential, regional radiative forcing

Methane emissions in the Arctic originating from terrestrial permafrost (Vonk et al., 2013) and marine ocean sediments, most notably on the shallow continental shelves such as the very large East Siberian Arctic Shelf (ESAS) (Shakanova et al., 2013), as well as from marine methane clathrates (both shallow and deep) are being observed.

The Arctic region stores about 33% of all the carbon held within the global terrestrial ecosystem, and roughly 40% of the carbon that is present globally in near-surface soils (AMAP, 2009). Large quantities of methane hydrate (methane trapped in the center of a frozen lattice of water) exist on the ocean floor and buried within the ocean sediments, kept in a stable state by high water pressure and low temperatures (for example at 0 ^{o}C and 200 m water depth (personal communication with Archer, 2013)). These are considered to be vulnerable to ocean and associated sediment warming (AMAP, 2009). According to the latest IPCC AR5 WG1, 2013 report, the amount of methane stored in the Arctic hydrates could be >10x the methane that is presently in the global atmosphere, and the Arctic permafrost (terrestrial and marine) holds >2x the amount of carbon present in the atmosphere today. This vast carbon storage could potentially be released as either CO_2 or CH_4 (depending on location O_2 level), and act as very large positive feedbacks causing even larger warming upon release. It is estimated that the Arctic is presently a source of from 3% to 9% (15 Tg (Gt) to 50 Tg) of the global net emissions of methane from land and ocean (AMAP, 2009). Arctic marine emissions of methane are thought to be roughly 1/3 of that emitted from wetlands in the Arctic tundra (Shakova et al., 2010 and McGuire et al., 2012). The various factors controlling the seasonality of the methane emissions from high-Arctic tundra have been examined in Mastepanov et al, 2013. Methane feedback emissions thought to be sourced from wetlands contributed to the natural warming rates as the planet transitioned out of ice age glacials (Levine et al., 2011, 2012).

The various factors controlling the seasonality of the methane emissions from high-Arctic tundra have been examined in Mastepanov et al., 2013. From 1750 to present, the global atmospheric concentration of methane increased roughly 2.5x (Dlugokencky et al., 2011) from about 750 ppb to 1850 ppb; levelling out since the mid-1990s. In 2007 to present, the global methane concentration (Earth System Research Laboratory (ESRL data)) has been increasing for reasons under scientific debate. The cause may be a rise in natural wetland emissions from a more vigorous hydrologic cycle, or from increased fossil fuel emissions perhaps sourced from widespread fracking (Kirschke et al., 2013). Fisher et al., 2011 attibutes the increase to wetland peat mainly in the tropics, and also in the far northern regions.

Another possibility is that a significant portion of the global methane increase since 2007 is from increased Arctic region emissions, and also from increased Antarctic emissions. Clearly, emissions are also increasing from anthropogenic sources, specifically fracking. Another major source of methane is tropical and boreal wetlands, whose emissions are expected to increase in regions with wetland areal growth (from increased rainfall, especially over northern continents) and decrease in other regions experiencing desertification. The ESRL Global Monitoring Division (GMD) Carbon Cycle Greenhouse Gases Group (CCGG) makes discrete measurements from land and sea surface sites, as well as from aircraft and towers allowing for spatial and temporal methane distributions to be determined.

Satellite data from AIRS (data set from Aug/2002 to present) and IASI instruments indicates that there are increasing levels of methane outgassing from both the ocean floor and land in high Arctic regions. Some of the largest emissions are ebullition from the ocean floor on the ESAS (Shakova. et al., 2013). Satellite data needs to be compared to flask measurements at surface stations to provide ground-truthing confirmation of the satellite data.

Despite the recently increasing methane emissions that have been measured, the IPCC AR5 models run on the assumption that methane emissions will not be significant this century. For this reason, I now briefly discuss some of these recent observations. During the record ice melt in boreal summer 2012 (significantly reducing area and thickness) the ocean water heating rates increased at all depths. Water over the relatively shallow (maximum depth 50 m) Eastern Siberia Arctic Shelf (ESAS) warmed with temperature anomalies typically ranging from 3 to 5 ^{o}C (maximum 7 ^{o}C) resulting in perforations of the frozen marine sediments and increases in methane emission ebullition through the water column (Shakova et al., 2013). Higher temperature sea water has lower gaseous solubility, leading to less storage of methane and carbon dioxide and higher atmospheric levels. Carbon dioxide levels as high as 400 ppm were measured in the Arctic for the first time in 2013, while methane levels up to 2200 ppb (2.2 ppm) were observed in flask measurements across widely separated Arctic regions (at both Svalbard and Barrow, AK) and in AIRS (Atmospheric Infrared Sounder) and IASI (Infrared Atmospheric Sounding Interferometer). Recent measurements in November, 2013 from IASI satellite date show measurements of methane as high as 2600 ppb.

Since the GWP (Global Warming Potential; relates radiative forcing of a gas relative to that of CO_2) of methane at short timescales of a few years is as high as 150x to 170x (80x over 20 years, 34x over 100 years) (IPCC AR5 WG1, 2013), the radiative forcing level of this Arctic methane was calculated to be around 384 ppm CO_2-e (equivalent) which is very close to the radiative forcing for CO_2 of 400 ppm. This large regional Arctic warming is maintained by the tendency of the strong polar vortex in the region (arising from the increased Coriolis force amplitude as a function of increasing latitude) which tends to contain and basically trap the gases in the Arctic for longer periods of time (less mixing with air from lower latitudes) reducing advection rates to the lower latitude global atmosphere. As fast as the sea ice decline was (namely a 49% area loss over 3 decades from PIOMAS data, and CryoSat-2 data published in Laxon et al., 2013), with a mean loss of 12 % per decade it was still much smaller than the terrestrial snow coverage loss (18.7 % per decade in the time period from 1979 to 2010) (Derksen and Brown, 2012).

These large rates of decline of highly reflective terrestrial snow cover and sea ice area (albedos above 80 % or so (snow and ice) are being replaced with albedos less than 30 % (exposed ground) or less than 10 % (dark sea water)). Greenland surface melting, and deposition of BC (black carbon) is also lowering albedo, although the area is lower (compared to sea ice loss and snow cover loss) so the effect is smaller. Thus, the increased absorption of shortwave solar radiation in the region causes large warming anomalies over extended periods of time. For example, Greenland underwent an exceptional and unprecedented warming over the space of 4 days in July, 2012. The area percentage of the ice cap undergoing surface melt increased from 40% of the Greenland ice cap to 97% within these 4 days, which was an incredibly abrupt change in its own right given the high altitude of the peak (about 3275 m). Albedo of the Greenland cap dropped significantly due to increased meltwater pooling on the surface, exposure of entrained dirt and soot in the ice, and possible increased levels of soot and ash deposition from Siberian fires being sucked into the cylonic type storm systems. In fact Greenland ice melt rates are estimated in a recent paper to have increased about 5x between the mid-1990s and the present (Shepherd et al., 2012); this represents a doubling melt rate of <7 years. Finally, the rapid tropospheric warming of the Arctic atmosphere is allowing less stratospheric heating such that in 2010 there was an unprecedented 40% drop in Arctic ozone concentrations (Manney et al., 2011). For the first time in the ozone record, the Arctic ozone hole size and magnitude rivaled that of the yearly ozone hole that forms in the much colder Antarctic stratosphere. Less often discussed than methane emissions in the Arctic are the increases in CO_2 and N_2O emissions in the region. Large emissions of CO_2 from permafrost in eroding shorelines have been reported (Vonk et al., 2012) and as the methane reacts with hydroxyl ions and is broken down the GHGs CO_2 and H_2O are formed. The mix of greenhouse gases emitted from warming tundra depends on the water content (Lund et al., 2012). In addition, the powerful GHG nitrous oxide N_2O, with a lifetime of 115 years and a GWP of 300 (IPCC AR5 WG1, 2013) is released into the atmosphere from melting permafrost (Repo et al., 2009 and Elberling et al., 2010). Although measurements of gas concentrations are generally in specific regions, the overall emissions are likely significant given the vast surface area of the permafrost regions. As discussed previously, the overall albedo in the Arctic region has declined from 52% in 1979 to 48% in 2011 with the bulk of this decrease being from sea ice and snow cover decline. It is clear that many changes are rapidly occurring in the Arctic climate system, and these in turn affect the jet streams and extreme weather statistics in lower latitudes, as will be examined in the next section.

It is of critical importance to determine the Global Warming Potential (GWP) of methane on various timescales. The GWP of methane is apparently not known to high accuracy. A review of GWP for a century timescale gives an increasing progression from IPCC AR3, AR4, AR5 of 22x, 25x, and 34x, respectively. For a two decade timescale, the values are 64x, 72x, and 86x, respectively, and for a year or two may be much higher than the previously mentioned 150x to 170x that of carbon dioxide. A literature review to clarify the reasons for this variance is needed since it is extremely important for determination of regional radiative forcing. Also, the value of GWP on a timescale of a year or two is likely to be the number of critical importance to short-term regional forcing feedbacks of methane on the melt rates of sea ice. An important reason for the uncertainty in the GWP of methane is the uncertainty in the localized lifetime of methane. The main sink of methane in the atmosphere is the hydroxyl ion (OH^-) which is produced by the photocatalyzed hydrolysis of water vapour in the atmosphere. Near the equator, where the solar intensity and atmospheric water vapour concentrations are large (due to high evaporation rates of warm ocean water) there are large concentrations of hydroxyl ions which can rapidly break down the large emissions of methane from equatorial wetlands. This is in contrast to the polar regions which are essentially dry deserts with very low precipitation and cold air containing little water vapour and hydroxyl ions. Thus, the lifetime of the methane in the Arctic is much longer, and since the air at the pole is somewhat confined due to the polar vortex atmospheric circulation there can be large regional warming in the Arctic before the methane is scavenged by hydroxyl ions or advects to lower latitudes.

As mentioned previously the IPCC AR5, 2013 report does not consider that methane emissions will ramp up sufficiently over the next century to cause significant warming, and thus this feedback is left out of the CMIP5 models (as it was for the IPVCC AR4, 2007 CMIP3 models). The main rationale for this is there is no generally accepted mechanism allowing for rapid release of methane since the timescale for heat penetration downward through sediment is centuries or longer. The physics for the heat transport assumes uniform 1-D slab models (heat flow only in the vertical z-direction, with uniform behaviour in the sediments in the x- and y- directions) resulting in slow transport. Direct measurements of methane in the water column (both dissolved methane and bubbles) and in the atmosphere over the ESAS by Shakova et al. in 2013 found that methane emissions are increasing. I hypothesize that the slab models are failing since there are fractures, taliks, and other discontinuities in the sediments that are allowing much more heat to penetrate deeply into the sediments, melting the methane clathrates and permafrost and leading to the observed emissions. Based on an examination of the physics, there is a research need to examine how these emissions are likely to change under the expected sea ice declines and Arctic amplification to assess how large the near-term feedbacks could become. I will also analyze my hypothesis that the methane feedbacks may be strong enough when combined with Arctic albedo decline from completely vanishing sea ice (perhaps even as early as 2016) (Maslowski et al., 2012) to lead to subsequent years having longer and longer durations of open Arctic Ocean such that within a decade or so the Arctic sea ice vanishes year round, leading to a great acceleration of global warming and basically a loss of northern hemisphere snow and ice in winters.

Examining paleorecords is necessary to understand how the climate system can change if we are in early stages of abrupt change as is hypothesized. There have been times in the past marine and ice core records when mean global temperatures changed by 6 to 8 degrees Celsius within a few decades, and even as high as 16 ^oC (DO oscillations:(Singh et. al, 2013) and (Lang et al. 1999); PETM: (Wright and Schaller, 2013)). These jumps in temperature have been attributed to reorganizations in Meridional Overturning Circulation (MOC) ocean currents arising from meltwater outbursts (Broecker, 2010) and also to methane hydrate outbursts (clathrate gun hypothesis) by Kennett et al., 2003; or perhaps a combination of these. For the PETM about 55 Ma in the Eocene North Pole water temperatures increased fro 18 ^oC to 23 ^oC due to a large increase in CH_4.

Potential analogues in the past for present changes may allow us to put the contemporary climate changes into context to allow more accurate predictive capability as to where our present day climate is heading and how quickly it will take to arrive. It is very clear that if the methane is released rapidly, even in a large pulse or "burp" from the terrestrial and/or marine permafrost (or from the ocean floor clathrates) then we will abruptly transition to a new climate state. Clearly, with this scenario there will be enormous societal costs (Whiteman et al., 2013). Recent examination of the ocean floor geomorphology off the coast of New Zealand has uncovered definitive evidence (in the form of crater-like geologic structures with diameters > 100 km) that there have been enormous catastrophic outgassing events of methane from clathrates on the ocean floor in the past Earth history (Davy et al., 2010). Large undersea slumps (>5600 km3) off Norway in the Storegga region also occurred in the past and may have led to large methane releases (Kennett et al., 2003). Such an event now would literally change the climate of the planet overnight. Recent measurements from speleothems in Siberian caves within permafrost regions that are proxies of climate in Siberia over 500 kyr suggest that there may be substantial thawing of the continuous permafrost with temperatures only slightly higher than those today, namely at 1.5 ^{o}C above preindustrial (Vaks et al., 2013), as compared to warming of 0.8 ^{o}C that we have thus far.

In a Russian study by 21 scientists, the degradation of marine permafrost and the destruction of hydrates on the ESAS were studied to determine the risk of a catastrophic methane release (Sergienko et al., 2012). A direct quote from this paper is that: "The emission of methane in several areas of the ESS (sic Eastern Siberian Shelf) is massive to the extent that growth in the methane concentrations in the atmosphere to values capable of causing a considerable and even catastrophic warming of the earth is possible". Research on risk-analysis of global climate tipping points suggested that we could reach a methane tipping point at warming levels above 2 ^{o}C which could be as early as 3 decades from now (Betts et al., 2011). A scenario envisioned would have warming of the deep ocean thawing the methane hydrates releasing large amounts of methane to the atmosphere leading to strong warming feedback loops; a continuing release of methane would likely overwhelm anthropogenic GHG emissions (Frieler et al., 2011). A review paper by O'Connor et al., 2010 examined the CH_4 feedbacks related to natural sources from wetlands, permafrost, and ocean sediments, considering the complex non-linear process affecting the sources, atmospheric chemistry, and terrestrial vegetation. As the methane causes localized warming in the Arctic there is increased growth of terrestrial vegetation and thus emissions of BVOCs (biogenic volatile organic compounds) which reduces the atmospheric hydroxyl and thus increases the local methane lifetime.

In summary, the key question for methane emissions in the rapidly warming Arctic region are how much can be emitted and at what rate? A recent paper by Duarte et al., 2013 examined the potential economic effects of a 50 Gt pulse of methane coming from the Arctic, and came up with a $60 Billion impact. In response to this paper, Nisbet et al., 2013 questioned the ability of the Arctic to have such a large release. The jury is still out on the likelihood or possibility of such large releases, and this is an area of great scientific research interest since societal implications are global and enormous.

Effect of the decline of the equator-to-Arctic temperature gradient on the general circulation and extreme weather patterns

With the albedo decline in the Arctic there is increased Arctic temperature amplification, and thus changes in Rossby waves (amplitudes, spatial locations of ridges and troughs, wind velocities (group velocities and phase velocities), and jet stream cohesion and fracturing. Connections between Rossby wave changes and extreme weather event statistical changes are being studied. Research to relate the changes in frequency, amplitude, duration, and spatial extent of extreme weather events (primarily torrential rain events with subsequent flooding, but also events such as very rare snowfalls at low latitudes) with the changing atmospheric circulation patterns (from the jet stream changes) is very important. Canadian examples for torrential rain events (rainfall levels in a day or two comparible to normal rainfall amounts over several (to even six) months) occurred in Calgary and Toronto in the summer of 2013 leading to major urban flooding. Even more widespread Colorado flooding occurred in that year due to unusual jet stream behaviour and long blocking durations. Comparison of atmospheric state metrics between various events may reveal common behaviours or conditions that are necessary for the realization of the event, perhaps leading to insight into predictions of future events.

Our knowledge of the connection between Arctic changes (albedo decline and methane feedback radiative forcing) to latitudinal temperature gradient decline and global extreme weather events is in very early stages. Any causal linkage needs to be studied and quantified in great detail since it has vital significance to human populations, in view of the rapidity of albedo decline in the Arctic and a possible increasing methane feedback effect on radiative forcing. Preliminary research by Francis et al. in 2012 studied distortions in the jet streams at mid-latitudes in the NH (paper too late to influence IPCC AR5 WG1, 2013 and NRC, 2013 conclusions). Francis et al., 2013a and Overland and Francis, 2012 describe the jet stream waviness perhaps being caused by Arctic amplification warming from sea ice and/or terrestrial snow cover reduction, and suggest an impact on extreme weather events. In Tang et al., 2013a a connection was made between reducing Arctic sea ice and extreme winter weather in mid-latitudes. Subsequently, Tang et al., 2013b linked extreme summer weather in northern mid-latitudes to a vanishing cryosphere (both sea ice and snow cover). Initial theory examining recent NH weather extremes based on quasiresonant amplification of planetary waves was examined by Petoukhov et al., 2012. The mechanistic connections are not well understood; these early papers show links (correlations) but not causality. Potential processes connecting these circulation changes to the overall climate system are considered below.

Air moves from the equator to the Arctic due to the thermodynamic temperature gradient driving force on the rotating frame of reference of the Earth surface. The physics of the circulation system (for example Piexoto and Oort, 1992; Salby et al. 2012) dictates that vorticity (angular momentum) must be conserved, and the vorticity is the sum of the absolute vorticity (for a packet of air on the surface of the earth) and the relative vorticity (arising from the rotation of the earth relative to a fixed distant point). Thus, as the air packet moves poleward it gains speed and becomes concentrated into jet streams which propagate primarily zonally (parallel to the pressure isobars) when stabilized by a balance of the coriolis force and the pressure gradient force. With the rapid albedo decline in the Arctic the smaller equator-to-pole temperature gradient reduces the impetus for heat transfer to the Arctic (since the high Arctic is waming at least 5x more rapidly than the global average). There is less need for heat to advect north via the atmospheric air currents (which results in slower and more meridional jet streams) or in the oceans via the Atlantic Meridional Overturning Circulation (AMOC) which has been observed to have decreasing currents over the last decade as reported by Srokosz et al. in 2012 in the Bulletin of the American Meteorological Society (BAMS). In 2010 there was a sharp decline in AMOC which has not yet been explained; and perhaps is connected to sea ice decline.

Since the zonal component of the jet stream decreases, the physics (Piexoto and Oort, 1992; Salby et al. 2012) necessitates the primarily zonal flow of the westerly jets become wavier (more meridional) and have much larger amplitude. There is always some waviness in this Rossby wave flow however with Arctic amplification the amplitude is increasing and is even reaching regions much farther south than usual. The Rossby wave locations are also determined to a large extent by the land/ocean temperature contrast. Since they are slowing (smaller PGF pressure gradient force) the land/ocean contrast component becomes more dominant and the ridges and troughs of the waves get locked into location by this unchanging land/ocean contrast leading to persistent weather patterns (for example the trough stayed over Pakistan in 2010 leading to 34 days of flooding) while the ridge of this stuck pattern stayed over Russia leading to a month of >30 degrees C temperatures resulting in fires and loss of 40% of grain crops (Coucou, Rahmsdorf, 2013, Decade of weather extremes) (BAMS, 2011).

Basically, the jet streams guide the storms and nature of the weather patterns; as they change they increase the frequency, duration, and magnitude of severe weather events like droughts, floods, derechos, haboobs, etc. People are used to stable and predictable weather and climate, and expect that higher latitude regions are colder than lower latitude regions (which arise from more zonal jet streams, where north of the jet it is cold and dry with air sourced from the Arctic) while south of the jet it is warmer and humid (with air sourced from the equatorial regions). However with the Rossby jets having much larger amplitude that can extend from ridges in the Arctic to troughs down to Florida or Mexico latitudes the weather in a given region can be either of these states depending on one’s location relative to the jet. I use the analogy of a flower with about 5 or 6 petals centered on the Arctic. If you are on the flower or petal you are cold/dry and if you are south of the petal you are hot/humid. And the pedal is slowly rotating about the center axis from west to east. Thus, as the pedal sweeps through and past your location you experience cold/dry to humid/wet back to cold/dry over the space of a week or less.

Another important transport system for heat is the ocean currents. Measurements of AMOC surface water flow across latitude 26.5 degrees in the Atlantic between South America and Africa. (Sroksov, BAMs Nov 2012, AMOC, past, present, and future) give flow rates northward of 18.7 ± 6.7 Sverdrups with seasonal swings. This flow carries about 1.4 PW of heat northward, about 4.2 PW is carried northward by the atmosphere (1/4 to 3/4 partitioning, others claim 1/3 to 2/3). This warm water is mostly carried via the Gulf Stream along the western part of the Atlantic basin and then crosses the Atlantic and reaches Iceland and eastward of Greenland where it has cooled and due to high salinity it decends to feed the NADW north Atlantic deep water flow which heads southward. Since the Arctic region is warming directly, thermodynamics lowers heat transport northward from the equator via both the atmosphere and oceans. AMOC flow data from Sroksov et al. in 2012 show AMOC flow actually reached zero, and appeared to even reverse in 2010/2011. A rapidly changing AMOC has global implications (Broecker, 2010) and in the past has been a trigger for abrupt climate change.

I also hypothesize that the decline in Arctic albedo results in Southern Hemisphere (SH) changes. The latest CMIP5 models from IPCC AR5 WG1, 2013 all predict that Antarctica sea ice should be declining and thus cannot explain why the sea ice is growing at an average rate of 1.5%/decade. The equator gets much more solar insolation on average than the poles, and is of course hotter. Due to the first law of thermodynamics, this heat wants to move to the poles, and it does so by the fluid motion of both the atmosphere and the oceans. Since the oceans have much higher density they transfer the heat much more slowly than the atmosphere. It is estimated that about 25% to 33% of the heat transported polewards is by the oceans with the majority transferred by the atmosphere. With less heat moving northwards (smaller temperature gradient force) there is additional warming at the equator and more heat is thus transported southward via the ocean currents and the atmospheric circulation (note that most heat is transferred meridionally via eddy vortices, both in the atmosphere and ocean; direction of vortices is ccw in the northern hemisphere and cw in the southern due to Coriolis deflection. The poleward region of the vortex carries heat poleward, while the southward region of the closed loop vortex carries cold air or water equatorward (which transfers heat poleward)). Thus the Arctic temperature amplification is causing more heat to move southward, resulting in heatwaves and extremes in South America and Australia. The Antarctica circumpolar current (ACC) that circles the globe unimpeded by land masses and the southern annular mode (SAM) atmospheric circulation are both strengthened by the increased temperature gradient and block the majority of this heat from reaching Antarctica (with the exception of the Antarctica Peninsula, and regions reached by meridional jet stream excursions) and therefore leads to surface cooling and increased coastal calving and thus annual increases in the Antarctica sea ice. With a stronger temperature gradient in the ACC region, the SAM can increase and contribute to the surface cooling. Since warm ocean currents reach the WAIS region and undercut the ice sheet from below as it is grounded on bedrock well below sea level, the GRACE satellite continues to measure increasing total mass loss from the ice sheet. Also, satellite data shows methane emissions from the continent are increasing, indicating there may be warm ocean thawing of marine sediments. This global heat redistribution that occurs when the Arctic amplification of temperature from increased solar absorption occurs can also be used to explain the bipolar seesaw behaviour that is observed in the paleorecords.

Intensity of storm events has increased greatly likely due to a 4% rise in atmospheric water vapor as compared to 30 years ago (Coumou et al., 2012; Hansen et al., 2013). The distribution of this water vapor and increased frequency of phenomena such as atmospheric rivers is also important to examine. Higher resolution and more sensitive remote sensing of atmospheric water vapor transport from equatorial regions with very large evaporative forcing to poleward regions of much lower humidity (humidity gradient forcing) has recently determined that the transport of water vapor is not uniform at all over space. Most of the water vapor is transported poleward in relatively localized regions of high filamentation, thus their description as “atmospheric rivers”. The Pineapple Express that carries large volumes of water vapor sourced near Hawaii across the Pacific to the California coast is an “atmospheric river” (Dettinger, 2011). Usually there are around ten such events per year; when the “river” reaches California it is forced upward and results in torrential rainfall with rainfall rates of 30 cm or higher within a few days. Such an event lasted for 3 days in early December, 2012. A well documented “atmospheric river” event in 1861 (Dettinger and Ingram, 2013) lasted 41 days; enormous quantities of water vapor went clear across the entire Pacific Ocean and inundated California enough to cause the formation of a lake in the central lowland area that spanned 400 miles long by 20 miles wide with over 3 meters of depth (submerging the city of Sacramento). This is not a one-time event, the sediment records in the region indicate that it is a phenomenon that occurs once every 150 or 200 years over the last several thousand years. It is also important to examine whether or not the 4% increase of water vapor and the changing nature of the jet streams will increase the probability of such occurences. These atmospheric rivers are related to sudden stratospheric warming events (SSW). Observations in January, 2013 show that such a “river” was forced upward over the Tibetan Plateau and continued into the stratosphere and travelled to the Arctic where it descended and severed the polar vortex creating a large reduction in the Arctic Oscillation (AO) and subsequent change in NH circulation and temperature patterns. The thesis emphasis is on the overall climate system changes, and thus when there are major changes in the Arctic region sea ice and snow cover resulting in possible methane feedbacks and changing global weather patterns leading to changes in Antarctica.

Tipping elements of the global climate system

In a review paper by Lenton et al., 2008 the tipping elements in the climate system were examined. A more recent review of the many tipping point elements located in the Arctic region is summarized by Duarte et al., 2012. These include Arctic sea ice, terrestrial snow cover, Greenland ice sheet, North Atlantic deep-water formation regions (for AMOC cycle), boreal forests, terrestrial permafrost, and marine permafrost and methane hydrates. This Lenton review paper used a panel of “climate experts” to assess risks of occurrence and resulting effects of occurrence for various magnitude tipping events and assessed risks and timescales of the possible occurrences. Table 1 summarizes their basic scope and determinations.

Table 1. Policy-relevant potential future tipping elements in the climate system and (below the empty line) candidates that we considered but failed to make the short list[*]

Tipping element	Feature of system, F (direction of change)	Control parameter(s), ρ	Critical value(s),[†] ρ_{crit}	Global warming[†,‡]	Transition timescale,[†] T	Key impacts
Arctic summer sea-ice	Areal extent (−)	Local ΔT_{air}, ocean heat transport	Unidentified[§]	+0.5–2°C	~10 yr (rapid)	Amplified warming, ecosystem change
Greenland ice sheet (GIS)	Ice volume (−)	Local ΔT_{air}	+~3°C	+1–2°C	>300 yr (slow)	Sea level +2–7 m
West Antarctic ice sheet (WAIS)	Ice volume (−)	Local ΔT_{air}, or less ΔT_{ocean}	+~5–8°C	+3–5°C	>300 yr (slow)	Sea level +5 m
Atlantic thermohaline circulation (THC)	Overturning (−)	Freshwater input to N Atlantic	+0.1–0.5 Sv	+3–5°C	~100 yr (gradual)	Regional cooling, sea level, ITCZ shift
El Niño–Southern Oscillation (ENSO)	Amplitude (+)	Thermocline depth, sharpness in EEP	Unidentified[§]	+3–6°C	~100 yr (gradual)	Drought in SE Asia and elsewhere
Indian summer monsoon (ISM)	Rainfall (−)	Planetary albedo over India	0.5	N/A	~1 yr (rapid)	Drought, decreased carrying capacity
Sahara/Sahel and West African monsoon (WAM)	Vegetation fraction (+)	Precipitation	100 mm/yr	+3–5°C	~10 yr (rapid)	Increased carrying capacity
Amazon rainforest	Tree fraction (−)	Precipitation, dry season length	1,100 mm/yr	+3–4°C	~50 yr (gradual)	Biodiversity loss, decreased rainfall
Boreal forest	Tree fraction (−)	Local ΔT_{air}	+~7°C	+3–5°C	~50 yr (gradual)	Biome switch
Antarctic Bottom Water (AABW)[*]	Formation (−)	Precipitation–Evaporation	+100 mm/yr	Unclear[¶]	~100 yr (gradual)	Ocean circulation, carbon storage
Tundra[*]	Tree fraction (+)	Growing degree days above zero	Missing[‖]	—	~100 yr (gradual)	Amplified warming, biome switch
Permafrost[*]	Volume (−)	$\Delta T_{permafrost}$	Missing[‖]	—	<100 yr (gradual)	CH_4 and CO_2 release
Marine methane hydrates[*]	Hydrate volume (−)	$\Delta T_{sediment}$	Unidentified[§]	Unclear[¶]	10^3 to 10^5 yr ($>T_E$)	Amplified global warming
Ocean anoxia[*]	Ocean anoxia (+)	Phosphorus input to ocean	+~20%	Unclear[¶]	~10^4 yr ($>T_E$)	Marine mass extinction
Arctic ozone[*]	Column depth (−)	Polar stratospheric cloud formation	195 K	Unclear[¶]	<1 yr (rapid)	Increased UV at surface

N, North; ITCZ, Inter-tropical Convergence Zone; EEP, East Equatorial Pacific; SE, Southeast.
[*]See *SI Appendix 2* for more details about the tipping elements that failed to make the short list.
[†]Numbers given are preliminary and derive from assessments by the experts at the workshop, aggregation of their opinions at the workshop, and review of the literature.
[‡]Global mean temperature change above present (1980–1999) that corresponds to critical value of control, where this can be meaningfully related to global temperature.
[§]Meaning theory, model results, or paleo-data suggest the existence of a critical threshold but a numerical value is lacking in the literature.
[¶]Meaning either a corresponding global warming range is not established or global warming is not the only or the dominant forcing.
[‖]Meaning no subcontinental scale critical threshold could be identified, even though a local geographical threshold may exist.

There have been many advances in the understanding of these tipping elements since this paper was published. For example, rates of change have increased greatly for Arctic summer sea-ice decline as well as for Greenland and Antartica ice loss rates, the latter two being accurately measured from GRACE satellite data. There have also been changes in the THC (more commonly referred to as the AMOC (Atlantic Meridional Oceanic Circulation) and in the ISM (Indian Summer Monsoon), as detailed in IPCC AR5, 2013. The Amazon rainforest had a severe drought in 2005 (Marengo et al., 2008), and another that was even worse in 2010 (Lewis et al., 2011), with the death of billions of trees and severe stress to many others, and became a carbon source instead of sink in those 2 droughts. Boreal forests are being subject to increasing occurrence of fires resulting from drought induced stress and increased risk of infestations, most notably from the pine beetle (Simard et al., 2011). Tundra and marine sediment methane (and CO_2) emissions have been increasing in the Arctic (Papers 1 and 2) and ocean oxygen levels are continuing to drop from increasing stratification of surface layers due to warmer SSTs and ocean acidification (Stramma et al., 2010). The Arctic ozone had a major ozone hole in 2011 for the first time (Manney et al., 2011), supporting the inclusion of this tipping element in the Lenton et al., 2008 paper. Missing from this table are Arctic snow cover decline (Liu et al., 2012), as well as atmospheric circulation (and jet stream) changes in waviness and blocking frequencies (Francis et al., 2012; Overland et al., 2012) leading to changes in storm tracks and cyclone behavior. In the NRC, 2013 assessment report on abrupt climate impacts there is an update on a number of the tipping elements from the Lenton et al., 2008 paper. As mentioned previously, the probability of large methane emissions from the Arctic is said to be low, and the probability of a WAIS (West Antarctic Ice Sheet) partial or full collapse leading to rapid global mean sea level rise by 3 to 4 m is assessed to be higher than previously thought. While there have been significant increases in knowledge on the individual elements since the 2008 study, there has been little connection between elements or reassessment of how close they may be to tipping points, and how susceptible they may be to cascading effects should one element pass a tipping threshold.

The element at highest risk of tipping is most certainly Arctic sea ice; the PIOMAS volume extrapolation trends to zero ice at the end of the melt season before the end of this decade. Next at risk may be the Amazon rainforest tipping over in a rapid transition from rainforest into savannah or shrublands via extreme drought and subsequent massive fire destruction. Greenland is another very important high-risk tipping element of the system with water storage in on-land glaciers having the capacity to raise global sea levels 7 meters. With Arctic sea ice strongly declining, a cascading effect can greatly increase the risk of Greenland calving acceleration and collapse. Another weak point is the West Antarctic Ice Sheet which is melting from below by increasing ocean water temperatures. Ocean acidity is another, having increased by 30 % to 40 % in the last few decades.

Global summary

In summary, there are many signs that we are presently undergoing an abrupt climate change, at least for some elements of the climate system like the Arctic region. Greenhouse gas levels have gone up enough to melt significant areas of the Arctic sea ice and snow cover and greatly reduce the albedo there enough to cause significant Arctic amplification of temperatures compared to the global mean temperature rise. This in turn has reduced the equator-to-north-pole temperature gradient reducing the amount of heat transport northward from the equator in the atmospheric circulation and ocean circulation patterns. This then leads to a slower and wavier jet stream, and combined with the elevated water vapor content of the atmosphere is leading to extreme weather events, most notably to torrential downpours and persistant regional droughts (i.e. California, New Zealand, Australia). The Arctic amplification is also leading to increasing amounts of methane emissions in the north, contributing to rising global methane levels and higher regional forcing in the Arctic further amplifying the warming. As the albedo continues to decrease in the next few years, it is expected that the frequency, intensity, duration, and spatial extent of the extreme weather events will continue to increase, with subsequent threats to human well being, the global food supply, and infrastructure, causing great economic hardship. System stability can no longer be taken for granted.

The key point is that Global Circulation Models (GCMs) for climate that are incorporated into the IPCC studies do not account properly for the rapid decrease in Arctic albedo (from sea ice and snow cover declines and Greenland darkening) and subsequent increase in Arctic temperature amplification, the decreased latitudinal temperature gradient, and the increased fracturing and waviness of the jet streams causing more extreme weather events. These models also assume that methane emissions to the atmosphere will not rise significantly this century.

Local Lake Winnipeg Effects

It is clear that large changes in the global climate system will affect regional climates around the planet. Details of the specific changes in any given region can be very challenging to predict, although there are a number of general conclusions that can be made.

1) Climate history (temperature and precipitation timeseries), over the last century in the Lake Winnipeg basin (historic normal and trends) are often used as a basis to extrapolate expected future changes. This method can be prone to very large errors and uncertainties since the global climate changes discussed have essentially changed the statistics of climate and thus weather events.

2) Variability has increased across most timescales including decadal, year-to-year and even seasonal, monthly and weekly timescales. The term “weather whiplashing” applies. For example, the Mississippi River in the U.S. experienced record flood levels one year, record low water levels the next year, and then record flood levels again the following year. A particular city can experience record high temperatures one week, record low temperatures the next week, and swing back to record high temperatures the subsequent week. The risk of this “whiplashing” is dependent on the regions location relative to the jet stream wave locations.

3) Climate projections for the local Lake Winnipeg region are based on “downscaling” the Global Circulation Models to the specific region. This makes perfect sense when the GCMs closely mirror the reality of a slowly varying, linear climate system. However it can be very risky to rely on these models when we are experiencing the rapid changes in the climate system that have been described earlier.

4) The Lake Winnipeg Watershed hydroclimate studies assess lake levels and streamflows and water temperatures based on data from the last century as well as projections from the regional models. With much greater variability due to global climate system changes, these studies are expected to be much less accurate.

5) Since climate statistics have changed, probabilities that are based on a stable climate, namely the risks of “one-in-a-hundred” or “one-in-a-thousand” events need to be carefully evaluated since they may no longer be valid. In this case, more weighting on recent behaviour over the nearest decade may lead to better risk assessment.

6) Lake temperature will become very important during heat waves with extended droughts. Annual evaporation will remove much more than 20% of the inflow, the lake volume will decrease and there will be much greater risk of eutrophication and

blue-green algae blooms, similar to what occurred on the west shore of Lake Erie in summer/2014.

7) It is difficult to know if the annual mean discharge increase in the watershed of 58% from 1924 to 2003 will maintain this trend. Given the recent abrupt changes in the global climate system it is very important to examine and weight the most recent data higher.

8) The decrease in the mean discharge of the Saskatchewan River needs to be studied carefully since many glacially fed rivers are drying up due to rapidly declining snowpacks in the mountains. For example, Sierra Nevada snowpack in California is only at 6% of normal capacity this year. Steadily rising temperature trends at mountain elevations are causing the rapid decline of glaciers, as well as a 20% decline in spring snow cover throughout the Rockies in the U.S. since 1980 (Pederson et al., 2013). The Peyto glacier which helps feed the Mistaya and North Saskatchewan Rivers has lost about 70% of ice mass. Glaciers in the Rocky Mountains supply the majority of the stream flow used in Alberta, Saskatchewan, and Manitoba. Also, runoff from snowpack supplies between 60 to 80% of annual water supplies to 70 million people in the American West (USGS, see article: http://e360.yale.edu/feature/loss_of_snowpack_and_glaciers_in_rockies_poses_water_threat/2785/) The glacier covered regions in the South and North Saskatchewan River Basins in Alberta have declined in area by 37% and 22% respectively since 1975 (Pomeroy, 2014, in link above). In the short term water glacially sourced water flows can temporaily increase during a “last gasp” of the glacier. Water access rights for one unit of water input into the Saskatchewan River in Alberta allow Alberta 50%, Saskatchewan 50% of the remainder (25% of input), and Manitoba the remainder (25% of input)). These ratios were determined under drought conditions and useage may need to be reevaluated. This reduction of high elevation glacier water storage is a risk to people around the planet, notably in the Himilayas, Andes and Rockies among others.

9) Climate normals from the thirty year period 1981 to 2010 are used in the analysis of climatic characteristics of the local Lake Winnipeg basin. Since most of the rapid changes in the global climate system have occurred in the time period from 2000 to present, it makes sense to also analyze climate based on the older 1971 to 2000 climate normals.

10) The Lake Winnipeg Basin in Manitoba has been experiencing a “wet cycle” for the last 15 years or so. There is no expectation that this will continue as the global climate system changes accelerate. Many climate models (noted previously to underestimate the rate of change) project increased global aridity in the 21st century over much of the planet (most of Africa, the Americas, Australia, Southeast Asia, southern Europe and the Middle East). It seems clear that variability between exceptional drought and severe flooding will increase in many regions. An excellent

review paper on drought under global warming (climate change) contains many details (Dai, 2010).

Figures

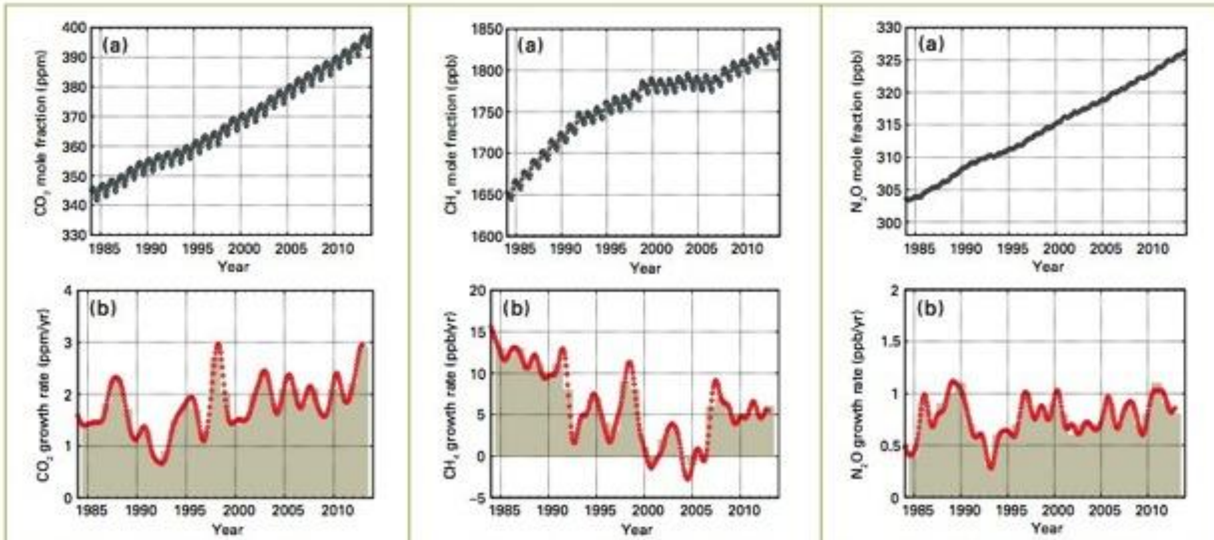

Figure 3. Globally averaged CO_2 mole fraction (a) and its growth rate (b) from 1984 to 2013. Differences in successive annual means are shown as shaded columns in (b).

Figure 4. Globally averaged CH_4 mole fraction (a) and its growth rate (b) from 1984 to 2013. Differences in successive annual means are shown as shaded columns in (b).

Figure 5. Globally averaged N_2O mole fraction (a) and its growth rate (b) from 1984 to 2013. Differences in successive annual means are shown as shaded columns in (b).

Source: WNO Greenhouse Gas Bulletin, 9 September 2014.

Figure 1: (a) Atmospheric carbon dioxide, methane and nitrous oxide concentrations and (b) growth rates (slopes). https://mogreenstats.files.wordpress.com/2015/01/ghg-levels-over-time.jpg

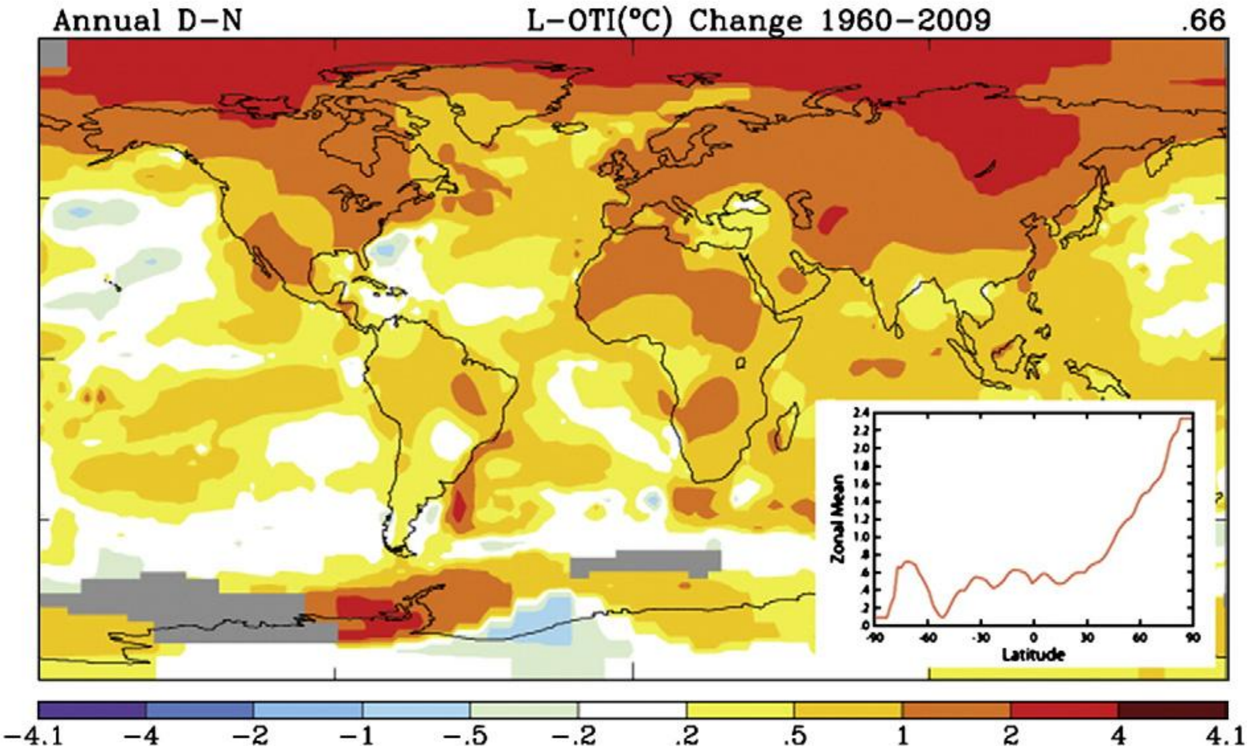

Figure 2: Mean surface air temperature change (°C). Inset shows zonal (west to east around Earth) average versus latitude. High Arctic warming (+2.4 °C) is 2.4/0.66 = 3.64 times global average increase of 0.66 °C. (Serreze MC, Barry RG (2011) Processes and impacts of Arctic Amplification: A research synthesis. *Global and Planetary Change*, 77, 85-96.)

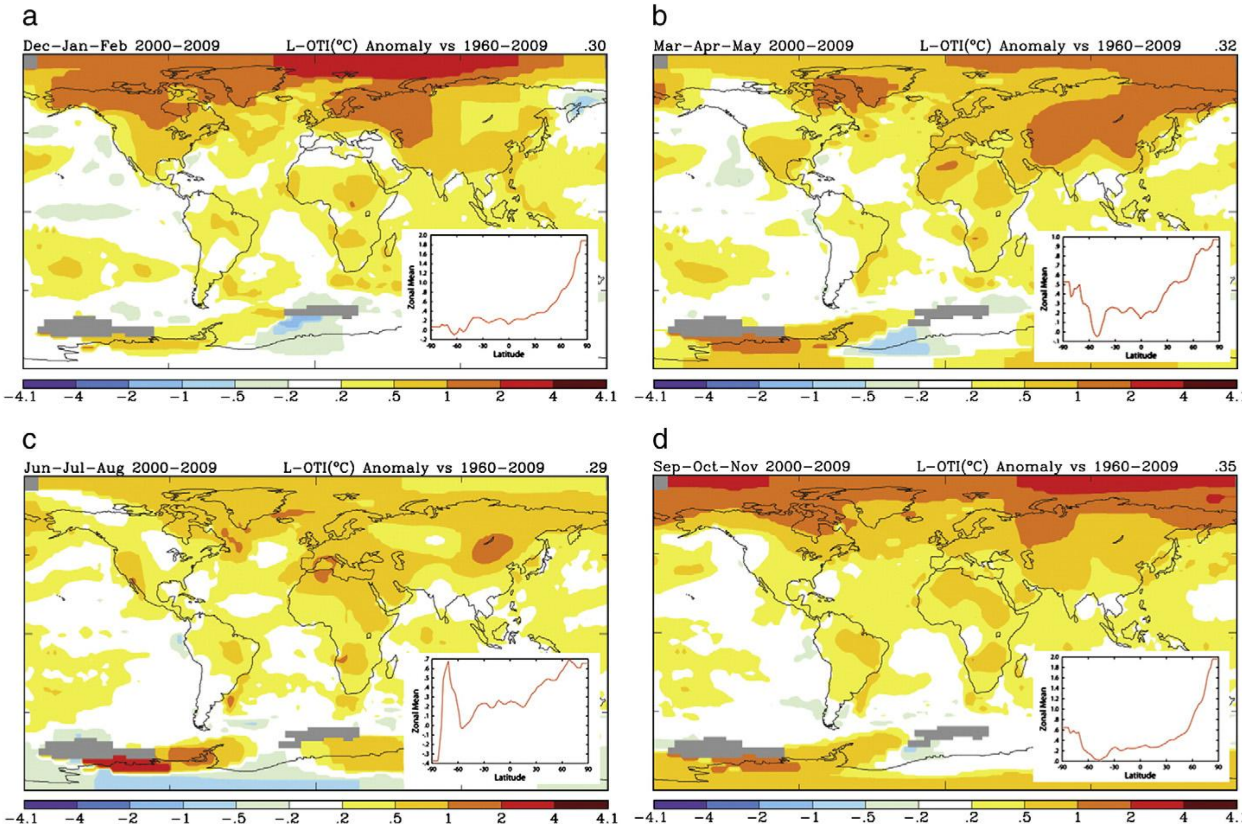

Figure 3: Seasonal variation of mean surface air temperature change (^{o}C). Inset shows zonal (west to east around Earth) average versus latitude. High Arctic warming is 6.33x, 2.97x, 2.24x and 5.71x global average increase for winter, spring, summer and fall, respectively. (Serreze MC, Barry RG (2011) Processes and impacts of Arctic Amplification: A research synthesis. *Global and Planetary Change*, 77, 85-96.)

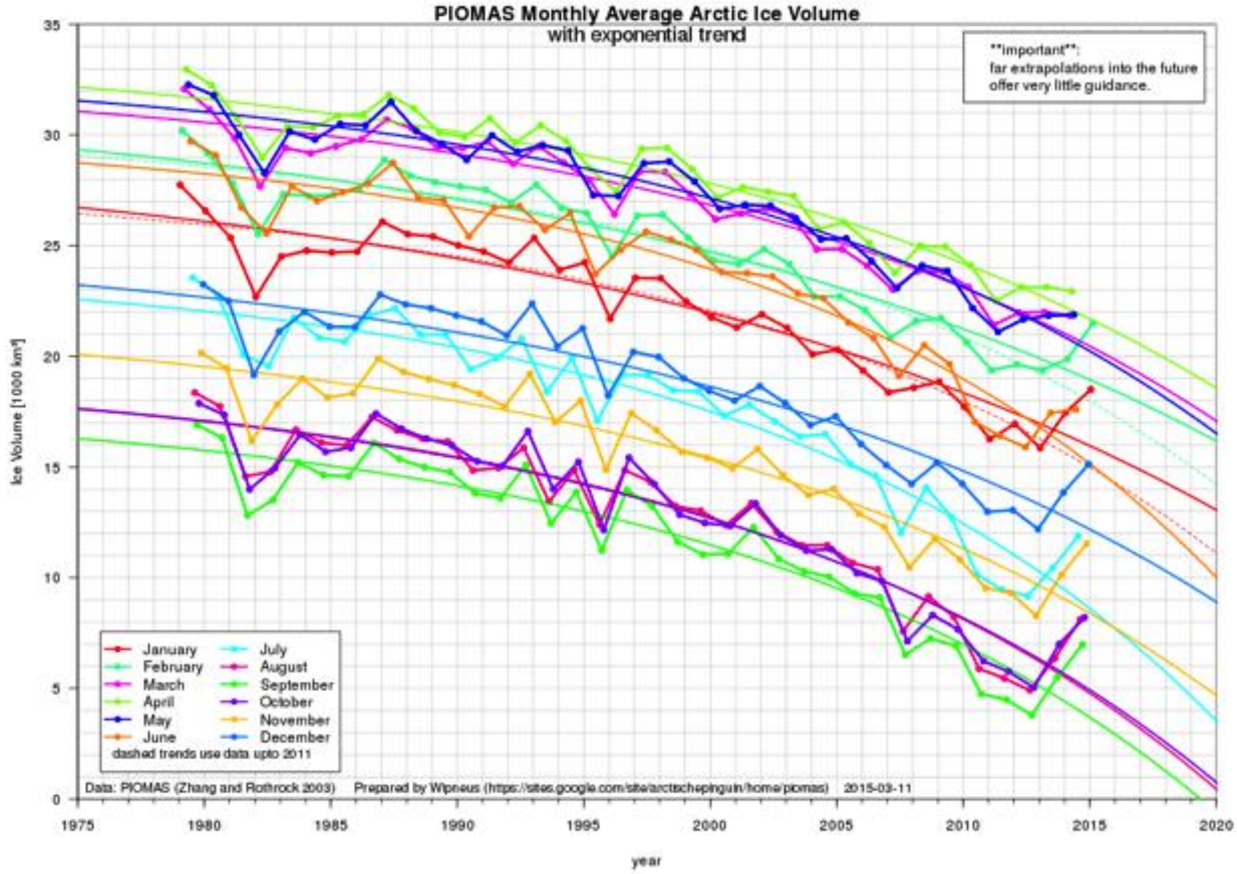

Figure 4: Monthly average Arctic ice volume with exponential trend lines. https://sites.google.com/site/arctischepinguin/home/piomas/grf/piomas-trnd2.png

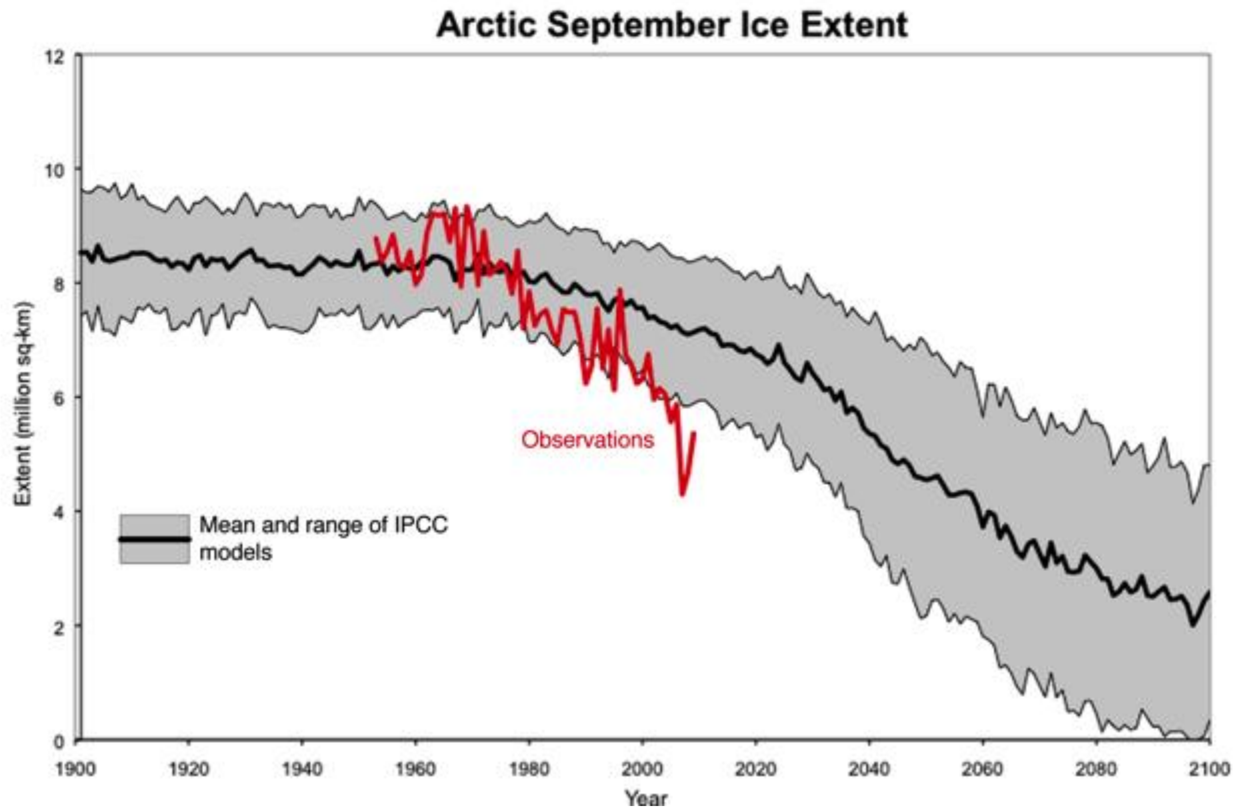

Figure 5: Arctic September sea ice extent observations versus mean and range of IPCC climate models. http://nsidc.org/icelights/files/2011/02/Decline_chart.png

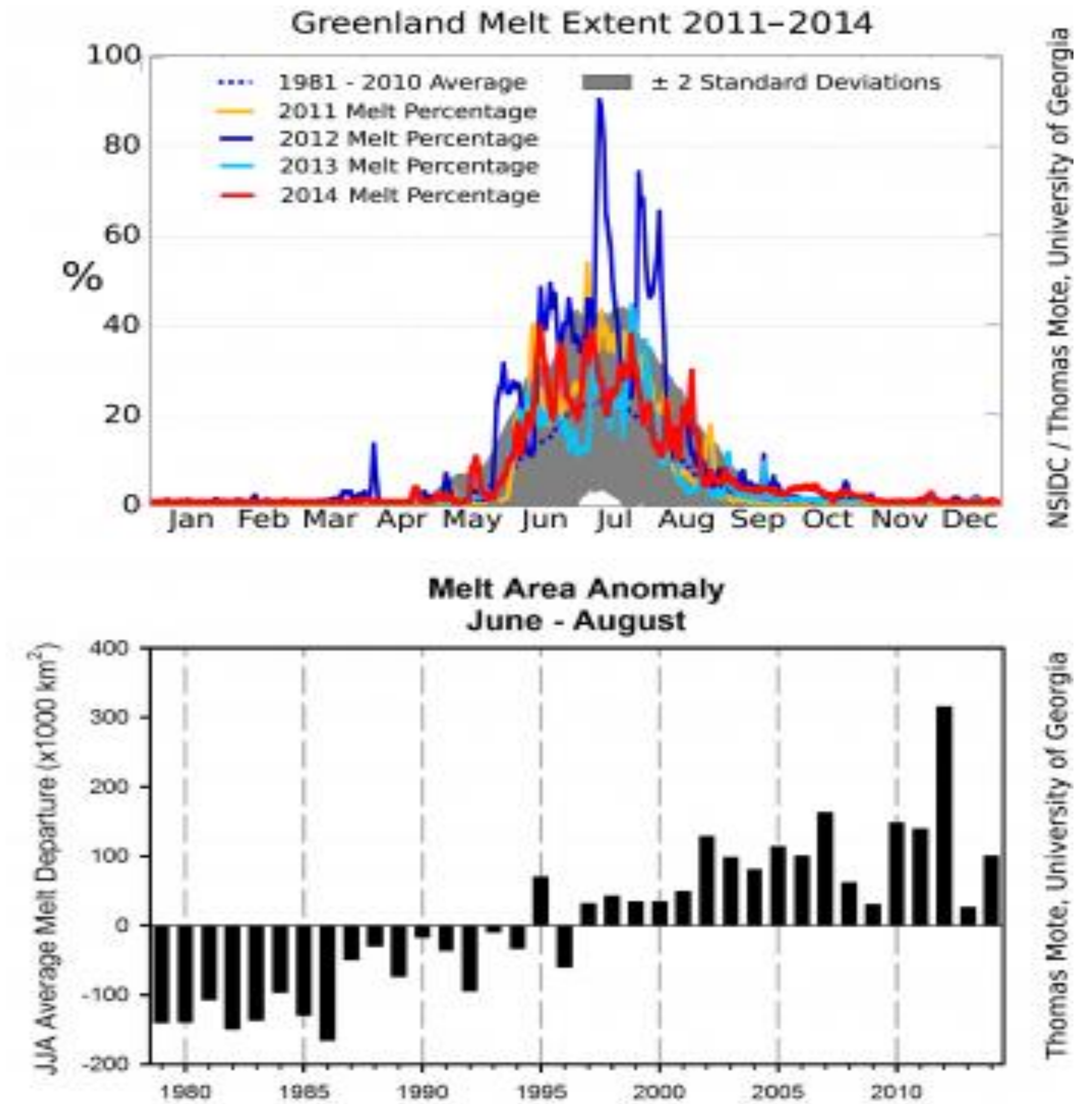

Figure 6: Fraction of ice sheet surface on Greenland subject to melting (albedo is lower in these regions) http://www.arctic.noaa.gov/reportcard/images-essays/fig3.1d-tedesco.png

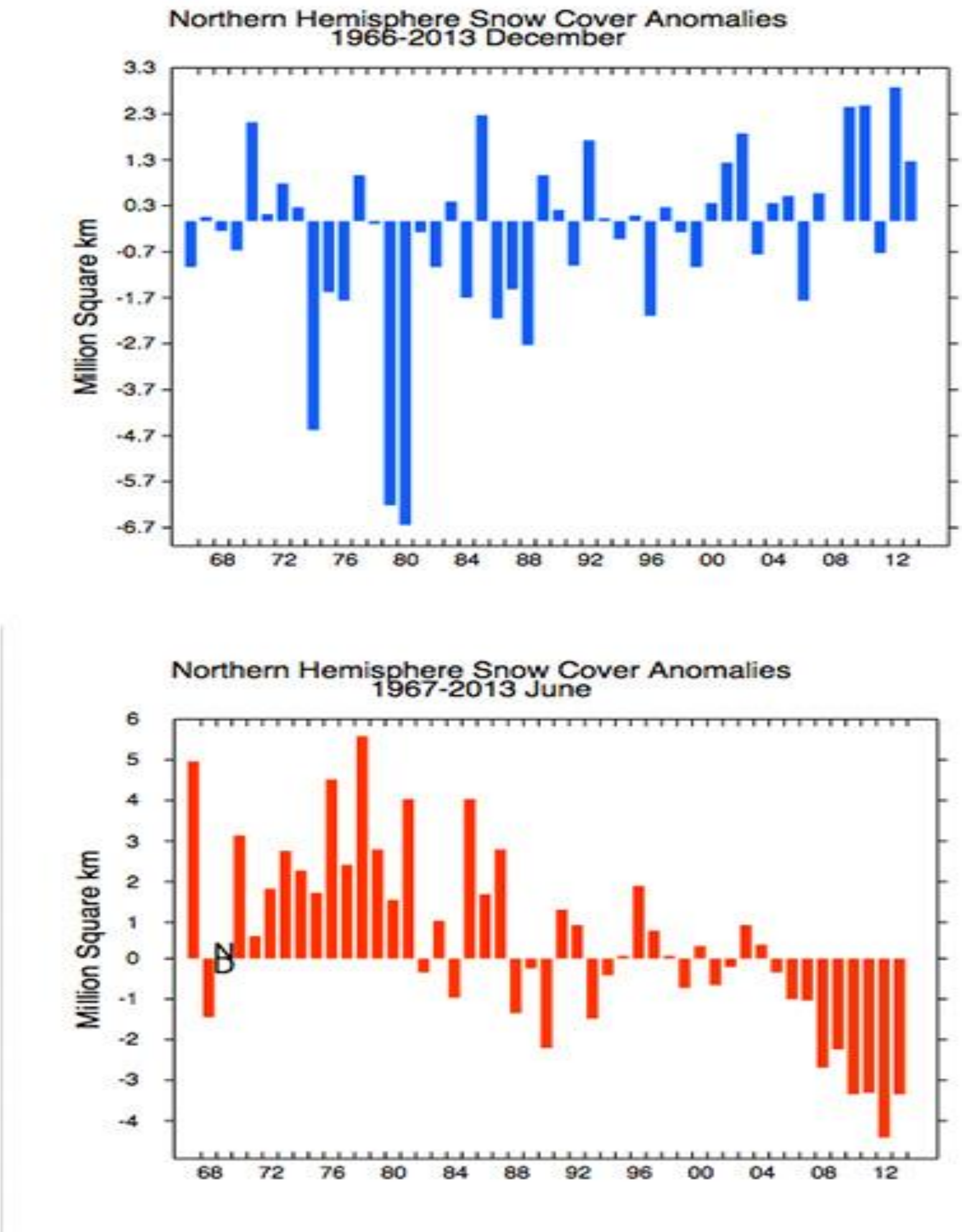

Figure 7: December and June Northern Hemisphere snow cover anomalies. https://www2.ucar.edu/atmosnews/perspective/11278/spring-snow-goes-downhill

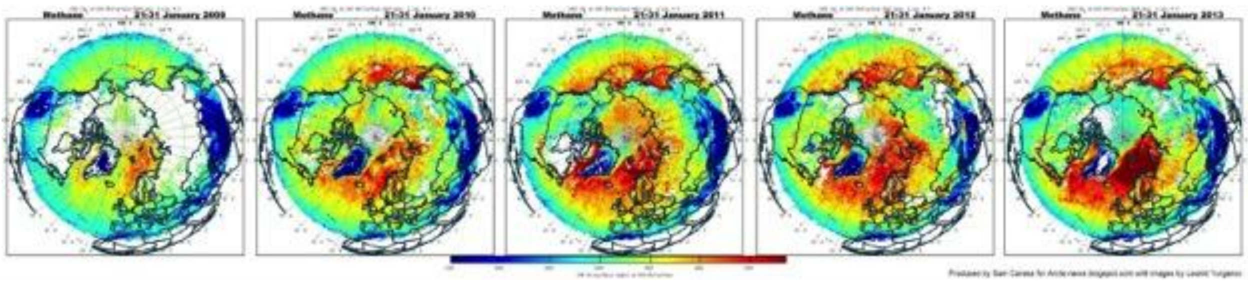

Figure 8: Methane levels over 5 years in the Arctic showing a large increase in open water regions near the sea ice. https://robertscribbler.files.wordpress.com/2015/03/methane-jan21-31.jpg

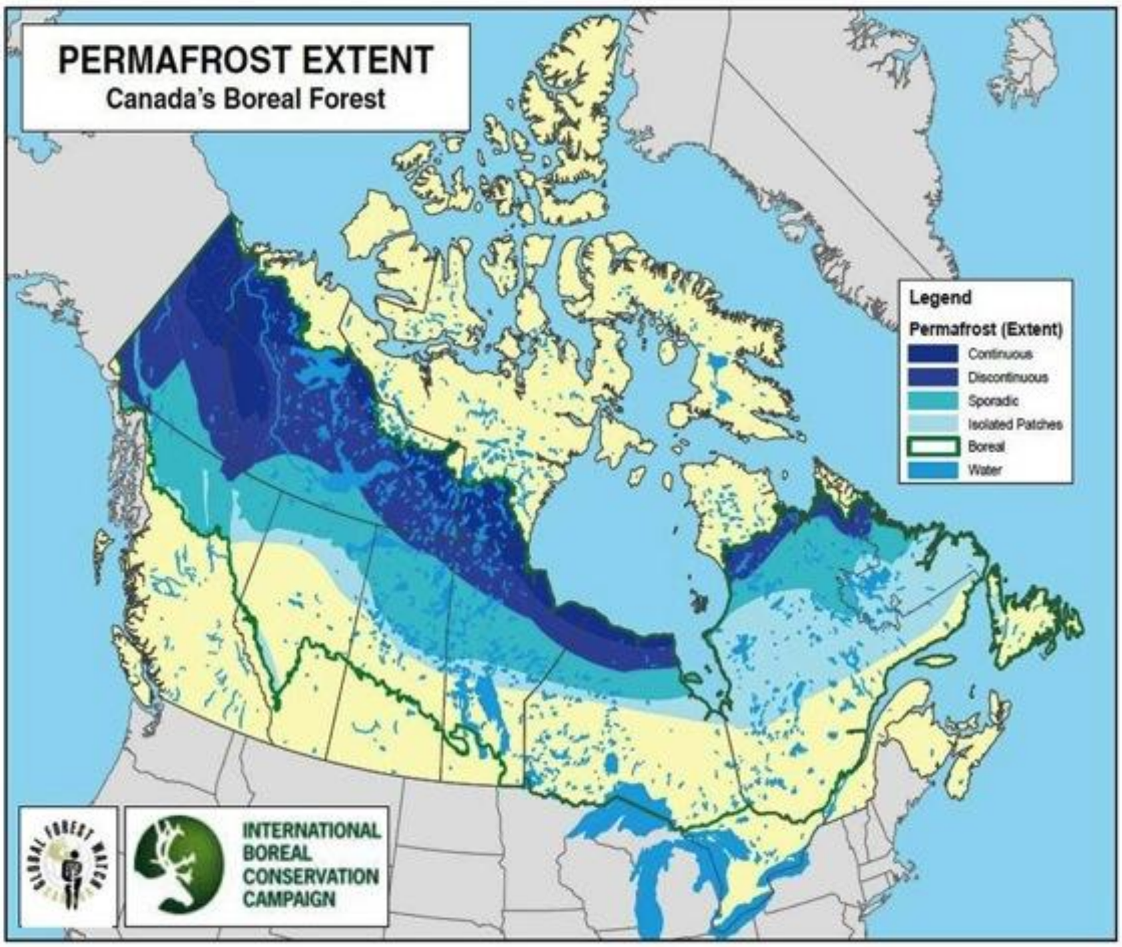

Figure 9: Permafrost map of Canada, showing “isolated patches of permafrost” extending down to northern Lake Winnipeg.
http://www.bing.com/images/search?q=canada+permafrost+map&id=BE72DD192108BF622FC43DCE8C362A44A42F68A0&FORM=IQFRBA#view=detail&id=6DF87AC241B6F514638D35789563E2007F1C9BE8&selectedIndex=14

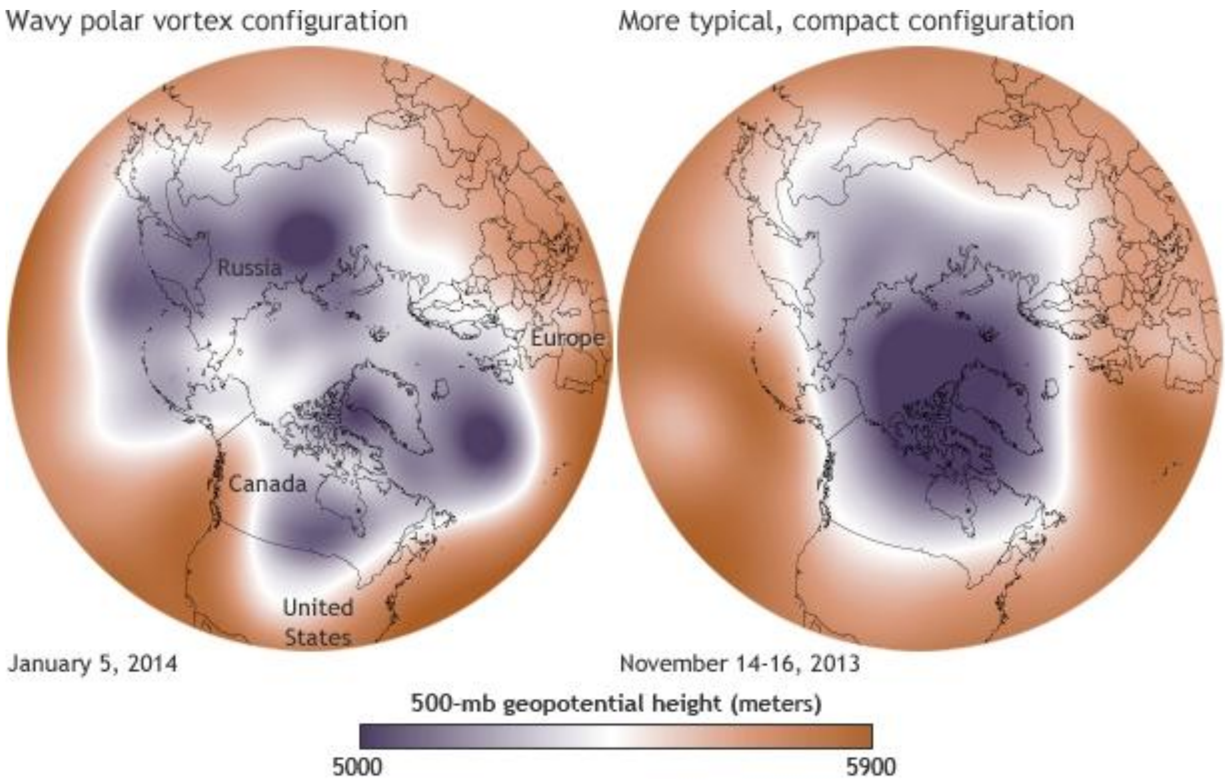

Figure 10: Downward looking view on Arctic, showing "normal" and "wavy" jet stream configurations. Purple areas are cold and brown areas are warmer. Jet streams are the white border lines between the cold and warm air masses. http://www.climate.gov/sites/default/files/styles/inline_all/public/Jan5_Nov14-16_500mb_geopotentialheight_mean_620.jpg?itok=zdAE3xoi

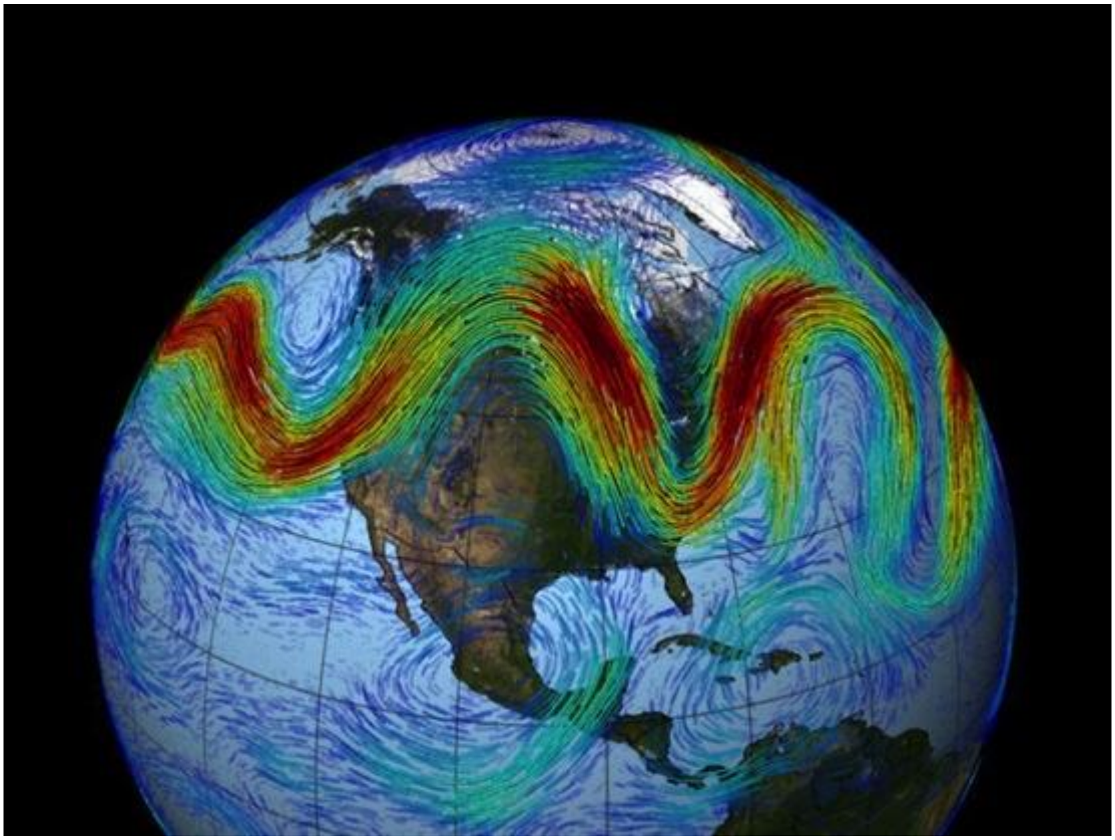

Figure 11: Side view of exceptionally wavy jet stream.
https://eos.org/wp-content/uploads/2015/02/GL060764_Hassanzadeh_cropped_web-800x600.jpg

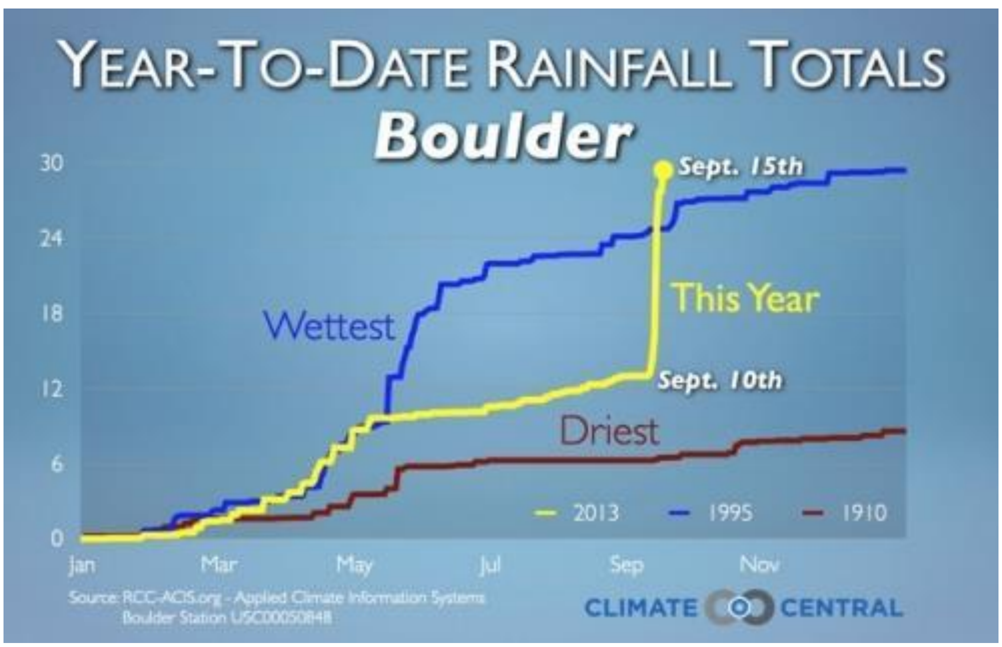

Figure 12: Example of weather whiplashing for precipitation.
http://apps.startribune.com/blogs/user_images/pauldouglas_1379366816_boulderstats.jpg

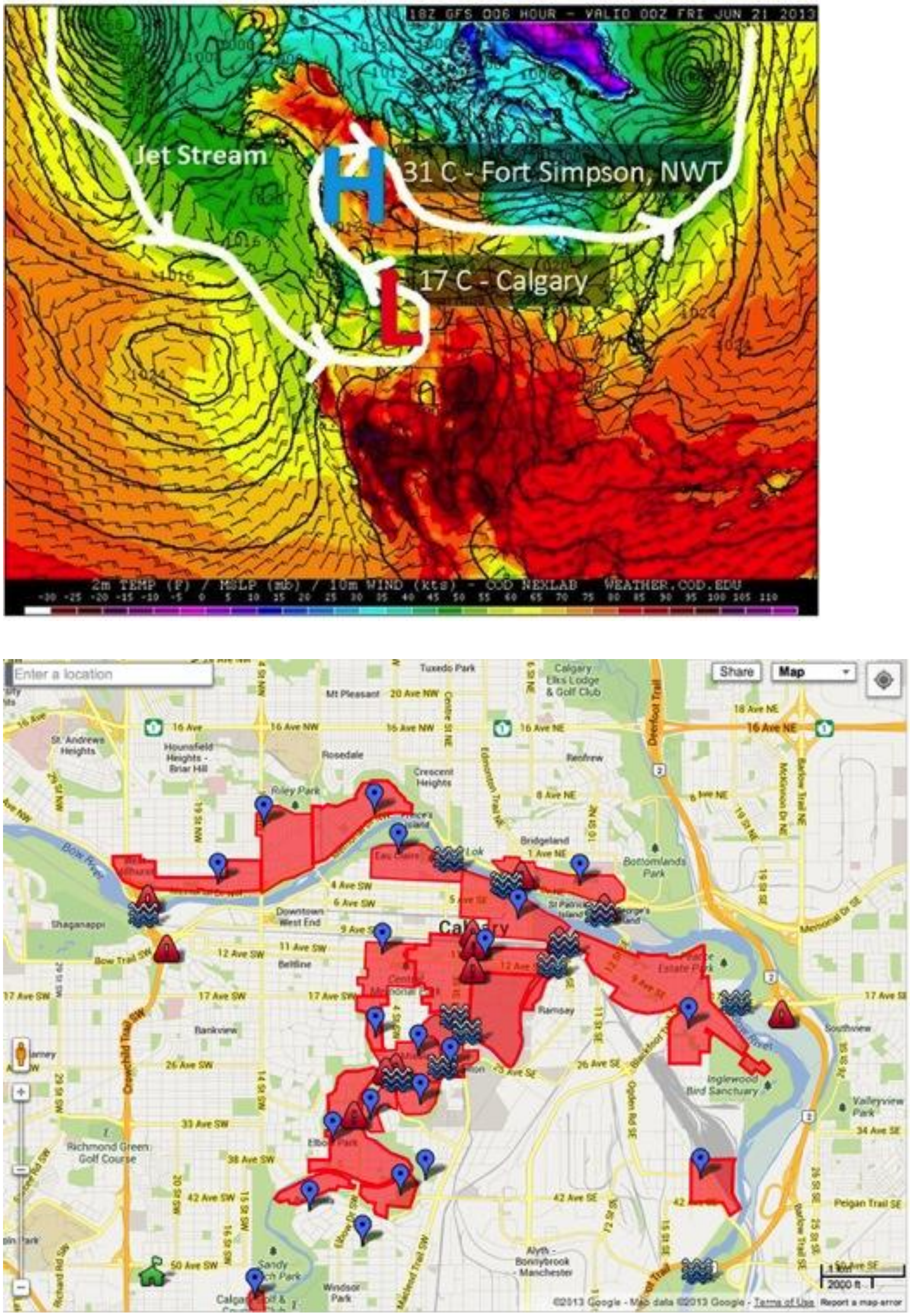

Figure 13: Upper: Jet stream configuration near Calgary during record flood of June, 2013 with insured costs exceeding $6 Billion; Lower: flooded regions of Calgary http://media.twnmm.com/storage/11698939/15

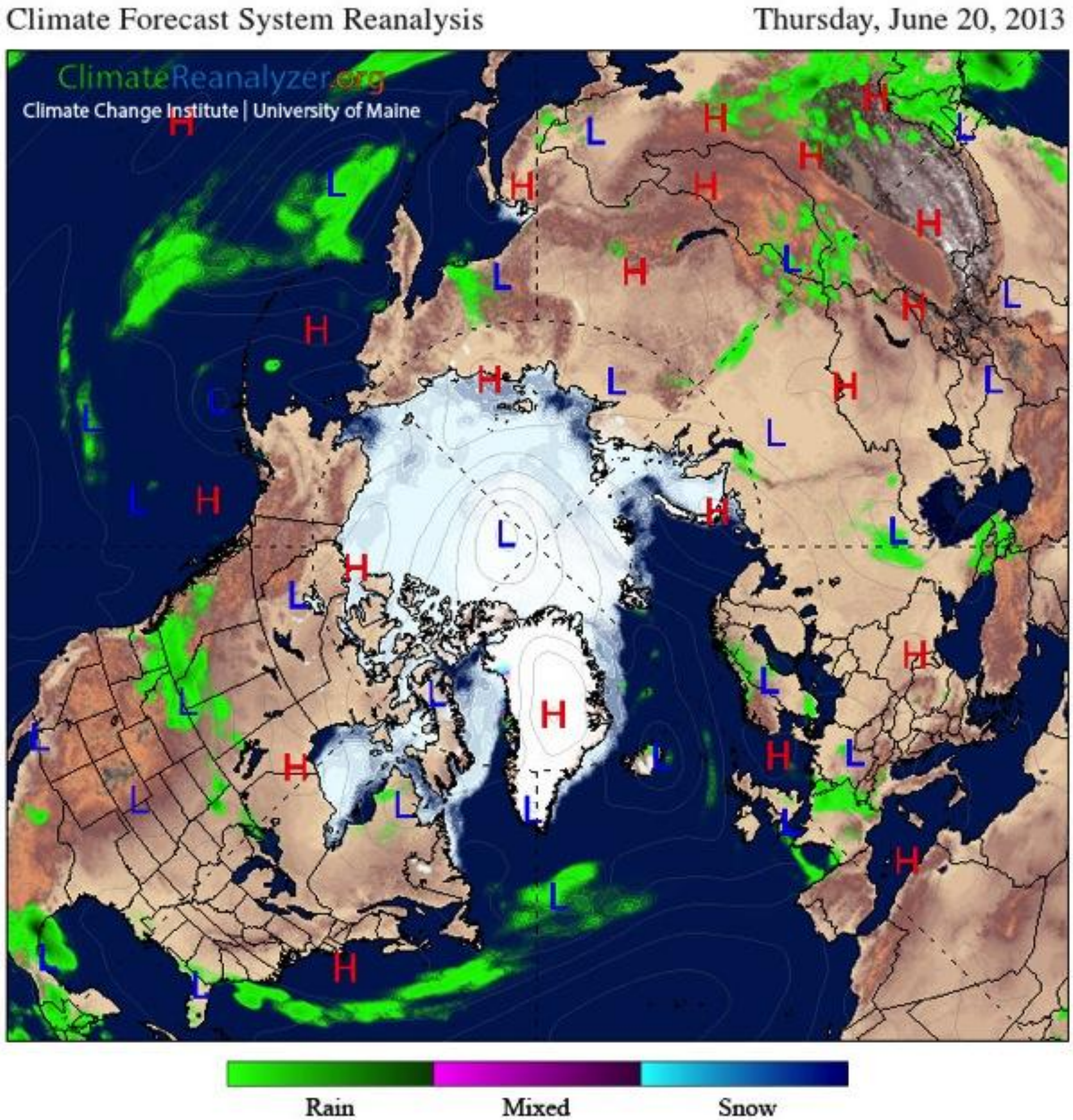

Figure 14: Intense rainfall-on-snow event over high elevation regions (near Banff) west of Calgary during record flood of June, 2013 from Climate Reanalyzer (in web link list).

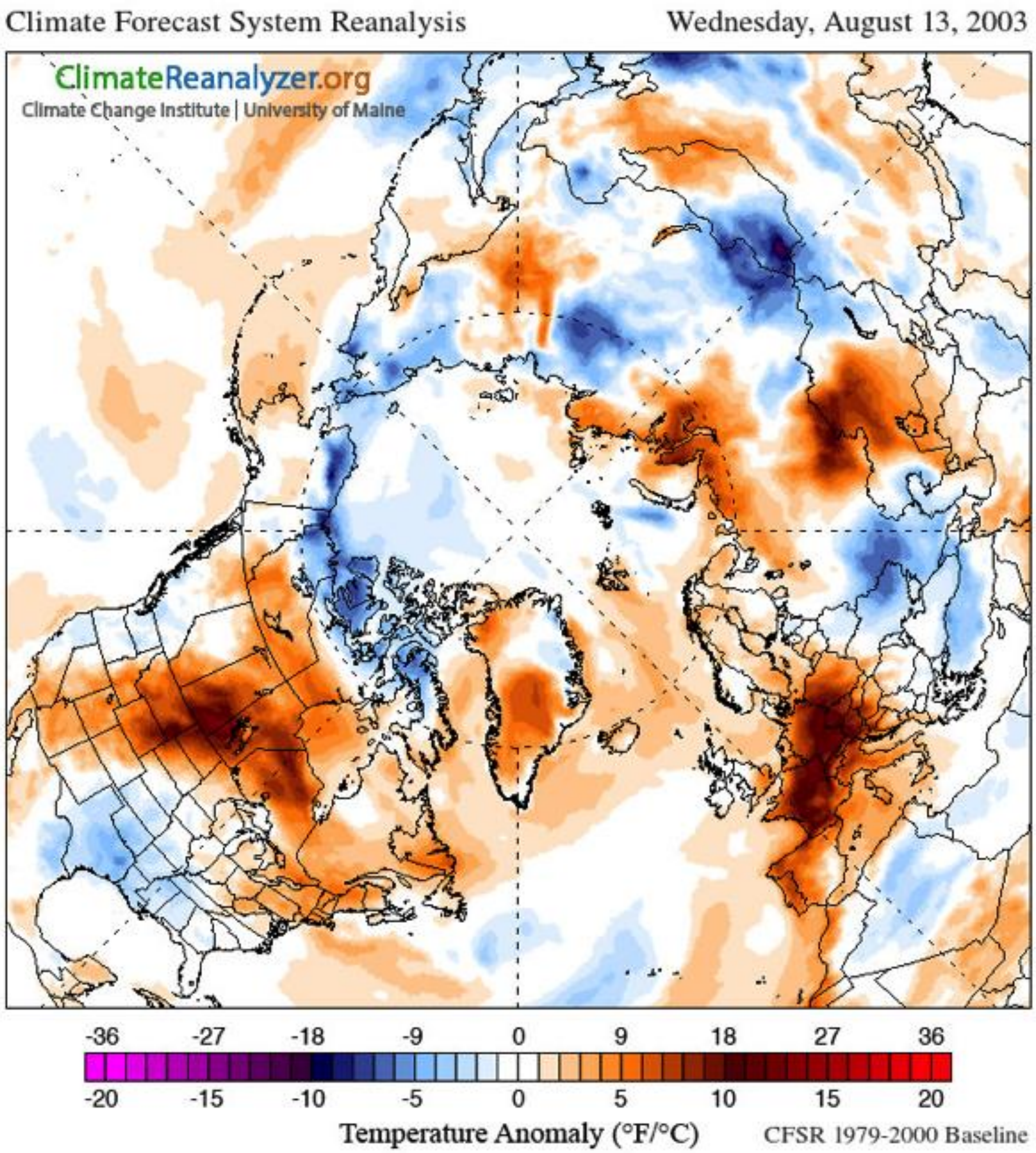

Figure 15: Temperature anomalies on Aug. 13, 2003, one of worst days in extensive, long-duration European heatwave that killed >70,000 people. From Climate Reanalyzer (see Links section). Root cause was wavy and stuck (persistant) jet stream ridge.

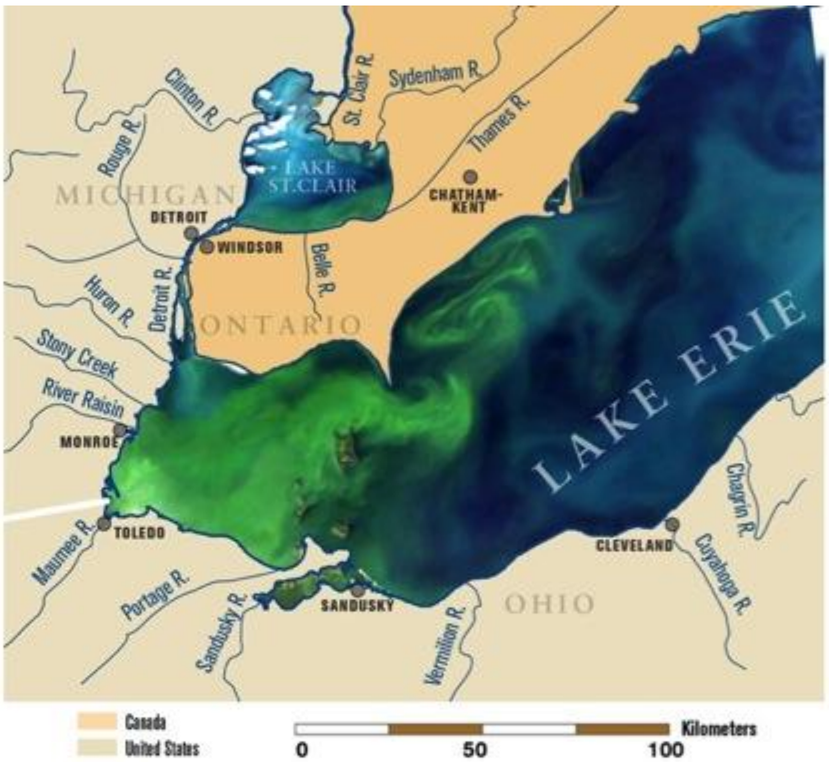

Figure 16: Blue-green algal bloom in 2014 that shut down Toledo water supply for many days.
http://voices.nationalgeographic.com/files/2013/04/Slide3.j

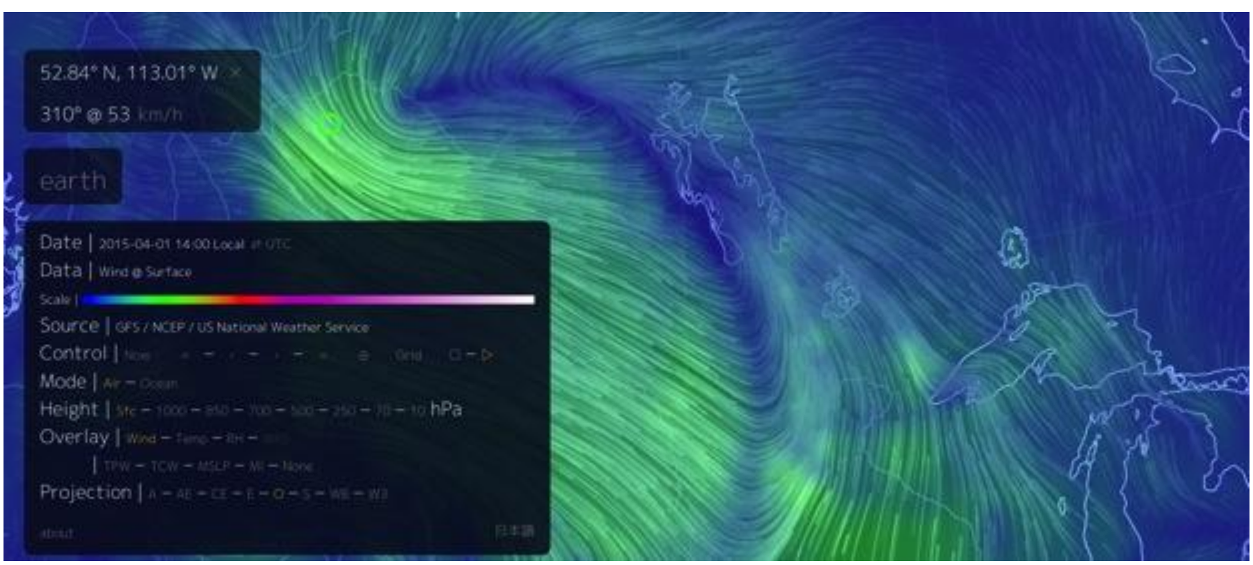

Figure 17: Example from Earth Nullschool (see links section) of Lake Winnipeg region, showing surface winds from April 1, 2015. The coordinates/windspeed and direction on the top left is data at the location of the green circle.

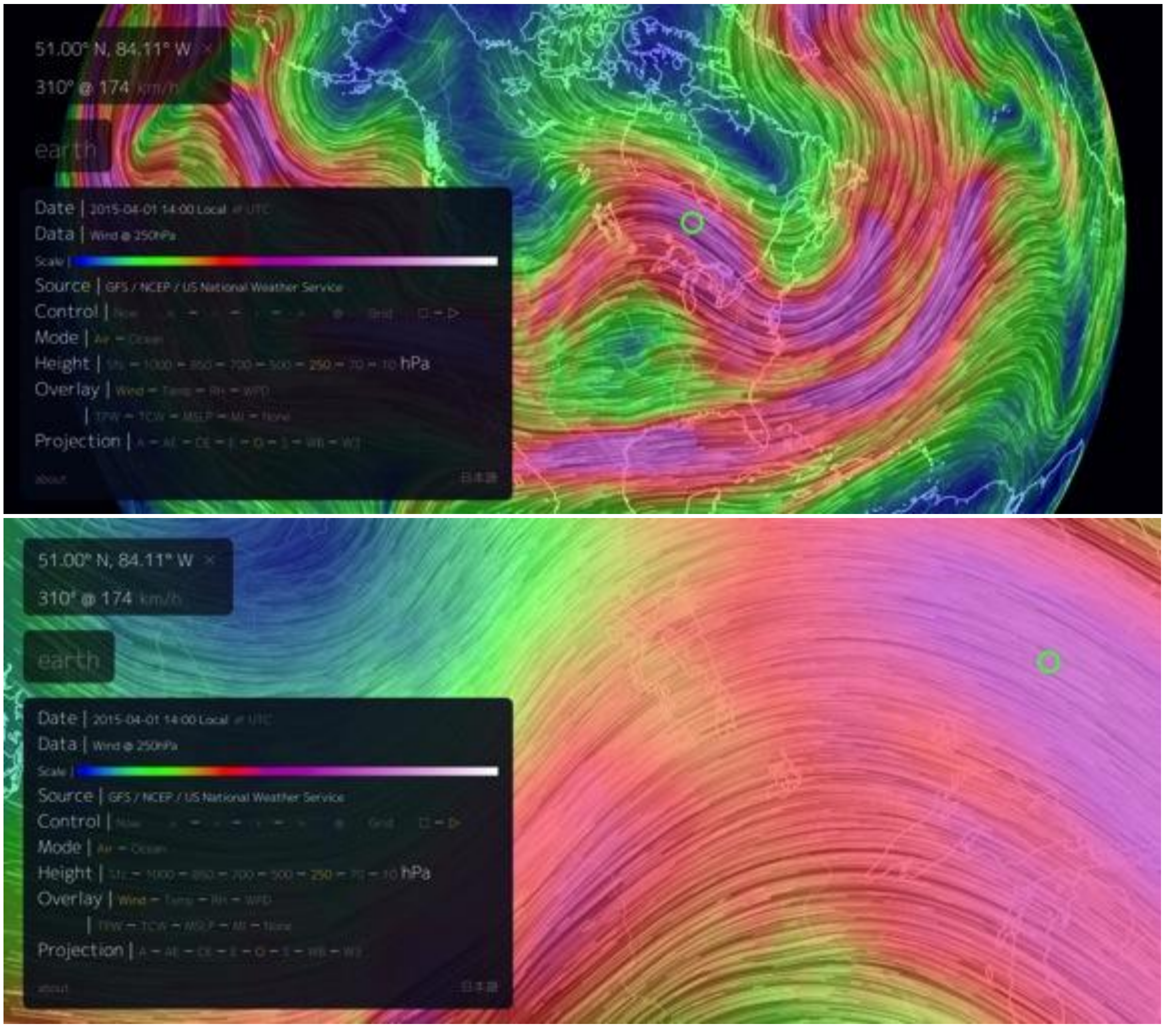

Figure 18: Examples from Earth Nullschool (see links section) of Lake Winnipeg region, showing jet stream winds (at 250 mbar pressure level) from April 1, 2015. The coordinates/windspeed and direction on the top left is data at the location of the green circle.

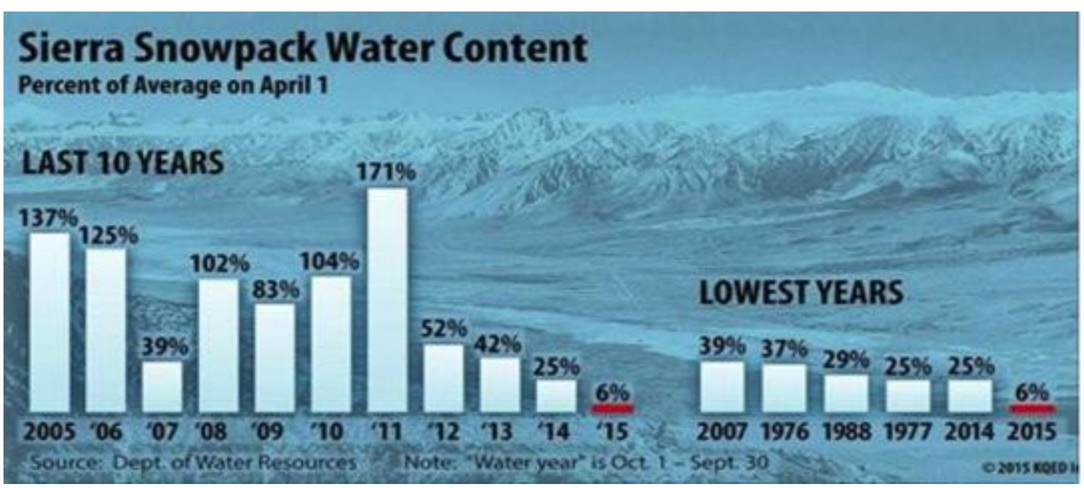

Figure 19: Sierra Nevada snowpack water content (percentage on April 1st). This is the lowest snowpack ever recorded in California history.

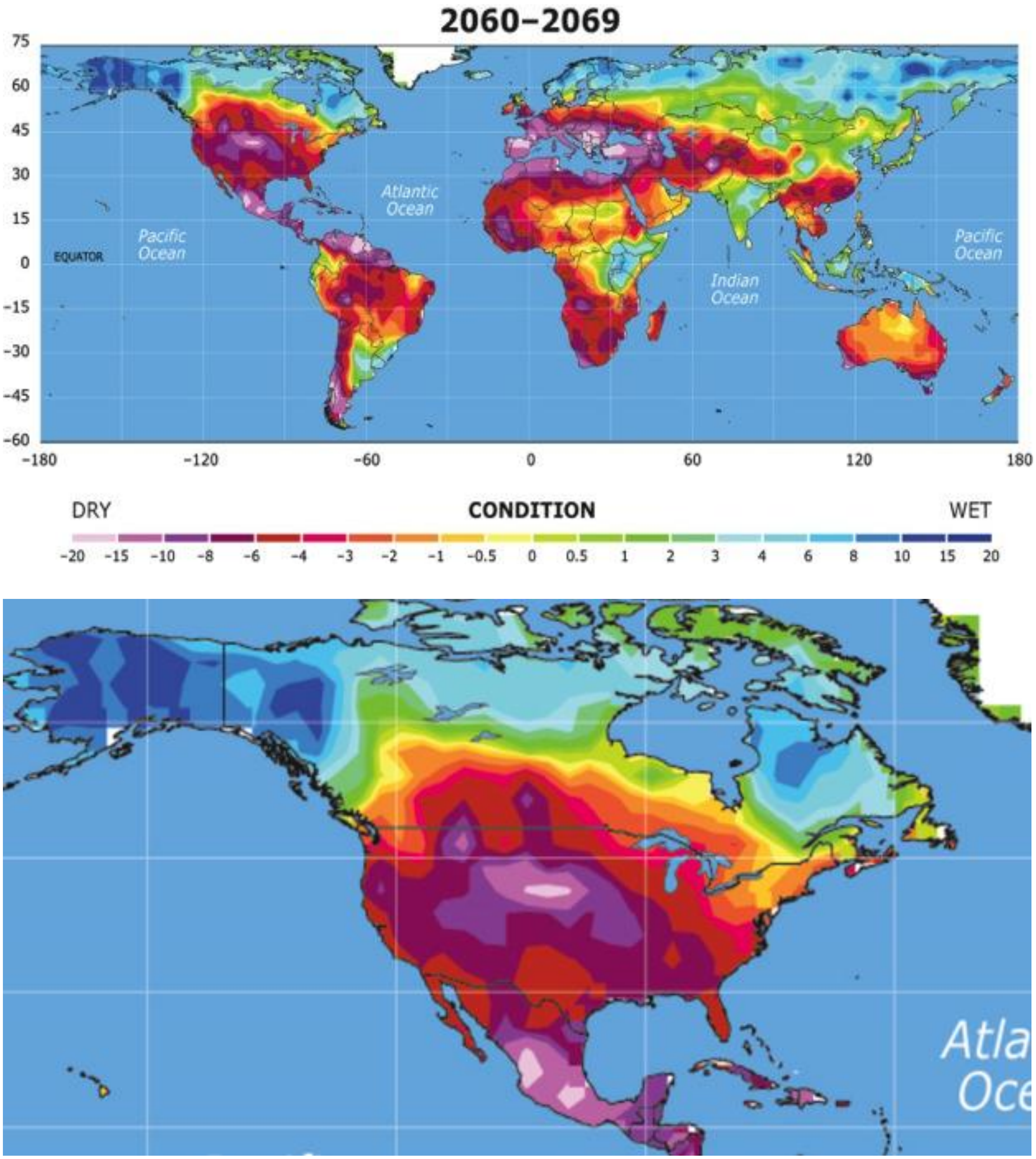

Figure 20: Projection of global spatial variability of wet/dry conditions from NCAR analysis (Dai, 2011) shows that many regions of the globe are expected to get much drier. The Winnipeg Lake Basin primarily straddles the light and dark orange regions (-1 to -3) and lower, reaching -6 to -8 as you move westward to central Canada.

Glossary

Abrupt climate change: nonlinear (such as exponential, versus a linear (straight line) increase; extremely rapid rates of change, tipping point, threshold passed and a change in state occurs. Good examples of abrupt processes are freezing, thawing, snapping a stick, tipping a canoe…

Albedo: Reflectivity of a surface, lower numbers darker, higher numbers whiter, average albedo of Earth from space is about 30%, albedo of fresh snow is about 90%, older snow and ice about 80 to 90%, dark sea water about 10%, forests about 30%. Arctic region albedo has declined from about 54% to 48% over 3 decades

Anthropogenic: Human caused/influenced

Climate system: Includes the elements of atmosphere, lithosphere, cryosphere, hydrosphere, biosphere, and also the external forcings (sun, volcanos which are really part of lithosphere)

Feedback: After applying a forcing to a system there is a response proportional to the forcing (linear regime). If the response causes the forcing to increase it is called a positive or reinforcing feedback, and if the response reduces the forcing it is a negative or braking feedback. Warming in the Arctic reduces the albedo. This darkens the surfaces, and results in more solar radiation absorbed and thus even more warming and even more albedo reduction (positive feedback).

Glaciers: Describes ice on mountain tops, and also ice caps. Glaciers flow downhill, and on Greenland and Antarctica they extend off the coasts to create Ice Shelves. Large calving events on the ice shelves create iceburgs.

Ice caps: Ice that sits on bedrock, such as on Greenland and Antarctica. This ice can be grounded on bedrock that is located far below sea level, and in this case is vulnerable to warm ocean water melting from below.

IPCC: Intergovernmental Panel on Climate Change, a group under UNFCCC (United Nations Framework Convention on Climate Change) that publishes climate change reviews every 5 to 7 years on a)Physical Science Basis, b) Adaptation, and c)Mitigation. AR5 (Assessment Report 5) is the 5th iteration of the report.

Jet streams: High altitude winds (at tropopause, which seperates lower atmosphere (troposphere) from higher atmosphere (stratosphere); they also at high latitudes and circle the globe primarily zonally (from west to east) with meridional waves (north to south and south to north components). Separate cold fronts (such as cold and dry Arctic air) from warm fronts (such as warm and moist air from the equator). Guide storms, wavier jet streams cause large pressure differences and thus increase frequency, severity and duration of extreme weather events.

Methane hydrates: An ice lattice that surrounds a methane molecule. When the lattice melts the volume expands by about 169 times and the methane is released. Exist at a combination of low pressures and high pressures, such as those that exist at ocean pressures at 200 meters (shallower in ocean sediments). Also located in permafrost regions.

Proxies: Indirect measurements of climate (temperature, precipitation) from marine sediment coring, ice cores, coral growth, tree rings for example. The instrumental record is the direct measurement of climate over the past century or so.

Rossby waves: Refers to the waviness in the jet streams as they circle the Earth at high latitudes and high altitudes.

Sea ice: Ice that forms over the ocean in winters, and melts back in summers. In the Arctic average sea ice thickness has exponentially declined over last 30 years. Sea ice extent is defined as the area over which the ice concentration is equal to or greater than 15% ice. Sea ice area is defined as the area over which the ice concentration is 100% (polynyas are regions within that are open water). Sea ice area and extent are easily measured with satellite sensors, sea ice thickness is measured from satellite via freeboard (thickness of ice above water surface) by precise radar altimetry. Sea ice volume is calculated from area and thickness.

Key web links

Arctic sea ice graphs: Real-time time series plots on sea ice extent, area, thickness, motion; maps on ice locations, meteorology, ocean temperatures and conditions, ocean buoy data, all updated daily: https://sites.google.com/site/arcticseaicegraphs/

Climate Reanalyzer: Real-time information on atmospheric weather and ocean conditions, displayed in a different format to Earth nullschool; great for examining global temperature anomalies (difference between present day and climate normal): http://www.cci-reanalyzer.org/

Earth nullschool: Real-time Earth sphere projections for atmospheric weather (temperatures, precipitation, winds at pressure levels up to top of troposphere (lower atmosphere where weather occurs); also data on oceans (temperatures, currents, etc.); click on text "earth" in bottom left corner to access variables, drag to rotate view, use slider to zoom, click on location for local (point) measurement: http://earth.nullschool.net/

Lima, Peru COP20 presentation that I gave at a press conference on the present state of the climate system: https://www.youtube.com/watch?v=QQkNxuQ0DoI
Climate system disruption video that I created March 24, 2015:
https://www.youtube.com/watch?v=GR2RDwhBFh4
Many other climate system videos on my YouTube channel, linked on Twitter and Facebook

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