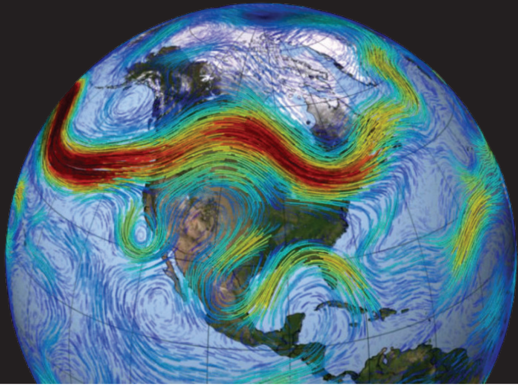
Implications of a Changing Arctic on Water Resources and Agriculture in the Central U.S.



University of Nebraska–Lincoln

Dr. Donald Wilhite
Kimberly Morrow

University of Nebraska–Lincoln

March 2016

Acknowledgments

We would like to thank the numerous sponsors of this important and timely workshop. NOAA's National Integrated Drought Information System and the U.S. Department of Agriculture's Office of the Chief Economist who provided significant financial support that lead to a highly productive interdisciplinary exchange of ideas, research needs and policy options in the water and agricultural sectors in the face of a changing climate. We also appreciate the ongoing support of the University of Nebraska's Office of Research and Economic Development and the Agricultural Research Division. The University of Nebraska's Daugherty Water for Food Institute also provided financial support.

Special thanks to the participants of this workshop for their outstanding contributions to the workshop. We also acknowledge the numerous staff from the School of Natural Resources who contributed in many ways to this successful meeting.

Donald Wilhite
Kimberly Morrow

Wilhite, D.A. and K. Morrow (eds.). 2016. Implications of a Changing Arctic on Water Resources and Agriculture in the Central U.S. Proceedings of a workshop, November 11-13, 2015. School of Natural Resources, University of Nebraska, Lincoln, Nebraska. 64 pp

Cover photos by Official White House photographer, Pete Souza.
Front cover: Melt runoff is shown from the Exit Glacier in Kenai Fjords National Park.
Back cover: Denali seen from Air Force One over Alaska.

Implications of a Changing Arctic on Water Resources and Agriculture in the Central U.S.

Dr. Donald Wilhite
Professor of Applied Climate Science

Kimberly Morrow
Climate Change Resource Specialist

November 10-12, 2015
Nebraska Innovation Campus
University of Nebraska–Lincoln

Sponsors:

NOAA/National Integrated Drought Information System (NIDIS)

USDA/Office of the Chief Economist

Office of Research and Economic Development, University of Nebraska–Lincoln

Agriculture Research Division/IANR, University of Nebraska–Lincoln

Robert B. Daugherty Water for Food Institute, University of Nebraska

School of Natural Resources, University of Nebraska–Lincoln

High Plains Regional Climate Center, University of Nebraska–Lincoln

National Drought Mitigation Center, University of Nebraska–Lincoln

Table of Contents

Introduction

The motivation to organize this workshop was the result of several key events that occurred in early 2015. First, we became aware that the United States was to assume leadership of the Arctic Council in April 2015. This provided an excellent opportunity to inform the science community and the public about the importance of the Arctic and why changes that are occurring in this region are important to the United States. Second, there is growing concern and debate occurring in the science community regarding the implications of climatic changes in the Arctic on mid-latitude weather and climate events. Although there are scientific uncertainties about the linkages between changes in the Arctic climate (i.e., reductions in snow and sea ice, warming temperatures, etc.) and mid-latitude weather patterns in winter and summer, the implications of these changes on agriculture, water resources, ecosystem health and other sectors for the Great Plains and Midwest regions of the U.S. could be profound. As we proceeded to pursue the idea of organizing this workshop, it became clear that the goal of the workshop should be to explore both the science associated with changes in Arctic climate on U.S. weather patterns as well as the implications of these changes on the frequency of extreme weather patterns (e.g., severe weather, droughts, floods, heat waves). Because of the importance of the central U.S. as one of the principal breadbaskets of the world, it was clear that the focus of this workshop should be on the implications of a changing climate on both the agriculture and water resources sectors.

The stated objectives of the workshop were:

- To build awareness of the importance of changes in the climate of the Arctic region on the United States and other regions;
- To initiate an interdisciplinary dialogue within the science community and between scientists and practitioners on the implications of changes in Arctic climate on Great Plains and Midwestern agriculture and water resources as well for other regions of the U.S. (e.g., California and other western states); and
- To identify, evaluate and propose actions in support of regional adaptation and mitigation strategies in response to and in anticipation of a changing climate on the Great Plains and Midwestern regions of the U.S.

In addition to producing this workshop summary report, the expected outcomes of this workshop were to:

- Create a workshop website to host reports, extended abstracts and PowerPoint presentations from the workshop;
- Publish the workshop summary in the scientific literature in order to create an archive of information on which future Arctic-related activities could build;
- Develop collaborative alliances within and between federal agencies and with interdisciplinary research entities at universities and elsewhere in order to better prepare for the effects of changing weather patterns in the U.S.
- Provide programmatic guidance to USDA, NOAA, the Department of State and other federal agencies as well as for state agencies and other entities.

This workshop was timely given the growing body of scientific literature on the influence of changes in the Arctic on mid-latitude weather and climate patterns. We are confident that the results of the workshop will also be beneficial to the work of the Arctic Council over the term of the U.S. leadership and beyond.

An Arctic Connection to Extreme Weather in Mid-Latitudes: New Evidence, Mechanisms, Metrics, and Emerging Questions

Jennifer Francis
Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey

Does it seem as though your weather has become increasingly "static" lately? Day after day of cold, rain, heat, or rainless skies may not be a figment of your imagination. Extremes in weather patterns are clearly on the rise, and there is increasing evidence that rapid Arctic warming – so-called Arctic amplification – may be playing a role.

Arctic amplification describes the tendency for high northern latitudes to be more sensitive to warming or cooling relative to the rest of the northern hemisphere. This heightened response is linked to the presence of snow and sea ice, and the feedback loops they trigger. For example, as sea ice retreats, sunshine that would have been reflected back to space by the bright ice is instead absorbed by the ocean, which then warms the water, and melts even more ice. As the Earth's temperature has risen since the fossil-fuel revolution following World War II, Arctic temperatures have increased at more than twice the rate of warming in northern mid-latitudes (Fig. 1). A dramatic indicator of this warming is the loss of Arctic sea ice in summer months, where the areal coverage has declined by about 40% and the ice volume by about 60% in just the past three decades (1). This leaves the Arctic ice cover much thinner and more vulnerable to any abnormalities in winds, ocean currents, or injections of warm air from the south. Studies have shown that the main driver is increased greenhouse gases resulting mostly from burning fossil fuels (1).

But Arctic amplification is not confined below the nearly ubiquitous low-level temperature inversion. The extra heat being absorbed by the vast expanses of open water, once covered in ice but now exposed, is substantial. Come fall, most of that heat is released back to the atmosphere, resulting in elevated geopotential heights with anomalies that increase with height over the Arctic (Fig. 2). All that extra heat and realignment of the north/south gradients cannot help but affect the weather, both locally and on a large scale. But how?

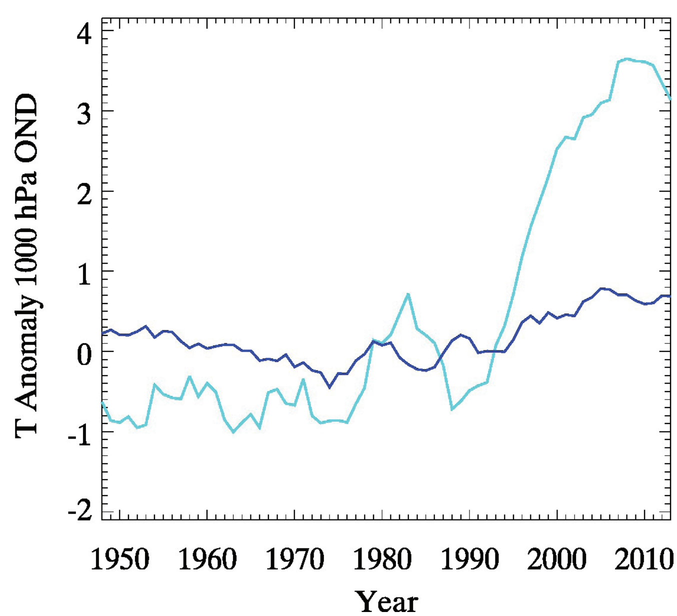


Figure 1: Difference in near-surface temperature anomalies between the Arctic (north of 70ºN, cyan) and mid-latitudes (30ºN-60ºN, blue) during autumn (Oct.-Dec.).

The Arctic is generally colder than mid-latitudes, and it is primarily this difference in temperature that propels the upper-level west-to-east river of wind known as the jet stream. This atmospheric feature tends to follow a wavy path as it flows around the northern hemisphere between about 30oN and 60oN, (at an altitude where jets fly, hence the name). So as high latitudes warm more than mid-latitudes, this north-south temperature difference weakens, which has two impacts on the jet stream.

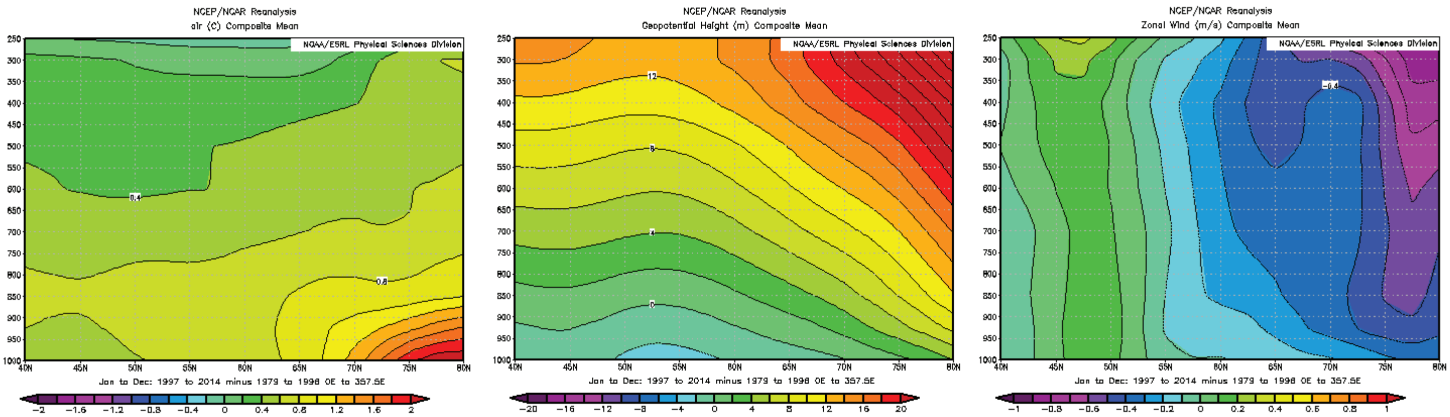


Figure 2: Zonal-mean anomalies in air temperature (left), geopotential height (middle), and zonal wind (right) during 1997-2014 relative to 1979-1996, from 40oN to 80oN and from the surface to 250 hPa.

The first effect is to slow its west-to-east winds, a phenomenon that is already occurring (Fig. 2., right plot). Upper-level winds around the northern hemisphere have decreased most during autumn months (Oct.-Dec.), which is exactly when sea-ice loss exerts its strongest effect on the north-south temperature gradient. Particular regions exhibit even larger drops in wind speed, such as over N. America and the N. Atlantic, where winds have slowed by about 14% since 1980 (2). Rossby wave theory tells us that a decrease in the west-east flow tends to slow the eastward progression of the large north-south waves in the jet stream. Because these waves control the formation and movement of surface weather systems, slower wave progression means that weather conditions will be more persistent, which may lead to extreme events caused by prolonged conditions (e.g., hot and cold spells, drought, and floods). Because the atmospheric circulation is so chaotic, however, it is difficult to detect a clear signal of this change amid the noise. As Arctic amplification continues to strengthen, these effects on jet-stream waves and weather patterns are expected to become more apparent.

The second way that Arctic amplification is expected to influence the jet stream and our weather is by increasing the "waviness" of the jet stream (2-4). Recent work shows that sea-ice loss in certain areas causes jet-stream ridges in those regions to intensify, which amplifies the ridges and creates a deeper trough downstream. This effect has been elucidated by analyses of observations (5-9) and model simulations (5-7), particularly as it relates to cold winters in northern hemisphere continents. Large swings in the jet stream allow frigid air from the Arctic to plunge farther south, while warm, moist tropical air can penetrate farther northward in the intense ridges. The past two winters in North America fit this pattern to a T, with drought and abnormal heat experienced in connection with the persistent ridge along the west coast, accompanied by cold, snowy winters in the east. This pattern is also associated with shifting sea-surface temperature patterns in the N. Pacific Ocean – a fluctuation known as the Pacific Decadal Oscillation – but it appears that sea-ice loss, which has been most pronounced in the Pacific sector of the Arctic in the past two winters, has prolonged the pattern and exacerbated its impacts (7, 10).

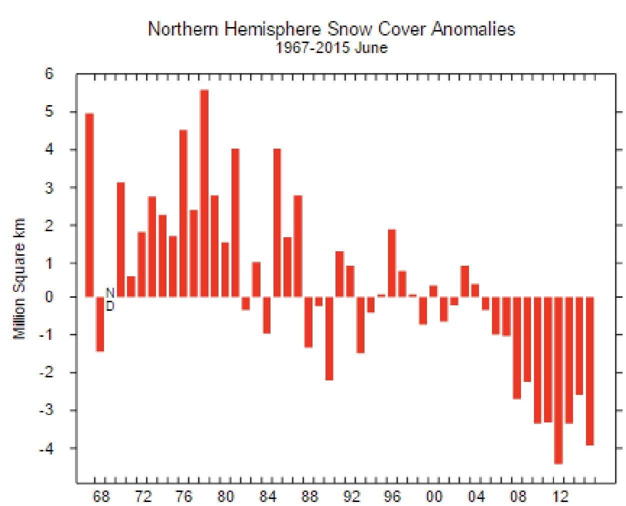


Figure 3: Differences between observed and normal snow cover during June in the northern hemisphere from 1967 to 2015. Data are from the Rutgers Global Snow Lab, http://climate.rutgers.edu/snowcover.

New work also suggests that weather patterns are becoming more persistent during summer months, as well (11,12), owing to the tendency for a weaker jet to split over continents and to meander more. AA in summer results primarily from earlier snow loss in spring (Fig. 3) and, consequently, the earlier drying/warming of underlying soils (14,15). Water resources, agriculture, and fire seasons will be disrupted by any changes in summer patterns that alter the frequency and intensity of precipitation, dry spells, and heat waves. Because Arctic amplification is weakest in summer, however, natural variability may dominate changes in summer weather, at least for the near future.

While much progress has been made in recent years to understand the mechanisms by which Arctic amplification affects the large-scale circulation of the northern hemisphere – the jet stream in particular – there are still many puzzles to solve. The diagram in Fig. 4 presents a “state of the art” of Arctic linkages to mid-latitude weather patterns. The two main branches emanating from Arctic amplification divide recent findings into two main categories – one related to intensified ridges and the other to effects of slowing jet-stream winds. Red, blue, and black shapes indicate whether the mechanism tends to occur mainly in summer, winter, or all year, respectively. Dashed shapes indicate where a mechanism is still a hypothesis, and thus additional work is required to verify its existence and importance. The main gaps in our understanding at this point revolve around the detection of changes in high-amplitude jet-stream patterns – such as shifts in the frequency and duration of blocking anticyclones – and whether those shifts are caused to some degree by the rapidly warming Arctic. Many new approaches and metrics are being developed, and targeted model experiments are being performed. This is a fast-evolving research topic, analogous to the climate system itself, and one that has captured the interest of the media and public.

While it’s difficult to say with any certainty whether Arctic amplification played a role in causing or exacerbating any particular extreme weather event, the evidence for a linkage is mounting. It is difficult to imagine that losing half of the sea ice floating on the Arctic Ocean – a key component of the Earth’s climate system – could have no effect at all on the large-scale circulation. Clearly the tropics still wield the largest stick in terms of energy and global influences, but this “new kid on the block” (AA) will likely have impacts that our outside our sphere of experience, resulting in more weather surprises in the future that are sure to affect water resources, agriculture, and our familiar way of life.

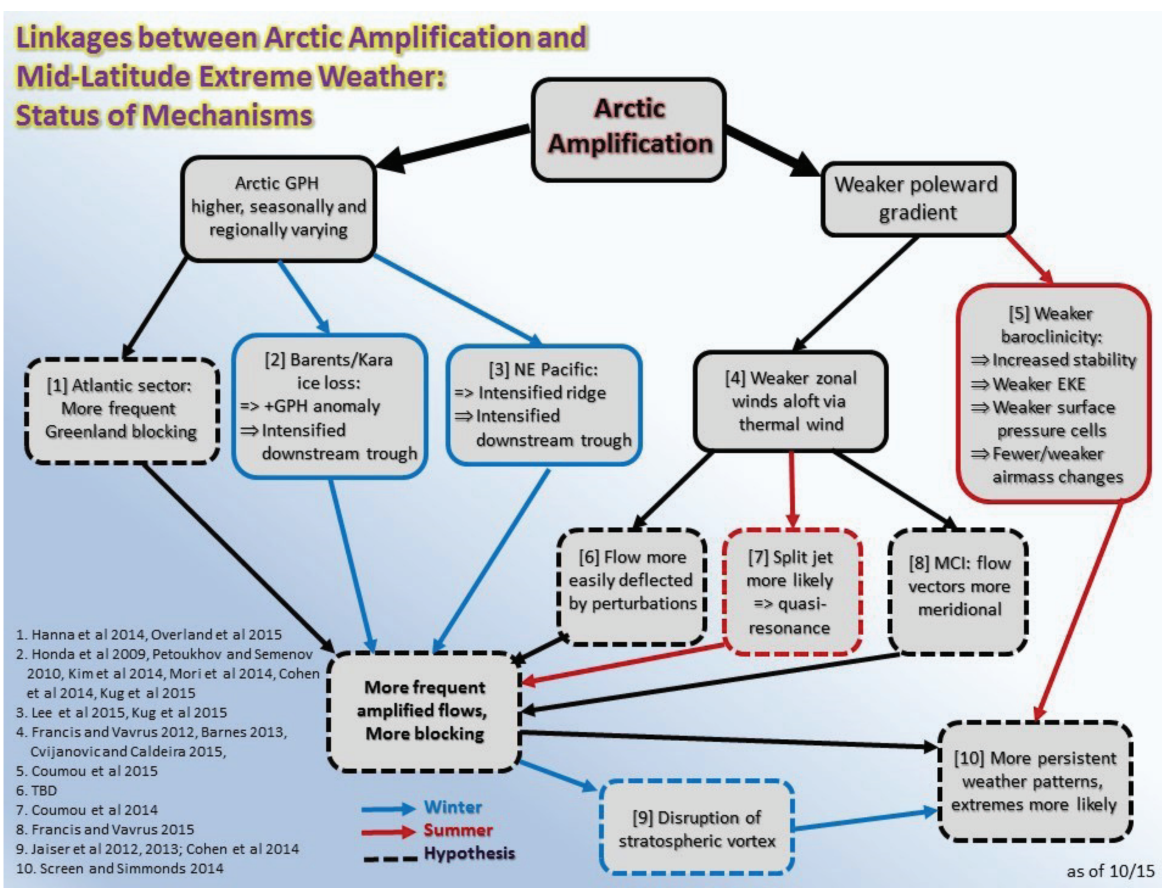


Figure 4: Graphical summary of research progress in understanding linkages between Arctic amplification and mid-latitude weather patterns. Red (blue) shapes indicate mechanisms that occur primarily in summer (winter) months. Dashed shapes indicate uncertain linkages that require further work to verify.

References

1. Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Maslanik, and A.P. Barrett (2011), The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, doi: 10.1007/s10584-011-0101-1.

2. Francis, J.A. and S.J. Vavrus (2012), Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys.* Res. Lett., 39, L06801, doi:10.1029/2012GL051000.

3. Francis, J.A. and S.J. Vavrus (2015), Evidence for a wavier jet stream in response to rapid Arctic warming. *Environ. Res. Lett.,* 10, 014005, doi:10.1088/1748-9326/10/1/014005.

4. Francis, J.A. and N. Skific (2015), Evidence linking rapid Arctic warming to mid-latitude weather patterns. *Phil. Trans.* R. Soc. A, 373, doi:10.1098/rsta.2014.0170.

5. Mori, M., M. Watanabe, H. Shiogama, J. Inoue, and M. Kimoto (2014), Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades. *Nat. Geosci.,* 7, 869–873, doi:10.1038/ngeo2277.

6. Kim, B.-M., S.-W. Son, S.-K. Min, J.-H. Jeong, S.-J. Kim, X. Zhang, T. Shim, and J.-H. Yoon (2014), Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nat. Commun.,* 5, 4646, doi:10.1038/ncomms5646.

7. Kug, J.-S., J.-H. Jeong, Y.-S. Jang, B.-M. Kim, C. K. Folland, S.-K. Min, and S.-W. Son (2015), Two distinct influences of Arctic warming on cold winters over North America and East Asia. *Nat. Geosci.,* 8, doi:10.1038/ngeo2517.

8. Hori, M. E., J. Inoue, T. Kikuchi, M. Honda, and Y. Tachibana (2011), Recurrence of intraseasonal cold air outbreak during the 2009/2010 winter in Japan and its ties to the atmospheric condition over the Barents-Kara Sea. *SOLA*, 7, 25–28, doi:10.2151/sola.2011-007.

9. Overland, J.E., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma (2015), The melting Arctic and midlatitude weather patterns: Are they connected? *J. Clim.,* 28, DOI: 10.1175/JCLI-D-14-00822.1.

10. Lee, M.-Y., C.-C. Hong, and H.-H. Hsu (2015), Compounding effects of warm SST and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013–2014 boreal winter. *Geophys. Res. Lett.,* 42, 1612–1618, doi:10.1002/2014GL062956.

11. Coumou, D., J. Lehmann, and J. Beckmann (2015), The weakening summer circulation in the Northern Hemisphere mid-latitudes. *Science,* doi:10.1126/science.1261768.

12. Coumou, D., V. Petoukhov, S. Rahmstorf, S. Petri, and H.J. Schellnhuber (2014), Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proc. Natl. Acad. Sci. U.S.A.*, 111, doi:10.1073/pnas.1412797111.

13. Screen, J.A. (2014), Influence of Arctic sea ice on European summer precipitation. *Env. Res. Lett., 8,* doi:10.1088/17489326/8/4/044015.

14. Ghatak, D., A. Frei, G. Gong, J. Stroeve, and D. Robinson (2010). On the emergence of an Arctic amplification signal in terrestrial Arctic snow extent. *J. Geophys. Res.,* 115, D24105, doi:10.1029/2010JD014007.

15. Brown, R., C. Derksen, and L. Wang (2010), A multi-dataset analysis of variability and change in Arctic spring snow cover extent, 1967-2008. *J. Geophys. Res.,* doi:10.1029/2010JD013975.

Arctic Change and Possible Influence on Mid-Latitude Weather Extremes

Judah Cohen
Atmospheric and Environmental Research, Inc., Lexington, Massachusetts 02421, USA

Introduction
The Arctic has warmed more than twice as fast as the global average, a phenomenon known as Arctic amplification (AA). These profound changes to the Arctic system have coincided with a period of ostensibly more frequent events of extreme weather across the Northern Hemisphere mid-latitudes, including extreme heat and rainfall events and recent severe winters. The possible link between Arctic change and mid-latitude weather has spurred a rush of new observational and modeling studies. These studies have argued that heavy precipitation events and heat waves are at least partially attributable to Arctic warming. A growing number of recent studies even argue that recent severe winter weather is related to AA. In part due to the high impact of extreme weather on our society, some of these studies linking AA to the increased frequency of extreme weather have garnered public and media attention. At the same time, uncertainties from the large intrinsic variability of the system, the short observational record due to the recentness of AA and the shortcomings of global climate models have also resulted in much skepticism in any argued links between AA and severe weather.

Arctic Amplification (AA)
Global surface temperatures are projected to warm due to rapid increases in greenhouse gases (GHGs) and over the entire length of the instrumental record, temperatures have undergone a warming trend (IPCC, 2013). The most significant and strongest warming globally has occurred in the most recent 40 years; with Arctic temperatures warming at nearly double the global rate (Screen and Simmonds 2010). Coupled climate models attribute much of this warming to rapid increases in greenhouse gases (GHGs) and project the strongest warming across the extratropical NH during boreal winter due to 'winter (or Arctic) amplification' (Cohen et al. 2014).

Rapid Arctic warming and sea ice loss has had significant impacts locally, particularly in late summer and early fall. September sea ice has declined at a rate of 12.4% per decade since 1979 (Stroeve et al. 2011) so that by the summer of 2012, nearly half of the areal coverage had disappeared. This decrease in ice extent has been accompanied by approximately 75-80% loss in volume (Overland et al. 2014). Anomalously low sea ice during the summer exposes darker (i.e., low albedo) ocean water to sunlight, producing strong Arctic warming via direct radiative impacts and anomalous latent and sensible heat fluxes. This reduction in summer sea ice extent subsequently affects fall re-growth of Arctic sea ice, allowing for warmer and moister Arctic air masses, particularly over nearby continents. The ensuing feedback contributes to amplified warming of the Arctic relative to the rest of the globe (Fig. 1a,b; e.g., Serreze and Francis 2006).

Snow cover in spring and summer has decreased at an even greater rate than has sea ice. June snow cover alone has decreased at nearly double the rate of September sea ice (Derksen and Brown 2012). The decrease in spring snow cover has contributed to both the rise in warm season surface temperatures over the Northern Hemisphere (NH) extratropical landmasses and in the decrease in summer Arctic sea ice. The rapid loss of snow cover in the spring and summer has also contributed to the amplification of Arctic warming.

Linking AA to Extratropical NH Climate Variability
With the Arctic at record warm levels, the eight years between 2007 and 2014 have exhibited the lowest minimum sea ice extents recorded in September since satellite observations began, with an all-time record low in 2007 followed by another in 2012, when sea ice extent fell below 4 million km2 for the first time in the observational record. However while the Arctic continues to warm, NH continental winters have recently grown

more extreme across the major industrialized centers. Several of these seven winters following the low sea ice minima have been unusually cold across the NH extratropical landmasses (Cohen et al. 2012, 2013, 2014). The recent winters of 2013/14 and 2014/15 were characterized by record cold and widespread snowstorms across the eastern United States and Canada with the most intense cold-air outbreak in decades associated with the weakening of the polar vortex both winters. Cohen et al. (2009) argued that the occurrence of more severe NH winter weather is a two-decade long trend starting around 1990 (Fig. 1c). Whether recent colder winters are a consequence of internal variability or a response to climate change remains an open question.

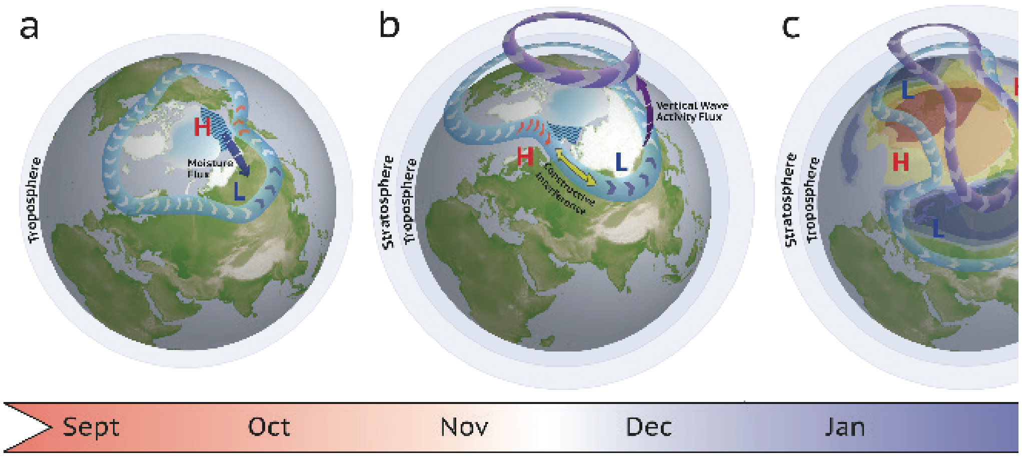


Figure 1. a) (right) Linear trend (°C per 10 years) in December – February (DJF) mean surface air temperatures from 1960/61-2013/14. Shading interval every 0.1°C per 10 years. Dark gray indicates points with insufficient samples to calculate a trend. (left) The zonally-averaged linear trend (°C per 10 years). b) Area-average surface temperature anomalies (°C) from 0°-60°N (solid black) and 60°-90°N (solid red) along with 5-year smoothing (dashed black/red lines). c) As in a) but from 1990/91-2013/14. Shading interval every 0.2°C per 10 years. Also note different scales between a) and c). Figure taken from Cohen et al. (2014).

Numerous compelling hypotheses linking changes in the Arctic to recent severe weather have been presented (e.g. Liu et al. 2012; Francis and Vavrus 2012). They propose that a warming Arctic results in a wavier polar vortex, leading to enhanced atmospheric blocking that often spawns extreme weather events.

The interaction between Arctic sea ice decline and the tropospheric circulation extends outside the Arctic and across multiple seasons. Several studies have examined these delayed and remote responses to Arctic sea ice decline, especially in relation to recent climate change. Francis et al. (2009), Jaiser et al. (2012), and Francis and Vavrus (2012) suggest that late summer Arctic sea ice conditions modify static stability of the Arctic troposphere, warm the lower levels, and ultimately change the poleward thickness gradient, implying a weakening of the polar jet stream. The decrease in static stability, however, also suggests enhanced baroclinic energy at higher latitudes and a change in the mid- and high-latitude planetary wave generation and propagation (Jaiser et al. 2012). Such changes persist through the following winter, impacting mid-latitude weather systems and temperature patterns. Honda et al. (2009) and Liu et al. (2012) use modeling experiments to illustrate that low summer Arctic sea ice conditions promotes anomalous and persistent high pressure across the North Atlantic (i.e., the negative phase of the North Atlantic Oscillation (NAO)), allowing for anomalously cold winters across much of Eurasia and parts of North America. In an observational analysis, Hopsch et al. (2012) also found a tendency for a negative NAO in late winter following low fall sea ice.

Links between summer Arctic sea ice variability and extratropical NH climate variability are not restricted to the following winter season, however, Tang et al. (2014) and Francis and Vavrus (2012) argue that Arctic amplification resulting from sea ice loss in fall and winter has imprints on the tropospheric circulation throughout the year, thus promoting weakened zonal flow and more frequent blocking episodes. Overland et al. (2012) argue that sea ice melt promotes earlier snowmelt and enhanced melting of the Greenland ice sheet.

Extreme Weather, Blocking, and Links to Sea Ice Loss

Although the term extreme weather is used to describe a range of phenomena, their common trait is the potential for high socioeconomic impact. Such events can be either short-lived (i.e., a strong hurricane or blizzard), or persistent for several days or weeks (i.e., droughts and floods).

Atmospheric blocking events play a key role in many extreme weather events (Coumou and Rahmstorf 2012). Blocking patterns result from the breakdown of the background flow pattern, which makes weather systems move slower or even become stationary (Rex 1950a,b). Like boulders blocking a river, once an atmospheric block forms, its impacts are felt both upstream and downstream of the block. For example, high winter precipitation over California is oftentimes associated with persistent (or 'cutoff') low pressure in the Eastern Pacific (e.g., Carrera et al. 2004). Extreme cold temperatures during the winter months over Europe and North America are associated with blocking anticyclones over northern Eurasia and Greenland, respectively (e.g., Thompson and Wallace 2001; Sillmann et al. 2011). The deadly Russian heatwave of 2010 was a direct result of a stagnant upper-level ridge over western Eurasia (e.g., Dole et al. 2011). Blocking events have been implicated as precursors for sudden stratospheric warmings (SSWs; Quiroz 1986; Martius et al. 2009), which in turn influence surface weather evolution for up to two months later (Baldwin and Dunkerton 2001).

Strong evidence links the observed increase in extreme events with anthropogenic climate change (Coumou and Rahmstorf 2012). However, the projected change in frequency and intensity of extreme weather events is considered one of the principal yet more poorly understood impacts of climate change (IPCC 2013; Sillmann et al. 2013). The main culprits for poor predictions of extreme weather events are a lack of understanding of dynamics and feedback mechanisms driving variability in weather extremes and subsequent model deficiencies (Christensen et al. 2008; Min et al. 2013). Quantifying the contribution of reduced Arctic sea ice to anomalous circulation patterns is particularly problematic because many of the possible candidates forcing extreme weather (e.g. sea ice) exhibit significant trends in the modern satellite era. This makes it impossible to establish a causal link between sea ice anomalies and extreme weather using statistical methods and historical data alone.

I argue that this unforeseen trend is likely not due to internal variability alone. Instead, evidence suggests that summer and autumn warming trends are concurrent with decreases in Arctic sea ice and increases in Eurasian snow cover, which dynamically induces large-scale wintertime cooling (Fig. 2). Arctic warming in summer may also slow and amplify atmospheric waves leading to more extreme summer weather. Understanding these poorly understood responses to radiative warming of the climate system has the potential to improve climate predictions and our understanding of severe or extreme winter weather across the mid-latitudes including the US.

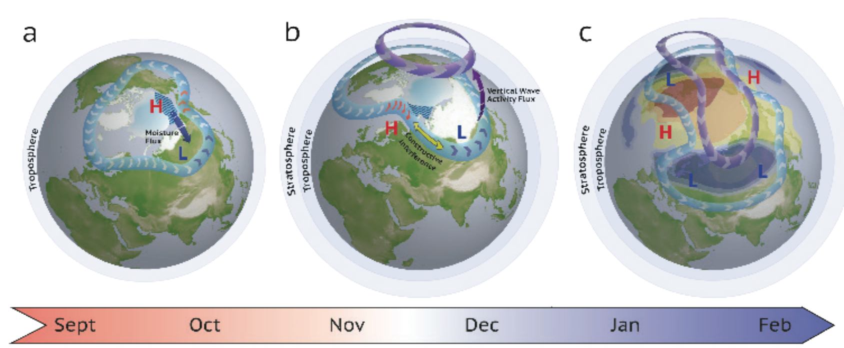


Figure 2. The schematic highlights a proposed way in which Arctic sea ice loss in late summer through early winter may work in concert with extensive Eurasian snow cover in the fall to force blocking a weakened polar vortex and ultimately the negative phase of the N/AO in winter. Snow is shown in white, sea ice in white tinged with blue, sea ice melt with blue waves, high and low geopotential heights with red "H" (red represents anomalous warmth) and blue "L" (blue represents anomalous cold) respectively, tropospheric jet stream in light blue with arrows and stratospheric jet or polar vortex shown in purple with arrows. On the right globe, cold (warm) temperature anomalies associated with the negative phase of the winter N/AO are shown in blue (orange). Figure taken from Cohen et al. (2014).

References

Baldwin, M. P., and T. J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. *Science,* 294, 581–584.

Carrera, M. L., R. W. Higgins, and V. E. Kousky, 2004: Downstream Weather Impacts Associated with Atmospheric Blocking over the Northeast Pacific. *J. Climate,* 17, 4823–4839.

Christensen, J. H., F. Boberg, O. B. Christensen, and P. Lucas-Picher, 2008: On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophys. Res. Lett.,* 35, L20709.

Cohen, J., M. Barlow, and K. Saito, 2009: Decadal fluctuations in planetary wave forcing modulate global warming in late boreal winter. *J. Clim.,* 22, 4418–4426.

Cohen, J., J. Furtado, M. Barlow, V. Alexeev, and J. Cherry, 2012: Arctic warming, increasing fall snow cover and widespread boreal winter cooling. *Environ. Res. Lett.,* 7, 014007 doi:10.1088/1748-9326/7/1/014007.

Cohen, J., J. Jones, J. C. Furtado, and E. Tziperman, 2013: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather. *Oceanography,* 26(4), http://dx.doi.org/10.5670/oceanog.2013.70.

Cohen, J. and co-authors, 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nature Geosci.,* 7, 627–637, doi:10.1038/ngeo2234.

Coumou, D., and S. Rahmstorf, 2012: A decade of weather extremes. *Nature Climate Change,* 2, 491–496.

Derksen, C., and R. Brown, 2012: Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections. *Geophys. Res. Lett.*, 39, L19504.

Dole, R., M. Hoerling, J. Perlwitz, J. Eischeid, P. Pegion, T. Zhang, X.-W. Quan, T. Xu, and D. Murray, 2011: Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.,* 38, L06702, doi:10.1029/2010GL046582.

Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.,* 39, L06801, doi:10.1029/2012GL051000.

Francis, J. A., W. Chan, D. J. Leathers, J. R. Miller, and D. E. Veron, 2009: Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent. *Geophys. Res. Lett.,* 36, L07503, doi:10.1029/2009GL037274.

Honda, M., J. Inue, and S. Yamane, 2009: Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. *Geophys. Res. Lett.,* 36, L08707, doi:10.1029/2008GL037079.

Hopsch, S., J. Cohen, and K. Dethloff, 2012: Impact of anomalous fall Arctic sea ice concentration on atmospheric patterns in the following winter. *Tellus A,* 64, 18624.

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

Jaiser, R., K. Dethloff, D. Handorf, A. Rinke, and J. Cohen, 2012: Planetary- and synoptic-scale feedbacks between tropospheric and sea ice cover changes in the Arctic. *Tellus,* 64, 11595, DOI: 10.3402/tellusa.v64i0.11595.

Liu, J., J. A. Curry, H. Wang, M. Song, and R. M. Horton, 2012: Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl. Acad. Sci.,* 109, 4074–4079.

Martius, O., L. M. Polvani, and H. C. Davie, 2009: Blocking precursors to stratospheric sudden warming events. *Geophys. Res. Lett.,* 36, L14806.

Min, E., W. Hazeleger, G. J. Odenborgh, and A. Sterl, 2013: Evaluation of trends in high temperature extremes in north-western Europe in regional climate models. *Env. Res. Lett.,* 8, 014011 doi:10.1088/1748-9326/8/1/014011.

Overland, J. E., J. A. Francis, E. Hanna, and M. Wang, 2012: The recent shift in early summer Arctic atmospheric circulation. *Tellus,* 62A, 1-9, DOI: 10.1111/j.1600-0870.2009.00421.

Overland, J. E., M. Wang, J. E. Walsh, and J. C. Stroeve, 2014: Future Arctic climate changes: Adaptation and mitigation timescales. *Earth's Future,* 2, 68–74.

Quiroz, R. S., 1986: The association of stratospheric warmings with tropospheric blocking. *J. Geophys. Res.,* 91, 5277–5285.

Rex, D. F., 1950a: Blocking Action in the Middle Troposphere and its Effect upon Regional Climate I. An Aerological Study of Blocking Action. *Tellus,* 2, 196–211.

Rex, D. P., 1950b: Blocking Action in the Middle Troposphere and its Effect upon Regional Climate (II). The Climatology of Blocking Actions. *Tellus,* 2, 275–301.

Screen, J. A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature,* 464, 1334–1337, doi:10.1038/nature09051

Serreze, M. C., and J. A. Francis, 2006: The arctic amplification debate. *Climatic Change,* 76(3-4), 241–264, doi:1007/s10584-005-9017-y.

Sillmann, J., M. Croci-Maspoli, M. Kallache, and R. W. Katz, 2011: Extreme Cold Winter Temperatures in Europe under the Influence of North Atlantic Atmospheric Blocking. *J. Climate,* 24, 5899–5913.

Sillmann, J., V. V. Kharin, X. Zhang, F. W. Zwiers, and D. Bronaugh, 2013: Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *J. Geophys. Res. Atmos.,* 118, 1716–1733.

Stroeve, J. C. et al. Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010. *Geophys. Res. Lett.,* 38, L02502 (2011).

Tang, Q., X. Zhang, and J. Francis, 2014: Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nature Climate Change,* 4, 45–50.

Thompson, D. W. J., and J. M. Wallace, 2001: Regional Climate Impacts of the Northern Hemisphere Annular Mode. *Science,* 293(527), 85–89. DOI: 10.1126/science.1058958.

Arctic Change: Implications for Central U.S. Water and Agriculture

Martin Hoerling[1], Lantao Sun[2], Jon Eischeid[2]*
[1]NOAA Earth System Research Laboratory
[2]University of Colorado-Boulder/CIRES

1. Background

There are many reasons why the Arctic is important. Resource conservation, safe navigation, improved commerce, national security, and societal impacts of Arctic change are all of key concern. This presentation addresses the last item, summarizing scientific evidence of how the Arctic climate has changed and why such change has occurred from a physical science perspective.

The presentation then examines the question whether Arctic change is having a detectable effect on middle latitude weather and climate at this time. Initially proposed as a hypothesis by Francis and Vavrus (2012), the supposition is that Arctic amplification of global warming may trigger a chain of events that ultimately lead to increased extreme weather in middle latitudes. Various subsequent studies have explored these possible links, and they are briefly discussed to illustrate what is currently known on how the Arctic matters for weather and climate patterns.

Much of the research has examined late Fall/winter consequences of Arctic change. Here we present results of new calculations to address how Arctic change is affecting the US Corn Belt during its growing season. It has long been known that US corn production is most sensitive to July rainfall and, to a lesser degree, August temperatures, dating from Wallace's classic agro-climate study published in Monthly Weather Review in 1920. We present results from a diagnosis of parallel climate simulations, one that includes Arctic change mechanisms operating in recent years and the other omitting such drivers of Arctic change. These are compared for the specific climate variables relevant for US Corn production, and an assessment of how Arctic change is likely affecting central US water and agriculture is provided.

Finally, long historical time series of meteorological conditions during 1895-2015 are presented for the US Corn Belt region. It is shown that climate in this region has become more favorable for corn production over the last century, with a general increase of rainfall during July and a cooling of maximum daytime temperatures during August. The presentation assesses whether Arctic change has been a critical factor creating a more favorable summertime Great Plains climate.

2. Discussion

a. What is known about Arctic change?

The Arctic has warmed, with a larger rate of surface warming than that occurring over the rest of the world---a global change pattern referred to as Arctic amplification (Serreze and Barry 2014). The timing of this warming reveals that Arctic amplification emerged during the last 10-20 years, a period coinciding with a rapid observed decline in Arctic sea ice. While the Arctic has warmed throughout the troposphere (as indeed much of the global troposphere has warmed since the 20th century), little or no Arctic amplification has occurred in the free atmosphere.

Physical considerations of the surface energy balance, in particular the increase in heat transfer to the atmosphere from exposed Arctic Ocean surfaces compared to ice surfaces, indicates that the amplification of

* Dr. Martin Hoerling, 325 Broadway, Boulder, Colorado 80305; martin.hoerling@nooaa.gov

Arctic surface warming has largely been driven by sea ice loss. Such sensitivity is affirmed in climate model simulations, which also produce Arctic amplification in historical experiments of atmospheric models driven by specified time varying Arctic sea ice (e.g. Kumar et al. 2010). Furthermore, historical simulations of coupled ocean-atmosphere models (CMIP5) driven only by the change in greenhouse gases (GHG) and anthropogenic aerosols generate a decline in Arctic sea ice and a warming of the Arctic Ocean that largely reproduces the observed pattern and its rate of change.

The interpretation of observations and models is thus of an Arctic climate system undergoing rapid change that is now largely (but not entirely) responding to human-induced climate change. The observed decline in September Arctic sea ice extent of ~13%/decade since the 1990s is of a rate roughly expected from effects of increasing GHG emissions. When Arctic climate is examined over the last 10-20 year average, Arctic amplification of surface warming is mostly a symptom of human-induced change through sea ice and snow cover feedbacks (and other factors including water vapor and cloud changes) that are strong drivers of high latitude climate. Some fraction of Arctic sea ice variability, especially on shorter time scales of year-to-year swings, is however unrelated to human-induced change. Natural factors also contribute to Arctic climate change on multi-decadal time scales, as suggested by the fact that the Arctic climate experienced a transitory warming during the first decades of the 20th century when anthropogenic forcing was small.

b. What is known about Arctic change impacts?

Arctic communities have experienced direct and visible effects of climate change owing to the strong local control on weather and seasonality of climate exerted by sea ice. For instance, the impact of storms on coastal communities is now radically different as they more often traverse open water rather than ice. The overall warming of the Arctic tundra has had additional effects on permafrost and ecosystems that are key to habitation in the Arctic.

Are such major changes in the Arctic affecting lower latitudes, in particular to an extent that noticeable changes in climate and weather patterns in middle latitudes are now being detected? Francis and Vavrus (2012; hereafter FV12) posed a hypothesis that, as a consequence of Arctic amplification, mid-latitudes would experience increased extreme weather resulting from a dynamical change in the westerlies and the behavior of atmospheric waves that are linked to the jet stream.

Climate science is fundamentally a hypothesis driven discipline, and experimentation is key to testing theories. Numerous studies have thus emerged to test the FV12 conjecture. Ultimately, confirmation of theories only counts if they are the result of predictions, but to date precise forecasts of the location and timing of extreme weather events resulting from Arctic change have not been attempted. Notwithstanding, the merit of a theory lies in its refutability, falsifiability, and testability; the various chain of events envisioned by FV12 have thus undergone extensive scrutiny. For example, the key first link in the proposed causality chain was tested by Perlwitz et al. (2015), who addressed the question of why the deep Arctic troposphere has warmed in the recent decade, and whether the deep warming was due to sea ice loss. Their results, consistent with a body of modeling evidence and physical arguments, show that sea ice loss only warms the lower-most troposphere, while other processes (originating from outside the Arctic) has been driving the deep tropospheric warming over the polar cap. Their analysis thus provides an alternate interpretation of Arctic-mid latitude interactions over the past decade ---- deep tropospheric conditions over the Arctic have been more responding to lower latitude weather and climate, rather than forcing them. The results further affirm prior findings that weakening of the *surface* poleward temperature gradient due to Arctic amplification is largely ineffective in influencing the mid-latitude jet stream owing to its shallow atmospheric warming effect at this time.

The detectability of Arctic change impacts on the jet stream has been most recently considered in Barnes and Screen (2015). They present evidence for substantial decadal variability in the location and intensity of the jet using a 140-yr historical observational data set. The recent decadal conditions are shown to be neither unusual nor extreme from the perspective of intrinsic climate variability. The presence of such significant decadal variability indicates that an effect on the jet stream from Arctic change is unlikely to be detectable at this time.

The overall effect of global climate change on temperatures and the jet stream is shown to be very different from that expected from Arctic amplification alone, as shown in Barnes and Polvani (2015). Projections for the latter half of the 2^{1st} century using CMIP5 models indicate that while the primary warming in the lower troposphere will occur over the Arctic, the primary warming in the middle and upper troposphere will occur in the tropics, increasing the pole-to-equator temperature gradient through a deep atmospheric layer. There is no model consensus on how the jet stream will respond overall in the Northern Hemisphere, either its strength or its location, perhaps owing to a "tug-of-war" between tropical and Arctic effects (Barnes and Polvani 2015). In summer, when Arctic amplification of surface warming is much weaker, the jet stream is especially dependent on tropical deep tropospheric warming.

Arctic change is, however, having a clear and present impact on some types of mid latitude weather. A direct consequence of Arctic amplification is that the reservoir of cold air over the polar cap is much diminished. This leads to a significant and detectable reduction in cold air outbreak severity in mid-latitudes. Screen et al. (2015) provide evidence for a substantial reduction in daily temperature variability over the contiguous US in winter as a result of Arctic change. Two case studies of 2014 cold winter conditions over the Great Upper Midwest (Wolter et al. 2015) and the eastern United States (Trenary et al. 2015) affirm the conclusions of Screen et al., noting a reduction of daily temperature variability and showing that the frigid 2013/14 Midwest winter was 20-100 times less likely than in the late 19th century.

c. How Has Growing-Season Climate Changed in the Corn Belt?

In Louis Thompson's (1962) report on how various weather factors influence US corn production, empirical evidence was presented of a particular sensitivity to monthly mean July rainfall and August temperature. According to data at that time, climatological conditions for corn yields in Illinois were estimated to be sub-optimal, and that cooler/wetter conditions would lead to higher bushel/acre yields.

In this presentation, we show that observed summer conditions over the US Corn Belt have become cooler (for daytime maximum temperatures) and wetter since the early 20th century. Since 1990, a majority of summers have experienced cooler daytime maxima and wetter conditions than the long term average.

We present the results from a new set of climate model simulations specifically focused on identifying how Arctic change has impacted Great Plains summer climate, and especially whether it has been responsible for this more favorable growing regime in recent decades. Climate conditions in two parallel sets of historical simulations are compared, one subjected to the known changes in greenhouse gases, ocean temperatures and sea ice concentration, and a second in which the recent sea ice concentrations and related Arctic ocean temperatures are set to a 1979-1989 climatology.

For July and August, although the sea ice loss is near its maximum, the experiments reveal little impact on climate of the Arctic, and no significant effect on the corn belt of Nebraska, Iowa, Illinois, Indiana, and Ohio. The weak sensitivity in the Arctic in summer is because of the reduced air-sea contrast during the mild perpetual summer days, limiting the thermodynamic impact of sea ice removal (compared to winter). This weak Arctic change is further ineffective in driving a remote dynamical effect on the jet stream and weather patterns of lower latitudes. Thus, the various thermodynamic and dynamic links surmised to occur in association with Arctic amplification largely fail to operate in summer, with little direct effect on mid-latitudes. The more favorable climate over the Corn Belt experienced in recent decades is thus unlikely the result of Arctic change.

3. Conclusions and Next Steps

The presentation showed that sea ice loss, largely resulting from human-induced climate change, has been the main cause for an Arctic amplification of surface warming. Sea ice loss however has been found not to drive a deep tropospheric warming over the Arctic, and observations indicate no Arctic amplification of warming in the middle and upper troposphere. As a result, the critical first link in a hypothesized chain to connect Arctic amplification to mid-latitude weather extremes is weak and the jet stream is not being appreciably perturbed by Arctic change at this time. Any effect of Arctic change on mid-latitudes that may be occurring would furthermore be undetectable given the large intrinsic variability in weather and climate. An exception is that Arctic amplification is having a substantial and detectable influence on mid-latitude weather by reducing the variability of daily temperature ---- a diminished reservoir of high latitude cold surface air reduces winter cold air outbreak severity in middle latitudes.

As has been emphasized recently, it is important to understand how a changing Arctic is affecting weather and climate in different seasons and regions (Francis 2015). Here we have examined how Arctic change has affected summertime growing season conditions over the US Corn Belt. Our model results and physical considerations indicate no effect on either July rainfall or August temperature in the Midwest, two key variables for water resources and agricultural productivity.

Yet, growing season climate has become more favorable for corn production, though for reasons that are unknown. Next steps are to evaluate physical processes linking temperature and rainfall in the corn belt, and further determine how long term change (not just Arctic sea ice loss) is affecting these processes. It is especially important to account for this "US Warming Hole", to explore reasons for the absence of warming or unusual heat waves in recent decades, and to reconcile the current conditions with climate projections calling for a much hotter corn belt climate in coming decades.

4. References

Barnes, E. A., L. Polvani: CMIP5 projections of Arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate,* 28, doi: 10.1175/JCLI-D-14-00589.1

Barnes, E., A., and J. Screen: The impact of Arctic warming on the midlatitude jetstream: Can it? Has it? Will it?. *WIREs Climate Change,* 6, doi: 10.1002/wcc.337.

Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.,* 39, L06801.

Francis, J. A., 2015: The Arctic matters: Extreme weather responds to diminished Arctic sea ice. *Environ. Res. Lett.,* 10, 091002.

Kumar, A., J. Perlwitz, J. Eischeid, X. Quan, T. Xu, T. Zhang, M. Hoerling, B. Jha, and W. Wang (2010), Contribution of sea ice loss to Arctic amplification, *Geophys. Res. Lett.,* 37, L21701, doi:10.1029/2010GL045022.

Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic Tropospheric Warming: Causes and Linkages to Lower Latitudes. *J. Climate,* 28, 2154–2167.

Screen, J. A., and Co-authors, 2015: Reduced risk of North American cold extremes due to continued sea ice loss. *Bull. Amer. Met. Soc.,* 96, 1489–1503, doi: 10.1175/BAMS-D-14-00185.1.

Serreze, M. C., and R. G. Barry, 2014: *The Arctic Climate System.* Cambridge University Press, 404 pp.

Thompson, Louis M., "An evaluation of weather factors in the production of corn" (1962). CARD Reports. Book 10. http://lib.dr.iastate.edu/card_reports/10

Trenary, L, and Co-authors, 2015: Was the cold eastern US winter of 2014 due to increased variability? [In "Explaining Extremes of 2014 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, 96 (12), S15-19.

Wallace, H. A., 1920: Mathematical Inquiry into The Effect of Weather on Corn Yield in the Eight Corn Belt States. *Mon. Wea. Rev.,* 48: 439-456.

Wolter, K., and Co-authors, 2015: How unusual was the cold winter of 2013/14 in the Upper Midwest? [In "Explaining Extremes of 2014 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, 96 (12), S10-13.

August 29, 2011

August 9, 2013

Michael Forsberg

Located on University of Nebraska–Lincoln's Gudmundsen Sandhills Laboratory, the camera location shows the winding stream of a branch of the Middle Loup River as it cuts through the Nebraska Sandhills. "Mick's Slide" is towards the back of the frame; a blowout of sand in the hillside, "Mick's Slide" has taught UNL researchers much about the geology and evolution of the Nebraska Sandhills, the largest stabilized sand dune region in the hemisphere.

A New Look at Precipitation Extremes in the Central United States

Kenneth E. Kunkel
Cooperative Institute for Climate and Satellites
North Carolina State University and NOAA's National Centers for Environmental Information

Introduction/Background

Numerous research studies have documented an increase in extreme precipitation events in the U.S. over the past 30 years or so. The recent Third National Climate Assessment (NCA3) summarized a number of these studies (Walsh et al. 2014). They show that the increases are most prominent in the northern and eastern U.S.

This paper provides an update and some further in depth analysis of the NCA3 results. A set of 726 long-term stations from the U.S. National Weather Service's Cooperative Observer Network (COOP), distributed throughout the U.S., was used to identify extreme daily heavy precipitation events. Extreme events were defined as 2-day precipitation totals exceeding the threshold for a 1 in 5-year recurrence. Annual time series of the number of events were constructed for each station. The station results were aggregated to 1° x 1°grid box time series by averaging the number for all stations in the grid boxes for each year. Regional time series were constructed as the average of all grid boxes in the region. These constructed regional averages are referred to herein as the "Extreme Precipitation Index" (EPI).

Regional definitions were the same as used in the NCA3. For the coterminous U.S., there are 6 regions: Northeast, Southeast, Midwest, Great Plains, Northwest, and Southwest.

Discussion

Annual time series of the EPI for the Northern Great Plains (NGP), the Midwest (MW) and the Northeast (NE) regions are shown in Figures 1, 2, and 3, respectively. The values for 2015 represent accumulated counts through October 15, 2015 and the final value for 2015 may increase depending on events during the remainder of 2015.

A notable characteristic is the generally above average values during the 2000s in all regions and during the 1990s in the Northeast and Midwest. In all regions, the highest annual value on record has occurred in the 1990s or 2000s, exceeding earlier records by a considerable margin.

Another characteristic is the very high interannual variability in the 2000s, particularly in the Northern Great Plains and Northeast. Some of the high peaks are associated with notable flooding events, such as 2008 in the Midwest and 2011 in the Northeast. Some low values are associated with drought episodes, such as the low value in 2012 in the Northern Great Plains. The magnitude of variability is higher than any previous period of similar length.

Kunkel et al. (2012) studied the meteorological causes of extreme precipitation events. In their study, they analyzed daily events exceeding a 1 in 5-year recurrence interval. The meteorological cause of each event was identified as one of the following: extratropical cyclone near a front (ETC-FRT), extratropical cyclone not near a front (ETC-NFRT), tropical cyclone (TC), mesoscale convective system (MCS), air mass convection (AMC), North American Monsoon (NAM), and upslope flow (USF). They found that events occurring near a front accounted for about half of all events, but represented about 90% of the overall trend.

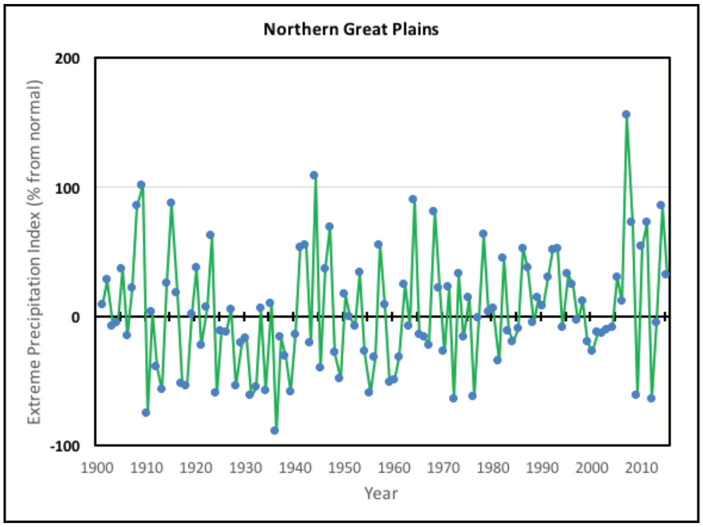


Figure 1. Annual time series of the Extreme Precipitation Index (% deviation from long-term average) for the Northern Great Plains for 1901-2015. The values for 2015 are for a partial year through October 15.

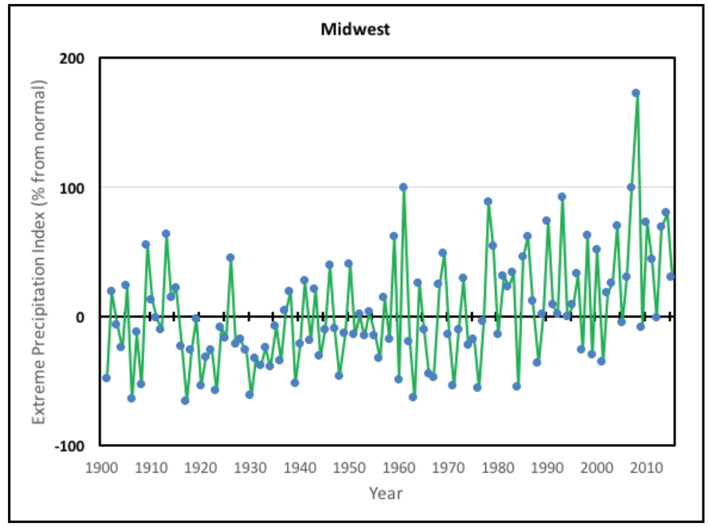


Figure 2. Annual time series of the Extreme Precipitation Index (% deviation from long-term average) for the Midwest for 1901-2015. The values for 2015 are for a partial year through October 15.

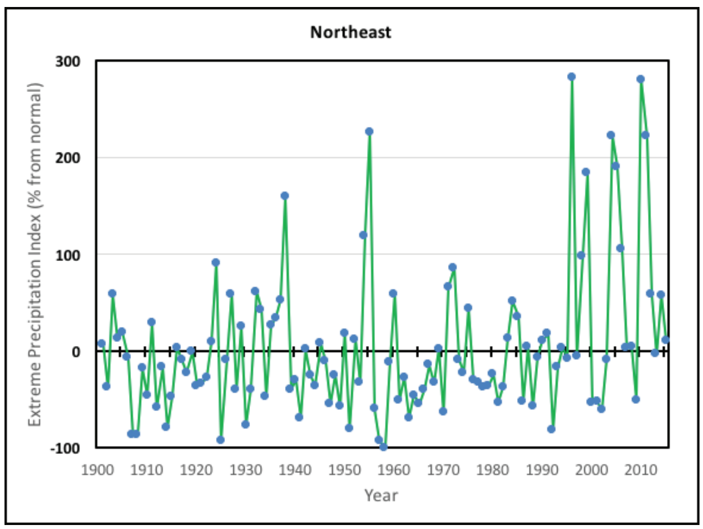


Figure 3. Annual time series of the Extreme Precipitation Index (% deviation from long-term average) for the Northeast for 1901-2015. The values for 2015 are for a partial year through October 15.

They used a different definition of regions than the NCA3, instead using regions defined by the National Climatic Data Center (NCDC). Figure 4 shows time series of the number of events caused by fronts for the NCDC regions most closely aligned with the NCA3 NE, MW, and NGP regions. In all of these regions, there is a strong upward trend over the period of 1910-2009 (their analysis stopped in 2009).

Most extreme precipitation events in these regions occur in the warm season. An interesting dimension of the Kunkel et al. (2012) findings is that, even in the summer, most events in the above regions were associated with fronts. This raises interesting questions about climatological characteristics and trends of fronts during a time of year when they are naturally weaker with weaker jet stream dynamics and (arguably) weaker links to larger-scale patterns.

Conclusions and suggested next steps

Historical analysis of precipitation observations indicates a strong upward trend in both the number and interannual variability of extreme precipitation in northern and eastern portions of the U.S. A meteorological analysis shows that this is predominantly a reflection of more events associated with the warm and cold fronts of extratropical cyclones. This is a proximate "cause" but raises the question of why? With respect to the particular focus of this workshop, fronts are an intrinsic feature of the mid-latitudes and jet stream dynamics. The role that large scale teleconnections play in this, including the effects of Arctic amplification and sea ice loss, is an obvious path for research inquiry. An interesting dimension of this is the major contribution of summer events to the overall trend and to the trend in events associated with fronts.

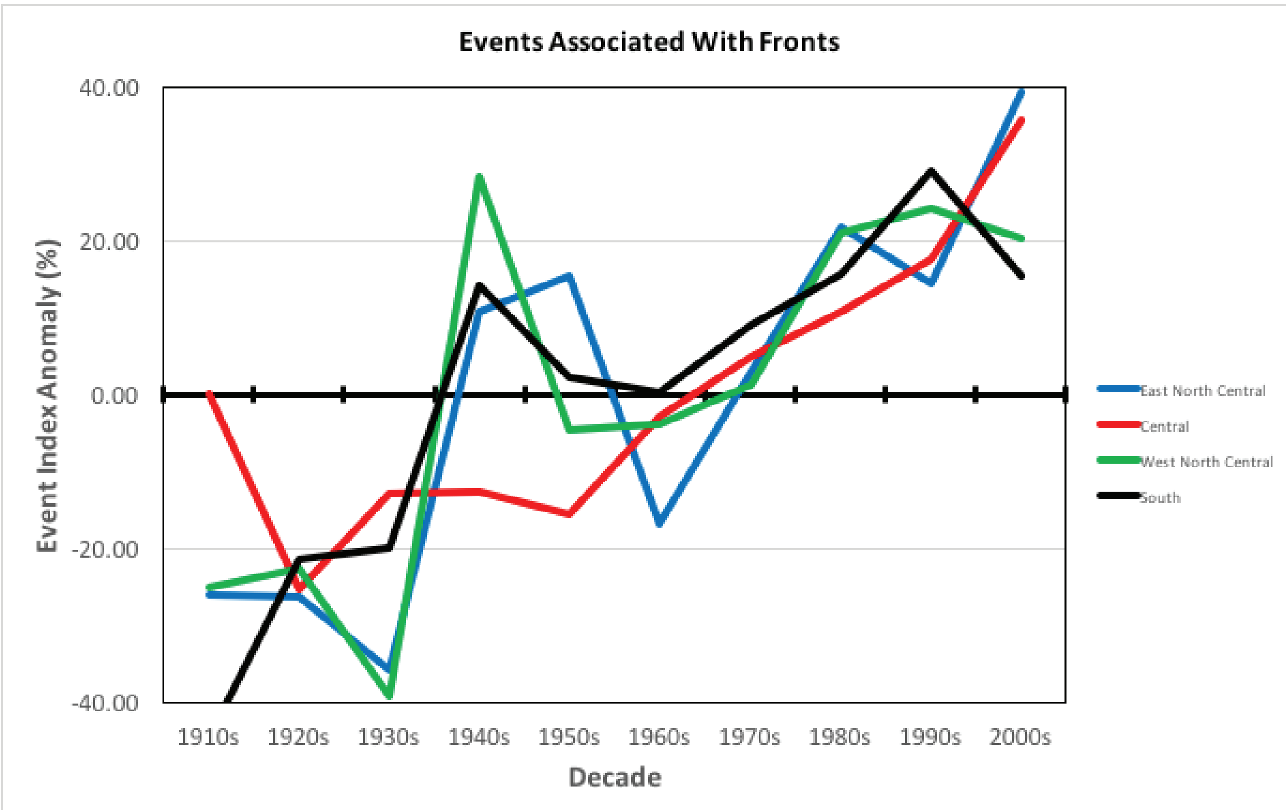


Figure 4. Decadal time series of an index of the number of events occurring near the warm or cold front of an extratropical cyclone for four regions in the north central and northeast U.S.

References

Kunkel, K.E., D.R. Easterling, D.A.R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *J. Hydromet.,* 13, 1131-1141.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT.

Healthy Soils as the Cornerstone of Climate Resilience for Agriculture

Jerry L. Hatfield
Laboratory Director and Supervisory Plant Physiologist
USDA-ARS National Laboratory for Agriculture and the Environment

Introduction/Background
Agricultural production is dependent upon a reliable water supply and limitations to productivity are often the result of the inability of the soil to provide adequate water (Hatfield, 2012). This is particularly evident in rainfed environments which are dependent upon precipitation events to replenish the soil water profile. Under irrigated conditions, where water is indirectly supplied to the surface from either surface or ground water supplies and these supplies overcome the short-term variation in precipitation. Crop productivity is directly related to water availability supplied by the soil. Egli and Hatfield (2014 a and b) showed that corn and soybean yields across the Midwest were a direct function of the soil quality as defined by the National Crop Commodity Productivity Index (NCCPI) and only in irrigated counties was the relationship between NCCPI and crop yield nonsignificant.

Climate change will increase the rate of soil water evaporation and crop evapotranspiration (ET) because of the increase in temperature and saturation vapor pressure deficit, thereby creating the potential for soil water deficits, crop drought stress, and economic losses. These effects are likely to occur unless they are mitigated by an increase in precipitation, an increase in use of supplemental irrigation; or adaptation of practices creating an increase in crop water use efficiency. One of the adaptation strategies to increase water availability is through an improvement in soil organic matter to increase the soil water availability as recognized by Hudson (1994). The projections of climate change for the United States through 2100 reveal that spring precipitation across the upper Midwest is expected to increase while summer precipitation across all of the United States and in particular the central US is expected to decrease (Melllio et al., 2014). Coupling this change with the increase in water demand for the crop ET has the potential to create cropping systems which suffer from increased yield limitations due to water deficits, especially in soils with low water holding capacity.

Projections of climate change in the US reveal two different responses. Drought can be expected to increase but this is offset by an increase in the frequency of extreme precipitation events (more than 5 cm in 24 hours). Hayhoe et al. (2007) and Mellio et al. (2014) and this trend is expected to be present in many regions of the US (Lettenmaier et al., 2008). One consequence of excessive rainfall is soil erosion in fields without adequate cover to reduce the impact of the intense rainfall. More rainfall concentrated into high precipitation events will increase the likelihood of water deficiencies at other times because of the changes in rainfall frequency (Hatfield and Prueger, 2004).

The ability of the soil to infiltrate and store precipitation is affected by the soil organic matter content. The continual loss of organic matter or nutrients from the soil through the combined processes of tillage and residue removal affects the physical, chemical, and biological processes and leads to soil degradation (Hatfield, 2014). Once a soil is degraded the susceptibility to erosion, compaction, and crusting increases and leads to a reduced biological capacity within the soil. All of these factors begin to limit the ability of the soil to supply adequate water for plant growth and creates a production system extremely susceptible to variations in weather during the growing season. Improving our soil and reversing the trend in degradation is a necessary step for climate resilience. Lal (2015) detailed the progression in agricultural systems when conservation agriculture is adopted that improve the ability to enhance climate resilience. Karlen et al. (2015) didn't address climate resilience but did show a framework for evaluating different conservation practices available from the Natural Resources Conservation Service (NRCS) which could enhance the soil resource. These factors lead to the potential to enhance the soil resource and create climate resilient agricultural systems and the dynamics of climate smart agriculture were discussed by Steenworth et al. (2014) in which they showed the value of the soil as the foundation.

Discussion of presentation content, key messages, research needs/gaps, policy suggestions

Degradation of the soil is increased through the use of tillage and residue removal and the first affect observed in this process is the decrease in aggregate stability. This leads to crusting and compaction of the soil and reduced infiltration of precipitation causing runoff and increased erosion. As the topsoil is eroded we observed reduced plant growth and productivity leading to reduced biological activity and reduced soil productivity. The impact of degraded soils is observed in the increased variation in production within fields among years and a decrease in overall productivity as observed in county level yields with differences in the quality of the soils. To increase soil health or the soil aggradation process requires that the first step be the implementation of practices which create a soil microclimate creating a stable environment for the soil biological complex. For the soil biological complex to function at the maximum efficiency there is a need for an adequate temperature range, food, and water supply. Maintaining the temperature regime and soil water within the range requires a residue layer to temper the extremes. Soil biological activity is necessary for the increase in organic matter content leading to improved soil water availability, nutrient cycling, and soil structure.

Climate resilience is a function of all factors that contribute to providing water and nutrients to plants throughout the growing season. If the soil doesn't supply these two critical factors then productivity will vary whenever there is variation in temperature or precipitation. Since the variation in these two factors are expected to increase in the near-term, a soil with limited water holding capacity and limited nutrients will exhibit increased variation in productivity. The process of enhancing the soil is the key to climate resilience.

Key messages to understand the intersection healthy soils and climate resilience:

1. Soil degradation is a facilitated by tillage and residue removal
2. Soil degradation is a process with the first evident change in the aggregate stability at the soil surface
3. Degraded soils exhibit lower productivity and greater variation in productivity when variation in weather occurs
4. Soil aggradation is based on creating a stable microclimate for the soil biological system and facilitated by maintaining a temperature and water regime within optimal ranges
5. Climate resilience is created by providing soil water, nutrients, and oxygen throughout the life cycle of the plant to offset the variation in weather
6. Expected variation in weather due to climate change will increase seasonal variation in temperature and precipitation
7. Enhancing the soil has the potential to decrease variation in productivity except for the extreme events

Research needs and gaps critical to enhance climate resilience in agricultural systems:

1. Determine the rates of soil degradation under different tillage systems and residue removal for a range of soils
2. Determine the rate of soil aggradation under different management regimes and soils to the offset climate variation
3. Evaluate soil erosion rates under different tillage and residue removal practices
4. Evaluate the interaction of climate variation, soil health, and yield variation of different crops to determine the most effective path to increased climate resilience
5. Evaluate the effects of improved soil health on the reduction of risk in production of crops under different climate scenarios
6. Determine the role of genetic resources in enhancing climate resilience

Suggestions for policy include:

1. Provide incentives for reduced tillage and maintenance of residue on cropping areas.
2. Provide incentives for enhanced soil health based on soil carbon and water quality and reduced risk in crop production

Conclusions and suggested next steps

Soil health is critical to climate resilience of cropping systems to variation in weather directly related to climate change. Variation in production is a function of the quality of the soil resource and soil degradation increases the inability of the soil to supply water. Since crop production is dependent upon soil water content, climate resilience is impacted by the inability of the soil to capture and store precipitation for crop water use. Soil degradation is increased by tillage and residue removal and current agricultural practices increase erosion and decrease soil water holding capacity. Increased soil health can enhance climate resilience; however, producers and landowners must become aware that climate resilience can be achieved through adoption of practices that enhance soil biology in their soils.

References Cited

Egli, D.B., and J.L. Hatfield. 2014a. Yield gaps and yield relationships in central U.S. soybean production systems. Agron. J. 106:560-566.

Egli, D.B., and J.L. Hatfield. 2014b. Yield gaps and yield relationships in central U.S. maize production systems. Agron. J. 106:2248-2256.

Hatfield, J.L. 2012. Spatial patterns of water and nitrogen response within corn production fields. In G. Aflakpui (ed.) Agricultural Science Intech Publishers. ISBN 978-953-51-0567-1 pp. 73-96.

Hatfield, J.L. 2014. Soil degradation, land use, and sustainability. In Songstad, D.D., J.L. Hatfield, and D.T. Tomes (eds.) Convergence of Food Security, Energy Security, and Sustainable Agriculture. Springer. New York. Pp. 61-74.

Hatfield, J.L., and J.H. Prueger, 2004: Impact of Changing Precipitation Patterns on Water Quality. J. Soil Water Conserv. 59:51-58.

Hayhoe, K, C Wake, T Huntington, L Luo, M Schwartz, J Sheffield, E Wood, B Anderson, J Bradbury, A Degaetano, T Troy, D Wolfe. 2007. Past and future changes in climate and hydrological indicators in the U.S. Northeast. Climate Dynamics 28:381-407.

Hudson, B.D. 1994. Soil organic matter and available water capacity. J Soil Water Conserv 49:189-194.

Karlen, D.L., L.W. Beeler, R.G. Ong., and B.E. Dale. 2015. Balancing energy, conservation, and soil health requirements for plant biomass. J. Soil water Conserv. 70:279-287.

Lal, R. 2015. A systems approach to conservation agriculture. J. Soil Water Conserv. 70:82A-88A.

Lettenmaier, D.P. D. Major, L. Poff, and S. Running. 2008. Water resources. In The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington DC, 362 p.

Melillo, J.M., T.C. Richmond, and G.W. Yohe. (Eds) 2014. Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment. . U.S. Global Change Research Program, 148 pp.

Steenwerth, K.L., A. K. Hodson, A. J. Bloom, M. R. Carter, A. Cattaneo, C.J. Chartres, J.L. Hatfield, K. Henry, J.W. Hopmans, W.R. Horwath, B.M. Jenkins, E. Kebreab, R. Leemans, L. Lipper, M. N. Lubell, S. Msangi, R. Prabhu, M.P. Reynolds, S. S. Solis, W.M. Sischo, M. Springborn, P. Tittonell, S.M.. Wheeler, S.J. Vermeulen, E. K.. Wollenberg, L. S. Jarvis and L.E. Jackson. 2014. Climate-smart agriculture global research agenda: scientific basis for action. Agriculture & Food Security 3:11 http://www.agricultureandfoodsecurity.com/content/3/1/11

June 24, 2011

July 18, 2012

Michael Forsberg

Located at Audubon's Rowe Sanctuary, this camera location provides a bird's eye view of a braided river channel and shifting sandbars along the central Platte River. The location is also one of several major roosting sites for migrating sandhill cranes during spring migration. Between late February and early April, nearly 500,000 sandhill cranes will use this critical stretch of habitat in south-central Nebraska.

Using the Arctic Oscillation to Improve Agricultural Decisions

Guillermo A. Baigorria[1]
School of Natural Resources and Department of Agronomy & Horticulture
University of Nebraska–Lincoln. Lincoln, NE 68583-0968, USA

Introduction/Background

Crop yield variability in space and time is almost always largely determined by variability in the weather, then by pest and diseases incidence, and the use of inputs and technology (Babb et al. 1997, Wheeler et al., 2000). An excellent forecast of weather conditions for the upcoming agricultural season would be really valuable for farmers as it would promote better decisions about what, when and how to cultivate a crop under the best management program (Quiring and Blair, 2000). Climate systems such as El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) have been demonstrated to considerably influence ecological processes (Stenseth et al., 2003). The El Niño and La Niña episodes affects weather and climate variability worldwide, causing interannual fluctuations of temperature and precipitation (Ropelewski and Halpert, 1989; Quiring and Blair, 2000; Higgins et al., 2007) whereas NAO represents the dominant climate pattern in the North Atlantic and in the Mediterranean, affecting the number and paths of storms and their associated weather (Gordo et al., 2011; Senseth et al., 2003). The Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO) are linked to recent interdecadal fluctuations. PDO is associated with these fluctuations over the western and southern U.S., while the AO is also associated with them but to a much lesser extent over the southeastern U.S. (Higgins et al., 2007).

Teleconnections, or teleconnection pattern, pertains to a persistent, large-scale circulation anomaly within the atmosphere. There are several teleconnections identified around the planet and they directly or indirectly drive the local and regional climate patterns. These patterns last weeks, months or even years and are often referred to as preferred model of low-frequency variability, affecting very large areas, including entire ocean basins (Quiring and Blair, 2000) and directly affecting agriculture. These teleconnections constitute the basis of categorical seasonal climate forecasts (Cabrera et al., 2009; Royce et al., 2011).

CropClimate is a platform intended to produce climate-related useful information for agricultural decision makers at scales finer than county level. Based on the state-of-the-art knowledge in categorical seasonal climate forecasts, soil and agronomic information, and dynamic models and tools; producers, lenders, agrochemical companies, and others can tailor their management and services according to the forthcoming season. By exploring these modeling capabilities CropClimate's focus is to improve field management of food, fiber, and fuel crops for more sustainable production systems. CropClimate.org is part of several tools and methods developed by the International Consortium of Categorical Climate Forecast Applications (IC3FA) lead by University of Nebraska-Lincoln. IC3FA has as objective to use globally available categorical seasonal climate monitoring and forecasts (teleconnection indices) and to translate them into useful information for decision makers.

Discussion of presentation content, key messages, research needs/gaps, policy suggestions (if applicable)

Monthly Arctic Oscillation (AO) indices are constructed by projecting the monthly mean 1000-hPa height field anomalies over 20°N-90°N latitude onto the leading EOF mode. Both time series are normalized by the standard deviation of the monthly index (1979-2000 base period). Since the loading pattern of AO is obtained using the monthly mean height anomaly dataset, the index corresponding to each loading pattern becomes one when it is normalized by the standard deviation of the monthly index. (Higgins et al., 2000, 2001, 2002; Zhou et al., 2001).

[1]Email: gbaigorria@unl.edu   Fax: +(1) (402) 472-2946

The AO is an important Arctic climate index with positive and negative phases, which represents the state of atmospheric circulation over the Arctic. When the AO is in its positive phase, a ring of strong winds circulating around the North Pole acts to confine colder air across Polar Regions. This belt of winds becomes weaker and more distorted in the negative phase of the AO, which allows an easier southward penetration of colder, arctic air masses and increased storminess into the mid-latitudes (http://ossfoundation.us/projects/environment/global-warming/arctic-oscillation-ao). The negative phase brings higher-than-normal pressure over the polar region and lower-than-normal pressure at about 45 degrees north latitude. The positive phase brings lower-than-normal pressure over the polar region, steering ocean storms northward, bringing wetter weather to Alaska, Scotland and Scandinavia, and drier conditions to areas such as California, Spain and the Middle East.

Over most of the past century, the Arctic Oscillation alternated between its positive and negative phases. Starting in the 1970s, however, the oscillation has tended to stay in the positive phase, causing lower than normal arctic air pressure and higher than normal temperatures in much of the United States and northern Eurasia (http://ossfoundation.us/projects/environment/global-warming/arctic-oscillation-ao). While the value of the AO index was strongly positive in the early 1990's compared to the previous forty years, the value of the AO has been low and variable for the last nine years (http://www.arctic.noaa.gov/detect/climate-ao.shtml). However, due to the warming effects of climate change it is projected to have an increase in the number of negative phases of AO.

Together with soils, genetics and management, crop yields are the crop response to the aggregated effect of daily weather during the cropping season and even few months before planting (soil moisture). Although some specific weather event such as a freeze event or hail can cause a crop to fail, yields cannot be link to a specific behavior of a given meteorological variable (e.g., corn yields in the Midwest do not depend on July's rainfall). Climate effects on crop production is not linear, and complex processes must be taken into account before attempting to use climate to predict yields.

Teleconnections vary on their level of persistence, from multidecadal (e.g. Atlantic Multidecadal Oscillation - AMO) to monthly (NAO, AO, etc). Depending on the crop, a crop season varies in length, from almost a month (e.g. radish) to several years (e.g. sugar cane). It also varies on 'when' the crop season begins, from large scale signals (e.g. spring in the northern hemisphere begins on March whereas in the southern hemisphere begins in September) to short scale signals (e.g. latitudinal effect of Sun's movement on melting frozen soils). To be able to measure the effects of climate in agriculture, it is necessary to match the spatial-temporal teleconnection signal window with both, the spatial-temporal crop season window and the specific crop requirements. For instance, after sowing, winter wheat needs to accumulate chilly units on freezing temperatures to be able to emerge; for other crops, same temperatures after sowing will kill the embryos within the seed.

AO changes due to climate change can affect differently to different crops and even the same crop at different regions. For instance; current corn varieties planted in most of the USA will be negatively affected by the projected changes to a more frequent negative phase of the AO; whereas winter wheat will be mostly positively affected (Figure 1). The effects of AO and other teleconnection indices on crops can be analyzed with information provided by CropClimate.org.

Thus it is possible to project the positive and negative effects of changes on teleconnection indices on different crops across all USA. What is important is that, within certain level of flexibility, crop management can be adjusted according to the upcoming season-by-season climate. Decisions of what to plant, when to plant, the selection of crop variety and crop insurance, investment in irrigation systems, etc., are some examples of decisions that can be improved by using simulation platforms such as the one provided by CropClimate. This climate to crop-management translation platform can be used by producers at field level, and by government agencies, financial institutions and private industries when the information is aggregated at country level as shown in Figure 1. Knowing the projected crop yield changes in the season by season levels as well as the long term level will allow to fit better products and support for producers and to guide future research in agriculture.

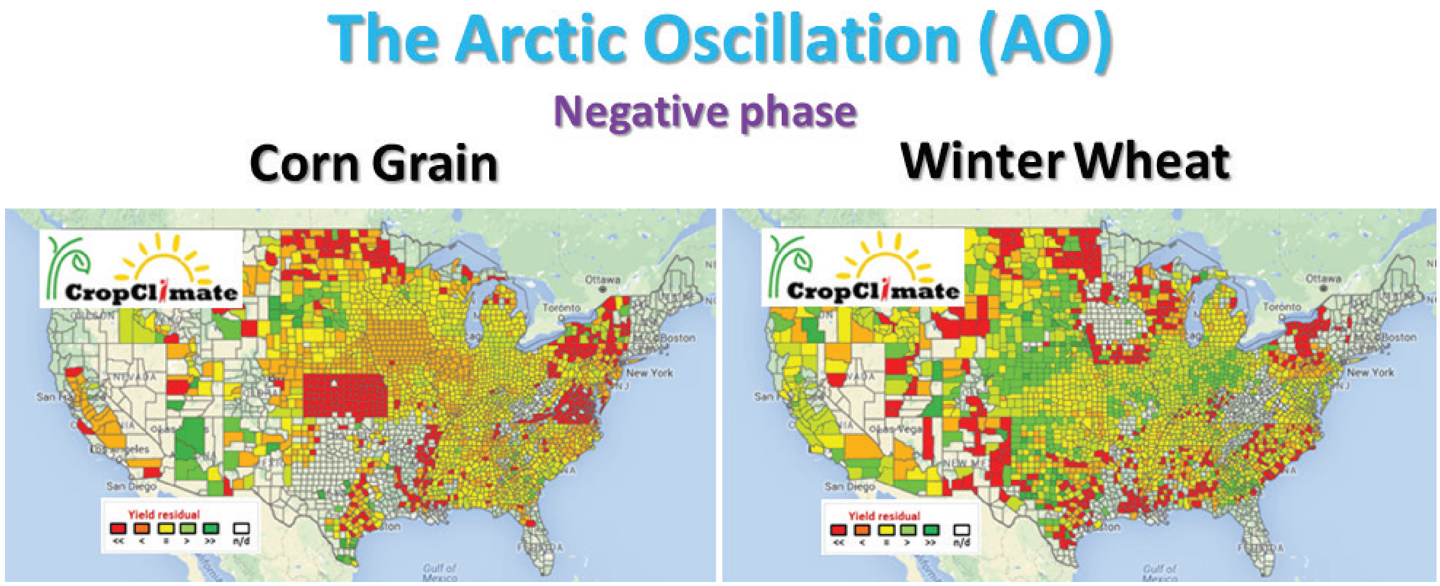


Figure 1: Inverse effect of the Arctic Oscillation negative phase on corn and winter wheat production in the USA.

Conclusions and suggested next steps

CropClimate should be considered and used as the USA's Agricultural Early Warning System to explore the season-by-season effects of climate on agriculture and to guide producers and decision makers at all levels in planning the near to long term future of food production and security in the USA.

The extrapolation of CropClimate-USA experience to other countries members of the International Consortium of Categorical Climate Forecasts Applications (IC3FA) will allow USA to lead the international efforts on food security under projected climate change.

References Cited

Babb, J.C., M.L. Khandekar, and E.R. Garnett. 1997. An analysis of PNA indices for forecasting summer weather over the Canadian prairies with implications for wheat yield and protein. Presented at: The Long-Range weather and Crop Forecasting Workshop, Dorval, Quebec, October 1997.

Cabrera, V.E., D. Solís, G.A. Baigorria, and D. Letson. 2009. Chapter 7th: Managing Climate Variability in Agricultural Analysis. In: Long, J.A. and Wells D.S. (Eds). Ocean Circulation and El Niño: New Research. p. 163-179. Nova Science Publishing, Inc. Hauppauge, NY.

Gordo, O., C. Barriocanal, and D. Robson. 2011. Ecological Impacts of the North Atlantic Oscillation (NAO) in Mediterranean ecosystems. In: Vicente-Serrano, S. M., Trigo, R. M. (eds.) Hydrological, socioeconomic and ecological impacts of the North Atlantic Oscillation in the Mediterranean Region. Advances in Global Change Research 46, doi 10.1007/978-94-007-1372-7_11, Springer Science+Business Media B. V.

Higgins, R. W., A. Leetmaa, and V. E. Kousky, 2002: Relationships between climate variability and winter temperature extremes in the United States. *J. Climate*, 15, 1555-1572.

Higgins, R.W., Y. Zhou and H.-K. Kim, 2001: Relationships between El Niño-Southern Oscillation and the Arctic Oscillation: A Climate-Weather Link. NCEP/Climate Prediction Center ATLAS 83.

Higgins, R. W., A. Leetmaa, Y. Xue, and A. Barnston, 2000: Dominant factors influencing the seasonal predictability of U.S. precipitation and surface air temperature. *J. Climate,* 13, 3994-4017.

Podestá, G., D. Letson, C. Messina, F. Royce, R.A. Ferreyra, J.W. Jones, J.W. Hansen, I. Llovet, M. Grondona, and J.J. O'Brien. 2002. Use of ENSO-related climate information in agricultural decision making in Argentina: a pilot experience. Agric. Sys., 74:371-392.

Quiring, S.M. and D. Blair. 2000. The utility of global teleconnection indices for long-range crop forecasting on the Canadian Prairies. In: Romanowski, J. I. (ed.) Prairie Perspectives: Geographical Essays. Vol. 3. Prairie division, Canadian Association of Geographers. Available at http://geography.tamu.edu/class/squiring/docs/quiring.pdf.

Ropelewski, C.F., Halpert, M.S., 1989. Precipitation Patterns Associated with the High Index Phase of the Southern Oscillation. J. Climate 2, 268–284.

Royce, F.S., C.W. Fraisse and G.A. Baigorria, 2011. ENSO classification indices and summer crop yields in the Southeastern USA *Agricultural and Forest Meteorology*, 151: 817-826.

Stenseth, N.Ch., G. Ottersen, J.W. Hurrell, A. Mysterud, M. Lima, K.S. Chan, N.G. Yoccoz, and B. Ådlandsvik. 2003. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Niño Southern Oscillation and beyond. Proc. R. Soc. Lond. B 270:2087-2096.

USDA-NASS (United States Department of Agriculture – National Agricultural Statistics Service), 2009. 2007 Census of Agriculture. United States Summary and State Data. Volume 1: Geographic Area Series – Part 51. Washington D.C. pp. 739.

Zhou, S., A. J. Miller, J. Wang, and J. K. Angell, 2001: Trends of NAO and AO and their associations with stratospheric processes. *Geophys. Res. Lett*., 28, 4107-4110.

Brett Hampton

Center pivots are used extensively in Nebraska.

Trends in Climate Teleconnections and Effects on the Midwest

[2]Donald J. Wuebbles and Zachary Zobel
Department of Atmospheric Sciences, University of Illinois, Urbana, Illinois, USA

Introduction/Background

Quantifying the relationship between global-scale anthropogenic forcing and its implications for atmospheric circulation patterns, specifically upper level wave patterns, is a challenging research area. Much of the research connecting human-induced warming to changes in atmospheric circulation has focused on the Arctic, as this area has been warming a rate much greater than that in the mid-latitudes. Various studies have suggested that this "Arctic Amplification" is not only resulting in a rapid melting of Arctic sea ice especially during the summer months, but could also be amplifying the jet stream in the months that follow (e.g., Francis et al 2009). A more amplified planetary wave pattern tends to result in more regional weather extremes, such as an increase frequency of precipitation anomalies and extreme temperatures (Screen and Simmonds, 2014, Overland et al., 2015). While model results have yielded some evidence that low sea ice summers in the Arctic can contribute to increased planetary wave amplification, the observational evidence remains somewhat inconclusive and highly debated (e.g., Screen et al., 2012, Mori et al., 2014, Jaiser et al., 2011, Porter et al., 2011, and references therein).

This study examines the connection between sea ice concentration in the Beaufort and Chukchi Seas north of Alaska and height anomalies in the following winter and early spring using NCEP (NOAA National Center for Environmental Prediction) reanalysis data. Most of the atmospheric wave amplification in modeling studies has the common theme of occurring within close proximity to summer sea ice negative anomalies (e.g., Screen et al., 2012). Modeling studies have been beneficial in this area because observational evidence is challenging due to the short time scales over which reanalysis and satellite data have both been available and reliable. With that being said, recent research has shown some robust changes in atmospheric circulation using reanalysis data (e.g., Francis and Vavrus 2014). Mori et al (2014) performed a similar study to this one over a different region of the Northern Hemisphere. They ran model simulations using the European reanalysis to conclude that changes in the Berents-Kara Sea ice concentration is affecting jet stream amplitude in Eurasia and subsequent weather patterns. That study also found there are downstream implications to localized amplification. Our study evaluates similar implications for the Midwest.

To start, we examine teleconnections height anomalies across the eastern Pacific Ocean have on regional precipitation. While doing this, we examine the possibility that, even without the effect of long-term ocean cycles, there is still a strengthening ridge south of Alaska that can be correlated with rapid sea ice loss over the previous three decades. We tested precipitation patterns in the climate regions across the United States for correlation to the geopotential height anomalies at these locations. Similar to previous studies on storm track, we examine how height anomalies in these locations affect storm track across the continental United States, CONUS (e.g., Bhatt et al. 2008; Screen 2013; Inoue et al 2012). This is done by testing the statistical significance of the correlation coefficient between monthly precipitation data and geopotential height anomalies. The goal in the first part of the discussion is to show that height anomalies within these areas can directly affect the precipitation throughout some regions of the United States, but that it is regionally dependent.

Outside of the potential seasonal forecasting applications from this research, we seek to determine whether there is a potential for semi-persistent long term ridging in the Pacific Ocean during these winter and early spring

[2]Contact information for Dr. Wuebbles: (217) 244-1568, his office at the University of Illinois, and (217) 840-0100, his mobile phone (best when he is in Washington, DC., or elsewhere).

months. This would have long-term impacts on regional and seasonal precipitation patterns throughout the United States. Our goal is not to pick one area and show that blocking patterns have increased or decreased at that location, but rather, to show that several consecutive months have experienced semi-persistent ridging over the past couple decades in similar locations. It can be hypothesized that, despite a ridge being centered at slightly different locations from month to month, there will still be climate altering affects to regional precipitation. Since the time period for this analysis is brief, we must consider the affects the SOI (Southern Oscillation Index) and PDO (Pacific Decadal Oscillation) cycles have on height anomalies in our domain. During the time period for this analysis, SOI shifts from primarily negative values, indicative of El Niño, to primarily positive La Niña years in the 2000s. This could lead to signals of false increases in the geopotential height anomaly count within the focus area. We develop an equation that empirically removes the role SOI has on the geopotential height field in these boxes. This tells us the robust climate signal without the influence of this long term ocean cycle.

Finally, it is at this point that we will examine the possibility that changes in the synoptic pattern are influenced by localized rapidly decreasing sea ice concentrations during the last two decades in parts of the Beaufort and Chukchi seas. We examine if there is statistical significance to sea ice north of Alaska during August and September to height anomalies within our area of interest during the winter and early spring. The highest correlations to late summer sea ice concentration and height anomalies should be during the wintertime based on results from previous research (e.g., Francis et al, 2009).

Results/Discussion

A ridge off of the west coast has long been tied to drier conditions in the western part of the U.S. (e.g., Bhatt et al. 2008). This is true for several grid boxes in this analysis during January through March, but especially in January. The results indicate that the driest years will occur when the most significant ridging takes place in these areas. There is also a noticeable downstream effect on precipitation in much of the Midwestern parts of the country, but especially, the Upper Midwest. These results are a reversal of sign from the West, indicating that strong positive height anomalies at these locations in February and April acts to bring heavy precipitation to these regions. Naturally, downstream effects on precipitation are less than the regions closest to the height anomalies. The remaining climate regions in the United States saw little or sporadic significance.

We show that SOI (ENSO) has strong connections to the height anomalies, especially in late winter. Our research shows that a time series of seasonal January-February-March-April (JFMA) SOI, using a running mean to eliminate some natural variability in the index, indicates that from 1979 to 2014 there is a steady increase with little variability. PDO has an inversely proportional trend to SOI. As we can show, the two indices are in phases that are closely tied to one another for sea surface temperatures in this part of the Pacific. SOI and PDO historically have been shown to go through long term cycles that are longer than our 36 year data period. The equation we develop is important to the analysis so that we can examine the climate signals after reducing the effects ocean cycles have on geopotential height in the Pacific. This equation successfully reduces all statistically significance SOI has on these grid boxes as well as greatly reducing the effect of PDO. After removing the SOI influence, there is sufficient evidence in the yearly and running means that there are at least modest increases in geopotential height anomalies during winter and early spring independent of these long term ocean cycles.

Our monthly results include sea ice concentration correlation with these height anomalies. These values show that there is a connection between sea ice concentration north of Alaska in the late summer months with the following winter and spring height anomalies. Like previous attempts to link the sea ice concentrations to height anomalies, the strongest significance to wave patterns occur in late winter and the beginning of meteorological spring. These correlation coefficients have confidence levels of at least 95% for at least one grid box in all four months. Attempting to correlate sea ice with localized geopotential height anomalies in the Pacific Ocean isn't a new idea, but the procedure used seems to be a relatively new way of quantifying the link. The connection between an increasing ridge and decreasing sea ice could be important for forecasting purposes, especially long term when issuing seasonal forecasts. This would have hydrological impacts for the United States, but especially, in the western part of the country. The primary long-term forecasting applications this research could have will be the focus of future projects.

After looking at monthly teleconnections for these anomalies, there is a possibility that some regions could have multi-month periods of evolving precipitation patterns leading to increased potential for long-term floods and droughts. JFM height anomalies are strongly connected with region precipitation in the West and Southwest. The confidence level of 99.9% for January-February-March (JFM) precipitation in the western part of the country means that if ridging continues to develop, seasonal dry conditions will continue for these regions. This is of great concern, especially for California, because the majority of their precipitation usually falls during these months and is vital for water in the region. Snowfall in the Sierra Mountains during these months eventually become one the primary water source for California in late spring and during the summer as the snow melts (Segal, 2013).

After adjusting the height anomalies to remove the effect of SOI, the contribution of sea ice to increased seasonal ridging remains at a confidence level of 99%. The high confidence between the two suggests that sea ice acted to increase the amplitudes of ridges forming in these months, while modulating any troughs that formed. The main uncertainty here is an insufficient amount of years. Like previous studies on this subject, the greatest changes in the amplification have taken place in the past decade and a half. Our results also show that most of the sea ice concentration loss north of Alaska has occurred since the summer of 2000. This coincides with the time period of significant changes to upper level jet stream patterns presented here as well as other research on this topic. (e.g., Francis et al 2009)

While the confidence levels are less for downstream impacts on seasonal precipitation, there are statistically significant results especially for Upper Midwest climate region. February has the highest confidence level that precipitation patterns are affected by ridging in the Pacific Ocean. February shows the most confidence in its connections to decreasing sea ice as well as high confidence the running means trending upward. Further research is needed, but this could hint at stronger, or more frequent, February Midwestern snowstorms as ridging increases in these areas. There are more influences on precipitation during April for the Upper Midwest leading to the belief that flooding conditions during the melting season could become an issue in the future decades.

Conclusions and Next Steps

Significantly decreasing sea ice concentrations north of Alaska in parts of the Arctic Ocean as well as the Chukchi and Beaufort Seas is aiding in the amplification to wave patterns in the North Pacific off of the west coast of the CONUS. Even when the effect of ocean cycles, such as PDO and SOI, are empirically removed from the height anomalies, a robust climate signal of increasing height anomalies is still being observed. This research provides increased confidence expressed in previous research that Arctic amplification is affecting wave patterns across the Northern Hemisphere (e.g. Francis et al., 2009). The increased ridging off of the West Coast of the United States not only affects the climate regions adjacent to that location, but also has downstream impacts on precipitation. This has major hydrological implications on the ongoing drought in the West Coast as well as late winter precipitation increases for the Upper Midwest. In 2012, R2 (NCEP-DOE Reanalysis 2)data shows that sea ice in late summer was so low that the area north of Alaska was almost entirely ice free. The following winter and spring of 2013 the jet stream over most of the United States saw the most amplification during our 36 year analysis. With that being said, this sample size of ice free years is not adequate. At some point in the near future, August and September sea ice concentration for this part of the Arctic will be near zero most years as Arctic amplification continues to warm this part of the World at a much faster rate. Some research suggests that the Arctic could be ice free frequently during the summer occurring sometime in the next 2 to 4 decades (Wang and Overland 2009; Stroeve et al. 2007). When this happens on a regular basis, it is unclear how much more the wave pattern will be affected. Based on this research there is marginally high confidence that years like the amplification seen in 2013 and much of the last decade will become more frequent.

Regarding future research, we would like to look more into the forecasting applications. For example, could using sea ice concentrations actually improve seasonal forecasts for certain regions more than just using the ENSO. Also, knowing the phase of PDO seems to be important. How does that factor into it? Also, we would like to look at surface temperature. Surface temperature will likely have better correlations with these amplified patterns than precipitation. We would like to see if understanding these concepts can better forecast winter temperatures in the Midwest.

References

Barnes, E. A., Dunn-Sigouin, E., Masato, G., and Woollings, T., 2014: Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters*, 41(2), 638-644.

Bhatt, U. S., Alexander, M. A., Deser, C., Walsh, J. E., Miller, J. S., Timlin, M. S., ... and Tomas, R. A., 2008: The atmospheric response to realistic reduced summer Arctic sea ice anomalies. *Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications,* 91-110.

Francis, J. A., Chan, W., Leathers, D. J., Miller, J. R., and Veron, D. E., 2009: Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent. *Geophysical Research Letter*s, 36(7).

Francis, J. A., and Vavrus, S. J., 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, 39(6).

Francis, J. A., and Vavrus, S. J., 2015: Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, 10(1), 014005.

Jaiser, R., Dethloff, K., Handorf, D., Rinke, A., and Cohen, J., 2012: Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation. *Tellus A*, 64

Mori, M., Watanabe, M., Shiogama, H., Inoue, J., and Kimoto, M., 2014: Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades. *Nature Geoscience*.

Overland, J. E., and Wang, M., 2010: Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus A*, 62(1), 1-9.

Overland, J., J. Francis, R. Hall, E. Hanna, S. Kim, and T. Vihma, 2015: The Melting Arctic and Mid-latitude Weather Patterns: Are They Connected? J. Climate. doi:10.1175/JCLI-D-14-0082.1, in press.

Porter, D. F., Cassano, J. J., and Serreze, M. C., 2012: Local and large-scale atmospheric responses to reduced Arctic sea ice and ocean warming in the WRF model. J*ournal of Geophysical Research: Atmospheres (1984–2012)*,117(D11).

Screen, J. A., 2013: Influence of Arctic sea ice on European summer precipitation. *Environmental Research Letters*, 8(4), 044015.

Screen, J. A., and Simmonds, I., 2014: Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nature Climate Change*, 4, 704-709

Screen, J. A., Simmonds, I., Deser, C., and Tomas, R., 2013: The atmospheric response to three decades of observed Arctic sea ice loss. *Journal of Climate*, 26(4), 1230-1248.

Segal, M., 2013: The Prophet of California Climate: A Dialogue with Bill Patzert. *Los Angles Magazine*.

Stroeve, J., Holland, M. M., Meier, W., Scambos, T., and Serreze, M., 2007: Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters*, 34(9).

Wang, M., and Overland, J. E., 2009: A sea ice free summer Arctic within 30 years? *Geophysical Research Letters*, 36(7).

July 31, 2011

September 25, 2013

Michael Farrell

Sunshine Beach is a public use area on Seminoe Reservoir just upstream from the dam and power plant. The shallow bay in the foreground shows water level fluctuations throughout the year, caused by decisions about how much water to store and how much to release in the 1.0 million acre feet Bureau of Reclamation reservoir.

Drought-Fusion: A Union of Past and Present Drought Characteristics and their Impacts

Mark Svoboda, Michael J. Hayes and Won-Ho Nam
National Drought Mitigation Center, University of Nebraska–Lincoln, School of Natural Resources

Introduction
Daniel Connell, a research fellow from the Australian National University, posits that "societies will manage climate variability and potential changes in climate in the same way that they manage droughts, for better or worse". Looking more deeply along those lines, one can certainly see the analogy and parallel themes linking the characteristics of drought and climate change. Droughts typically evolve slowly and can cover large areas, potentially affecting millions of square miles and millions of people while lasting months or years in the process. In addition, the cross-cutting nature of drought across many economic sectors, coupled with both direct and indirect impacts, makes drought stand out as one of the most costly of all hazards around the world, year in and year out. Planning and preparing for future droughts builds more resilient societies, not only for drought events but also for other extreme events and the effects of climate change.

The mission of the National Drought Mitigation Center (NDMC) is to help people lessen their vulnerability to drought through a proactive drought risk management approach. As a boundary organization, the NDMC works with a variety of stakeholders at all scales in order to help better translate drought science to the media, public, and policy/decision makers. To help accomplish this, the NDMC serves as a developer, integrator and conveyer of a variety of tools and methods as a means of creating *value added and usable information* to a variety of audiences through a variety of dissemination vehicles. Stakeholder input and feedback takes place from the onset in the development of a variety of decision support tools, databases and web portals. This *"fusion"* (Fig. 1) of drought information is packaged and presented through a variety of data, decision support tools, resource guides and a web portal, which are all aimed at helping people understand, monitor and prepare for drought. The NDMC serves as a catalyst in this process given its role in working with the National Integrated Drought Information System (NIDIS) along with a variety of local, state, federal and regional organizations as well as individual producers and citizens.

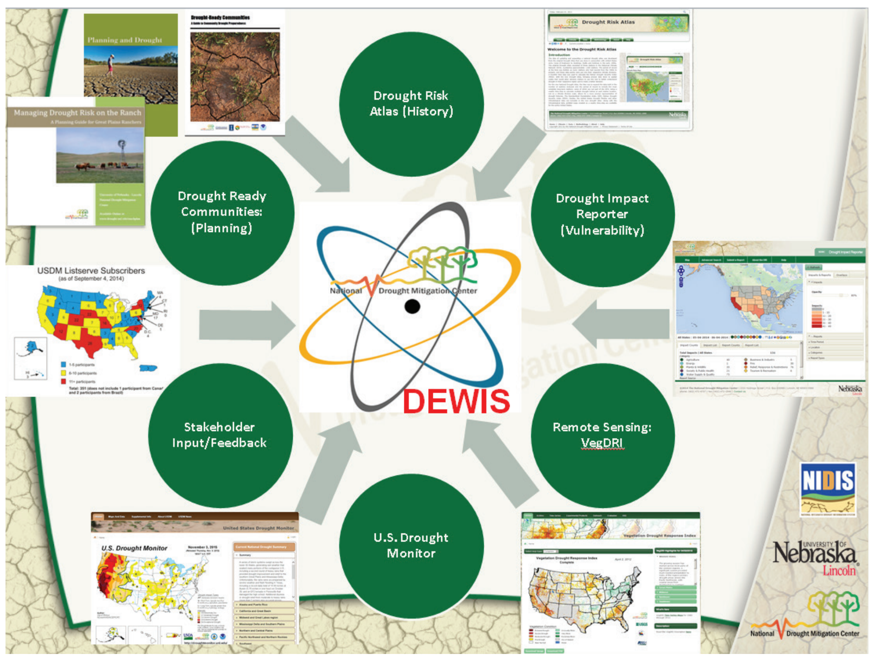


Figure 1. The NDMC develops and integrates a variety of drought products and tools as a means of producing value added and usable drought science information. This "fusion" process leads to a more comprehensive Drought Early Warning and Information System (DEWIS) approach.

What Can We Learn from the Past?
We know from studying various pre-instrumental proxy data (e.g. tree rings, ice cores, lake sediment cores) that droughts have the potential to last several decades. Paleoclimate data have shown that these multi-decadal

"mega-droughts" were prevalent over multiple regions at one time. The impact today of such droughts on a pan-continental scale would no doubt lead to impacts beyond anything reported in the modern era. In fact, the roughly decade long Dust Bowl drought of the 1930s would pale in comparison to these paleo mega-droughts of the past (Figure 2). Given the fact that climate is always changing, and is a moving target for planners and managers, one of the challenges that global warming presents is in how we use and trust these paleo data in planning and designing water systems for the future.

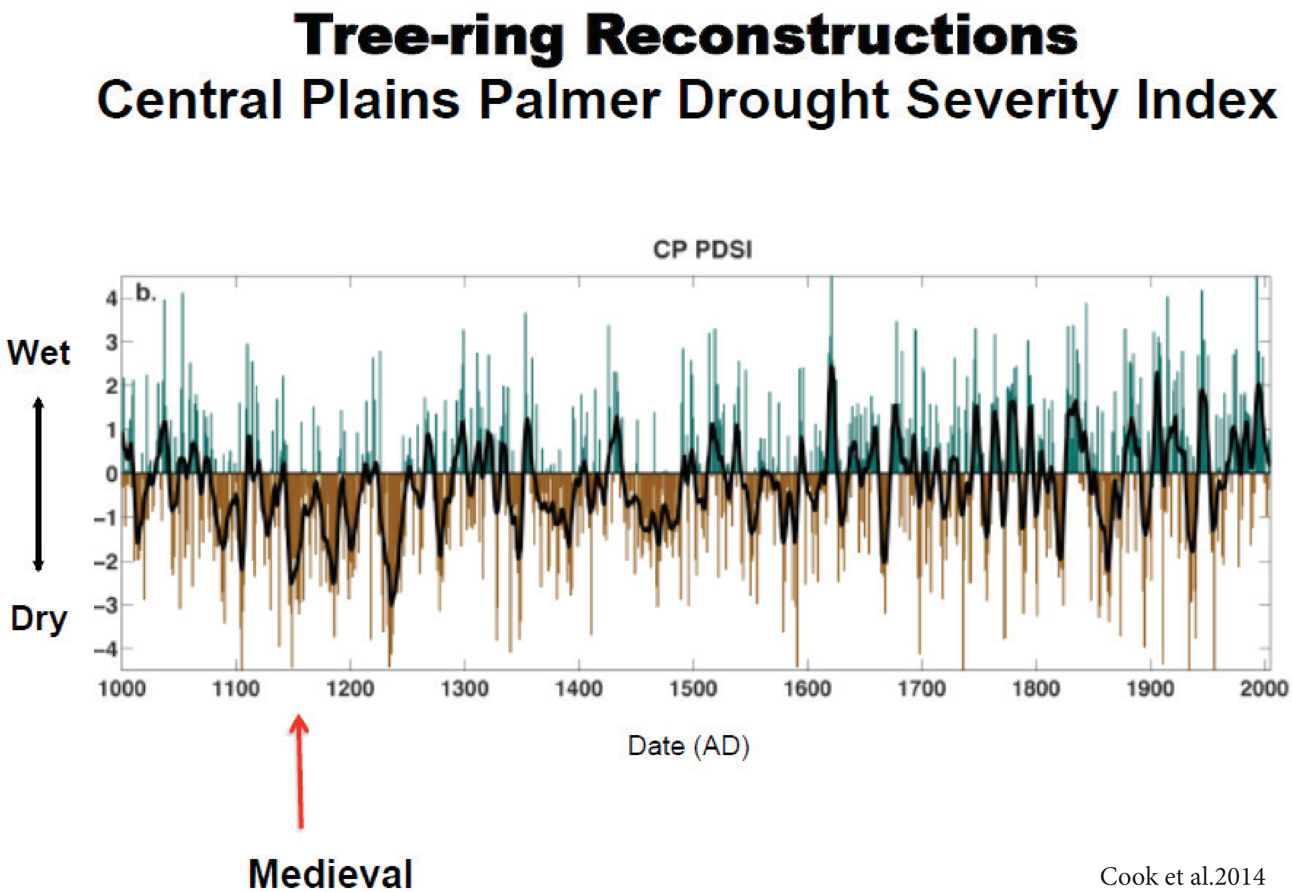


Figure 2. Paleo droughts can be determined from "proxy" data such as tree rings to reconstruct historical drought indicators such as the Palmer Drought Severity Index. The arrow points to the Medieval Warm Period, a time when droughts were more prevalent across the central Plains.

Drought in the Instrumental Past

Drought, a temporary aberration, is a very normal part of the climate cycle. As illustrated in Figure 3, we can see the ups and downs of drought over the instrumental era. As noted earlier, the Dust Bowl years of the 1930s stand out clearly, peaking at about 80% in the mid-1930s. What we shouldn't ignore is that there are many other examples of large-scale, intense droughts, such as the 1950s, late 1980s and more recently in the early 2000s, including 2010-2015 droughts of the southern Plains, Midwest/central Plains and the western drought in California, Nevada, Pacific Northwest and surrounds.

Understanding our risk of exposure to drought, along with the impacts that can accompany such events, is an important part of the drought risk management approach. Knowing our "drought climatology", along with the return intervals (frequency), duration, severity and other characteristics can help planners revise or develop drought plans.

As a way of helping people assess their risk to drought exposure, the NDMC has created a National Drought Risk Atlas (DRA) (http://droughtatlas.unl.edu). The DRA was launched in 2014 and contains over 3,100 long-term, high quality climate reference stations across the country. Over 1 billion climate/drought indice records and gridded maps have been archived and are freely accessible from the web interface. The DRA contains drought index values for the Standardized Precipitation Index (SPI), Standardized Precipitation and Evapotranspiration Index (SPEI), Deciles, Palmer Drought Severity Index (PDSI) and the self-calibrated PDSI.

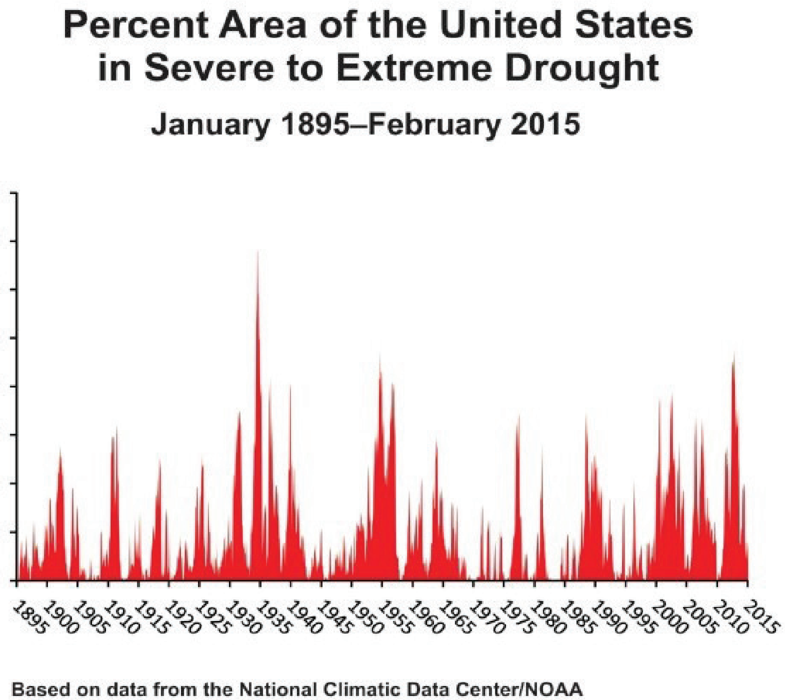


Figure 3. Time series of the PDSI from the historic instrumental record for the U.S.

The DRA was created to help answer questions such as:

- How does the current drought ***compare*** to other droughts ***historically***?
- When was the ***last time*** a drought like this happened?
- ***How often*** (frequency) does a drought of this magnitude happen?
- Are we seeing ***any trends or characteristic changes*** in drought frequency or magnitude?
- What did the ***spatial footprint*** of the last drought look like?

For this initial study, the DRA was used (Fig. 4) to analyze and look for any changes in drought characteristics such as frequency, duration, intensity and magnitude.

Time series for Urbana, Fairmont and Geneva were run using the various indices contained in the DRA. Figure 5 shows time of drought in red and periods of wetness in blue. Those times when all three locations shared drought or pluvial (wet) periods are indicated by the shaded yellow (dry) and blue (wet) bars indicating that these conditions were widespread across most of the north-central U.S. at the same time. Not surprisingly, the Dust Bowl years of the 1930s stand out as do those in the 1950s, 1988-89 and the recent drought of 2012. The larger wet patterns are found in the early 1950s, mid-1970s, early 1980s and then again in the early 1990s with 1993 being a very wet year.

So how does the recent drought of 2012 compare to the more iconic Dust Bowl year droughts? 2012 was a remarkably hot and dry year for many locations in the north-central U.S. and country in general as shown in Figures 6 and 7. In fact, Nebraska (and Wyoming) observed both its driest and hottest year on record in 2012. For the north-central region, 6 states (IL, KS, MO, NE, OH and SD) recorded their hottest year on record and the remaining states (ND, MN, IA, WI, MI and IN) came in at either their second or third hottest year with records for all states going back to 1895. For 2012 as a whole, the southern tier states came in with dryness around or below their top ten driest years. Keep in mind that these numbers reflect annual totals and as such don't take into account the actual timing of this drought, which came at a critical time of the growing season and peaked between June and September. The seasonal ranks for summer 2012 indeed showed dryness across the entire north-central region with Nebraska, South Dakota, Iowa and Missouri all experiencing top five record dryness for the June-August period.

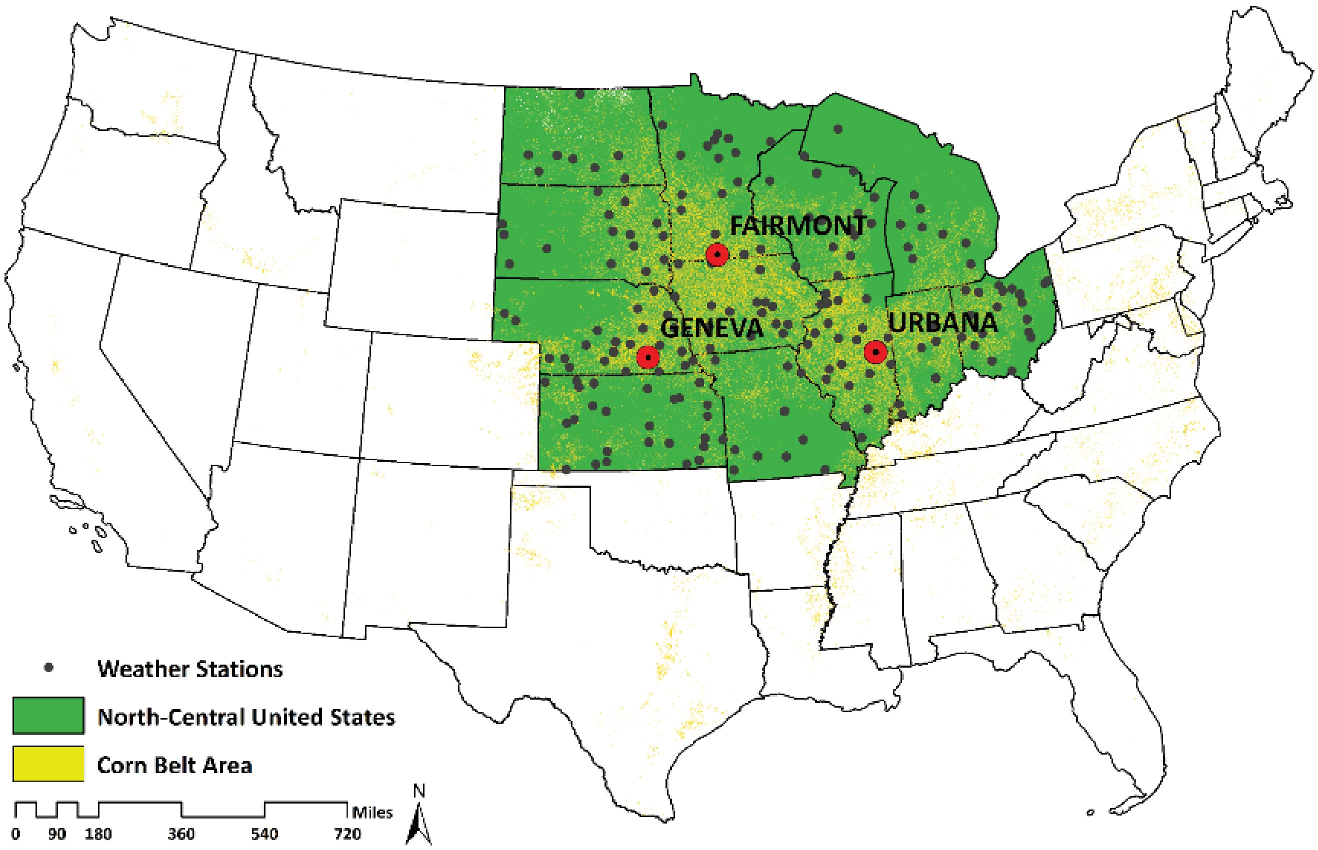


Figure 4. 186 climate stations from the NDMC's Drought Risk Atlas were selected for the North-Central U.S. having a period of record of 1911-2012. Case study results focused on locations in Illinois (Urbana), Minnesota (Fairmont) and Nebraska (Geneva).

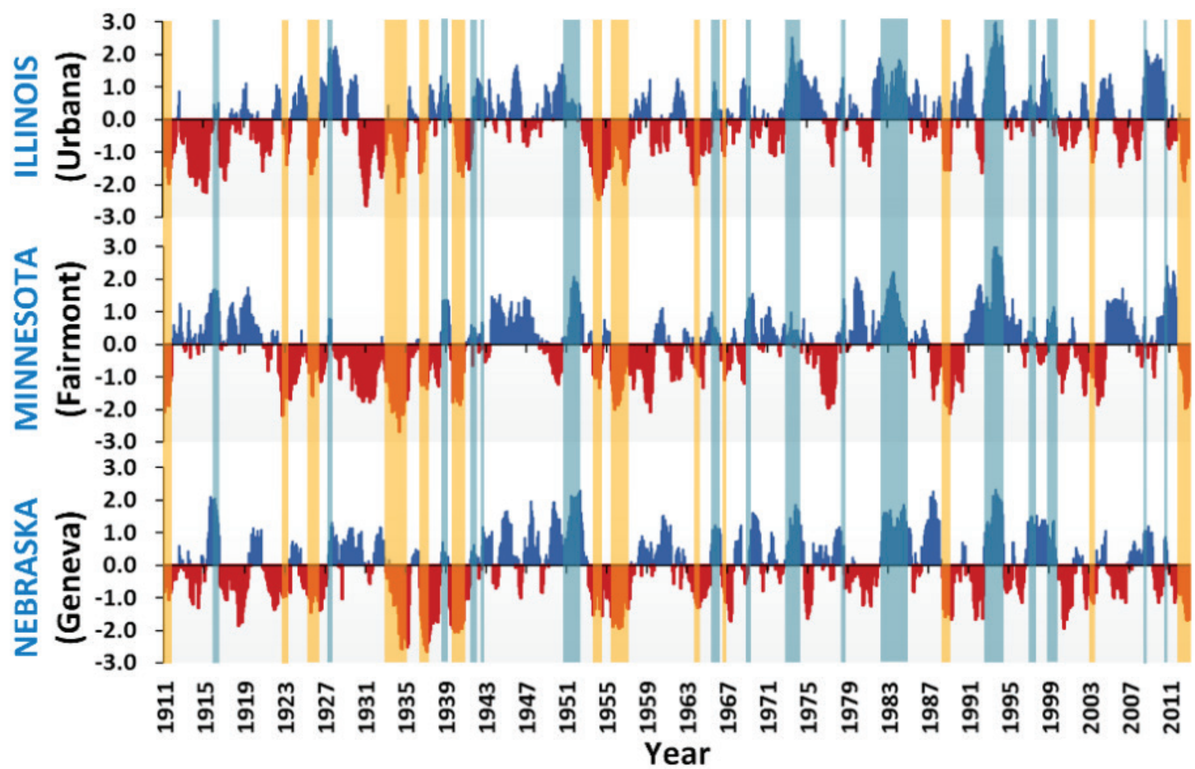


Figure 5. Drought indices for locations in Illinois, Minnesota and Nebraska as determined by the SPEI (12-month) in the North-Central U.S. (3 STATES) during 102 years (1911-2012) of historical record. Station data are taken from the Drought Risk Atlas.

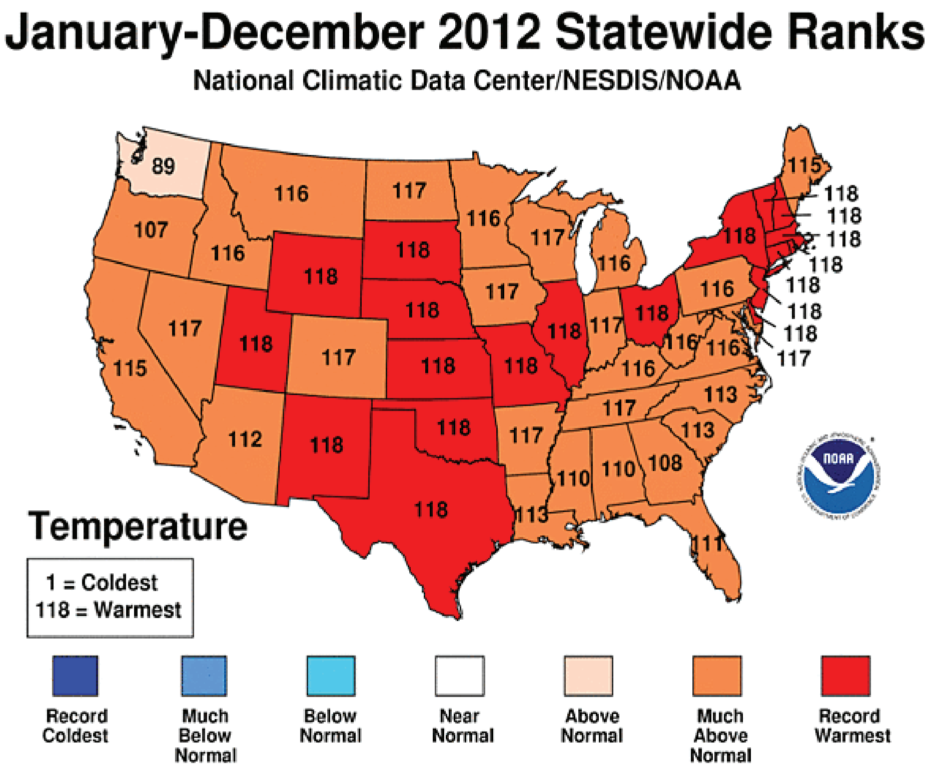


Figure 6. Statewide temperature rankings illustrating how the drought of 2012 historically hot across the country's mid-section and most everywhere else. Source: National Climatic Data Center (NCDC), now the National Centers for Environmental Information (NCEI).

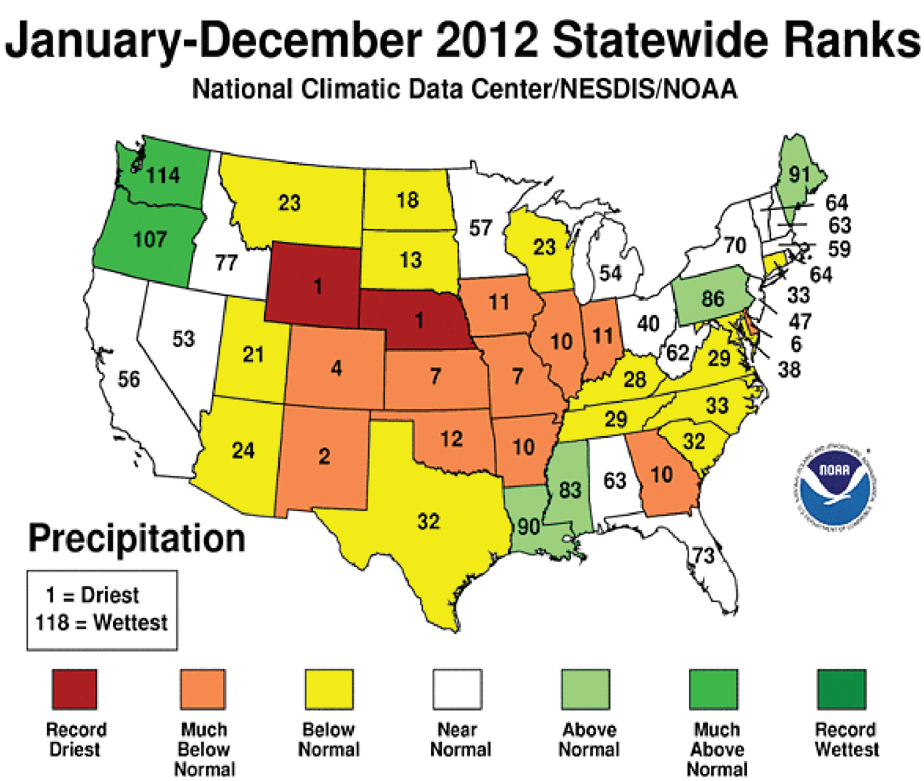


Figure 7. Statewide precipitation rankings illustrating how the drought of 2012 was fed by top ten dryness across the country's mid-section. Source: National Climatic Data Center (NCDC), now the National Centers for Environmental Information (NCEI).

The question that comes to mind a lot is can/does the "flash drought" of 2012 serve as a potential harbinger of future droughts in a warming world given the influence of depleted soil moisture levels and record setting heat during the growing season? Many annual record hot and/or dry years were broken for several locations during 2012, for a one year period only. The fact that the persistent, multi-year duration component was lacking, which means as a whole the magnitude of the 2012 drought and its characteristics don't lend itself well to those of the 1930s, which were decidedly of greater duration and thus magnitude.

In order to capture these larger drought footprints, we focused on the entire region in this initial analysis and in the future we will be looking at state, basin or other various sub-regional breakdowns along with other parts of the U.S. You can see from Figure 8 that 2012 brought drought to nearly two-thirds of the country. The timing (summer/growing season) and rapid development (flash drought) caught many off-guard in the north-central region given the wet period that proceeded it. At its peak, nearly 90% of the U.S. corn producing areas was in drought and this applied to many other commodities as well as livestock.

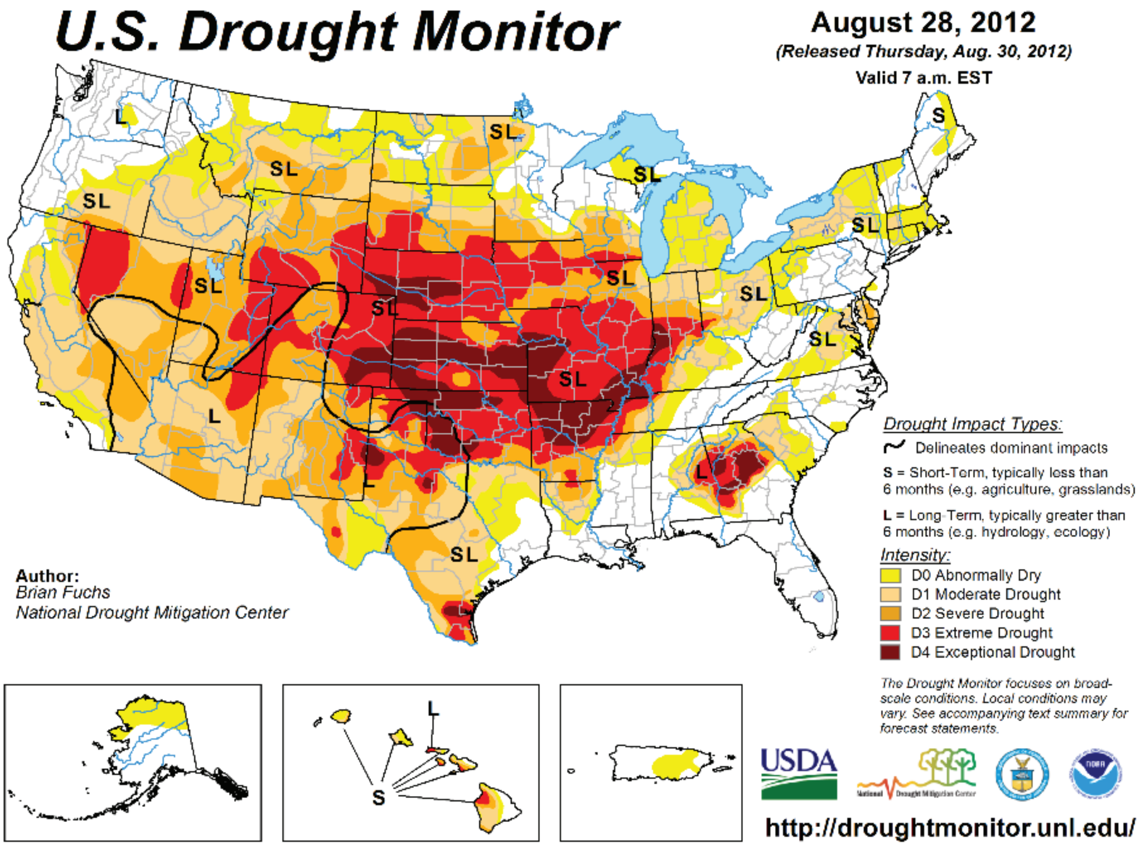


Figure 8. The U.S. Drought Monitor showing the extent of drought across the country as of August 28, 2012. Over 62% of the Lower 48 states were in at least moderate (D1) drought, marking the highest percent of the country in drought since the Dust Bowl years of the 1930s.

Final Thoughts

Are we on the precipice of seeing how drought characteristics today may be a harbinger of future droughts due to a warming world? Only time will tell, but perhaps no other hazard like drought today that we have to deal with and plan for can come close to the challenges that climate change will pose.

The linkages between drought, water, food security, and climate change illustrate complex problems, from which solutions are going to depend on the information and integration that partnerships and networks provide. In the end, it all comes down to the water, a commodity taken for granted all too often. Droughts can often force conflicts over water and can provide us lessons on how to better manage this precious resource in the future.

The Physics of Great Plains Drought: Its Predictability and Its Changed Risk in a Warmer World

Martin Hoerling[1] and Ben Livneh[2]*

[1]NOAA Earth System Research Laboratory
[2]University of Colorado-Boulder, Department of Environmental and Civil Engineering

1. Background

Drought is broadly understood to be a condition of deficient moisture in the land surface (e.g. Wilhite and Glantz 1987), a natural hazard associated with agricultural loss, water resource shortfalls, and other economic impacts. The Great Plains, a region of primary US grain production especially corn and soybeans in its central portions, has a distinct rainy season coinciding with its growing season of May through August. Grain yields are highly sensitive to the meteorological delivery of timely and abundant rains.

In this presentation on the physics of drought, based largely on the study by Livneh and Hoerling (2015), we focus on the land surface sensitivity to meteorological drivers, particularly precipitation and temperature. A set of questions regarding the nature and understanding of drought are posed, answers to which are sought via a set of land surface model (LSM) simulations driven by meteorological data derived from historical observations, climate model simulations, and scenarios of plausible future change.

Are droughts and rainfall deficits synonymous? While it is well established that summer rains are critical moisture sources for the land surface supporting agricultural productivity especially in the Corn Belt (Wallace 1920), temperature is also a critical variable particularly in late summer (Thompson 1962). Here we explore the joint influence of temperature and precipitation on the land surface response during drought, focusing initially on the 2012 Great Plains drought as a recent case.

Is the drought prediction problem merely the seasonal rainfall prediction problem? As indicated in historical LSM experiments (Livneh and Hoerling 2015), soil moisture is persistent on multi-seasonal time scales, and thus its initial value is often a useful predictor of drought regardless of subsequent meteorological conditions (see also Quan et al. 2012). Here we show the physical links between antecedent conditions and severe summertime Great Plains drought.

How will Great Plains drought change as climate warms? LSM simulations using prescribed scenarios of temperature and precipitation change are diagnosed, and inter-compared to projections of drought change in the Great Plains based on coupled climate models driven by projections of future greenhouse gas emissions (Cook et al. 2015).

2. Discussion

a. A Case study of the 2012 Central Great Plains drought

A previous study on the meteorological causes of the 2012 drought characterized the event as a "flash drought" that developed suddenly (Hoerling et al 2014). The event was preceded by near normal antecedent precipitation during winter and spring, offering little apparent forewarning of the subsequent failed summer rains. The spring of 2012 was, however, unusually warm. Large portions of the Corn Belt from eastern Colorado to Ohio recorded their warmest March/April since record keeping began in 1895. Was the land surface materially dried by these

* Dr. Martin Hoerling, 325 Broadway, Boulder Colorado 80305; martin.hoerling@nooaa.gov

antecedent temperature conditions, and how important were those for the drought risk in the subsequent summer as compared to the impact of failed summer rains?

Two different Land Surface Models (VIC and the Unified Land Model [ULM]) were driven by daily observed meteorological forcing at a ~ 50 km scale from 1950-2013. The 1-meter depth soil moisture variability during 2002-2013 over the Central Plains agrees well among the two models and also with independent satellite estimates using the terrestrial water anomalies of the Gravity Recovery and Climate Experiment (GRACE) satellites.

A key finding from the land models is that the high spring temperatures did not materially reduce antecedent soil moisture. The subsequent summer drought, and severe soil moisture deficits, were largely the result of diminished rains. The summer temperatures were also near record highs, and the VIC simulations indicate that while approximately 70% of the Great Plains soil moisture was precipitation driven, 30% was related to evapotranspiration resulting from increased atmospheric demand owing to the heat (ULM indicated even greater relative precipitation sensitivity).

The nature of summer drought in the Great Plains is typically one in which low rainfall and high temperatures coexist. Diagnosis of the physics of that link indicates that most of the Great Plains summer temperature variability is itself a consequence of how rainfall alters the surface energy budget. As such, the net effect of failed rains in 2012 on the drought was found to be larger than the 70% estimated from the LSM simulations.

b. General Characteristics of Central Great Plains drought

To overcome the limited sample size of observed Central Plains droughts, the meteorological and land surface variations occurring in large ensembles of historical atmospheric model simulations (AGCM) are diagnosed. A total of 1050 years of model data for the climate conditions spanning the post-1979 period are studied. The AGCM's daily meteorology is also used to drive VIC simulations for this same 1050 years of data to explore uncertainties in land surface response to meteorological forcing.

The presentation explores the role of initial land surface conditions for the AGCM 1% simulated driest, and also for the 1% of AGCM simulated hottest summers (May-August), totaling 10 events for each (e.g. 1% of 1050 years). Consistent with case study results of 2012, the summers having lowest rainfall also exhibited among the lowest soil moisture by summers end, affirming again the prominence of precipitation control on the land surface and the associated drought severity. Antecedent soil moisture was found to be quite variable, and of limited predictive value for the summer rainfall.

By contrast, the hottest summers exhibited somewhat more variable soil moisture deficits in summer, though all were below normal. The result indicates that hot summers are usually linked with low rainfall in the central Plains (as in 2012), with the rainfall mainly driving the soil moisture deficits rather than the temperatures driving the soil moisture deficits. Interestingly, the antecedent conditions for these hottest summers were much more constrained than for the driest summers--- large spring soil moisture deficits occurred in all of the 1% hottest summers. This indicates the important effect of soil moisture on the surface energy balance that largely dictates the intensity of heat waves in general, and during droughts in particular.

Results of the surface energy balance, based on the model data, provide insight on the physics of drought, and clarify the link between summer droughts and heat waves over the Central Plains. We find a linear relation between soil moisture and rainfall deficits in summer over the Great Plains. By contrast, a nonlinear relation exists between soil moisture and surface temperature, with a rapid escalation in the magnitude of heat waves for incrementally drier land surface conditions as one progresses from moderate to severe drought. This is a symptom of the nonlinear relation between surface sensible and latent heat flux, or more generally between soil moisture and the Bowen ratio, which becomes asymptotically large (i.e. sensible heat flux exceeding latent heat flux) as soil moisture progressively dries.

c. How Will Great Plains Drought Change as Climate Warms?
The projected effect of increasing greenhouse concentrations is to warm the Central Plains and the planet overall (IPCC 2013). Summer temperatures are expected to increase by more than 4°C by the end of the century under an aggressive RCP8.5 emission scenario, though the magnitude of the warming varies among models. The projected change in rainfall is far less certain for the Central Plains, with even the sign of mean summer rainfall change uncertain. Cook et al. (2015) analyzed the result of a subset of the CMIP5 climate models subjected to RCP8.5 emissions scenarios, and determined that high future emissions would lead to unprecedented drought conditions during the last millennium. Their diagnosis of the climate models suggests a high risk of multi-decadal droughts occurring over the Central Plains during the last half of the 21st Century exceeding persistent droughts of the Medieval era. The physics of this is argued to result from an acute land surface drying resulting from the high surface temperature. It is important to note, however, that not all models used in their study (17) yielded such a strong sensitivity of drought risk, even though all models warm---indicating that open questions remain on the physics of land surface responses to meteorological forcing.

In this presentation, we show 1-m soil moisture responses of VIC to a range of surface warming scenarios from +1°C to +4°C. Also shown are the results for changes in precipitation from -20% decline to a +20% increase. These roughly capture the range of projected Central Plains climate changes and also the range of multi-decadal variability in historical rainfall. The results indicate that a 10% change in mean rainfall has a greater effect on soil moisture than even a +4°C warming. A warming of +4°C alone, in the absence of rainfall change, is found to reduce soil moisture, but with a magnitude that is appreciably less than 0.5 standardized departure of the historical soil moisture variability over the Great Plains. This sensitivity is considerably less than implied by the results of Cook et al. (2015).

3. Conclusions and Next Steps
Land surface model simulations indicate precipitation explained in excess of 70% of soil moisture depletion during the 2012 summer Great Plains drought, and drove most of the Central Plains soil moisture variability since 1950. Physical considerations and energy balance calculations reveal that growing season temperature variability is strongly driven by precipitation, indicating that the net effect of rainfall on soil moisture is appreciably greater than 70%.

A nonlinear relationship between soil moisture and the Bowen ratio of sensible to latent surface energy flux indicates an amplifier of heat waves during severe drought conditions. The record hot summer in 2012 is thus seen as largely consistent with the record low rainfall and resulting dry soil moisture conditions.

Antecedent wintertime-spring soil moisture conditions affect growing season drought probabilities, and appreciably affect summer temperature though having less of an effect on summer rainfall.

Within a paradigm where precipitation deficits are the principal underlying cause for drought in the Great Plains region, near-future semi-permanent drought conditions, as suggested by Cook et al. (2015) are unlikely given the intrinsic variability in precipitation. The analysis presented herein finds that under various scenarios of future warming, the land surface response of our land surface models is appreciably smaller than the effect of interannual and decadal rainfall variations, implying low detectability of drought changes for the foreseeable future.

Next steps will involve better understanding the physical reasons for differences among climate model projections of Great Plains drought change. It was also noted in the presentation that Great Plains summer temperature have not warmed during the last century, a situation that appears inconsistent with that expected from effects of GHG forcing to date. Detailed study is needed to explain this “warming hole”, and determine whether it has been a climate surprise of a highly variable Great Plains climate, or may be an artifact of changes in forcing including land use and land cover that may not be well represented in climate models at this time.

4. References

Cook, B. I., T. R. Ault, and J. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci. Adv.,* 1:e1400082.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, R. Seager, 2014: Causes and Predictability of the 2012 Great Plains Drought. *Bull. Amer. Meteor.* Soc., 95, 269–282. doi: http://dx.doi.org/10.1175/BAMS-D-13-00055.1

IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. and Co-authors. (Eds)],

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Livneh, B., and M. Hoerling, 2015: The Physics of Great Plains Drought. J. Climate, submitted.

Quan, X.W., MP Hoerling, B Lyon, A Kumar, MA Bell, MK Tippett and H Wang, 2012: Prospects for Dynamical Prediction of Meteorological Drought. *J. Appl. Meteorol. Climatol.* , 51 (7) 1238-1252, issn: 1558-8424, ids: 978TR, doi: 10.1175/JAMC-D-11-0194.1

Thompson, L. M., "An evaluation of weather factors in the production of corn" (1962). CARD Reports. Book 10. http://lib.dr.iastate.edu/card_reports/10

Wallace, H. A., 1920: Mathematical Inquiry into The Effect of Weather on Corn Yield in the Eight Corn Belt States. *Mon. Wea. Rev*., 48: 439-456.

Wilhite, D. A. (1987). Drought in the Great Plains: a bibliography. *In Drought in the Great Plains: a bibliography.* University of Nebraska.

Pete Souza, White House photographer

The view from Air Force One of Kivalina Island, an Arctic town that's receding into the ocean as a result of rising sea levels.

Summary of Breakout Discussions

In the afternoon of November 11th, two groups formed to discuss key issues related to water resources and agriculture. These were structured conversations around prepared questions, facilitated by four conference attendees with expertise in these areas. There were about 30 participants in each group. What follows are summaries of the two discussions.

Water Resources Group

Key Concerns for the Water Resources Sector in Association with a Changing Climate

1. *Water Availability.* The issue of how to utilize our groundwater supply in the Central Plains amid increasing drought conditions is a prime concern. There were serious concerns about decreased future snowpack in the Rockies and its implications for the Central Plains. Management practice considerations need to balance short-term concerns with longer-term. The question was raised about at what point it would no longer be prudent to drill and pump water (water mining concerns).

2. *Water Management and Policy.* Issues of water rights, competition between users, water use allocations, infrastructure and water policy are key. Surface and groundwater resources are separate legally, but in natural systems they intersect. The question of who owns water rights and of one region sending water to another will be ongoing issues to address as the climate changes. It was noted that interstate compacts and decrees are based on a wet record from the past, which may now be incorrect. The difference between consumptive use and re-use needs to be explored. It is critical to understand the intervals between the two extremes (drought and excessive precipitation), if possible, in order to make informed decisions for management practices. Conservation practices could be implemented as part of city policies. There are competing needs between agriculture, environment, municipalities, energy generation and navigation in Nebraska and in other states in the region. These conflicts are likely to become more pronounced in coming decades. The need to prepare for more frequent flooding events is also an issue. Maintaining bridges and other infrastructure in floodplains is critical.

3. *Water Quality.* There is an increased probability of sediment and other pollutants in our water supply in the future. Flooding may exacerbate water quality concerns.

4. *Energy Use.* There are concerns about increased demand for electricity across sectors, which may strain our energy supply.

Primary Mitigation and Adaptation Actions

1. *Conservation.* Decrease consumptive use of water. Increase storage (surface or underground). Policy. Policies need to be re-examined, including government, management and pricing policies. The issue of realigning private property rights in relation to water rights should be examined. Proactive drought and flood planning is needed. The design of floodplain maps should be Water supply planning should also incorporate climate change information.

2. *Plant Adaptation.* Crops could be adapted to a changing climate through genetic engineering.

3. *Infrastructure.* New infrastructure needs to be designed for increased future extremes.

Data and Information Needs for Effective Climate Responses

1. *Planning for Future Variability.* It is agreed that climate variability cannot be predicted. However, planning for the future must continue. Various planning methods should be explored to determine which strategies are most robust in face of uncertainty in order to make good decisions. The areas of uncertainty should be characterized. Short-term versus long-term climate impacts need to be addressed.

2. *Soil, Water, Land and Weather Data.* Data needs include the following:
    a. Soil moisture monitoring
    b. Land use data
    c. More streamflow gauges/groundwater measurements
    d. Understanding subsurface geology and surface water/groundwater interactions

3. *Inter-Sector Communication.* There is a need for increased communication between and among sectors, agencies, organizations and academic institutions to share the most current and relevant data. Interdisciplinary communication at academic institutions should be improved. There is a need for the co-production of information in order to produce useful answers for management – actionable science.

4. *Social Science.* There is a need for social science research on exposure and vulnerability to climate changes. There is also a need to articulate social values regarding climate change, i.e.,, how do social values intersect with expected changes in climate to determine what should be our priorities for implementing adaptation and mitigation options.

Key Communication Strategies to Promote Changes in Water Management Practices

Various communication strategies were shared by the discussion participants:

1. Leverage trusted sources (e.g. local universities, local water providers, extension agents). Local credibility is important. Scientists and researchers need to communicate with these trusted sources.
2. Communicate at the level your audience understands.
3. Make academic work accessible.
4. Make it safe for scientists to be protected from retaliation.
5. Talk about potential climate impacts first rather than the science. A bottom-up approach that encourages taking action is more effective than losing people in the science. Communicate what will happen and when and be honest about it.
6. Communicate the immediacy of the problem – this is a problem now, and it is also a global problem.
7. Separate climate change from climate variability; explain the difference between weather and climate.
8. In Nebraska, share stories of who fared better and worse during the historic 2012 drought to better inform management practices.
9. Express that there are climate winners and opportunities in the midst of the changes.
10. Foster interagency and inter-entity collaboration and a bottom-up approach.
11. Collect polling information and share it.
12. Find a way to reach the climate change dismissive groups as well as the accepting groups.

Research Gaps and Priorities

1. Researchers should work more closely with managers concerning questions that involve actionable science. There is a need for researchers to find out what kinds of information are needed for specific scenarios.
2. Social scientists should be engaged (e.g. how people will be impacted, how to communicate information effectively).

3. Cost-benefit analyses are needed (e.g. estimate of economic risks due to climate change).
4. Inter-agency communication-- and error propagation that can emerge-- through interagency efforts very important.
5. Ecosystem forecasts/impacts, pest management.
6. Implications to legal system from future uncertainties.
7. Consideration of the best institutional setting (public or private) for managing drought in Nebraska (government, co-op, NGO, etc.) Scale is important. Managing our natural resources is key.
8. Land-surface models need improvement – there is difficulty in getting subsurface information.
9. The problem has become translating science into political will.
10. Soil moisture at all scales.
11. Global climate models: sea ice, snow cover, general precipitation (and downscaling issues).
12. Warm season convective precipitation research needed.
13. Carbon cycling, sequestration (how we manage carbon).
14. Overlapping water and agricultural research (policies cannot exist in silos).

Policy Options

1. Change the Farm Bill.
2. Start with local policy.
3. Science education at all levels (esp. K-12).
4. Funding is needed for an effective climate change program.
5. A serious reexamination of the governance system of higher education is needed to make it safe to speak openly.
6. Strongly advocate long-range planning at all levels.
7. Policy options need to be scaled (near- to long-term).
8. Millennials should be involved in policymaking.
9. Bring adaptive management into water laws.
10. Push back on anti-government culture.
11. Place a price on carbon.
12. Changing water supplies will impact the global economy and international relationships.
13. Policy changes are needed to address the fossil fuel industry.
14. Campaign finance reform is needed.
15. University of Nebraska could divest from fossil fuels.

Agriculture Group

Key Concerns for the Agriculture Sector in Association with a Changing Climate

1. *Water Availability.* Agriculture is dependent on water resources. Snowfall in the Rocky Mountains directly affects surface water availability. Nebraska's irrigation needs are high. The changes in the Arctic will likely change water availability or alter its distribution and timing for mid-latitude agriculture. Warmer temperatures may mean less snow, and/or earlier melting. We need more storage capacity to hold water longer. The bigger question is whether circulation patterns will change. The vast majority of pine forests are dead due to pine bark beetle infestation—this changes the surface albedo and runoff patterns and rates, contributes to earlier melt-off. The size of current water storage facilities may not be appropriate for the future. Greater swings from wet to dry periods may make water management more difficult. Increasing climate variability has an impact on many management decisions. With increasing demands for water, the way water is allocated to ecosystems in the future will need to be reevaluated. Bioenergy brings increased demand for water. Nebraska is the highest ranking state for groundwater pumping; the current rate of pumping is not sustainable. Less than 1% of Nebraska municipalities use surface water.

2. *Flooding.* Currently, all dams are full in the Platte River watershed, and we are anticipating a full snowpack. There is the question of where that water will go. Extreme flooding events will become more common in coming decades.

3. *Cropping Systems.* Will we be able to grow the same crops? The Corn Belt is moving north. Can a longer growing season be taken advantage of in management decisions? In some cases, crops can be planted earlier, but in other cases not. We need to question this assumption that we will still be able to grow corn for people and animals. Will it be appropriate to grow corn in the climate of the future? We are close to reaching temperature thresholds whereby we will not be able to keep up with irrigation needs. Grain yields go down with higher nighttime temperatures. There may be physiological reasons to shift away from corn as well as other reasons. Geneticists can tell us whether we can keep modifying corn to grow in new environments. The Farm Bill is key- if we decide to support growing other crops, there can be changes.

Primary Mitigation and Adaptation Actions

1. *Crops.* New types of plants should be explored for changing climates. Cropping patterns need to be more resilient. Planting could go back to perennial vegetation. Crop failure due to extreme weather events is a growing concern. Crop insurance is beginning to recognize this fact.

2. *Water Management.* The Natural Resource Districts (NRDs) in Nebraska are unique. They are watershed-based water management entities. The lessons learned from the NRDs may make them important models for other states. The NRDs oversee a system of monitoring wells. Regulations are based on these and crop irrigation requirements. The NRD system is unique and provides an example of leadership in managing groundwater. The NRDs have taxing authority. The NRDs have developed several incentive programs. They buy down water allocation rights. They would like to switch out water-intensive crops in western Nebraskaand have in place mechanisms to encourage that practice. They do retirements of groundwater and leasing of surface water. There is a very diverse aquifer system in Nebraska which prevents much groundwater pumping in some locations.

3. *Soil Health and Land Management.* Increasing soil resilience is a key need. Carbon sequestration in agriculture must be considered. Some land should be converted to pasture. The USDA has ten building blocks for adaptation- increase acreage in grasslands, pasture, easements, etc. Methods for sequestering carbon in agriculture need to be explored. Agroforestry is a big part of the solution.

4. *Livestock.* Livestock needs have to be considered along with agriculture with future climate changes.

5. *Policy*
    - The NRDs should do more to incorporate climate change planning into their long-term plans. They spend a lot of time talking about floods but not enough time talking about drought. Their charge is to protect groundwater. It has been politically too easy to ignore climate change for fear of conflict. NRDs are required to update their hazard mitigation plan every five years; a climate change action plan should become a component of all strategies.
    - FEMA requires a hazard mitigation plan from every state and county to qualify for federal funding. This is a way to deal with infrastructure needs.
    - Farm Bill. Changes to the farm bill to encourage different crops would make the biggest difference. This is difficult; the attention of policy makers and media tends to follow population centers. It seems more difficult than ever to make changes to the Farm Bill given political realities.

Data and Information Needs for Effective Climate Responses

- Soil moisture data.
- Groundwater levels. Some NRDs require meters on groundwater. Studies show that landowners will use less water if they know how much they are using.
- Weather data. More weather stations are needed in Nebraska. The new Nebraska State Climate Office can work with NRDs to set up more stations. There are soil moisture monitoring stations at 60 locations in Nebraska. COCORAHS is a resource for precipitation monitoring. Some remote sensing is being used for precipitation data; this technique requires more research in order to be more useful for monitoring precipitation. There is a need to match those who are managing water with those who are monitoring. Scientists need to know more about stakeholder use- how they use data to make decisions.
- Foodshed. We need to rebuild our foodshed in Nebraska. We don't grow food here; we grow commodities. We rely on grocery stores for our food. It is not sensible to rely on California for our food – we need to grow the fresh produce that we need. Local food fits into mitigation strategies
- Usable climate data. Farmers need usable, reliable, and consistent information to make long-term planning decisions. Many decisions are made from a series of incremental changes, all of which need to be informed by good data and predictions.. Farmers tend to think that climate scientists vary wildly in their predictions, when this is not the case—we need more coherent and usable data for producers. It is very important to track needs to stakeholders. It is helpful to identify short-term, mid-term and long-term scales.
- Empower farmers. Corporations are key players who need to be engaged. A lot of times it is the big agriculture companies who in effect are doing the decision-making for farmers. There is a need to put the decision-making back in the hands of the farmers.
- Sustainable agriculture. Sustainable agriculture is growing in Iowa and Nebraska. There is a much wider array of choices in local food growing than is commonly thought. It fills a desire that many people have who go into agriculture. This is a mitigation strategy. Current monoculture operations are not set up to incorporate livestock. Diversified small family farms were better resource managers.

Key Communication Strategies to Promote Changes in Agricultural Management Practices

- *Proactive Communication.* Temperature forecasts might suggest shifting the growing season—but this may not align with precipitation patterns. How can we manage water differently to prepare for an earlier growing season? It is hasn't warmed very much in the Great Plains yet, but it might accelerate. Can we get people to buy into adaptation strategies before the issues become evident?
- *Usable Data.* Climate data needs to be packaged so that it is usable. Linda Prokopy's work is an example of what we need more of- engaging social scientists and bridging the gap between scientists and users.
- *Reaching the intended audience.* Who helps to disseminate climate information? Farmers go to retailers and crop insurance folks, not always to extension—usable climate data must tap into those networks to reach our targeted population. Farmers can play a big part in mitigating C02 with carbon sequestration through plant matter. Nebraska's rural poll showed that 61% of rural Nebraskans support a climate action plan. This should include increasing our soil health through increasing biological activity. The series of sector-based roundtables the University of Nebraska hosted in fall 2015 are an effort toward the development of a climate action plan. FFA, faith communities, rural orgs should all be working on communicating about climate change.
- *Predominance of Corn Growing May Need to Change.* The University of Nebraska supports increasing irrigated agriculture around the state. This is no longer appropriate given the implications of

climate change to the state. The government's support of corn and soybeans limits options for change. Much of the university's grant funding—as well as climate scientists' grant funding—is tied to the support of corn and soybeans.

Research Gaps and Priorities

- Carbon Sequestration
- Diversified cropping systems- economic impacts and climate impacts. There is interest in the question of how different cropping patterns could actually affect the climate. We have made so many changes to the land that have already had an effect on our climate.
- Renewable energy storage.

Policy Options to Consider

- Changing the Farm Bill.
- Climate Action Plan. Have stakeholders talk about it? There will be so many demands on limited resources that we need to set priorities.
- We need Gene Takle's decision wheel diagram to apply to infrastructure decisions based on climate change.
- Renewable Fuel Standard needs to be reexamined. Forty percent of corn goes to ethanol.
- Renewable Energy Development. Incentives for wind farms in NE are needed. Sales tax abatement is in place but there are not many incentives. Incentives are dependent on the federal Production Tax Credit. The issue with wind farm development is that the energy transmission is difficult; there are not enough transmission lines in rural areas. There are bottlenecks in transmission on the national energy grid. How can we change policy to facilitate more renewable energy?
- New paradigms for decision-making. We need ways to make decisions based on a lot of uncertainty. We already have lots of uncertainty in other areas in which we make decisions. Insurance industry understands the issue of probabilities and risk. We need to apply this kind of decision-making to agriculture.
- There needs to be an organized and cohesive push from the public to demand that elected leaders deal with climate change in a long-term way. We are notoriously bad at looking into the future and making long-term decisions. It is much easier as a public official to defer decisions to a later time.
- Universities need to have the mindset that they not only do the research but they also must be engaged in the evaluation of policy options. They are still trusted sources of information and can make a very positive impact.

Chuck Kennedy, White House photographer

A sea lion watches from the rocks.

Recommendations and Next Steps

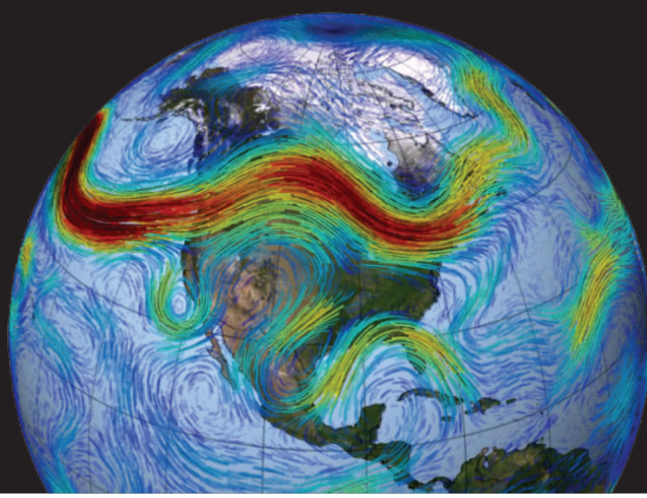
1. Consider scale (local to global)
    a. Could have a broader, national workshop on this topic
    b. Engage other nations dealing with Arctic issues
    c. How to do this at a small scale too (e.g., Nebraska) – people's world view really drives what they are doing; engage citizen scientists to do politics
2. Engage with NGO sector
    a. They should be in the conversation, they can help reach the public
    b. But they often do not adapt national strategies and goals to local/regional scale
3. Create actionable science and engage stakeholders through NWS
    a. NWS WFOs (Weather Forecast Offices): improve forecasts based on climate information, can amplify message through media
    b. Communication has improved across agencies and sectors – agencies that we've never engaged with before
    c. Use recent events as a tool to engage the public
4. Reconvene this group within a year
    a. Reconvene to discuss progress (perhaps update on dynamic conditions that change during U.S. chairmanship of Arctic Council)
5. Move breakout group discussion points forward regionally
    a. University working group to ensure these items get addressed – maybe through climate resiliency group at UNL within Extension – climate change is an issue team, although you could argue it would play a role in most of them
6. Foster discussion to break down barriers of mistrust between scientists and public
7. Conduct co-produced, interdisciplinary research
    a. Incorporate temperature change/connections with Arctic research, not just precipitation, to help with agricultural decisions
    b. Social science research needed to bridge gap between when a decision is needed and when a product is received (physical/social science must be integrated from the beginning)
8. Create internal working group to reconcile all this information
9. Develop a University of Nebraska (and other universities) climate action plan
    a. Many people rely on land-grand institutions for guidance and leadership because they know more about their region than anyone else, and they have more resources – what they're doing for the citizenry to help them cope
    b. Bring together mid-latitude land-grant universities on this topic

Chuck Kennedy, White House photographer

The President's boat heading toward Bear Glacier.

Workshop Program

Implications of a Changing Arctic on Water Resources and Agriculture in the Central U.S.



November 10-12, 2015
Nebraska Innovation Campus
University of Nebraska-Lincoln

University of Nebraska Lincoln

School of Natural Resources
High Plains Regional Climate Center
National Drought Mitigation Center
Office of Research and Economic Development
Institute of Agriculture and Natural Resources

Water for Food
ROBERT B. DAUGHERTY INSTITUTE
at the University of Nebraska

Robert B. Daugherty
Water for Food Institute

NOAA/National Integrated Drought
Information System (NIDIS)

USDA/Office of the
Chief Economist

Share with: #ArcticUNL

Tuesday, November 10

8:00-8:30 Registration

8:30-9:00 Welcome and Opening Remarks

Don Wilhite, Professor, Applied Climate Science, School of Natural Resources, UNL
Martha Shulski, Director, High Plains Regional Climate Center, UNL
Roberto Lenton, Executive Director, Daugherty Water for Food Institute, University of Nebraska

9:00-10:00 An Arctic Connection to Extreme Weather in Mid-Latitudes: New Evidence, Mechanisms, Metrics, and Emerging Questions

Jennifer Francis, Research Professor, Department of Marine and Coastal Sciences, Rutgers University

10:00-10:30 Refreshment Break

10:30-12:00 Implications of a Changing Arctic on Mid-Latitude Weather Patterns and Climate Extremes

Michael Hayes, Director, National Drought Mitigation Center, UNL (Moderator)

Arctic Change and Possible Influence on Mid-latitude Weather Extremes
Judah Cohen, Principal Scientist,Climate Analysis Group, Atmospheric and Environmental Research

Science of Arctic Change-Implications for Central U.S. Water and Agriculture
Marty Hoerling, Physical Sciences Division, NOAA/ESRL

12:00-1:30 Lunch

1:30-3:00 Building Resilience to a Changing Water Regime: Implications for Water Resources in the Great Plains and Midwest Regions

Roberto Lenton, Executive Director, Daugherty Water for Food Institute, University of Nebraska (Moderator)

Implications of Extreme Climate Events for Water Management and Policy
Richard Palmer, Director of the DOI Northeast Climate Science Center, University of Massachusetts

A Fresh Look at Central U.S. Extreme Precipitation Trends
Ken Kunkel, NOAA's National Centers for Environmental Information

3:00-3:30 Refreshment Break

3:30-5:00 Building Resilience to a Changing Climate Regime: Implications for Agriculture in the Great Plains and Midwest Regions

Mark Brusberg, Deputy Chief Meteorologist, USD (Moderator)

Healthy Soils as the Cornerstone of Climate Resilience forAgriculture
Jerry Hatfield, Research Plant Physiologist, National Laboratory for Agriculture and the Environment, USDA/ARS, Ames, Iowa

Using the Arctic Oscillation to Improve Agricultural Decisions
Guillermo Baigorria, Crop Simulation Modeler, UNL

Discussant: **Gene Takle,** Director, Climate Science Program, Iowa State University, Ames, Iowa

5:00-6:30 Dinner: Banquet hall, Nebraska Innovation Campus

7:00-8:30 Public Lecture: Crazy Weather and the Arctic Meltdown: Are they connected?

Jennifer Francis, Research Professor, Department of Marine and Coastal Sciences, Rutgers University

Wednesday, November 11

8:00-9:30 Climate Change, Drought and Agriculture

Clinton Rowe, Department of Earth and Atmospheric Sciences, UNL (Moderator)

Trends in Climate Teleconnections and Effects on the Midwest

Donald Wuebbles, Professor of Atmospheric Science, University of Illinois and Assistant Director, Office of Science and Technology Policy, and **Zach Zobel,** University of Illinois

Drought Fusion: A Union of Past and Present Drought Characteristics and their Impacts

Michael Hayes, Director, National Drought Mitigation Center
Mark Svoboda, Climatologist and Monitoring Program Leader, National Drought Mitigation Center, UNL

9:30-10:00 Refreshment Break

10:00-10:30 Climate Change, Drought and Agriculture

The Physics of Great Plains Drought, Its Predictability and Its Changed Risk in a Warming World

Marty Hoerling, NOAA/ESRL, Physical Sciences Division

10:30-12:00 Breakout groups

12:15-1:45 Lunch

Capturing Climate Variability and Change in the Platte River Basin

Michael Forsberg, Conservation Photographer

1:45-3:30 Management Strategies Associated with a Changing Climate: A Local, Regional and Global Perspective (Stakeholder Panel)

Donald Wilhite (Moderator)

Panelists:

Douglas Bereuter, Co-chairman, Chicago Council on Global Affairs' Global Agricultural Development Initiative; Member, State Department's International Security Board (Arctic Policy Study Committee)
John Berge, Manager, North Platte Natural Resources District
Martha Kauffman, Managing Director, Northern Great Plains Program, World Wildlife Fund
John Hansen, President, Nebraska Farmers Union

3:30-4:00 Refreshment Break

4:00-5:00 The Arctic Council and More: U.S. Engagement on International Climate

Karen Florini, Deputy Special Envoy for Climate Change, U.S. Department of State

Sunshine Beach, July 2011

Sunshine Beach, September 2013

Michael Forsberg, Conservation Photographer

Thursday, November 12

8:00-9:00 Water Resources and Agriculture Breakout Group Reports

9:00-10:30 Adapting to a Changing Regional Climate

Martha Shulski, Director, High Plains Regional Climate Center, University of Nebraska-Lincoln (Moderator)

Panelists:

Linda Prokopy, Natural Resource Social Science, Purdue University

Taryn Finnessey, Colorado Water Conservation Board

Dennis Todey, South Dakota State Climatologist, South Dakota State University

Tom Buman, AGREN

10:30-11:30
Recommendations and Next Steps

11:30-12:00
Wrap-up and Adjourn

Pete Souza, Official White House Photographer

WIFI Access:
Connect to UNL Conference
Open browser
Username: Arctic2015
Password: Innovate2015!

Questions:
Call/text Kim Morrow
402-405-9425

The University of Nebraska-Lincoln is an equal opportunity educator and employer.

Participants

Anderson, Mark
University of Nebraska–Lincoln (UNL)
214 Bessey Hall
Lincoln, NE 68588-0340
(402) 472-6656
mra@unl.edu

Atkeison, John
EnergyLinc
5100 N 27th Street, Suite A-2, Box 181
Lincoln, NE 68521
(402) 915-3210
john@EnergyLinc.org

Baigorria, Guillermo
UNL
823 Hardin Hall, 3310 Holdrege Street
Lincoln, NE 68583-0968
(402) 472-8727
gbaigorria@unl.edu

Bathke, Deborah
UNL
214 Bessey Hall
Lincoln, NE 68588-0340
(402) 472-6199
dbathke2@unl.edu

Bereuter, Douglas
Chicago Council of Global Affairs
105 Tracy Court
Alamo, CA 94507
dougb1939@yahoo.com

Berge, John
North Platte NRD
P O Box 280
Scottsbluff, NE 69363-0280
308-632-2749
jberge@npnrd.org

Bevans, Rebecca
UNL, School of Natural Resources (SNR)
3833 Woods Blvd
Lincoln, NE 68502
402-416-0734
bevansbecca@gmail.com

Birge, Hannah
UNL, SNR
3310 Holdrege St
Lincoln, , NE 68583
(612) 750-1111
hbirge@gmail.com

Bleed, Ann
LES and LPSNRD
1315 N 37 St
Lincoln, NE 68503
(402) 466-6805
ann.s.bleed@gmail.com

Brusberg, Mark
USDA
Room 4441 USDA South Building,
1400 Independence Ave, SW
Washington, DC 20250
(202) 720-2012
mbrusberg@oce.usda.gov

Buman, Thomas
Agren
1238 Heires Ave.
Carroll, IA 51401
(712) 792-6248
tom@agreninc.com

Buttler, Chris
National Weather Service-North Platte, NE
5250 East Lee Bird Drive
North Platte, NE 69101
308-520-7668
christopher.buttler@noaa.gov

Cetola, Jeff
Atmospheric & Environmental Research, Inc.
3561 S. 185th Ave
Omaha, NE 68130
(402) 896-8501
jcetola@aer.com

Chalecki, Elizabeth
University of Nebraska–Omaha (UNO)
Dept. of Political Science, 6001 Dodge St., ASH275
Omaha, NE 68182
(402)554-3613
echalecki@unomaha.edu

Clayton, Chris
DTN/The Progressive Farmer
9110 West Dodge Road
Omaha, NE 68112
(402) 255-8353
chris.clayton@dtn.com

Cohen, Judah
AER
976 Centre Street
Newton, MA 02459
(617) 610-3624
jcohen@aer.com

Demisse, Getachew
UNL
243A Hardin Hall
Lincoln, NE 68583-0962
402-472-0825
gdemisse2@unl.edu

Dewey, Ken
UNL
715 Hardin Hall
Lincoln, NE 68583
(402) 472-2908
kdewey1@unl.edu

Ekwurzel, Brenda
Union of Concerned Scientists
1825 K St NW 800
Washington, DC 20006
(202) 331-5443
bekwurzel@ucsusa.org

Finnessey, Taryn
DNR/CWCB
1313 Sherman St, Suite 721
Denver, CO 80203
(303)868-5302
taryn.finnessey@state.co.us

Florini, Karen
U.S. Department of State
2201 C St. NW, HST 1427
Washington, DC, DC 20037
202-485-1657
FloriniKL@state.gov

Forsberg, Michael
UNL
2628 High Street
Lincoln, NE 68502
(402) 525.1449
forsberg.mike@gmail.com

Francis, Jennifer
Rutgers University
107 Cove Circle
Marion, MA 02738
732-688-2382
francis@imcs.rutgers.edu

Haar, Ken
Nebraska Legislature
PO Box 94604, State Capitol
Lincoln, NE 68509
402-471-2673
khaar@leg.ne.gov

Hansen, John
Nebraska Farmers Union
1305 Plum Street
Lincoln, NE 68502
402-476-8815
john@nebraskafarmersunion.org

Hanson, Paul
UNL
3310 Holdrege St.
Lincoln, NE 68588
(402) 472-7762
phanson2@unl.edu

Hatfield, Jerry
National Laboratory for Agriculture and the Environment
2110 University Blvd.
Ames, IA 50011
(515) 294-5723
jerry.hatfield@ars.usda.gov

Hayes, Michael
UNL, National Drought Mitigation Center
819 Hardin Hall, 3310 Holdrege Street
Lincoln, NE 68583-0988
(402) 472-4271
mhayes2@unl.edu

Helda, Noordiah
UNL
1331 G Street #102
Lincoln, NE 68508
(402) 405-9734
noordiah_helda@yahoo.com

Hoerling, Martin
NOAA
325 Broadway
Boulder, CO 80305
(303) 497-6165
martin.hoerling@noaa.gov

Hunt, Eric
AER
6610 Benton St.
Lincoln, NE 68507
ehunt@aer.com

Hunter-Pirtle, Ann
6000 Deerwood Dr.
Lincoln, NE 68516
(402) 310-6043
ann.hunterpirtle@gmail.com

Kauffman, Martha
WWF
13 S. Willson, #1
Bozeman, MT 59715
(406) 582-0235
martha.kauffman@wwfus.org

Kunkel, Kenneth
North Carolina State University
Cooperative Institute for Climate and Satellites
151 Patton Avenue
Asheville, NC 28801
(828) 257-3137
kekunkel@ncsu.edu

Lenton, Roberto
Robert B. Daugherty Water for Food Institute
2021 Transformation Drive
Suite 3220
Nebraska Innovation Campus
Lincoln, NE 68588-6203
(402) 472-5145
rlenton@nebraska.edu

Little, Christopher
Atmospheric and Environmental Research
131 Hartwell Ave
Lexington, MA 02421
267-254-2178
clittle@aer.com

Livneh, Ben
University of Colorado
216 UCB
Boulder, CO 80309
(303) 725-0288
ben.livneh@colorado.edu

Mariano, Denis
UNL
3272 Starr St. Apt 7
Lincoln, NE 68503
4024137649
mariano@huskers.unl.edu

Mayes Boustead, Barbara
National Weather Service
2320 S. 183rd Circle
Omaha, NE 68130
(402) 889-3644
barbara.mayes@noaa.gov

Morrow, Kim
UNL
703 Hardin Hall, 3310 Holdredge St.
Lincoln, NE 68583-0968
402-405-9425
kmorrow2@unl.edu

Munoz-Arriola, Francisco
UNL
246 L.W. Chase Hall
Lincoln, NE 68583
402-472-0850, fmunoz@unl.edu

Nam, Won-Ho
UNL
808 Hardin Hall, 3310 Holdrege Street
Lincoln, NE 68503
(402) 416-8859
wonho.nam@gmail.com

Neale, Christopher
Robert B. Daugherty Water for Food Institute
2021 Transformation Drive
Suite 3220
Nebraska Innovation Campus
Lincoln, NE 68588-6203
(402) 4725359
cneale@nebraska.edu

Nelson, W. Don
Prairie Fire newspaper
2430 South Canterbury Lane
Lincoln, NE 68512
(402) 430-3027
donnel@windstream.net

Oglesby, Robert
UNL
221 Bessey
Lincoln, NE 68588
(402) 472 1507
roglesby2@unl.edu

Pomerance, Rafe
Arctic 21
2026 Allen Place, NW
Washington, DC 20009
202 423 6885
rafe.pomerance@gmail.com

Prokopy, Linda
Purdue University
195 Marsteller Street
West Lafayette, IN 47907
765-496-2221
Lprokopy@purdue.edu

Reidmiller, David
U.S. Department of State
320 C St NW OES/EGC, Suite 2480
Washington, DC 20001
(202) 647-3961
reidmillerdr@state.gov

Rinne, Tim
Nebraskans for Peace
605 N. 26th Street
Lincoln, NE 68503
(402) 730-6675
walterinne@gmail.com

Rowe, Clinton
UNL
Earth & Atmospheric Sciences
Lincoln, NE 68588-0340
(402) 472-1946
crowe1@unl.edu

Schoeneberger, Michele
US Forest Service - Natl Agroforestry Center
1945 N 38th [East Campus -UNL]
Lincoln, NE 68583-0822
402-437-5178 ext 4021
mschoeneberger@fs.fed.us

Shiferaw, Andualem
UNL
3310 Holdrege Street
Lincoln, NE 68583
402-419-9605
andus@huskers.unl.edu

Shulski, Martha
UNL
3310 Holdrege Street
Lincoln, NE 68583-0997
402-472-6711
mshulski3@unl.edu

Snell, Hilary
AER, Inc
131 Hartwell Ave
Lexington, MA 02421
(781) 761-2281
hsnell@aer.com

Stiles, Crystal
UNL, High Plains Regional Climate Center
3310 Holdrege Street, Hardin Hall 716
Lincoln, NE 68583-0997
(402) 472-8208
cstiles3@unl.edu

Stoppkotte, John
NOAA/NWS
5250 E. Lee Bird Drive
North Platte, NE 69101
(308) 539-0261
john.stoppkotte@noaa.gov

Strickler, Laura
Arctic 21
70 I St SE, Apt 1005
Washington, DC 20003
(404) 538-3465
Laura.Strickler@garnetstrategies.com

Svoboda, Mark
UNL, National Drought Mitigation Center
3310 Holdrege Street, 815 Hardin Hall
Lincoln, NE 68583-0988
(402) 472-8238
msvoboda2@unl.edu

Tadesse, Tsegaye
UNL, National Drought Mitigation Center
816 Hardin Hall, 3310 Holdrege Street
Lincoln, NE 68583
(402) 472-3383
ttadesse2@unl.edu

Takle, Eugene
Iowa State University
3013 Agronomy Hall
Ames, IA 50011
(515) 294-9871
gstakle@iastate.edu

Taylor, Elwynn
Iowa State University
2210 Agronomy Hall
Ames, IA 50011-1010
(515) 294-7839
setaylor@iastate.edu

Timlin, Michael
Midwestern Regional Climate Center
2204 Griffith Dr
Champaign, IL 61820
(217) 333-8506
mtimlin@illinois.edu

Todey, Dennis
South Dakota State University
South Dakota State Climate Office
SAE 213 Box 2120 SDSU
Brookings, NE 57007
dennis.todey@sdstate.edu

Uttal, Taneil
NOAA
325 Broadway
Boulder, NE 80305
Taneil.Uttal@noaa.gov

Wagner, Matthew
Ogilvy Public Relations
2519 Wabash Street
Denver, CO 80238
303-929-2822
matt.wagner@ogilvy.com

Westwood, Jack
British Consulate-General Chicago
625 N Michigan Avenue   Suite 2200
Chicago, IL 60640
(312) 970-3835
Jack.Westwood@fco.gov.uk

Wilhite, Donald
UNL
811 Hardin Hall
Lincoln, NE 68583
(402) 472-4270
dwilhite2@unl.edu

Wilson, Mike
USDA-NRCS
100 Centennial Mall N., Rm 152
Lincoln, NE 68506-3866
402-437-4134
mike.wilson@lin.usda.gov

Wodder, Rebecca
6106 Union Camp Drive
Fairfax Station, VA 22039
(703) 474 9130
rebecca.wodder@cox.net

Wolf, Ray
NOAA / National Weather Service
9050 Harrison Street
Davenport, IA 52806
5633917094
ray.wolf@noaa.gov

Wuebbles, Donald
University of Illinois
3405 S. Persimmon Circle
Urbana, IL 61802
(217) 840-0100
wuebbles@illinois.edu

Pete Souza, White House photographer

Another view of Exit Glacier in Kenai Fjords National Park.

School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

University of Nebraska Lincoln