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Improving Impact-based Seasonal Outlooks for South Central Texas

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1. Introduction

"Is this an above normal year?" Forecasters and broadcast meteorologists get questions like this on a regular basis. Although for different reasons, the answer to that question may be useful to both meteorologists and members of the public, but how does one truly answer it? Currently, the meaning of "above normal" generally lies in terms of subjective perceptions based on experiences as opposed to objective measures (temperature and precipitation being two notable exceptions). As impact-based decision support services (IDSS) for weather and climate continue to expand in the National Weather Service (NWS), one question arises immediately: "Can we accurately quantify impacts at seasonal and sub-seasonal timescales, especially for extreme weather?"

As improvements come in statistical and dynamical tools, consolidation tools used to create an objective forecast from multiple sources, and skill in forecasts driven by ENSO, the Climate Prediction Center's (CPC's) seasonal outlooks will continue to increase in skill and provide more insight to users (O'Lenic *et al.* 2008). However, proper interpretation of these outlooks is sometimes not done correctly. In addition, some users have trouble taking a national outlook and scaling it to a regional or local level. Thus, the NWS Weather Forecast Office Austin/San Antonio (WFO EWX) began delivering impact-based seasonal outlooks to their stakeholders in fall 2015. These outlooks use a blend of national outlooks (*e.g.*, CPC's seasonal outlooks, NOAA's drought outlooks, *etc.*) and local research to combine various levels of expertise into a single outlook [for more information on delivering these outlooks, see Hopper *et al.* 2018]. The Austin-San Antonio metroplex is currently one of the most rapidly growing urban areas in the United States. Current estimates have the population in this area tripling by 2050 compared to 2000. Rapid population growth combined with hydrological challenges, such as a lack of soil infiltration due to low depth to bedrock over a region with relatively complex terrain, cause the ever-increasing vulnerability to high-impact weather to become quickly apparent. National climate outlooks are currently used most in the agricultural sector and for drought planning. Haigh *et al.* (2015) found climate information to be very useful for agricultural risk management. Several studies continued this point to develop useful seasonal climate outlooks for agriculture, such as Finnessey *et al.* (2016), Klemm and McPherson (2017) and Prokopy *et al.* (2017). Climate information is also used across emergency management networks, but these networks sometimes face challenges in using complex scientific information, such as ambiguous data and unclear uncertainty (Roberts and Wernstedt 2016). The delivering of these outlooks directly to stakeholders from a WFO provides an opportunity for the scientific information being presented to be explained clearly while also building on operational capabilities by expanding the tree of national climate outlooks to various high-impact weather. Thus, the primary objective of this study is to develop impact-based verification indices for severe weather, flooding, and fire weather. These indices attempt to quantify a relatively subjective perception of which tercile a season falls into so that more objective, verification-driven forecasts may be developed in the future.

Section 2 discusses the development of an index to measure impacts from severe weather, river and flash flooding, and fire weather. Section 3 explains how the index is then used to verify forecasts made by the office. Lastly, Section 4 describes ongoing and future work to further improve this process.

2. Methodology: The verification index

The overarching question of this study is how does one quantify impacts, and can they be objectively measured and predicted? We attempt to design our objective metrics in such a way that it matches public

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perception and "reality" for any given season as well as be a repeatable but customizable process. The first step in objective forecasts is to have a baseline climatology for this WFO's county warning area (CWA) in South Central Texas. Baseline climatologies are created for severe weather, river and flash flooding, and fire weather; river flooding and flash flooding are combined because most river floods are also flash floods where most of the population within WFO EWX's CWA live. These climatologies utilize "indicators", various data to describe one aspect of the weather phenomena that, when used collectively, will fully depict the season as it pertains to the respective weather event. We call these climatologies complete with indicators as verification indices because they are initially acting to verify outlooks done by the office.

We began by defining seasons to be tested: December, January, February (DJF, hereafter referred to as winter); March, April, May (MAM, referred to as spring); June, July, August (JJA, referred to as summer); and September, October, November (SON, referred to as fall). For each index, indicators fall into one of three categories: occurrence, impacts, or meteorology/severity. These categories capture a full description of a season offering the strongest overall quantification. The basis for each index utilizes the number of reports and the number of report days for occurrence, damages and a blend of injuries and fatalities for impacts, and total CWA rainfall for meteorology/severity. Damages are adjusted to 2010 levels using the consumer price index (DOL 2017). Total CWA monthly rainfall was found using Texas Water Development Board quadrangles (TWDB 2017). These quadrangles divide Texas into a 1° latitude by 1° longitude grid. Any quadrangle that contained more than 75% of the CWA was considered in the analysis. An average of each quadrangle's seasonal value then was used as total CWA rainfall. Additional indicators, like a blend of fatalities and injuries that is discussed in Section 2.1, were then added to each index to hone in on specifics from each hazard.

Our verification indices are modeled after the CPC's nonparametric tercile approach. Each indicator in the index in ranked, where 1 is the greatest number (i.e., the most number of reports/most damages) and n is the smallest number where n is the number of years in the climatology. Total CWA rainfall in the fire weather index is the only exception (smallest rainfall value given 1, largest given 30) since lower rainfall totals are more indicative of enhanced fire weather. In the case of a tie, all tied values are assigned the rank that is equal to the midpoint of the unadjusted ranks. Then, we take the sum of all indicator ranks across a year and find the rank of this sum. The final rank analysis thus weights all indicators equally throughout the index (see Table 1 for a simplistic example of this process). The final rank analysis is done so that the smallest sum is given the top rank. The upper third ranks are deemed above normal, middle third are near normal, and bottom third are below normal. To check the internal consistency of our indices, a statistical measure called Cronbach's Alpha was used (Cronbach 1951). Cronbach's Alpha is a number from 0 to 1.0 where 1.0 represents perfect internal consistency. Commonly accepted rules to describe Cronbach's Alpha values are: 0.90 and above is excellent, 0.80 to 0.90 is good, 0.70 to 0.80 is acceptable, and anything below 0.70 should be questioned. Analysis was done with every indicator in each season in each index and then by taking one indicator out; the maximum value of Cronbach's Alpha represented the group of indicators that were the most consistent and thus used as the final index.

Table 1 An example of how ranking works in the verification index using only two indicators. Note that a low sum is given a higher rank as low sums indicate more significant indicator values.

Year	Reports	Report Days	Report Rank	Days Rank	Sum	Sum Rank
2006	22	6	3	3	6	3
2007	279	35	1	1	2	1
2008	8	4	4	4.5	8.5	4
2009	7	4	5	4.5	9.5	5
2010	25	8	2	2	4	2

2.1. Severe weather

Severe weather was analyzed first, and the storm reports were collected from the National Center for Environmental Information's Storm Events Database (NCEI 1999). Our 1981-2010 climatology includes storm reports for severe thunderstorm wind, severe hail, tornadoes, and lightning. We kept all penny-size hail reports and above (> 0.75 in) because this was the severe criteria for virtually the entire climatology prior to it increasing to quarter size (> 1 in) in January 2010. Although lightning is not considered in making a thunderstorm severe, if it was listed as a storm report it means that there was either a fatality, injury, or damage figure associated with it, which by definition is an impact. Lightning reports were not added to the Storm Events Database until 1996 under NWS Directive 10-1605 so all Storm Data Publications prior to 1996 were read and appropriate additions were made.

Initially, fatalities and injuries were two separate indicators. Upon looking at the data, it was seen that there were a significant number of zeros for fatalities, especially in the winter. This presents a problem in statistical analysis (although certainly not in societal analysis) because all the zeros would share a common rank. As a result, there was not much differentiation between any given year when looking at the fatalities (and injuries) ranks alone. As a result, we define a blend of fatalities and injuries to capture both impacts while also providing differentiation among years. This blend ranks fatalities but uses injuries to break tied ranks in fatalities. This provided a solution that allowed the impacts of a fatality to have more weight than an injury and still accounted for both fatalities and injuries because the range and variability of fatalities was not large.

To design an index specific for severe weather, we added the following indicators into the index: total tornado path length (occurrence) and maxima of tornado width, hail diameter, and non-tornadic wind magnitude (meteorology/severity). Cronbach's Alpha analysis showed spring was the least consistent, but still good at about 0.80 for all indicators, and winter was the most consistent at about 0.87. However, it was found that by removing total CWA rainfall from the index, the Cronbach's Alpha value increased. Since it is expected that increasing the number of items in the analysis would increase the Cronbach's Alpha value (Cortina 1993), total CWA rainfall was making the index less internally consistent. From a meteorological standpoint, this makes sense since severe weather impacts, more often, come with discrete storm modes as opposed to a widespread rainfall event.

2.2 River and flash flooding

Like severe weather, storm reports were collected from NCEI's Storm Events Database. However, the database only has reports from 1996 forward, again due to NWS Directive 10-1605. In order to expand our climatology to 30 years, Storm Data Publications and archived E-5 reports were thoroughly investigated for reports of flooding impacts. Although it may not have been perfect, since our index uses ranks, and not the raw data for each indicator, it is not so much the actual values as much as where it falls in comparison to the other years. It is almost certain that highly unusual years would become evident in the final ranks.

In addition to the foundational indicators, we added the number of times river gages went above moderate flood stage (occurrence) and maximum one- and two-day rainfalls (meteorology/severity) to the index. 52 river gages located on major rivers throughout the CWA were selected. All instances of a river gage going over its moderate flood stage threshold were recorded and then split into the seasons of each year. The collective total among all river gages for a single season was used as the indicator. In determining maxima in rainfall, 54 COOP stations were used. COOP stations were selected to cover all counties in the CWA, with several in larger population areas. The overall maximum for both one day and two days at these 54 stations given in xmACIS2 were used as the indicators. Cronbach's Alpha analysis showed the index was very good, as three out of four seasons were above 0.9; spring was the exception and had a Cronbach's Alpha of 0.85.

2.3 Fire weather

Fire weather was the last hazard we investigated. We were able to obtain an extensive dataset of all fires, including prescribed burns from the Texas State Fire Marshal's Office spanning from 1982-present. Any prescribed burn that did not have acres burned entered was discarded from the dataset. After analysis, it was noticed that there were zero acres burned for every fire entered from 1982 through 1999. Therefore, we were forced to use a 15-year climatology of 2000-2014.

Three indicators were added to the fire weather index: total acres burned (impacts), average maximum temperature (meteorology/severity), and a blend of frontal passages and a Keetch-Bynum Drought Index analysis (meteorology/severity; see Table 2 for a summary of all indicators used for the various indices).

Average maximum temperature was calculated using climate division data gathered from NOAA's Local Climate Analysis Tool (Timofeyeva-Livezey *et al.* 2015); about 45.5% of the CWA lays within climate division 6 and about 54.5% of the CWA lays within climate division 7. Each climate division's average maximum temperature was multiplied by the respective decimal to determine a spatially-weighted average. This is a process that can be done to determine total CWA rainfall if other datasets are not available. Cronbach's Alpha values for this index were excellent. Like total CWA rainfall in the severe weather index, total damages were found to be making the fire weather index less internally consistent possibly due to inconsistencies in reporting monetary impacts caused by fires, so it was removed.

Table 2 A summary of all indices and the indicators that comprise them. Total CWA rainfall was taken out of the severe weather index and total adjusted damages was removed from the fire weather index due to having poor statistical relationships in their respective indices. This was shown through Cronbach's Alpha values increasing when the indicator was removed.

Weather Hazard	Occurrence	Impacts	Meteorology/Severity
Severe Weather	Number of storm reports	Fatalities/Injuries Blend	Maximum tornado width
	Number of report days	Damages	Maximum hail diameter
	Total tornado path length		Maximum non-tornadic wind magnitude
River and Flash Flooding	Number of storm reports	Fatalities/Injuries Blend	Total CWA rainfall
	Number of report days	Damages	Maximum 1-day rainfall
	Frequency of river gages above moderate flood stage		Maximum 2-day rainfall
Fire Weather	Number of fire reports	Fatalities/Injuries Blend	Total CWA rainfall
	Number of report days	Total acres burned	Average maximum temperature
			KBDI/Frontal passages blend

3. Verification of South Central Texas climate outlooks

Figure 1 displays the plot made after analysis using the verification index for severe weather. Although all 4 seasons are plotted on the same graph, comparisons between one season and another is dangerous. For example, a below normal year in the spring, the season that is climatologically most active for severe weather, tended to have about 20 to 30 severe reports while in the other seasons a below normal year could have less than 5. A better interpretation of the sum of any given year is how it compares to other sums relative to the season of interest. The top overall sum of 223 corresponds to fall 2001; that season saw 56 severe reports and 39 injuries due to severe weather. Meanwhile, the lowest sum for a top rank corresponds to spring 1997 which is the year of the deadly Jarrell EF/F5 tornado. Spring 1997 had a total of 140 severe reports and 28 fatalities. Obviously, these two seasons are much different in their associated impacts, displaying how the same process can lead to varied results depending on the timeframe that is being analyzed. This is useful because it can quickly point out highly anomalous seasons relative to the season's climatology. Finally, the

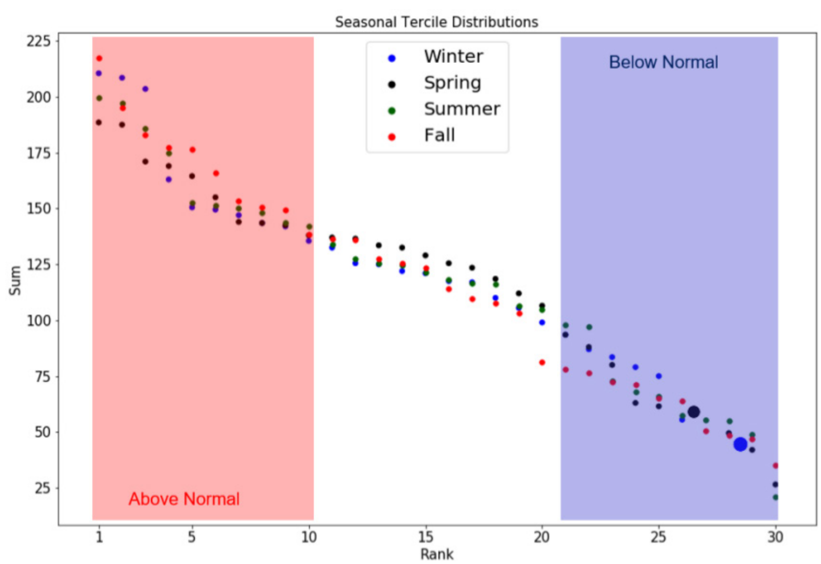

Fig. 1 A plot displaying the distribution the distribution of years in the severe weather climatology. A larger dot means more than one year was tied for a final rank. The y-axis is the sum of the indicators and is reversed so that a larger sum correlates with above normal impacts.

meteorological forcings driving a season can vary yet still verify as the same tercile. In other words, a more active weather pattern may not necessarily lead to more impacts than a season with one single large event. While spring 1997 was largely driven by one large event, the second overall spring rank was 2007, a year where several moderate severe weather days aggregated to verify as above normal. This is a positive result since verification of above normal impacts can come from multiple types of seasons.

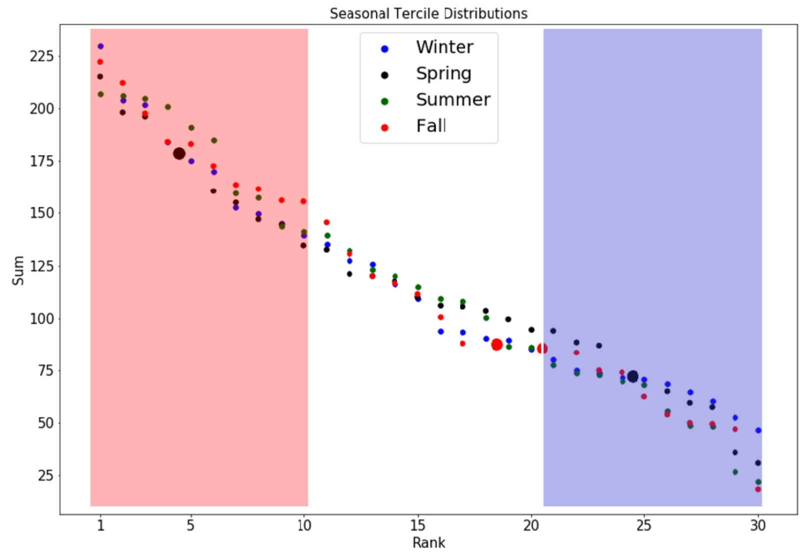

Fig. 2 As in Fig. 1, but for river and flash flooding.

Figure 2 depicts the river and flash flooding analysis plot. The overall distribution is similar to severe weather with less change of slope for the near normal points. Although the summertime is the season with the most flooding reports, spring and fall have relatively high climatological percentages of reports. For this reason, the distribution is more linear than the one for severe weather but not nearly as linear as the fire weather plot shown in Fig. 3 discussed below). For river and flash flooding, the top six above normal years clearly separate themselves and is a major motivation for delivering impact-based outlooks. This CWA has over half of Texas's flooding deaths since 1996 and as the Austin/San Antonio metroplex continues to expand the potential for significant river and flash flooding will also grow.

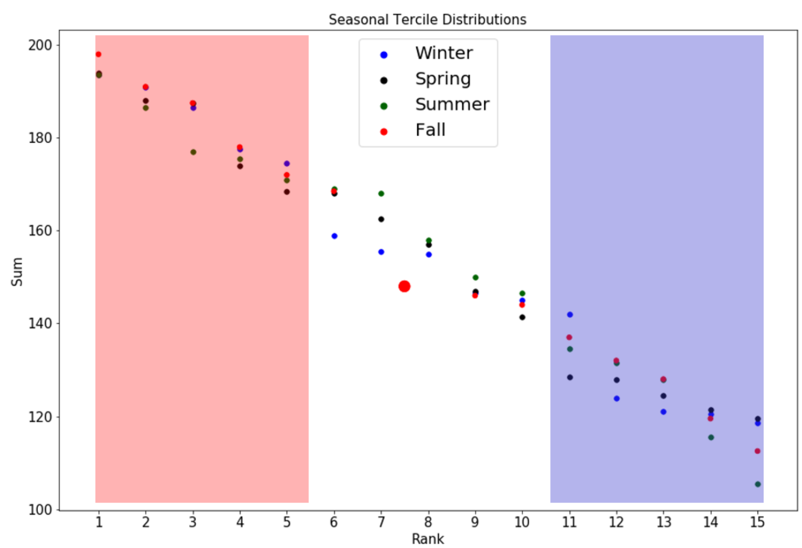

Fig. 3 As in Fig. 1, but for fire weather.

Figure 3 shows the results of the fire weather analysis. This plot is virtually linear, most likely owing to the climatology being 15 years as opposed to 30 years and that the occurrence of fire reports is virtually uniform across all four seasons. However, interseasonal comparisons should be avoided because the meteorological and agricultural mechanisms enhancing fire weather threats have a seasonal variability component. The large dot in the middle of the plot represents two years that ended having the same final rank. This point displays the need for a 30-year climatology; in one year, the first half of the season was very dry and hot which enhanced fire potential while the second half of the season was the opposite: wetter and cooler than normal. The other year comprising that single dot was one where fewer acres burned and the entire season had moderate fire risk. Hence, there is less discrimination between years in this index, especially in the near normal range. Fine tuning the indicators and expanding to a longer climatology as more data becomes available will act to make this index much better moving forward.

Now that there is a baseline climatology, objective verification techniques can be undertaken to verify outlooks already issued by the WFO. The verification scheme developed using the indices outlined above can be broken down into 7 steps (Table 3 is another depiction of the process):

Table 3 A depiction of the verification process for severe weather. For example, fall 2015 had 19 severe reports. The closest value in the severe weather index was 18 in 1997. Fall 2015 was then assigned the 1997 rank of 9. The index score is the sum of all ranks (*e.g.*, 75), the closest value is again found, and given that rank (in this case, is 6)

Fall Season	Reports	Report Days	Fatalities Injuries	Tornado Track	Adjusted Damages	Largest Hail Size	High Wind	Widest Tornado
2015	19	6	0	18.6 mi.	$2.07M	1.0 in.	71 mph	440 yd.
Rank	9th	9th	20th	3rd	6th	20th	5th	3rd
Value (Year)	18 (1997)	6 (3 times)	0 (21 times)	26 mi. (2004)	$1.75M (2000)	1.0 in. (1994)	70 mph (3 times)	400 yd. (2004)

1) Collect observed values for each indicator of an index;
2) For any given indicator (*e.g.*, number of reports), find the closest value within the index to the observed value;
3) Assign the rank for the indicator of the season being verified as the same rank assigned to the value identified in step 2;
4) Repeat steps 2 and 3 for each indicator in the index;
5) Sum all the indicator ranks;
6) Find the closest sum value from the index to the result found in step 5;
7) The final rank of the season being verified is then assigned the same rank as the year with the closest sum value (*i.e.*, the sum value found in step 6).

Table 4 A summary of forecasts issued by WFO Austin/San Antonio and the season's corresponding verification using our indices. Severe weather hit 6 of 9 forecasts while river and flash flooding and fire weather hit 3 out of 6.

	Severe Weather		River and Flash Flooding		Fire Weather	
Season	**Forecast**	**Verification**	**Forecast**	**Verification**	**Forecast**	**Verification**
Fall 2015	Slight Above	Above (6)	Above	Above (3)	Near Normal	Near (6)
Winter 2016	Above	Near (12)	Slight Above	Below (21)	Below	Below (11)
Spring 2016	Slight Above	Above (6)	Slight Above	Above (3)	Near Normal	Below (15)
Summer 2016	Slight Above	Below (26)	Slight Above	Above (8)	Slight Below	Below (11)
Fall 2016	Slight Below	Below (26)	Below	Near (13)	Slight Below	Near (6)
Winter 2017	Slight Below	Above (3)	Slight Below	Near (11)	Slight Below	Near (8)
Spring 2017	Slight Above	Above (6)				
Summer 2017	Near Normal	Near (11)				
Fall 2017	Slight Below	Below (27)				

This verification scheme has been done to date completely for 21 forecasts made between fall 2015 to fall 2017 for severe weather (9 seasons) and fall 2015 to winter 2016-17 for river and flash flooding and 6 fire weather (6 seasons each) (shown in Table 4). Six out of nine severe weather forecasts hit the correct tercile and three out of six forecasts hit for both river and flash flooding and fire weather. Skill in these seasonal forecasts was found using Heidke Skill Scores (HSS; Heidke 1926). The formula for a HSS is

$$HSS = \frac{C - (\frac{1}{3} * T)}{\frac{2}{3} * T}$$

where C is the number of correct forecasts and T is the number of forecasts being scored. Using this formula, HSS's were found to be 0.50 for severe weather and 0.25 for both river and flash flooding and fire weather. A HSS for climatology is 0 since it is assumed one out of every three climatology forecasts is correct. Therefore, WFO EWX's skill is 50% better than climatology for severe weather and 25% better than climatology for river and flash flooding and fire weather for forecasts made since fall 2015.

4. Conclusions and next steps

Overall, objective verification indices that capture impacts can be created and are meaningful to both meteorologists and the public. Impacts are captured from a quantitative aggregation of various data describing the season quantitatively. Each indicator is weighted equally in the ranking process that produces a single number that sorts years within each season by their impacts. These ranks may then be sorted into terciles, much like CPC's temperature and precipitation outlooks. The indices presented here are baseline indices that will be improved as operational capabilities and our understanding of quantifying impacts also are improved. In addition, these indices are used to verify the forecasts made by the office. Currently, the office has shown to have skill in combining national outlooks and local expertise to produce a forecast tailored to a CWA's stakeholders.

There are currently several areas of work still being explored to improve this process. For example, streamflow is being considered as an additional indicator to the river and flash flooding index. In addition, some measure of fuel moisture, such as fuel release component, looks to replace the KBDI blend in the fire weather index. Lastly, using the PRISM dataset to more accurately quantify total rainfall is being explored. Winter weather is an additional index being designed with guidance from WFO Detroit. The overarching process has been shown to have successes thus far and has also been designed in a repeatable but customizable way so that indices can be tailored to specific regional nuances.

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References

Cortina, J. M., 1993: What is coefficient alpha? An examination of theory and applications. Journal of Applied Psychology, **78**, 98-104, http://dx.doi.org/10.1037/0021-9010.78.1.98.

Cronbach, L. J., 1951: Coefficient alpha and the internal structure of tests. *Psychometrika*, **16**, 297-334, https://doi.org/10.1007/BF02310555.

Department of Labor Bureau of Labor Statistics, 2017: Consumer price index. Accessed June 2017, https://www.bls.gov/cpi/

Finnessey, T., M. Hayes, J. Lukas, and M. Svoboda, 2016: Using climate information for drought planning. *Climate Research*, **70**, 251-263.

Haigh, T., E. Takle, J. Andresen, M. Widhalm, J. S. Carlton, and J. Angel, 2015: Mapping the decision points and climate information use of agricultural producers across the U.S. *Corn Belt. Climate Risk Management*, **7**, 20-30, https://doi.org/10.1016/j.crm.2015.01.004.

Heidke, P., 1926: Berechnung des Erfolges und der Gute der Windstarkevorhersagen inm Sutrmwarnungsdienst (Measures of success and goodness of wind force forecasts by the gale-warning service). *Georg. Ann.*, **8**, 301-349.

Hopper, L. J., T. Dickinson, and J. W. Zeitler, 2018: Delivering impact-based seasonal outlooks for South-Central Texas. *Special Symposium on Impact-Based Decision Support Services*, Austin, TX, Amer. Meteor. Soc., 1.5A, https://ams.confex.com/ams/98Annual/webprogram/Paper329900.html.

Klemm, T., and R. A. McPherson, 20162017: The development of seasonal climate forecasting for agricultural producers. *Agricultural and Forest Meteorology*, **232**, 384-399, https://doi.org/10.1016/j.agrformet.2016.09.005

NOAA/NCEI, 1999: Storm Events Database, Version 3.0 (updated monthly). National Center for Environmental Information. Subset used: December 1980 – February 2017, accessed June 2017, https://www.ncdc.noaa.gov/stormevents/

O'Lenic, E. A., D. A. Unger, M. S. Halpert, and K. S. Pelman, 2008: Developments in operational long-range climate prediction at CPC. *Wea. Forecasting*, **23**, 496-515, https://doi.org/10.1175/2007WAF2007042.1.

Prokopy, L. S., J. S. Carlton, T. Haigh, M. C. Lemos, A. S. Mase, and M. Widhalm, 2017: Useful to useable: Developing useable climate science for agriculture. *Climate Risk Management*, **15**, 1-7, https://doi.org/10.1016/j.crm.2016.10.004.

Roberts, P. S., and K. Wernstedt, , 2016: Using climate forecasts across a state's emergency management network. *Natural Hazards Review*, **17**, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000222

Texas Water Development Board, 2017: Precipitation and Lake Evaporation. Accessed June 2017, http://www.twdb.texas.gov/surfacewater/conditions/evaporation/

Timofeyeva-Livezey, M., F. Horsfall, A. Hollingshead, J. Meyers, and L. A. Dupigny-Giroux, 2015: NOAA Local Climate Analysis Tool (LCAT): Data, methods, and usability. *Bull. Amer. Meteor. Soc.*, **96**, 537-545.