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# Developing a flash drought indicator for the US Great Plains

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# Developing a flash drought indicator for the US Great Plains

**by**

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# Abstract

## Developing a flash drought indicator for the US Great Plains

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Flash droughts refer to those droughts that intensify rapidly in spring and summer, coupled with a strong increase in summer extreme temperatures, such as those that occurred over Texas in 2011 and the Great Plains in 2012. Climate models failed to predict these flash droughts in 2011 and 2012 and are ambiguous in projecting their future changes, largely because of models' weaknesses in predicting summer rainfall and soil moisture feedbacks. In contrast, climate models are more reliable in simulating changes of large - scale circulation and temperatures during winter and spring seasons. Thus, we developed and tested a physical climate indicator of the risk of "flash" droughts in summer by using the large-scale circulation and land surface conditions in winter and spring based on observed relationships between these conditions and their underlying physical mechanisms established by previous observational studies and numerical model simulations.

My master research focuses on the spatial distribution of this indicator globally to see how broadly it could be applied. We also compare the different factors to see which one is the dominant contributor to drought in different area. We find that the indicator performs well at capturing the development and termination of a drought. There is much opportunity to develop and improve the indicator further.

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# INTRODUCTION

Drought is the most costly natural disaster [*Wilhite*, 2000; *Witt*, 1997]. Drought is more nebulous than other disasters and does not lend itself to traditional assessments or forecast methods [*Svoboda et al.*, 2002]. Flash droughts refer to those droughts that intensify rapidly in spring and summer, coupled with strong increase of summer extreme temperatures, such as those that occurred over Texas in 2011 and the Great Plains in 2012.

Climate models failed to predict these flash droughts in 2011 and 2012 and are ambiguous in projecting their future changes, largely because of climate models have major uncertainties in modeling tropical-like or mesoscale convection systems [*Fritsch et al.*, 1986] and soil moisture feedbacks [*Koster et al.*, 2004], which largely control summer rainfall over the Great Plains and the central US.

However, climate models have less uncertainty in capturing the large-scale circulation anomalies that dominate winter and spring rainfall and temperature variations. Observational studies also suggest that summer extreme drought over the southern Plains is preceded by dryness in spring [*Fernando et al.*, 2013].

Thus, we plan to develop and test a physical climate indicator of the risk of “flash” droughts in summer by using the large-scale circulation and land surface conditions in winter and spring based on observed relationships between these conditions and their underlying physical mechanisms established by previous observations and numerical model simulations. This approach aims to mitigate the influence of models weaknesses in predicting on summer drought.

# SCIENTIFIC BACKGROUND

We identify three key factors as contributing to summer drought based on a literature review：anomalously high geopotential height，soil moisture，Convective Inhibition Energy.

Previous studies have shown that droughts over the US Great Plains are mainly initiated by ENSO-induced large-scale circulation anomalies in late fall and winter, with anomalously high geopotential height or anticyclonic circulation centered over the western and central US [*Lyon and Dole*, 1995; *Mo et al.*, 1991; *Wallace and Gutzler*, 1981]. The Pacific Decadal Oscillation (PDO) is generally associated with ENSO and incorporates multiple-frequency responses to ENSO. The PDO is considered to be a low-frequency expression of ENSO [*Alexander et al.*, 1999; *Newman et al.*, 2003]. The Altantic Multi-decadal Oscillation (AMO) is also a significant factor contributing to large-scale circulation anomalies over North America [*Enfield et al.*, 2001]. For example, 52 percent of drought timing and location across the United States is explained by the PDO and AMO. When both of PDO and AMO are in their positive phase, the most extensive droughts occur across the United States [*McCabe et al.*, 2004]. The above factors are forcing from sea surface temperatures (SSTs). Anomalous circulation associated with these SST forcing factors shift synoptic weather disturbances away from the Great Plains and central US, leading to a reduction of rainfall and increased drought incidence, especially in winter and early spring. While ENSO is associated with rainfall anomalies in the winter, perhaps extending into the spring, the AMO and PDO primarily influence summer circulation.

In addition, summer droughts in this region are also caused by dry land surface and a stronger cap inversion due to westerly advection from the Rockies or the Mexican plateau [*Myoung and Nielsen-Gammon*, 2010]. Severe to exceptional summer droughts are mostly due to persistent rainfall deficits from winter to summer. Previous numerical experiments attributed summer droughts to soil moisture deficits in spring over the Great Plains [*Hong and Kalnay*, 2002; *Koster et al.*, 2004; *Oglesby and Erickson III*, 1989; *Schubert et al.*, 2004]. Thus, the conditions that cause dryness in spring could be a key factor in determining summer drought.

Our recent observational analysis shows that summer droughts over the Southern Great Plains are generally associated with increases of Convective Inhibition Energy (CIN) during spring and summer. Myoung and Nielsen-Gammon show the importance of CIN during summer drought [*Myoung and Nielsen-Gammon*, 2010] while Fernando et al. show its role during spring - particularly related to past extreme drought events. [*Fernando et al.*, 2013]. For example, the strongest four summer droughts over the southern Great Plains since 1898 were all preceded by sharp increases of CIN during April and May. Such sharp increases of CIN were caused by a strong increase of cap inversion due to either anomalous large-scale anticyclonic circulation or westerly advection of warm and dry air from the Rockies and Mexican Plateau, as well as land surface dryness caused by winter droughts. Excessive CIN is caused by surface dryness and warming at 700 hPa, leading to precipitation deficits on a monthly time scale. While the dewpoint temperature and thermodynamics at the surface are greatly affected by the soil moisture, the temperature at 700 hPa was found to be statistically independent of the surface dewpoint temperature since the 700-hPa temperature represents free-atmospheric processes. [*Myoung and Nielsen-Gammon*, 2010].

Strong increases of CIN suppress rainfall during spring, which further dries the land surface and re-enforces and intensifies drought during the summer through a rapid increase of surface temperature and ET loss. Thus, the anomalous large-scale anticyclonic circulation and surface dryness in spring set a stage for rapid intensification of the drought and extreme temperature in summer.

Furthermore, soil moisture and its feedback is an important process whose regional positive feedback associated with lower evaporation and precipitation contributed substantially to the maintenance of drought [*Hong and Kalnay*, 2000]. The low level jet has a strong influence on the summer rainfall over the great plain [*Helfand and Schubert*, 1995; *Higgins et al.*, 1997]. Due to its uncertainty in observations and models, we do not consider the low level jet as a factor.

# THE MECHANISM

Let us look at the relationships between the three factors mentioned above. ENSO, PDO, AMO trigger the large scale circulation anomalies which will reshape the geo-potential height. The geo-potential height anomalies will impact the precipitation and thus change the land surface condition. Both of the geo-potential height anomalies and the land surface condition will affect the drought directly as well as the Convective Inhibition Energy. Big Convective Inhibition Energy is a dominant character of drought. The mechanism is shown as Figure 1.

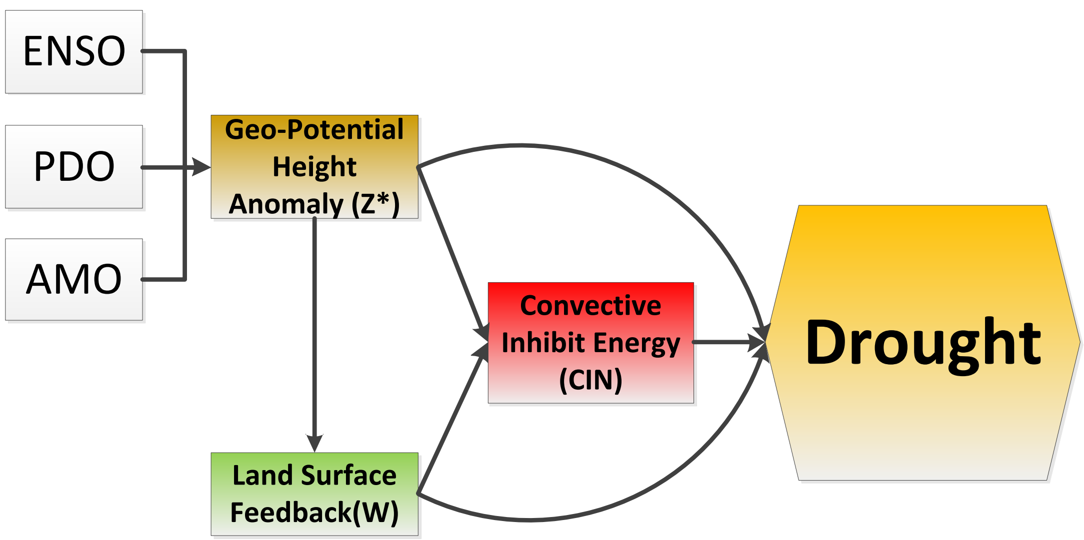


Figure 1: The key factors that control drought over the Great Plains.

## DATASET AND DESCRIPTION

We obtain 500 hPa geo-potential height, surface dew point, and temperature at 700 hPa from National Centers for Environmental Prediction (NCEP) [*Kalnay et al.*, 1996]. The soil Moisture data come from Climate Prediction Center (CPC) [*Fan and van den Dool*, 2004; *van den Dool et al.*, 2003]. For the existing drought indices used for computing the weighting factor (detail refer to A, B, C used in equation 1 and 2 in METHODS secession), we select Standardized Precipitation-Evapotranspiration Index (SPEI): http://sac.csic.es/spei/ [*Vicente-Serrano et al.*, 2010] and Self-calibrated Palmer Drought Severity Index (scPDSI): [*Dai*, 2011] http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html

There are many other drought indices such as: SPI(Standardized Precipitation Index), Palmer Hydrological Drought Index(PHDI), Crop Moisture Index (CMI), Surface Water Supply Index (SWSI), Reclamation Drought Index (RDI), Standardized Runoff Index (SRI), Deciles, SSI(Soil Moisture Index), Streamflow, Percent of Normal, Satellite Vegetation, Multi-Index Standardized Drought Index (MSDI). Based on the data availability, and the mechanism we identify as important for drought, we chose the SPEI and scPDSI.

Although the resolution for SPEI and scPDSI is as high as 0.5x0.5 degree, the resolution for geo-potential height is 2.5X2.5 degree. We interpolate all data to 2.5x2.5 degree resolution prior to data analysis. The land mask comes from SPEI.

# METHODS

The proposed indicator will be constructed based on anomalous geo-potential high at 500 hPa (δZ500hPa), anomalous air temperature at 700 hPa minus surface dew point (δ(T700hPa-Td)), anomalous cumulative soil moisture (δ W).

$$\mathrm{D}(\mathrm{lat},\mathrm{lon},\mathrm{t}+3) = \mathrm{A}[\delta \mathrm{Z}^{*}_{500hPa}(\mathrm{lat},\mathrm{lon},\mathrm{t})] + \mathrm{B}\left[\int_{t_0}^{t}(\delta W)dt\right] + \mathrm{C}[\delta(\mathrm{T}_{700hPa}(\mathrm{lat},\mathrm{lon},\mathrm{t}) - \mathrm{T}_{d}(\mathrm{lat},\mathrm{lon},\mathrm{t}))] \quad (1)$$

Equation 1 is used to construct the Indicator of Flash Drought Warming (IFDW: or Flash Drought Warming Indicator). The left term represents the indicator we plan to build. The first right term represents the average geopotential anomaly in the spring season. The second right term represents the accumulated soil moisture anomaly from autumn to spring. The last right term represents the Convective Inhibition Energy which is represented as anomalies in temperature at 700 hPa minus surface dew point. The three factors cover the large circulation pattern, soil moisture and land thermodynamic condition. All the anomalies are computed by removing the mean from 1961-1990.

A, B and C are weighing factors, which will be calculated using multi-variable regression (Equation2) with SPEI (Standardized Precipitation-Evapotranspiration Index). The regression equation is as follows:

$$\mathrm{Index}(\mathrm{lat},\mathrm{lon},\mathrm{t}+3) = \mathrm{A}[\delta \mathrm{Z}^{*}_{500hPa}(\mathrm{lat},\mathrm{lon},\mathrm{t})] + \mathrm{B}\left[\int_{t_0}^{t}(\delta W)dt\right] + \mathrm{C}[\delta(\mathrm{T}_{700hPa}(\mathrm{lat},\mathrm{lon},\mathrm{t}) - \mathrm{T}_{d}(\mathrm{lat},\mathrm{lon},\mathrm{t}))] \quad (2)$$

This equation is the same as equation 1 but the left term is replaced with the existing drought index.

# DROUGHT EVENTS LIST

Here we list all the drought years in US Great Plain. The year in red represents only part of the interested area (22°N-40°N, 90°W-110°W) suffers from drought.We use the following criteria to determine a year is drought year or not:

Roughly more than half of the selected area with SPEI<-1

The drought event from 1949 to 2011 in US Great Plain is as follows:

- 1951-1956
- 1963, 1964, 1967
- 1971, 1974, 1976, 1978
- 1980
- 1996, 1998
- 2000, 2002, 2006, 2009, 2011

We use another drought index to validate the above list. The area-averaged PDSI for Texas climate divisions obtained from the National Climatic Data Center (NCDC) with help of Dr. Fernando. The drought years from 1895-2011 for Texas are: 18 severe to extreme droughts (PDSI<-3): 1902, 1911, 1917, 1918, 1925, 1951, 1952, 1953, 1954, 1955, 1956, 1963, 1971, 1996, 1998, 2000, 2006, 2011. 10 moderate droughts (-2.99<PDSI<-2): 1896, 1901, 1909, 1910, 1934, 1964, 1967, 1978, 1980, 2009.

There are slight disagreements in the list, however the severe to extreme droughts year are the same. The reason for the disagreement might be:

1. Different index has different algorithm and focus on different process. The indices might not truly reflect the real situation and disagreements exist between those indices.

2. Area averaged PDSI might give a biased indication for a specific area especially when only part of the area suffers from drought.
3. A drought initiation time is usually identified as the point when the cumulative anomaly begins a substantial decline, which is determined subjectively [*Keyantash and Dracup*, 2002].

# EVALUATION THE PERFORMANCE

## COMPARE THE PERFORMANCE OF DIFFERENT DROUGHT INDICES

This chapter aims to compare the different drought indices used for building the new drought warning indicator.

We select 2 existing indicators: Standardized Precipitation-Evapotranspiration Index (SPEI) [*Vicente-Serrano et al.*, 2010] and Self-calibrated Palmer Drought Severity Index (scPDSI) [*Dai*, 2011] to make the comparison. Computation of the PDSI is complicated and the in-depth discussions of the numerical steps have been documented in many literatures [*Alley*, 1984; *Dai*, 2011; *Dai et al.*, 2004]. Dai's 2011 version of PDSI is a more complicated approach which using Penman-Monteith equation instead of the commonly-used Thornthwaite equation. In this way, surface net radiation, humidity, wind speed and air pressure are introduced to the index. The self-calibrated PDSI using Penman-Monteith equation considers much more factors than we use. However, the SPEI is generally focused on precipitation plus evapotranspiration which has a similar mechanism as we considered. This might be a reasonable explanation in this case that SPEI seems superior to scPDSI.

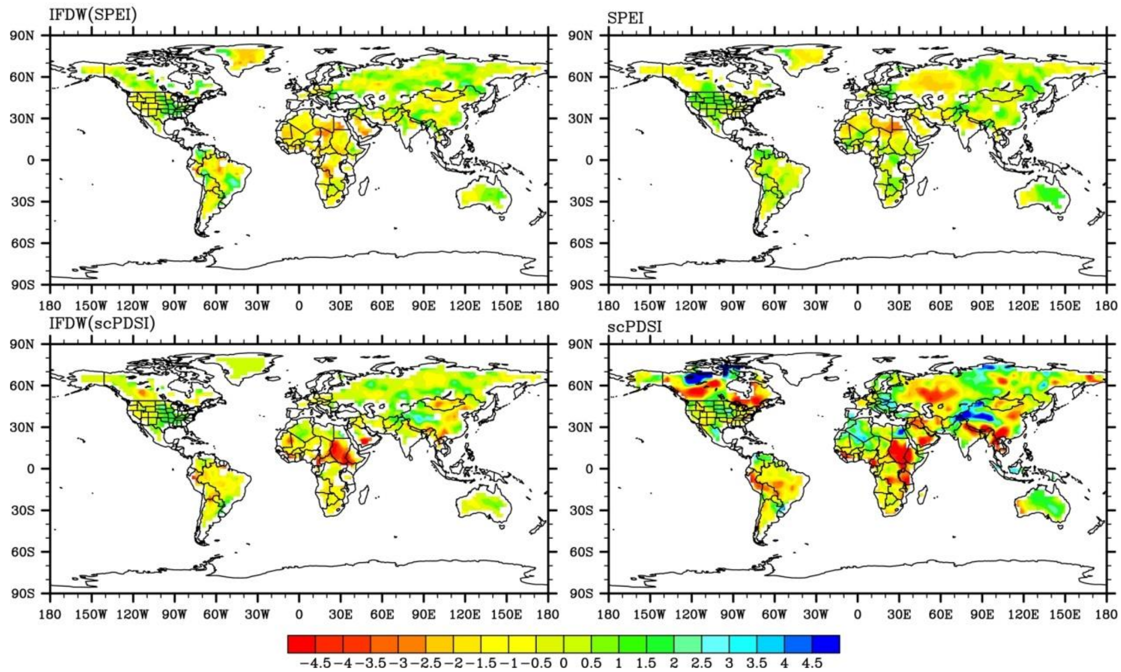


Figure 2: The comparison between IFDW and observed SPEI and scPDSI, respectively.

Figure 2 is an example of 2010 predicted and observed map. The left 2 panels show the predicted map of IFDW computed using SPEI and scPDSI respectively. The right 2 panels are the SPEI and scPDSI themselves. From these figures, we can see that the IFDW computed using SPEI is a better choice according to its spatial distribution and amplitude. It is the same situation for all other individual years (not shown). So the following discussion will focus on the Flash Drought Warming Indicator computed by SPEI only.

## COMPARE DIFFERENT REGRESSION COEFFICIENT

This session we discuss 2 methods to do the regression. A, B, C are the regression coefficient or weighting factors. The details have been discussed in METHODS chapter.

The left panel shows the coefficient derived using the whole period: 1949-2011. The right panel shows the coefficient using only the drought year listed in chapter DROUGHT EVENTS LIST.

From figure 3, we can see the coefficient of soil moisture anomalies (B) does not have any significant change for different regression time serials which shows the soil moisture feedback is stable for different time periods. Furthermore, B is positive almost at global scale which means the role of soil moisture in drought is similar globally.

For 500 hPa geo-potential height anomalies (A) and Convective Inhibition Energy (C), they show a different spatial pattern for different regression period. Those 2 coefficients are highly dependent on the regression period.

Finally, we compare the constructed IFDW using SPEI with 2 sets of coefficients (figures not included). We find the performance varies a little. Typically, the full time period regression has a similar pattern in non-drought at most of the cases. By evaluating the overall performance, we consider that using the full time period for the regression is a better choice, although the drought only time period regression can capture the termination of 1950s multi-year drought, while the full time period regression cannot.

This test shows that tuning the coefficient can impact the performance of this indicator. Multi-variable regression might not be the best way to find the coefficient. Like many other popular drought indices such as PDSI, SPEI which also use the experiential parameters, the experiential parameters will introduce uncertainty. Since we use SPEI as a reference to build IFDW, the uncertainties come from at least 2 sources: the SPEI themselves and the multi-variable regression.

The current approach we use can capture almost all drought events, except the termination of 1950s multi-year drought, in the Great Plain during 1949-2011 periods. This is discussed in detail in the following chapter.

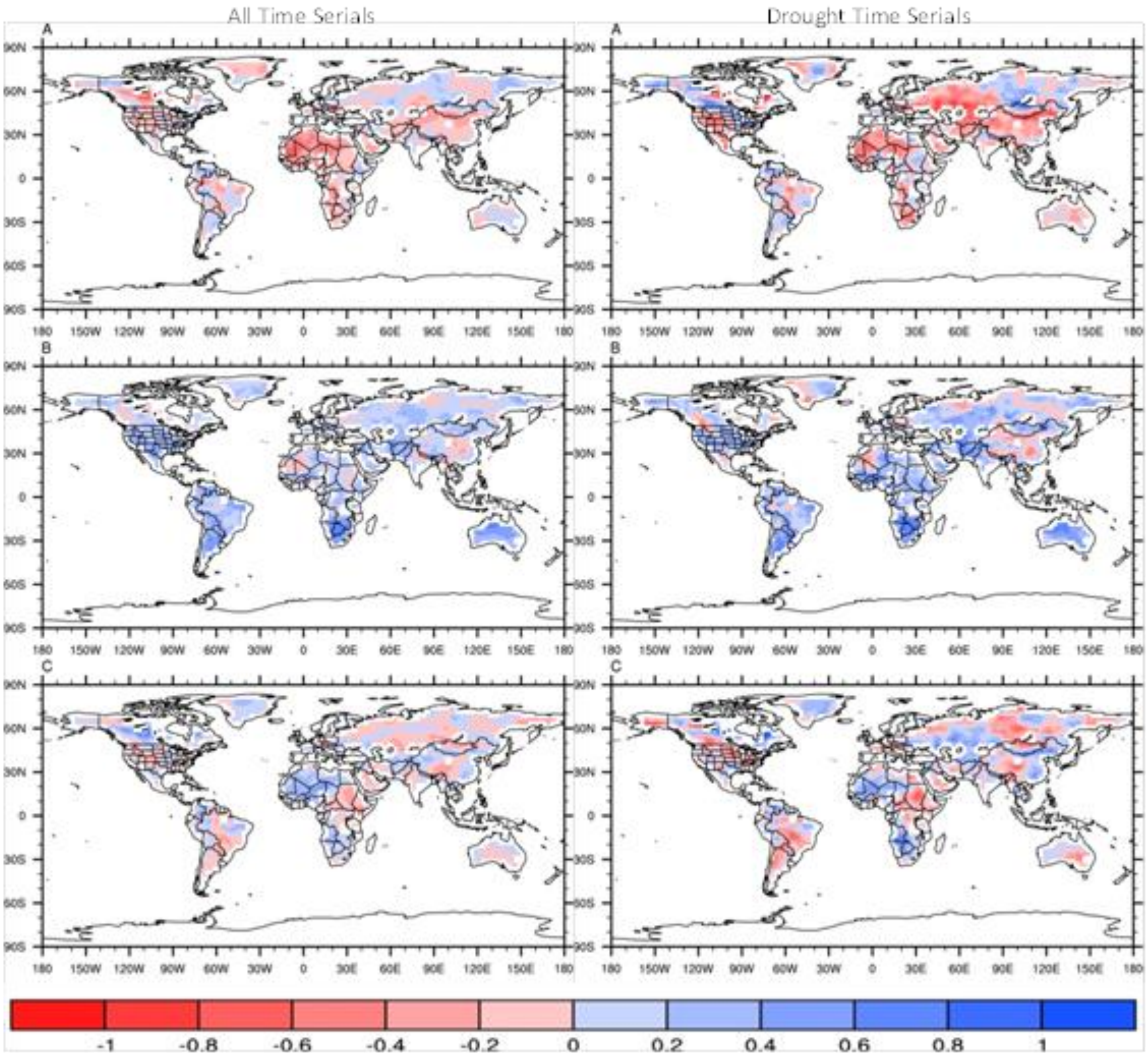


Figure 3: The comparison of different regression coefficients.

# CASE DISCUSSIONS

This section will discuss several drought events in the US Great Plain captured using the Flash drought Warming Indicator (IFDW) and Standardized Precipitation-Evapotranspiration Index (SPEI).

### 2011 DROUGHT

The top panel shows the IFDW and the bottom panel shows the SPEI. The Southern Great Plains suffered from exceptional drought in 2011. The IFDW can predict the condition is changing from wet to dry. This is very good result for no traditional method could capture this exceptional drought before it occurred.

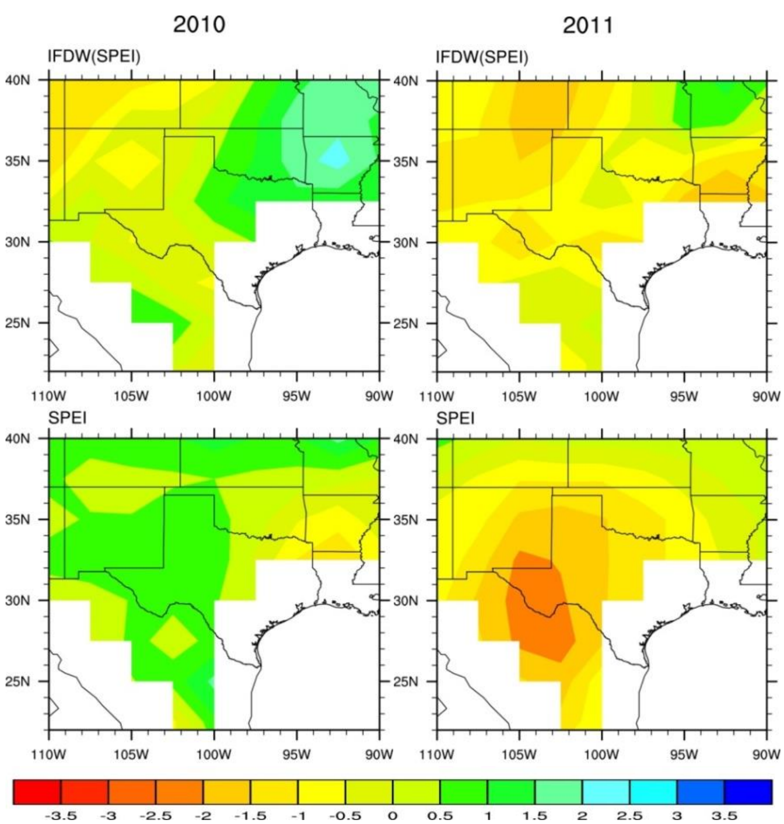


Figure 4: The 2011 drought.

**2006 DROUGHT**

The top panel shows the IFDW and the bottom panel shows the SPEI.

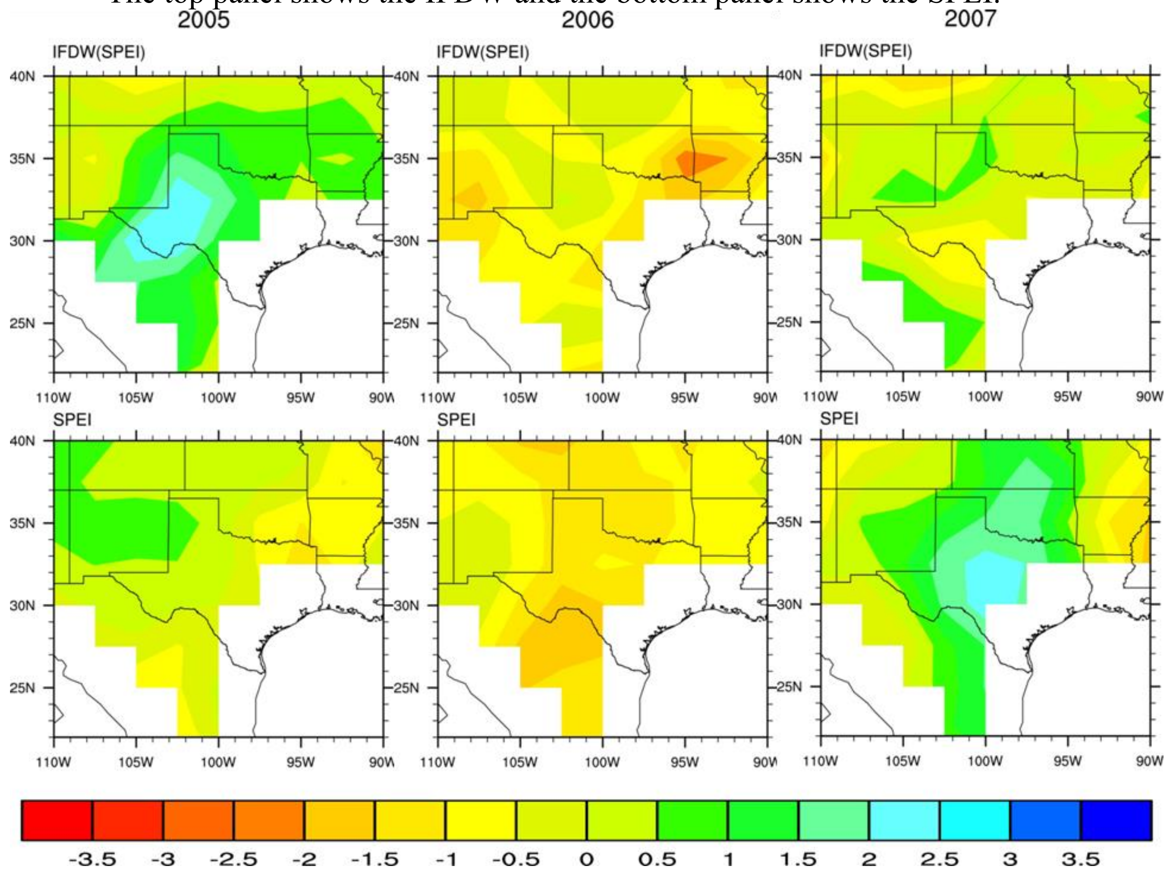


Figure 5: The 2006 drought.

Here is another example: 2006 drought. We can see the IFDW can predict the development and the termination of 2006 drought. Although the detailed pattern does not match exactly, the large feature is captured. All indices are the estimation of a real situation and different drought indicators can show different spatial pattern and its performance for different area is not equal [*Dai*, 2011; *Richard R. Heim*, 2002; *Vicente‐Serrano et al.*, 2011]. The more similar to SPEI can only mean the regression coefficient is very good which does not necessarily imply that it captures the real situation quite well. Similarly, the disagreement doesn't necessarily mean it's not good

For the purposes of this study, we only focus on the big picture that the indicator can or cannot capture the drought warning signal in the US Great Plain.

### 1951-1956 Multi-Year Drought

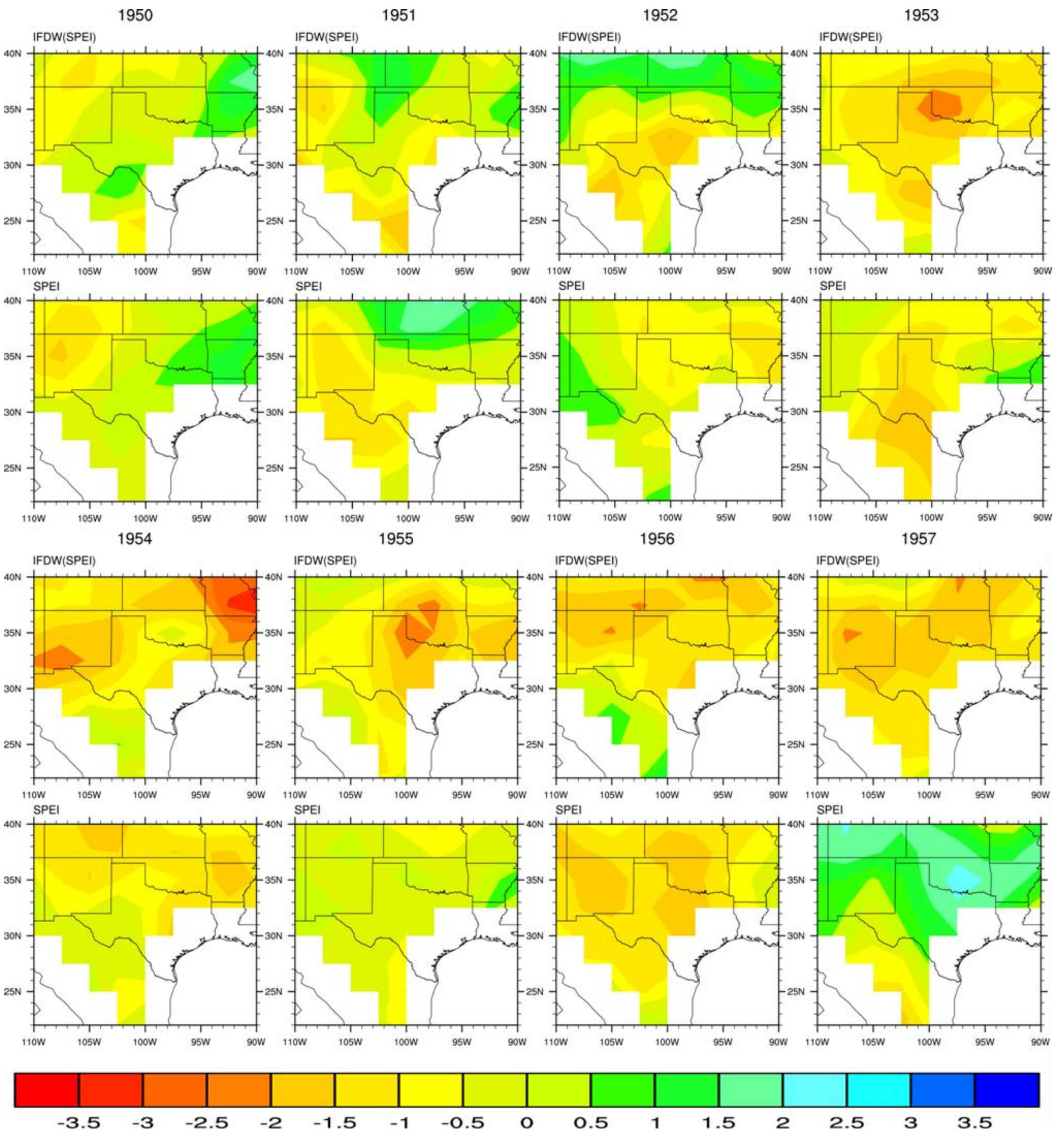


Figure 6: The 1950s multi-year drought

We can see the drought started from 1950 and continue to 1951, 1952, 1953, 1954, 1955, 1956 and ended at 1957. However, the IFDW cannot predict the termination of this drought.

As mentioned above in the section on COMPARE DIFFERENT REGRESSION COEFFICIENT in the chapter on EVALUATION THE PERFORMANCE, the coefficients based on Drought time periods have a better performance in simulating the 1957 condition (Figure 7).

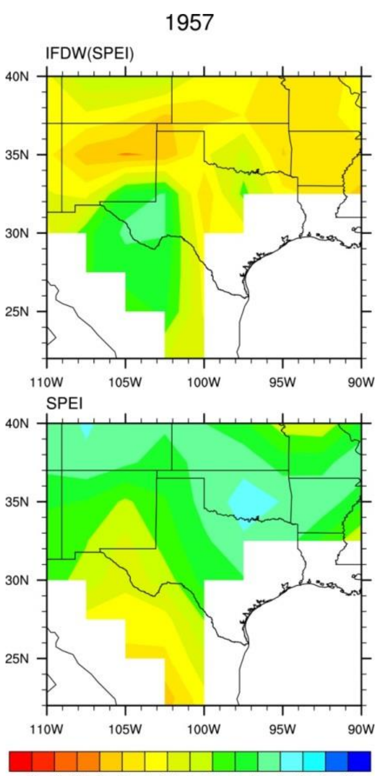


Figure 7: The 1957 drought termination year using coefficient based on Drought time period regression

While this approach predicts the wet condition, the spatial pattern is reversed.

Overall, the new indicator reasonably captures drought events over the US Great Plains.

## IFDW FOR OTHER AREAS

Encouraged by the result of IFDW hind cast over the US Great Plain, we consider to broaden the indicator to other areas. We study whether there are other regions in the globe were this indicator could be potentially applied for drought early warning

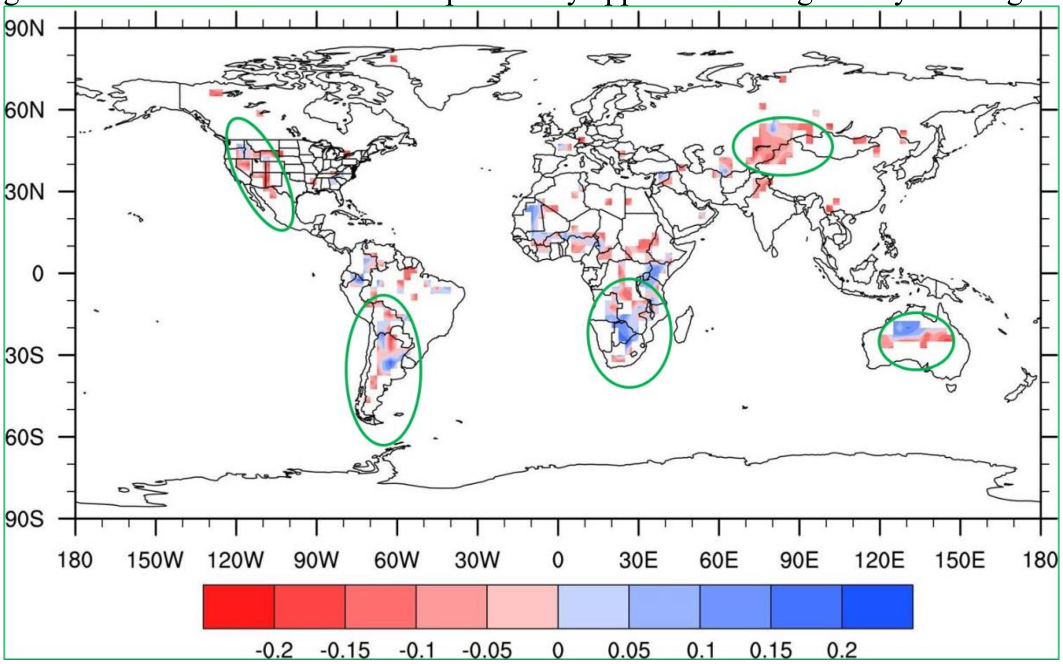


Figure 8: The averaged IFDW-SPEI from 1949 to 2011

Figure 8 is the averaged IFDW-SPEI from 1949 to 2011. The color bar is the value of difference between IFDW and SPEI. The values greater than 0.25 and less than -0.25 have been masked out. The remaining circled areas are potentially the suitable areas for our indicator. So we may conclude that the suitable regions could be S. Great Plain, Southern S. America, S. Africa, N. Australia, Central Asia.

Since this is only a statistical result and we have not looked into the details of those regions. How convincing is this conclusion? Let us refer to previous literature.

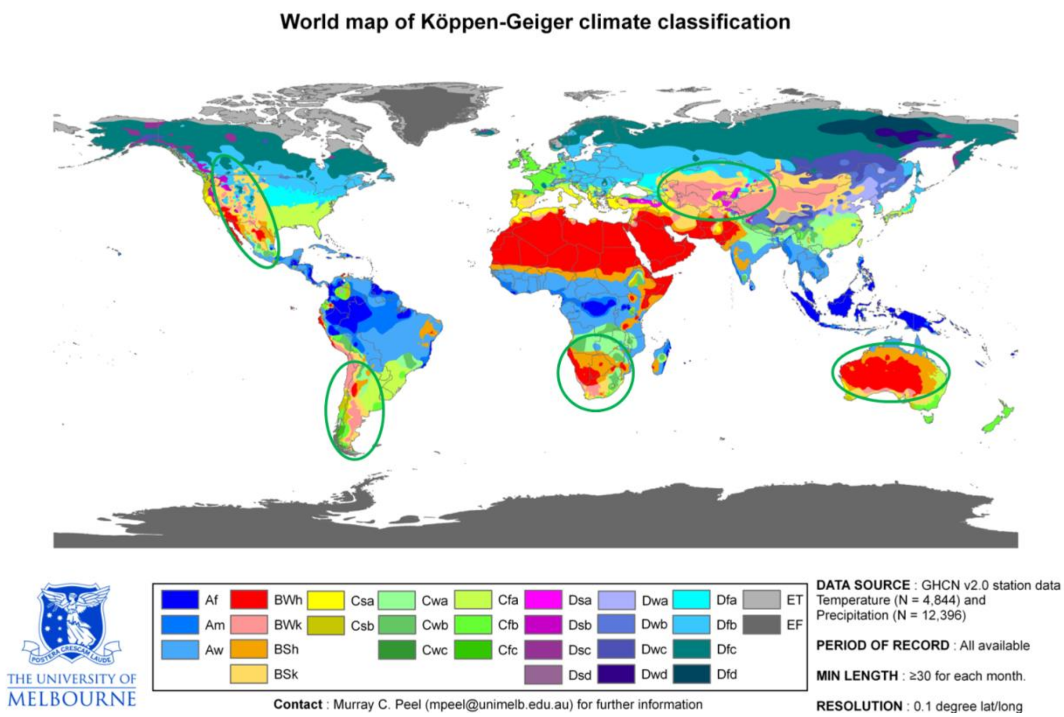


Figure 9: World map of Koppen-Gelger climate classification

This is a climate classification map produced by Koppen-Geiger. [*Ahrens et al.*, 2011; *Wikipedia*] We can see the 5 **circled regions** fall into the same group of classification that is the semi-arid region which shows in the 2nd column except the desert in red color.

# CONCLUSION

This flash drought indicator appears to capture all drought event in US Great Plain from 1949-2011 including the start and termination of all single-year drought (except the termination of 1951-1956 multi-year drought).

The indicator can be improved by more careful training of the coefficient.

This drought indicator could potentially be broadened to other semi-arid regions with the similar drought mechanism such as Southern. S. America, S. Africa, N. Australia, Central Asia.

## FUTURE WORK

Look into the details of all potentially suitable regions and their detail drought climatology.

Construct independent drought indicator without using the existing drought index if possible to train the weighting factors. The weighting factors might not come from the regression of existing indices. Instead, we try to look for more physics or dynamic based weighting factors.

Look into detail algorithm of all most prominent indices. [*Richard R Heim*, 2000; *Keyantash and Dracup*, 2002]. Review the empirical parameterization methods used existing drought indices.

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