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## Introduction

Human inputs of nitrogen into the atmosphere have increased dramatically as a result of fossil fuel emissions and fertilizer use. When this excess nitrogen deposits onto the Earth's surface, it has many diverse and harmful effects, ranging from reduced drinking water quality to altered chemical composition of ecosystems.

Wet deposition rate of nitrogen is governed by precipitation amount and frequency and thus is influenced by large-scale climate. This study uses wavelet analysis to determine the relationship between nitrogen wet deposition and the following four indices of climate variability.

- 1 The **El Niño Southern Oscillation** (ENSO) is a climate cycle that can be measured by NINO3.4, an index quantified by the sea surface temperature in the area of 5S-5N latitude and 170-120W longitude. El Niño (positive phase of ENSO) winters are associated with warm, dry weather in the Pacific Northwest and cool, wet weather in the Southwest and Southeast US; the opposite is true of La Niña winters (negative phase of ENSO).
- 2 The **Arctic Oscillation** (AO) is an index defined by opposing atmospheric pressure patterns in northern middle and high latitudes. The positive phase of AO corresponds to low pressure over the polar region and high pressure at the mid-latitudes, which keeps the eastern US warmer than normal and brings drier conditions to the western US.
- 3 The **Pacific/North American** (PNA) teleconnection pattern is associated with above average temperatures in the western US and below average temperatures in the southeastern US in its positive phase; the opposite is true of the negative phase.
- 4 The **North Atlantic Oscillation** (NAO) is an index characterized by differences in pressure between a station on the Azores and one on Iceland. Positive phases of NAO are associated with above-average temperatures across the eastern US.

## Objectives

- To identify inter-annual variability of total nitrogen (sum of ammonium and nitrate) wet deposition
- To evaluate the correlation between precipitation and nitrogen wet deposition
- To determine the correlation between dominant signals of climate indices and nitrogen wet deposition through wavelet transforms.

## Data and Methods

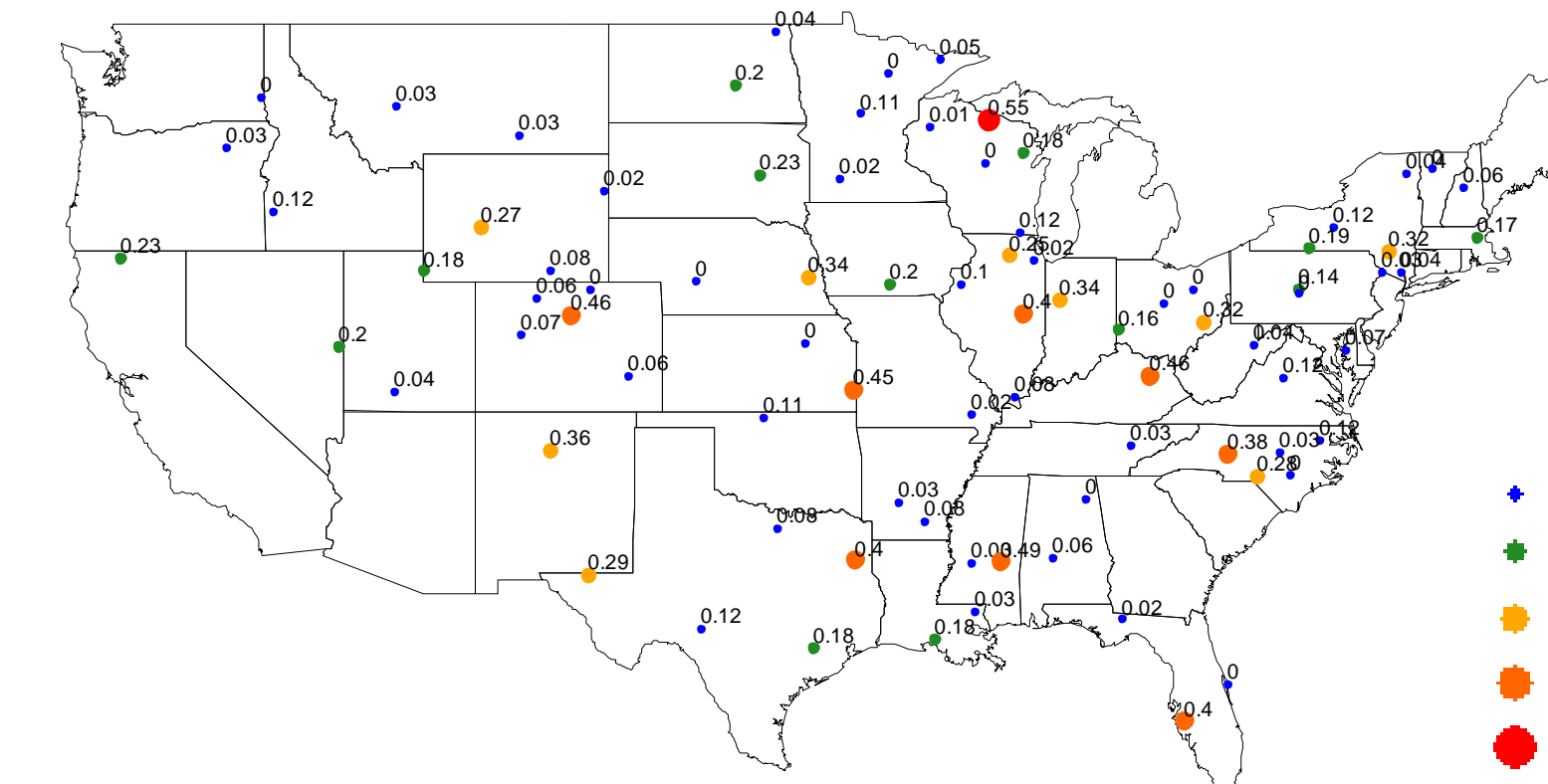
- Nitrate (NO<sub>3</sub>) and ammonium (NH<sub>4</sub>) wet deposition data and precipitation data were collected for 79 stations across the United States from the National Atmospheric Deposition Program (NADP)<sup>1</sup>, National Trends Network in the range of 1979-2011. Selected stations all had at least 21 years of continuous data.
- Standardized anomalies were calculated by subtracting seasonal means from each seasonal value and dividing by the seasonal standard deviation in order to remove the annual cycles.
- Climate index data was obtained from the National Oceanic and Atmospheric Administration's Climate Prediction Center<sup>2</sup>.
- The wavelet analysis tool<sup>3,4,5</sup> was used in order to decompose one or two time series into both time and frequency space.

## Correlation Coefficients

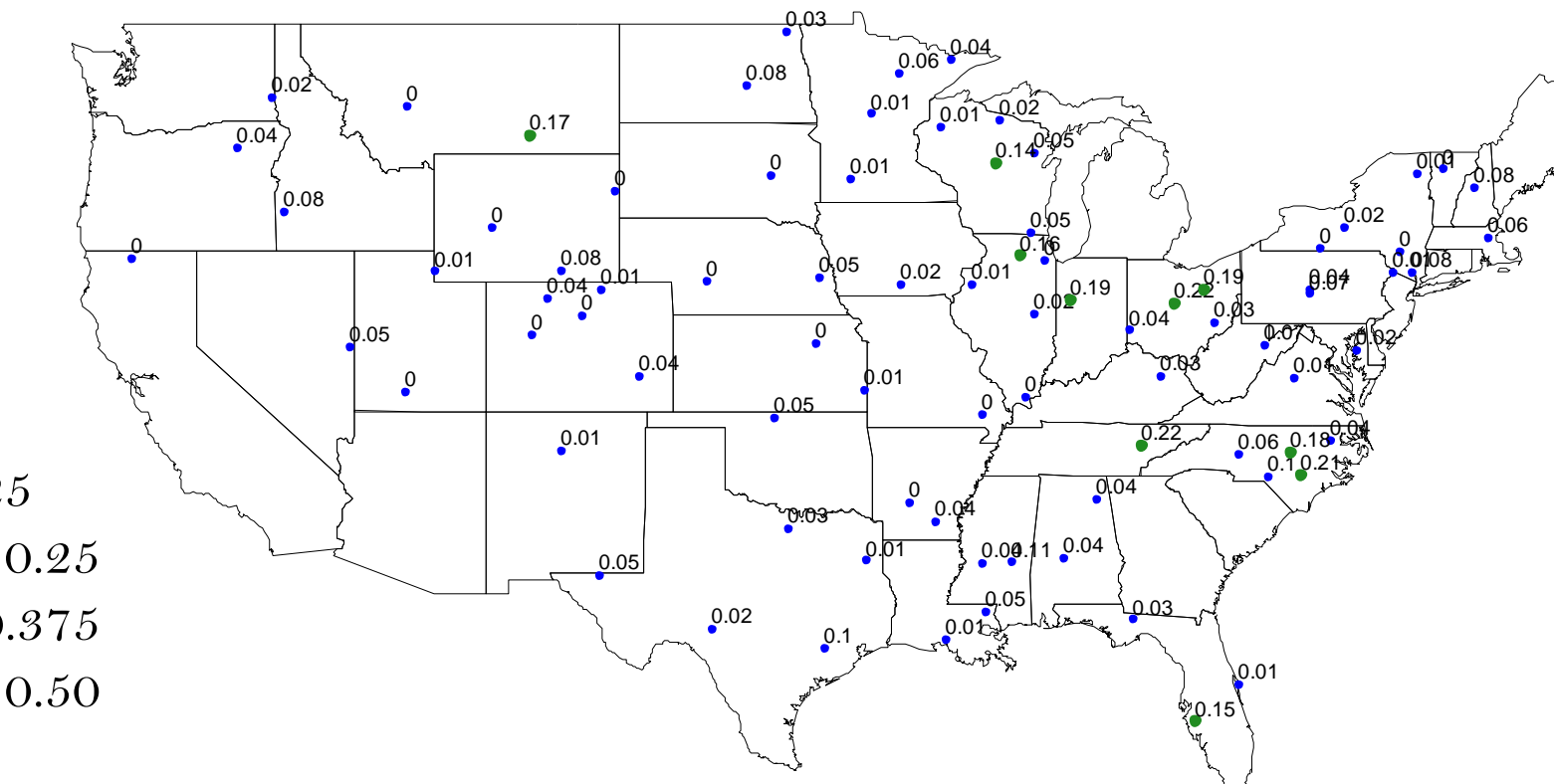
Correlations of precipitation and total nitrogen wet deposition with each of the climate indices were determined based on the dominant mode of climate variability. For the ENSO cycle, the coefficients were calculated using the 2-6 year scale-averaged variance (band), which was found to be the dominant periodicity in the 1950-2012 data set based on the wavelet analysis. The correlations with other indices were calculated for the 0.5-2 year band. Results are shown here for both the NINO3.4 and the NAO with precipitation and combined NH<sub>4</sub> and NO<sub>3</sub> wet deposition. The red arrow indicates station FL41, which is used as an example for the wavelet transforms below.

**Figure 1.** a) Correlation coefficient ( $R^2$ ) values for NINO3.4 and precipitation; b)  $R^2$  values for NINO3.4 and N wet deposition; c)  $R^2$  values for NAO and precipitation; and d)  $R^2$  values for NAO and N wet deposition. All results shown are without considering lag time.

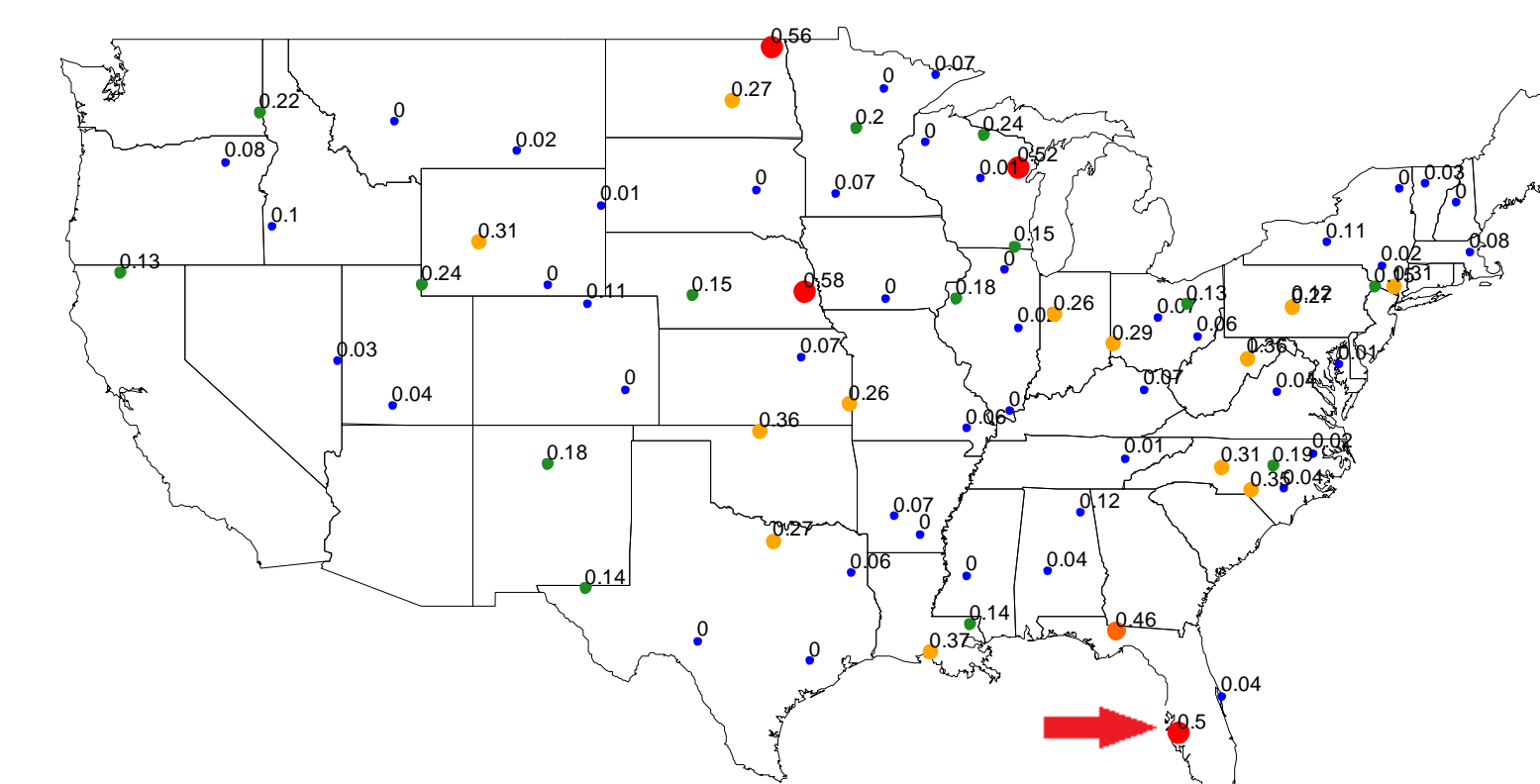
a) Correlation between NINO3.4 and Precipitation



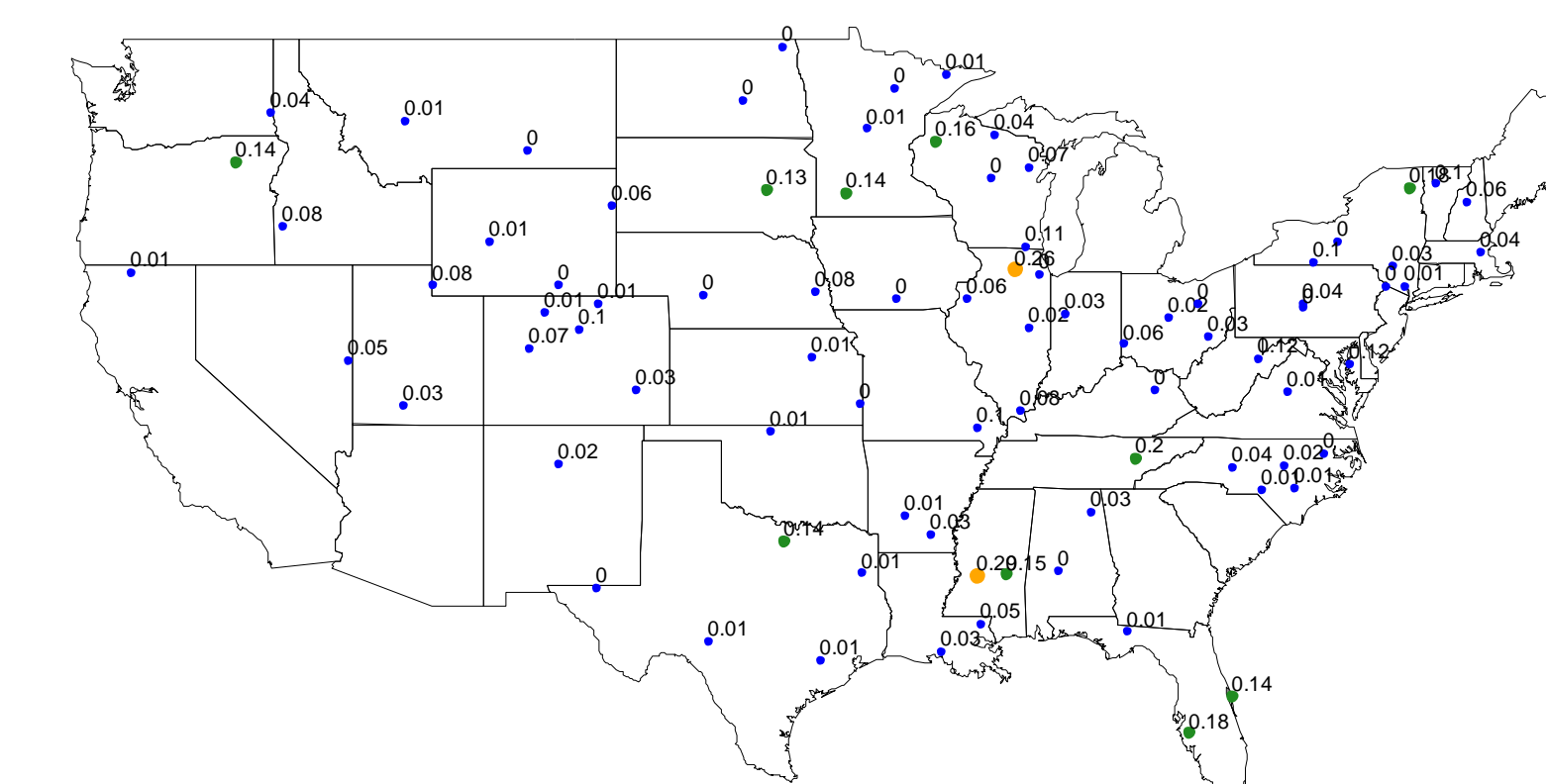
c) Correlation between NAO and Precipitation



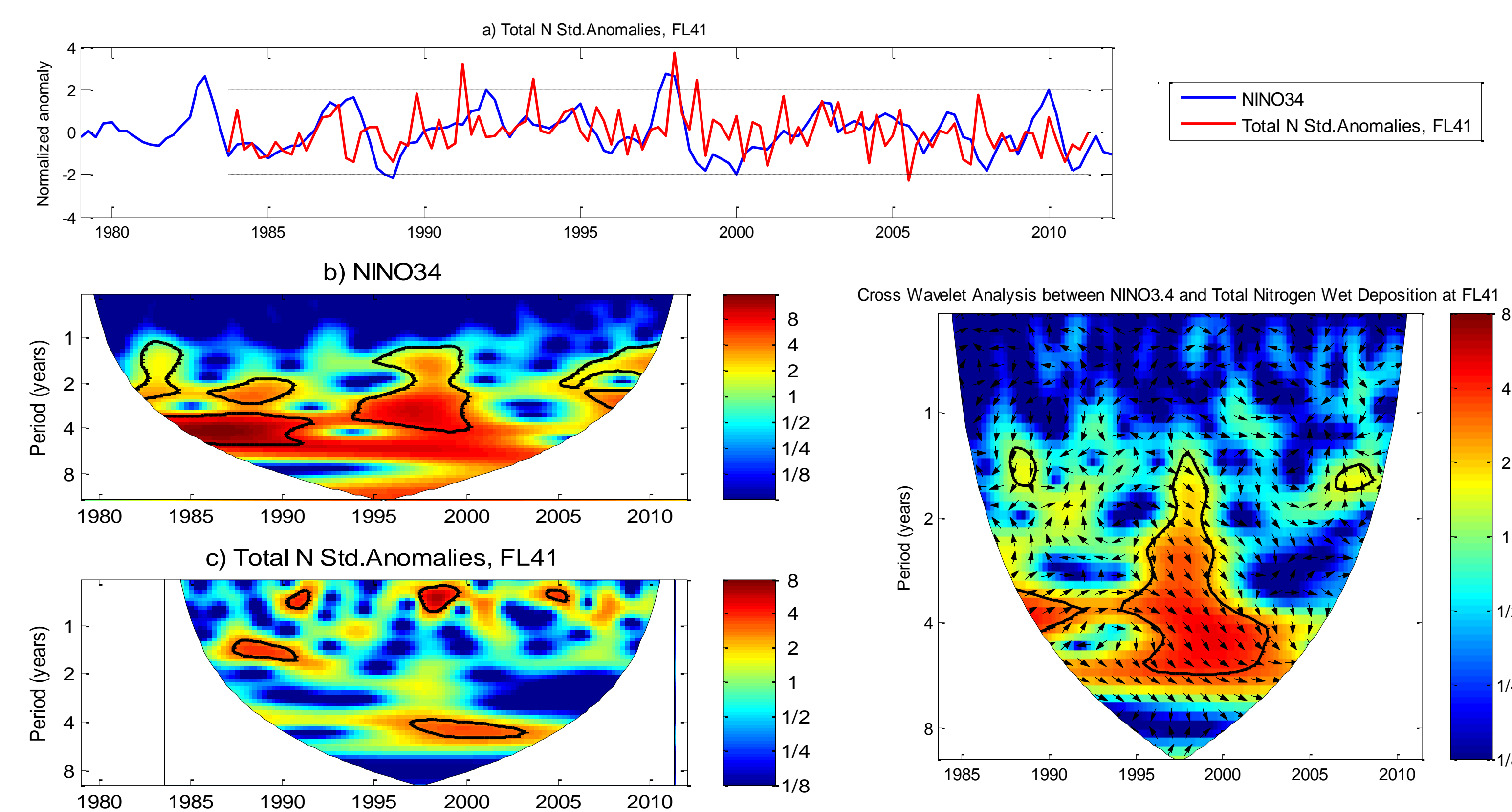
b) Correlation between NINO3.4 and Total N Wet Deposition



d) Correlation between NAO and Total N Wet Deposition



## Continuous Wavelet and Cross Wavelet Transforms



**Figure 2.** a) Time series of NINO3.4 and FL41 total nitrogen wet deposition standardized anomalies; b) continuous wavelet transform of NINO3.4; c) continuous wavelet transform of FL41 nitrogen wet deposition; and d) cross wavelet transform between NINO3.4 and FL41 nitrogen wet deposition.

- The wavelet analysis tool makes it possible to determine the dominant periodicities of a time series and where in time these occur. The darker red colors indicate areas of high power, or areas where the variance is largest. The black contours display statistically significant variances at the 95% confidence level.
- As seen in both the time series and the continuous wavelet spectra, nitrogen wet deposition at FL41 has an area of significantly high variance around 1997, which corresponds to the strong El Niño event of 1997-1998.
- The cross wavelet transform reveals that the two time series share a period of high common power centered around 1997.
- The arrows represent the phase relationship, with right-pointing arrows representing in-phase and left-pointing representing out of phase. In this case, the arrows, which point roughly southeast, indicate that NINO3.4 leads N deposition by about 4-5 months.

## Conclusions and Future Work

- Results of the wavelet analysis were very site specific, but in general, they reveal that nitrogen wet deposition has a dominant periodicity of 0.5-2 years; for ENSO it is 2-6 years, and for AO, NAO and PNA, it is 0.5-2 years in the range of 1979-2011.
- Precipitation and nitrogen wet deposition were most correlated in the Great Plains region, in the states of South Dakota, Kansas, Iowa, Tennessee and Ohio, with  $R^2$  values in the range of 0.50 to 0.75. Lower correlations ( $R^2$  values less than 0.125) were seen in the states such as Montana, Wyoming and Utah.
- ENSO was found to be most correlated with precipitation and nitrogen deposition in the Midwest and eastern US, with many  $R^2$  values in the range of 0.38 to 0.50; smaller values were found for the western US, but there were very few NADP sites in this region.
- Calculated correlations between NAO, AO and PNA and precipitation and nitrogen deposition were not as strong as for ENSO, and the strongest of these were again seen in the Midwest and eastern US, with a maximum  $R^2$  value of 0.29.

Future research will include:

- The use of precipitation frequency instead of precipitation rate data in the analysis with N wet deposition.
- Analysis with dry deposition data from CASTNet.

## References & Acknowledgements

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