Background

The **Jet Stream** is a current of westerly, fast-moving air typically on the 250hPa pressure surface in the atmosphere. It typically lies below the tropopause, where the tropopause varies in altitude as a function of latitude. It is result of the pressure gradient force due to differential heating between the equator and poles and the Coriolis force imparted by the rotation of the Earth. Firstly, because warmer air expands and cooler air contracts, the thickness of an atmospheric layer over the equator is greater than the layer thickness over the poles (Fig. 1a). This induces a pressure gradient force (PGF) from the equator to the poles and in a non-rotating environment, fluid would be driven poleward. However, since Earth's rotation results in the Coriolis force, fluid flow is deflected to the right of the PGF in the northern hemisphere and to the left of the PGF in the southern hemisphere. These forces drive 4 different Jet Streams, two Polar Front Jets located on the boundary between the Polar Cell and the Ferrel Cell (60th Parallels) and two weaker Subtropical Jets on the boundary between the Hadley Cell and Ferell Cell (30th Parallels) (Fig 1b). The Polar Front Jet in the Northern Hemisphere is the fastest due to the strongest temperature gradient existing at this latitude (around 60N). Since most of Earth's land masses and therefore humans inhabit the northern hemisphere, the effects of this jet influence most people. Consequently, the northern Polar Front Jet is often referenced as the "Jet Stream" by the media.
Rossby waves are planetary scale long waves that form due to differential heating of the Earth's surface and Earth's geography such as mountains. When mountains get in the way of atmospheric flow (wind), the parcel of air (or a columnar vortex) must change its absolute vorticity in response to changes in the depth of the vortex to keep its potential vorticity constant. Essentially, high-reaching mountain ranges cause changes in direction and rotation of the flow and thus cause meanders (a wave-like pattern), in the Jet Stream, downstream. The Jet Stream often dictates the weather a region receives. Deviations in the mean Jet Stream can be caused by modes of climate variability. Hence, modes of climate variability cause changes in regional weather due to changes in the flow of the Jet Stream. In the next sections, I will be looking at influences of ENSO and the Arctic Oscillation on the Jet Stream and thus regional weather.

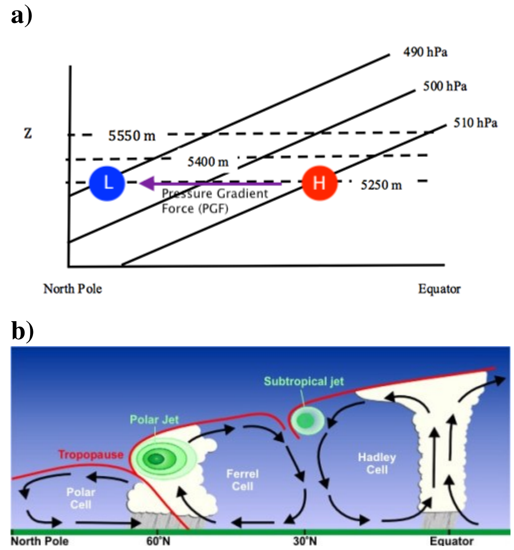

Figure 1: **a)** Layer thickness of the atmosphere depends on latitude. Layer thickness is higher at low latitudes and lower and high latitudes which induces a permanent pressure gradient from the equator to the poles. Adapted from PennStateMet. **b)** General atmospheric circulation and Jet Streams. Image from UBS EOAS.

Data Analysis

I use global monthly-averaged zonal wind speed on the 250hpa pressure surface (IRI Columbia) along with the Nino 3.4 Sea Surface Temperature anomaly time series (NOAA PSL) and the Arctic Oscillation (AO) time series (NOAA NCEI) from January 1950 to October 2020.
Doing a multiple linear regression on these data, the problem is:

$$Y = Xb$$

$y \epsilon \mathbb{R}^{850x1}$, $X \epsilon \mathbb{R}^{850x3}$ and $b \epsilon \mathbb{R}^{3x1}$ where we want to solve for b, the regression coefficients. X = [AO, ENSO, Mean-term] is an over determined system where N > M with $X \epsilon \mathbb{R}^{NxM}$. Since we have more equations than unknowns, there is no unique solution. However, we can find the least squares solution such that X solves the system $Y = Xb$ to the smallest residual. In other words, we solve the minimization problem

$$\min_{b \epsilon \mathbb{R}^3} ||Y - Xb||$$

The minimization problem leads to the normal equation

$$Y = Xb \Leftrightarrow X^T Y = X^T Xb \Leftrightarrow b = (X^T X)^{-1} X^T Y$$

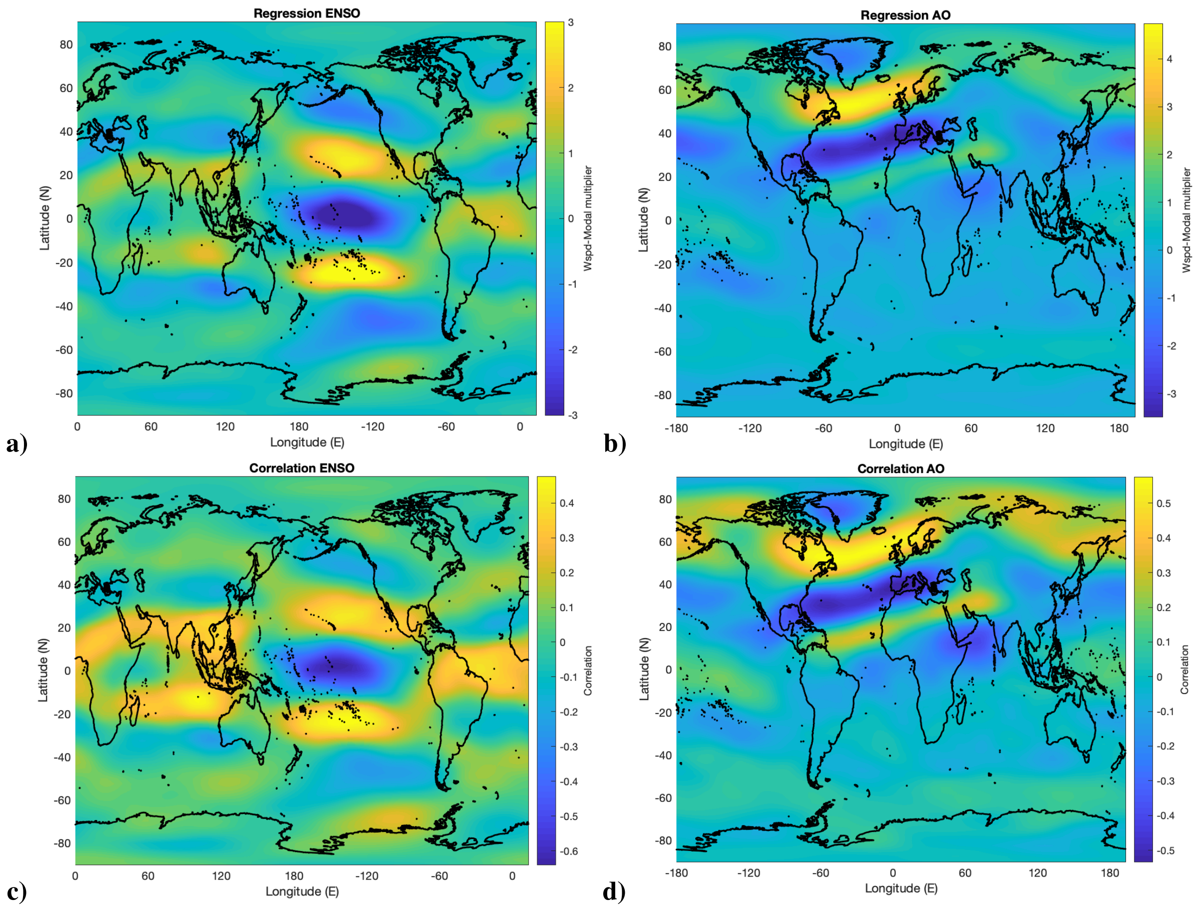

Figure 2: ENSO and AO regression and correlation plots with 250hPa wind speed anomaly.

where b are the regression coefficients we're solving for. This is equivalent to doing $b = \text{regress}(X,Y)$ in Matlab.

In Fig 2a, is the regression coefficients of 250hPa wind speed *anomaly* with the ENSO time series and in Fig 2b is the regression coefficients of 250hPa wind speed *anomaly* with the AO time series. It's important to note that a westerly wind returns positive values of wind speed while a easterly wind returns negative values. The regression plots illustrate what value is needed to multiply one set of data by to get the best estimate of the other. However, the regression plots don't illustrate how good the regression coefficient "guess" is. For that, a correlation plot is needed. Below each regression plot the respective correlation plot, and we see the high similarity between the two. This means that in areas showing harsh shading, there is decent correlation between the data sets.
Yellow shading represents positive regression coefficients. This means that wind speed has a positive relationship with ENSO/AO (i.e., as ENSO/AO is positive, wind speed is positive but since I'm looking at wind speed anomalies, wind speed is greater-than-normal). The dark blue indicates negative regression coefficients. This results in a negative relationship between the two where if ENSO/AO is positive, wind speed is negative meaning winds are weaker-than-normal, and vice-versa if ENSO/AO is negative. We can identify this in Fig 3a,b. Where the ENSO regression plot had yellow shading (positive relationship between ENSO and wind speed, we should see a greater-than-normal wind speed during El Nino and weaker-than normal winds during La Nina. Where the ENSO regression plot has blue shading (negative relationship between ENSO and wind speed, we should see weaker-than-normal winds during El Nino and greater-than-normal winds during La Nina. Comparing Fig 2 and Fig 3, we do see that this is the case.

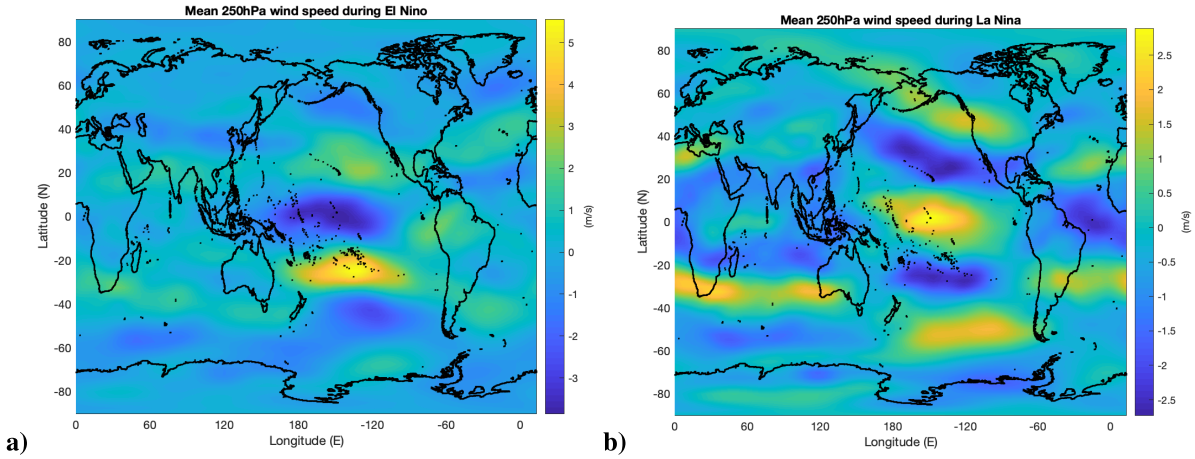

Figure 3: Mean 250hPa surface wind speeds from monthly averages. The magnitudes of wind speed are low because I use data that are already monthly averaged. Then I to get the mean state of winds at 250hPa, I averaged these data again over each phase of ENSO.

Consequences of Climate Variability on the Jet Stream and Regional Weather

ENSO and the Jet Stream

I will focus on the Jet Stream over the Norther Pacific, North American continent, and North Atlantic due to the lack of information of the Jet Stream elsewhere. During El Nino events, it's probable the subtropical jet strengthens and moves up into the southern US, while the polar jet stream swings farther east, creating a trough like pattern over the northeastern US. Typically, we see increased precipitation across the California and the southwest, greater than average snowfall across the southern Rockies and Sierra Nevada ranges, and below normal snowfall in the Midwest and Great Lakes [1]. Furthermore, we see an decrease in Atlantic hurricane activity due to increased upper level wind shear, and an increase in hurricane activity in the Eastern Pacific due to a decrease in upper-level wind shear [2]. Interestingly, the subtropical jet in the Southern Hemisphere is displaced equator-ward from its average position, which we see in the plot.

During La Nina, its probable that the Jet Stream diverges into two as a result of stationary high pressure over the northeast Pacific. The polar jet stream swings up into Alaska, then dips down back into Canada and curves upward again, passing through the Midwest and northeastern US. The other part of the Jet stream bends upward slightly into the Pacific Northwest and then rejoins the polar jet. As a result, increased precipitation of snowfall and rain is diverted into the Pacific Northwest, Midwest and Great Lakes. Consequently, we see a drier southern and eastern US [3]. Additionally, La Nina results in increased wind shear in the Pacific resulting in a decrease in TC activity while we see a decrease in upper level winds in the Atlantic leading to an increase in TC activity [4].

AO and the Jet Stream

The AO is often described in terms of pressure anomalies over the North pole and mid-latitudes. During a positive AO, we see lower-than-average air pressure of the Arctic and higher-than-average air pressure over the the mid-latitudes. Physically, this corresponds to a band of strong winds circulating the North Pole tends to restrict colder air to the polar regions. Hence, the jet stream is farther northward [5] and we see less storms track through the mid-latitudes. In the event of a negative AO, pressure anomalies reverse with higher pressures over the Arctic and lower pressures in the mid-latitudes. Here, winds become weaker, more distorted and cold arctic air masses can penetrate southward. Physically, we observe the jet stream meandering more southward into the mid-latitudes, bring along with it increased storminess.

References

[1] El Nino and the Jet Stream. https://climate.ncsu.edu/edu/ElNino. Accessed: 2020-12-12.

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[5] Arctic Oscillation. https://www.climate.gov/news-features/event-tracker/how-polar-vortex-related-arctic-oscillation. Accessed: 2020-12-12.