REPORT

Western University - London

Mitacs Globalink Research Internship 2021

Topic: “Improving probabilistic flood forecasting using teleconnection signals”

Name of GRI	**RAVINDRANATH PRASAD YADAV**
Application ID:	93819
Institute Where Working	Western University – London
Name of Guide	DR. Mohammad Reza Najafi

TABLE OF CONTENTS

ABSTRACT

In Canada, flooding ranks second among the costliest natural disasters, after the Fort McMurray wildfires in 2016. It is estimated that flood events risk over 1.7 million Canadian homes over the next 5 years, and the federal government could require about $3.4 billion on flood disaster relief. Accurate forecasts that properly characterize uncertainties combined with effective warning systems can reduce the negative consequences of future floods. This project develops an adaptive flood forecasting and warning system to improve the accuracy and lead-time of streamflow forecasts in particular in urban watersheds. Unlike deterministic approaches that rely on a single prediction of extreme events, the probabilistic ensemble-based flood forecasting system can characterize forecast uncertainties explicitly. The significant effects of low-frequency variability modes (such as El-Nino Southern Oscillation) on the regional hydroclimate of Canadian watersheds have been highlighted in several studies. We use these signals to improve forecast accuracy, reduce uncertainties and increase forecast lead times in the Upper Thames River Basin. Results are useful for future design, planning, and management of water infrastructure such as stormwater systems, culverts …, and increasing preparedness for future flood events.

CHAPTER-1

LITERATURE REVIEW

1. INTRODUCTION TO COMPOUND FLOODING

When coastal and river floods coincide, their impacts can be worse than when they occur in isolation. These are examples of 'compound events', defined by Zscheischler et al (2018) as 'the combination of multiple drivers and/or hazards that contribute to societal or environmental risk'. Regions can become more vulnerable in the immediate aftermath of a preceding natural disaster (e.g., Budimir et al 2014, Gill and Malamud 2014) [1]. In United States, the likelihood of joint occurrence of storm surge and heavy precipitation was calculated and it was evident that number of compound events has increased significantly over the past century at many of the major coastal cities. Long-term sea-level rise is the main driver for accelerated flooding along the US coastline [2]. How a better understanding of compound events may improve projections of potential high-impact events, and can provide a bridge between climate scientists, engineers, social scientists, impact modellers and decision-makers, who need to work closely together to understand these complex events [3]. Given that most previous climate-related studies of hazards focus on single drivers, and given the evidence that the events that are particularly worrisome are typically multivariate in nature as illustrated by the examples in this manuscript, we encourage a deeper focus on multivariate drivers and hazards of large climate-related impacts. Two distinct mechanisms—storm surges and heavy precipitation, either through direct runoff (pluvial) or increased river discharge (fluvial)— can lead to flooding in coastal areas. If they occur concurrently (or in close succession) the adverse consequences can be greatly exacerbated.

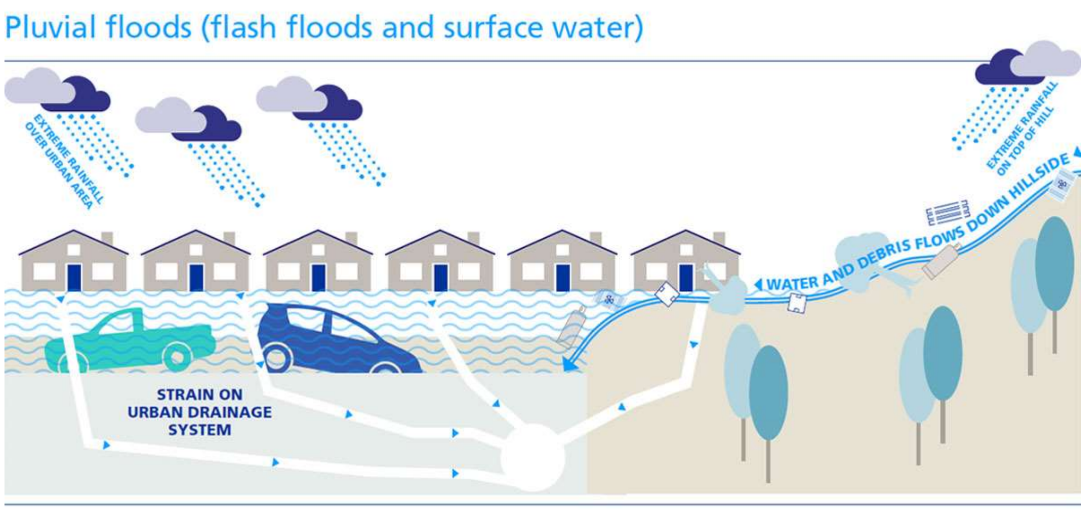

Figure 1: Pluvial Floods

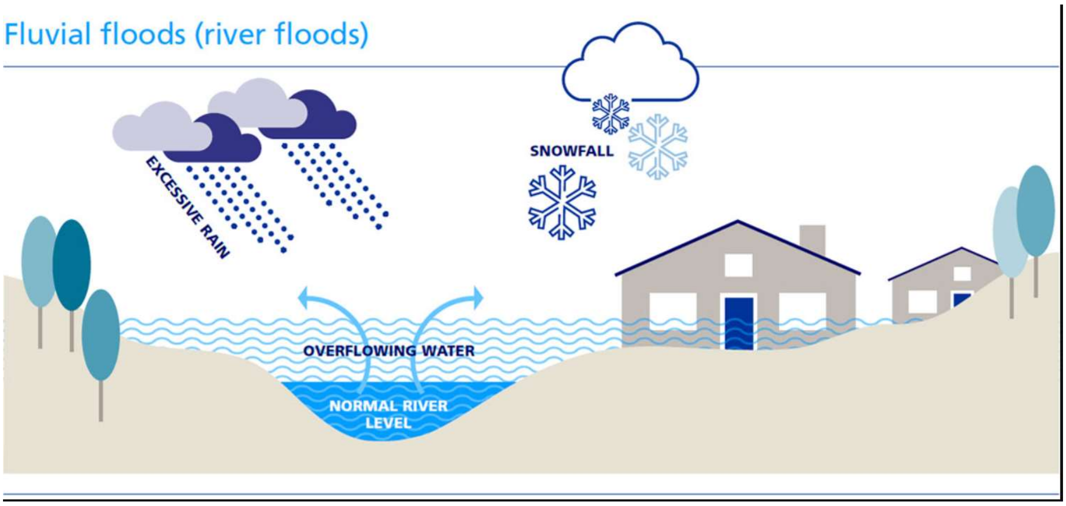

Figure 2: Fluvial Floods

Analysis of compound events using storytelling techniques is very appropriate because of their rare and often unprecedented nature. In practice, the analysis of compound events using storytelling techniques relies on realistic modelling capacity to simulate relevant events or sample them from large enough observation- or model-based event archives. Constructing portfolios of relevant compound events has to be inspired by both the drivers and the impacts of the events, where multiple features jointly operate to generate a large impact. Programme focused on these systems is overdue and is necessary to improve risk management for vulnerable communities. While efforts to understand single drivers of extreme events will continue, a refocusing of activity towards compound events would help to bridge the gap between the climate science and impact modelling communities

2. INTRODUCTION TO TELECONNECTIONS

The term teleconnection is often used in atmospheric sciences to describe the climate links between geographically separated regions. The remote region need not exhibit fluctuations of the same sign in order to be 'tele connected'. In fact, the interesting teleconnections often involve contemporaneous variations of opposite signs [4]. While Climate analysis is facilitated by the construction of a teleconnection map, which describes the linkage between a region of interest (a base point) and all other points in the domain that are farther than the de-correlation length scale of the variable. The understanding of these teleconnection patterns over multidecadal time-scale helps in prediction of climate and natural disasters. Globally, different recognized teleconnection indices like the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO), and/or the Pacific Decadal Oscillation (PDO), among others, are used in streamflow forecasting. These indices can provide sources of predictability for streamflow forecasting, over different regions of the world. However, these forecasts are not without limitations, because these predefined teleconnection indices have a defined spatial scale and use sea level pressure or sea surface temperature data aggregated over specific regions [5].

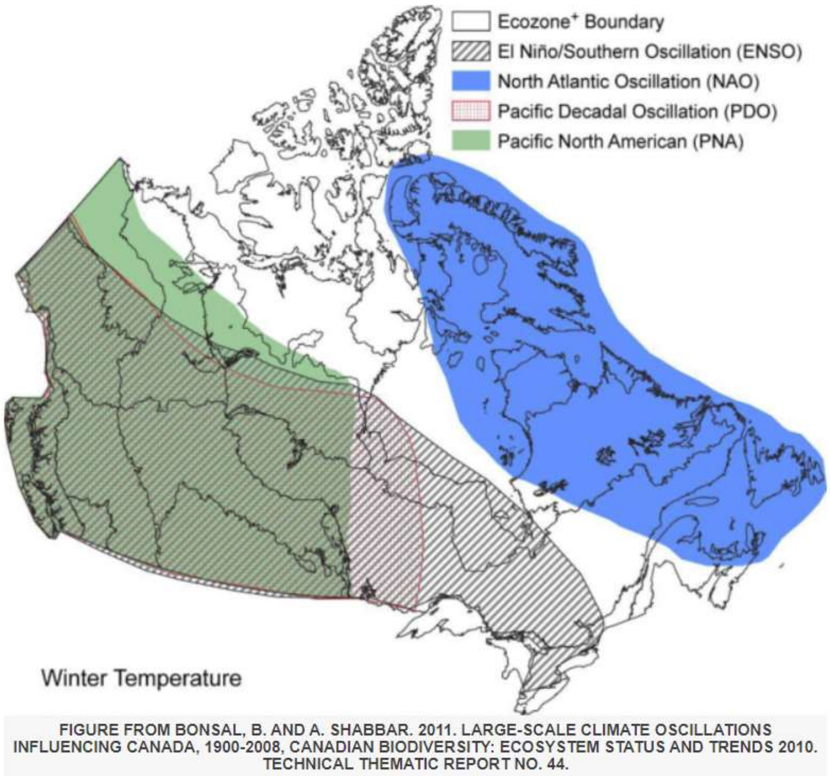

Figure 3: Teleconnections influencing in Canada Region

a. North Atlantic Oscillation (NAO)

North Atlantic Oscillation (NAO) index is primarily based totally at the surface sea-stage pressure distinction among the Subtropical (Azores) High and the Subpolar Low. It is quite simple to measure, it's just the difference in pressure between two points over a period of time across the North Atlantic. Sometimes the pressure difference is high and the other the pressure difference is not so strong, and this variation is NAO.

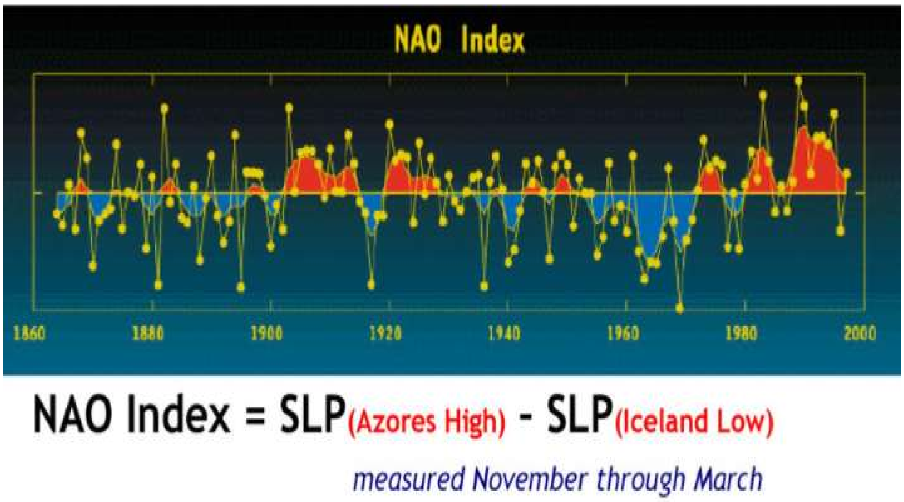

Figure 4: NAO Teleconnection

This pressure pattern is the reason why we normally get westerly winds across the UK. The difference in pressure dictates how strong those winds are. When we have positive NAO, the difference in pressure is large, there is a strong gradient. They are bringing mild air from the Atlantic and that leads in winter months to mild and wet conditions and potentially stormy winds too.

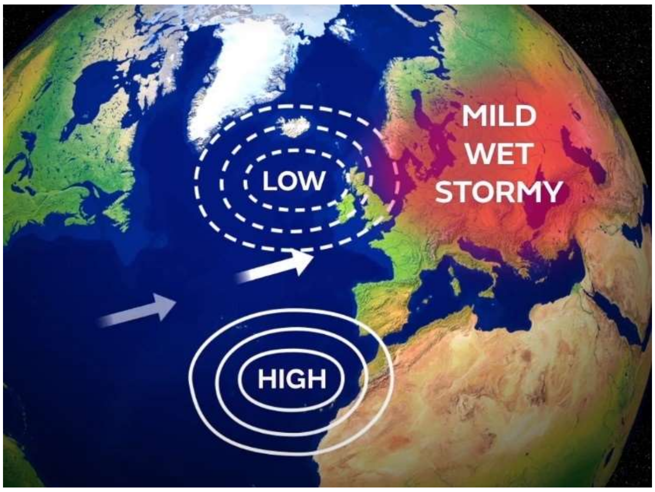

Figure 5: NAO Teleconnection

When we have negative NAO, the pressure difference is weaker, the westerly winds are weaker, there are great chances for easterly winds to come across the UK. In winter they bring cold air. And at this point there is a greater chance for a snowier winter.

The positive phase of the NAO displays below-normal heights and pressure throughout the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative segment displays a contrary pattern of height and pressure anomalies over those regions.

Both phases of the NAO are related to basin-wide adjustments withinside the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport, which in turn outcomes in adjustments in temperature and precipitation patterns frequently extending from eastern North America to western and central Europe.

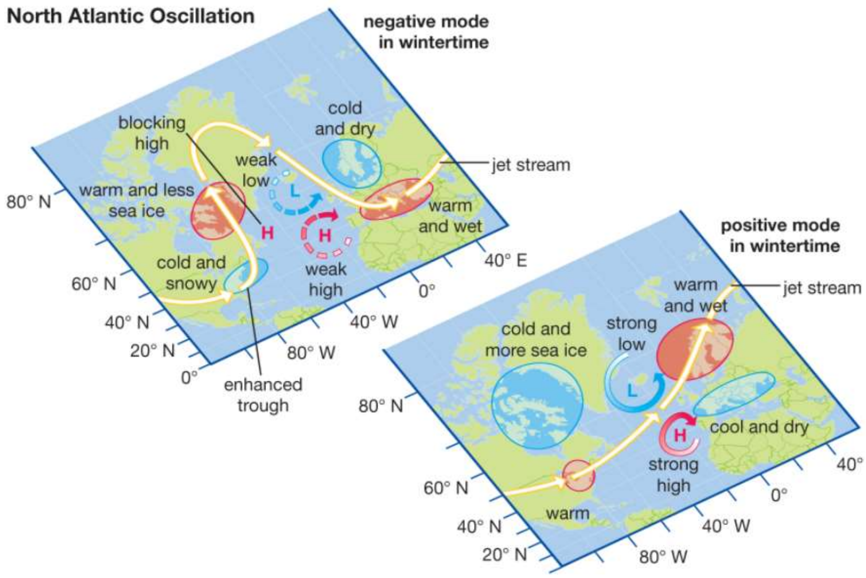

Figure 6: NAO positive and negative phase

The NAO index is obtained by projecting the NAO loading pattern to the daily anomaly 500 millibar height field over 0-90°N. The NAO loading pattern has been chosen as the first mode of a Rotated Empirical Orthogonal Function (EOF) analysis using monthly mean 500 millibar height anomaly data from 1950 to 2000 over 0-90°N latitude.

b. EL Nino Southern Oscillation

Temperature in the equatorial Pacific Ocean rises 0.5 degrees Celsius over the historic average for three consecutive months, and once atmospheric conditions and rainfall patterns shift accordingly- Scientists officially declare this as an El Nino. An El Nino event takes place about every 2-7 years. Normal east to west trade winds over the

Pacific weakens. And Warm water that normally travels westward is now moving towards the east. Moisture then rises into the air and the effects of El Nino are felt across America. Effect of El Nino in the ocean, warm water pushes the cold water downward. Noticeable repercussions in the western US and Central (Central America is part of North America, along with Canada, the United States, Mexico, and the Caribbean Island countries) and South America - the warm air and moisture leads to increase storms, rainfalls, floods, and the increase of vector borne diseases like malaria.

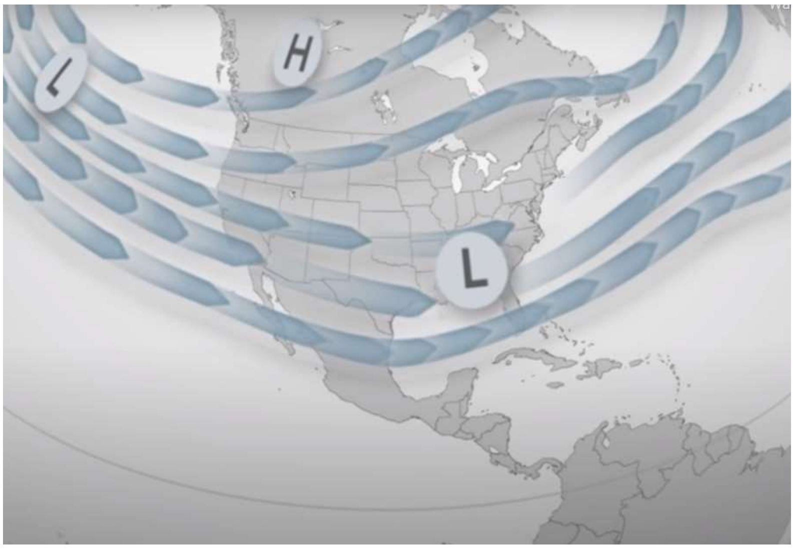

Figure 7: El Nino Teleconnection

In south east Asia and Australia, the opposite takes place. These areas suffer from droughts, wildfires and colder ocean waters. In 1997&98 the world recorded the biggest El Nino in history.

PHASE 1:

The central Pacific Ocean is warm (equatorial region). Trade winds (winds that blow in tropical regions from eastern side to western side) pushes the warm ocean current towards the Asian side. Which makes the western Pacific Ocean (around New Zealand, Australia and Indonesia) warm. The Warm Ocean current affects the surrounding atmosphere by increasing the temperature as well as the moisture content. And as we know that warm air rises high into the atmosphere through the convection process (is the process of heat transfer by the bulk movement of molecules within fluids such as gases and liquids.) results in formation of clouds and then it rains. The warm air then travels towards the eastern Pacific Ocean (region near South America, Ecuador and Peru).

Figure 8: ENSO Phase- 1

The warmer air when it goes up reaches the end of the troposphere, and as we know that the top of the atmosphere is cold. When warm air meets cold air, it slowly loses its moisture content and the air becomes dry. Which travels towards eastern pacific side and comes down over the Peruvian coastal region, making the region cold. This pattern of rising air in the West and falling in the east continues also known as Walker circulation.

PHASE 2: EL NINO (warm ocean current)

Trade winds are weak (few months in a year), the warm ocean currents don't experience any push. So, the warm pool of ocean water at western Pacific slowly moves towards the central and eastern side of the Pacific Ocean. This is what the oscillation refers to. Warm ocean current is replacing (cold water is dense and it settles down in deep ocean, and warm water takes over on the surface of the ocean) cold ocean current which is present in central and eastern pacific. When this warm ocean current moves everything associated with it (like the convection process, and formation of rain clouds) moves. Walker circulation that we have seen in phase 1 (looping pattern) breaking into 2 parts. As a result, the ocean temperature near Australia is cool and there is no rain, though the inland parts of Australia witness a severe drought condition but on the other hand near the Peruvian coast the warm pool of ocean currents brings heavy rain and floods to the American continent.

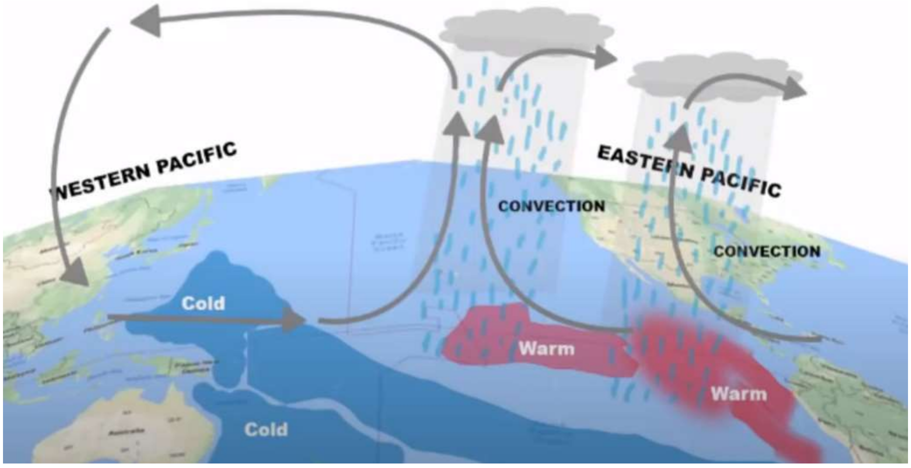

Figure 9: ENSO Phase- 2

PHASE 3: LA NINA (cold ocean current)

In this phase the trade winds are strong, they move the warm ocean currents from eastern pacific to western Pacific. Cold water is dense and it settles down in the deep ocean, the temperature of the ocean surface is warm. And because of the trade winds, the cold water from the deep ocean immediately comes up to the surface known as Thermocline (rising path of water temperature). The rest of the process is the same as in phase1. The western Pacific region (around New Zealand, Australia and Indonesia) gets heavy rains. The effect of La Nina is more on these countries than EL Nino [6].

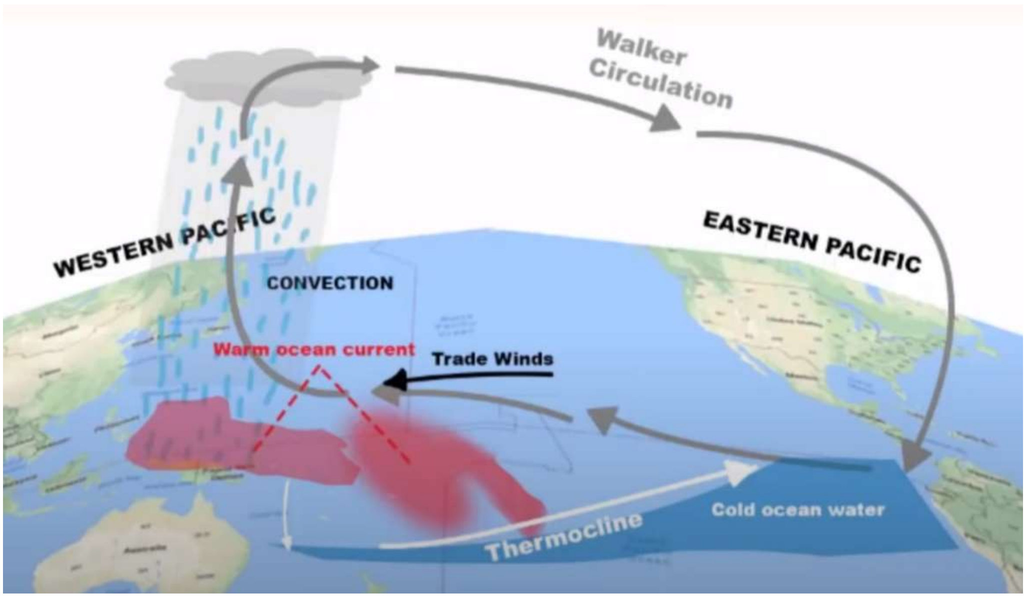

Figure 10: ENSO Phase- 3

c. Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with the better-known El Niño/Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in the Pacific Basin and the North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. When SSTs are anomalously cool in the interior North Pacific and warm along the Pacific Coast, and when sea level pressures are below average over the North Pacific, the PDO has a positive value. When the climate anomaly patterns are reversed, with warm SST anomalies in the interior and cool SST anomalies along the North American coast, or above average sea level pressures over the North Pacific, the PDO has a negative value (Courtesy of Mantua, 1999).

The NCEI PDO index is based on NOAA's extended reconstruction of SSTs (ERSST Version 5). It is constructed by regressing the ERSST anomalies against the Mantua PDO index for their overlap period, to compute a PDO regression map for the North Pacific ERSST anomalies. The ERSST anomalies are then projected onto that map to compute the NCEI index. The NCEI PDO index closely follows the Mantua PDO index.

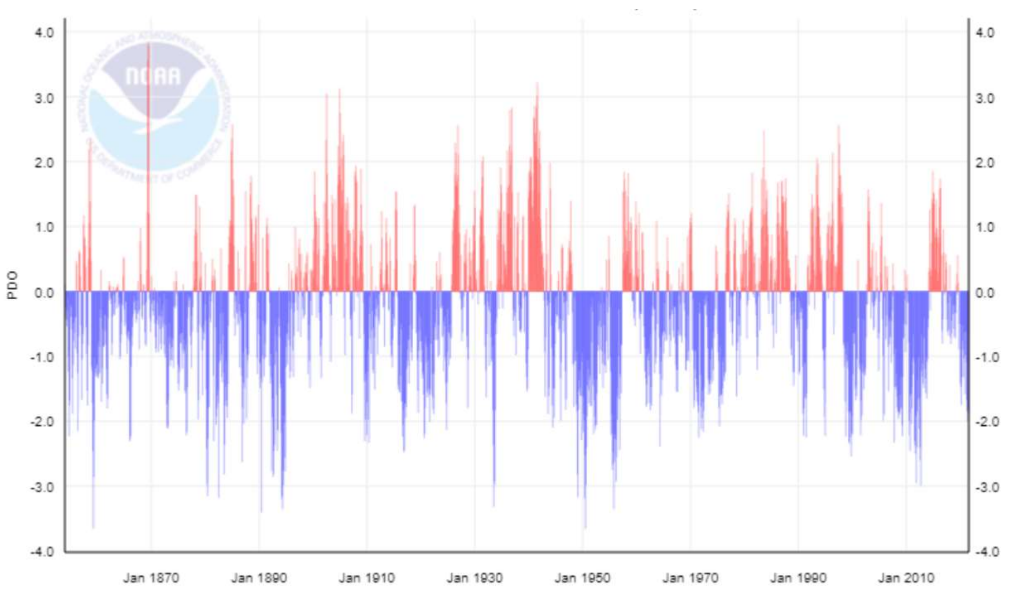

Figure 11: Pacific Decadal Oscillation

3. CONNECTION BETWEEN COMPOUND FLOODING AND TELECONNECTIONS

Hydro-climatic forecasting is a crucial issue, particularly for those regions suffering increased rainfall intensity and/or reoccurring, persistent droughts in a changing climate. An established method for hydro-climatic forecasting is the usage of “teleconnection” patterns. Compound event caused due to cooccurrence of high precipitation and high total water level or high stream flow and total water level or high streamflow and skew surge or high precipitation and skew surge. There is a high probability that it has a connection with teleconnection. A longer historical perspective of climatic changes at interannual and decadal time scales can aid in analysing the correlation between teleconnection and compound flooding. The usage of teleconnection patterns for streamflow forecasting has been published by a number of previous studies. Earlier work can be exemplified by Kahya and Dracup (1993) and Hamlet and Lettenmaier (1999); whereas the former examined the relationship between ENSO and the unimpaired streamflow over the contiguous United States, the latter devised an empirical model for forecasting of the Columbia River streamflow using ENSO and PDO. Another earlier work by Chiew et al. (1998) linked ENSO to the Australian streamflow, and then Chiew and McMahon (2002) later extended their discussion to global ENSO-streamflow teleconnection.

The dependence between extreme storm surge and extreme rainfall is assessed under different ENSO phases and in different seasons. Observed cumulative rainfall data, observed storm surge and modelled storm surge were used for many locations in Australia [7]. In 2017 Hurricane Harvey provided another example of compound flooding. From a meteorological perspective, the simultaneous occurrence of a high-pressure system over the western United States pushed the storm back into the Gulf of Mexico instead of allowing it to follow the typical track further inland, where the system would have dissipated much faster. Instead, Harvey circled back and made landfall a second time in the greater Houston area [3]. Parallel to the Russian heatwave, a record-breaking flood occurred in Pakistan, which affected more than 20 million people21. There is strong evidence that these features are connected through atmospheric dynamic

It is evident from history that the study of correlation between compound events and teleconnection is important. Given that most previous climate-related studies of hazards focus on single drivers, and given the evidence that the events that are particularly worrisome are typically multivariate in nature as illustrated by the examples in this manuscript, we encourage a deeper focus on multivariate drivers and hazards of large climate-related impacts that contributes to societal or environmental risk.

4. HISTORY OF CYCLONES IN CANADA

Canada is the second largest country in the world sharing its boundaries with the Arctic Ocean towards north, North Atlantic Ocean in the east and North Pacific Ocean towards the west. The understanding of these teleconnection patterns over multidecadal time-scale helps in prediction of climate and natural disasters. It is important because floods are the second costliest natural disaster in Canada. And it's also estimated that flood event risk over 1.7 million Canadian homes over the next 5 years, and the federal government would require about $3.4 billion on flood disaster relief. And hence a flood alarming system can reduce the negative consequences of future floods using the data types such as precipitation, total water level, stream flow and geopotential heights which are available from decades and centuries of practical observations.

Floods are primarily caused by naturally occurring changes in the height of rivers, lakes and oceans. According to Public Safety Canada, floods are the most common natural hazard in the country and among the costliest. Historic floods have occurred across Canada, with many of the worst happening on major river systems that pass through populated areas. Scientists predict that flooding linked to the impacts of climate change will increase as the 21st century progresses, particularly in coastal areas of the country.

The cause of flooding is due to excessive runoff following heavy rains. The rate of runoff increases by conversion of open land to water resistant surfaces like buildings and roads. And by removal of vegetative cover, i.e., changing forest land into crop land. For much of Canada, spring is the peak flood season.

Canada is usually only hit with weak storms, due to the generally cool waters immediately offshore. However, some hurricanes can strike the area full force as the warm Gulf Stream extends fairly close to Atlantic Canada. Due to the cool waters for a great distance from the Pacific coast of Canada, there has never been a storm of any intensity to directly affect the Pacific coast. On occasion tropical systems can transition into, or be absorbed by, non-tropical systems that strongly affect western Canada, most notably by the remnants of Typhoon Freda that were absorbed by the Columbus Day Storm of 1962. September 9, 1775: The 1775 Newfoundland hurricane killed over 4,000 in Newfoundland. Not only is it the earliest recorded Canadian hurricane, it is also by far the deadliest. Sometimes, a hurricane will make landfall in the United States and continue northward to dissipate over (or partially over) Canada. Till date the number of events every year has only increased.

Month	Number of recorded storms making landfall in Canada while still tropical since 1950
January	0
February	0
March	0
April	0
May	0
June	0
July	4
August	6
September	11
October	5
November	1
December	0

Figure 12: Number of storms listed by month

Cause of flooding in our region of interest St. John's, Newfoundland and Labrador (47.56667 -52.71667167)

Type of Event	% Occurrence of Flood Events by Type of Event
Rainfall	72%
Coastal Flooding	17%
Ice Jam	5%
Snowmelt	2%
Other	1%
N/A	3%

Figure 13: Cause of flooding in St John's, Newfoundland and Labrador

CHAPTER-2

METHODOLOGY

The dependence between extreme total water level and other drivers of flooding and its correlation with teleconnection is found using the following steps:

1) Datasets and selection of station

The area of study Canada (47.56667 -52.71667167) a city on Newfoundland Island off Canada's Atlantic coast, is the capital of Newfoundland and Labrador province. We have downloaded dataset for teleconnections from National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information. Merge the data frames: random variables (total water level, precipitation, streamflow and skew surge with timeseries) responsible for flooding of the location and teleconnections (NAO, PDO with time series).

2) Find the threshold for the level of TWL

From Literature we can see the location of 463 Canadian precipitation stations, together with the threshold values used for the POT (Peak Over Threshold) analyses.

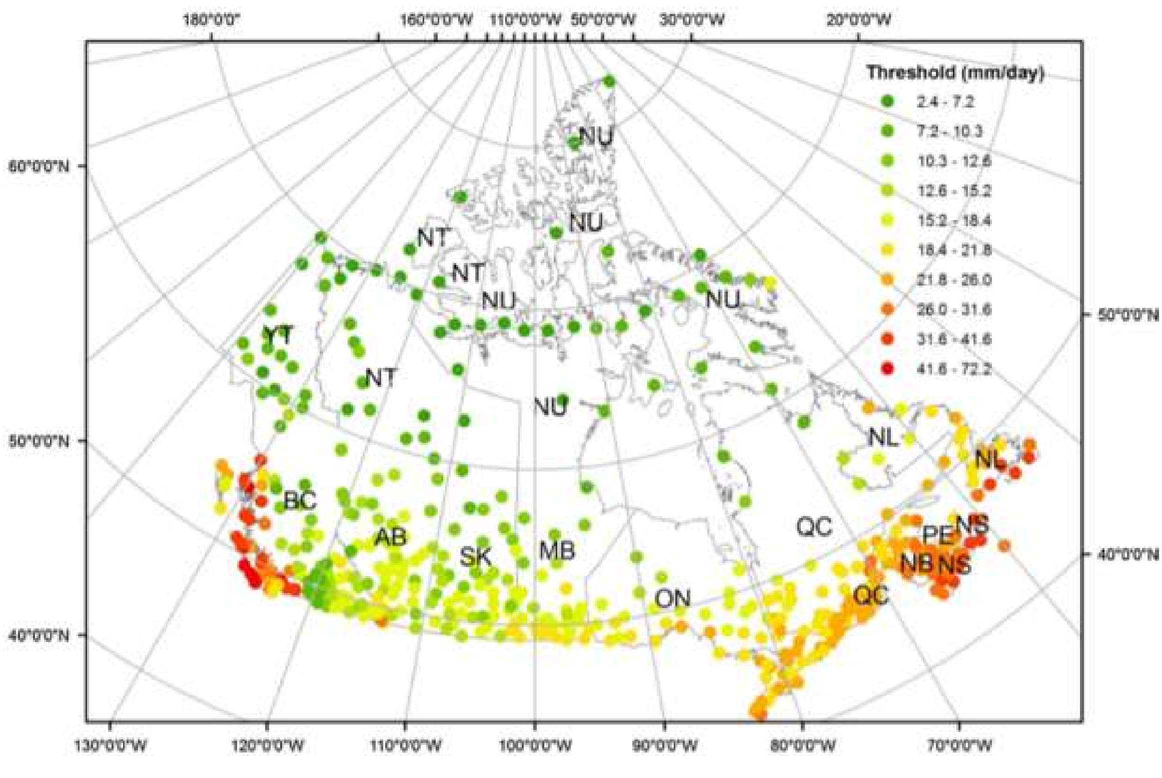

Figure 14: Threshold for the Province or territories of Canada: AB Alberta, SK Saskatchewan, MB Manitoba, NL New Foundland and Labrador, PE Prince Edward Island,

NS Nova Scotia, NT North west Territories, NU Nunavut, ON Ontario, NB New Brunswick, YT Yukon Territory, BC British Columbia, QC Quebec

After downloading the data, we can find the 95 percentile of the total water level by using the NumPy function np.percintile to obtain the threshold value, similarly to obtain threshold values of precipitation and streamflow.

3) Extracting time-series of high precipitation and sea-levels

We use the threshold value found in step 2 to extract the time series. All the days on which the total water level is greater than the threshold value are the compound events. Then, select the highest precipitation within +/- 1days of this event and create individual data frames (tables) of the extracted compound events.

4 Scenarios:

1) Threshold Total Water level and highest precipitation in +/-1 days.
2) Threshold Total Water level and highest streamflow in +/-1 days.
3) Threshold Total Water level and highest skew surge in +/-1 days.
4) Threshold Precipitation and highest skew surge in +/-1 days.

4) Frequency of compound events in all years

We find the frequency of compound events for all the four scenarios by counting number of rows in table. i.e., number of compound events. Now sort the data by number of events in each annual year and find the Man- Kendall trend test (analyses the sign of the difference between later-measured data and earlier-measured data.) to analyse the frequency behaviour of the trend of compound events in all these years. Repeat the same for daily scenario.
We will consider total water level or TWL, precipitation or PCP, streamflow or streamflow and skew surge or s_surge.

5) Intensity of compound events in all years

After obtaining the empirical probabilities of all the random variables (total water level, precipitation, streamflow and skew surge). We find the intensities by adding two random variables taken into account in the scenario.

1) Intensity = empirical probability of Total Water level + empirical probability of precipitation.
2) Intensity = empirical probability of Total Water level + empirical probability of streamflow.
3) Intensity = empirical probability of Total Water level + empirical probability of skew

surge.
4) Intensity = empirical probability of Precipitation + empirical probability of skew surge.

Find the Man- Kendall trend test (analyses the sign of the difference between later-measured data and earlier-measured data.) to analyse the intensity behaviour of the trend of compound events for all the scenarios.

6) Relationship between different teleconnections and Compound events

We calculate the frequency of compound events in positive and negative phase for NAO (North Atlantic Oscillation) and PDO (Pacific Decadal Oscillation) for all the 4 scenarios. And form different data frames for negative and positive phase of the teleconnection. And now find the Kendall's correlation between the positive and negative phase of teleconnection with intensity and frequency of 4 scenarios.

7) Seasonal analysis

Perform all the above steps for different seasons. To obtain which season is having more frequency (greater number of compound events), intensity and its correlation with negative and positive phases of the teleconnections in all the scenarios discussed in step 3.

Season1: January to March

Season 2: April to June

Season 3: July to September

Season 4: October to December

CHAPTER-3

RESULTS

1) The threshold for TWL: 1.65

2) Analysing the trend in frequency: increasing using Mann_Kendall_Test trend

3) analysing the trend in intensity: no trend (TWL empirical probability + precipitation empirical probability) using Mann_Kendall_Test trend

4) Daily data total water level trend: increasing

5) Daily data precipitation trend: no trend

6) Daily data streamflow trend: increasing

7)correlation between NAO index and intensity: Samples are correlated - Kendall correlation coefficient: -0.096

8)Frequency of compound events in NAO positive phase: 362
and negative phase: 421

9)Correlation between NAO positive phase and intensity: Samples are uncorrelated Kendall correlation coefficient: 0.034

10)correlation between NAO negative phase and intensity: Samples are uncorrelated Kendall correlation coefficient: -0.049

11)Frequency of compound events in all months of all years: increasing

12)correlation between NAO index and frequency: Samples are uncorrelated Kendall correlation coefficient: -0.065

13)Correlation between NAO positive phase and frequency: Samples are uncorrelated Kendall correlation coefficient: -0.021

14)Correlation between NAO negative phase and frequency: Samples are uncorrelated Kendall correlation coefficient: -0.002

15) Kendall correlation between NAO index and intensity for NAO negative and positive phases

Negative phase -monthly average intensity and NAO index for:

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.062
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.067
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.054

- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.070

Positive phase- monthly average intensity and NAO index correlation for:

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.043
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.051
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.062
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.018

16) Intensity Mann Kendall trend test for NAO negative and positive phases

Negative phase- monthly average intensity Mann Kendall trend test results

- TWL and PCP - no trend
- TWL and streamflow - no trend
- streamflow and skew surge - no trend
- PCP and skew surge - no trend

Positive phase- monthly average intensity Mann Kendall trend test results

- TWL and PCP - no trend
- TWL and streamflow - no trend
- streamflow and skew surge - increasing
- PCP and skew surge - no trend

17) Seasonal correlation between NAO index and intensity for NAO negative and positive phases

January to March

Kendall correlation between NAO index and intensity for NAO negative and positive phases

Negative phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.114
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.041
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.041
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.095

Positive phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.053
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient:0.027
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.080
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.039

April to June

Kendall correlation between NAO index and intensity for NAO negative and positive phases

Negative phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.037
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.183
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.110
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.056

Positive phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.067
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.156
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.244
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.022

July to September

Kendall correlation between NAO index and intensity for NAO negative and positive phases

Negative phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.394

- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.364
- TWL and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.303
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.303

Positive phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.061
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.121
- TWL and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.121
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.061

October to December

Kendall correlation between NAO index and intensity for NAO negative and positive phases

Negative phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.062
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.067
- TWL and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.054
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.070

Positive phase- monthly average intensity and NAO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.043
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient:0.051
- TWL and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.062
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.018

18)Seasonal frequency in NAO negative phase

- ➔ January to March: 164 compound events
- ➔ April to June: 17 compound events
- ➔ July to September: 15 compound events
- ➔ October to December: 225 compound events

19)Seasonal frequency in NAO Positive phase

- ➔ January to March: 200 compound events
- ➔ April to June: 13 compound events
- ➔ July to September: 18 compound events
- ➔ October to December: 131 compound events

Pacific decadal oscillation index correlation with intensity (sum of empirical probability of random variables: TWL, PCP, streamflow, skew surge)

1)correlation between PDO index and intensity: Samples are uncorrelated - Kendall correlation coefficient: 0.002

2)Frequency of compound events in PDO positive phase: 333
and negative phase: 439

3)Correlation between PDO positive phase and intensity: Samples are uncorrelated Kendall correlation coefficient: 0.018

4)correlation between PDO negative phase and intensity: Samples are uncorrelated Kendall correlation coefficient: 0.010

5)Frequency of compound events in all months of all years: increasing

6)correlation between PDO index and frequency: Samples are uncorrelated Kendall correlation coefficient: 0.076

7)Correlation between PDO positive phase and frequency: Samples are uncorrelated Kendall correlation coefficient: -0.006

8)Correlation between PDO negative phase and frequency: Samples are uncorrelated Kendall correlation coefficient: 0.077

9) Kendall correlation between PDO index and intensity for PDO negative and positive phases
Negative phase -monthly average intensity and PDO index for:

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.030

- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.105
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.086
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.028

Positive phase- monthly average intensity and PDO index correlation for:

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.004
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: 0.142
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.115
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.006

10)Seasonal correlation between PDO index and intensity for PDO negative and positive phases

January to March

Kendall correlation between PDO index and intensity for PDO negative and positive phases

Negative phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.090
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.125
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.109
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.002

Positive phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.034
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient:0.197
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.156

- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.043

April to June

Kendall correlation between PDO index and intensity for PDO negative and positive phases

Negative phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.180
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.405
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.494
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.180

Positive phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.180
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: 0.289
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.156
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.315

July to September

Kendall correlation between PDO index and intensity for PDO negative and positive phases

Negative phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.105
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: 0.010
- streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.105
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.181

Positive phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: -0.222
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.167
- 3) streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.222
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.278

October to December

Kendall correlation between PDO index and intensity for PDO negative and positive phases

Negative phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.030
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient: -0.105
- 3) streamflow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.086
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.626

Positive phase- monthly average intensity and PDO index

- TWL and PCP - Samples are uncorrelated with Kendall correlation coefficient: 0.004
- TWL and streamflow - Samples are uncorrelated with Kendall correlation coefficient:0.142
- stream flow and skew surge - Samples are uncorrelated with Kendall correlation coefficient: 0.115
- PCP and skew surge - Samples are uncorrelated with Kendall correlation coefficient: -0.006

11)Seasonal frequency in PDO negative phase

- ➔ January to March: 196 compound events
- ➔ April to June: 13 compound events
- ➔ July to September: 22 compound events
- ➔ October to December: 208 compound events

12)Seasonal frequency in PDO Positive phase

- ➔ January to March: 168 compound events
- ➔ April to June: 16 compound events
- ➔ July to September: 11 compound events
- ➔ October to December: 138 compound events

CONCLUSION

- Compound events has shown increasing trend in frequency and intensity from 1965 to 2011 both daily and annually.
- There are a greater number of compound events in negative phase than in positive phase for NAO teleconnection.
- There are a greater number of compound events in negative phase than in positive phase for PDO teleconnection.
- There are a greater number of compound events in January to March and October to December for NAO negative and positive phase.
- There are a greater number of compound events in January to March and October to December for NAO negative and positive phase.

So, considering the following points we can draw the conclusion that number of compound events has been increasing over the years and it is observed mostly in October to March.

REFERENCES

[1] Ward, Philip J., et al. "Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries." Environmental Research Letters 13.8 (2018): 084012.

[2] Wahl, Thomas, et al. "Increasing risk of compound flooding from storm surge and rainfall for major US cities." Nature Climate Change 5.12 (2015): 1093-1097.

[3] Zscheischler, Jakob, et al. "Future climate risk from compound events." Nature Climate Change 8.6 (2018): 469-477.

[4] Nigam, S., J. Pyle, and J. A. Curry. "Teleconnections. Encyclopedia of atmospheric sciences." (2003): 2243-2269.

[5] Ionita, Monica, and Viorica Nagavciuc. "Forecasting low flow conditions months in advance through teleconnection patterns, with a special focus on summer 2018." Scientific reports 10.1 (2020): 1-12.

[6] Zhang, Tao, Judith Perlwitz, and Martin P. Hoerling. "What is responsible for the strong observed asymmetry in teleconnections between El Niño and La Niña?." Geophysical Research Letters 41.3 (2014): 1019-1025.

[7] Wu, Wenyan, and Michael Leonard. "Impact of ENSO on dependence between extreme rainfall and storm surge." Environmental Research Letters 14.12 (2019): 124043.